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SENSOR BASED NITROGEN MANAGEMENT FOR COTTON PRODUCTION IN COASTAL PLAIN SOILS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Biosystems Engineering

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by
Wesley M. Porter
August 2010

Accepted by:
Dr. Ahmad Khalilian, Research Advisor
Dr. Young J. Han, Academic Advisor
Kendall R. Kirk

ABSTRACT

The main objective of this four year study was to develop, refine, and employ sensor-based algorithims to determine the mid season nitrogen requirements for production of irrigated and dryland cotton (*Gossypium hirsutum L.*) in Coastal Plains soils. The secondary objective of the project was to develop and test equipment for variable rate application of nitrogen to commerical cotton fields utilizing the developed algorithim. Two different production fields at Clemson's Edisto Research and Education Center near Blackville, SC were used. One field, equiped with an overhead irrigation system, was used during the 2007 and 2010 production seasons to develop the algorithm for irrigated cotton. The second field was used during the 2008 and 2009 seasons for developing the algorithm for dryland cotton nitrogen management. Each field was divided into three separate zones based on soil electrical-conductivity (EC) data. The algorithim was developed using "Nitrogen Ramp Calibration Strips" (N-RCS) and varied prescription rate nitrogen plots. Three N-RCS were established in each production field, one per EC zone. The N-RCS was composed of 16 nitrogen rates (0 to 168.13 kg-N/ha) on 5.0 meter intervals. For the varied prescription rate plots, five different rates of nitrogen fertilizer (0, 33, 67, 100, and 134 0kg-N/ha) were replicated four times in plots of each zones using a Randomized Complete Block desgin arrangement.

Optical sensor readings were collected from the test plots to determine cotton plant Normalized Difference Vegetation Index (NDVI) at different growth stages. The sensor readings were used to develop two different algorithims to be used in the estimation of mid-season nitrogen need of the cotton plants. Sensor readings collected

between 40 and 60 days after planting were highly correlated (average $R^2 > 0.80$) with the final yield and nitrogen requirement. The Response Index (RI), the extent to which the crop will respond to additional N, was calculated by dividing the highest NDVI reading from N-RCS and N-rich strips (established in each zone) by NDVI measurements of the adjacent area in each zone. In Season Estimated Yield (INSEY) was used along with the actual field yield to produce a yield potenial (YP_0) for each growing season one for irrigated cotton and one for dry land cotton. The algorithm is N rate= (YP_0*RI-YP_0)*%N/NUE. Where the %N is the percentage of nitrogen in cotton seeds after harvest and NUE is the nitrogen use efficiency, typically 50%.

The algorithim developed from the 2008 growing season was used during the 2009 growing season to estimate the amount of mid-season side-dress nitrogen required for specific research plots in the production field. The algorithm reccommended a reduced rate of nitrogen (40% less) across the entire field compared to the normal grower practice (101 kg-N/ha) with no reduction in cotton yield. Similar results were obtained when using the Oklahoma State University Algorithm.

Three different methods of nitrogen application were tested, one during each of the growing seasons of 2007-2009. During the 2007 production year a typical pull behind nitrogen side-dress applicator with a ground driven piston pump was used. This applicator was the most crude and innacurate method of fertilizer application used during the study. During the 2008 production year a custom built applicator was used. The applicator operated using a hydraulic pump in combination with an in-cab control system. The rates were adjusted using various orifices and solenoids. The final applicator, tested in 2009, was a typical three point hitch pull behind side-dress coulter rig controlled using a hydraullic Rawson controller for the piston pump. The three point hitch applicator has the potential to be the most accurate and versatile of any used during the project.

Various equipment was tested throughout the study to determine the best and most accurate way to apply the mid-season N algorithm fertilizer recommendation. The parameters of specific equipment such as the GreenSeekers® for measuring NDVI were tested to determine the true accuracy based on height above crop canopy and time of day, which is related to the sun angle and solar radiation. The results of this test proved that the sensor is height sensitive with an optimal height range of .8128 to 0.9144 meters. It was determined from the test that the sensors are not sun angle sensitive and return a non statistical difference in readings throughout the day between the hours of 10 a.m. and 8 p.m. (EST). The sensors returned a lower number once the sun had set but the main reason for the lower number is due to the physiological response of the plant. It was found due to the response of the plant that it is not possible to obtain an accurate sensor reading at night. Sensor readings taken from two different travel directions were found to not be statistically different, thus the sensors were found not to be travel direction specific. The data remained constant independent of the orientation of the field. This study confirmed that there is a significant possibility to accurately predict in-season expected yield (INSEY) in cotton using mid-season NDVI sensor readings in conjunction with an accurate prediction of a reduced nitrogen requirement without a significant reduction in yield.

Two different ultra-sonic height sensors were tested during the growing season of 2010 to determine the feasibility of determining plant height on-the-go. Both sensors gave promising results to accurately predict plant height with more testing and reprograming.

DEDICATION

I would like to dedicate this thesis to my parents, Mark and Carol Porter for their encouragement for me to attend college and do whatever makes me happy, for without their support I would have never been able to make it this far.

I would also like to dedicate this thesis to all of my true friends who have been there along the way to keep me motivated, driven, and hardworking.

ACKNOWLEDGMENTS

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I would like to give a special thanks to Kendall R. Kirk an advisor, teacher, and friend of mine for which one could ask no better.

I would like to thank the South Carolina Cotton Board for the monetary support of this project because the project would not have been possible without them.

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Lastly, I would like to thank my friends and family for getting me to where I am today and keeping me on that track.

TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

List of Figures (Continued)

List of Figures (Continued)

List of Figures (Continued)

Figure Page

CHAPTER ONE

DEVELOPMENT, REFINEMENT, AND TESTING OF A SENSOR-BASED ALGORITHM FOR NITROGEN APPLICATION OF COTTON UNDER DRYLAND AND IRRIGATED CONDITIONS IN COASTAL PLAIN SOILS

1.1 INTRODUCTION

Total cotton acreage in the United States has varied over the years and currently is below the 1964 average. The average rate of nitrogen (N) applied to cotton has increased gradually since the late 1970's and is currently near 100.88 kg-N/ha. The lint production per pound of fertilizer N applied to cotton has remained virtually the same since 1964 (Snyder et al., 2005). Growers are currently spending more money on inputs on the same amount of crop grown, since the 1960's with the production of lint per pound of fertilizer remaining constant.

The parallel rising trend of nitrogen and gasoline prices coupled with a constant cotton commodity price since 2003 are leaving producers with a challenging decision to make. A breakeven point on how much fertilizer to apply to produce enough lint to be profitable must be decided. A method and tool must be devised to allow producers to make an educated decision on the amount of nitrogen they should apply to any given field, either irrigated or dry land, during any given growing season. The method will allow the amount of nitrogen needed for the particular conditions to be applied at variable or reduced rates to reduce the input costs of the lint production. The devised method can be most easily implemented in the form of a nitrogen prediction algorithm. The algorithm should be refined an evaluated under actual field conditions to ensure its accuracy.

Nitrogen management is one of the most important practices in high-yielding cotton production systems. Both N deficiency and excess N negatively affect plant growth, boll retention, lint yield, and fiber quality. Insufficient N supply often reduces leaf area, leaf photosynthesis rate, and biomass production in cotton resulting in low lint yield and poor fiber quality. Irrigated cotton has a higher yield potential than dry land cotton. However, lint yield of irrigated cotton does not always continue to increase as the amount of N fertilizer is increased. Excess use of N fertilizer increases not only production costs but also the potential for environmental problems, such as groundwater contamination by NO_3^- leaching (Zhao 2009 et al.). The elimination of water stress allows an irrigated crop to naturally have a higher yield potential. This means that the irrigated crop can better use the available nutrients and produce at an elevated level compared to a dry land crop. The higher yield potential of irrigated cotton means that two separate methods of nitrogen prediction must be developed, one for the dry land crop and one for the irrigated crop.

Nutrient management is an important factor in the production of cotton. It begins at the level of soil texture. Different soil textures have different nutrient holding capacities, thus management zones must be designed to account for the high variation of soil textures found in the Central Savannah Valley Region of the United States.

Nutrient management is very important in cotton fiber production. An excessive amount of nitrogen can cause poor fiber quality, thus reducing the sale price of the cotton. Plant physiological responses are directly related to nutrient management. An over application of nitrogen can lead to increases in vegetative growth, while an under application can lead to a low boll loading.

1.2 OBJECTIVES

Main Objective: To develop an algorithm that utilizes an optical sensor and soil Electrical-Conductivity to predict mid-season nitrogen requirement for cotton on irrigated and dry land fields in the southeastern United States.

The specific objectives were to:

- To develop/refine algorithms for predicting the mid-season side-dress nitrogen requirements for irrigated and dry land cotton utilizing plant normalized difference Vegetation index (NDVI) and soil electrical conductivity data.
- To determine the efficacy of the Clemson algorithms compared to a typical grower's practice and other algorithms developed for southern USA
- To determine the effects of nitrogen application rates on crop parameters such as fiber quality and seed nitrogen contents.

1.3 REVIEW OF LITERATURE

The focus of this section is to review the literature related to the study objectives. It consists of five subheadings including:

1. Nitrogen Use by Cotton
2. Yield Goals
3. Remote-Optical Sensors
4. Optical Sensor Based Nitrogen Management
5. Lint Yield and Fiber Quality

1.3.1 Nitrogen Use by Cotton

Excessive N application to cotton is an unnecessary cost and a potential cause of elevated ground water N concentrations (Hunt et al. 1997). Poor N management can cause detrimental effects on yield either due to over or under application of the nutrient. Over application of N can cause excessive vegetative growth, increased susceptibility to aphids and boll rot, delayed crop maturity, defoliation difficulty, and in some instances a decrease in yield. An under-estimation and application of N can cause detrimental losses to yield proportional to the fertilizer shortfall, depletion of the soil N reserve, and depletion of soil fertility (Nichols and Green 2009). The most efficient method in which to supply N to any plant, that is widely accepted, is to have N in place only at the time when the plant is in need (Arnall 2008). Boquet and Breitenbeck (2000) observed a maximum N uptake of 2.9 to 4.3 kg ha^{-1} occurring during the period of 49 to 71 days after planting (DAP). Maximum uptake was recorded between early square and early bloom in both Acala and Pima cotton by Fritschi et al. (2004a).

A four year study in Florida found that the optimum time to apply N is at the first pinhead square stage. The results suggested that on heavier soils only one side-dress application was needed, however, on sandier soils two N applications sufficed, at squaring and at first bloom (Wright et al., 2003). The case has been proven that different soil textures and types require different nutrient management to ensure the plant receives the proper amount of nitrogen at the proper times.

The environment has to be considered when making fertilizer timing and rate decisions. In most cases split applications are more beneficial and are used to prevent losses. Mullins et al. (2003) suggested that when leaching potentials are great in sandy soils of the Coastal Plain, N should be applied in a split application of at least two or more applications. The split application allows the plant to better utilize the available nitrogen without environmental losses due to excessive rainfall and other factors.

1.3.2 Yield Goals

Cotton nitrogen recommendations are determined using yield goals based on estimating crop removal of N. Cotton Incorporated suggests that available N can come from 5 sources: atmospheric deposition, N mineralized from soil organic matter, residual soil nitrate N measured prior to planting, N credits from preceding crops, and N derived from animal wastes and other organic amendments. According to Arnall (2008) the result of using yield goals is explained to be the minimum quantity of fertilizer N needed to ensure sufficient N to achieve the yield goal. Fertilization based on yield goals is a vast improvement over simply applying the same amount of N year after year, especially when credits and residual N are accounted for (Arnall 2008). This can be a very limited practice depending on the knowledge of historical field average yields, and the effect of uncontrollable environmental factors on yield each year.

1.3.3 Remote Optical Sensors

The modern applications of remote sensing to agriculture have their foundation in pioneering work by ARS scientists William Allen, Harold Gausman, and Joseph Woolley, who provided much of the basic theory relating morphological characteristics of crop plants to their optical properties (Pinter et al. 2003). Optical sensors are seen to have an advantage over yield monitors due to their ability to collect data throughout the entire season rather than just once at the end of the growing season. Optical sensors also have an advantage over yield monitors due to their increased spatial and spectral resolution (Pinter et al. 2003). The GreenSeeker® optical sensor is an active sensor that emits two bands of light, red and Near Infrared (NIR), and measures the amount of reflectance. The value reported from this measurement is the indices termed Normalized Difference Vegetation Index (NDVI) (Arnall 2008):

$$NDVI = \frac{(NIR - R)}{(NIR + R)} \tag{1.1}$$

According to Yoon and Thai (2009) the NDVI requiring measurements of two spectral wavelengths at NIR and red spectral regions has been widely used in remote sensing as an index to estimate various vegetation properties including chlorophyll concentration in leaves, leaf area index, plant biomass, and plant productivity. The sensor works because plants with more leaf area and chlorophyll absorb higher levels of red light and blue light. Therefore, healthy plants are able to reflect more NIR than less healthy plants due to turgid and healthy mesophyll cells. The ratio of the level of reflectance of red and NIR are highly useful when using NDVI as an indirect measure of plant health (Arnall 2008). To put it simply, a high NIR reflectance and a low visible reflectance means a healthy plant while a low NIR reflectance and a high visible reflectance means an unhealthy plant with usually a more yellow color.

1.3.4 Optical Sensor Based Nitrogen Management

Cotton produced in the Coastal Plain of South Carolina is grown in fields that have tremendous amounts of within field soil variability. This soil variability usually results in the development of cotton plants with a tremendous amount of growth variability associated with them (Jones 2008). An optical sensor can be used as the solution to N management in the fields with soil variability in most cases. Read et al. (2002) noted that as the N deficiency in cotton increases, chlorophyll content and the rate of leaf expansion and canopy development will decrease. With this in mind the authors concluded that remote sensing of chlorophyll has the potential to quickly estimate cotton N status and therefore crop productivity (Read et al. 2002).

Taking an indirect approach, Raun et al. (2001) reasoned that a mid-season, remote estimate of potential yield would help growers adjust top-dress N applications based on pre-plant soil N tests, within season rates of mineralization, and projected N removal (Pinter et al. 2003). According to Earnest and Varco (2005) the utilization of canopy reflectance to determine leaf N concentrations and plant height could be a useful tool in improving N use efficiency. In a variable N rate plot study conducted at Mississippi State by Earnest and Varco an on-the-go crop reflectance sensor accurately detected cotton growth differences. The results showed NDVI correlated strongly to leaf N concentrations at peak bloom and reflectance data acquired at or after peak bloom could be useful in predicting yield. The results of a study conducted by Emerine of InTime, Inc (2006) showed a field average reduction of 50.4 kg-N/ha of N fertilizer without significantly reducing yield.

Research has shown that leaf N is correlated to reflectance in the green band and that the vegetation indices containing green reflectance are significantly correlated to leaf N concentration and N uptake. Furthermore, leaf N concentration can be an indicator of available soil N (Emerine 2006). Plant et al. (2000) observed a potential for NDVI to give a false positive indication of yield loss, because NDVI was able to indicate the presence of N stress in the cases where the deficiency did not result in a reduction of final yield (Arnall 2008). NDVI N management is still a new practice which still requires more research to better understand plant responses to sensor readings.

A statistical correlation among the NDVI sensor readings, and number of days after planting versus the N rate was found in multiple studies. In a study conducted by Khalilian et al. (2008) it was found that the optimum dates of sensing falls somewhere within the time frame of 39-67 days after emergence. Sensor readings collected before and after this range were poorly correlated with the actual yield and could not be used to accurately predict the in-season N requirements for the plant. Taylor et al. (2007) found similar results and stated there was no significant difference in NDVI readings as affected by pre-plant N rate before 38 days after planting (DAP) and after 70 DAP. The correlations found in multiple studies of sensing date and pre-plant nitrogen rate have shown that there is a possibility to predict the in-season nitrogen requirements of the cotton plant using mid-season sensor readings, however these sensor readings must be collected within a specific range of DAP to accurately predict the N requirement. The optimum range of sensing discovered in these studies falls well within the optimum range of N uptake by the cotton plant discovered in the study performed by Boquet and Breitenbeck (2000).

1.3.3 Lint Yield and Fiber Quality

Nutrient stress in upland cotton depresses lint yield, particularly of late-season fruit (bolls), and may disrupt fiber development (Read et al 2006). Adoption of precision farming is driven by cotton farmers' perceptions about the effectiveness of precision technologies in improving lint yields and reducing input costs relative to the cost of adoption (Roberts, et al. 2009). According to Snyder (2005) recent concerns about lint quality issues have been raised within the cotton industry, especially since more of the United States' production is being marketed and milled overseas. Farmer and industry concerns about length and micronaire discounts have been exposed in popular articles in the Southeast region of the United States.

In a two year study conducted by Read (2005) nitrogen deficiency decreased yield through early termination of reproductive growth. In 1999, although N-deficient cotton had low length, strength, and micronaire, values for weighted-sum micronaire (whole-plant micronaire) increased under N stress by about 12% in 0% N treatment and about 18% in 20% N treatment. Many published reports have shown a decrease in nitrogen fertilizer will lead to a decrease in lint yield directly proportional to the fertilizer shortfall. An over application of N fertilizer to cotton will cause the fiber micronaire to rise to a higher than industry standard level. A higher or lower than standard micronaire number will cause the price the seller of the fiber receives to be discounted to account for the poor fiber quality.

1.4 MATERIALS AND METHODS

1.4.1 Equipment

1.4.1.1 Soil Electrical-Conductivity Meter

A commercially available Veris 3100 soil electrical conductivity meter (Veris Technologies, Salina, Kansas) was used to measure soil-texture variability of the test fields. The Veris 3100 EC meter consists of six straight-blade coulter disks attached at the back of a pull type frame (Figure 1.1). . The height and depth into the soil of the six disks are controlled with a hydraulic cylinder. The six disks work in pairs to send and receive electrical current through the soil as the meter is pulled through the field. One pair sends the current while the other pair receives it (Figure 1.2). The controller uses the amount of time measured for the current to travel from one disk to the other to determine the amount of electrical current conducted by the soil and is measured in milliSemens per meter (mS/m). A loss in the strength of the current represents the soils ability to conduct electricity and is related to the soil's property and texture.

Figure 1.1. Geo-Referenced Veris 3100 Soil EC Meter.

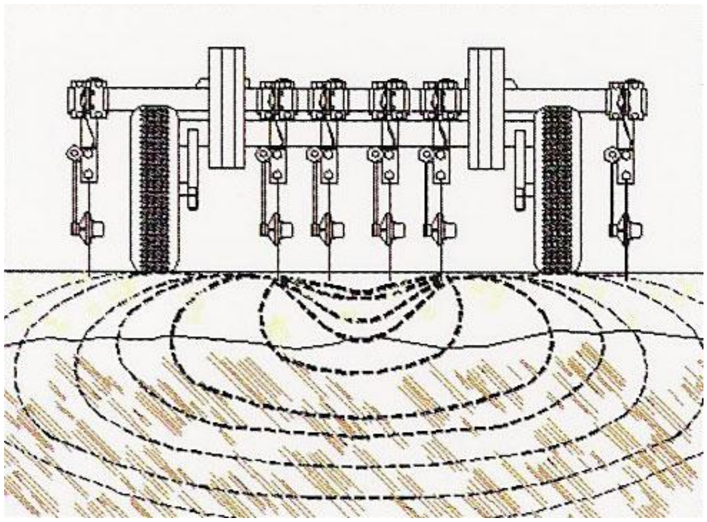

Figure 1.2. Schematic of Veris 3100 Soil EC Meter (Veris Technologies).

The Veris is capable of measuring soil EC at two depths, shallow (0-30cm) and deep (0-91cm). As can be seen from the schematic in Figure 1.2, the greater the distance between the pairs of disk coulters the deeper a soil EC measurement can be obtained. Once data is collected it is reliable for a ten year time period unless the area of interest experiences a drastic change in soil topography. The unit can be linked to a Global Positioning System (GPS) to produce continuous geo-referenced soil texture map (Figure 1.3). Data points are collected on a 1 Hz signal thus a new data point is created every second for each of the sampling depths (Figure 1.3).

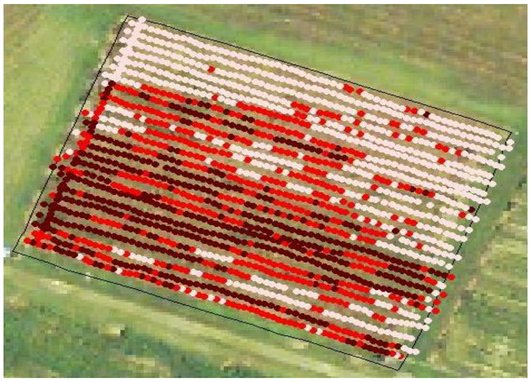

Figure 1.3. Raw EC data Points.

The collected data points can be viewed using any Geographic Information System (GIS). The GIS program can be used to average the EC data within designated plots.

1.4.1.2 Nitrogen Applicator

Conventionally, growers apply nitrogen to cotton two or three times during the growing season. The typical application process is as follows: the first application occurs at planting with a rate of 33.6 kg*ha^{-1}, then one a side-dress application must occur at the 6-8 leaf stage (or during the first pin head square) but before the first bloom at a rate of 67.2 kg*ha^{-1}, or two split side-dress applications with the first a rate of 33.6 kg*ha^{-1} occurring during the 6-8 leaf stage and the second application, at the same rate, occurring two weeks later (Jones 2010). During this four year study three different nitrogen applicators were used to obtain the desired N rates in test plots (as explained in Chapter2). In 2007 a pull type Reddick ground-driven liquid N applicator was used. The following year an in-house-developed applicator was used along with a specially designed controller. The fabricated applicator had four solenoid valves of which each controlled a separate set of application nozzles. The last two years of the study, commercially available variable-rate control equipment was retrofitted to an existing four row N fertilizer applicator. The existing ground driven John Blue piston pump was attached to a hydraulically-operated variable-speed motor. This motor was controlled by a Rawson control system (Trimble Navigation Company Flows Division Ukiah, CA). The Rawson system is capable of controlling single to multiple N rates either by a manual user mode or in GPS mode as a map based applicator. These applicators will be discussed more in depth during the second chapter of this thesis.

1.4.1.3 GreenSeeker® RT200 System

A commercially available optical sensor, the GreenSeeker® RT-200 (NTech Industries, Inc. Ukiah, CA), was used to measure plant NDVI during the growing season. The RT-200 system consists of six optical sensors which were mounted on a John Deere 6700 self-propelled sprayer (Figure 1.6). The system was designed to map the center six rows of an eight row plot on 96cm centers. The six sensor readings are averaged into one reading and the data is sampled on a 1 Hz cycle. Individual sensor data can be viewed from the exported file if necessary. The data was collected and stored using an onboard computer linked to a Differential GPS (DGPS) receiver. The stored data was exported as a shape file after all collections were completed. The shape file could then be imported into a GIS based program where the collected data could be averaged and analyzed based on plot design.

