Precision Nitrogen Injection Using Integrated Optical Sensing and Variable Rate Technologies

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Deliverables

1. Twenty nine sites of field demonstration trials in the four participating states;
2. Reliable data quantifying the impacts of in-season optical sensor-based variable-rate precision N management systems on seasonal fertilizer N consumption, potential post-harvest N losses, estimates for improved water quality, fertilizer N use efficiency, and grower profitability;
3. Field tours, presentations, and publications about the precision N management systems;
4. Tested algorithms for variable-rate precision N applications based on vegetation indices;
5. Semi-annual reports submitted to NRCS CIG Program Management Office; and
6. Supplemental narratives to explain and support payment requests.

Final Project Report Submitted: March 2016

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EXECUTIVE SUMMARY

This project was funded through the funding category: Mississippi River Basin. The funds were spent as anticipated according to the relevant laws and regulations. This project targeted the NRCS designated priority: nutrient management: demonstrate new and innovative advances in precision farming technologies related to low disturbance fertilizer injection and document the effects on nutrient losses and producer risk.

Twenty nine field demonstration trials were conducted on cotton (*Gossypium hirsutum* L.) mostly on private farms with EQIP eligible producers in West Tennessee, the Delta region of Mississippi, Missouri, and North Louisiana within the Mississippi River Basin during 2011 to 2014. Felds representative of land used for cotton production were used for this project. Historical cropping information was collected from the cooperative producers. The in-season sensor-based variable-rate nitrogen (N) management systems were demonstrated in comparison with the local farmer's uniform-rate N application systems in large strip plots under a randomized complete block design with three replicates. A variety of Extension and outreach activities were conducted to show the demonstration sites and precision equipment, and to disseminate the results to cotton producers and other interested groups. This project used seasonal fertilizer N consumption, fertilizer N use efficiency (lint yield/fertilizer N applied), and post-harvest residual N levels in the soil profile to estimate its potential impacts on water quality in the Mississippi River Basin, which is scientifically sound and very cost-effective.

The goal of this project was to encourage producers' adoption of optical sensing and variable-rate application technologies and the related precision N management systems on their farms to reduce N fertilizer consumption and potential N losses, improve cotton productivity, and thus improve water quality and grower profitability in the Mississippi River Basin. The specific objectives for this project were to demonstrate to producers and other interested groups the integration of sensor-based variable-rate N fertilization into their current production systems, demonstrate the impacts of variable-rate precision N management systems based on optical sensing of crop canopy compared with the current uniform-rate N application systems in terms of fertilizer N use efficiency, post-harvest residual soil N subject to loss, potential improvements to water quality, cotton yield, and grower profitability, and show the benefits of incorporating yield maps and other field and soil information into the optical sensor-based variable-rate precision N management systems. The goal and objectives of this project were fully met be the successful completion of this project.

In Louisiana, a total of nine demonstration trials were completed from 2012 to 2014 in Tensas Parish, Louisiana to evaluate the performance of farmer standard N management practice and variable-rate applicator/optical sensor systems (VRT/sensor systems) in cotton production using yield and net return from N fertilization as performance metrics. Six out of the nine site-years benefitted from using VRT/sensor systems with an average of $34.14/ac higher net return than the farmer's standard N practice; the savings incurred from using lesser amount of N fertilizer offset the minimal dollar losses for having lower lint yield still resulting in higher net profit. In some cases, both increased in lint yield and savings from fertilizer cost contributed to higher profit. While the VRT/sensor systems N recommendation incurred lower net profit than the farmer's standard N practice at three site-years, the reduction was relatively low averaging only $8.93/ac. Refining the VRT/sensor systems N recommendation based on soil productivity zoned worked better than farmer's standard N practice in four out of the nine site-years with an average higher net return of $30.87/ac. The results of this project demonstrated the potential of VRT/sensor systems as an effective N decision tool in cotton production in Louisiana. This project has allowed the investigators to understand some of the aspects of the technology that need to be addressed: the 2nd N application requirement is a challenge to accomplish by producers because of the lack of time; and that the narrow window to accomplish 2nd N application can also limit the timely application of midseason N to cotton. For future project, it is ideal to have the participating producers operate and implement the VRT/sensor systems themselves, and some economic factors should be considered for evaluation of economic return using this technology.

In Missouri, from 2012 to 2014, variable-rate nitrogen applications to cotton were demonstrated in three fields of EQIP-eligible farmers per year. Demonstrations covered the entire field; total area for the nine fields was 525 acres. Six EQIP-eligible cotton growers participated (two each year). Variable-rate nitrogen fertilizer applications were compared to a uniform application of nitrogen fertilizer at the rate normally used by the farmer. These approaches were alternated in strips across the entire field. For the variable-rate approach, fertilizer rate was controlled by an optical sensor that would sense the color of the cotton plants and adjust the fertilizer rate accordingly. Adjustments were made once per second. Conversion of optical sensor readings to nitrogen fertilizer rates was based on previous research at the University of Missouri. In four fields, a third approach was also used: sensor-based rate recommendations which were adjusted according to soil zones. Over eight of the fields, use of sensors reduced nitrogen fertilizer rate by 6 pounds N per acre and increased cotton yield by 7 pounds lint per acre. Combined value of the fertilizer savings and yield increase were $9 per acre. Yield data was lost from one of the demonstration fields. When combined with six similar demonstrations in 2009-2010 from a previously-funded project, use of sensors reduced nitrogen fertilizer rate by 6 pounds N per acre and increased cotton yield by 19 pounds lint per acre. Combined value of the fertilizer savings and yield increase were $19.50 per acre, averaged over 14 fields. Using soil zones in combination with optical sensors had no effect on fertilizer rate or yield in the four fields in which this approach was tested. Sensors cost about $20,000 for a set. Based on the results from the eight demonstration fields in this project, the sensors would pay for themselves by the time they were used on 2,200 acres. Results from all 14 demonstration fields conducted in Missouri are more favorable, indicating payback after just over 1,000 acres. Either way, the economics seem viable for many cotton growers. We helped farmers to overcome the technical aspect of getting optical sensors installed and running. This remains a key barrier to adoption. Consultants or technical representatives from the sensor companies could fill this role.

