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An Examination of Fertilizer Use Efficiency and Irrigation Management in Tennessee Agricultural Production

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I am submitting herewith a thesis written by Timothy James Grant entitled "An Examination of Fertilizer Use Efficiency and Irrigation Management in Tennessee Agricultural Production." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental and Soil Sciences.

Brian G. Leib, Hubert J. Savoy, Major Professor

We have read this thesis and recommend its acceptance:

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Accepted for the Council:
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(Original signatures are on file with official student records.)

An Examination of Fertilizer Use Efficiency and Irrigation Management in Tennessee Agricultural Production

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Timothy James Grant

August 2015

Dedication

This work is dedicated to my fiancée, my family, and friends. Thank you Maddie for pushing me to write and inspiring me with your work ethic. Thank you to my parents, sister, and grandparents for continual support and encouragement throughout my education. Thank you to my friends for humor and humility, and for understanding the busy schedule of a graduate student.

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Abstract

Understanding the effect of supplemental irrigation and timing of nitrogen availability on yield of cotton is pertinent to the success of Tennessee cotton producers. Response to irrigation and nitrogen source is likely to vary across greatly differing soil types. This research indicated the need for higher amounts of water and earlier irrigation initiation to optimize yields in coarse-textured, low water holding capacity soils. Deep silt loam soils did not respond to irrigation in two wet years. Delaying nitrogen availability via use of a polymer coated urea fertilizer generally either lowered or did not affect yield. Delaying nitrogen availability was less detrimental to yield in coarse-textured soils, but was not a superior method to supply crop nitrogen demand.

Soil sampling is the foundation for addressing a field's nutrient status and possible need for fertilization. Proper fertilization is economically and agronomically attractive, as well as environmentally responsible. To facilitate precision nutrient management, sampling methods are needed to more precisely define nutrient variability than a field average. We looked at techniques for grid sampling, delineation of management zones, and optimal intensity of cores necessary. Grid sampling is a popular method for diagnosing in-field nutrient variability, but is time consuming. We found grid-point sampling to capture more variability across a field than grid-cell sampling, agreeing with the majority of previous research. Delineation of management zones was successful in grouping nutrient variability using soil maps of varying scale and yield maps. A sampling intensity of 2-8 cores/acre was optimal.

Table of Contents

List of Tables

List of Figures

Introduction

Constant advances in agriculture must be made to keep up with the demand of a rapidly growing world population. Producers are always learning, through the experiences of each growing season, and are continually compiling information to improve efficiency of operation. Improving profitability by gaining some kind of edge or advantage is a top priority. Simultaneously, the environmental impact of large-scale agriculture is becoming a focus of regulators and industry. Not only should producers allocate resources as to maximize their profit margin, but they should also bear in mind their environmental impact, and manage resources accordingly. From an agronomic perspective, fertilizer use efficiency and irrigation management allow one to most appropriate apply nutrients and water to optimize crop yield and minimize economic input. From an environmental perspective, fertilizer use efficiency and irrigation management ideally allow one to minimize added nutrients and to vary application of them spatially at rates matching crop demand, and to irrigate appropriately, avoiding nutrient leaching and wasted water caused by over-irrigation.

Chapter I

Effect of Delayed Nitrogen Availability via Use of Polymer-Coated Urea on Cotton Yield and Nitrogen Uptake Across a Range of Soil Water Holding Capacities and Irrigation Regimes

1 Abstract

Achieving optimal cotton yields is dependent on adequate supplies of nitrogen and water to the crop. In the Mid-South, cotton has traditionally been grown without irrigation, however, irrigated cotton acreage is on the rise as a means of protection against the risk of dry growing seasons. Supplemental irrigation often provides yield boosts, even in wet years. Response to irrigation varies across soil types, with coarse-textured, low water holding capacity soils requiring greater water input to optimize yields. While heavy water input is necessary to provide adequate soil moisture in coarse-textured soils, questions arise about its effect on nitrogen availability. With an interest in water and nitrogen interactions across soils, our objective was to examine the effect of delaying nitrogen availability using a polymer-coated urea on cotton yield, especially in coarse-textured soils and under heavy irrigation.

Cotton was grown on soils ranging from deep silt loam to shallow silt loam over sand, with some coarse material throughout. Irrigation treatments were applied ranging from rainfed to 1.5 inches/week beginning at square. Ammonium nitrate and a polymer-coated urea were used as nitrogen sources. In two wet years, deep silt loam soils did not respond to irrigation. Shallow, more coarse-textured soils showed significant yield boosts with irrigation in both years, and decreases in yield with over-irrigation in both years. Polymer coated urea generally either negatively affected yield or did not result in yield differences. Yield on shallower, more coarse-textured soil was slightly increased as a result of delayed nitrogen availability, but were still overall lower than yields with

ammonium nitrate. Nitrogen uptake, as indicated by leaf nitrogen content, and nitrogen removal by harvested cotton was higher for ammonium nitrate than polymer coated urea.

2 Introduction

Nitrogen and water are the two greatest yield-limiting factors for cotton production. Proper nitrogen management in cotton (Gossypium hirsutum) growing systems is important economically and environmentally. In Tennessee, the nitrogen recommendation for cotton is 60-80 pounds of nitrogen per acre annually. While nitrogen requirements are not extremely high for cotton, yield is sensitive to over and under-fertilization of nitrogen. Similarly to many crops, a limited supply of nitrogen in cotton will restrict yield potential. Cotton without adequate accessible nitrogen will exhibit slow growth, an increase in fruit shed, and premature cutout. Premature cutout will limit the potential sites of boll formation, and boll-shed is a very evident loss of potential yield because of inadequate nitrogen to support filling of that boll (Hake et al., 1991).

An excess supply of nitrogen to a cotton crop can also be detrimental to yield, which is inconsistent with the response of many crops. Cotton is naturally a perennial, tropical plant, but in a row crop setting, it is grown as an annual. In order to achieve a harvestable crop by fall, cotton should quickly establish vegetative growth and set fruit compared to its natural progression. An excess supply of nutrients, especially nitrogen, will encourage the cotton to continue vegetative growth for too long, delaying maturity. If maturity is delayed too long, optimal lint yield will not be achieved because harvest or frost will end the growing season before bolls fully develop. Excess nitrogen can also promote rank vegetative growth, which leads to several problems. Rank vegetation increases attractiveness to insects, increases incidence of boll rot, and decreases the effectiveness of harvest preparation measures (Guthrie et al., 1994).

In addition to being sensitive to adequate nitrogen availability, cotton yields are also dependent on the timely availability of nitrogen. Nitrogen uptake is small during vegetative establishment, about the first forty to fifty days after planting. The uptake of nitrogen increases rapidly at flowering, as bolls are set and boll loading begins. Twenty-five to forty percent of cotton's seasonal nitrogen accumulation occurs during the first two weeks of bloom (Guthrie et al., 1994). To ensure that nitrogen is readily available at flowering, growers sometimes delay nitrogen application until after planting or split nitrogen application and apply some at first flower (Morrow and Krieg, 1990).

Cotton in west Tennessee is grown on soils ranging from deep silt loams with excellent water holding capacity and good nutrient retention to sandy soils with poor water holding capacity and less ability to retain applied nutrients. Irrigated cotton acreage is currently small in west Tennessee, but is growing steadily (Gwathmey et al., 2011). Irrigation management for cotton in the humid southeastern U.S. is an important area of study. Small amounts of water applied at proper timing can significantly boost yield. With an increase in irrigated cotton acreage, questions arise about how it might affect nitrogen management. Soils with poor water holding capacity (WHC), caused by coarse texture, are inherently more prone to leaching loss of nitrogen, even with proper management of irrigation. Over-irrigation could exacerbate the issue of nitrogen loss in coarse texture soils. With the growing acreage of irrigated cotton in west Tennessee, new fertilizer technology should be evaluated on various soils and under various irrigation scenarios.

3 Literature Review and Background

3.1 Nitrogen Fertilizer Technologies

Applied nitrogen fertilizer is most commonly lost to the environment through leaching of nitrate and denitrification. Nitrate leaching contributes to ground and surface water contamination, while denitrification releases greenhouse gases, such as nitrogen gas and nitrous oxide (Rochester, 2012)(Wilson et al., 2010). The two most limiting factors for the loss of applied nitrogen fertilizer are the amount of nitrogen present in the soil environment and the length of time the nitrogen fertilizer resides in the soil environment. Higher amounts of nitrogen present lend the nitrogen to becoming more susceptible to loss. The longer the nitrogen resides in the soil without being taken up by the crop, the higher the probability of nitrogen loss. Slow or controlled release fertilizer technology attempts to address the issues of higher nitrogen concentrations in the soil at any given time and the length of time nitrogen fertilizer resides in the soil. Controlled release fertilizer nitrogen is released gradually from a protective coating, so the total amount in the soil at any given time is minimized, and residual time in soil is reduced because of the time spent protected by the coating.

Sulfur-coated materials were among the first widely used slow-release fertilizer technologies. Sulfur coated urea has been used as a slow-release nitrogen source, but the main problem with sulfur-coated materials is their unpredictability in regard to nutrient release. Release of nitrogen from sulfur-coated urea relies on a coating failure mechanism. Holes in the coating made by microorganisms, cracking of the sulfur shell, or adsorption of the wax sealant by soil particles act as pathways for diffusion of urea into the soil environment. This coating failure mechanism has proven hard to predict accurately and calls for more sophisticated fertilizer technology (Jarrell and Boersma, 1979).

Other slow release technologies include resin, wax, and aldehyde condensate coatings, as well as complex polymers (Chen et al., 2008). More advanced fertilizer technologies have begun to use the term controlled-release as opposed to slow-release. Controlled-release nitrogen fertilizers have shown promise in cotton production. Oosterhuis and Howard (2008) compared a polyolefin thermoplastic resin-coated urea (Meister programmed-release N) to ammonium nitrate. They found that MPR-N material achieved similar yields to ammonium nitrate, even when application rates were reduced to 60% of the recommended rate. They concluded this controlled-release material could potentially increase nitrogen use efficiency in cotton production, while maintaining yields. This research, however, failed to also reduce rates of application for ammonium nitrate (AN) from current recommendations to see if those recommendations are just higher than necessary to begin with. Also of concern was lack of a control plot with no applied nitrogen to incorporate residual nitrogen supply into results. Shoji et al. (2001) examined MPR-N in barley, potato, and corn systems and found promising results in each system. In each cropping system, controlled-release materials reduced denitrification losses of nitrous oxide and showed potential for improved nitrogen use efficiency. Nitrogen tracer studies indicated less movement of nitrogen to deeper parts of the soil profile when using controlled-release fertilizer in several cropping systems (Wilson et al., 2010).

Slow or controlled-release fertilizers could be useful in reducing nitrate leaching and/or denitrification. Soil types and irrigation management can influence the effectiveness and susceptibility to loss of nitrogen fertilizers. For example, potato production systems often combine sandy soils and heavy irrigation, causing farmers to traditionally apply multiple sidedressings of nitrogen with around eight fertigation treatments per season to keep ample nitrogen available (Shoji et al., 2001). Slow or controlled-release fertilizers have been shown to markedly increase nitrogen use efficiency and nitrogen fertilizer recovery in potato production while achieving similar or greater tuber yields (Wilson et al., 2010). Low-lying areas prone to denitrification and fields subject to over-irrigation are other examples of situations that could see potential benefits from the use of controlled-release fertilizers.

3.2 Environmentally Smart Nitrogen

Environmentally Smart Nitrogen (ESN) is a polymer-coated urea fertilizer. The manufacturer, Agrium Inc., describes ESN as quality urea granules encapsulated by a flexible polymer coating that reduces the risk of nitrogen loss by protecting the nitrogen and releasing it over time. ESN technology is advertised as temperature-controlled release that is slightly moisture dependent, as adequate antecedent moisture is necessary to support diffusion of water into and out of polymer coating. Moisture permeates the coating, creating a nitrogen solution that moves out of the coating at a rate dependent on soil temperature ("How ESN Technology Works", 2014). The effect of temperature on nitrogen release from ESN may be due to an increased difference in water vapor pressure between the environment and the internal surface of the fertilizer granule with increasing temperature, as well as the increased moisture permeability of polymer coating with increasing temperature (Gandeza et al., 1991). Agrium Inc. advertises ESN as releasing 80% of its nitrogen between 30 and 60 days at 23 C (ESN Polymer Coated Urea (MSDS No. 14250), 2004).

Golden et al. (2011) tested and proved the information provided by Agrium Inc. to be true for a wide range of Arkansas soils. In the clayey soils tested, ESN released nitrogen at a rate that followed a curvilinear pattern, while nitrogen was released at a linear rate in silt loam and sandy soils. Initial release of nitrogen by ESN was more rapid in the clayey soils. By forty days after application, nitrogen retention by the ESN fertilizer was similar among soils and ranged from 17 to 25%. Golden et al. (2011) found that nitrogen release was not affected by soil moisture in the range 125 to 389 g H2O kg-1, except for a slight increase in initial release (first five days) in higher moisture conditions. They also found temperature to truly be the driving factor behind nitrogen release from ESN. By forty days after application, nitrogen release ranged from 29% at 15 C to 87% at

30 C. At 15 C, nitrogen release was minimal, but increased to a linear response that ended up releasing similar amounts to the highest temperatures at 20 C. At 25 and 30 C, nitrogen release occurred curvilinearly, with release slowing over time, and similarly releasing the majority of nitrogen by forty days.

ESN merits study because of its potential to reduce nitrogen loss, increase fertilizer nitrogen recovery, and therefore improve nitrogen use efficiency. Other potential benefits include a wider fertilizer application window, a longer shelf life than uncoated fertilizer, and grower incentives for use of ESN (“How ESN Technology Works”, 2014). Even considering potential environmental benefits, a product like ESN will struggle to be desirable if cost is prohibitive compared with conventional fertilizers. ESN is being marketed primarily to Midwestern U.S. corn growers, indicating it may be economically feasible for large-scale agriculture (Golden et al., 2011).

3.3 ESN in Production Systems

Research on ESN has begun to evaluate the potential of increasing nitrogen use efficiency and fertilizer nitrogen recovery. ESN has been studied in several cropping systems and has shown promise as an alternative nitrogen source. In Arkansas, ESN achieved slightly higher yields than urea when pre-plant incorporated in corn production (Mozaffari et al., 2012). Corn research in North Carolina showed ESN achieving similar and sometimes greater yields as compared to urea ammonium nitrate on coastal plain, piedmont, and mountain sites. ESN achieved greater nitrogen use efficiency, stover % nitrogen, and nitrogen uptake compared with urea ammonium nitrate (Cahill et al., 2010).

Potato production typically creates a system prone to loss of nitrogen, leading to environmental degradation as well as wasted inputs (Wilson et al., 2009). The combination of sandy soils, heavy irrigation, and high nitrogen requirements create an environment highly susceptible to leaching of nitrate. Researchers in Minnesota found a single application of the total nitrogen requirement applied as ESN pre-plant, at planting, or at emergence all performed similarly to traditional split nitrogen applications, with up to six conventional nitrogen applications being used. Tuber yield and quality were not affected by nitrogen treatment. They suggested ESN to be economically feasible and possibly favorable over conventional fertilizer in this system because of reduced fertigation and associated management costs (Wilson et al., 2009). ESN has also been shown to reduce nitrate leaching and improve fertilizer nitrogen recovery over two split applications of conventional nitrogen in potato production (Wilson et al., 2010).

Although literature on ESN use in cotton production is sparse, Agrium Inc. claims it to be a good match of nitrogen release for the needs of a cotton crop. They recommend applying either pre-plant or as a side or top-dress application, noting that a side or top-dress application two to four weeks after planting may offer an optimal match between nitrogen release from ESN and cotton nitrogen uptake. They also recognize split nitrogen application strategies and would recommend sufficient soluble nitrogen at planting to last several weeks, then the remainder of nitrogen requirement applied as ESN. Incorporation of ESN is preferred but not essential (“Maximizing Cotton Performance with ESN”, 2014).