Figure 1.4. Sprayer Mounted GreenSeeker® RT-200 System.

1.4.1.3 Minolta Chlorophyll Meter

A commercially available Minolta SPAD 502 (Figure 1.5) (Spectrum Technologies, Plainfield, IL) was used to gauge mid season N stress through a surrogate measure of leaf chlorophyll level. The SPAD meter works very similar to an optical sensor that reads NDVI. Chlorophyll is not directly measured but the meter measures the ratio of transmitted light at 650-nm wavelength (red light), which is sensitive to chlorophyll activity, to light transmitted at 940-nm wavelength (near infrared, NIR), which is relatively insensitive to chlorophyll (Jaynes 2007). A proper reading is taken by choosing the first fully developed leaf from the top of the plant, and clamping the SPAD meter somewhere in the middle of the leaf away from the ribs to obtain a proper reading, and a relative value of 0 (no chlorophyll) to 80 (high chlorophyll) is recorded. The meter can store numerous readings and average those at the users will to obtain a plot average reading from the meter.

Figure 1.5. Minolta SPAD 502 Chlorophyll Meter.

1.4.2 Field Experiments

1.4.2.1 Test Fields

The study was conducted at Clemson University's Edisto Research and Education Center (EREC) about three miles west of Blackville, SC, USA. Two specific fields located on the research center were used to conduct the various field experiments (Figure 1.6). One field was under full irrigation (Lateral) with a lateral irrigation tower, while the other field (Arrowhead) only had a traveling gun for irrigation used only in extreme conditions to prevent termination of the field experiment, thus the field was used as a dry land study.

Figure 1.6. The Experimental Fields Used during the four years of the research study.

Soil management zones were created in the research production fields based on the deep and shallow EC measurements. Each field was divided into three EC zones (low, medium, and high) and each zone was divided into 15-m by 7.7-m (8-row) cotton plots. The soil management zones can be viewed in Figures 1.7 and 1.8 for the dry land and irrigated fields respectively.

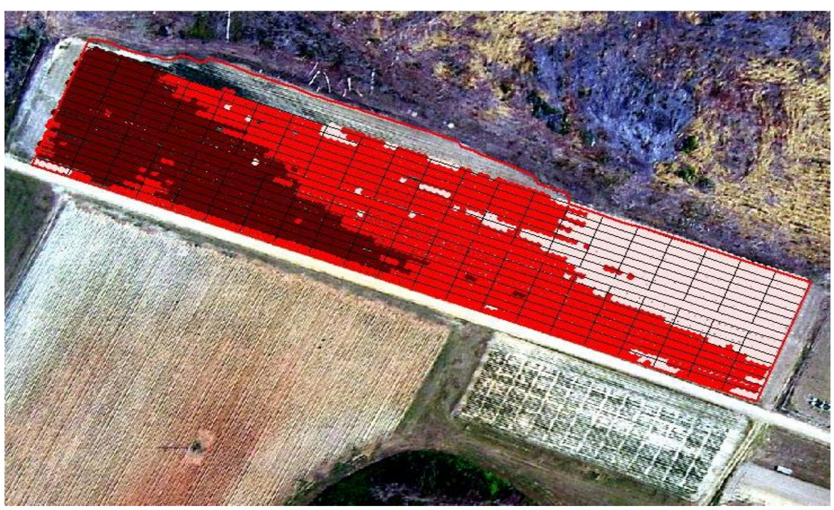

Figure 1.7. Raw Soil EC points in the dry land test field (2008, 2009).

Figure 1.8. . Average EC Plots in the Irrigated test Field (2007).

Despite the divisions based on soil EC, the original soil survey maps aligned very well with the EC data (Figures 1.9). The test plots were arranged in randomized block design, and the treatments were replicated four times in plots of each soil EC zone. For developing N-algorithm, five rates of nitrogen (0, 33.63, 67.25, 100.88, and 134.50kg-N/ha) were applied at random to plots of each block, in each management zone, during all four years of this study.

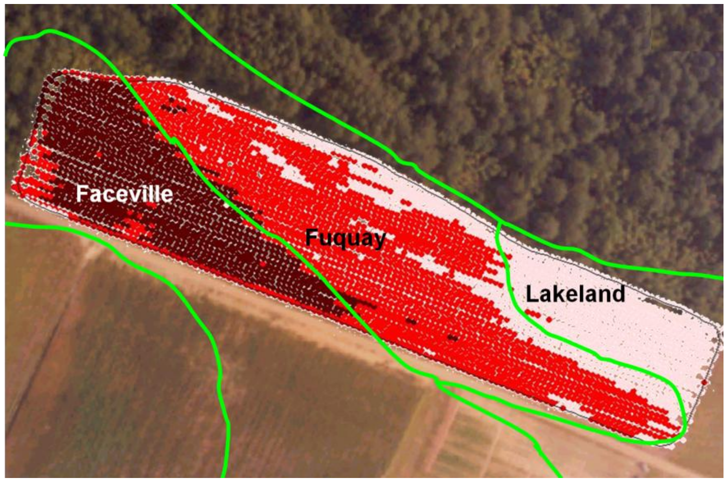

Figure 1.9. Typical NRCS Soil Survey Map and Soil EC Data.

In addition, one Nitrogen Ramped Calibration Strip (N-RCS) was established in each zone during the 2007 to 2009 growing seasons. The N-RCS consisted of sixteen different N rates, 0 to 168kg-N/ha, increasing at a rate of 11.2kg-N/ha every 5.08 m (Figure 1.10). In 2010, three N-rich strips (approximately 168kg-N/ha) were applied one per soil zone. The N-RCS and N-rich strips were used for calculating the Response Index (RI) for site-specific application of side-dress nitrogen.

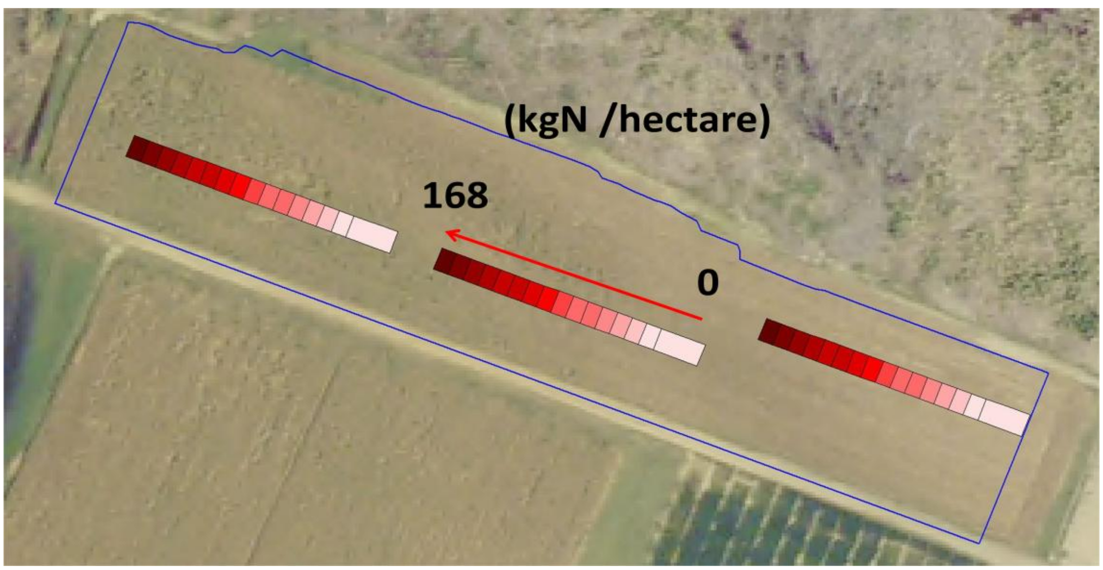

Figure 1.10. An example of the established N-RCS strips from the 2009 study.

During the 2009 and 2010 growing seasons, 12 plots in each soil zone were used to determine the efficacy of the Clemson algorithms compared to a typical grower's practice and other algorithms developed for southern USA (the Oklahoma State algorithm) for side-dress nitrogen application. The N rates were calculated using the

Clemson and OSU N-prediction algorithms and conventional growers' practice for the region. The side-dress N treatments were replicated four times in each zone of the test field using a RCB design arrangement.

Delta Pine 555cotton variety was planted during the 2007 and 2008 and Delta Pine 0935 variety was planted during 2009 and 2010 growing seasons. The crop carried to yield using recommended practices for seeding, insect, and weed control. The DP 0935 variety like the DP555 variety is a drought tolerant, long season cotton variety. Each of the varieties had the genetic modifications of boll-guard, and round-up ready flex. During each year of the study cotton was planted in the research fields between the time periods of early to mid-May except in the 2009 due to a heavy rainfall and flooding event which caused the seeds to rot (Figure 1.11). Therefore the entire field was replanted during the first week of June.

Figure 1.11. The flooded test field after the heavy rain event in May 2009.

Pre-plant nitrogen was applied to the research plots within the first week of planting each year at a rate of 33.63kg-N/ha except the zero control plots and the N-RCS and N-Rich Strips. Cotton was harvested at crop maturity using a spindle picker equipped with an AgLeader yield monitor and DGPS unit to map changes in lint yield within and among all treatments and fields.

1.4.2.1 Data Collection and Algorithm Development

The main objective of the 2007 growing season was to develop an algorithm for variable rate application of nitrogen in cotton production utilizing plant NDVI and soil EC data under irrigated conditions. The Delta Pine 555 cotton variety was planted on May 14th and was carried to yield using recommended practices for seeding, insect, and weed control. The plots were irrigated 8 times during the growing season for a total of 13.34cm. Plant NDVI sensor readings were measured and collected during the growing season using a 6-row sprayer-mounted GreenSeeker® RT-200 mapping system. NDVI readings were taken from the test plots 39, 47, 58, 67, and 80 days after cotton emergence. Plant height and SPAD readings were taken three times (58, 67, and 80 days after cotton emergence) from all test plots. For each sampling date, 10 leaves collected from each test plot, were analyzed for N concentration.

In-season estimated yield (INSEY) was calculated by dividing NDVI measurements by the number of days from emergence to sensing.

$$INSEY = \frac{NDVI}{\#of\_days\_after\_emergence} \qquad 1.2$$

Linear and non linear regression models were used to determine the relationships present between actual cotton yield and the In-season estimated yield (INSEY) for developing yield potential (YP_0) and the N prediction algorithm. Identifying a specific yield potential (YP_0) does not directly mean an N recommendation. Determining the extent to which the crop will respond to additional N is equally important (Raun et al. 2005). Crop reflectance was calibrated using multiple N rate calibration plots or Ramp approach similar to those used for wheat and corn by Raun et al. (2006). The Nitrogen Ramped Calibration Strip (N-RCS) is a relatively new technology that applies increasing levels of nitrogen in a strip across a fixed distance.

The N-RCS were applied on June 7, 2007 about 25 days after the planting date. The response index (RI) was calculated by dividing the highest NDVI reading in the ramped calibration strips by average NDVI measurements of the adjacent area in each zone.

$$RI = \frac{NDVI_{N-RCS}}{NDVI_{FIELD}} \qquad 1.3$$

The predicted attainable yield (YP_N) with added nitrogen was calculated by multiplying YP_0 by RI.

$$YP_N = RI * YP_0 \qquad 1.4$$

The predicted yield potential should not exceed the maximum cotton yield (YP_{MAX}) for a given region and management practices. In this case the YP_{MAX} was set at seven and a half bales per hectare for the dry land field in the "Savannah Valley Region" of South Carolina. Nitrogen fertilizer rate was then determined by dividing the difference in lint and seed N uptake of YP_N and YP_0 by the nitrogen use efficiency for cotton (50%) and can be seen in the basic algorithm form below.

$$N\_Rate = \frac{(YP_N - YP_0) * \%N}{NUE} \qquad 1.5$$

The main objective of the 2008 growing season was to develop an algorithm for variable rate application of nitrogen in cotton production utilizing plant NDVI and soil EC data under dry land conditions. Delta Pine 555variety was planted on May 16 and carried to yield using normal crop advisor recommendations for seeding, insect, and weed control. The plots were irrigated 4 times for a total of 7.87cm of water. The irrigation was kept at a minimum and used only in cases to keep the plants from dying since the objective of the study was to produce a dry land algorithm. As in the 2007 growing season sensor readings were measured and collected using the N-TECH 6-row GreenSeeker® system. NDVI sensor readings were taken from the test plots 25, 28, 34, 49, and 62 days after cotton emergence. Plant height and SPAD readings were collected two times during the growing season, during the 16 and 19 node stages of plant growth. Ten leaves were collected from the each plot to be analyzed for total plant N concentrations.

Nitrogen Ramped Calibration Strips were established (one at each management zone) approximately two weeks after emergence. In-season estimated yield (INSEY) was calculated again, along with the RI. The predicted attainable yield (YP_N) with added nitrogen was calculated by multiplying YP_0 by RI. The predicted yield potential should not exceed the maximum cotton yield (YP_{MAX}) for a given region and management practices. In this case the YP_{MAX} was divided based on soil EC zones from yield history for the field and was set at seven and a half bales per hectare for the high EC zone, five bales for the medium EC zone, and two and a half bales for the low EC zone.

The main objective of the 2009 growing season was refinement and testing of the developed dry land algorithm for variable rate application of nitrogen in cotton production utilizing plant NDVI and soil EC. The algorithm development test was conducted in the field again to compare to the dry land values from the 2008 growing season. In addition, 12 plots in each EC zone were used to determine the efficacy of the Clemson algorithms compared to a typical grower's practice and he OSU algorithm for side-dress nitrogen application. The N rates were calculated using the Clemson and OSU N-prediction algorithms and conventional growers' practice for the region. The side-dress N treatments were replicated four times in each zone of the test field using a RCB design arrangement. Delta Pine variety 0935 B2RF was originally planted on May 22. However, due to a heavy rain in flooding in May 25, cotton was replanted on June 3. Plant NDVI was measured during the growing season using a six-row sprayer mounted GreenSeeker® RT-200 mapping system coupled with a NORAC boom-height control system (NORAC Control Systems Saskatoon, SK Canada). The height controller was used to ensure the NDVI readings were collected from the optimum height range (approximately 91.4 centimeters which is discussed along with the height controller in Chapter 2). NDVI readings were collected from the entire field 20, 33, 42, 47, 55, 69, 75, and 83 days after emergence. The nitrogen application prediction algorithm was developed for 2009 using the same procedures described earlier by Raun et al., 2005 and Khalilian et al., 2008.

Three N-RC strips were established, and applied on June 12 (two days after emergence) one in each EC zone, to determine the RI for predicting yield potential when N is applied (YP_N). The highest NDVI value from the N-RCS in each zone was used along with the average NDVI from the test plots (conventional, Clemson, and OSU algorithm) to calculate RI. All test plots had received 33.6kg-N/ha at plantings followed by side-dress nitrogen applications on July 27 (47 days after emergence with GDD60= 1020). This was the optimum N application time for both Clemson and OSU algorithms as indicated by Arnall et al. (2008) and Khalilian et al. (2008).

The conventional treatment received 67.2kg-N/ha side-dress N to bring the total N for the season to the typical grower practice of 100.8kg-N/ha. The Clemson algorithm predicted 4.48, 17.92, 21.28 kg-N/ha side-dress N in the high, medium, and low EC zones, respectively. The piston pump on the N applicator could only operate at a minimum of 150 rotations per minute before the application rate became inaccurate. Therefore, 26.88kg-N/ha (the minimum accurate application of the pump at an operating speed of 2.5kilometers per hour) was applied to the plots of all three zones. The OSU algorithm predicted 0, 26.88, and 51.52 kg-N/ha in the high, medium, and low soil EC zones respectively.

Nitrate soil data was collected from each plot of the N-RCS in each soil EC zone after the last side dress nitrogen application was applied. The soil data was collected to verify plant N usage and residual N left in the soil from an excess application. The soil samples were collected using a 45.72 cm long soil probe with a diameter of 2.54 cm. The soil was only sampled in the top 30.48 cm of soil.

Plant data was collected throughout the growing season to determine the effect of soil texture and nitrogen rate on cotton plant parameters, such as number of nodes, boll development and opening, and plant height. The numbers of nodes above white flower (NAWF) were collected from the same ten plants located in five of the twenty variable rate nitrogen plots (0, 33.63, 67.25, 100.88, and 134.50kg-N/ha) in each soil EC zone 61, 72, 78, and 84 DAP. Data collection was stopped after 84 DAP because there were no long white flowers present on the cotton plants, meaning all flowering had stopped in the plant growth cycle dedicating all energy to fruit development and growth. At 120 DAP the numbers of nodes above cracked boll (NACB), numbers of nodes, numbers of bolls, and plant height were collected from the same ten plants in each of the variable rate nitrogen plots from each soil EC zone.

The main objective of the 2010 growing season was refinement and testing of the developed irrigated algorithm for variable rate application of nitrogen in cotton production utilizing plant NDVI and soil EC. The algorithm development test was conducted in the field again to compare to the irrigated values from the 2007 growing season. In addition, the Clemson algorithm was compared to the OSU nitrogen prediction algorithm and conventional growers practice.. Again the same variety of cotton from the 2009 production year, Delta Pine 0935 B2RF was planted on May 11, 2010. Five different rates of nitrogen fertilizer were replicated four times in plots of each soil EC zone using a Randomized Complete Block design arrangement. The cotton was carried to yield using normal crop advisor recommendations for seeding, insect, and weed control. Plant NDVI was again measured during the growing season using a 6-row sprayer mounted GreenSeeker® RT-200 mapping system coupled with the NORAC boom-height control system (NORAC Control Systems Saskatoon, SK Canada). Due to time constraints the data collection and results of the 2010 test are not included in this thesis, but will be included in a future publication.

Cotton lint yield is a crucial parameter in this research study because the yield results confirm or deny if the algorithm can properly predict mid-season N requirements for the cotton plant utilizing plant NDVI and soil EC. Yield data was collected during each of the growing seasons from the study fields using the AgLeader Yield Monitor attached to a John Deere two row spindle cotton picker. In the first two years of the study the yield was used just to confirm the nitrogen rates and predicted attainable yield, YP_N, in developing the algorithm. Yield was specifically analyzed during the 2009 growing season to determine the variability between the typical grower practice, the Clemson algorithm, and OSU algorithm. The yield data was separated into the three soil EC zones to ensure a more accurate representation of the algorithm required N rates. Fiber samples were hand collected from the same plots that the plant physiological data was collected from. The fiber samples were hand ginned using a micro-gin and the seeds were collected from each of the samples and analyzed for weight, seed count, and nitrogen content. The ginned fiber from each of the samples was analyzed for micronaire.

1.5 RESULTS AND DISCUSSION

1.5.1 Algorithm Development and Refinement

Figures 1.12, 1.13, 1.14, 1.15 show the effects of N rate on plant NDVI for 39, 47, 58, and67 days after cotton emergence respectively during the 2007 growing season. A clear trend of increasing NDVI and EC numbers is very prevalent. Management zone one (low soil EC values-green line) had the lowest NDVI values followed by management zone two (mid soil EC values- red line) and management zone three (high EC values-blue line), respectively. For the sampling dates of 39, 47, and 58 days after emergence, the NDVI increased as N rates increased up to 100.8 kg-N/ha. However, no further response to higher nitrogen rates could be found.

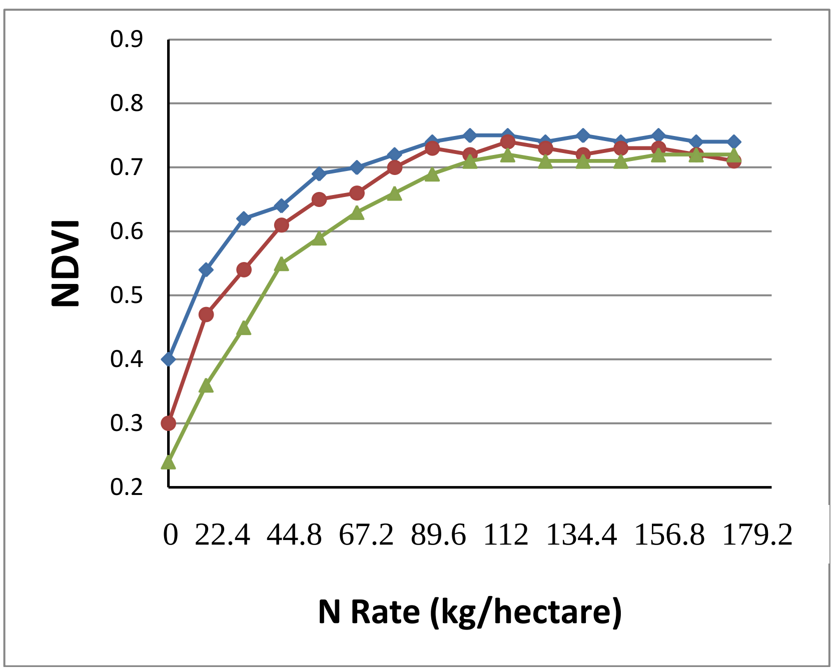

Figure 1.12. Effects of N-rate on NDVI 39 days after emergence.

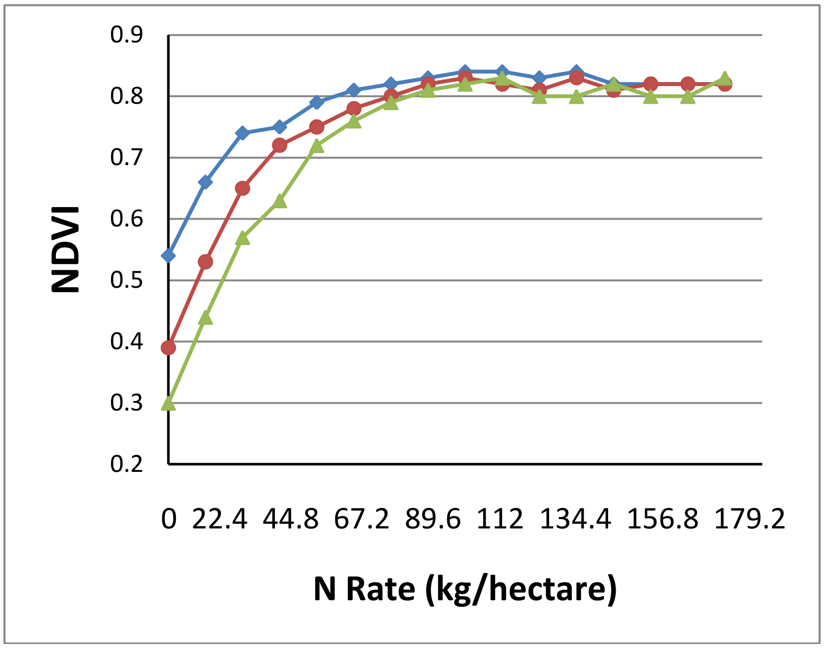

Figure 1.13. Effects of N-rate on NDVI 47 days after emergence.