In Mississippi, sensor based adjustment of fertilizer N rates utilizing a vegetation index with known sensitivity to plant N status shows great promise to improve accuracy across spatially variable fields as compared to the standard practice of applying a constant rate. Although post-harvest available soil N was not sampled in this study it was obvious from the samples taken near planting that considerable variability in soil nitrate and ammonium existed in the fields utilized. Recommendations are to further refine the technology in terms of script writing to more easily facilitate the data processing steps and turnaround time from data acquisition to fertilization. Greater testing and development of algorithms is needed to make applicable across more regions.

In Tennessee, leaf N concentrations and canopy vegetation index were generally comparable under the in-season sensor-based variable-rate N management systems relative to the current uniform-rate N application systems during early square to mid-bloom in the eight field trials on EQIP eligible farms. The in-season variable-rate N management systems produced higher cotton lint yield at one location-year, similar lint yield at six location years, but lower lint yield at one location-year than the current uniform-rate N application systems. The in-season variable-rate N management systems did not affect post-harvest residual N levels in top 60 cm of the soil profile relative to the current uniform-rate N application systems. Averaged over the eight location-years, the in-season variable-rate N management systems had significantly lower seasonal N fertilizer consumption, but higher N use efficiency than the current uniform-rate N application systems. Specifically, the in-season variable-rate N management systems reduced the seasonal N fertilizer consumption by 9.3 to 14.8% (9.8 to 15. 6 kg N ha^{-1}), but increased N use efficiency by 9.2 to 11.0% compared with the current uniform-rate N application systems. No significant positive effect of in-season variable-rate N management systems was observed on post-harvest residual N levels in the top 60 cm of soil. The benefits of incorporating yield maps of previous years into the in-season sensor-based variable-rate precision N management systems were generally not noticeable in terms of cotton yield, seasonal N fertilizer consumption, N sue efficiency, and post-harvest residual soil N level. Our results suggest that in-season sensor-based variable-rate N management systems via side-dress use less N fertilizer to produce comparable cotton yield via increasing N use efficiency relative to the current uniform-rate N application systems. The in-season sensor-based variable-rate N management systems are viable tools that can be used by producers on their farms to manage variations within the field.

This project addresses USDA NRCS priority to accelerate conservation in the Mississippi River Basin (MRB) to continue to reduce nutrient and sediment loading to local and regional water bodies and to improve efficiency in using water supplies, particularly in the southern states. The goal of this project was to encourage producer adoption of new precision N management technologies and systems on their farms to reduce N fertilizer consumption and potential N losses, improve cotton productivity, and thus improve water quality and grower profitability in the MRB states of Louisiana, Missouri, Mississippi, and Tennessee. Precision agriculture (PA) may benefit cotton farms in the MRB by reducing the amount of excess N from cotton production released into the environment, increasing net returns to the grower, and reducing the risk of profit losses due to spatial and temporal variability. The objectives of the demonstration project economic analysis were to determine the profitability, risk management potential, and N production use efficiency of using real-time optical sensing and variable-rate technologies (VRT) to manage spatial variability in cotton production. Data collected from 29 field demonstration trials in Tennessee, Louisiana, Mississippi, and Missouri from 2011 to 2014 included lint yields harvested and N rates calculated from three N rate management strategies. The first N treatment was the existing farmer practice, the second was a VRT treatment using optical sensing technology information, and the third was a VRT treatment using optical sensing and yield monitor information. The two PA strategies were compared to the existing farmer practice. In addition, soil properties, landscape, and weather were examined to determine their effects on lint yields, net returns, N rates, and N production use efficiency. Three statistical models were used in the project to evaluate the lint yields, N rates, net returns, and N production use efficiency from the strip-plots on the 29 fields. The first model was an analysis of variance (ANOVA) model used to identify treatment mean differences while controlling for soil, landscape, and weather factors. The second model was an ANOVA model that measured soil and climate effects on mean differences between the optical sensing and VRT technologies and the farmer practice. The third model was a logistic model to determine the risk (probability) of lint yield and net return losses using optical sensing and VRT relative to the current farmer practice. The statistical and economic analysis with the models was used to identify conditions where optical sensing and VRT was profitable, provided potential risk management benefits, and improved N production use efficiency.

The two key findings of the statistical and economic analysis were as follows. First, the real-time optical sensing and VRT treatments indicated some N fertilizer savings but were not more profitable on average than the existing farmer N management practices. There was some evidence of significantly higher mean net returns using VRT to manage N compared to the current practice at the sub-plot level, but the field level showed no difference. Second, there were risk management benefits identified at the field level using VRT compared to the farmer practice. Fields with lower lint yields tended to produce higher net returns with optical sensing and VRT than with the farmer practice which may help farmers manage risk on fields with this characteristic. Three additional inferred conclusions may aid in cotton farmers' decisions about the precision N management technologies evaluated in this project. First, the optical sensing and VRT treatments may not apply enough N to significantly increase lint yields relative to the existing farmer practice. Second, changes in the N rate for optical sensing and VRT relative to the farmer practice were field/farm specific. Four locations (Tensas Middle, LA, Gibson, TN, Lauderdale, TN, and Leflore, MS) realized significantly lower N rates applied in at least one form of VRT N fertilizer application. Four locations had higher N rates with optical sensing and VRT (Madison North, TN, Adams, MS, Tensas North, LA, and Tensas South, LA). Finally, the N rates across the 29 field demonstrations were not low enough to increase N use efficiency and encourage environmental benefits. Even though the fields in the demonstration project represented a range of soils, landscapes, and weather in the southern MRB locations used in the project, there was likely not enough spatial and temporal variability within the fields that optical sensing VRT treatments did not make a difference in field level mean net returns.