Mozaffari et al. (2012 a) found similar yields in Arkansas cotton when ESN and urea were applied pre-plant and incorporated in a Marvel silt loam in a dry year. The next year, they tested several combinations of urea and ESN and saw no difference among fertilizer combinations. It was another dry spring and summer for Arkansas, so potential for leaching and denitrification was lower than normal (Mozaffari et al., 2012 b). Research has not been done to evaluate ESN in cotton production in soils with limited water-holding capacity or across a range of irrigation management schemes. Questions also remain about the effectiveness of ESN or other granular controlled release fertilizers in no-till cotton production, as is prevalent in west Tennessee, in which case the material would likely be broadcast and not incorporated.

3.4 Cotton Irrigation

Use of irrigation for cotton in the Mid-South is heavily dependent on climactic conditions from year to year. Rainfed yields sometimes are no lower than irrigated yields, but in many years, cotton yields can be significantly boosted by supplemental irrigation. The framework for the irrigation portion of this research was part of an ongoing irrigation rate and timing study for cotton across soils varying in water holding capacity, surface soil texture, and depth to sand. From 2006 to 2009, rate and timing research was conducted in uniform deep silt loam soils. Findings in the deep silt loam soils indicated a need for one inch/week of irrigation in two years, one and a half inches/week in a severe drought year, and no yield boost from supplemental irrigation in one year (Gwathmey et al., 2011). Optimal yields were often achieved when irrigation was delayed until bloom or two weeks post bloom, except in years with early dry periods. Data collected on the deep silt loam soils was generally in agreement with findings from Barber and Francis (2011) on cotton in Arkansas. They found that irrigation should be started around first flower to optimize yield and that 2-3 weeks after first flower was a critical time to have adequate soil moisture. Jalota et al. (2006) also concurred that flowering is the most sensitive stage of cotton to water stress, in terms of effect on yield. Huber et al. (1999), also in the Mid-South, found a rate of one inch per week to significantly boost yields in the majority of years in a silt loam soil. Application rates above one inch per week were not beneficial to yield.

From 2010 to 2012, the rate and timing research was moved to the field of study discussed in this paper. Significant soil variability exists in this field, as is discussed in Materials and Methods. The goal of using this field was to collect data for the various rates and initiation timings on soils like those used in the prior study as well as soils with lower water holding capacities, caused by more coarse texture in the surface soil and a shallower depth to sand layer. Lower WHC soils did respond differently to irrigation, as they required 1.5”/wk to optimize yield and starting at square or first bloom (Duncan, 2012). Detar (2008) noted that not only do sandy soils require higher water input to maintain adequate soil moisture, but they also can not withstand significant deficits in soil moisture without negatively affecting yield, as deeper higher WHC soils can withstand to a degree. Cotton yields in the lower WHC soils, when irrigated appropriately, were often close to optimal yields in intermediate or deeper soils. To achieve good yield in the low WHC soil, however, heavy irrigation input is required. Could heavy irrigation in coarse textured soils lead to significant nitrate leaching such that yield potential is limited, and can delaying nitrogen availability using controlled release fertilizer technology prove effective in improving crop nitrogen removal?

Coarse texture, low WHC soils are inherently more prone to nitrate leaching than finer texture, higher WHC soils for several reasons. A coarse textured soil profile leads to a less tortuous path for water to travel through, while less sorption capability and the effect of gravimetric potential further allow water to move downward through the profile with more ease than in other soils. Coarse texture soils are also typically lower in soil organic matter and cation exchange capacity, contributing to ease of water and nutrient movement. Nitrate movement deeper into a profile can happen quickly in coarse texture soils with water input, but as texture slowly becomes finer in composition, rate of nitrate leaching quickly decreases (Aulakh and BijaySingh, 1997). Wang et al. (2010) further supported the notion that extreme conditions, whether coarse soil texture or heavy water input or both, are necessary to facilitate significant leaching of nitrate. In monitoring soil water status for cotton research preceding this study, we found irrigation events did not penetrate past about 5-10 inches, and multi-inch rain events were necessary to penetrate to near the bottom of cotton rooting depth, depending upon existing soil water status.

While excessive soil moisture can move nitrate downward through a profile and negatively affect availability, adequate soil water is necessary for optimum nitrogen uptake. To realize full yield potential, not only is adequate available nitrogen in the crop rooting zone critical, but so is ample water input to facilitate uptake of the nitrogen by the crop. The effect of varying levels of nitrogen fertilization can be overshadowed by a lack of adequate soil moisture to support plant growth and accessibility of nutrients (Pettigrew and Zeng, 2014). While water stress and nitrogen availability stress can each alone lower yields, the two stresses together form the most detrimental situation to yield potential (Zelinski and Grimes, 1995). For cotton grown in the many soil types in our study, the research question was how do we apply supplemental irrigation as to optimize yield, and how will traditional and controlled release fertilizer respond to the varying levels of irrigation across soil types.

Interactions are often found in cotton research between irrigation and nitrogen, with soil being as uniform as possible (Boquet and Coco, 1988; Bronson et al., 2006; Bronson et al., 2001; Bronson, 2008; McConnell et al., 1989; Vories et al., 2014; Pettigrew and Zeng, 2014; Singh et al., 2010). Often, these interactions are among varying rates of water application and levels of nitrogen application. Interactions are also found between irrigation and soil type, with nitrogen source and rate held constant (Vories et al., 2015; Jalota et al., 2006; Tolk and Howell, 2010). Interactions between soils, irrigation, and nitrogen, while important, are complex, and as such are not often examined. Li et al. (2000) conducted field-scale research to examine the effect of differing levels of water input and nitrogen application rates on yield across a field that varied in soil type. Our research is unique in that it examines varying soils, irrigation, and nitrogen source simultaneously, and that it does so using irrigation regimes with varying initiation timings and application rates and nitrogen sources, as opposed to rate of nitrogen application.

4 Objectives

The objectives for this research are:

- Observe the potential effect of delayed nitrogen availability via use of ESN on cotton yield, nitrogen uptake, and nitrogen removal in soils ranging from low WHC to high WHC and under various irrigation regimes.
- Add to our current knowledge about appropriate irrigation initiation timing and rate of water application for cotton in variable soils in west Tennessee.

5 Materials and Methods

The research was located at the West Tennessee Research and Education Center (WTREC) in Jackson, TN and was done in 2013 and 2014. The experiment was arranged in a randomized complete block (RCBD) split-plot design. Cotton plots were six rows wide, with 38-inch row spacing, and thirty feet long. Four center rows of each whole plot were harvest rows, while the outer two rows served as border rows. Cotton rows were kept as similar as possible to their position in years' past, to continue the validity of soil evaluation for each plot. Each of these plots was randomly assigned an irrigation treatment, within soil block. Whole plots were then split, and half the plot received ammonium nitrate fertilizer, while the other half received ESN. Each subplot, therefore, consisted of two harvest rows and one border row nearest to the next whole plot. The fertilizer treatments were assigned randomly to each plot.

Cotton (Phytogen 375) was direct seeded on May 8, 2013 and May 6, 2014 in a no-till cropping system that has been cropped in cotton since 2010. All areas of the study site tested high in phosphorous and potassium in both years according to University of Tennessee recommendations, so no additional fertilizer was added. Nitrogen fertilizer was hand spread once cotton plants had emerged so that we could be certain of plot location. This resulted in nitrogen application two to three weeks after planting. Ammonium nitrate and ESN were both broadcast applied at a rate of 80 pounds N/acre.

A location with variation in soils was chosen for this study. Soils ranged from a deep silt loam to a moderately deep silt loam over sand to a shallow silt loam over sand (Figure 1-1). The experiment was blocked on soils, differing markedly by their texture, horizonation, and water holding capacity. Soil delineations were made by a combination of ground-penetrating radar, electrical conductivity measurements, and soil cores (Duncan, 2012). Seven soil blocks were used in the experiment, with average water-holding capacities ranging from 0.7 to 1.9 in/ft.

Seven irrigation treatments were used as part of an ongoing deficit irrigation study (Table 1-1). Irrigation treatments varied in rate of water application, as well as timing of irrigation initiation. Irrigation was applied through a drip irrigation system, which achieved varying irrigation rates through use of three different John-Deere T-tape sizes. One line of drip tape was laid per row of cotton. To achieve 0.5, 1.0, and 1.5 inches/week, drip tapes rated .110, .220, and .340 gallons/minute per 100 feet were used. This allowed the entire system to run the same amount of time, while applying three different rates. Irrigation was applied three days a week, Mondays, Wednesdays, and Fridays, and was adjusted for rainfall. Irrigation time, adjusted for rainfall, was based on the 1.0 inch per week treatment. With no rainfall, the irrigation system was run long enough to apply 0.4” on Monday, 0.3” on Wednesday, and 0.3” on Friday, in the 1.0”/week treatment. This schedule was adjusted for rainfall to achieve as close to 1.0 inch per week as possible. Some rainfall events brought over an inch in a short amount of time, so response to these events was made based on judgment of soil water status over the following days. At the beginning of the irrigation season, valves were opened for plots receiving irrigation starting at square. The remaining plots were irrigated at first bloom, except the dryland plots. All irrigated plots received supplemental water as required until cracked boll.

To monitor the nitrogen status of the cotton throughout the growing season, leaf samples were taken at first flower and at mid-bloom, approximately five weeks past first flower. Leaf samples were taken from plots in irrigation treatments 1, 5, 6, and 7 and from all combinations of soil block and N source. Dates of sampling were July 8 and August 14 in 2013 and July 17 and August 22 in 2014. The uppermost mature leaf on a given plant was sampled, and twenty per plot were taken. Petioles were discarded. Samples were sent to the UT Soil Plant and Pest Center, where they were analyzed for total combustible nitrogen content.

Both years of this study could be considered wet years, even for the humid mid-south (Table 1-2). In 2013, WTREC received 21.5 inches of rain from planting to harvest (May 8-October 8), of which, 6.7 inches fell from square to cracked boll. The rainfall was fairly evenly distributed and growing conditions were very good in 2013, as evidenced by high yields. In 2014, WTREC received 32.7 inches of rain from planting to harvest (May 6-October 5), of which, 9.0 inches fell from square to cracked boll. Rainfall was more biased toward early season events in 2014. May through mid-June was very wet in 2014, while rainfall the rest of the season was more sporadic and came mostly in several large events.

Cotton was harvested by a combine with a two-row header and a load cell used for obtaining seed cotton weights by plot. After cotton harvest, subsamples of the seed cotton were ginned to collect seed samples and cottonseed was analyzed for total nitrogen content. Like leaf samples, seed samples were only collected for irrigation treatments 1, 5, 6, and 7. Nitrogen content in lint is minimal, so cottonseed nitrogen content can be considered the nitrogen removal by the cotton crop. Larger samples of seed cotton were ginned for turnout values and lint was sent to the USDA Agricultural Marketing Service's Memphis Classing Office for quality analysis. With turnout for each plot, a production yield in lbs/acre can be calculated following the formula: plot seed cotton weight (lbs) x turnout x 43,560 sq. ft. per acre / 190 sq. ft. per two harvest rows. Turnout and seed N data also yield N removal values in lbs N/acre for each plot following the formula: seed N (%) / 100 x plot seed cotton weight (lbs) x (1-turnout) x 43,560 sq. ft. per acre / 190 sq. ft. per two harvest rows. Quality information was produced for each plot including color grade, leaf grade, micronaire, length, strength, and uniformity. In both years, this quality data was input into the 2013 and 2014 Cotton Loan Price Valuation Program developed by Cotton Inc. and Mississippi State University to assign a price in cents/pound to the cotton lint from each treatment combination (Cotton Inc., 2013; Cotton Inc., 2014).

For statistical analysis, the two years were analyzed separately. Mixed model analysis of variance was run in SAS 9.3, and the experiment was analyzed as an RCBD split-plot. Experimental area was blocked on soil, irrigation was the whole plot treatment factor, and N source was the sub-plot treatment factor. For yield and quality data, all irrigation treatments were included in the analysis. When looking at leaf N and N removal, the program was reduced to just include irrigation treatments 1, 5, 6, and 7. For yield in both years, a significant block*treatment interaction existed (Figures 1-3 and 1-4). A block*treatment interaction in our case indicates differences in treatment response across soil types. To address this interaction and study how the response of treatment combinations varied across soil type, a variable “soil type” was added to the analysis. The variable “soil type” grouped soil blocks in to low, intermediate, and high WHC based on apparent groupings by yield response in the block*treatment interaction plots (Figure 1-2). This division was the same in both years, soil block 1 was low WHC, blocks 2 and 3 formed the intermediate WHC soil type, and blocks 4-7 formed the high WHC soil type. Mean separation was achieved using LSD p=0.05. Quality data, leaf N, and N removal saw no significant block*treatment interactions, so only main treatment effects were examined for significance.

6 Results and Discussion

6.1 Cotton Yields

The nature of this research, in observing effects of N source, irrigation regime, and soil impact, was designed with an interest in interactions. Main treatment effects were reported and should be noted before examining interactions. Main effects, however, may be of little value when interactions are significant and show differing responses from levels of one treatment factor to levels of another treatment factor. Nitrogen source had a significant main effect on lint yield in 2013 and 2014 (Table 1-3). In both years, ammonium nitrate resulted in higher yields, 1458 to 1375 lbs lint/acre in 2013 and 1233 to 1105 lbs lint/acre in 2014, compared to ESN averaged across all soil blocks and all irrigation regimes. Irrigation also had a significant main effect in both years. In 2013, initiating irrigation at bloom and at a rate of 1.5”/wk optimized yield, averaged across all soil blocks and both fertilizers, and was the only irrigation treatment yielding significantly greater than rainfed (Figure 1-5). In 2014, the bloom 1.5”/wk treatment as well as the square 0.5”/wk, bloom 1.5”/wk treatment optimized yield averaged across soil blocks and N sources (Figure 1-6). All irrigation treatments significantly boosted yield over dryland, except square 0.5”/wk, the lowest application treatment. Effect of soil type alone on yield was examined to further validate separation of soil blocks into the three soil types (Table 1-3). In 2013, low WHC soils yielded, on average, 1112 lbs lint/acre, intermediate WHC soils yielded 1461 lbs lint/acre, and high WHC yielded 1676 lbs lint/acre, all significantly different from one another. In 2014, low WHC soils yielded an average of 875 lbs lint/acre, intermediate WHC soils yielded 1238 lbs lint/acre, and high WHC soils yielded 1396 lbs lint/acre, all significantly different from one another. These results indicate grouping of soil blocks for an additional variable in analysis was justified and helpful.

In 2013, there was a significant irrigation*fertilizer interaction (Figure 1-7). Recall, the values reported in this interaction are averaged over all soil blocks. Four of the seven irrigation treatments yielded significantly higher when using AN. Two of the irrigation treatments, square 0.5"/wk and square 0.5"/wk, bloom 1.5"/wk, resulted in similar yields between N sources. One irrigation treatment, bloom 1.0"/wk, resulted in higher yield using ESN. Irrigation*fertilizer interaction was non-significant in 2014.

Significant irrigation*soil type interactions existed in 2013 and 2014 (Figures 1-8 and 1-9). The differences between soil types were more pronounced in 2013. In both years, yields on high WHC soils were unaffected by irrigation treatment. Not surprising was the fact that high WHC soils saw no yield increase from irrigating in two wet years. It was unexpected, however, to see no yield decrease from over-irrigation in the high WHC soils, as observed in previous studies (Gwathmey et al., 2011; Duncan, 2012). For intermediate WHC soils, significant yield loss was seen without irrigation or without enough irrigation in both years. In 2013, initiating irrigation at square and applying 1.0"/wk to total 3.4 inches yielded similarly to high WHC soils, while waiting until bloom to irrigate and applying 1.5"/wk to total 3.7 inches achieved optimal yields. In 2014, in intermediate WHC soils, irrigating beginning at bloom and applying 1.0”/wk, resulting in total application of 3.8 inches, was sufficient to achieve optimal yields. Irrigation regimes beginning earlier or applying more water did not result in further yield increase. For low WHC soils, increases in yield were observed in both years with application of optimal irrigation. In 2013, applying 1.5”/wk starting at bloom was necessary to optimize yield, with total input of 3.7 inches, above which extra water was significantly detrimental to yield. In 2014, the same treatment reached optimal yield, applying 5.7 inches. At the heaviest irrigation, a significant yield downturn was seen. These results in low WHC soils affirm our findings in previous years that water is not always needed early in these soils, but it is needed at a high rate once initiated. The effect of over irrigation being detrimental to yield in low WHC soils, however, had not occurred on this field prior to these two growing seasons. Of note in Figures 1-8 and 1-9 is that low WHC and intermediate WHC soils can yield just as well as high WHC soils can. Achieving high yields on these soils, however, requires precise irrigation management, as yield is quickly diminished by under or over irrigation. It seems the high and, to a degree, intermediate WHC soils are much less difficult to manage and provide appropriate amounts of supplemental irrigation, due to their inherent buffer in soil moisture and water holding capacity.