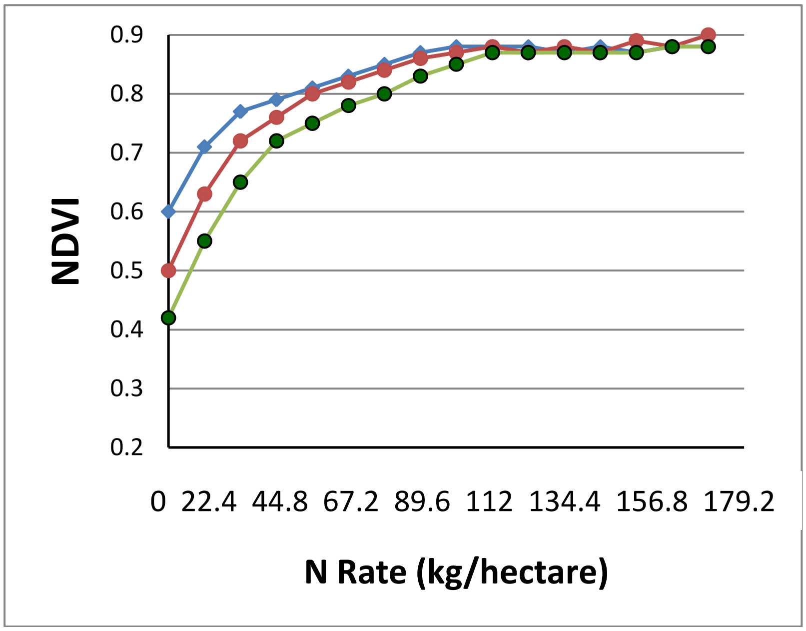

Figure 1.14. Effects of N-rate on NDVI 58 days after emergence.

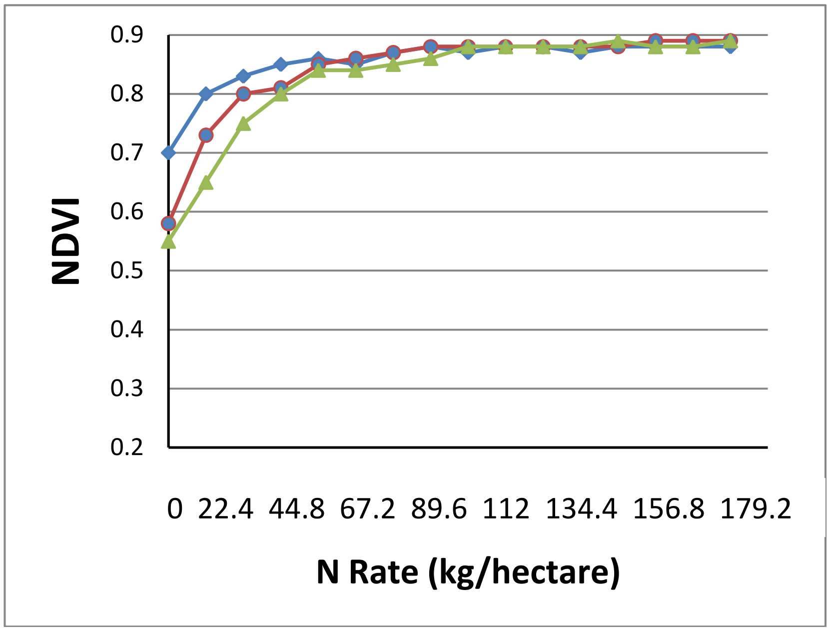

Figure 1.15. Effects of N-rate on NDVI 67 days after emergence.

NDVI values increased with days after cotton emergence for all sampling dates and all EC zones. The graphs represent a decreasing trend of sensor response to the higher nitrogen rates as crop matured during the season. The very last sensor reading shows no response to an increase in N rate over 44.8 kg-N/ha. It is hard to differentiate the effects of soil EC zones and N rate on the NDVI values the farther into the season the readings are collected. This could be due to canopy closure which will increase the NDVI values and also plant height, which could saturate the GreenSeeker sensors due to insufficient distance between the sensors and plant canopy. This is explained in detail in Chapter Two.

A reduce in response to nitrogen, of the cotton plant, throughout the season proves that there is a specific range of growth stages the plants require and have and even have an elevated response to N. According to Arnall (2008) and Khalilian (et al. 2008) this range, as determined from NDVI sensor readings, occurs between 40 days after emergence and 60 days after emergence. The above graphs from the 2007 growing season confirm the results from other studies and prove that there is a strong correlation between nitrogen rate and plant NDVI but only during the specific date range during the growing season.

Figure 1.16 shows the yield prediction equation developed from the irrigation test plot during the 2007 growing season. There was a high correlation between INSEY and actual seed cotton yields.

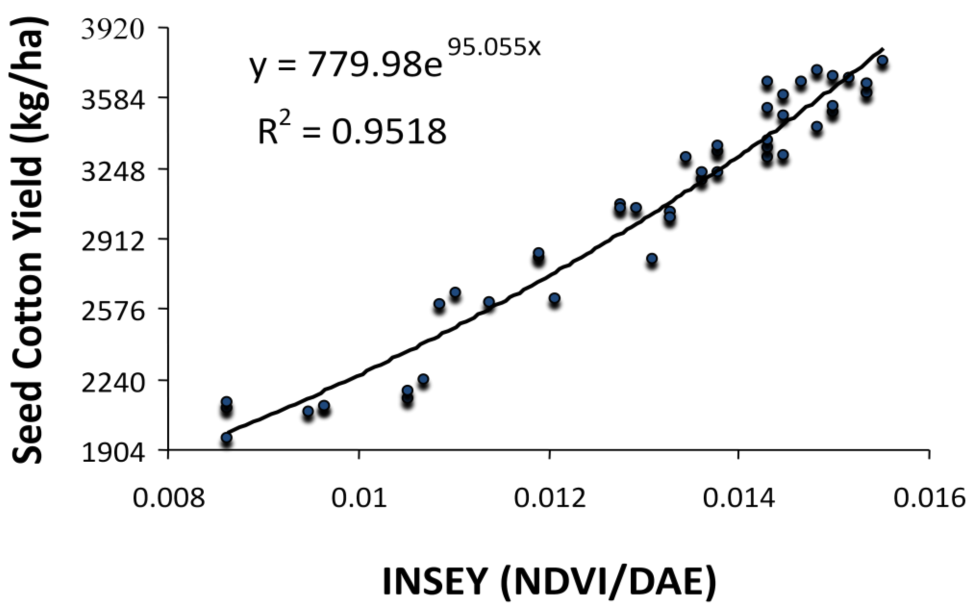

Figure 1.16. Yield prediction equation from 2007 (all soil EC zones combined).

The R^2 values increased significantly when the yield prediction equations were divided into the three predetermined soil EC management zones (Figure 1.19). The results showed there is potential to use mid-season specific plant NDVI data for variable-rate application of N fertilizer in cotton production. The results also showed that the soil EC data should be included in the N-rate prediction equation for the Southeastern Coastal Plain region.

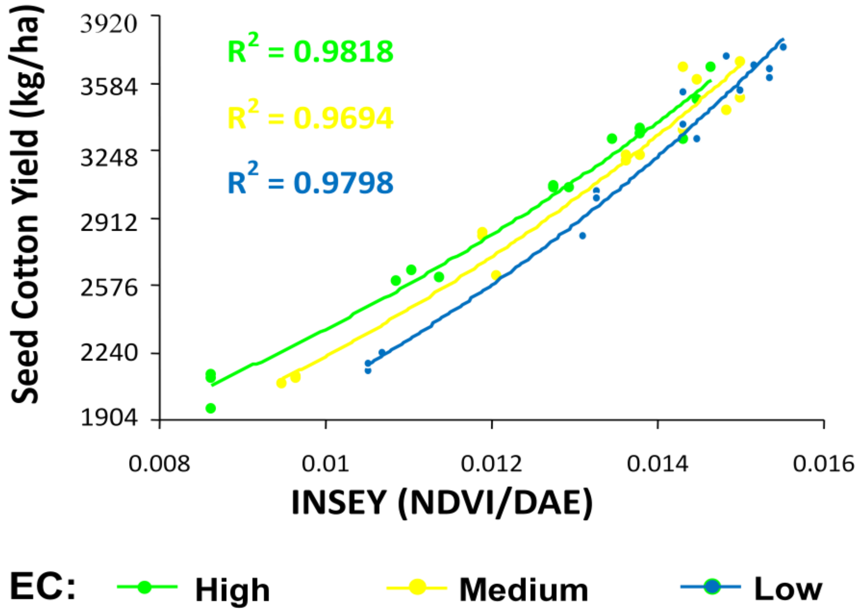

Figure 1.17. R^2 values and graphs of the three divided management zones.

The yield prediction equation (YP_0), calculated values of YP_N, and the YP_{MAX} are all represented in Figure 1.20. The RI value for this test was 1.5 and the YP_{MAX} was set to seven and a half bales per hectare for the "Savannah Valley Region" of South Carolina. The N recommendation was calculated by dividing the difference in lint and seed N uptake of YP_N and YP_0 by the nitrogen use efficiency for cotton (50%). The variable-rate N application predicted an overall reduction of 31% N across the entire field compared to the uniform N application rate. In low soil EC areas, seed cotton yield increased as N rates increased. However, in the medium and high soil EC zones there was no yield response above 100.8 kg N*ha^{-1}. Even though there is an increased response to higher nitrogen rates in lower soil EC zones, the extra fertilizer required to achieve the yield goal may not be cost effective or even possible in some cases. It is very important that the YP_{MAX} is set to the maximum historical and obtainable yield for the specific zone of the field being analyzed. The maximum yield prevents the equation from over-estimating the possible yield of that particular field zone. Figure 1.18 represents the nitrogen rate as predicted by the developed algorithm. As the INSEY increases so does the N requirement for plants until the set YP_{MAX} is reached. As is shown by the recommended nitrogen rate from figure 1.19, once the YP_{MAX} is reached the recommended nitrogen rate begins to fall back down to zero. As explained earlier, this prevents an over-application of nitrogen when it will not have a positive effect on yield or profit.

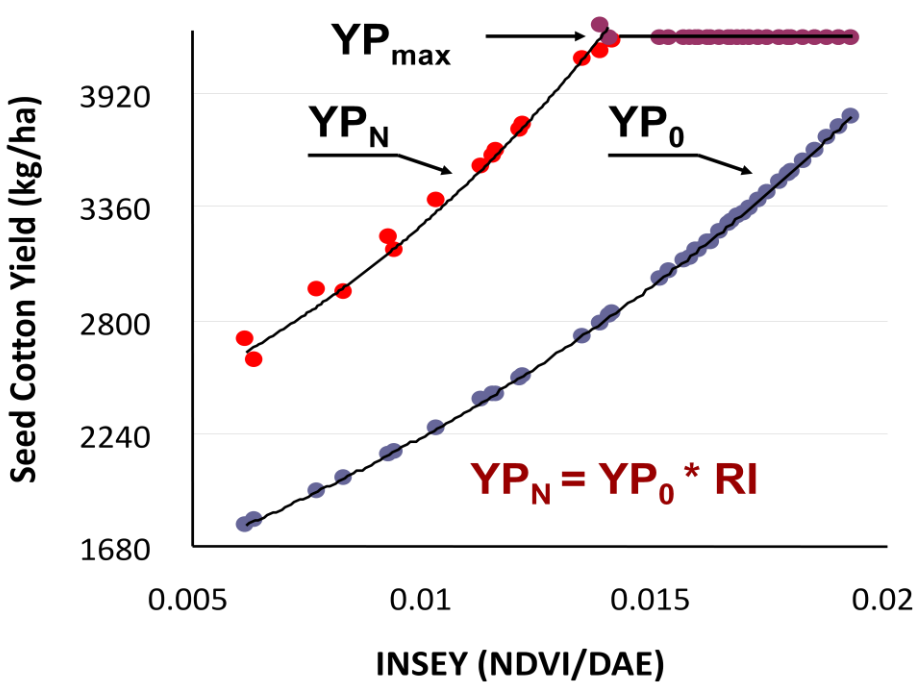

Figure 1.18. Graphical representation of YP_N, YP_0, and YP_{MAX}.

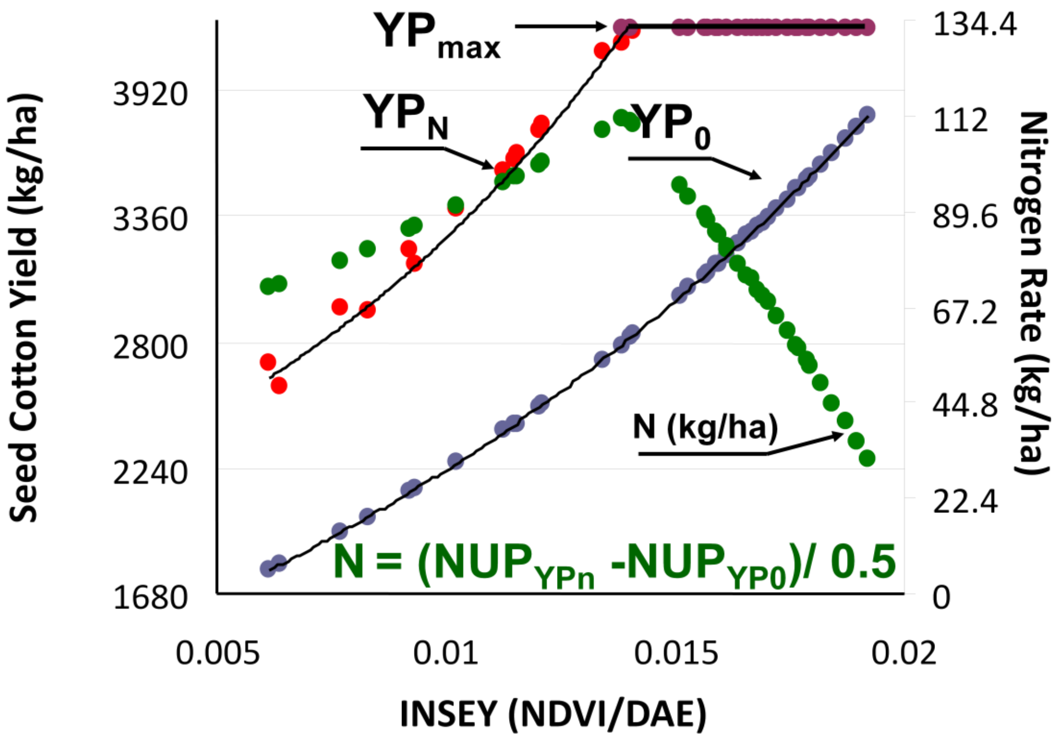

Figure 1.19. Nitrogen rate vs. INSEY.

The 2008 growing season provided similar results. Figure 1.20 shows the yield prediction equation developed during the dry land study. Again, as in 2007, a high correlation between seed cotton yield and INSEY was found. This means that both algorithms have a good potential to estimate mid-season nitrogen requirements for the cotton crop under both irrigated and dry land conditions.

The yield prediction equation developed in 2008 had a lower value than the one developed in 2007. The lower prediction number is correlated to the yield results from dry land versus irrigated cotton. A fully irrigated crop has a higher yield potential than a dry land crop, which causes the developed yield potential equation to follow the same trend. A dry land crop with an excess amount of nitrogen will have water as the limiting factor rather than nutrients, thus forcing the yield to be proportional to the available water throughout the growing season. Water acting as the limiting factor will cause the yield prediction equation to fall to a lower level and the equation will recommend less nitrogen based on the plant yield potential. A dry land field will have a lower YP_{MAX} than an irrigated field causing the recommended N rate to start its decline at a lower INSEY.

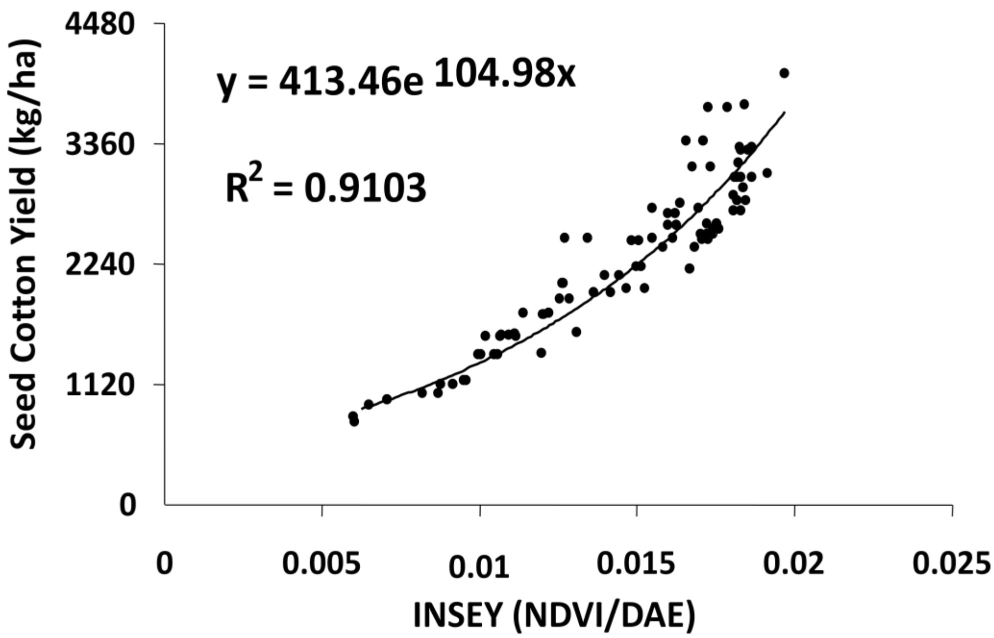

Figure 1.20. Yield prediction equation from 2008.

Figure 1.21 represents the developed yield prediction equation from the 2009 growing season. The 2009 yield prediction equation is visibly lower than the one developed in the same field from 2008. The two graphs however, represent an almost parallel trend (Figure 1.22). The correlation was not as high during the 2009 growing season due to the reduced inconsistent yield. The controllable growing conditions were held constant for both years. However, two main factors changed between the two years. The Delta Pine 555 was replaced with a new cotton variety (Delta Pine 0935)and the planting date was delayed about one month, due to excess rain fall in May 2009. Both varieties of cotton are long season varieties and require approximately six full months to fully mature and for all bolls to open. The shortened growing season (caused by replanting) prevented all of the bolls from being open at time of harvest. Cotton was handpicked from plots containing the same variety and results proved that the yield was reduced by approximately 30% across the entire field due to the reduced growing season and unopened bolls. An added increase to the yield data from 2009 of approximately 30% caused the 2009 data to be an exact replica of the data from 2008. The added yield will cause the INSEY to more accurately predict the yield thus the equation will have a higher correlation.

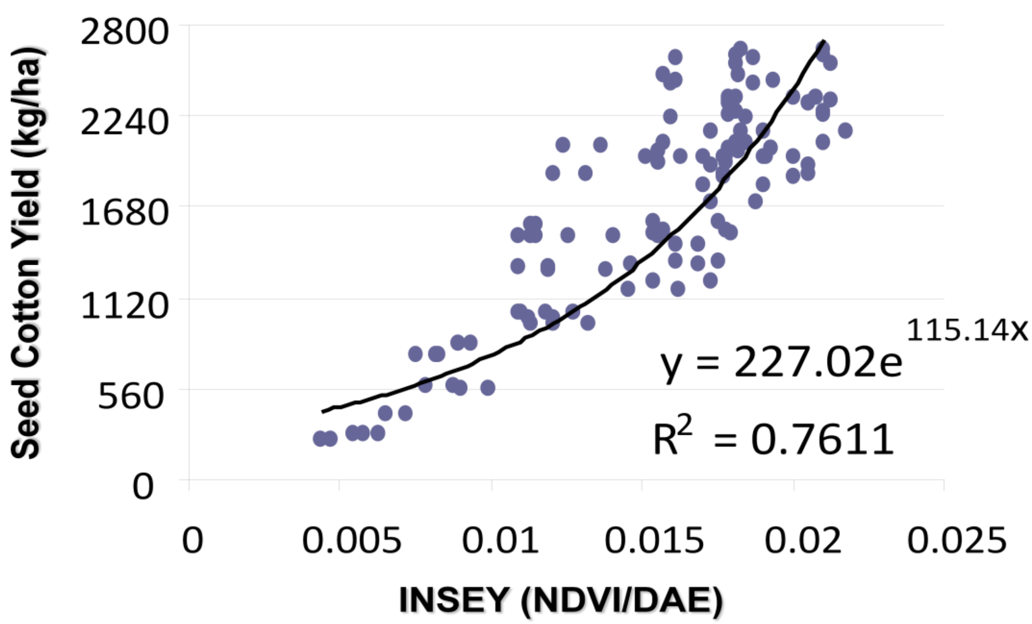

Figure 1.21. 2009 yield prediction equation.

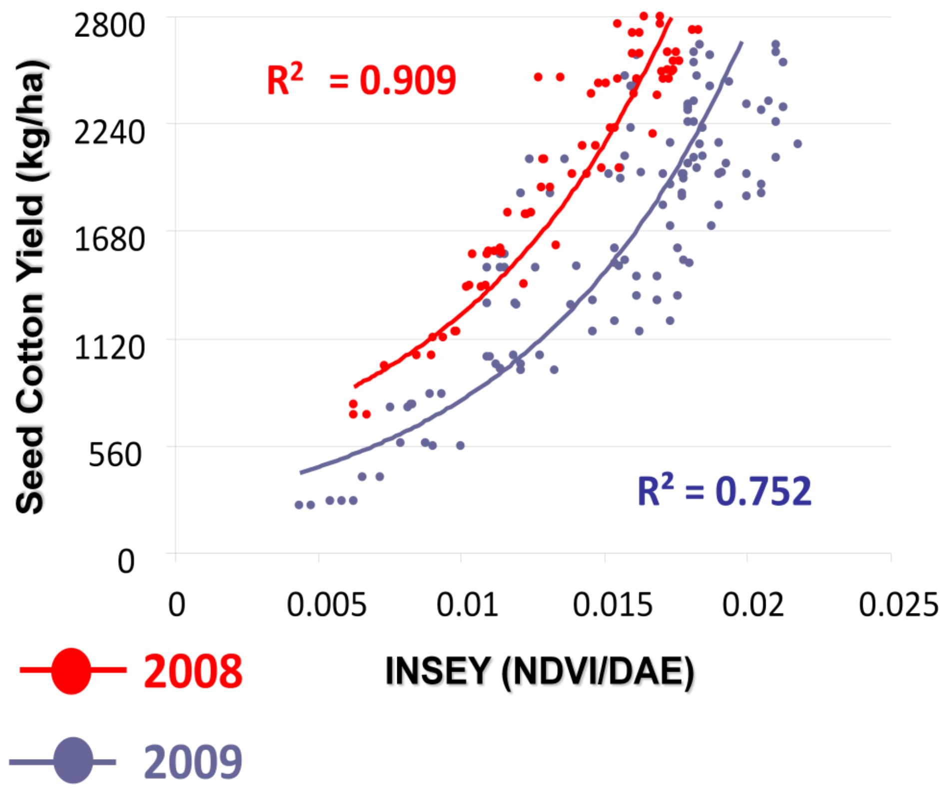

Figure 1.22. 2008 and 2009 yield prediction equations.