Overall, cotton and other crop producers, private consultants, university Extension agents, government personnel, and industry agronomists in the four participating states and other adjacent states within the Mississippi River Basin are the customers that benefit from this grant. The sensor-based variable-rate N management systems via side-dress during the early growing season are reliable to be used to implement precision N management on cotton with environmental or/and economic benefits.

This project requested for one-year (Jan. 1, 2015 -- Dec. 31, 2015) extension with no cost due to the following reason. Dr. James Larson, a professor in the Agricultural and Resource Economics Department at University of Tennessee was doing the economic and risk analyses for this project as what was proposed in the original proposal. Since the year of 2014 data were not available to him until November or December of 2014 or even later (cotton is usually harvested in Sept. and Oct. in the Mid-South. Each state needed to compile all the data together before they could be sent to James), then there would not be enough time for him to run the models to analyze the data and write the summary report relating to the economic and risk analyses accordingly by the ending date of this project (Dec. 31, 2014). Therefore, we had to ask for a no-cost one-year extension for this project to allow him to have enough time to do the economic and risk analyses on the 3-year data (2012-2014). This request was approved by the CIG Program Manager immediately after the receipt of the request.

Precision Nitrogen Injection Using Integrated Optical Sensing and Variable Rate Technologies

USDA NRCS Conservation Innovation Grant No. 69-3A75-11-177

September 2011 – December 2015

Final Report

Louisiana

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EXECUTIVE SUMMARY

A total of nine demonstration plots were completed from 2012 to 2014 in Tensas Parish, Louisiana to evaluate the performance of farmer standard N management practice and variable-rate applicator/optical sensor systems (VRT/sensor systems) in cotton production using yield and net return from N fertilization as performance metrics. Six out of nine site-years benefitted from using VRT/sensor systems with an average of $34.14/ac higher net return than the farmer's standard N practice; the savings incurred from using lesser amount of N fertilizer offset the minimal $ losses for having lower lint yield resulting still in higher net profit. In some cases, both increased in lint yield and savings from fertilizer cost contributed to higher profit. While the VRT/sensor systems N recommendation incurred lower net profit than the farmer's standard N practice at three site-years, the reduction was relatively low averaging only $8.93/ac. Refining the VRT/sensor systems N recommendation based on soil productivity zoned worked better than farmer's standard N practice in four out of nine site-years with an average higher net return of $30.87/ac. The results of this project demonstrated the potential of VRT/sensor systems as an effective N decision tool in cotton production in Louisiana. This project has allowed the investigators to understand some of the aspects of the technology that need to be addressed: the 2nd N application requirement is a challenge to accomplish by producers because of the lack of time; and that the narrow window to accomplish 2nd N application can also limit the timely application of midseason N to cotton. For future project, it is ideal to have the participating producers operate and implement the VRT/sensor systems themselves and some economic factors should be considered for evaluation of economic return using this technology.

INTRODUCTION

This project was led by Frank Yin of the University of Tennessee where Louisiana State University Agricultural Center (LSU AgCenter) in Baton Rouge, LA is one of the collaborating institutions. The LSU AgCenter team was led by Dr. Brenda S. Tubana in cooperation with Dr. John Kruse, two extension agents (Dennis Burns and Ralph Frazier), and three EQIP-eligible cotton-corn producers whose fields are located in Tensas Parish (Jay Hardwick, Allan Crigler, and Ben Guthrie). Brenda Tubana is an Associate Professor of Soil Fertility. She has over ten years of experience in soil fertility and precision agriculture and was in-charge of the experimental design, trial establishment, data collection, conducting demonstration activities, writing summary reports and extension publications, and delivering extension talks. Dr. John Kruse (now with Koch Company) was a Cotton and Small Grain Agronomist at the LSU AgCenter Dean Lee Research Station. He worked closely with Dr. Tubana in executing all the activities to achieve the goal and objectives of this project. Dennis Burns and Ralph Frazier worked closely with the participating producers in establishing the demonstration plots and training them on the logistics of mid-season N application via the VRT/sensor systems. They were also responsible in generating field maps and recording field data (sensor readings and yield data).

The project overall goal was to show producers and other interested groups the method and benefits for the utilization of innovative technologies – optical sensing and variable-rate applications to manage spatial variability within individual fields of cotton. Specific objectives included:

1) To demonstrate to producers and other interested groups the procedures and entire process of how to use the GreenSeeker® optical sensing data collection and mapping

systems to generate canopy NVDI maps and variable-rate N algorithms which can be used to guide variable-rate N applications within field;

2) To show how to integrate the two new but commercially available technologies – optical sensors and a variable-rate applicator into a variable tool for the on-going real-time diagnosis of cotton N status and variable-rate applications of N simultaneously during the season.
3) To demonstrate impacts of the variable-rate precision N management system based on optical sensing of crop canopy compared with the current uniform-rate N application system in terms of N fertilizer use, lint yield, net return from N fertilizer, and inorganic N distribution in the soil profile; and
4) To show the benefits of incorporating soil productivity maps (soil type and electrical conductivity) into the optical sensor-based variable-rate precision N management system based on NDVI indices

The scope of project tasks encumbered work both in research (field and laboratory) and extension. Works involved in the field included establishment of demonstration plots, treatment application (involved operation of variable-rate applicator/sensor systems), collection of field data (sensor readings, plant tissue samples, deep core soil samples) whereas in the laboratory, the analysis for plant total N content, and soil inorganic N content were among the tasks. Data analysis and interpretation were requirements for communicating the results in field day demonstration, visitation with the participating farmers, and presentations at conference and workshop meetings.