Both 2013 and 2014 also saw significant three-way interactions between soil type (or soil water regime), fertilizer, and irrigation. These interactions are depicted in Figures 1-10 and 1-11. These interactions are complex, but illustrating them attempts to capture all we have discussed previously about each of the three factors. Irrigation treatment effects are evident by soil type, as mentioned previously. Main effect of soil type is evident, in that high WHC soils yielded higher, on average, than intermediate WHC soils, which yielded higher than low WHC soils. Main effect of N source is also evident. AN yields are almost always either similar to or greater than ESN yields for a given irrigation treatment and soil type. The greatest additional benefit received from examining the three-way interactions is the observation of changing yield response to N source as soil type changes. In 2013, two of seven irrigation treatments responded with statistically higher yields when N source was AN in high and intermediate WHC soils, while the fertilizers yielded similarly in all other treatments. For low WHC soils, however, two of seven irrigation treatments responded with statistically higher yields when N source was ESN, while only one irrigation treatment yielded higher paired with AN. In 2014, four of seven irrigation treatments significantly favored high yields with AN in high WHC soils, two of seven favored high yields with AN in intermediate WHC soils, and in low WHC soils, only one irrigation treatment paired with AN resulted in significantly higher yield than with ESN. All other treatment combinations yielded similarly between N sources. These three-way interactions indicate more competitiveness of the ESN in low WHC soils than in deeper, higher WHC soils. However, this competitiveness may be viewed more as simply catching up to AN in low WHC soils, and not as a clear yield advantage achieved by using ESN in low WHC soils. Yields when using ESN were often similar to those achieved using AN, but AN more often outperformed ESN.

6.2 Leaf Nitrogen Content, Nitrogen Removal, and Lint Quality

Main effects and treatment interactions were examined for significance in leaf N content, N removal, and lint quality aspects as block*treatment interactions were not significant. All leaf sampling events were significantly affected by N source (Table 1-4). AN resulted in higher leaf N values compared to ESN at both sampling times in both years. The leaf N values obtained were all within sufficient range at the first bloom sampling (3.0-4.5%). However, all leaf N values sampled mid-late bloom were under the lower level of sufficiency range (3.0-4.5%) provided in the SERA6 bulletin (Mitchell and Baker, 2000). Leaf N main effect of N source indicates potentially more N availability from AN, which was indicated by a yield main effect reflecting higher yields with AN. Higher leaf N contents at first bloom presumably indicate uptake and storage of N that is soon transported to boll formation sites where it is actively used in seed production. Lower leaf N contents at the second sampling show a shift from vegetative growth toward a reproductive focus.

Nitrogen removal by the cotton crop via seed N content was also significantly affected by only N source (Table 1-5). Averaged across soil blocks and irrigation treatments, cotton fertilized with AN removed an average of 82 lbs N/acre in 2013, while cotton fertilized with ESN removed 75 lbs N/acre. In 2014, N removal when using AN was 63 lbs N/acre and was 54 lbs N/acre when using ESN. These N removal values were high, relative to the 80 lbs N/acre that was applied regardless of N source. The significant effect of N source of N removal again indicates higher available N with AN compared to ESN.

Lint quality components color grade, leaf grade, micronaire, length, strength, uniformity, and price were analyzed for main effect significance. No significant block*treatment interaction existed for any quality components in either year. In 2013, N source had a significant effect on micronaire (p=.0006), with ESN having higher micronaire values, and on length (p=.0451), with AN yielding higher length values. Irrigation treatment had a significant effect on micronaire (p=.0194), due to lower water application treatments giving lower micronaire values. These differences in quality components did not lead to any significant difference in lint price due to N source, irrigation treatment, or interaction of the two. In 2014, irrigation treatment had a significant effect on micronaire (p=.0060), this time with the dryland cotton having higher micronaire values than all irrigated treatments. No significant effects were detected on lint price due to N source, irrigation treatment, or interaction of the two. Cotton lint quality, in general, was unaffected by applied treatments, as lint price is the most important of the quality components to consider.

6.3 Nitrogen Source Considerations

Concerning N source comparison, our results favor higher yields and N uptake/removal on average when using AN compared with ESN. While ESN did show more promise, in the form of either similar or sometimes higher yields than AN, in low WHC soils, it still was not observed to be a superior N source in that situation. AN was used as the standard for comparison because there was little concern for loss to volatilization when broadcast.

The nature of polymer-coated urea is such that water must diffuse in and out of the coating to release nitrogen. When broadcast applied, the surface area that is in contact with soil is much less than it would be if incorporated. Less surface area in contact with soil could mean less opportunity for moisture diffusion. Being only in contact with the surface of soil also exposes the polymer coated material to the first part of the soil profile to dry out, which could lead to less potential amount of time for water diffusion to occur. Being a urea-based fertilizer, there is also some concern about volatilization loss. While protected in polymer coating, urea should be stable, but a window of volatilization opportunity may exist as the nitrogen solution is released from coating. Another potential issue with broadcast ESN is physical movement of the fertilizer material. While a conventional granular material like AN will quickly dissolve into soil profile, ESN prills remain on the soil surface even after N release has likely fully occurred. While no-till production systems leave a good amount of crop residue on the surface, still some movement of ESN with large rain events is expected. On low WHC soils, even when yield is good, plants are often smaller and leave significantly less residue cover. Movement of ESN within a plot or even off plot could lead to less N release than desired within the area of interest. Finally, when dealing with controlled release fertilizer material, it is necessary for release of N to match crop N demand for optimal performance. Our delayed broadcasting of ESN until post-emergence was within the allowable application window suggested by Agrium Inc. for cotton, but perhaps ESN could be applied at planting or even before planting and still provide ample available N at appropriate times and without exposing the nitrogen to potential leaching loss with heavy rains early in growing season. While ESN was generally outperformed by AN under conditions of this study, it warrants examination using different application strategies and timing. ESN could be mixed with a more quickly available form of N to compliment its slow release, or applied at an earlier time. ESN also could be incorporated after application, though the feasibility of this in no-till cotton production could be questionable.

7 Conclusion

Cotton yields in the Mid-South are most limited by water and nitrogen. Being a humid environment, supplemental irrigation is not always necessary to grow a profitable crop, but irrigation can often increase yields with relatively small inputs. Irrigated cotton acreage is growing in west TN and is present on fields of widely ranging soil types, textures, and water holding capacities. It is important to know how varying soils are best managed with irrigation to promote optimal yields. New and promising nitrogen fertilizers also should be evaluated for potential effectiveness or yield benefit. This research compared a polymer-coated urea, ESN, with AN in soils ranging from low to high WHC, and from primarily sandy texture to primarily silt loam texture. Irrigation regimes from rain-fed up to 1.5”/wk starting at square were implemented over soil blocks and with both N sources.

Cotton yields in 2013 and 2014 revealed several treatment interactions. High WHC soils did not respond to irrigation, positively or negatively, in either year. Intermediate WHC soils did require some supplemental irrigation to optimize yield, applying either 1.5” or 1.0”/wk starting at bloom, for 2013 and 2014, respectively. Low WHC soils saw the most dramatic yield increase from irrigating, when 1.5”/wk was applied starting at bloom. Low WHC soils also saw a decrease in yield with apparent over-irrigation. N sources responded somewhat differently between soil blocks. ESN was more competitive with, even sometimes out-yielding AN, in low WHC soils. High and intermediate WHC soils favored higher yields when using AN over ESN. Leaf N samples and N removal values further indicated higher available N from AN, in general. N availability from ESN may have been lower due being broadcast and unincorporated, as less surface area of the coating was available for diffusion. It also may be vulnerable to physical movement away from area of deposition, and to some volatilization. Finally, timing of N release from a controlled release fertilizer should match or precede N demand from the crop, and ESN may benefit from earlier application. While ESN was outperformed, in most cases, by AN, it showed some promise in low WHC soils, as hypothesized. The price of ESN is also prohibitive to its use unless significant yield benefit is observed or growers are subsidized for its use. ESN polymer-coated urea material warrants further investigation with varying application strategies and timing for soils or management systems vulnerable to N loss.

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9 Appendix: Figures and Tables

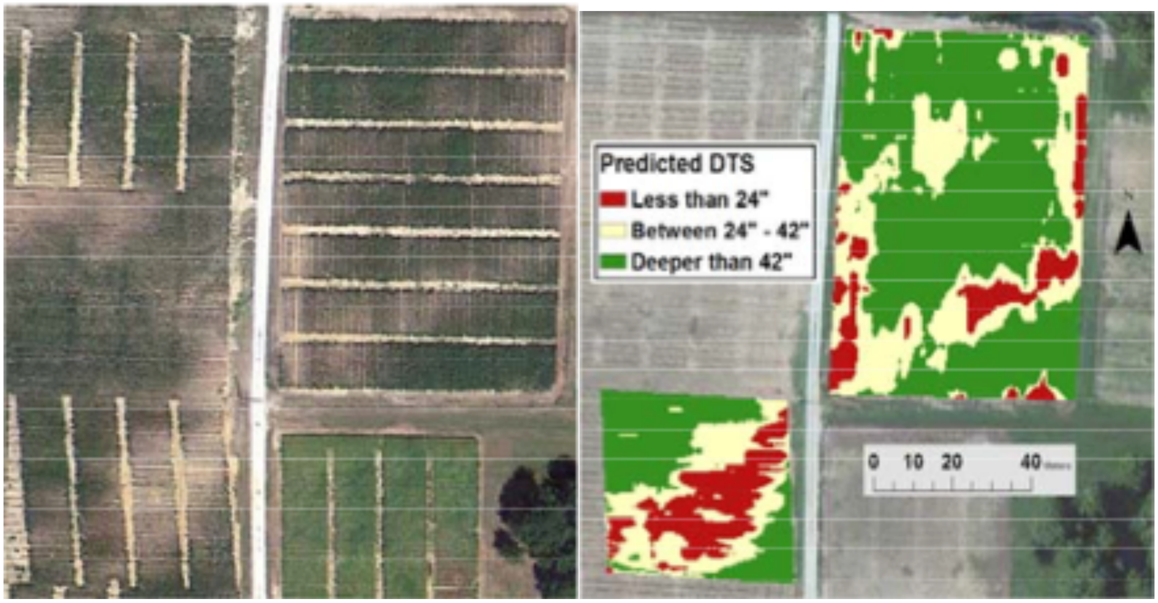

Figure 1-1: Aerial view of variable soils in field of study (left). Predicted depth to sand map of field of study (right). Note similarity between red areas in predicted depth to sand map and dry/less established crop areas on aerial image (Duncan, 2012).

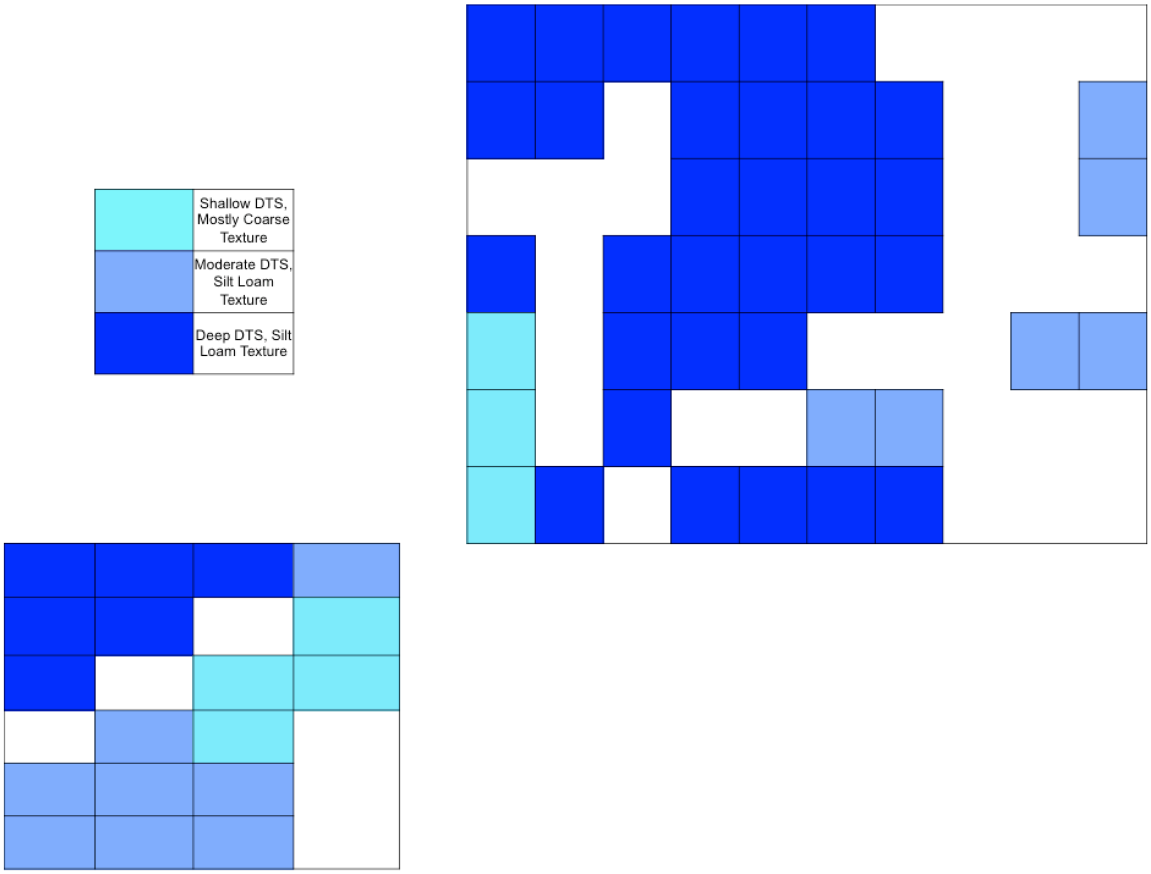

Figure 1-2: Plots in use for experiment separated by soil type.

Table 1-1: Irrigation treatments and applied water per treatment.