The two algorithms can be combined (Figure 1.23) to account for specific uncontrollable variables such as heavy rainfall, short growing seasons, and any other natural event out of the grower's control. The combined algorithms still have an R^2 value high enough to accurately predict the mid-season N requirement for the cotton and will be adequate for grower use. The predicted N rates utilizing the Clemson algorithm will usually be lower than normal grower rate with comparable cotton yields which will result in reduced input costs and increased profit.

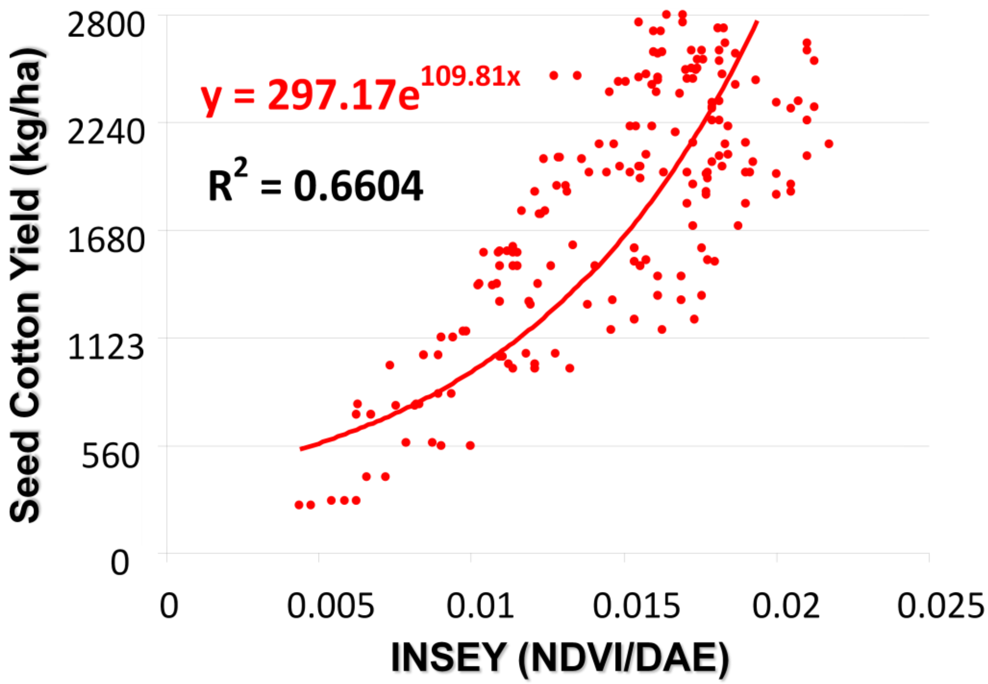

Figure 1.23. Combined 2008 and 2009 yield prediction equations.

Figure 1.24 confirms that soil EC data is an important factor in making proper nutrient recommendations for crops in the southeastern United States. All three of the yield lines, in 2009, showed parallel nitrogen response trends to each other with the low soil EC zone being the lowest and the high soil EC zone being the highest. As presented in the results from the earlier studies, a leveling trend and reduced response to a higher N rate can be seen around 100.8 kg-N/ha.

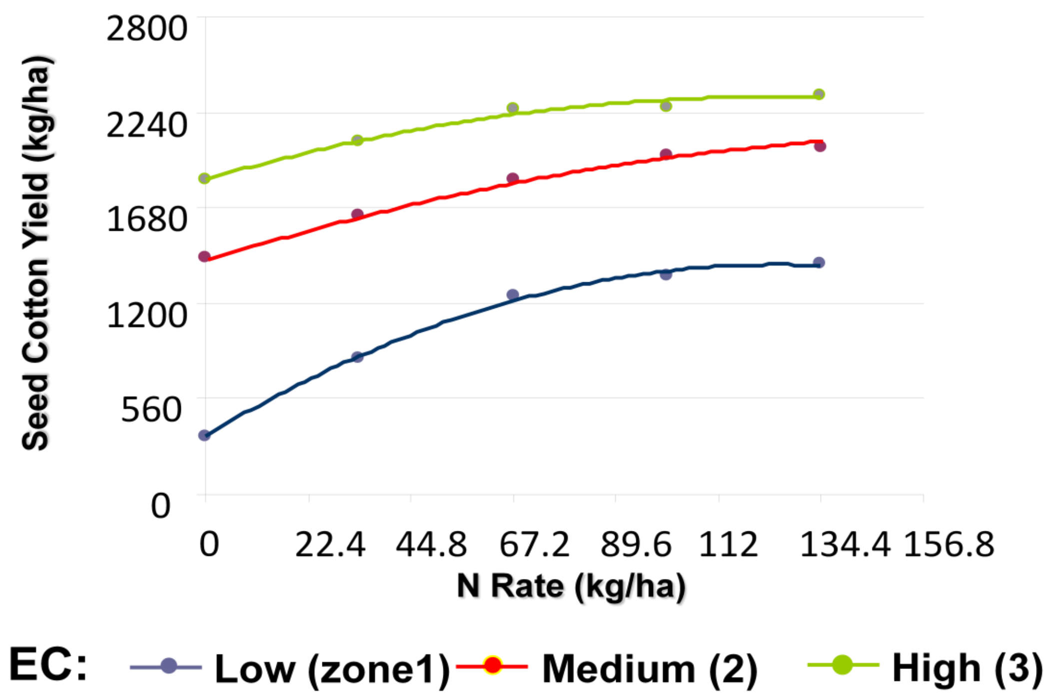

Figure 1.24. Nitrogen response based on soil EC zones (2009).

Two specific algorithms were developed using the data from the three growing seasons. The algorithm developed from the 2007 growing season is sufficient for irrigated cotton. The irrigated cotton algorithm has a higher yield prediction equation because the crop has a better opportunity to obtain higher yields due to the crop having full irrigation. This algorithm should not be used on dry land crops because the mid-season N rate will be overestimated and the crop will not have the ability to use the excess N, thus it will be wasted. The INSEY will be an overestimate as well and the true yields will fall far short of the predicted amounts. The algorithms developed during the 2008 and 2009 growing seasons combined have a high enough statistical correlation to accurately predict the mid-season N requirement for the dry land cotton crop. Again the dry land algorithm should not be used on irrigated crops because it will predict a lower

INSEY and, in this case, N will not be wasted but the proper amount needed will not reach the plant, thus the expected yield will produce a shortfall.

1.5.2 Algorithm Testing

Table 1.1 represents a spreadsheet for calculating the side-dress nitrogen, utilizing the two algorithms (Clemson and OSU) tested during the 2009 growing season. Figure 1.26 shows the two algorithms side by side with their differences and similarities. A running calculator was developed to keep up with the days after emergence (DAE) for the Clemson algorithm and the growing degree days ’60 (GDD ’60) for the Oklahoma algorithm. The spreadsheet was updated daily with new temperature data from the weather station located within the station boundaries. The spreadsheet was updated every time NDVI was collected to monitor the nitrogen prediction rate throughout the growing season. The N recommendation rate changed daily with the new GGD ’60 numbers and as the DAE increased. A daily change is expected due to the nature of the cotton plant having an optimum time for N uptake. The decision was made on the 48th DAE and GDD’60 equal to 1020 to apply the nitrogen to the algorithm plots. The application date fell well within the acceptable range of optimum nitrogen uptake based on the studies of Khalilian et al. (2008) and Arnall (2008).

Table 1.1. Algorithm N-prediction spreadsheet.

Oklahoma State Nitrogen Algorithm						
NDVI Zone Average				**NDVI N-Rich Rates**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
0.86775	0.86925	0.848		0.896	0.905	0.891
INSEY				**YP0**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
0.000917	0.000918	0.000896		1799.487	1805.818	1718.175
Response Index				**Max Yield (Lbs./Acre)**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
1	1	1		2000	1700	1500
YPN				**N_Rate (lbs./acre)**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
1799.487	1805.818	1718.175		0.00	0.00	0.00
			GPA	0.00	0.00	0.00
Clemson University Nitrogen Algorithm						
NDVI Zone Average				**NDVI N-Rich Rates**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
0.86775	0.8635	0.827		0.896	0.905	0.891
INSEY				**YP0**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
0.017355	0.01727	0.01654		4060.039	4027.367	3757.383
Response Index				**Max Yield (Lbs./Acre)**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
1.032555	1.04806	1.077388		4761.905	4047.619	3571.429
YPN				**N_Rate (lbs./acre)**		
Zones				**Zones**		
High	**Medium**	**Low**		**High**	**Medium**	**Low**
4192.215	4220.923	4048.16		10.57	15.48	23.26
			GPA	3.975231	5.821238	8.74517

❑ Clemson Algorithm

❑ OSU Algorithm

$$\text{N Rate} = \frac{(YP_0 * RI - YP_0) * \%N}{NUE}$$

Clemson Algorithm

- ✓ $YP_0 = 413.46\ e^{104.98 * INSEY}$
- ✓ INSEY=NDVI/# Days After emergence
- ✓ RI =High NDVI/Field Avg. NDVI
- ✓ %N= 0.04
- ✓ NUE= 0.50

OSU Algorithm

- ✓ $YP_0 = 235.96\ e^{2216.2 * INSEY}$
- ✓ INSEY= NDVI/Cumulative GDD
- ✓ RI = 1.8579 * RINDVI – 0.932
- ✓ %N= 0.09
- ✓ NUE = 0.50

Figure 1.25. Comparison of the Clemson and OSU algorithms.

Yield data were collected from the field at the end of the growing season using an Ag Leader optical yield monitor attached to a Trimble DGPS receiver to ensure the data was accurately geo-referenced. The yield was analyzed to compare the difference between the algorithms and typical farmer practice in each of the soil EC zones. Figure 1.26 shows the results from the yield monitor. The yields are divided into the three soil EC zones. Based on the yield results there was no statistically significant difference between each of the treatments within each zone. However, there were significant differences in lint yields between the soil EC zones, which confirm the fact that soil EC is a basis for developing management zones within a production field. The Clemson algorithm and the typical grower practice seem to have produced almost the same yield in each zone. This is because the algorithm was developed for the specific soil types of the southeastern United States and, specifically, South Carolina. The OSU algorithm still has a great potential to be used in the "Savannah Valley Region" of South Carolina. However, the mid-season N recommendations calculated by the OSU algorithm are an over-estimate from an actual recommended rate because this algorithm has been formulated at one standard deviation above the recommended rate. The soil conditions in Oklahoma and the mid-western United States are much better than in the southeastern United States because the organic matter content and nutrient holding capacities are much higher in the mid-west than in the southeast. Thus, developed algorithms from this part of the nation will have a lower nutrient recommendation rate. In addition, the OSU algorithm utilizes a single value for Y_{Max} for the entire production field. In this study, different value was assigned to Y_{Max} in each soil EC zone, therefore, improving the performance of the OSU nitrogen prediction algorithm.

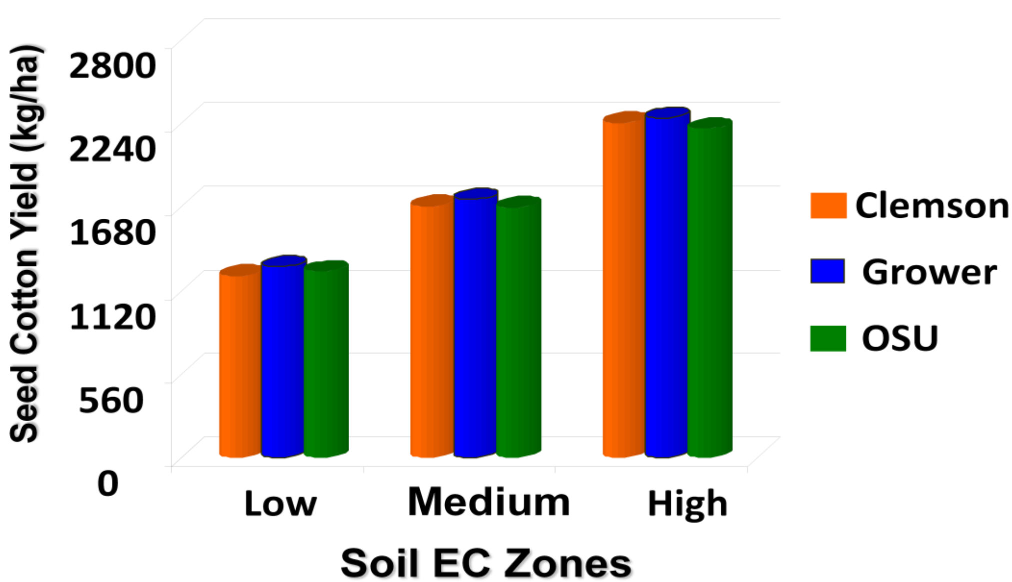

Figure 1.26. Yield results from the Algorithm test.

The results displayed in Figure 1.26 prove the possibility of using mid-season NDVI readings to predict INSEY and an accurate nitrogen recommendation rate without a significant reduction in yield. The conventional treatment received 67.2kg-N/ha side-dress N to bring the total nitrogen for the season to the typical grower practice of 100.8kg-N/ha. The Clemson algorithm predicted 4.48, 17.92, 21.28 kg-N/ha side-dress N in the high, medium, and low EC zones, respectively. However, due to limitations of the N applicator, all three zones received 26.88kg-N/ha side-dress nitrogen. The rate applied based on recommendations of the Clemson algorithm brought the total N to 60.48kg-N/ha for a reduction in total nitrogen use of 40% across the field. This can be directly related to a savings and profit of 40% for this field because the yield had no significant reduction. The OSU algorithm predicted 0, 26.88, and 51.52 kg-N/ha in the high, medium, and low soil EC zones respectively. The average nitrogen rate across the OSU "field" was 26.13, a recommendation very close to that of the Clemson algorithm, for a total of 59.73kg-N/ha. The average field savings for the OSU algorithm came to 49.17%; again this can be directly related to profit.

1.5.3 Plant and Soil Data Results

Correlations were found between nitrogen rate and the percent N in a cotton leaf within the variable nitrogen plots during the 2007 growing season. These results are displayed in Figure 1.27. The data shows an increase in percent nitrogen in cotton leaves as the soil applied N rate increases. This indicated that the more N available to the plant the higher the uptake rate will be.

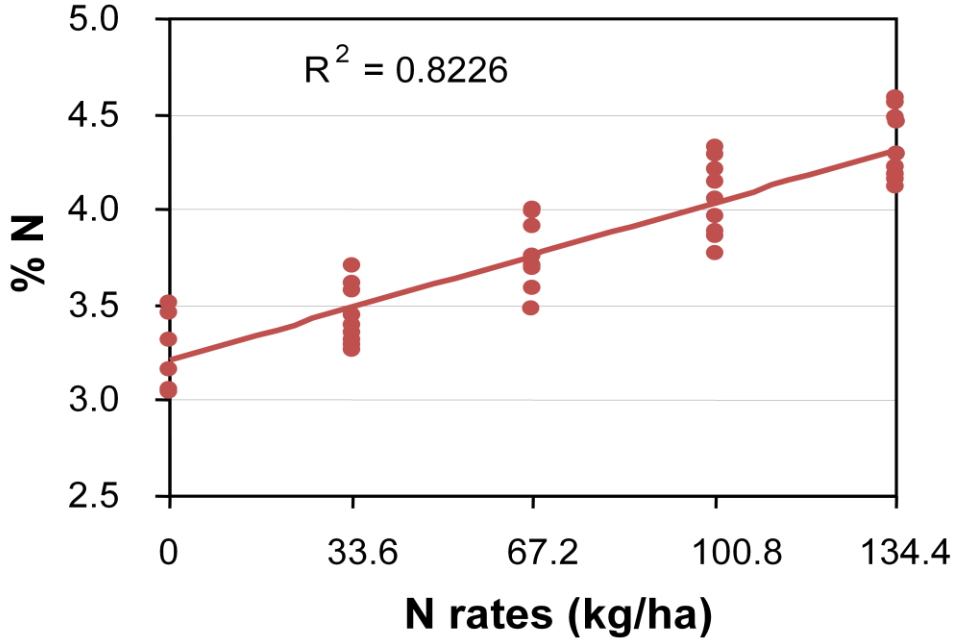

Figure 1.27. Percent N in Cotton leaves for all three soil EC zones combined.

Table 1.2 represents percent leaf N from 2008 divided into soil EC zones; the correlations were not as high as those achieved during the 2007 growing season. The plants were dry land and therefore did not have the same opportunity to use the available N in the soil as during the 2007 growing season. Apparently, the plants under dry land production system did not have the same opportunity to use the available N in the soil as in irrigated plots during the 2007 growing season. There were good correlations between percent leaf N and applied N rates with R2 greater than 0.5. This indicates that the more available N in the soil the higher the percentage of N will be in the plant.

Table 1.2. 2008 plant leaf percent N.

% Leaf Nitrogen in EC zones			
N-Rate	**High**	**Medium**	**Low**
0.00	3.03	3.67	2.90
11.20	2.92	3.57	2.77
22.40	3.27	3.41	2.77
33.60	3.58	3.53	3.37
44.80	4.05	4.47	3.63
56.00	4.14	4.25	3.80
67.20	3.45	3.83	3.78
78.40	4.33	4.53	3.55
89.60	4.15	4.49	4.09
100.80	4.39	4.28	3.91
112.00	4.42	4.32	4.18
123.20	4.24	4.28	4.20
134.40	4.58	4.39	4.24
145.60	4.30	4.50	4.10
156.80	5.07	4.96	4.14
168.00	3.83	4.27	4.01
Average	**3.984**	**4.172**	**3.715**

The collected SPAD readings from the 2007 tests were analyzed and a relatively good correlation was found between percent leaf nitrogen and SPAD meter readings (Figure 1.28). In 2008, there was a strong correlation between N-rate and the SPAD readings in the high soil EC zone (Figure 1.29). However, in low and medium soil EC zones, these factors were not correlated. Our results during the two years (2007 & 2008) of studies showed that the SPAD meter is not a good indication of applied nitrogen rate or percent leaf nitrogen in cotton.

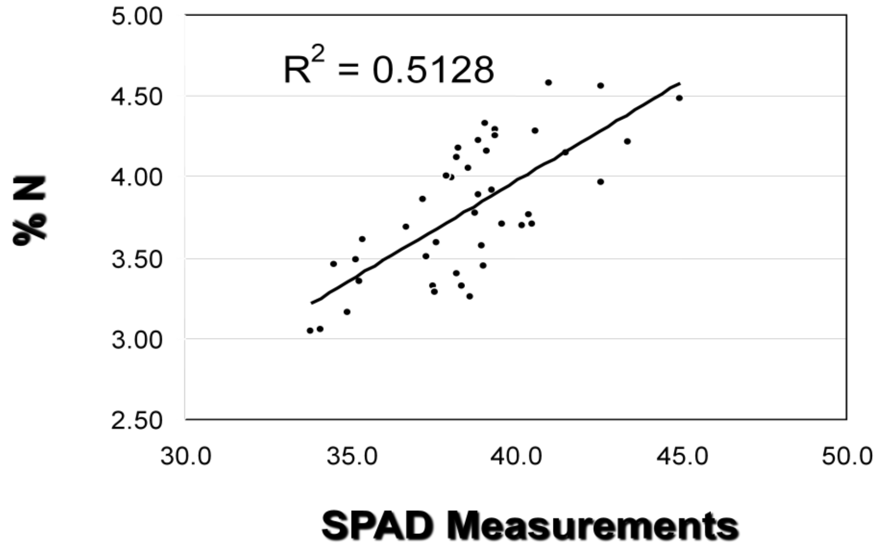

Figure 1.28. Combined SPAD versus percent Nitrogen in plant leaf.

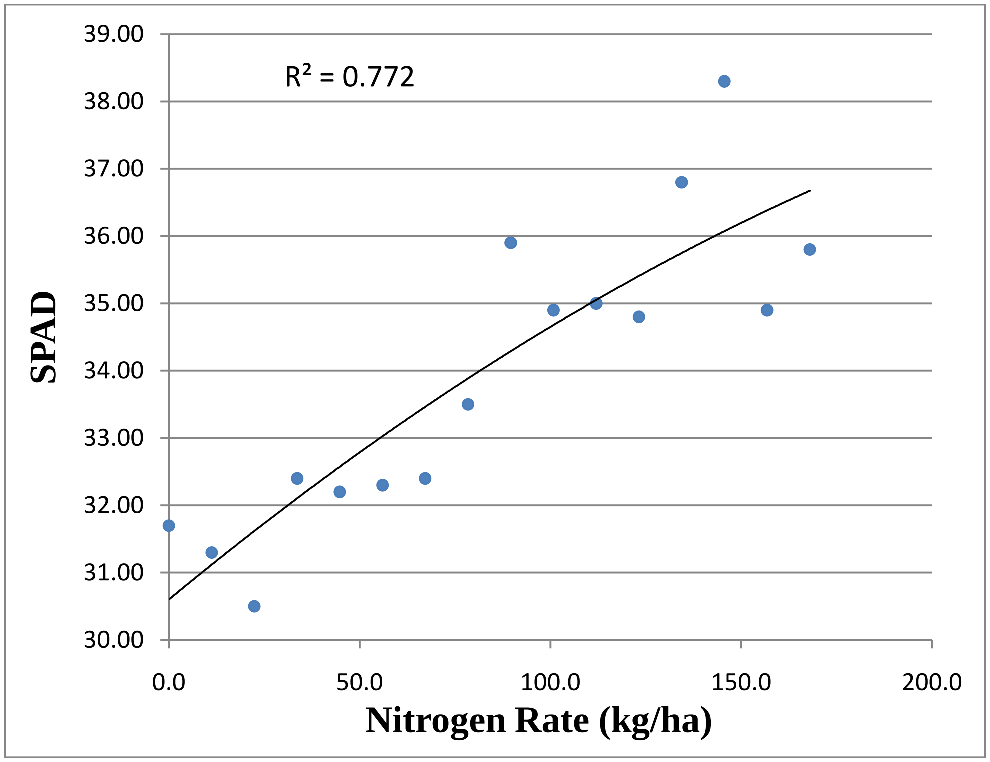

Figure 1.29. High soil EC zone correlation of N-rate and SPAD readings.