There were two LSU AgCenter investigators (B. Tubana and J. Kruse) who provided leverage (direct support). There was no other funding support for this project other than the Conservation Innovation Grants through NRCS.

BACKGROUND

As the largest source of natural fiber, increasing cotton (*Gossypium hirsutum* L.) productivity and competitiveness in the global textile market remains a big challenge to the U.S. cotton industry. The recent decline in acreage due to competition from grain crops and the increase in public concerns on environment degradation necessitate the cotton industry to be more productive under sustainable, environment-friendly production systems. Nitrogen (N) fertilizer is one of the major agricultural inputs and considered as the most expensive plant nutrient in cotton production. Apart from large expenses for N fertilizers, the perennial growth habit of cotton requires an effective and refined fertilizer-N management system (Gerik et al., 1998). Deficiency results in poor vegetative and reproductive growth, premature senescence, and reduced yields (McConnell et al., 1993) while excessive amounts of N can inhibit fruit formation and retention (Boquet and Breitenbeck, 2000), and pose serious threats to the environment (Prasad and Power 1995). When N is unnecessarily applied, productivity is also reduced due to higher expenses for N fertilizers, and additional maintenance costs for controlling pests (Cisneros and Godfrey, 2001) and for applications of growth regulators. Majority of the soils in Louisiana under cotton production are diverse and it is therefore imperative that a robust management scheme for N fertilizer is implemented to reflect these spatial differences in soil productivity. In 2008, collection of sensor data was initiated to build the database for developing sensor N-based decision tool for cotton. The objective of this project was to evaluate the performance of an on-site decision tool for N consisting of variable-rate application and optical sensor systems, and N reference strip. A reference strip is a plot in a field applied with high amount of N for gauging the probability of in-season response of cotton to N fertilization. Performance measures will include yield level, N fertilizer use efficiency and net return from N fertilizer.

The use of VRT/sensor systems and N reference strip as a decision tool for N fertilizer recommendation is the first precision agriculture-based approach in the region (Louisiana). Currently, N recommendation is based on optimum rate established from many years of calibration trials. So far, there has been no attempt made on altering this N recommendation approach until this project was initiated. The project documented the performance of this technology in cotton production thus will provide an overview and guidance to farmers and consultants to this rather new N decision tool. For researchers, the outcomes of this project highlighted the areas that can be or need to be improved to facilitate full-scale adoption of this N decision tool.

REVIEW OF METHODS

This project was conducted to evaluate the performance of an on-site N decision tool in cotton in the form VRT/sensor systems in comparison with the farmer's standard N practice. The farmer's standard N practice is generally described as a one-time application of N fertilizer at early growth stage of cotton using optimum rate (120-150 lbs N/ac, depending on soil type, i.e. heavy vs. light-textured soils) established for Louisiana cotton production area. The technology introduced the implementation of split application of N fertilizer wherein the first application is done at planting or few days after planting while the second application is done at early bloom using the VRT/sensor systems. Another treatment included VRT/sensor systems recommendation that was further refined based on soil productivity zone. For this project, soil type or electrical conductivity map was used to adjust the rate such that: low soil productivity zone - the recommended rate was scaled down by 30 lbs N/ac; medium soil productivity zone – no adjustment; and high soil productivity zone – recommended rate was scaled up by 30 lbs N/ac.

With the use of VRT/sensor systems, N fertilizer was applied on-a-need-basis where it was needed in the field. The ability of this technology compared with farmer's standard N practice enable farmers to use N in a more accurate manner. While generally, the overall rate applied was lower than what the farmer's standard N practice, the proper distribution of right rate of N maximize cotton N use efficiency subsequently reducing the amount of N in the soil that is subject to different lost pathways to bodies of water. This technology require on additional trip to the field (second application at mid-bloom) which incurs additional expenses to pay fuel and labor. It is expected that this additional cost can be offset by the savings made from applying lesser amount of N fertilizer and/or increase in gross profit due to higher lint yield.

Producers needed to set aside about 10 acres of their field each year to accommodate the project. As participants, producers were asked that all cultural management practices were implemented similarly within this 10 acres field (except N management). They were also the ones who applied or treated the plots under the farmer's standard N practice.

The implementation of technology involved running the VRT/sensor systems on N reference strip (or N ramp) to determine in-season response of cotton to N fertilization. After this procedure, the VRT/sensor system went off to treating corresponding plots four rows at a time. Implementing this technology during the project period showed no major problems to hinder its operation in the field. However, there were situations that could potentially reduce the probability by which the recommended N distributed by the VRT/sensor systems maximizes yield and return. Rain prevented a number of the 2nd application of N at early flowering on a timely manner. Essentially, this growth period lasts for only one week and this is quite a narrow period of time to accomplish this task when rain interferes even for two days only within a week. Rain immediately after the 2nd application also reduced the benefits of implementing this technology. It is important to take note that such interference (rain) can happen anytime, anywhere regardless of N management systems. Just like any new technology, producers, consultants or end-users of the technology are recommended to undergo training on the use of equipment and associated software. The proficiency on the technology is required such that in future projects, participating producers should try operating the VRT/sensor systems themselves repeatedly or for the entire duration of the projects. This means that the involvement of participating producers is expected to be substantial which will serve as an additional metric to gauge how this technology will fare in the real world. This will be perhaps what the team should have done differently if given the opportunity to start the project today. This will also increase the familiarity of the participating producers to minimize or completely eliminate errors during the implementation of the treatments. One site was dropped out due to fertilizer errors. One important challenge posted by the VRT/sensor system to producers is the 2nd application requirement; they expressed the difficulty in terms of time to do a second application of N fertilizer despite of the clear benefits of using this technology in terms of increasing yield and profits. Thus, this is another aspect of the VRT/sensor system that needs to be addressed.