Treatment Number	Initiation	Rate (in/week)	2013 Total Water Applied (inches)	2014 Total Water Applied (inches)
1	Square	1.5	5.1	7.5
2	Square	1	3.4	5.0
3	Square	0.5	1.7	2.5
4	Bloom	1.5	3.7	5.7
5	Bloom	1	2.4	3.8
6	Square, Bloom	0.5, 1.5	4.1	6.3
7	Dryland	0	0	0

Table 1-2: Weekly and cumulative rainfall and crop water use (“MOIST”, 2015)

		2013		2014	
	Week #	Rainfall (in)	Crop Water Use (in)	Rainfall (in)	Crop Water Use (in)
May	1	1.7	0.3	0.4	0.5
	2	0.7	0.4	3.1	0.3
	3	3.0	0.5	0.1	0.5
	4	2.6	0.4	0.5	0.4
June	5	0.4	0.5	3.5	0.5
	6	0.8	0.8	4.7	0.7
	7	1.5	0.9	0	1.1
	8	0.2	1.2	0.6	1.0
July	9	0.7	1.1	2.8	1.3
	10	0.5	1.4	0.5	1.5
	11	1.1	1.3	2.3	1.2
	12	2	1.2	0.2	1.6
August	13	0.5	1.1	0	1.5
	14	0.6	1.1	2.3	1.3
	15	0.8	1.1	0.3	1.5
	16	0.3	1.3	2.5	1.4
	17	0	1.4	0.4	1.2
September	18	0.4	1.1	1.7	1.0
	19	0.6	1.0	5.8	0.7
	20	2.4	0.8	0.3	0.6
	21	0	0.7	0	0.7
October	22	0.8	0.4	0.7	0.5
	Total	21.5	20.1	32.7	21.0

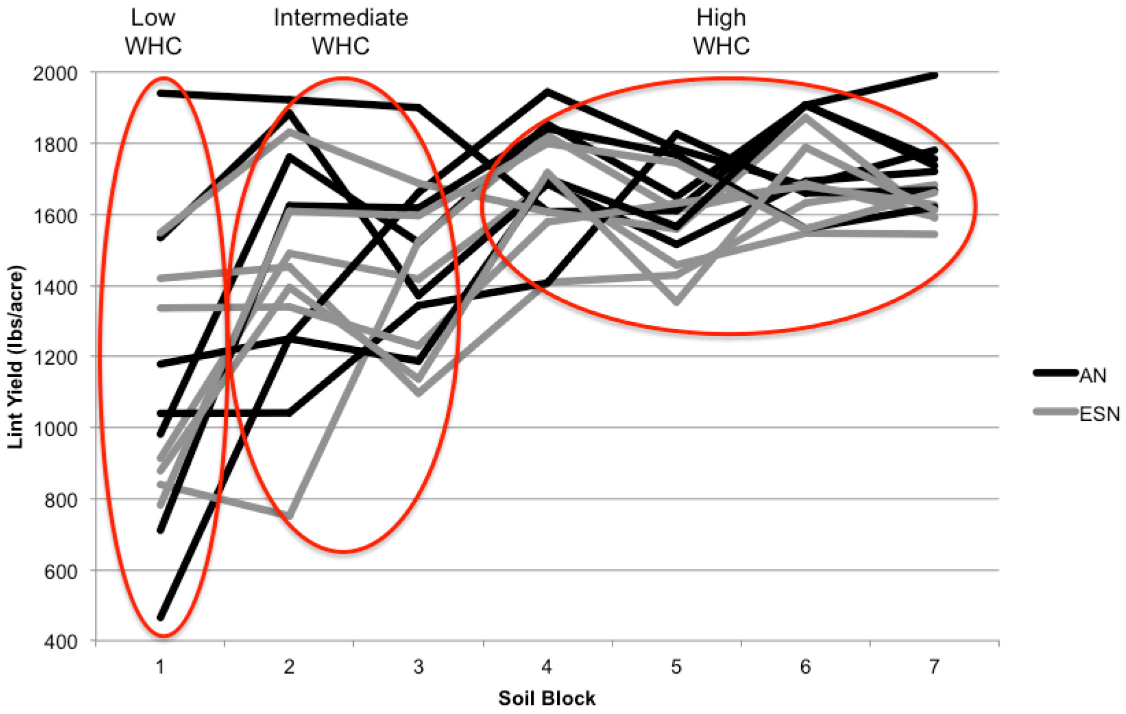

Figure 1-3: The interactive effect of fertilizer source and soil on lint yield in 2013 (p=0.0004).

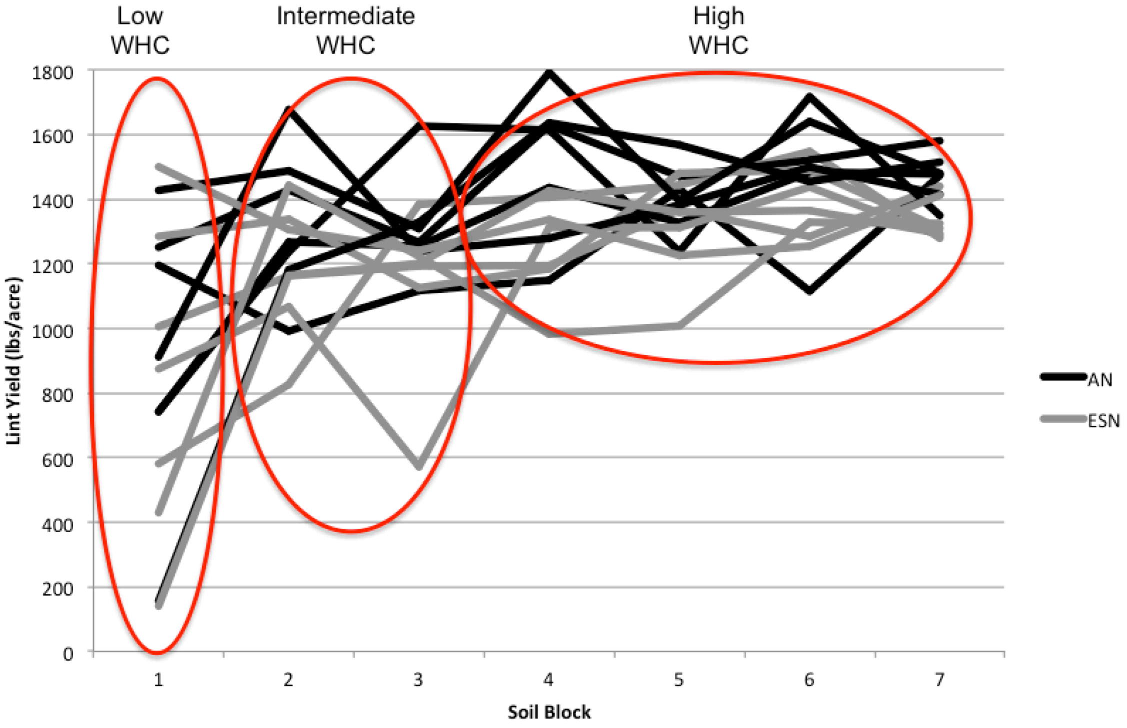

Figure 1-4: The interactive effect of fertilizer source and soil on lint yield in 2014 (p=0.01).

Table 1-3: Fertilizer and soil type main effects on yield. Mean values are cotton lint yields in lbs/acre, and letter groupings were established using LSD means separation at p=0.05.

2013			**2014**		
(p=.0005)	**Fertilizer Main Effect**		(p<.0001)		
	Mean	Letter Group		Mean	Letter Group
AN	1458	A	AN	1233	A
ESN	1374	B	ESN	1105	B
(p<.0001)	**Soil Type Main Effect**		(p<.0001)		
	Mean	Letter Group		Mean	Letter Group
Low WHC	1112	C	Low WHC	875	C
Intermediate WHC	1461	B	Intermediate WHC	1238	B
High WHC	1676	A	High WHC	1396	A

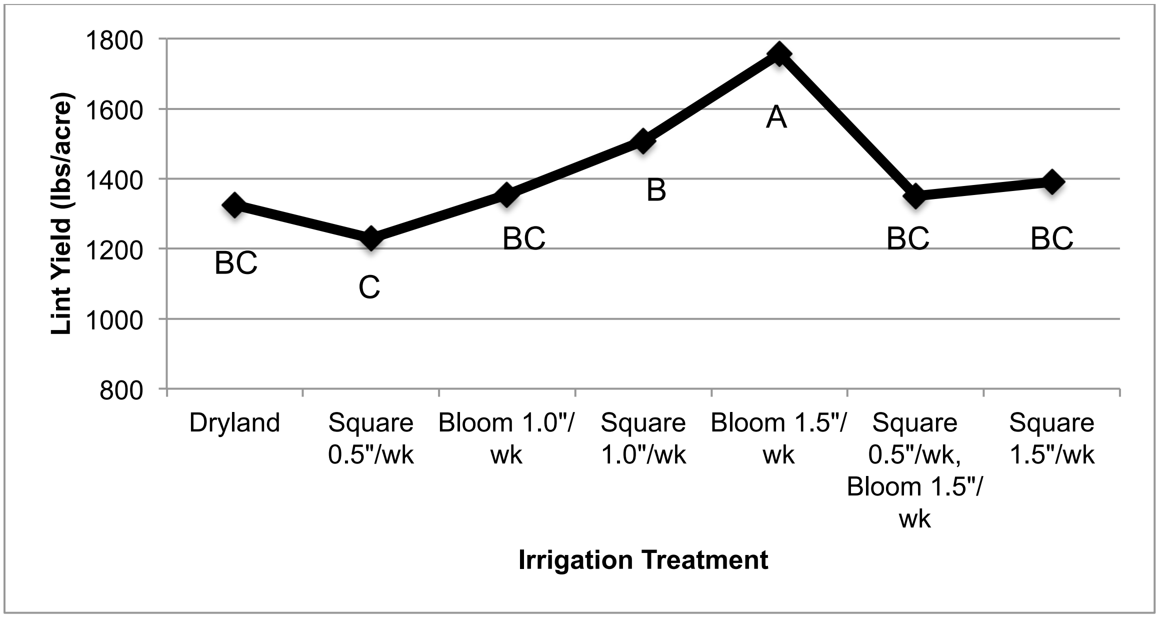

Figure 1-5: Cotton lint yield per irrigation treatment in 2013. Irrigation main effect was significant (p=.0001). Irrigation treatments arranged from least amount of applied water (left) to most applied (right). Mean separation achieved using LSD p=0.05.

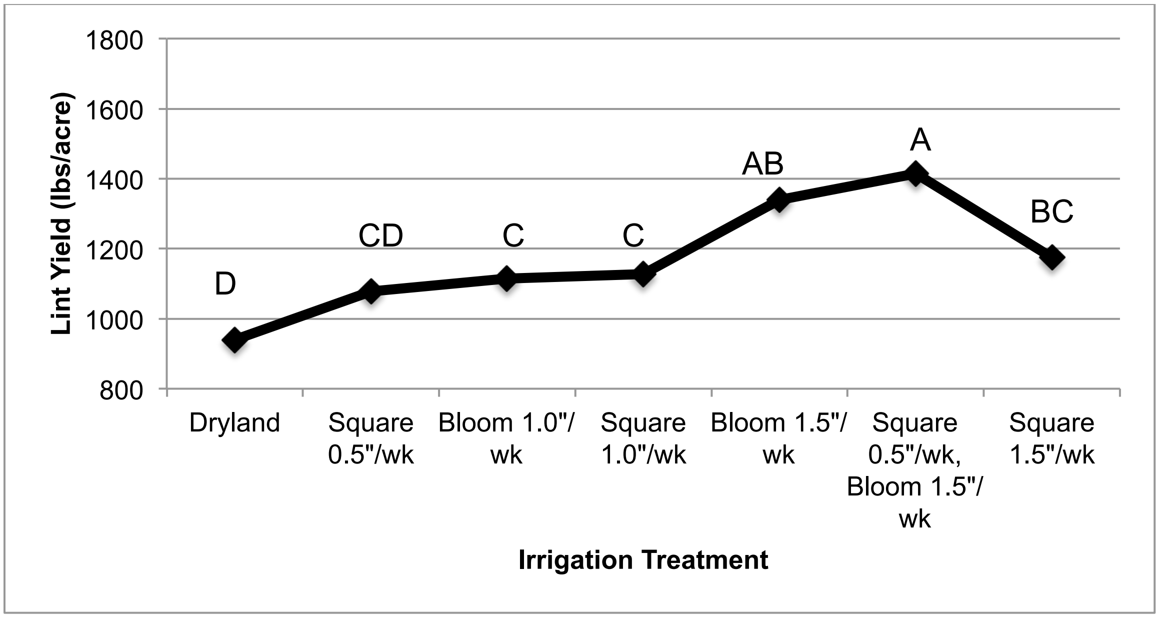

Figure 1-6: Cotton lint yield per irrigation treatment in 2014. Irrigation main effect was significant (p<.0001). Irrigation treatments arranged from least amount of applied water (left) to most applied (right). Mean separation achieved using LSD p=0.05.

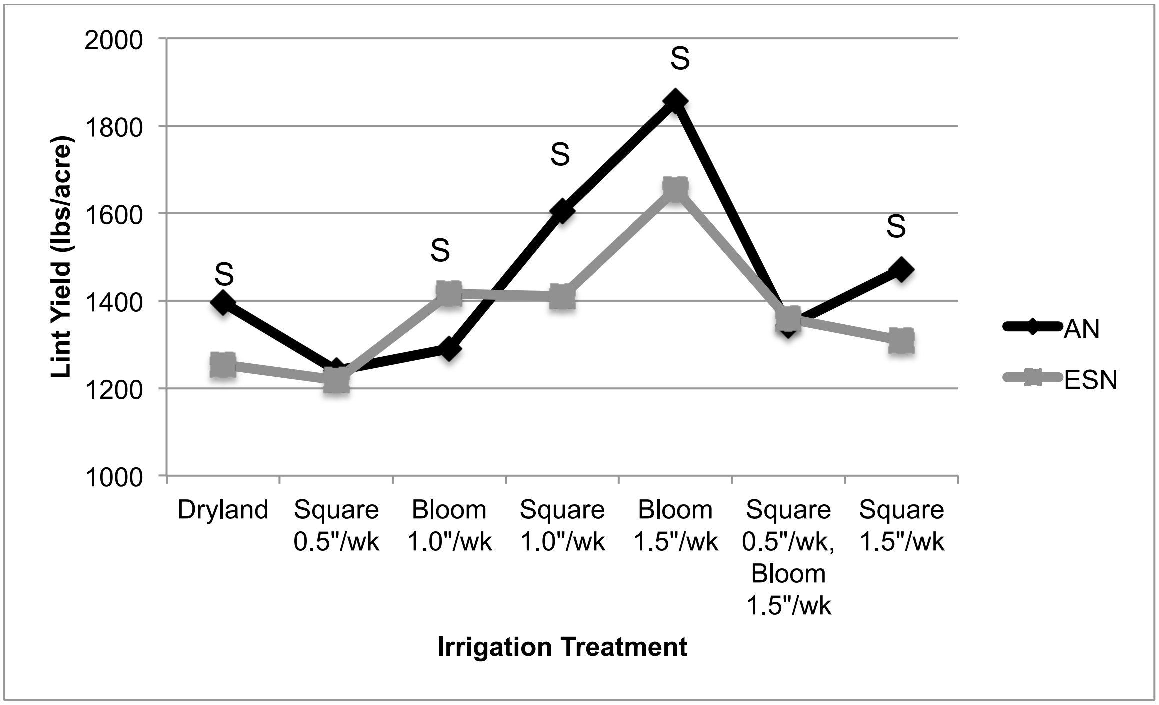

Figure 1-7: Cotton lint yield, as influenced by N source, per irrigation treatment in 2013. Irrigation*fertilizer interaction was significant (p=.0015). Irrigation treatments are arranged from least amount of water applied (left) to most applied water (right). S denotes significant difference between N source at given irrigation treatment, p=.05.

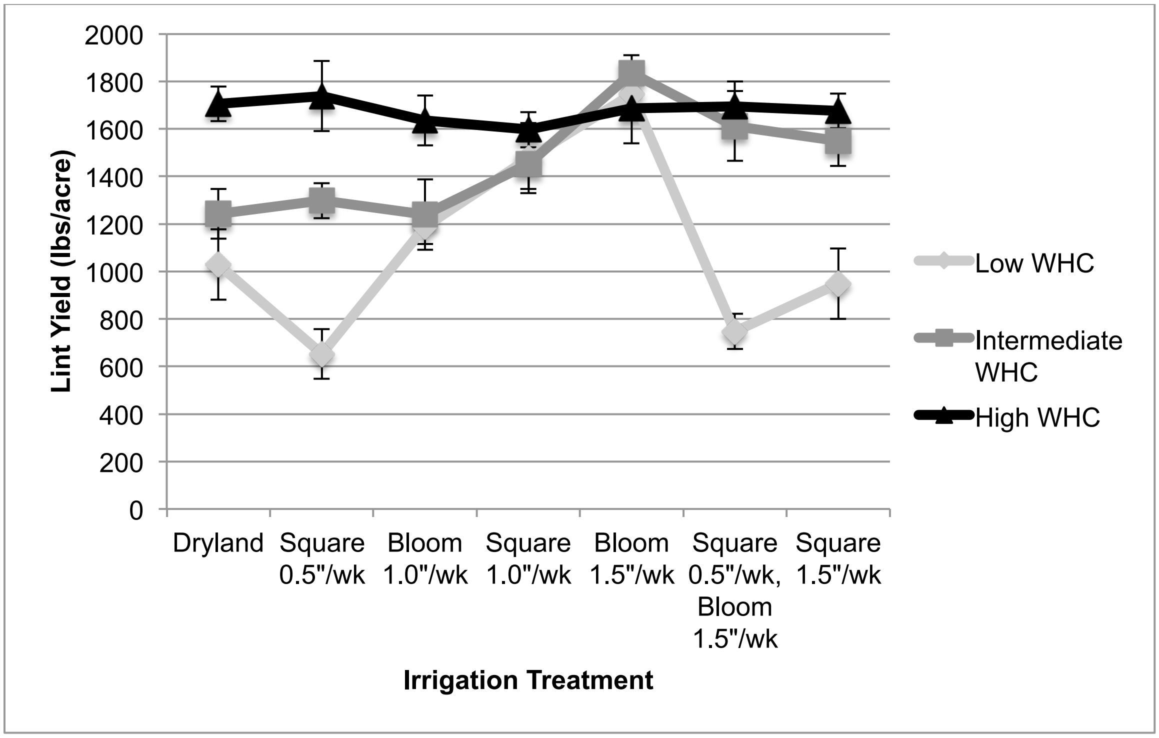

Figure 1-8: Cotton lint yield, as influenced by soil type, per irrigation treatment in 2013. Irrigation*soil type interaction was significant (p=.0006). Irrigation treatments are arranged from least amount of water applied (left) to most applied water (right).