NDVI is a much better indicator of plant N and a better measurement standard to accurately predict INSEY and the mid-season N requirement of cotton even though the SPAD meter works on the same principle as NDVI.

Soil test results from the same plots were collected during the early bloom growth stage of the plants after the last nitrogen application had occurred on the crops. Sixteen samples were collected from the N-RCS, one from each application zone, for a total of 48 soil samples. Figure 1.29 represents the results from the high soil EC zone; the strongest trend of residual nitrogen was found in this zone. The result is expected since a higher EC soil is usually a finer textured soil with smaller soil particles meaning a higher nutrient holding capacity. The cotton crop used all the nitrogen needed and available while the rest was left as residual in the soil.

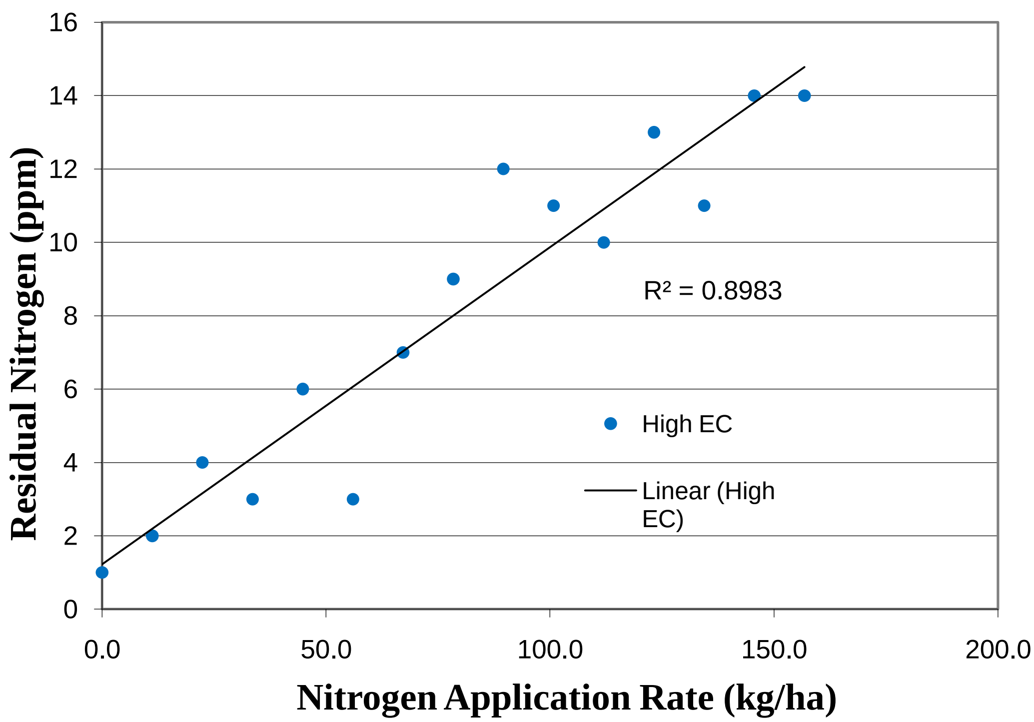

Figure 1.30. Soil test results from the high soil EC N-RCS (2008).

Plant height data was collected during the 2008 growing season and was correlated to the applied N rates. Only the low soil EC zone had a general increasing trend (R^2 = 0,755) in plant height as N rate increased, during the 16-node stage (Figure 1.31). The same results were obtained during the 19-node growth stage, with the lowest soil EC zone having the strongest correlation (Figure 1.32).

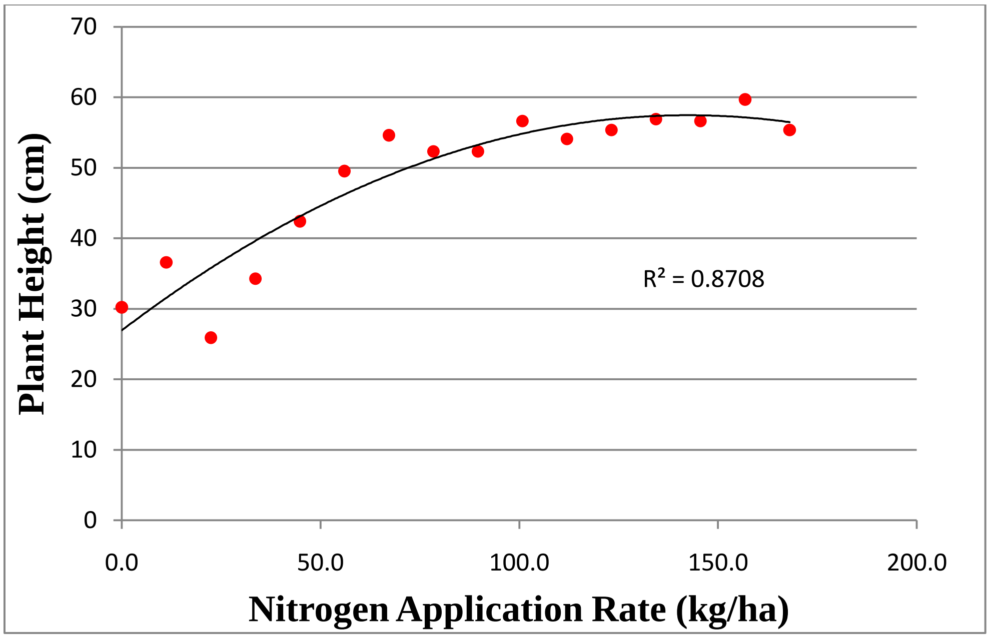

Figure 1.31. Correlation between plant height and N-rate (16 node stage).

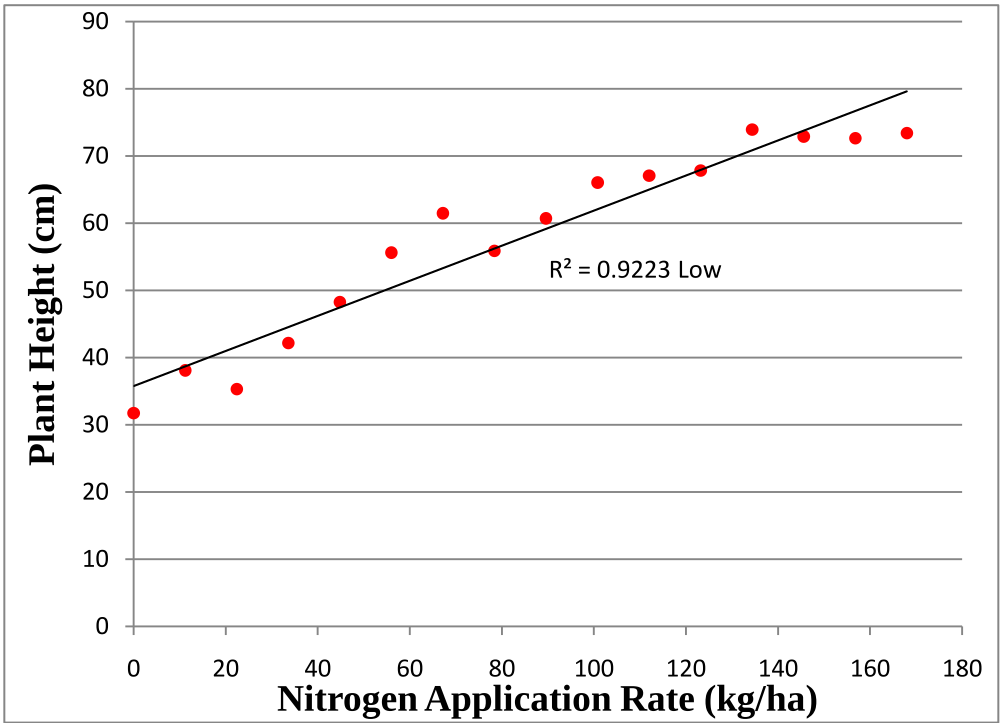

Figure 1.32. Plant height versus N rate (19 node stage).

As the plants matured, a leveling in vegetative growth and plant height could be observed from the results of the height versus nitrogen rate graph from the 19 node stage. The soil in the lower EC zone has a lower nutrient holding capacity thus the cotton plant will have a higher response to increases in nitrogen rate. As presented earlier, the medium and high soil EC zones did not show an increased response to the increase in N rate above 100.8kg-N/ha. This helps to explain why the plant heights of these two zones did not have a strong correlation with increases in N rate. Extra nitrogen was not required by the plants because more residual nitrogen was present causing no response in the heavier soil zones. Fewer residual nutrients in the lighter soil types enabled the plants to react to higher nitrogen rates in these soil EC zones.

Figure 1.33 represents the average micronaire of the cotton fiber samples collected at the end of the 2009 growing season from the variable rate nitrogen plots. There was a very strong correlation (R^2 =0.938) between applied nitrogen rates and the fiber micronaire. As the nitrogen rate increased so did the fiber micronaire. However, this is not a good trend in the southeastern United States, because discounts are given on the seller's price of cotton due to micronaire numbers that are either too high or too low. Optimum rate nitrogen application is a solution to high micronaire numbers. The lower requirement of nitrogen with a consistent yield will allow for better micronaire numbers, confirming the fact that a variable rate application of nitrogen should be used.

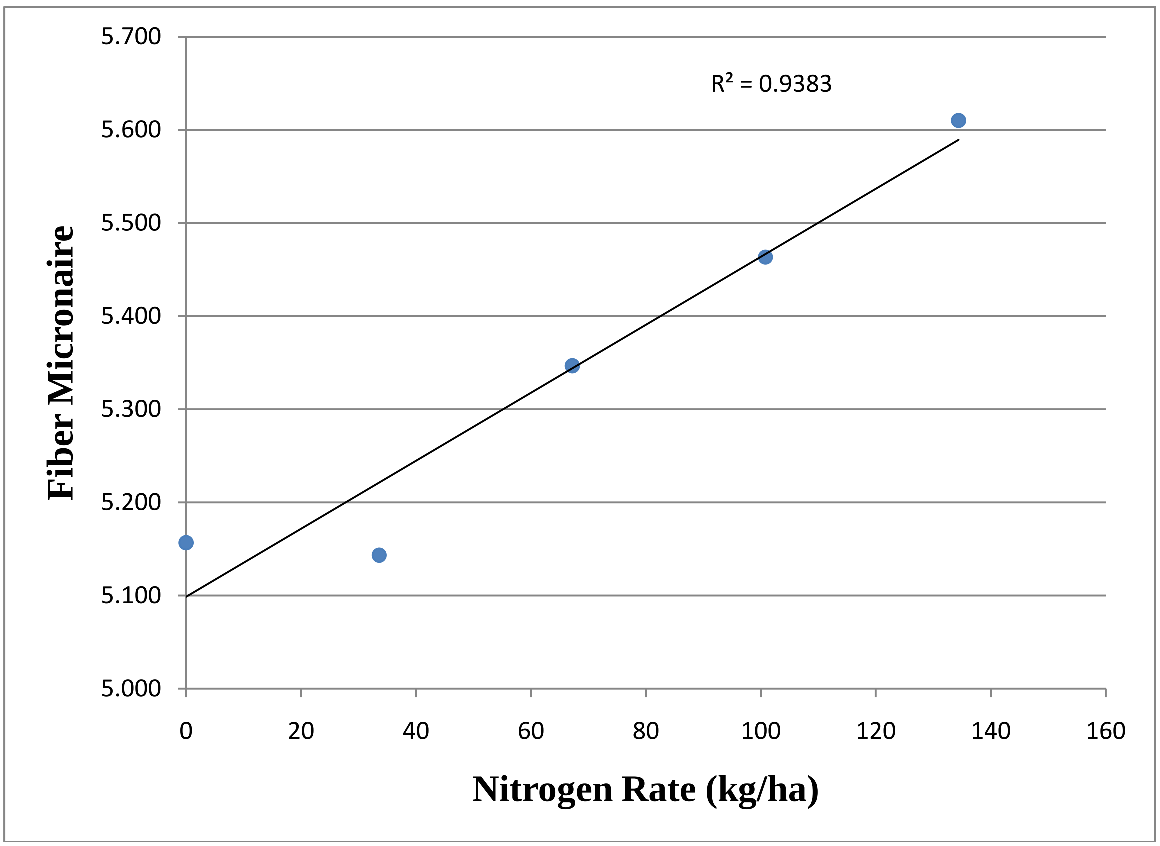

Figure 1.33. The effect of Nitrogen rate on fiber micronaire.

Tissue analysis tests were performed on the cotton seeds from the variable rate nitrogen plots to determine the percent of nitrogen in an average cotton seed. The results showed the average percentage was 3%. A very strong linear statistical correlation (R^2=0.93) was found between the percent nitrogen in harvested cotton seeds and nitrogen rate. Also there was an inverse correlation between percent residual nitrogen in cotton seeds and the total number of seeds produced by the plant. The higher the number of seeds contained in a plant the lower the total percentage of nitrogen in an individual seed. Table 1.3 represents the applied nitrogen rate in combination with the average number of seeds and percentage of nitrogen per seed in each of the three soil EC zones.

Table1.3. Relationship of the number of seeds and percent Nitrogen in individual seeds.

	High		**Medium**		**Low**	
Nitrogen Rate	**Number of Seeds**	**%N in Seeds**	**Number of Seeds**	**%N in Seeds**	**Number of Seeds**	**%N in Seeds**
0.00	1803.960396	2.71	1957.009346	2.75	1480.909091	2.65
11.30	1980.392157	2.92	1785.849057	2.35	1453.571429	2.96
22.56	1880.188679	3.02	1898.076923	2.68	1687.962963	3.28
33.83	1893.75	2.82	1857.894737	2.95	1625.087719	3.63
45.11	1937.142857	3.09	2041.747573	2.58	1723.909091	3.6
Average	**1899.0868**	**2.912**	**1908.1155**	**2.662**	**1594.2881**	**3.224**

The results did not follow the expected trend but can be easily explained. The medium soil EC zone had the highest number of seeds while the low soil EC zone had the lowest with the high soil EC zone falling in-between. The plants from the high soil EC zone had more vegetative growth thus less energy was devoted to seed and boll development. Table 1.4 represents the trend of a the high soil EC zone having the highest amount of vegetative growth and the lowest soil EC zone having the lowest vegetative growth. This trend is expected since the higher soil EC zones have higher nutrient holding capacities, thus the plants have the ability for more growth.

Table 1.4. Plant height and Nitrogen rate in each soil EC zone.

EC Zone:	High	Medium	Low
Nitrogen	Plant	Plant	Plant
Rate (kg/ha)	Height (cm)	Height (cm)	Height (cm)
0.00	99.06	84.07	29.97
11.28	82.30	95.25	36.32
22.56	91.19	83.06	48.77
33.83	97.54	90.17	40.64
45.11	102.11	103.38	59.94
Average	94.44	91.19	43.13

1.6 CONCLUSIONS

Two mid-season nitrogen prediction algorithms were developed during this research study including one for dry land cotton and one for irrigated cotton. Positive correlations between the in-season estimated yield (INSEY) and the actual yield were found in both studies. Very strong correlations were found between NDVI measurements and plant nitrogen requirements between the time periods of 40 to 60 days after plant emergence. Thus the developed algorithms have the ability to accurately predict the mid-season nitrogen requirements for the cotton plant in the southeastern United States specifically in the “Savannah Valley Region” of South Carolina.

The developed algorithms have been refined through multiple replications, and multiple years of testing. The developed irrigated algorithm has a higher yield prediction equation than the dry land equation because cotton under full irrigation has a higher yield potential. The dry land algorithm tests produced two N prediction equations. However, the algorithm for 2009 predicted slightly lower side-dress N rates, due to short growing season during 2009, caused by flooding and delayed replanting. The two algorithms followed a parallel trend between the two years. Each year, there was a high correlation between the INSEY and actual harvested yield data. This indicates that it is feasible to use mid-season plant NDVI data for variable-rate application of N fertilizer in cotton production.

The developed algorithms were tested during the 2009 growing season in conjunction with the OSU Nitrogen prediction algorithm and grower s' conventional practice. Statistically, there were no significant differences in cotton yields between the treatments in each zone. However, a significant difference was found between the soil EC zones. The fact has been confirmed that soil EC is a very important factor in deciding nutrient management zones to ensure plants receive the proper applications of fertilizers throughout the growing season.

An important part of the developed algorithms, the percent of residual nitrogen in cotton seeds, was tested and confirmed to ensure the proper numbers were being used in the Clemson algorithm. The test results showed that the average cotton seed contains approximately three percent nitrogen. A positive correlation was found between the applied nitrogen rate and the percent nitrogen in cotton seeds.

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CHAPTER TWO

DEVELOPMENT AND TESTING OF EQUIPMENT TO ACCURATELY APPLY SENSOR-BASED VARIABLE RATE NITROGEN FERTILIZER ON COTTON IN COASTAL PLAIN SOILS

2.1 INTRODUCTION

Currently most farmers apply a uniform rate of N fertilizer across an entire field or even an entire farm. However, plant demand, response to N changes from year to year, and the manner in which mobile nutrients (such as N) are used, lost, and stored change as soil texture varies. Therefore, a uniform application of N fertilizer over the entire field can be both costly and environmentally detrimental. Sensor-based, site-specific nitrogen application (SSNA) is an innovative technology that matches field variability of nitrogen utilization with an appropriate variable-rate fertilizer application, minimizing negative environmental effects while optimizing farm profit (Porter et al. 2010).

The development of sensor-based algorithms (Clemson University and Oklahoma State University) for mid-season N fertilizer estimation in the cotton crop (*Gossypium hirsutum L.*) has left grower's with a need for specific specialized equipment to perform the necessary field operations to apply the correct rate of variable rate nitrogen on the crop in the southeastern United States. Typical nitrogen fertilizer applicators are usually pull type with a ground driven sprocket wheel that turns a variable displacement piston pump. The application rate is a direct function of the stroke length setting on the piston pump. These types of pumps have limitations to apply variable rate N due to the mechancial requirement needed to change the settings of the pump with no automated control system. Map based variable rate controllers are much more accurate, can be controlled without much effort from the operator, and have the potential to be much more efficient in application than a typical uniform rate controller.

Optical sensors used in conjunction with a developed algorithm can accurately predict the mid-season nitrogen requirements of cotton. The GreenSeeker® (NTech Industries, Inc. Ukiah, CA) is an active optical sensor that measures plant Normalized Difference Vegetation Index (NDVI), which has been shown to be a good estimator of total plant biomass (Freeman et al., 2003; Raun et al., 2001; Raun et al., 2002). The sensor is a good biomass predictor because healthy plants with more leaf area and chlorophyll absorb higher levels of red light and are able to reflect more near infrared (NIR) than less healthy plants. Healthy plants reflect more NIR because they have more turgid and healthy mesophyll cells and denser canopies. The ratio of the level of reflectance of red and NIR are highly useful when using NDVI and an indirect measure of plant health (Arnall 2008).

2.2 OBJECTIVES

The main objective of this study was to develop equipment for variable rate application of nitrogen fertilizer utilizing previously developed algorithms.

The specific objectives were to:

- Develop, test, and calibrate a map-based variable rate nitrogen application system that can be retrofitted onto growers' existing fertilizer applicators.
- Determine the effects of equipment height and time of day on performance of the GreenSeeker® optical sensor.
- Evaluate the feasibility of utilizing ultra-sonic height sensors for predicting plant height on-the-go.

2.3 REVIEW OF LITERATURE

The focus of this section is to review the literature related to the study objectives and consists of three subheadings including:

1. Variable Rate Fertilizer Applicators
2. Factors Affecting the GreenSeeker Performance
3. On-The-Go Prediction of Cotton Plant Height

2.3.1 Variable Rate Fertilizer Applicators

Cotton production costs are typically greater than those for other crops traditionally grown, which makes it an attractive crop for precision agriculture technologies (Taylor et al. 2007). Variable rate fertilization aims to improve fertilizer use efficiency and reduce leaching by varying fertilizer rates according to the needs of each area within a field (Yang 2001). While optical sensors and algorithms have been shown to be useful for predicting the optimum rates of a variable rate nitrogen application, proper equipment is needed to implement the task. Without equipment which can automatically regulate application rates as it travels across a field, the prescription map will be useless in practical applications. Many research projects have been conducted in the development of variable rate systems (Robert et al., 1991; Fisher et al., 1993; Cahn and Hummel, 1995; Yang et al., 1998, 2001), and several companies are currently marketing variable rate application equipment (Clark and McGuckin, 1996).

Typically the control system for a variable rate applicator consists of an onboard computer (supplying variable rate application maps), a GPS receiver (supplying vehicle position), and a controller that controls material rates (Yang, 2001). Variable rate application equipment is available for a variety of materials including liquid fertilizers (Searcy, 1997). This equipment need to be refined and the applicator's hardware and software should be modified to make the system more user friendly for real-time variable-rate nitrogen applications.

Several researchers have evaluated the static and dynamic performance of variable-rate controller systems (Cugati et al., 2007; Dilawari et al., 2008; Yang, 2001; Porter et al., 2010). Tests were conducted by Cugati et al. (2007) to determine the effects of two speed sensors (GPS and real-time sensor) on dynamic performance of two commercially available controllers. They reported that both controllers had longer response time when GPS was used. The total application error was the criteria used to determine how well the system followed the prescription map issued by the controller. They also, reported that, the increased response time was mainly due to the search algorithm in the controller for determining the application rate from a prescription map at a particular spatial location. Porter et al. (2010) reported software lag time in using a hydraulic controller under true field conditions. Dilawari et al. (2008) reported that variable rate application of liquid fertilizer is challenging with standard fixed orifice nozzles due to limited rate changes. Limitations of electrical, hydraulic, and mechanical components and operating ranges of liquid fertilizer pumps could also have significant affects on fertilizer rates in many instances.

Dynamic and static performance tests were performed on a custom designed liquid knife nitrogen applicator by Yang (2001). Static tests gave promising results in controller response time and application rate, while the dynamic test had an average rise time of about 0.5 seconds. One study performed by Cugati et al. (2006) determined there was a longer delay in the dynamic performance of the control system for a fertilizer spreader compared to the static results.