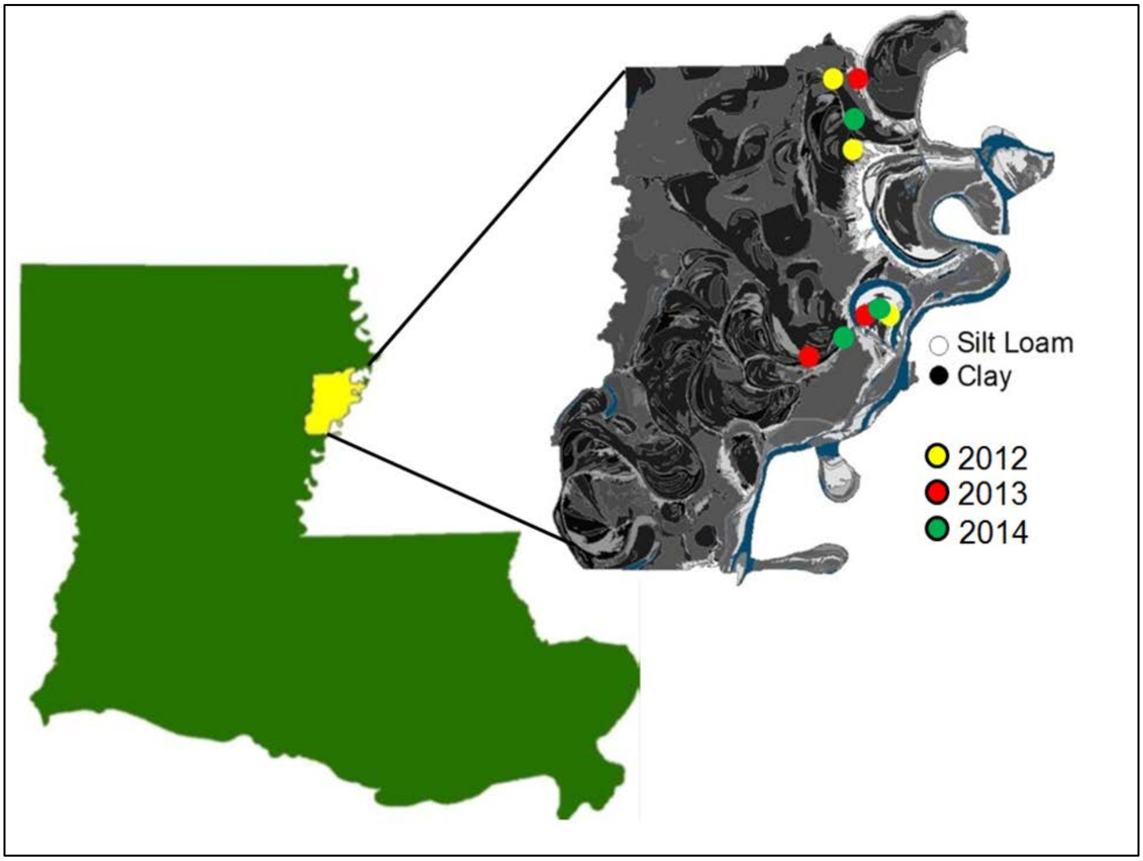

Figure 1. Tensas Parish in Louisiana (yellow shaded region) and locations of the demonstration plots within the parish from 2012 to 2014.

Table 1. Schedule of activities from 2012 to 2015, Tensas Parish, Louisiana.

Year	Month	Activities
2012	Jan – March	Meetings with collaborators and participating farmers to plan the establishment of the demonstration plots Locating the sites and collection of composite soil samples for characterization Installation of the variable-rate applicator and optical sensor system on high-clearance tractor (spider)
	April	Pre-planting deep core sampling Planting N application (1st dose for VRT/sensor systems; farmer's standard practice)
	May – June	N application (2nd dose for VRT/sensor systems at early bloom) Sensor reading collection Plant tissue sampling (early square, early bloom)
	June – July	Sensor reading collection and plant tissue sampling (mid-bloom)
	Aug – Sep	Processing and analysis of soil and plant tissue samples collected
	Sep – Oct	Harvesting Post-harvest deep core sampling
2013	January	Presentation at the National Conservation Systems Cotton & Rice Conference
	April	Pre-planting deep core sampling Planting N application (1st dose for VRT/sensor systems; farmer's standard practice)
	May – June	N application (2nd dose for VRT/sensor systems at early bloom) Sensor reading collection Plant tissue sampling (early square, early bloom)
	June – July	Sensor reading collection and plant tissue sampling (mid-bloom)
	Aug – Sep	Processing and analysis of soil and plant tissue samples collected
	Sep – Oct	Harvesting Post-harvest deep core sampling
	Nov	Presentation at the ASA-CSSA-SSSA Annual International Meetings
2014	April	Pre-planting deep core sampling Planting N application (1st dose for VRT/ sensor systems; farmer's standard practice)
	May – June	N application (2nd dose for VRT/ sensor systems at early bloom) Sensor reading collection Plant tissue sampling (early square, early bloom)
	June – July	Sensor reading collection and plant tissue sampling (mid-bloom)
	Aug – Sep	Processing and analysis of soil and plant tissue samples collected
	Sep – Oct	Harvesting Post-harvest deep core sampling
	Nov	Presentation at the ASA-CSSA-SSSA Annual International Meetings
2015	Jan – Sep	Finish analysis of the soil and plant tissue samples

Reports were made on a semi-annual basis; extension requested were made to finish analysis of all the soil (total: 4,050) and plant tissue (total: 2,430) samples collected.