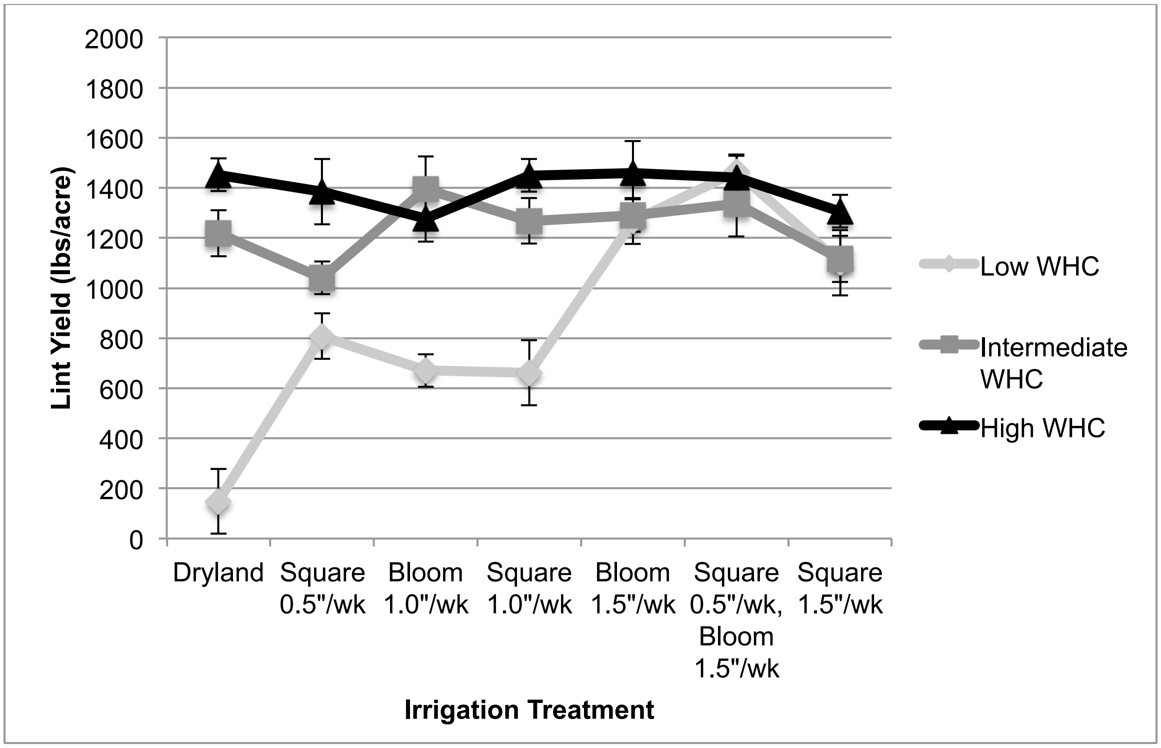

Figure 1-9: Cotton lint yield, as influenced by soil type, per irrigation treatment in 2014. Irrigation*soil type interaction was significant (p=<.0001). Irrigation treatments are arranged from least amount of water applied (left) to most applied water (right).

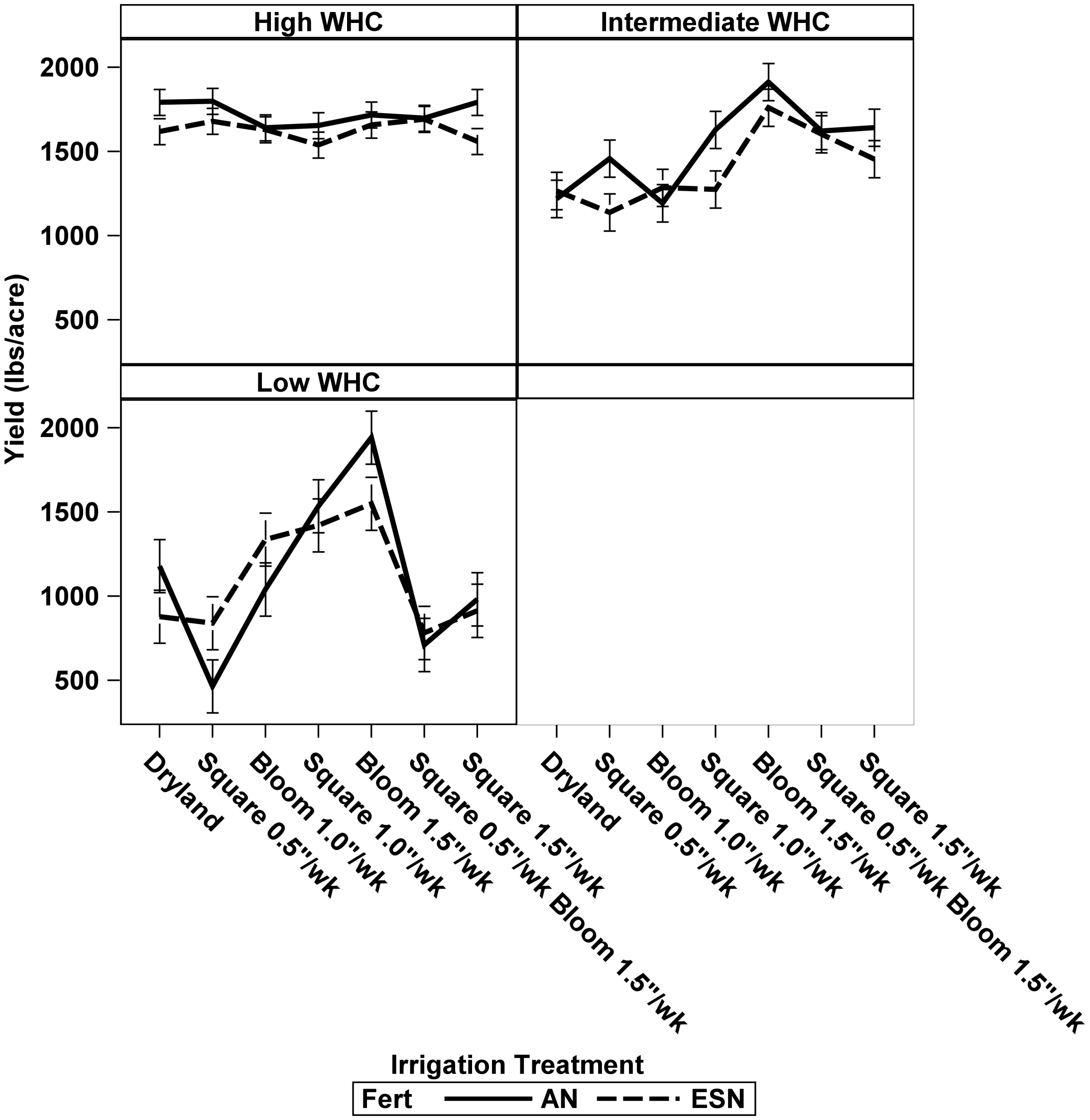

Figure 1-10: Cotton lint yield, as affected by soil type and N source, per irrigation treatment in 2013. This three-way interaction between soil type, fertilizer, and irrigation was significant (p=.0045).

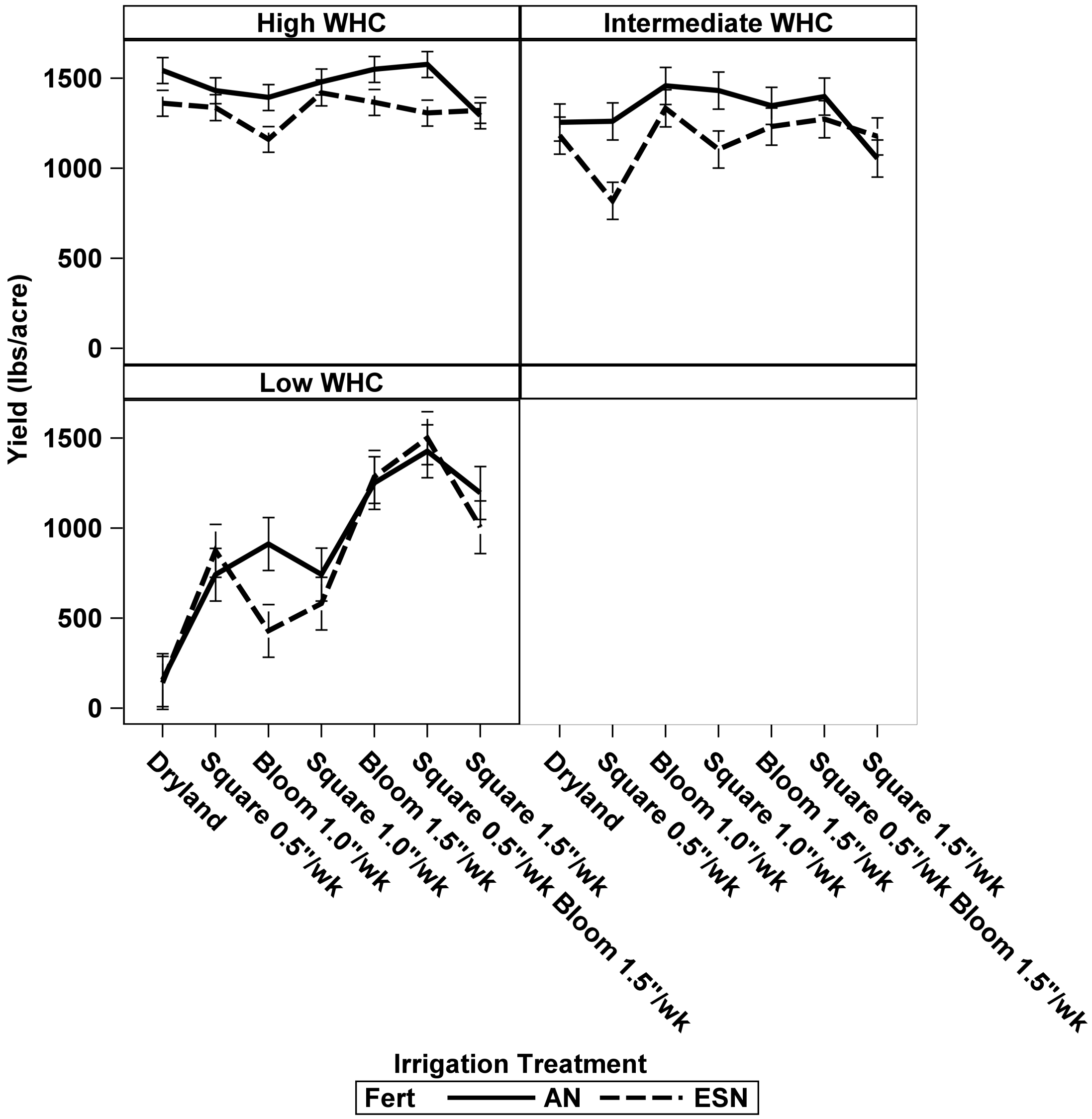

Figure 1-11: Cotton lint yield, as affected by soil type and N source, per irrigation treatment in 2014. This three-way interaction between soil type, fertilizer, and irrigation was significant (p=.0246).

Table 1-4: Fertilizer main effects on total leaf N content. Letter groupings achieved using LSD mean separation at p=.05.

N Source Effect on Total Leaf N Content					
First Bloom Sampling					
2013 (p=.0067)			2014 (p<.0001)		
	Leaf N (%)	Letter Group		Leaf N (%)	Letter Group
AN	3.7	A	AN	3.5	A
ESN	3.6	B	ESN	3.0	B
Mid-Bloom Sampling					
2013 (p=.0001)			2014 (p=.0001)		
	Leaf N (%)	Letter Group		Leaf N (%)	Letter Group
AN	2.7	A	AN	2.6	A
ESN	2.4	B	ESN	2.4	B

Table 1-5: Fertilizer main effects on N removal. Letter groupings achieved using LSD mean separation at p=.05.

N Source Effect on N Removal by Cotton					
2013 (p=.0038)			2014 (p<.0001)		
	Mean (lbs/acre)	Letter Group		Mean (lbs/acre)	Letter Group
AN	82	A	AN	63	A
ESN	75	B	ESN	54	B

Chapter II

Precision Soil Sampling Strategies for Agricultural Fields of Tennessee

1 Abstract

Soil sampling is the foundation for managing the nutrient aspect of production agriculture. A soil sample should be representative of a selected area, to appropriately address the fertility status of that area and recommend potential applications. To implement variable rate fertilizer application, some degree of detail is necessary about nutrient variability across a field. Grid sampling and zone sampling are methods of soil sampling that may give a better resolution of nutrient variability than a field average value. Grid sampling may be the more time and labor-intensive of the two, but zone sampling requires some prior knowledge of the field as a basis on which to form zones. For any sampling method, the question exists as to how many cores should be taken to form a composite sample that one can be reasonably confident in the result obtained.

Nutrient levels obtained by grid-point and grid-cell sampling are frequently not in agreement. Grid-point sampling captures more in-field variability, when examined across a whole field. Grid-cell sampling tends to dilute some high and low areas, thus decreasing measured and apparent variability across a whole field. Yield maps and soil maps were all successful in grouping some variation when used to form zones. It is difficult to assess the utility and practicality of using these zoning techniques without a large-scale study and economic analysis. Optimal sampling intensity varies between fields exhibiting different degrees of variability; more cores are needed in highly variable areas to assess nutrient status. For conditions of this study, 2-8 cores/acre achieved repeatable results.

2 Introduction

Providing sufficient plant-available nutrients is crucial to successful agriculture. Soil sampling is the tool by which native nutrient levels are estimated and supplemental nutrient applications are recommended to increase the likelihood of obtaining best yields. Nutrient recommendations from soil tests are subject to a number of potential sources of error. While errors are possible from the extraction process and in the critical levels achieved by soil test calibration, the greatest source of error resides in the collection of the soil sample in the field (Beegle, 2005). Proper sampling technique, like appropriate depth and adequate sample mixing, must be adhered to. The heterogeneous nature of soil spatially complicates the necessary goal of obtaining a representative sample. Collecting a large number of samples to form a composite sample is typically the approach used to achieve a soil sample that results in an extracted nutrient value that is a representative mean value of the area sampled. Even considering the errors associated with the steps in obtaining a soil test value and recommendation, soil sampling has proven vastly beneficial to the profitability of agriculture.