Many performance evaluation tests have been executed on hydraulically controlled granular and liquid fertilizer applicators. Most of these studies utilized servo-valves, DC motor-operated valves and centrifugal pumps, for controlling the rates of fertilizers, which were different than the way Rawson (Trimble Navigation Limited Flows Division, Ukiah, CA) controller operates. The Rawson system is designed to control the speed of a piston pump by utilizing a variable-speed hydraulic motor. The development and refinement of optical sensor-based algorithms has given growers the ability to accurately predict the mid-season nitrogen requirement for cotton grown in the southeastern United States. Affordable variable-rate nitrogen application systems (such as the Rawson controller), which can be retrofitted to growers' existing equipment needs to be evaluated under actual field conditions. Results of these tests may provide cotton growers with affordable tools to apply side-dress, variable-rate nitrogen (Porter et al., 2010).

2.3.2 Factors Affecting the GreenSeeker Performance

The GreenSeeker RT series is one of the most widely used active optical sensors to determine the mid-season nitrogen requirement for many crops across the United States including cotton. The NTech Company states that NDVI data can be related to nutrient response, condition of the crop, yield potential, stress, or the pest or disease impact on the crop. According to the manufacturer, the sensor will perform the same during any time of the day or night if operated at the sensing height of in-between 81 to 122 cm above the plant. These factors should be evaluated under actual field condition to improve the performance of the sensor.

In a study conducted by Ramirez et al. (2010), ultra-sonic plant height was well correlated with NDVI measured by the GreenSeeker. This data supports prior findings by the investigators that NDVI and plant height are closely linked, particularly early in the growing season when the canopy has not closed down on the row (Ramirez 2010). In a study conducted by Kim et al. (2010), on young apple leaves under laboratory environment showed that the GreenSeeker sensor was height sensitive. They reported an optimal standoff distance from the apple leaves of 100-180 cm, which was much higher than the manufactures recommendations. They also conducted tests to determine the effects of zenith or sun angle on the sensor readings over a grass surface. They reported that there was no difference in sensor readings due to the sun angle. The external temperature likewise was found not to have an effect on the sensor responses. Majority of these studies were conducted under controlled environments or did not evaluate the effects of travel direction, and time of the day on performance of the GreenSeeker. Furthermore, the studies involving sensor height either were not involved in cotton or did not specify optimum height for sensor operation. This study was performed to evaluate the effects of travel direction, sensor height, and time of day on performance of the GreenSeeker optical sensor.

2.3.3 On-the-Go Prediction of Cotton Plant Height

Relationships have been found in multiple studies between plant height and NDVI. Varco (2006) reported that it is apparent that a strong relationship can be developed and that NDVI can then be used to predict cotton plant height differences. Thus, NDVI data can be used to predict plant height at each sampling date or across sampling dates. Plant height data collected simultaneously with NDVI measurements showed good correlations at the University of Tennessee (Ramirez et al, 2010). Ultra-sonic sensors were mounted on a fixed boom attached to a plot sprayer, and the sensor data was logged along with GPS position on a single board computer using a custom logging software. They reported that plant height can be successfully estimated on-the-go using ultrasonic sensors, which could be used during NDVI analysis. Incorporation of the height data reduced P-values for differentiating between nitrogen treatments with NDVI.

Plant height is used in specific programs for cotton scouting to ensure Plant Growth Regulators (PGR) and defoliants are applied at the correct time and at the correct application rate. Varco (2006) reported that plant height differences as influenced by N rates were most evident from 44 days after planting on. Earlier sampling dates concluded that the differences in plant height readings estimated by NDVI readings were mostly due to greenness differences and not plant height differences.

An optical cotton height sensor was developed using a commercial light curtain, and was evaluated under field conditions by Searcy and Beck (2000). The light curtain was placed across cotton rows and the blocked beams were interpreted to determine the height of the cotton plants in a section of row. The initial system tested in 1998 was based on a moving average of the highest blocked beam. A regression equation was developed for post-processing the light curtain data and was found to predict the hand measured height data with a 95% prediction interval of 3.3cm (Searcy and Beck 2000).

This work was conducted at Clemson simultaneously with Tennessee study. At the time of our experiment there was no published data on the utilization of ultra-sonic sensor for cotton plant height measurement. Furthermore, this study compared two commercially available ultra-sonic sensors, one of which is already used by some farmers for controlling sprayer boom height.

2.4 MATERIALS AND METHODS

2.4.1 Nitrogen Fertilizer Applicator

A multi-orifice variable rate nitrogen applicator was developed during the 2008 growing season. The boom consists of four different size orifices on each side of the crop row. The orifices were sized and calibrated such that any combination of them would allow the application of rates from 0 to 168 kg-N/ha in increments of 11.2 kg-N/ha. Each set of orifices were controlled by an individual solenoid valve. A flip of a switch or trip of the limit switch will open and close the valves in sequence, allowing for an instantaneous rate change. The applicator has the potential to apply “Nitrogen-Ramped Calibration Strips” (N-RCS). A ground driven wheel with a limit switch changes the rate every 5.09 meters. The ground driven wheel allowed for an application of 16 different application rates (0-168 kg-N/ha) without any controller change from the driver.

Figure 2.1. Multi-orifice variable rate Nitrogen applicator.

The controller was modified using a push-wheel switch so that the applicator could be used to apply variable-rate nitrogen to the test plots. The push-wheel switch allowed for easier driver control compared to the original design of four switches system shown in (Figure 2.2).

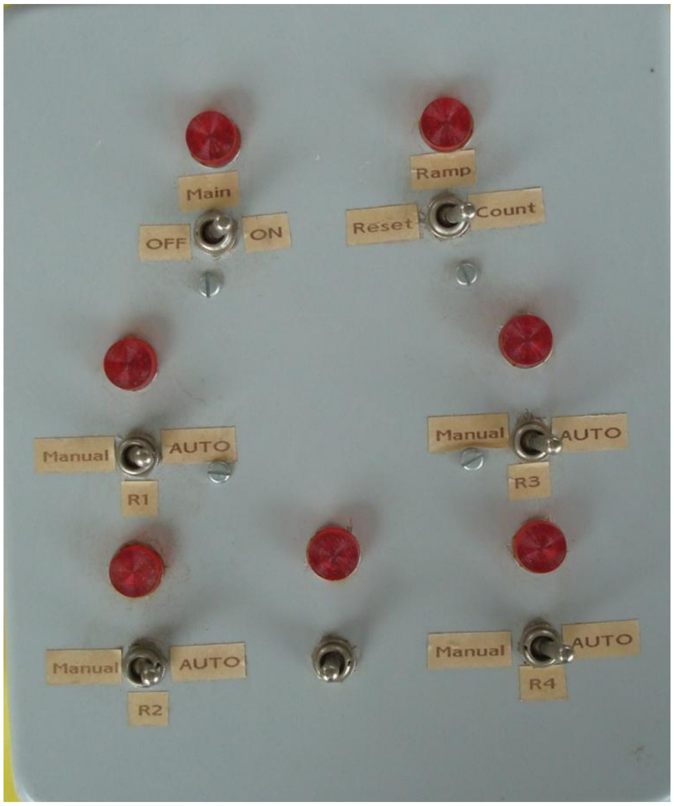

Figure 2.2. Original controller for the multi-orifice Nitrogen applicator.

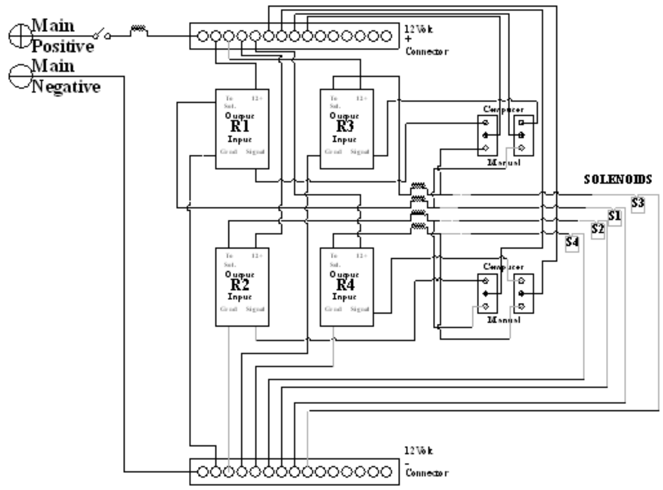

Figure 2.3. Wiring diagram for a redisigned controller for the multi-orifice applicator.

The new controller replaced the original circuit controls with a Programable Logic Computer (PLC) to control the application of the N-RCS. The orifice applicator was proven to be very accurate but was not map based. All applications except the N-RCS applied by the counter wheel were controlled by the operator. Operator error was a factor in this type of controller because of the difficulty in driving the crop rows while also ensuring that the correct application rate was being applied in the correct plots. Calibration rate for the orifice applicator was speed dependent thus, once calibrated for a specific speed, the application rate was only accurate for that specific speed. The applicator was proven to work for plot work but will likely never be a viable part of growers equipment due to its inpracticality. The main objective of this study was to develop, test, and calibrate a map-based variable rate nitrogen application system that can be retrofitted onto growers' existing fertilizer applicators. During the 2009 growing season variable-rate control equipment was retrofitted to an existing four row nitrogen fertilizer applicator (Figure 2.4). A typical ground driven applicator with a John Blue piston pump (CDS-John Blue Company, Huntsville, Al) was chosen because many growers use this type of nitrogen fertilizer applicator. The existing ground driven John Blue pump was attached to a hydraulically-operated variable-speed motor. The motor was controlled by a Rawson Control system (Figure 2.4). The Rawson system is capable of vaying liquid N rates, either by manual or map based control. A benefit of the Rawson controller over the original orifice applicator was that the hydraulic controller's calibration wa relativelys independent of speed.

Figure 2.4. The side-dress Nitrogen applicator with retrofitted Rawson controller.

Speed for the Rawson controller can be obtained either through ground radar or through the output speed from the GPS. In the GPS case, the controller required an input signal of 5 Hz or greater. A Trimble Ag GPS 332 (Trimble Navigation Company) with the "fast rate" option (10 Hz) was used to supply the speed to the controller for the test plots to ensure the highest possible accuracy. The accuracy of the GPS for measuring ground speed was tested at different operating speeds of 5.63, 6.43, 7.24, 8.04, and 9.66 kph.

The accuracy of the Rawson controller for applying variable-rate N was tested multiple times to evaluate its static and dynamic performances. The nitrogen application system was calibrated at different application rates to ensure maximum accuracy. Six target rates (44.7, 59.6, 74.5, 89.4, 104.3, 119.2 kg-N/ha) were selected for application uniformity tests. The tests were perfomed while the applicator was stationary. Samples were colected for 17 seconds and were compared to the target nitrogen rates. To determine uniformity of application within rows, all four rows were sampled separetly and the tests were replicated four times for each rate. To ensure greater accuracy, the nozzle bank on the applicator was relocated from the right side of the applictor to the middle. All pressure hoses leaving the nozzle bank traveling to the coulters were replaced with four hoses of uniform length to ensure consistent pressure drop throughout the system. Pressure regulating chemical diaphragm valves were added to the applicator tips to ensure pressure uniformity throughout the pressure side of the system. The diaphragm valves remain closed until the entire system pressure reaches a minimum of 34.47 kilopascals. An equal pressure combined with equal cross-sectional area in the four orifices improves flow uniformity across all application nozzles of the fertilizer applicator.

The variable-rate nitrogen applicator was also evaluated under actual field conditions (dynamic test). A geo-referenced nitrogen-rate-map was developed using SSToolbox GIS software (SST Software Stillwater, OK) and transferred into the

FarmWorks system. Six target rates (44.7, 59.6, 74.5, 89.4, 104.3, 119.2 kg-N/ha) were selected for the nitrogen application uniformity test. For each target rate, an application uniformity test was conducted by running the N side-dress system at field speed with the coulters running above the ground and dispensing the liquid fertilizer. Catch pans (86.36cm by 96.52cm), each covering one cotton row width, were used to collect the N fertilizer as the applicator was driven through the test field. The applicator was lifted up from the ground to prevent damage to the test pans. The tractor was driven at 6.43 kilometers per hour to simulate normal field application speed. Four samples from each rate were collected, measured using a graduated cylinder, and the results were compared to the actual target rate.

The FarmWorks Site Mate software provided the nitrogen rate information to the Rawson controller. The FarmWorks software updated the GPS-location signal every second. After several tests, it was obvious that this software did not update the applicator's location in the field fast enough to allow for the Rawson controller to utilize the sub-foot accuracy of the differentially corrected GPS signal sent from the Trimble Ag GPS unit. The update rate allowed for 1.8 meters of error while traveling at a typical field application speed of 6.43 kilometers per hour. Although this error may not be a problem in a grower's field, it could be a major factor in research plots, especially when combined with GPS differential correction errors. GPS travel direction errors must also be factored into the loss of area in a research plot. A typical GPS will have a little under a meter of lag time in whichever direction it is traveling. Thus in an eight row plot using a four row applicator, error will occur from two different travel directions. An aerial photograph from the 2009 production year shows the travel direction and software update errors (Figure 2.5).

Figure 2.5. Aerial photo of uneven plots caused by GPS and software errors.

2.4.2 Normalized Difference Vegetation Index (NDVI)

The GreenSeeker RT-200 six-row NDVI system (Figure 2.6) was used to determine if the GreenSeeker® sensors are height and time of day, or more specifically sun angle sensitive. A standard section of a test field was used to conduct two specific tests.

The first test performed was to determine the height sensitivity of the GreenSeeker sensors. A commercially available NORAC UC4+ (NORAC Systems Fridley, MN) (Figures 2.7 and 2.8) ultra-sonic height controller was used to standardize the above canopy sensor height. The UC4+ system was attached to a typical John Deere 6700 self-propelled sprayer (Figure 2.6).

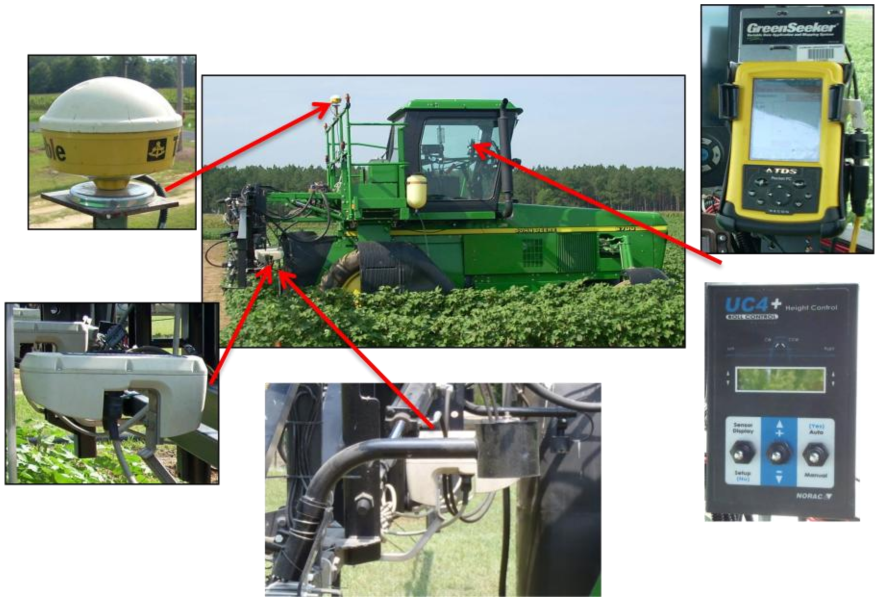

Figure 2.6. John Deere 6700 with NTech GreenSeeker® RT-200 system.

The control system, when placed on automatic mode, used the average of three ultra-sonic height sensors to determine the canopy height of the crop below. The system then automatically adjusted the height of the sprayer's boom to keep it at the user defined height above canopy as the sprayer traveled through the field. The ultra-sonic control system is typically used in standardizing the height of a sprayer's boom when non-uniform field conditions were present. A nitrogen study typically results in non-uniform field conditions in the sense of plant height due to variable rates of nitrogen and various soil types. The ability of the UC4+ to maintain a uniform height above crop canopy made it an excellent aid in standardizing the sensor heights above the plant canopy for NDVI measurements.

Figure 2.7. UC4+ Ultrasonic Sensors and GreenSeekers®.

Figure 2.8. UC4+ Height Controller.

Tests were conducted between 9 a.m. to 10 a.m. to determine the effects of sensor height on NDVI readings. Six different heights (50.8, 61, 76.2, 91.4, 106.7, and 121.92 cm) above plant canopy were used during this test. The section of the field chosen for the height sensitivity test consisted of nine plots for a total of 137.2 meters in length. The two plots on the end of each of the tests were eliminated to prevent border effect. The remaining plots were divided into 7.62 meter long plots. A total of fifteen plots were constructed from the original nine for a total length of 114.3 meters. The chosen plots all had an equal amount of nitrogen and the crop rows run from east to west. Each height measurement was collected throughout the plots traveling from the east to west then immediately from the west to east direction to determine the effects of direction of travel and sensor height on the NDVI readings. Each pass was exported and saved as an individual file to ensure no data overlap. The exported data was imported into the SSToolBox GIS software program to be averaged within each plot. The averaged data was exported as a text file and analyzed using Microsoft Excel (Microsoft Redman, WA) and SAS (SAS Institute, Cary, NC) (statistical analysis software).

The time of day and sun angle sensitivity test was conducted on the same fifteen plots in the test field to ensure that similar NDVI readings would be collected as in the height sensitivity test. A standard height of 91.4 centimeters was chosen for this test. This height was chosen because the height sensitivity test confirmed it returns more uniform readings from the sensors. NDVI measurements were collected beginning at 8 A.M. in the morning and stopped at 11 P.M. at night at a rate of two passes per hour.

One pass was collected from the east to west direction and the other from the west to east direction. The passes were collected within a five minute time window of each other to ensure the sun angle was as close to the same position as possible. The passes were collected from two different directions to see if the sun angle and travel direction have an effect on the sensor readings. Each pass was saved and stored in a different file to prevent data overlap. The files were exported from the GreenSeeker® data logger and imported as shapefiles into the SSToolBox GIS software program for analysis. Once SSToolBox was used to average the sensor readings throughout the plots, the data was exported to be analyzed using Microsoft Excel and SAS software.

To ensure the accuracy of the sensor responses from the "time of day" test, one sensor was placed at a standard height above a piece of green cloth and allowed to collect NDVI data from 8 a.m. until 11 p.m. (Figure 2.9). The data was continuously collect on a 10 Hz signal throughout the day. The hourly readings were averaged and compared to the NDVI data collected from the cotton plants.

Figure 2.9. GreenSeeker® data collection over green cloth.

2.4.3 On-the-Go Ultra-Sonic Cotton Plant Height Prediction

Two different types of ultra-sonic height sensors were tested and compared to determine the feasibility of determining plant height on-the-go. Two sensors of each type were used in this comparison. The first type was a Hyde Park (HP) ultra-sonic sensor (Trask Instrumentation, INC. Greer, SC). The second type of sensor was a NORAC (NORAC Control Systems Fridley, MN) ultra-sonic sensor which works very similar to the UC4+ system.

The Hyde Park (HP) sensor has a range from 11.4 to 208.3 centimeters. The user defined operating range can be set anywhere within this range and according to the manufacturer will have a repeatability of 3 millimeters in a lab setting. The user defined heights will give a range of 2 volts for the upper limit and 10 volts for the lower limit. Based on manufacturers of the sensors the voltage and height will have a linear relationship. Initial tests and calibration equations were developed for the HP sensors in a lab setting to determine their full accuracy and the feasibility of using the sensors in the field. A test stand (Figure 2.10) was built so that the sensors could be connected to a power source, the data collected, and calibration equations were developed using Microsoft Excel. During the initial test the data was collected manually to ensure the accuracy of the sensors for their intended purpose before developing any software.

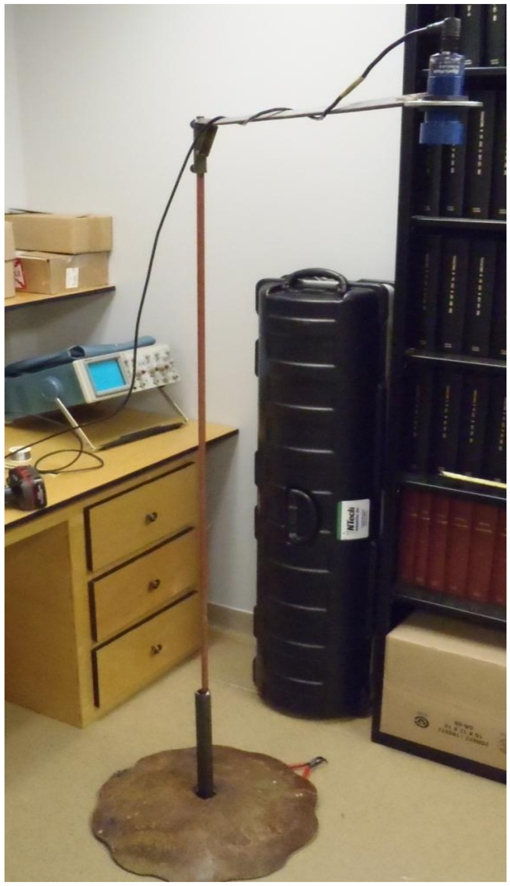

Figure 2.10. Test calibration stand for the HP sensors.

The test stand was designed so that the sensors could be easily moved to multiple heights and the voltages were measured using a Fluke multi-meter (Fluke, US). Each time the sensor was positioned to a new height, the height was recorded along with the displayed voltage from the multi-meter.

Mounting brackets were developed to install the HP sensors on the boom of the John Deere 6700 sprayer. One sensor was mounted in between the crop rows and the other was mounted directly over the plant canopy (Figure 2.11). The sensors were mounted over row seven of an eight-row plot. Optimally multiple sets of these sensors should be used (possibly over rows two and seven of an eight-row plot) to obtain more accurate plant height measurements with respect to the spatial data.

New calibration equations were developed for the sensors once they were mounted on the boom to ensure the sensors were giving the most accurate height data possible. For this purpose a flat surface (plywood board) was used.

A program was developed to record the output voltages of the two sensors along with the GPS coordinates on a 10 Hz signal to ensure a high accuracy level throughout the test field. The HP sensors have the ability to record the height data on a user defined interval. In this case 10 Hz was chosen because it matched the rate of the GPS unit, thus allowing for each recorded GPS point to have an associated height measurement. If a higher sampling rate was used for the sensor data logging, each GPS reading could have multiple height readings that could be averaged. The program uses the signals from a MiniLab-1008, a 12-bit data acquisition multi-function module, (Measurement and Computing Corporation Norton, MA) to collect the voltage (and therefore height) data into a standard laptop computer. A Trimble Ag GPS 132 (with differential correction) was used to collect the location of the height data. The software (written in Visual Basic by Brittany Lampson and Young J. Han) created a comma delimited text file which was imported into the SSToolBox GIS software program.