DISCUSSION OF QUALITY ASSURANCE

All demonstration plots were located in Tensas Parish of Louisiana (Figure 1). All the soils types at the sites are generally classified as alluvial soils with texture as either silt loam or clay. These locations were selected since these are the areas in Louisiana that are cultivated for cotton production. The soil types in these fields are diverse thus in each of these fields, the possibility of having multiple soil productivity management zones was high. The plot size was large almost equivalent to an acre, thus for three replications combined together, the total area of one treatment could represent at least a small field management zone.

Each plot consisted of 12 40-inch x 1000-ft long rows divided into 10 subplots (100-ft long). At early square, early flowering, and mid-bloom stage, 20 to 30 leaf tissue samples from each subplot were collected, oven-dried, processed (to pass a 1 mm sieve), and analyzed for total N (%) content using dry combustion method with an Elementar CN analyzer. Deep core samples were taken up to 3-ft deep before planting and post-harvest using a hydraulic probe attached to a pick-up truck. Core samples were divided into 6-inch sections, placed in a Ziploc plastic bags then stored in cooler containing ice. A total of five cores (evenly spaced) were taken from each plot. It is important to keep the temperature low while the samples were being transported to the laboratory. After arriving to the destination, soil samples were immediately dried using a forced-air convection oven at 50 to 65°C for at least four days, ground to pass a 2-mm sieve then analyzed for ammonium and nitrate content (mg/kg) using a Lachat QuickChem® 8500 series flow injection analysis (FAI) system. Soil samples were extracted with 1 M KCl solution and filtered using a Whatman filter paper no. 42. Sample extracts were analyzed using FAI following the Salicylate method for ammonium and cadmium reduction column method for nitrate. For these analyses, reference samples, blanks, and water samples (spiked with known concentration – for soil samples only) were included along with repeats of randomly selected samples as quality control procedures. Table 2 shows the different field data collected and the corresponding data processing conducted.

Table 2. Data collected from the demonstration plots and processing approach.

Data	Processing/Presentation	Unit
Lint yield	Lint yield data for each subplot was determined. Lint yield was averaged per plot and per treatment	lbs/ac
Total N applied	For the VRT/sensor systems treated plot, the amount of N applied at the 2nd application at early flowering stage for each subplot was recorded; data was also presented per plot and average per treatment	lbs/ac
NDVI readings	For all the plots, normalized difference vegetation (NDVI) readings for each subplot was recorded	unitless
Soil ammonium	Data was computer as concentration (mg/kg) and content (lbs/ac) for each depth (0-6, 6-12, 12-18, 18-24, and > 24 inches) of each core.	mg/kg lbs/ac
Soil nitrate	Data was computer as concentration (mg/kg) and content (lbs/ac) for each depth (0-6, 6-12, 12-18, 18-24, and > 24 inches) of each core.	mg/kg lbs/ac
Inorganic N	Expressed as total content or sum of soil ammonium and nitrate content for each depth.	lbs/ac
Leaf tissue N	For all plots and each subplot, total N content was determined using dry combustion method	%

Collection, analysis, and storage of both soil and plant samples were done under the supervision of Drs. Brenda Tubana and John Kruse while the collection of sensor reading, creation maps, and maintenance of the VRT/sensor systems were accomplished by Dennis Burns and Ralph Frazier (extension agents).

FINDINGS

The analysis of return based on lint yield and N fertilizer used from 2012 to 2014 demonstration plots is shown on Tables 3, 4, and 5. There was a fertilizer application error incurred in field administered by one of the participating producers (Hardwick 2014) thus this was removed from the list and replaced by the demonstration plots established near the LSU AgCenter Research Station in 2012.

In most cases, VRT/sensor systems recommended lower average N fertilizer rate than the farmer's standard N practice. Because the N rates were selectively applied by the VRT/sensor systems to the right place in the field, the reduction in overall N applied did not result in notable decline in lint yield. The losses in profit due to lower lint yield were offset by the savings incurred from applying lesser amount of N fertilizer, for example at Crigler (2012 and 2014) and Guthrie in 2012. On the other hand, there were cases that VRT/sensor systems recommended higher N rate such as Hardwick in 2012 and 2014 which resulted in higher lint yield which then offset the extra cost of N invested by the producers resulting in still a positive net profit. A larger return was noted in Guthrie 2014 where both increase in yield and savings from fertilizer were combined to improve the net profit by as much as $69/ac. All in all, six out of nine site-years benefited from using VRT/Sensor systems with an average of $34.14/ac higher net return than farmer's standard N practice. The three site-years incurred $8.93/ac lower net profit than the farmer's standard N practice. Our results showed also that further refinement of VRT/Sensor systems with the use of soil productivity zone, resulted in positive outcome on yield and profit in some fields and year (e.g. Crigler in 2013, and all fields in 2014). Average profit was $30.87/ac higher than the farmer's standard N practice.

Table 3. Results of 2012 demonstration plots conducted at Tensas Parish of Louisiana.