Agricultural fields have traditionally been treated as homogeneous in fertility status and nutrient need by sampling large areas and fertilizing uniformly. While significant field spatial nutrient variability has been recognized for quite some time, addressing this spatial variability by varying fertilizer rates has only become feasible and attractive in the last few decades (Sawyer, 1994). Mallarino and Wittry (2004) summarized the numerous factors that cause spatial variability in nutrient levels across a given field. On a regional scale, geography, climate, and vegetative characteristics affect expected nutrient levels. On a field scale, soil type, topography, and field history, including prior crops and management practices, can be expected to influence nutrient variability. Orientation of cropping rows, nutrient application method and uniformity, and compaction can further complicate the issue of variability of soil nutrients throughout a field. Uniform application of nutrients has the benefit of simplicity and low sampling cost/labor. Uniform application, however, is subject to significant under and over fertilization throughout a field (Penny et al., 1996). Assuming a representative sample is collected that represents the mean nutrient status, there are inevitably areas with greater and lower extracted nutrient values. Under fertilization is undesirable because of potential yield loss, while over fertilization could mean unnecessary monetary input as well as potential environmental loss.

Variable rate fertilizer application attempts to redistribute application of nutrients to these areas of differing native soil fertility. Ideally, improving the correlation of applied nutrient with nutrient need across a field will improve nutrient use efficiency, maximize yields across a larger portion of a field, and improve crop uptake across a larger area. Soil sampling is fundamental to learning and acting upon the degree to which soil nutrients vary spatially. An important consideration for variable rate application is the suitability of a particular field. For example, Mueller et al. (2001) sampled a field that did not contain sufficient inherent variability to economically warrant any more detail than a simple field average value. Grid sampling and management zone sampling are methods for assessing soil nutrient variability about the field with the goal of applying rates of fertilizer that more appropriately meet crop demand, in specific field areas, than a uniform rate application. An objective look at these sampling methods is needed to provide a better understanding of pros and cons for Tennessee farmers considering their use.

3 Literature Review and Background

3.1 Grid Soil Sampling

Grid soil sampling involves subdivision of a field at regular intervals and can be conducted two basic ways. Grid-cell sampling is a random sampling of the whole area of a grid-cell of whichever shape is used. Grid-point sampling is a sample of usually a smaller number of cores taken near grid intersections or center points (Havlin et al., 2014). Note that both methods involve collecting multiple cores and mixing to form a composite sample. Grid-point sampling is the more often practiced grid sampling scheme. Grid-cell sampling requires more labor as more cores are collected and are more physically spread out than the cores collected for a grid-point sample. Also, with GPS and GIS technology, grid-point sampling locations are easily found, while grid-cell sampling requires flagging of a cell’s borders or constant contact with GPS. Another difference lies in the use of received soil test values. Grid-point samples are typically geospatially interpolated using Kriging or Inverse-Distance-Weighting methods to achieve a continuous map of nutrient values. Grid-cell samples give a pixelated, but complete, map of field nutrient values. Wollenhaupt et al. (1994) suggests that grid-cell produced maps are not ideal for variable rate application because of their non-continuity.

Much research has focused on grid size and its effect on resolution of nutrient maps. The consensus of grid size research has been a better resolution from smaller grid size (Sawchik and Mallarino, 2007; Mallarino and Wittry, 2004; Stepien et al., 2013; Bronson et al., 2000). Economics of more intense sampling and differences in applied fertilizer costs and returns from yield differences must be examined, but as Anderson and Bullock (1998) noted, the most appropriate sampling scheme will vary by field. Some fields are better suited to variable rate application because they present more nutrient or pH variability and at least some areas where nutrients test less than optimal. Although grid size has been researched frequently, relatively few studies have compared grid-cell and grid-point sampling. Disagreement exists in the literature on which grid sampling method captures the most variability. A common perception is that grid-cell sampling tends to dilute the effect of local highs and lows, while grid-point sampling will catch more areas of high and low nutrient status. Wollenhaupt et al. (1994) and Thompson et al. (2004) noted these differential tendencies and concluded that grid-point sampling revealed more variability than grid-cell sampling. Flowers et al. (2005), however, found a grid-cell sampling scheme captured more variability than grid-point sampling. Our objective is to compare the variability revealed by grid-point and grid-cell sampling.

3.2 Zone Soil Sampling

Another soil sampling strategy to facilitate variable rate fertilizer application is management zone sampling. This method requires dividing a field into zones that encompass areas of similar fertility status and that are different from other parts of the field. A benefit of zone sampling over grid sampling is less intensive sampling and fewer samples to be analyzed (Khosla et al., 2002). While simple in theory, management zone sampling is more complex in design than grid sampling because of the necessity of some kind of field knowledge to base zones on. Many techniques for zone delineation have been used, including yield maps, bare soil imagery, electrical conductivity maps, topography, soil maps, remote sensing, slope, and farmer knowledge (Thompson et al., 2004; Khosla et al., 2002).

Using yield history to form zones has consistently proven an effective technique to group soil nutrient variation (Thompson et al., 2004; Flowers et al., 2005; Hornung et al., 2006). Electrical conductivity maps show promise for some fields (Peralta and Costa, 2013), and remote sensing images have been successfully used to form nutrient management zones (Thompson et al., 2004). Electrical conductivity data and remotely sensed images are relatively hard to obtain, while yield maps are becoming more common for farmers interested in precision agriculture. Among the more easily obtained data for delineating zones, less certainty exists about their ability to accurately divide fields into management units. Thompson et al. (2004) successfully used soil maps to form management zones, as did Kravchenko and Bullock (2000), who also noted that organic matter content was the soil property most related to soil nutrient status. Franzen et al. (2002), however, concluded that Order 2 soil surveys, the commonly published scale, were not consistently effective at forming management zones. They found Order 1 soil surveys to better represent nutrient management zones, but noted the difficulty of obtaining such detailed soil maps. Topographic elements such as slope and elevation have been used successfully to delineate management zones (Franzen et al., 1998; Khosla et al., 2002), which makes sense because several studies have noted the interrelationships between topographic elements and yield and soil properties (Changere and Lal, 1997; McConkey et al., 1997). Incorporation of farmer knowledge into a zone delineation plan has proven important (Khosla et al., 2002), and can be a standalone method for forming management zones. Hornung et al. (2006) pointed out that using multiple data layers when forming zones is not always beneficial, and that a farmer's intimate knowledge of the field should always be consulted. Our objective is to examine the effectiveness of several more readily available zone delineation techniques for forming nutrient management zones in Tennessee.

3.3 Soil Sampling Intensity

Soil sampling intensity, or the number of individual cores taken per composite sample, is also an important component of proper soil sampling to implement variable rate nutrient application. The inherent and human-induced spatial variability of soil nutrients is the underlying cause of the uncertain nature of soil sampling, while errors in sampling technique and analysis further exacerbate uncertainty. Even considering uncertainty, soil sampling has proven a greatly beneficial guide for improving agricultural productivity and profitability. The number of cores taken can have a great impact on the accuracy to be expected of results. Kariuki et al. (2009) noted that too few cores would lead to greater uncertainty about the resulting test values and too many cores would incur unnecessary labor. University recommendations are often 15-25 cores to form a composite sample (Daniels et al., 2015), but often lack a recommendation of size of area that should be sampled. Several researchers have recommended a need for significantly more subsamples; Daniels et al. (2001) recommended 48 subsamples to be within reasonable error of the mean value, while Friesen and Blair (1984) suggested 40-80 cores were necessary. Kariuki et al. (2009) arrived at a lower recommended number of subsamples of 22. The recommended number of subsamples should be aimed toward the nutrient measure that shows the highest variability for that area. The University of Tennessee recommends a minimum of 20 cores to be taken from an area no larger than ten acres for field crops, resulting in an intensity of about 2 cores/acre (Savoy and Joines, 2015). While several studies have used iterative processes to determine a minimum number of cores to reach a certain level of certainty, it is of interest to physically take cores at differing intensity levels, with replication, to observe the variation associated with each level of intensity.

4 Objectives

The objectives for this study are:

- Compare grid sampling techniques for capturing field variability
- Evaluate zone delineation methods for potential to group variability in Tennessee fields
- Test and verify University of Tennessee recommendation for soil sampling intensity

5 Materials and Methods

5.1 Grid Soil Sampling

Two fields were sampled at the University of Tennessee Research and Education Center in Milan in March 2014. A field exhibiting a high degree of variability in soils, topography, and yield potential and another field exhibiting little variation were chosen. The two fields sampled were recommended by staff of the research center for these qualities. Each field was divided into one-acre grids using ArcGIS 10.1 software. This resulted in 33 grid-cells in the more variable field, and 25 grid-cells in the less variable field. Grid orientation was north-south to avoid any sampling bias that could be introduced by adjusting grid orientation (Flowers et al., 2005). ArcMap shape-files were created to identify the center point and borders of each one-acre grid cell. In field, a Trimble Nomad unit running ArcPad was used for orientation and navigation.

Each grid was sampled in triplicate at its center (grid-point) by taking six cores in a ten-foot radius about the center point, and doing so three times. Each grid was also sampled in triplicate by randomly taking sixteen cores throughout the grid area in a zig-zag pattern (grid-cell), and doing so three times (Figure 2-1). Cores were hand-crushed and mixed in field, and a composite sample was taken. Samples were analyzed at the University of Tennessee Soil, Plant, and Pest Center. Samples were air-dried, ground, and passed through a no. 10 mesh sieve with an opening of 2.00 mm. Soil nutrients P, K, Ca, and Mg were extracted using Mehlich 1 reagent and test levels determined using inductively coupled plasma optical emission spectrometry. Lime requirement was determined using the Moore-Sikora buffer, and water pH was determined using a pH electrode at a 1:1 soil to water solution ratio.

The mean was calculated for each grid, and each sampling strategy within that grid. These mean values were averaged across a field within sampling strategy to give an overall field mean. An overall field SD was calculated using the mean values for each grid, within sampling strategy, therefore using 33 values in the more variable field and 25 values in the less variable field (Table 2-1). Coefficient of variation (CV) values were calculated for each sampling strategy, in each field, using these overall field mean values and SD (Table 2-1). CV values were compared as suggested by Thompson et al. (2004), with a reduction in CV indicating less variability found by that scheme. Proc GLM routine of SAS 9.3 was used to separate averaged mean values within each field, nutrient, and sampling scheme (LSD p=.10). pH test values were converted to [H+] for statistical analysis then back to pH for reporting mean and CV. Also within Proc GLM, Levene's test for equality of variances and a Zarr approximation were used to identify significance of differences between the SD and CV values, respectively. Grid-point and grid-cell mean sampled values were charted with their SD error bars for each field, and a percentage agreement between the two methods was calculated by number of grids where the error bars overlapped, divided by total number of grids (Table 2-2).

5.2 Zone Soil Sampling

Grid-point mean values for each grid were used in evaluating success of management zone delineation techniques. CV for all grid-point mean values within a field was calculated for each field as a standard for comparison. When zones were formed, grid-point mean values that resided within the boundaries of each zone were used to calculate a CV, and each zoning method was assigned an average CV value calculated by averaging the multiple zone CVs for that zoning technique. Zone delineation techniques were evaluated by comparing zone CV to overall field CV and comparing zone CVs to one another (Tables 2-3 and 2-4). Lower CV values achieved with zoning techniques would indicate some grouping of nutrient variability.

5.2.1 Yield Zones

Cotton yield maps from the 2013 growing season were used to construct yield-based management zones. Yield data was cleaned up as recommended by Blackmore and Moore (1999) and Weisz et al. (2003) by buffering data around field edges and removing unreasonable outliers. Yield increments were formed to create four classes of yield potential. Jenks Natural Breaks procedure in ArcMap was used as a basis for size of yield increments. These increments were adjusted to include a reasonable amount of field area in each zone. Yield intervals were not the same for both fields, as the less variable field tended to have higher yields overall and a smaller range of yields, while the more variable field had lower average yield but covered a greater range of yields (Figure 2-2).

5.2.2 Soil Zones

Published Order 2 soil surveys of each field (NRCS Web Soil Survey) were used to delineate soil zones. Each different soil series mapped was used as a separate management zone. In our case, this led to a reasonable number of management zones (3-4), but if needed, similar soil series could likely be grouped. Order 1 soil surveys had also been prepared for each field. In the less variable field, each soil series was used as an individual management zone, as done for the Order 2 survey zones (Figure 2-3). However, for the more variable field, the soils map produced by an Order 1 soil survey became complex. To keep the number of zones reasonable, all variations of a soil series were grouped as one. For example, Loring soils with differing slopes and erosion classes were grouped together because of their common series description (Figure 2-4).

5.3 Soil Sampling Intensity

A two-acre area of each field was divided into nine equal-size grid cells, each of approximate size .22 acres. Each grid cell yielded a composite sample achieved by taking sixteen random cores. These nine values from the .22 acre areas were averaged for each nutrient to give a representative mean value for the full two-acre area. Each full two-acre area was then sampled in triplicate at intensities of 1, 2, 4, 8, and 16 cores/acre (2, 4, 8, 16, and 32 physical cores taken in each two-acre area). A mean was calculated for each sampling intensity, with the three samples taken at each intensity in each field. Mean separation was conducted using LSD at p=.05 (Tables 2-5 and 2-6). Standard deviations and CVs about the overall mean were calculated to evaluate the repeatability of a given intensity. Levene’s test for standard deviations was used as a separation method within field and nutrient and between sampling intensities (Tables 2-5 and 2-6). CV for sampling intensities was plotted for each field to observe patterns in variation across changing core intensities (Figures 2-5 and 2-6).

6 Results and Discussion

6.1 Grid Soil Sampling

Mean nutrient test values, along with their standard deviations, were calculated for each sampling method, within each field (Table 2-1). While mean soil test value and standard deviation are useful in showing agreement, or disagreement, between sampling methods, comparing CV values most appropriately indicates which sampling method captured more in-field nutrient variability by acting as a standard index. CV values can simply be compared numerically or ranges can be used to differentiate degrees of variability, as suggested by Wilding et al. (1994). CV values of 0-15%, 15-35%, and 35-100% represent low, medium, and high variability, respectively. In side-by-side comparison, grid-point sampling resulted in greater CV values than did grid-cell sampling for all measured nutrients (P, K, Mg, Ca, and pH), and in both fields. In several instances, shifting from grid-cell to grid-point sampling resulted in a higher variability classification. In the more highly variable field, P increased from 31 to 49%, medium to high, and Ca increased from 15 to 23%, low to medium. In the slightly variable field, P increased from 23 to 46%, medium to high, K increased from 14 to 26%, low to medium, Ca increased from 14 to 19%, low to medium, and pH increased from 34 to 63%, medium to high. Our findings strongly support the hypothesis that grid-point sampling captures more in-field nutrient variability than does grid-cell sampling, and agree with the conclusions of Wollenhaupt et al. (1994) and Thompson et al. (2004). This conclusion is contrary to that of Flowers et al. (2005), who suggested greater variability was captured using grid-cell sampling.

Overall mean soil test levels were similar between grid-point and grid-cell sampling for all nutrients in the more highly variable field. In the less variable field, significant difference existed between the overall mean achieved by the two sampling methods for K and pH. Similar overall means, for the most part, lend credence to each method’s ability to thoroughly assess a whole field average value. SD varied significantly between the sampling methods for P, K, and Mg in the more variable field and for P, K, Ca, and pH in the less variable field. CV varied significantly between sampling methods for P and Mg in the more variable field and for P, K, Ca, and pH in the less variable field. As noted previously, SD and CV were numerically higher for grid-point sampling than grid-cell sampling for all nutrients in both fields. More significant differences were detected in the less variable field than the more variable field for mean (2/5 vs. 0/5), SD (4/5 vs. 3/5), and CV (4/5 vs. 2/5). The less variable field, while not as uniform in nutrient levels as suspected, was cleaner, i.e. the data was not as noisy, leading to better separation between sampling methods in that field. Mean nutrient test values were generally higher in the less variable field. All nutrients except Mg had higher test values in that field. Interestingly, SD values were also commonly higher in the less variable field, except for Mg. Partially, this could be due to the higher test values allowing more inherent room for variability around the mean. It also indicates, however, that apparent variability of a field in topography, soils, and yield potential does not always predict degree of nutrient variability in that field.