Height tests were performed over a concrete surface first to validate the usefulness of the sensors, calibration equations, and software program for collecting height data. Two sheets of plywood were placed under the sensors, one at ground level and the other on variable height stands to represent plant canopy. Once the initial test was performed field static and dynamic tests were performed to evaluate the performance of the sensors. The static test was performed by collecting stationary data over specific plants, then hand measuring the actual plant height. The heights collected from the dynamic test throughout the field were correlated to the actual plant height measured manually.

Figure 2.11. Mounting locations of the HP sensors on the sprayer boom.

A process of ground truthing was conducted after data collections from the sensors were completed. The plants located in the randomly selected points were measured by hand and their heights were recorded. The actual plant height data then was compared to the data collected by the sensors. The purpose of ground truthing was to determine the feasibility of ultra-sonic sensors for measuring plant height on-the-go.

The NORAC sensors were mounted on rows three and six of the eight-row plots. The two ultra-sonic sensors came with mounting brackets and were attached to the back of the boom on the sprayer since there was not ample room without interference on the front of the boom (Figure 2.12). The NORAC Company instructed that the sensors should not be within 1.83 meters of the other height controlling sensors due to signal interference.

Figure 2.12. NORAC ultra-sonic height sensors.

The NORAC sensors work with an already programmed touch screen data logger that works with a Windows CE operating system (Figure 2.14). The program works with a CAN-Bus data collection system, thus digital signals are sent from the sensors to the data logger. The data logger stores the coded signals to a memory card, and then the raw data is sent to the NORAC Company for processing. The raw data from the two sensors is averaged into one reading for the near return and one reading for the far return targets.

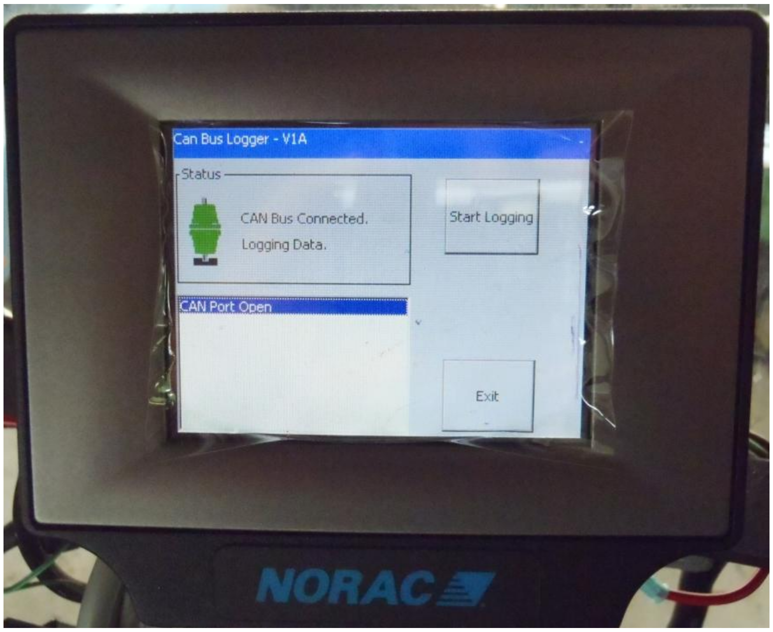

Figure 2.13. Touch screen NORAC data logger.

The two sensors were located directly over the crop canopy because these sensors have the ability of reading multiple targets at the same time. The sensors work on a first return, last return data collection system. This means that the first return is stored and is estimated to be the crop canopy while the last return is stored and is estimated to be the bare soil below the crop. The difference between the two readings should give plant height. This explains the reason the sensors have to be almost two meters away from the other ultrasonic sources; otherwise the sensors may pick up the wrong signals and give false height readings. The NORAC sensors for measuring plant height are new technology and have not been field tested to check their viability for accurately reading and recording plant height. The sensors have been proven to work well for accurately controlling the height of a sprayer's boom for field operations.

As with the Hyde Park sensors a series of ground truthing was performed with the NORAC sensors. Specific locations were chosen throughout the test plots in the field to collect plant height data using the sensors. The data was collected for approximately two to four seconds in each location. Then the actual plant height under the sensors was measured manually. The CAN-Bus collects data on a 100 Hz signal thus in four seconds there will be four hundred data points to average to obtain an accurate plant height reading. Again the recorded actual heights were compared to the collected data from the ultra-sonic sensors. The NORAC data logger does not easily adapt to a typical Trimble Ag GPS system, therefore, the height data were not geo-referenced for this test. To eliminate this problem, the sensor measurements and actual plant height measurements were taken simultaneously. The results of this test will determine the feasibility of using the NORAC sensors for on-the-go plant height measurements.

2.5 RESULTS AND DISCUSSION

2.5.1 Nitrogen Fertilizer Applicator

The results of the static calibration test showed an excellent correlation (R^2=0.9976) between targeted and actual nitrogen rates (Figure 2.14). Measurement errors for the "Static Test" ranged from -6.6 to 3.9% with a mean error of -0.6%. The static test proved to be very accurate with minimal error.

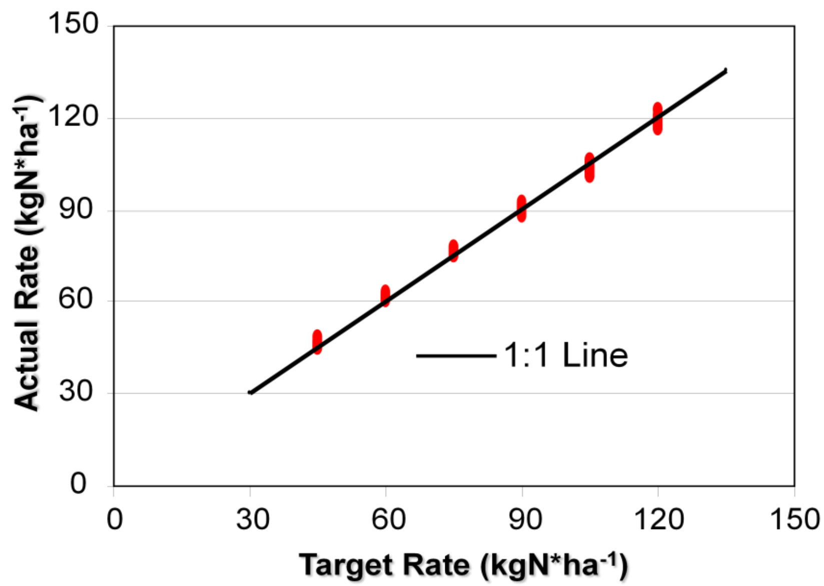

Figure 2.14. Graphed results from static calibration test.

The measurement errors for the dynamic test ranged from -16 to 34% with mean error of 18%. The variable-rate nitrogen application system closely followed the recommended fertilizer-rate maps. The measurement errors were mainly due to equipment limitations for applying lowest and highest rates of nitrogen and limitations in the FarmWorks software for rapidly updating the applicator's location in the field. The

John Blue piston pump's application rate is directly related to its rotational speed (rpm) and the piston stroke length which could be manually controlled by operator. When a hydraulic controller is attached, its rotational speed can no longer be controlled by the operator. Under this condition the piston stroke length is still set manually and the application rate is controlled by changing the rotational speed of the hydraulic motor. The accurate delivery rate of the piston pump used occurs between the rotational speeds of 150 to 500 rpm for each stroke length setting. However, when the pump speed is outside of this range the application rate becomes skewed. The errors during the dynamic test can be explained because of the above described pump limitations (Figure 2.15).

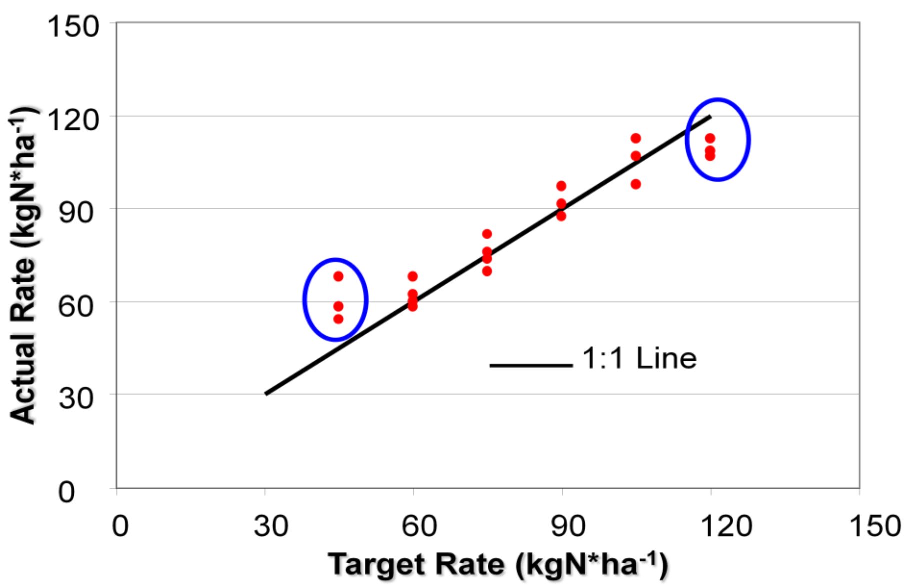

Figure 2.15. Graphed results from the dynamic calibration test.

As shown in Figure 2.15, the upper and lower ranges of application rates during the dynamic test were skewed down and up respectively. The lower and upper end of the performed test fell out of the optimum operating speed of the piston pump. The Rawson software has a built in safety factor to ensure the pump never operates out of the optimum speed range. The software overrides the control signal sent from the map-based software and selects a range that falls well within the optimum range. Therefore, the actual applied rates chosen by the controller were different from the prescription map-based rates being received from the SiteMate software. These results showed that as long as the required application rates fall within the optimum operating speed of the pump the applicator will apply the correct rates.

The slow update rate of the software combined with control lag time caused a loss of approximately 1.8 meters from each end of each test plot, meaning approximately 24% of the 15.24 meter long plots was lost. Overall, the software did a good job, controlling the Rawson system for fertilizer application neglecting the lag time. It is good software for on the farm use for controlling fertilizer applications in growers' fields; however more precise software is recommended for research plots.

2.5.2 Factors Affecting the GreenSeeker Performance

Figure 2.16 represents the results from the NDVI height sensitivity test. It was found that the GreenSeeker® sensors are height sensitive within the range tested. An inverse linear relationship was found that represents a decreasing sensor reading with an increasing sensor height above canopy.

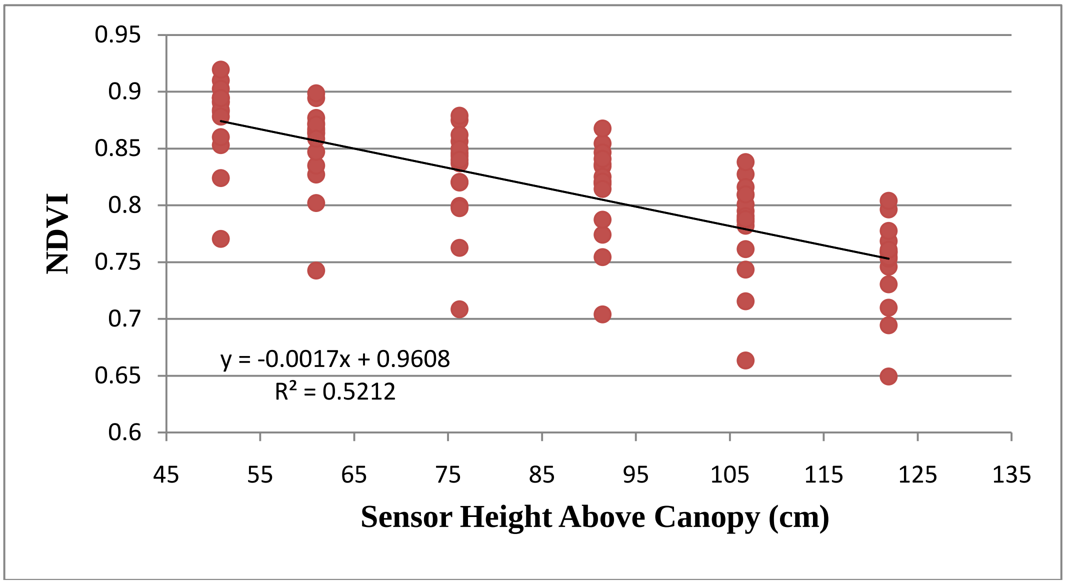

Figure 2.16. Inverse linear relationship of sensor height above canopy and NDVI.

A significant statistical difference in NDVI was found between all sensor heights tested, except within the 76.2 to 91.44 centimeter collection range, using SAS. The 76.2 to 91.44 cm range represents an equal optimum range to collect data within to prevent a variation in collected data points.

Travel direction was tested to ensure the direction of sunlight reflecting off of the plants did not interfere with the readings. It was found that the travel direction does not have significant effects on NDVI data. Thus, NDVI data can be collected correctly regardless of the direction of travel.

From the number of repetitions, data collected, and the analyzed results it was evident that the GreenSeeker® sensor would perform best from the height range of 76.2 to 91.44 centimeters and is not travel direction sensitive. If the sensors are located closer to the plant canopy, the sensors will become saturated. A saturated sensor reading means that no difference in NDVI values will be seen between plants with different canopy size or plant health.. Saturation usually occurs because the sensor is only seeing a very small portion of the plant which does not give an accurate representation of the NDVI measurements of the entire plant. The saturated sensor usually records a maximum value for the plant NDVI, about 0.9. If the sensor is too high from the plant canopy, too much soil in the early growing season and too much canopy overlap in the latter part of the growing season will be present. More visible soil causes the sensor to return lower numbers than the actual value. An overlapping of plant canopy means that part of sensor readings may be actually coming from the plants of the neighboring rows. Figure 2.17 shows a very highly inverse linear correlation (R^2=0.9865) between the plant NDVI and sensor height above the plant canopy for data averaged over each height setting.

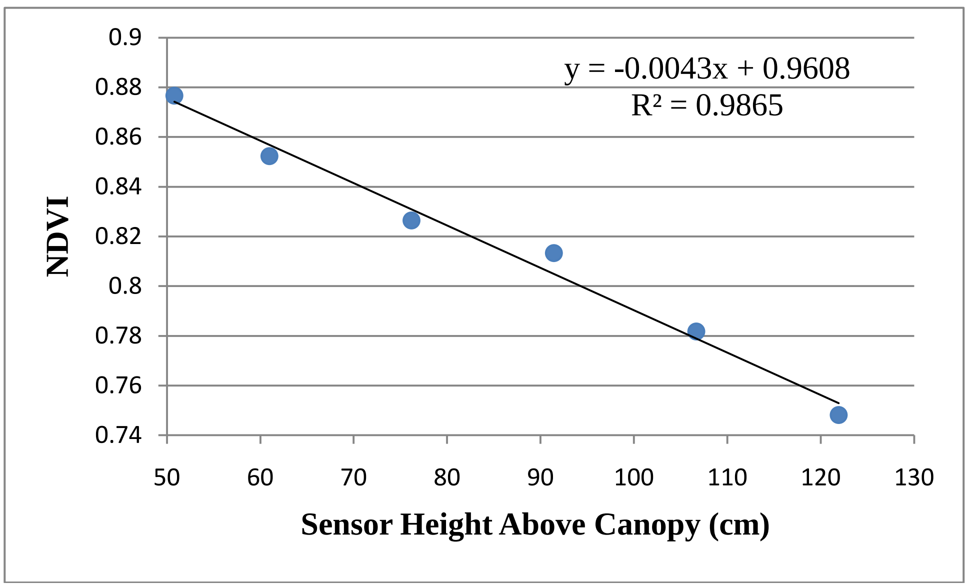

Figure 2.17. Average inverse linear relationship of NDVI and sensor height above canopy.

Figure 2.18 represents the GreenSeeker® sensor readings throughout the day starting at 8 a.m. and ending at 11 p.m. The sensors returned higher readings early in the morning (8:00 to 10:00 am) and then leveled off throughout the rest of the day until around 7 p.m. The higher values of NDVI collected early in the morning could be due to lover ambient temperatures as shown later in this chapter. NIR absorption will be higher as temperature increases (Hollis, 2002). Therefore, the reflectance values would be higher, resulting in higher NDVI readings. After 7:00 pm, the sensor readings began to reduce as the light conditions lowered. The NDVI values are affected by plant photosynthesis. Since later in the day, plant photorespiration increases and photosynthesis decreases, therefore, NDVI values would decrease accordingly. Statistically there were no differences in sensor readings between 10 a.m. and 8 p.m. (four hours after sunrise and one hour before sunset). The direction of travel again did not have an effect on NDVI readings throughout the day. Overall the test proves that the sensors are not sensitive to the angle of the sun and can be used four hours after sunrise until one hour before sunset to collect data.

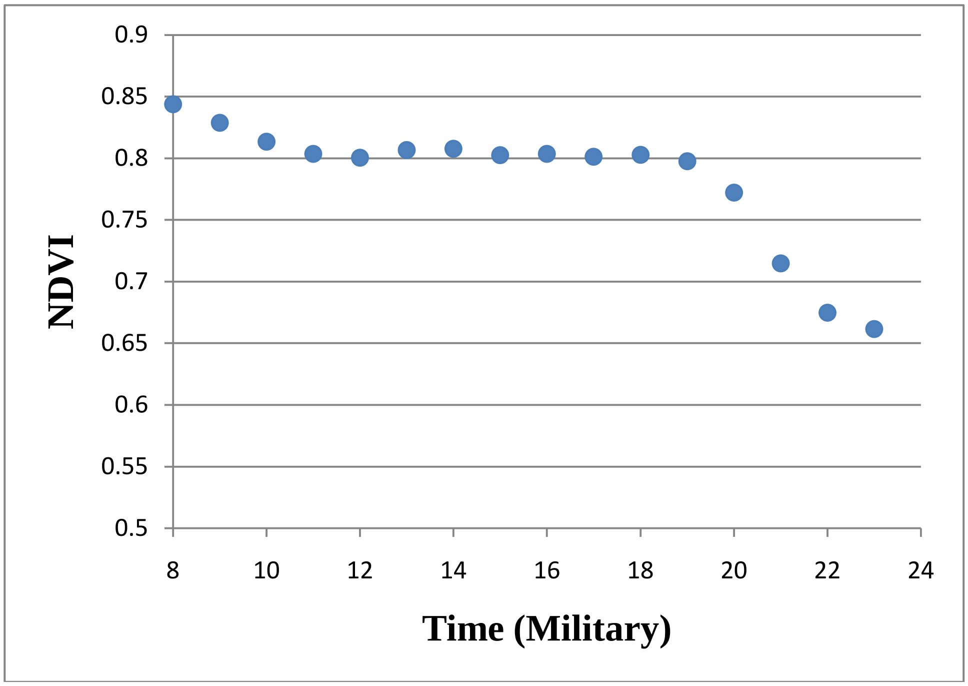

Figure 2.18. GreenSeeker® sensor readings throughout the day.

Figure 2.19 shows that the sensor returns a relatively flat, equivalent reading throughout the day, when it was placed over a large piece of green cloth. Comparison of NDVI values collected using a green cloth and cotton plant, showed that the NDVI values are not affected by sensor responses to time of the day. The cloth returns a lower number than the plants (Figures 2.18 and 2.19) because NIR light in plant is more highly reflected by mesophyll cell walls. Uniform reflectance from the green cloth throughout the day, makes it a perfect standard to test the sensor against.

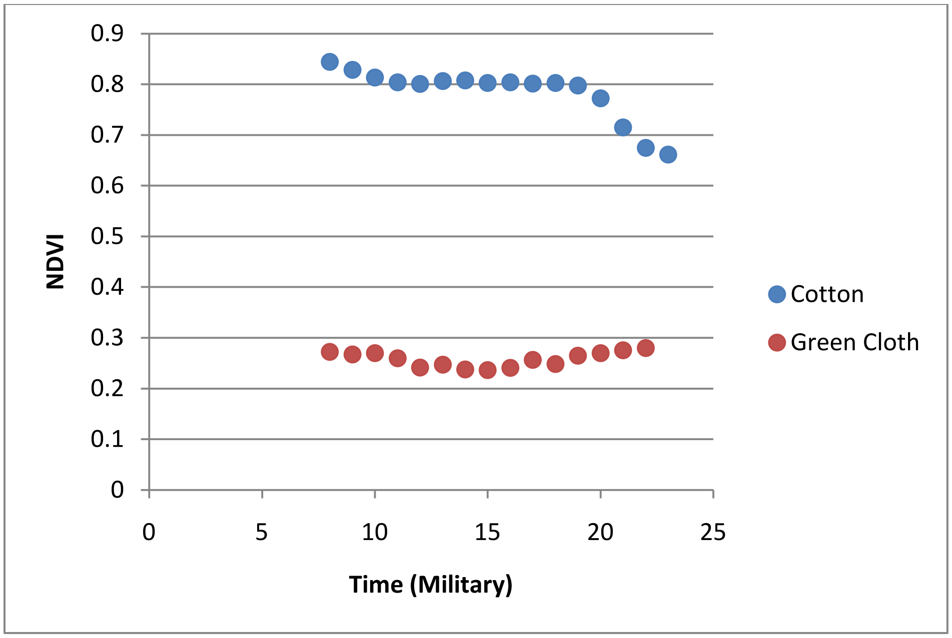

Figure 2.19. Comparison of Cotton and a green cloth NDVI sensor reading.

NDVI has a good correlation to plant health due to a few specific factors. During the day, the chloroplast is capable of producing sugars faster than they can be exported. The extra sugars are converted to starch and stored within the chloroplast, until at night when the starch is converted to sucrose and transferred to the plant organs that are actively growing. The chlorophyll pigment in plants absorbs most energy at about the 650 nanometer (red) and 450 nanometer (blue) ranges on the visible light spectrum. A healthier plant will be visibly seen as a darker green color since the absorbed red and blue light wavelengths are not seen by the human eye. Unhealthy plants will have less chlorophyll and will appear visibly brighter and will have a yellower color to them. Near infrared light is more highly reflected by healthy plants that have turgid and healthy mesophyll cell walls. When a plant is not vigorously photosynthesizing it will have a lower amount of active chlorophyll thus the reflected NDVI number will be lower.

Therefore, the lower NDVI readings collected after the sun light faded at the end of the day can be explained due to plant physiological reasons.