Treatment	N Rate	Lint Yield	Difference from FS		Difference from FS		Net
			N Rate	Lint Yield	N Rate	Lint Yield	
	lbs/ac	lbs/ac	lbs/ac	lbs/ac	$/ac	$/ac	$/ac
Crigler							
FS	98	1078	-----	-----	-----	-----	-----
VRT/Sensor	72	1072	-26	-6	+17.42	-4.20	+13.22
VRT/Sensor†	93	1059	-5	-19	+3.35	-13.30	-9.95
Guthrie							
FS	130	1576	-----	-----	-----	-----	-----
VRT/Sensor	88	1552	-42	-24	+28.14	-16.80	+11.34
VRT/Sensor†	118	1543	-12	-33	+8.04	-23.1	-15.06
Hardwick							
FS	42	1284	-----	-----	-----	-----	-----
VRT/Sensor	142	1360	-82	+76	-54.94	+53.20	-1.74
VRT/Sensor†	150	1326	-108	+42	-72.36	+29.40	-42.96

Table 4. Results of 2013 demonstration plots conducted at Tensas Parish of Louisiana.

Treatment	N Rate	Lint Yield	Difference from FS		Difference from FS		Net
			N Rate	Lint Yield	N Rate	Lint Yield	
	lbs/ac	lbs/ac	lbs/ac	lbs/ac	$/ac	$/ac	$/ac
Crigler							
FS	100	1772	-----	-----	-----	-----	-----
VRT/Sensor	88	1802	-12	+30	+8.04	+21.00	+29.04
VRT/Sensor†	105	1841	+5	+69	-3.35	+48.30	+44.95
Guthrie							
FS	130	1653	-----	-----	-----	-----	-----
VRT/Sensor	125	1636	-5	-17	+3.35	-11.90	-8.55
Hardwick							
FS	75	1117	-----	-----	-----	-----	-----
VRT/Sensor	147	1242	+72	+125	-48.24	+87.50	+39.26

Table 5. Results of 2014 demonstration plots conducted at Tensas Parish of Louisiana.

Treatment	N Rate	Lint Yield	Difference from FS		Difference from FS		Net
			N Rate	Lint Yield	N Rate	Lint Yield	
	lbs/ac	lbs/ac	lbs/ac	lbs/ac	$/ac	$/ac	$/ac
Crigler							
FS	100	1519	-----	-----	-----	-----	-----
VRT/Sensor	116	1595	+16	+76	-10.72	+53.20	+42.48
VRT/Sensor†	120	1572	+20	+53	-13.40	+37.10	+23.70
Guthrie							
FS	130	1335	-----	-----	-----	-----	-----
VRT/Sensor	89	1395	-41	+60	+27.47	+42.00	+69.47
VRT/Sensor†	85	1353	-45	+18	+30.15	+12.60	+42.75
Hardwick‡							
FS	70	948	-----	-----	-----	-----	-----
VRT/Sensor	104	957	-34	+9	-22.78	+6.30	-16.48
VRT/Sensor†	99	993	-29	+45	-19.43	+31.50	+12.07

Footnotes apply for Tables 2, 3, and 4:
FS – farmer's standard N practice; based on LSU AgCenter recommendation.
VRT/Sensor – variable rate applicator and optical sensor system + N algorithm
† - VRT/Sensor recommendation on-the-go but further adjust (+ or – 30 lbs/ac or no change) based on soil productivity management zone; In Hardwick and Guthrie, this was not implemented since there were no factors to use to divide the field based on productivity zone since these fields have the same soil type.
‡ - replaced by another site near the Northeast Research Station which was conducted in 2012

CONCLUSIONS AND RECOMMENDATIONS

The results obtained from this project thus far demonstrated that VRT/Sensor systems as another effective approach in managing N in cotton production in the region. For future projects, it will be ideal to have the participating producers to implement the VRT/Sensor systems themselves. For this team, the three producers involved in this project alone can significantly contribute in extending this technology to other producers. This is under the stipulation that they (producers) are convinced about the use of this technology. In addition to this, bringing this technology to the field can be enhanced with continued extension and education outreach program through field day demonstrations, workshops, and even personal visit by the researchers and extension agents with the producers.

APPENDICES

<u>Publications Lists:</u>

Tubaña, B.S., D. Harrell, H. Mascagni, Jr., D. Boquet, and S. Viator. 2013. On-site optical sensor-based nitrogen recommendation makes sense. Louisiana Agriculture 56 (2):16-19.

Tubaña, B. 2013. Variable nitrogen rate technology in cotton production using an integrated optical sensing system. In Proceedings: National Conservation Systems Cotton and Rice Conference, Baton Rouge, LA, January 31 – February 1, 2013.

Tubana, B., M. Martins, P. Dupree, B. White, M. Dalen, S. Chanda, T. Babu, D. Munoz, F. Agostinho, R. Frazier, and D. Burns. 2014. Analysis of within-field variability in cotton on large-scale field tests in north Louisiana. ASA-CSSA-SSSA International Annual Meetings. November 2-5, 2014, Long Beach, CA.

Burns, D., B. Tubana, and R. Frazier. 2014. Mid-season applications of nitrogen in cotton using crop sensors. Beltwide Cotton Conference, January 6-8, 2014-, New Orleans, LA.

Tubana, B., D. Burns, R. Frazier, P. Dupree, W. Maddox, Y. Kanke, S. Chanda, M. Dalen, T. Babu, B. White, and J. Kruse. 2013. On-farm implementation of optical sensing system to increase nitrogen use efficiency in cotton production in Louisiana. ASA-CSSA-SSSA International Annual Meetings. November 3-6, 2013, Tampa, FL.

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Boquet, D.J. and G.A. Breitenbeck. 2000. Nitrogen Rate Effect on Partitioning of Nitrogen and Dry Matter in Cotton. Agronomy Journal. 40:1685-1693.