CV values followed a more expected pattern; within sampling schemes, CV was always higher in the more variable field. In other words, with respect to the mean level of each nutrient, the SD values were relatively higher in the more variable field. It should be noted in comparing sampling methods, that mean values and their subsequent effect on SD and CV were composed of differing numbers of input values between sampling methods. In grid-cell sampling, 16 cores were taken per composite sample, leading to a mean of more values than grid-point sampling, which consisted of 6 cores per composite sample. The greater number of cores per grid-cell sample could lead to more dilution of variability and a seemingly lowered ability to indicate variation across a field. The differing number of cores for each sampling method was instituted to mimic technique commonly used for each sampling method in production agriculture. Per area covered in each sampling scheme (one-acre square for grid-cell vs. a 20 foot diameter circle for grid-point), either method could be considered an intense sampling of that area.

Percent agreement between grid-point and grid-cell sample nutrient values was calculated for each nutrient in each field (Table 2-2). Percent agreement is a measure of how often the two sampling strategies give a statistically similar measured nutrient value for that grid. Percent agreement values between grid-point and grid-cell sampling were not particularly high. Only two of ten instances were greater than 70% in agreement, while the majority of percent agreement values were less than two-thirds. Variability of the field did not have a consistent impact on how often the sampling strategies were in agreement. For P, K, and pH, the more highly variable field had higher percent agreement values. For Mg and Ca, however, the less variable field had higher percent agreement values.

Percent agreement values that are not exceedingly high are not an indicator of improper sampling, rather, they are an artifact of natural soil variability and of the inherent differences in grid-point and grid-cell sampling and what each strategy attempts to capture. Grid-cell sampling is used to pursue a nutrient value that is averaged for and representative of that entire grid area. Grid-point sampling is focused on sampling a much smaller area, in an attempt to capture an accurate nutrient value of a literal and spatial point in the field. Grid-point values should not be assumed to accurately represent the entire grid area around them. Percent agreement values in Table 3 suggest this extrapolation could be flawed in a significant number of cases. Grid-point values are best suited for geospatial interpolation, which is how they are often managed, and production of continuous maps of nutrient values.

6.2 Zone Soil Sampling

Evaluation of zoning success is best approached by numerical comparison of CV values, as suggested by Thompson et al. (2004). Successful zoning for a particular nutrient is indicated by a reduction in CV from overall field CV. Two main questions were addressed when testing strategies for creating nutrient management zones; were these zone delineation techniques useful for grouping variability, and were there differences in response to zone delineation between fields?

Each of the zone delineation strategies implemented seemed to successfully group some variation and improve upon overall field CV. Delineating zones was unsuccessful in only a few instances - detailed soil maps P zoning in the highly variable field (Table 2-3), NRCS-WSS K zoning in the less variable field, and NRCS-WSS pH zoning in the less variable field (Table 2-4). Differences between the techniques were small. Numerically, CV values are lowest when using yield maps to form zones across all nutrients and both fields except for K and Mg in the highly variable field.

Response to zone delineation varied more significantly between fields than between zoning technique. Average reduction in CV achieved by zoning was greater for all nutrients except P in the more highly variable field. Zoning for P resulted in similar reductions in both fields. Zone delineation could be predicted to be more successful in fields exhibiting greater variability, if zones are created appropriately, so as to group variation. With less overall variability, zoning, even at its best, can only help to a certain degree. A key concern that is not addressed by this research is potential agronomic and economic impact of this zoning effect. While our results show the potential for these zoning techniques to group nutrient variability, further research should seek to discover the agronomic and economic validity of implementing zoning practices.

6.3 Soil Sampling Intensity

Recommendations for soil sampling intensity perhaps should be nutrient-specific, and choosing an intensity level that is appropriate for all nutrients requires some compromise. While a high degree of confidence in values obtained is desirable, a practical number of physical cores is also a necessity. We examined our soil sampling intensity data with two different approaches. Firstly, means and standard deviations were compared for each intensity within nutrient and within field (Tables 2-5 and 2-6). Mean values were separated using LSD mean separation. SD values were statistically separated using Levene's test for equality of variances. A lower SD value is more desirable, as this indicates sampled values that were closer to one another, or in better agreement. High standard deviations are indicative of widely separated values and less confidence in the values obtained if that sampling intensity was used.

Mean values, for the most part, did not change with changes in sampling intensity. Only in a couple instances, P and Ca in the less variable field, did mean value show a change when sampled more intensely. When multiple composite samples are taken, it seems the mean of those samples can be assumed a good representation, but when only one composite sample is taken, as is practical and commonplace, the SD about the representative mean value gives an indication of how confident one can be in the value received. Ideally, standard deviation would consistently, perhaps nonlinearly, decrease as sampling intensity increases. This was observed, for the most part. Exceptions did exist, however, as soil sampling is inherently a messy and imprecise science. Possible errors exist in all facets of the soil sampling and analyzing process, as mentioned earlier. A recommendation of sampling intensity can be made by finding the sampling intensity that statistically minimizes standard deviation or at least results in a statistically lower standard deviation than the least intense level used.

Using this strategy, let us first examine the more highly variable field. For P, an intensity of 8 cores/acre must be used to achieve a significantly lower SD compared to 1 core/acre. A further improvement in SD can be seen when intensity is increased to 16 cores/acre. For K, an intensity of 8 cores/acre is needed to realize a significant decrease in SD. For Mg, increasing sampling intensity to just 2 cores/acre significantly lowered SD. For Ca, an intensity of 8 cores/acre was again needed to achieve a decrease in SD. For pH, simply increasing intensity to 2 cores/acre significantly lowered SD. For P, K, and Ca, an intensity of 8 cores/acre was needed to significantly improve confidence in repeatability of sampling, while an intensity of 2 cores/acre was required for Mg and pH. Recall, the area sampled in the more highly variable field was not uniform in soil type, topography, or yield potential. The variability of this area sampled in the highly variable field may lend itself to a more pronounced benefit from increased sampling intensity compared to a more uniform area.

The area sampled in the less variable field was uniform in soil type and much less variable in yield potential. There was no clear decrease in SD for P, K, Mg, or Ca with increased sampling intensity. In fact, SD increased at the highest sampling intensity over at least one of the lesser intense sampling intensities for each of the nutrients in the less variable field. For pH, sampling intensity of 2 cores/acre significantly reduced SD over 1 core/acre. The area sampled in the less variable field represents a more uniform sampling area, which is ideally what a producer aims to create by using zoning techniques. The lack of decreasing SD with increasing sampling intensity in this field suggests that sampling intensities do not need to be as high if an area is uniform in soil type, topography, and yield potential. Increasing SD at high sampling intensities in this field further support a notion of fewer needed cores. Physical mixing of too many cores in field is exhausting and likely leads to error in obtaining a representative sample.

The second method we used to look at sampling intensity data was comparison of CV, and in doing so we could compare all nutrients simultaneously. Using CV puts all nutrients on the same percentage scale, whereas SD is unique to each nutrient. Kariuki et al. (2009) suggests achieving CV lower than 20% is an acceptable level of confidence for soil sampling. Using this guideline, we see similarities to recommendations derived from SD. In the more variable field (Figure 2-5), 4 of the 5 nutrients start over 20% CV at 1 core/acre. When intensity increased to 2 cores/acre, only 3 of the 5 are above 20% CV, and P and K are close to that threshold. At 4 cores/acre, only P and pH are still above 20% CV, and at 8 cores/acre, only pH remains high. In both fields, pH consistently decreases in CV with increased sampling intensity, but never reaches the 20% mark. pH is notoriously highly variable, due to inconsistent spreading of lime and fertilizer (Flowers et al. 2005). In the less variable field (Figure 2-6), only P and pH are over 20% CV at an intensity of 1 core/acre. At 2 cores/acre, K rises slightly above 20% CV, but is probably just noise as it is well below 20% CV at all other intensities. For the most part, all nutrients are below or at least hovering near the 20% CV threshold at all intensities in the less variable field, reflecting the trend seen with SD. Curiously, P and Ca rose to their highest

CV at the most intense sampling, probably a result of the physical mixing issue with an excessive amount of soil mentioned prior.

While the results of the less variable field suggest no benefit of sampling intensity greater than 1 core/acre, except for pH, the results from the more variable field should not be ignored. Ideally, uniform areas could be identified and sampled, but in practice, fields are often sampled as a whole or field divisions are made arbitrarily or improperly. When more variability existed within a sampling area, 2-8 cores/acre were needed to assess nutrient status consistently. Current University of Tennessee recommendation of at least 2 cores/acre seems accurate. Sampling areas should always be formed in such a way to make them as uniform as possible, and should be sampled at intensities of 2-8 cores/acre. Sampling intensities higher than 8 cores/acre may not be practical because of the physical limitation of proper mixing of soil cores.

7 Conclusion

The basic goal of soil sampling is to identify soil supplies of critical nutrients and to address any nutrients that are deficient so as to optimize the probability of achieving best economic yields. Whether soil sampling aims to simply obtain a field average for uniform application or attempts to capture and address in-field variability with variable rate application of nutrients, proper sampling techniques should be followed and adequate numbers of cores collected. This research looked to provide information for Tennessee row crop producers on techniques for sampling to address nutrient variability and how intensely an area should be sampled. Grid soil sampling is a popular strategy for assessing in-field nutrient variability, but an important distinction should be made between grid-point and grid-cell sampling. Our data show that grid-point sampling captures more variability, but the point samples are not necessarily representative of the full cell area around them. Zone soil sampling can be used to capture more nutrient variability than a field-average value and is less time/labor intensive than grid sampling, but requires prior knowledge of some field characteristics. Zone delineation using soil maps of varying survey intensity and yield maps consistently grouped and reduced variation compared to whole field, but questions remain about economic and agronomic effectiveness of zoning strategies. Suggesting a sampling intensity, in cores/acre, is difficult because some nutrients tend to exhibit more variability than others. Also, data concerning the repeatability of sampling intensity tends to be noisy, leading to inconclusiveness on the appropriateness of a given intensity. Nevertheless, a sampling intensity of 2 cores/acre is recommended as a minimum, while no more than 8 cores/acre are recommended due to the physical size of soil sample that is possible at higher intensities. This study reveals promise for the use of precision soil sampling strategies in Tennessee to address nutrient variability, yet suitability of a field for precision soil sampling is an important consideration. A field should have enough spatial variability to warrant varying of nutrient application rates to better suit crops in specific field areas, and a field should certainly have areas low enough in one or more nutrients that fertilization is even recommended. While variability within the high or very high range may be recognized and identified, nutrient recommendations are not going to change.

Further study of these techniques and ideas should begin to evaluate economic and agronomic effectiveness of precision soil sampling.

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9 Appendix: Figures and Tables

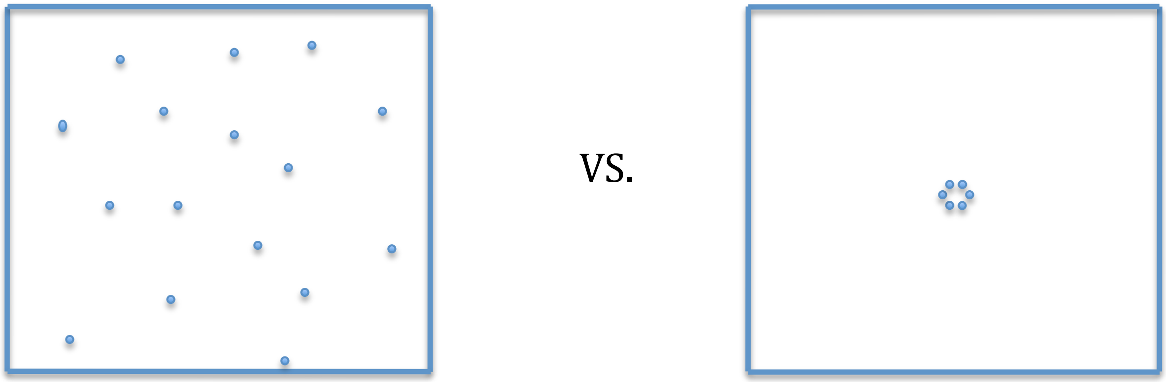


Figure 2-1: Grid-cell sampling (left) vs. grid-point sampling (right). Each grid was sampled six times in total, three by each grid sampling method.

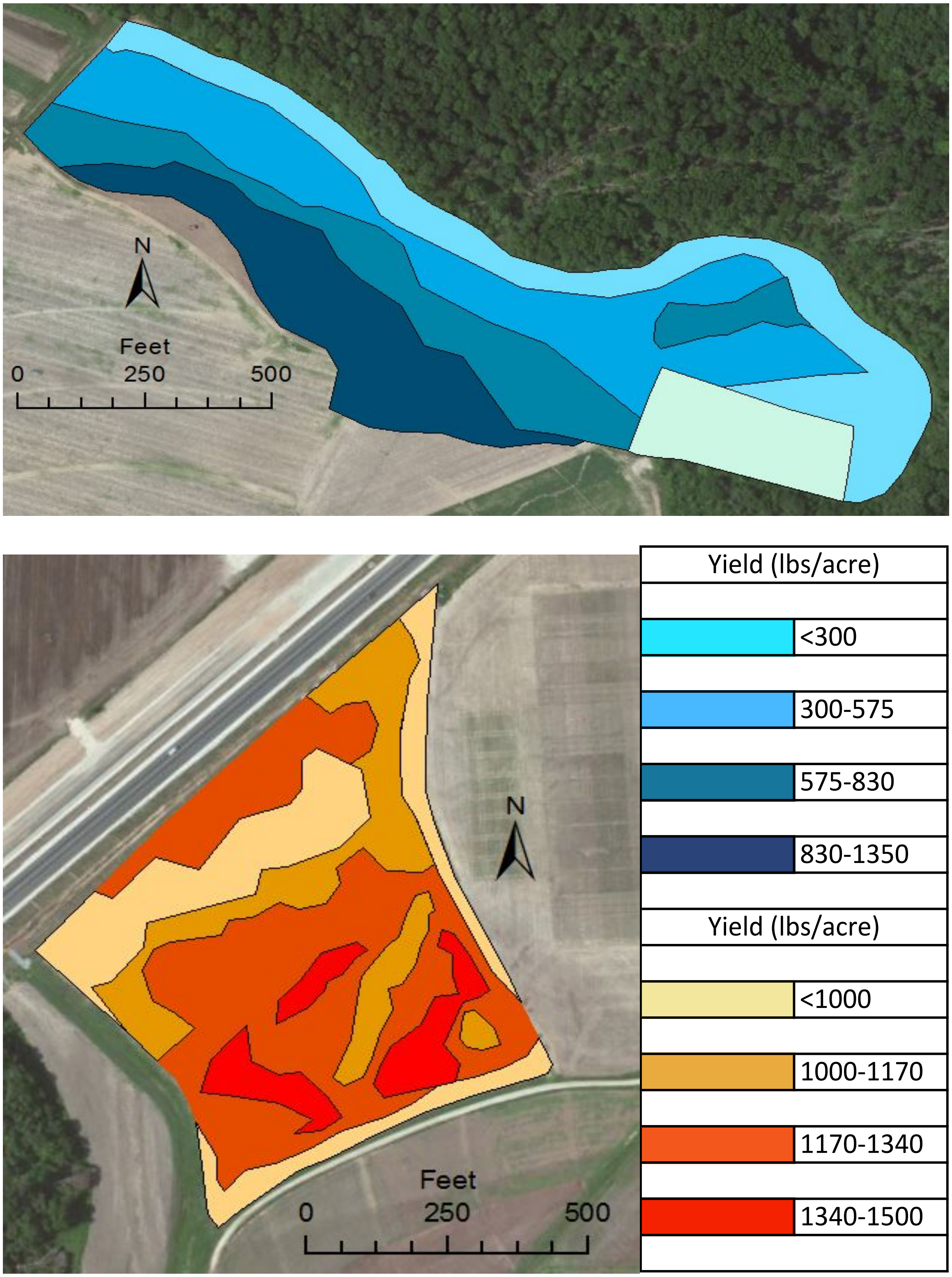
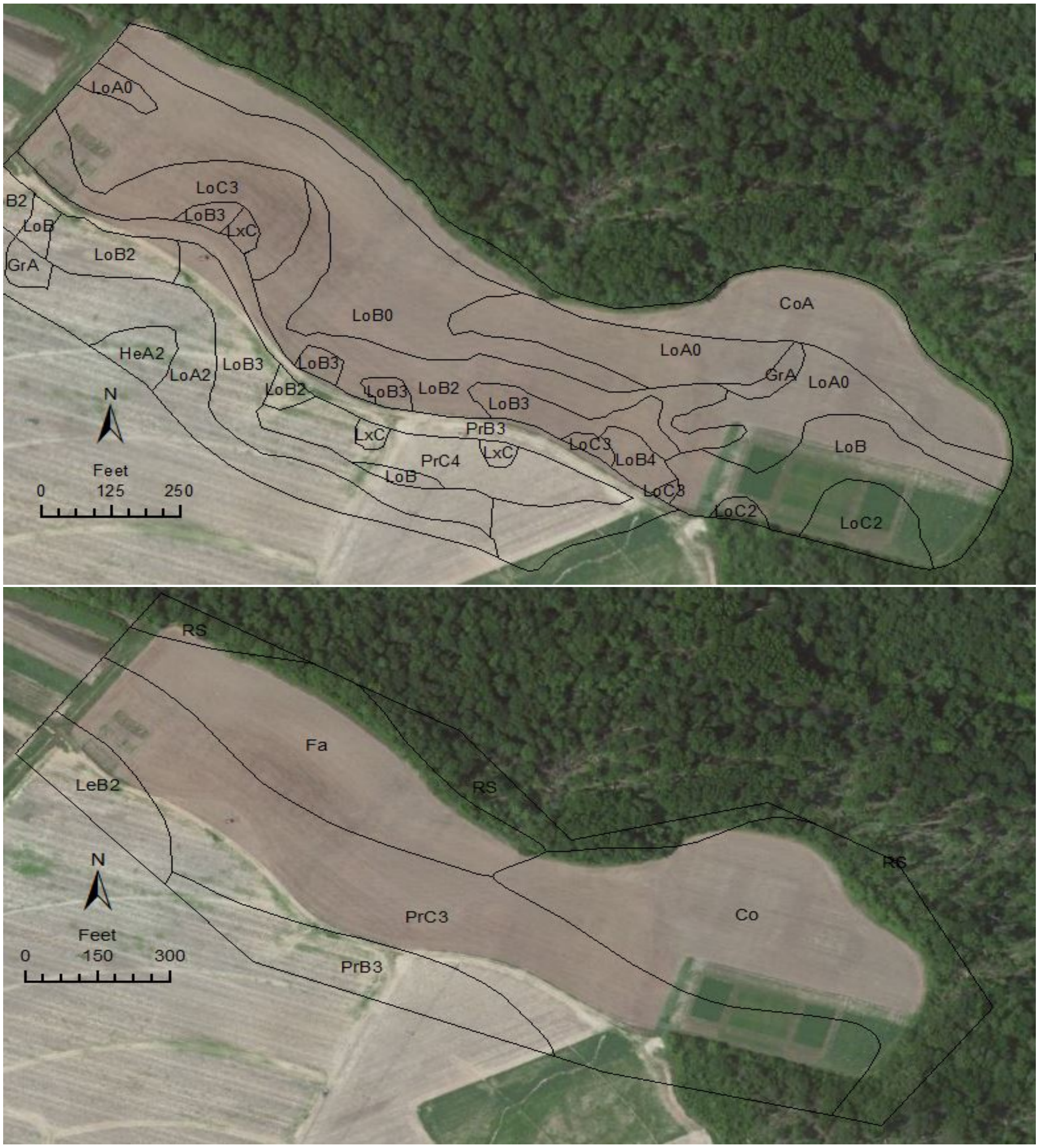