Temperature data (Figure 2.20) and solar radiation data (Figure 2.21) was collected for the hours of sensor measurements and compared to the NDVI readings. No statistical correlation was found between the NDVI sensor readings and the collected temperature or solar radiation data during the time of the collection. Some of the solar radiation data represents times when cloud cover was present and there was still no statistical correlation between the two. The sensors perform to an equivalent level independent of the sun angle, temperature, or solar radiation conditions, except early in the morning witch lower temperature will results in higher NDVI values.

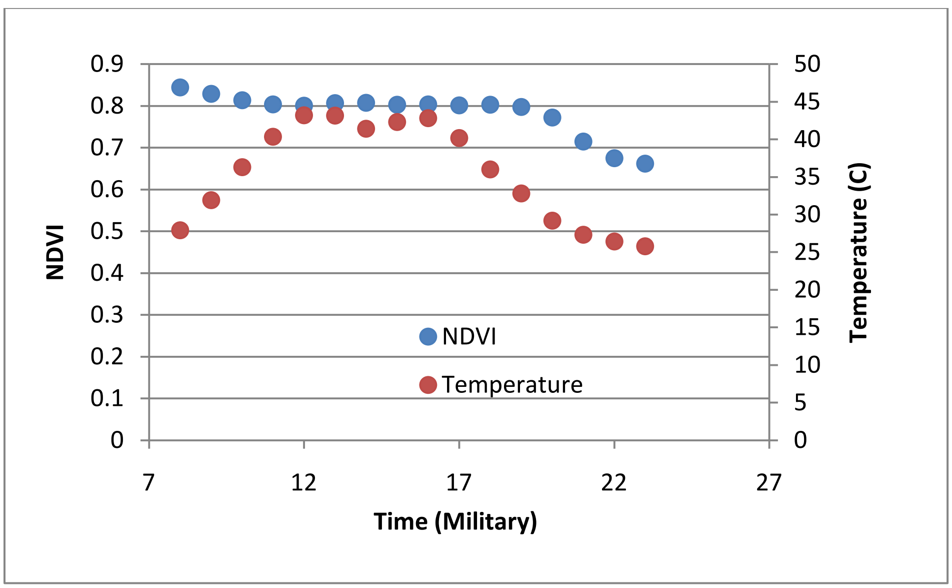

Figure 2.20. Temperature and NDVI collected from 8 am to 11 pm.

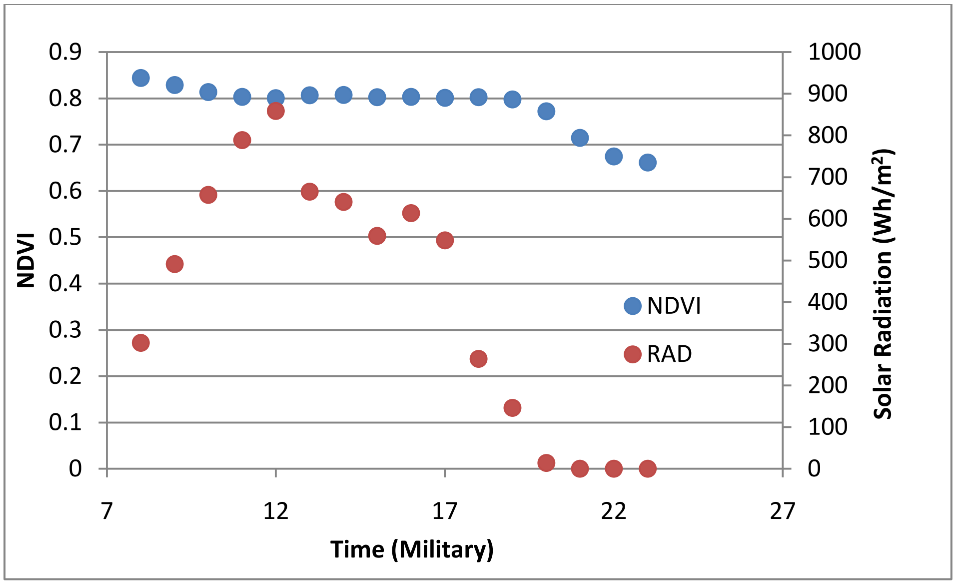

Figure 2.21. Solar Radiation and NDVI collected from 8 am to 11 pm.

The GreenSeeker® is a very good sensor that can be used to determine many different crop parameters including stresses and nutrient requirements, as long as it is used at optimum height and time of the day. Based on the results of this study the optimum height range was found to be 91.4 cm to 121.9 cm above crop canopy. Similar results were reported by Kim et al. (2010). The optimum time of the day for measuring NDVI should be between four hours after sunrise and one hour before sunset.

2.5.3 On-The-Go Ultra-Sonic Cotton Plant Height Prediction

Calibration equations developed for both sensors in the initial lab tests produced an R^2=1. Table 2.1 shows the results from the calibration equations along with the graph from one sensor in Figure 2.22.

Table 2.1. Height readings and voltage outputs from the HP sensor.

Sensor Height	Voltage Output
162.40125	2.0075
154.305	2.54
143.35125	3.21
132.87375	3.91
121.6025	4.65
108.74375	5.49
94.9325	6.41
79.21625	7.43
62.865	8.515
51.91125	9.22
43.02125	9.8
44.92625	9.68

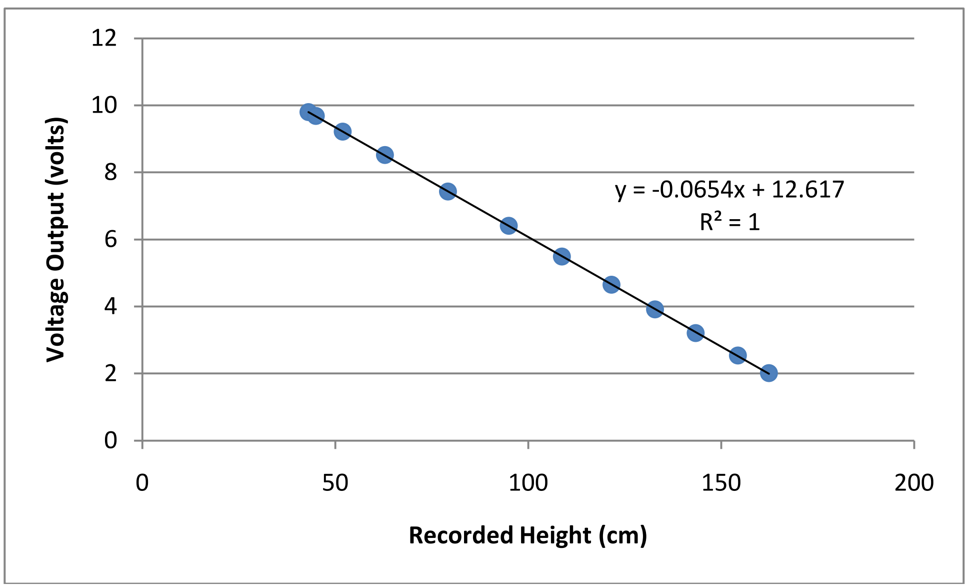

Figure 2.22. Calibration equation for HP sensor.

Figure 2.23 represents the results from the static performance test of the ultrasonic sensors over the plywood, performed to determine the accuracy of the sensors, calibration equations, and software. The calibration equations, developed after the sensors were mounted on the boom, are given in the following equations for the lower (soil) and upper (canopy) sensors

$$Soil\_Sensor = -15.23 * volts + 176.34 \qquad 2.1$$

$$Canopy\_Sensor = -14.7 * volts + 158.43 \qquad 2.2$$

$$Plant\_Height = Soil - Canopy + 33.8 \qquad 2.3$$

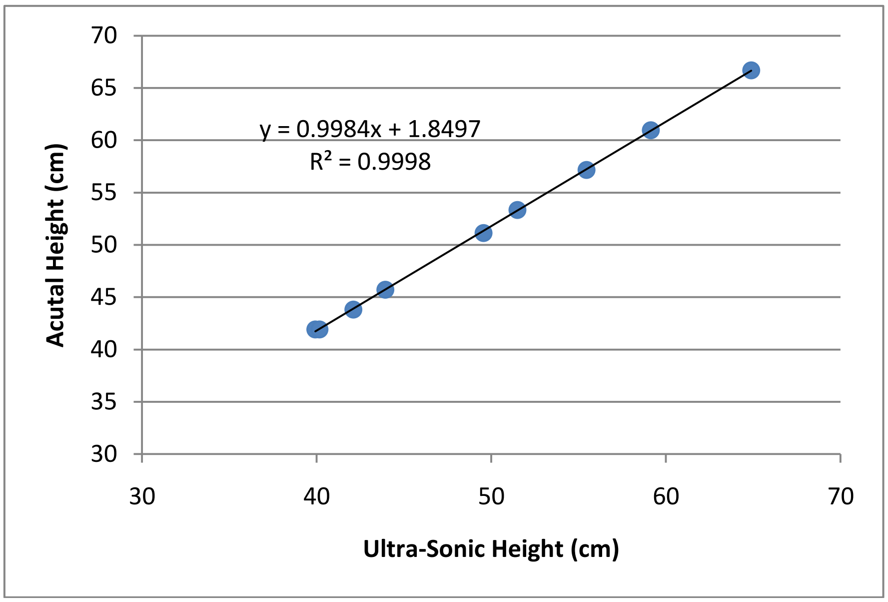

Figure 2.23. Initial static performance test of the Hyde Park sensors.

As shown in the graph, the HP sensors performed extremely accurate for height measurement with the slope of the regression line near unity and small bias (about 1.85 cm). . Multiple target heights and sensor heights above target were used during this test to ensure the sensors had an acceptable repeatability. During a lab setting on the sprayer the sensors performed to the needed accuracy level (R^2=1). However this is expected because the lab tests are a very similar set up to the scenario used while the sensors were calibrated. The lab test was performed on a flat very uniform surface as opposed to uneven plat canopy. A static field test was performed on the two sensors. The results are displayed in Figure 2.24. The sensors did not perform to the same level in the field as they did on a uniform object (R^2=0.81). They did accurately predict the stationary height of a cotton plant using the regression equation given in with an R^2 =0.8147. This means that the sensors could be used to accurately predict plant heights for research purposes in stop-and-go mode.

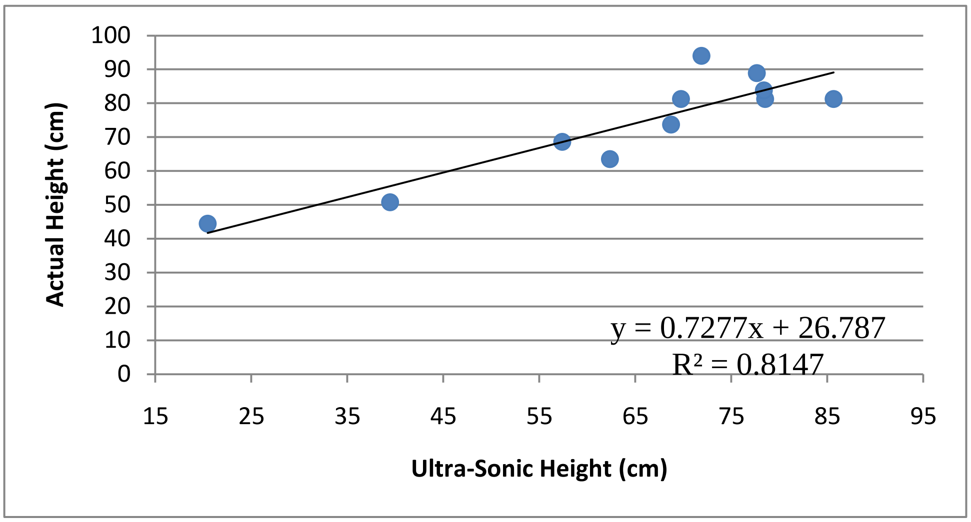

Figure 2.24. Static field test results of the Hyde Park sensors.

The sensors do not predict the height of the cotton plants as accurately as they did the stationary board over concrete due to two main reasons. The first being the lower sensor that detects the height from the soil could pick up outlier readings due to plant debris or soil disturbances giving a higher than ground level reading and producing a lower plant height, or holes and indentions in the ground causing a higher than actual plant height. The second reason is that the canopy sensor may not always get an ultra sonic return from the top of the plant. The sensor may pick up readings from further down into the plant canopy giving a false, shorter than actual height of the plant. More in-depth work with the sensors and their programming could get them to return more accurate numbers. The soil sensor should be reprogrammed to record the average return from its field of view. The canopy sensor should be reprogrammed to record the first return seen from its field of view. This reprogramming would allow for the soil sensor to average out any indentions or trash on top of the soil and would allow the canopy sensor to return the first reading it sees, which in most cases should be the highest part of the plant.

The dynamic test results did not give as good of a correlation (R^2=0.60) as did the static test. Figure 2.25 represents the results from the dynamic test. This could be due to the fact that sensor was moving over a non-uniform plant canopy.

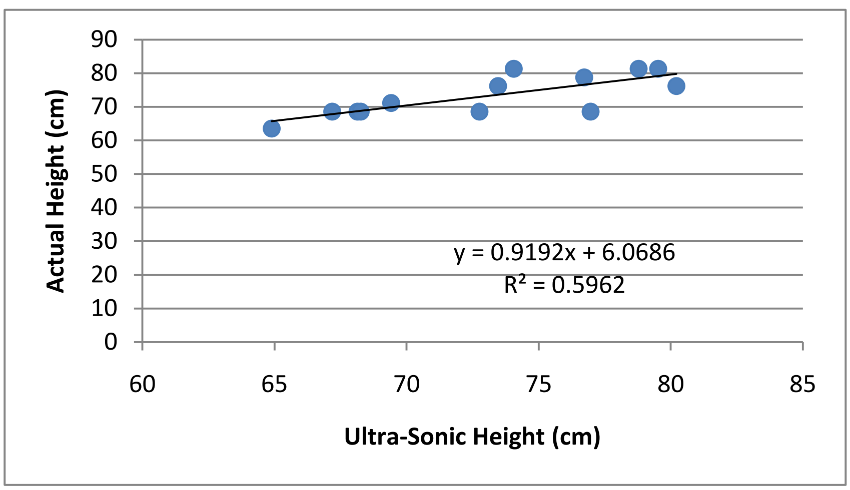

Figure 2.25. Results from the Hyde Park dynamic test.

As the sensors were moving through the field, multiple readings were collected at 10 Hz, thus some of the returned readings included readings collected from farther down on the plant along with trash in between the rows. With the data readings being recorded at ten times per second each plant is measured more than once, therefore, sampling multiple parts of a plant with non-uniform heights. In most cases multiple readings over a uniform surface, would be good, however; in this case the plant canopy causes error. As in the static test these sensors have a good potential to be used in the on-the-go collection of plant height but more work and testing must be done to ensure proper and accurate data collection.

The NORAC ultra-sonic sensors produced similar results to the Hyde Park sensors. The data collected from each of the NORAC sensors was averaged into one reading which included an average of the “far” (soil) reading or last return and an average of the “near” (canopy) reading or first return. The NORAC sensors sampled on a 100 Hz signal, and the data logger stored all of the data. The raw files were processed by engineers at the NORAC Company and then sent back for analysis. Sensor readings were collected from various points in the field and then ground truthing was performed to check the accuracy of the sensors. Figure 2.26 represents data collected from one plant that was at a 25.4 centimeter height. The data shows that the sensor is accurate to within a few centimeters but still has certain error associated with using ultra-sonic sensors on crop canopies.

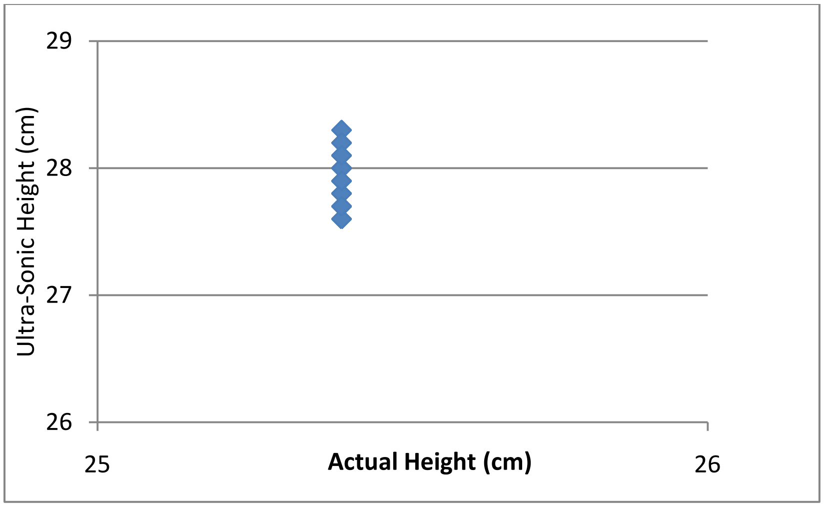

Figure 2.26. Recorded stationary plant height from NORAC sensors.

The sensors are off by a few centimeters because the actual plant height recorded was an average of the plants surrounding the sensor. The target window on the sensor widens the farther away from its target it is placed, thus it could detect multiple plants at one time. If the sensor is moved to close to the target it may not be able to penetrate the canopy and will not return a true far target reading. The sensor instead will return a reading from somewhere in the middle of the plant canopy as the far target reading. The sensors are very accurate and record enough data to eliminate most errors. Figure 2.27 represents correlation between actual and measured plant heights.

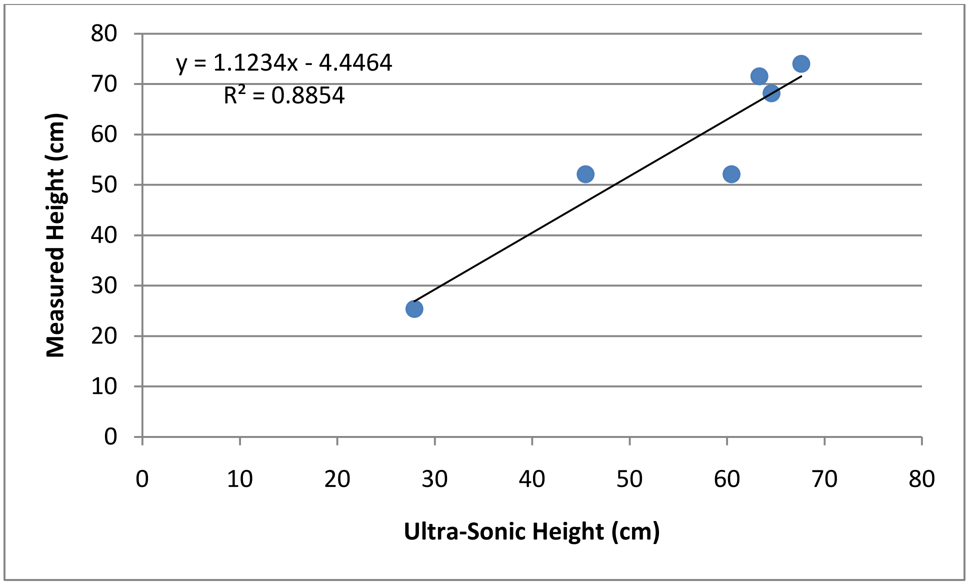

Figure 2.27. NORAC collections from different plant heights.

The above figure represents the accuracy level of the NORAC sensors. As earlier described the sensors are accurate if they return the correct reading from the proper target. In certain instances the sensors when located too close to the canopy height will return false far readings. According to the engineers of the company the sensor should be located approximately 51 centimeters above the crop canopy. If the sensors are located closer saturation can occur. A height equal to or greater than 51 cm above the canopy will allow the last signal return to penetrate and return from the soil.

As with the Hyde Park sensors the NORAC sensors could be reprogrammed to account for being used in a cropped field to ensure higher accuracy. The sensors still have good potential to be used for stationary and on-the-go plant height prediction. The consistent 100 Hz sampling rate of the NORAC sensors will help in averaging out error associated with using an ultra-sonic sensor on a crop canopy setting. However, the Hyde

Park sensors have the ability sample on a user program defined rate, thus making them a very valuable tool to be used in a production field. The ability to change the sampling rate of the sensors means that more research could be performed to determine the optimum sampling rate of an ultra-sonic sensor over crop canopies to eliminate potential errors. Future studies correlating the plant height, determined by ultra-sonic sensors, and the applications of plant growth regulators (PGR) could help growers to apply optimum amounts of PGR to cotton plants.

2.6 CONCLUSIONS

Variable rate nitrogen application equipment which can be used by growers was retrofitted to an existing nitrogen fertilizer application system and tested to ensure top performance and accuracy in true field conditions. Static and dynamic tests were performed on the Rawson hydraulic control system. The standard error was lower for the static tests and averaged to be less than 1%. The standard error for the dynamic test was higher when rates that were out of the optimum operating speed range of the John Blue piston pump were chosen. The controller was connected to a field computer which had FarmWorks SiteMate software installed for map based field control. The FarmWorks software operates on a 1 Hz signal, which lacks the accuracy required for plot and research work, but will likely be acceptable for growers' use.

The GreenSeeker® NDVI sensors were tested for their performance under variable heights, sun angles, temperatures, solar radiation, and time of day. It was found that the sensor gave a statistically similar reading between the heights of 76.2 and 91.44 centimeters above crop canopy. It was found that the sun angle, temperature, and solar radiation did not have a statistically significant effect on the performance of the sensor. It was found that the time of day, which can be directly related to weather and plant conditions, did have a significant effect on the sensors output. It was determined from the collected data that the best time to collect NDVI data falls between the time period of four hours after sunrise and one hour before sunset. The readings that fell outside of this time range had a significant statistical difference in value. A test performed over a green cloth proved that the sensor will perform to the same level throughout the day and night because the error collected over the plant is associated with the plants photosynthesis and photorespiration reactions during the day and night.

Two different types of ultra-sonic height sensors were used to determine plant height in both stationary and on-the-go scenarios. Field tests determined that the Hyde Park ultra-sonic sensor in combination with custom designed software has a good potential to determine both stationary and on-the-go plant height. However, more tests and calibrations need to be conducted for the Hyde Park sensors before they will be able to accurately predict plant height on-the-go. Similar to the results from the HP sensor test the NORAC sensors still require more testing and programming. However, the sensors were able in most instances to accurately predict stationary plant height. The consistent 100 Hz sampling rate of the NORAC could prove useful for data collection, but the ability to adjust the sampling rate of the Hyde Park sensors makes them a very useful sensor. Once the sensors are fully developed they could be linked with a feedback system to a controller on a sprayer. A determined spray threshold could then be determined thus, real time PGR applications could occur in a production field based on the real time plant height readings from the ultra-sonic sensors.

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