Figure 2-2: Yield-based management zones in the more variable field (top) and less variable field (bottom).

Abbreviation	Soil Series	Abbreviation	Soil Series
Ce	Center	Fa	Falaya
Le	Lexington	Lo	Loring
Pr	Providence	Rt	Routon

Figure 2-3: Order 1 soil survey (left) and Order 2 soil survey (right) for the less variable field.



Abbreviation	Soil Series	Abbreviation	Soil Series
Co	Collins	Fa	Falaya
Gr	Grenada	Le/Lx	Lexington
Lo	Loring	Pr	Providence

Figure 2-4: Order 1 soil survey (top) and Order 2 soil survey (bottom) for the more variable field.

Table 2-1: Mean, standard deviation, and CV compared between nutrients and sampling method within each field. Bolded values indicate significant differences between numbers for that nutrient in that field at significance level p=.10.

			Mean			
		P	K	Mg	Ca	pH
Highly Variable Field	Grid-Cell	15.5	97.0	147.5	1457.5	6.2
	Grid-Point	15.7	97.9	149.3	1465.1	6.3
Slightly Variable Field	Grid-Cell	44.3	**147.4**	137.0	2267.3	**6.8**
	Grid-Point	43.5	**152.2**	129.0	2175.6	**6.7**

			Standard Deviation			
		P	K	Mg	Ca	[H+]
Highly Variable Field	Grid-Cell	**4.9**	**22.3**	**36.8**	218.6	3.2E-07
	Grid-Point	**7.7**	**30.6**	**48.1**	337.3	6.9E-07
Slightly Variable Field	Grid-Cell	**10.1**	**21.1**	31.5	**308.7**	**5.7E-08**
	Grid-Point	**19.8**	**39.6**	35.3	**416.9**	**1.9E-07**

			Coefficient of Variation			
		P	K	Mg	Ca	[H+]
Highly Variable Field	Grid-Cell	**31.3**	23.0	**24.9**	15.0	50.2
	Grid-Point	**49.0**	31.2	**32.2**	23.0	96.9
Slightly Variable Field	Grid-Cell	**22.9**	**14.3**	23.0	**13.6**	**33.6**
	Grid-Point	**45.6**	**26.0**	27.4	**19.2**	**63.2**

Table 2-2: Percent agreement between grid-point and grid-cell sampling.

	Percent Agreement				
	P	K	Mg	Ca	pH
Slightly Variable Field	57	65	74	65	52
Highly Variable Field	65	77	65	58	68

Table 2-3: CV values achieved by each zoning method compared to overall field CV in the more highly variable field.

	CV (%)				
Zone	P	K	Mg	Ca	pH
Overall Field	49	31	32	23	97
NRCS-WSS	44	25	29	21	84
Soil Maps	51	24	24	22	91
Yield	40	27	29	21	81

Table 2-4: CV values achieved by each zoning method compared to overall field CV in the less variable field.

	CV (%)				
Zone	P	K	Mg	Ca	pH
Overall Field	46	26	27	19	63
NRCS-WSS	44	27	26	19	65
Soil Maps	39	24	27	17	59
Yield	36	23	26	17	55

Table 2-5: Mean and standard deviation for each sampling intensity in the field more variable in soil type, topography, and yield potential. Mean separation LSD p=.05, and SD separated with Levene's test, p=.10.

Nutrient	Cores	Mean	Letter Sep.	SD	Letter Sep.
P	1/Acre	16	A	5	A
	2/Acre	16	A	4	AB
	4/Acre	19	A	4	AB
	8/Acre	21	A	2	B
	16/Acre	20	A	1	C
K	1/Acre	98	A	15	A
	2/Acre	86	A	16	A
	4/Acre	95	A	9	AB
	8/Acre	94	A	7	B
	16/Acre	85	A	6	B
Mg	1/Acre	181	A	46	A
	2/Acre	140	B	14	B
	4/Acre	145	AB	14	B
	8/Acre	141	B	9	B
	16/Acre	145	AB	10	B
Ca	1/Acre	1268	A	172	A
	2/Acre	1236	A	90	AB
	4/Acre	1282	A	84	AB
	8/Acre	1311	A	72	B
	16/Acre	1275	A	52	B
[H+]	1/Acre	1.79E-06	A	9.19E-07	A
	2/Acre	1.16E-06	A	3.36E-07	BC
	4/Acre	8.21E-07	A	4.17E-07	B
	8/Acre	8.15E-07	A	3.12E-07	BC
	16/Acre	8.77E-07	A	1.84E-07	C

Table 2-6: Mean and standard deviation for each sampling intensity in the field less variable in soil type, topography, and yield potential. Mean separation LSD p=.05, and SD separated with Levene's test, p=.10.

Nutrient	Cores	Mean	Letter Sep.	SD	Letter Sep.
P	1/Acre	30	B	7	A
	2/Acre	37	AB	2	B
	4/Acre	41	A	6	A
	8/Acre	40	A	6	A
	16/Acre	43	A	9	A
K	1/Acre	144	A	17	AB
	2/Acre	154	A	25	A
	4/Acre	128	A	12	B
	8/Acre	132	A	9	B
	16/Acre	147	A	13	AB
Mg	1/Acre	131	A	17	AB
	2/Acre	158	A	22	A
	4/Acre	142	A	6	B
	8/Acre	145	A	9	B
	16/Acre	151	A	12	AB
Ca	1/Acre	2022	B	121	B
	2/Acre	2396	AB	286	A
	4/Acre	2372	AB	296	A
	8/Acre	2229	AB	216	AB
	16/Acre	2477	A	370	A
[H+]	1/Acre	5.09E-07	A	3.63E-07	A
	2/Acre	1.61E-07	B	7.30E-08	B
	4/Acre	1.76E-07	AB	5.20E-08	B
	8/Acre	1.79E-07	AB	5.50E-08	B
	16/Acre	1.89E-07	AB	4.40E-08	B

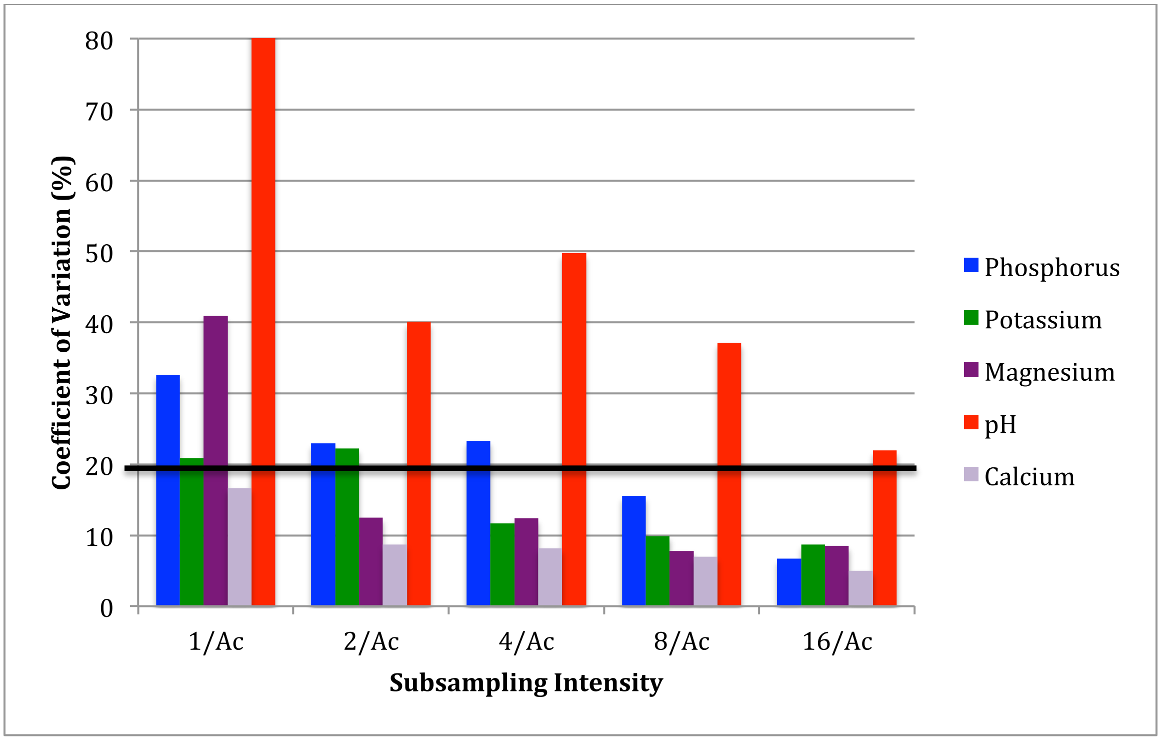


Figure 2-5: CV for each nutrient and sampling intensity in the more highly variable field. 20% CV threshold is marked with bold line.

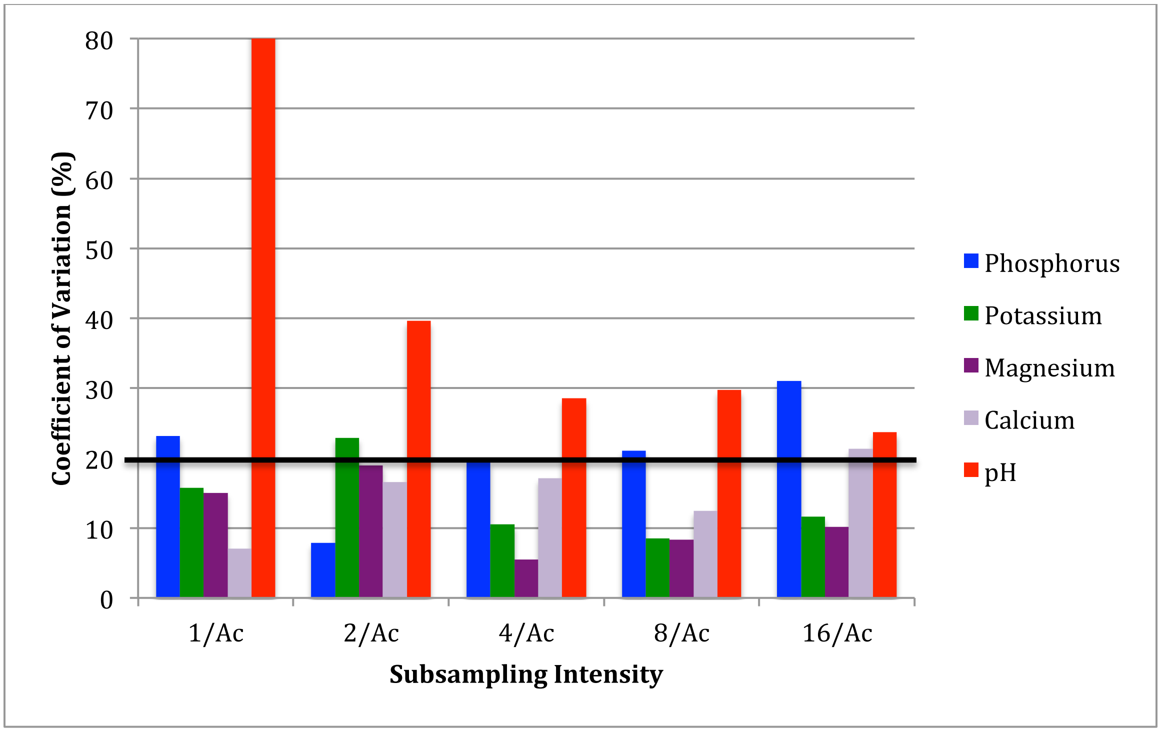


Figure 2-6: CV for each nutrient and sampling intensity in the less variable field.

20% CV threshold is marked with bold line.

Conclusion

Agriculture is an ever-evolving and actively changing pursuit. Production techniques, like irrigation management should be continually refined, in order to optimize probabilities of good yields. New advances in technology, such as controlled-release fertilizers, should be evaluated for their effectiveness agronomically and economically. Producers are in need of sound research to provide guidance on these aspects of production. Environmental pressures are also mounting on agriculture, as potential negative impacts of production inputs are being studied and brought into focus. With the well-being of producers in mind, and the importance of the environmental impact of fertilizer and water inputs, this research strives to provide guidance on appropriate application techniques and strategies for fertilizers and water.

Vita

Timothy Grant was born in Heiskell, TN to parents Ron and Stacy Grant. Timothy has a younger sister, Rebecca Grant. He attended Powell High School, and embarked on his college career at the University of Tennessee, Knoxville. Timothy received his B.S. degree in Environmental and Soil Science, and quickly accepted an opportunity to continue his education, working toward an M.S. degree in Environmental and Soil Science. Upon completion of his M.S. degree, Timothy is furthering his passion for research and extension by working as a research associate in the department of Biosystems Engineering and Soil Science.