Cisneros, J.J. and L.D. Godfrey. 2001. Midseason pest status of cotton aphid (Homoptera: Aphididae) in California cotton: Is nitrogen a key factor? Environmental Entomology 30:501-510.

Gerik, T.J., R.G. Lemon, K.L. Faver, T.A. Hoelewyn and M. Jungman. 1998. Performance of ultra-narrow row cotton in central Texas. p. 1406–1409. In P. Dugger and D. Richter (ed.) Proc. Beltwide Cotton Conf. San Diego, CA. 5–9 Jan. 1998. Natl. Cotton Council, Memphis, TN.

McConnell, J.S. W.H. Baker, D.M Miller, B.S. Frizzell, and J.J. Varvil. 1993. Nitrogen Fertilization of Cotton Cultivars of Differing Maturity. Agronomy Journal 85:1151-1156.

Prasad, R. and J.F. Power. 1995. Nitrification inhibitor for agriculture, health and environment. Adv. Agron. 54:233-281.

TECHNOLOGY REVIEW CRITERIA

Description of the Technology

The technology is a variable-rate applicator and optical sensor systems utilizing the N algorithm specifically established for the cotton production in Louisiana. The N rate recommended by this technology is on a plant need basis using optical sensor (GreenSeeker®) readings of the target plots, N reference strip (plots applied with high N rate), and N algorithm (serving as a communicator between sensor and computer interface with spray controller). The N algorithm (proprietary item) is convertible to program format which is compatible to most on-board computer systems interface with controller in a variable rate fertilizer applicator which takes place in millisecond to obtain the N rate recommendation from the time the sensor reading is taken thus sensing and application can happen on-the-go. The application can be done on a working resolution as high as 3 ft^2 (or 1 meter).

Precision Nitrogen Injection Using Integrated Optical Sensing and Variable Rate Technologies

USDA NRCS Conservation Innovation Grant No. 69-3A75-11-177

September 2011 – December 2014

Final Report

Missouri

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EXECUTIVE SUMMARY

From 2012 to 2014, variable-rate nitrogen applications to cotton were demonstrated in three fields of EQIP-eligible farmers per year. Demonstrations covered the entire field; total area for the nine fields was 525 acres. Six EQIP-eligible cotton growers participated (two each year).

Variable-rate nitrogen fertilizer applications were compared to a uniform application of nitrogen fertilizer at the rate normally used by the farmer. These approaches were alternated in strips across the entire field. For the variable-rate approach, fertilizer rate was controlled by an optical sensor that would sense the color of the cotton plants and adjust the fertilizer rate accordingly. Adjustments were made once per second. Conversion of optical sensor readings to nitrogen fertilizer rates was based on previous research at the University of Missouri. In four fields, a third approach was also used: sensor-based rate recommendations which were adjusted according to soil zones.

Over eight of the fields, use of sensors reduced nitrogen fertilizer rate by 6 pounds N per acre and increased cotton yield by 7 pounds lint per acre. Combined value of the fertilizer savings and yield increase were $9 per acre. Yield data was lost from one of the demonstration fields.

When combined with six similar demonstrations in 2009-2010 from a previously-funded project, use of sensors reduced nitrogen fertilizer rate by 6 pounds N per acre and increased cotton yield by 19 pounds lint per acre. Combined value of the fertilizer savings and yield increase were $19.50 per acre, averaged over 14 fields.

Using soil zones in combination with optical sensors had no effect on fertilizer rate or yield in the four fields in which this approach was tested.

Sensors cost about $20,000 for a set. Based on the results from the eight demonstration fields in this project, the sensors would pay for themselves by the time they were used on 2,200 acres. Results from all 14 demonstration fields conducted in Missouri are more favorable, indicating payback after just over 1,000 acres. Either way, the economics seem viable for many cotton growers.

We helped farmers to overcome the technical aspect of getting optical sensors installed and running. This remains a key barrier to adoption. Consultants or technical representatives from the sensor companies could fill this role.

INTRODUCTION

Half or more of the nitrogen (N) fertilizer application to cotton in southeast Missouri is normally made during crop growth. I believe that this is typical for cotton production across the southeastern U.S.

This practice means that adoption of real-time optical sensing to control N fertilizer rate for cotton in this region would be relatively straightforward.

Relative to current practice of putting the same N fertilizer rate across whole fields and often whole farms, optical sensor-based management offers the potential to tailor the fertilizer rate in each part of each field to meet its needs more precisely. Cutting back fertilizer rate in areas where current management is applying more than is needed reduces the potential for N to escape from cotton fields to rivers and to air.

Nitrogen escape from agriculture to rivers is a major contributing factor in low-oxygen zones in coastal waters where the rivers deliver the N. In poorly-drained soils, agricultural N is also prone to loss to the air. Some of this lost N is in the form of nitrous oxide, a very efficient heat-trapping gas.

Optimizing N fertilizer rate also can potentially increase crop yield. Cotton yield can be reduced by either too little or too much N. Too much N can also lead to rank growth, leading the farmer to spend more money on growth regulator and/or defoliant.

BACKGROUND

Cotton response to N fertilizer

Cotton yields are often very responsive to N fertilizer, thus it is almost universally used as a production input. Insufficient N leads to yield limitation and loss of income. Excess N causes lush vegetative growth, which is undesirable because it diverts the plant's resources away from boll production and because it makes harvest preparation and harvest more difficult.

Variability in soil N contribution

Previous research has established that soil contributions to the N needs of the plant often vary widely from place to place within a field. Techniques that can leverage this fact to put less fertilizer N where the soil is contributing more will save money and reduce the amount of N that is vulnerable to loss.

The amount of N that is available from the soil does not necessarily follow a consistent pattern from one year to the next. This is because weather interactions with soil properties have a large influence on how much N is released from soil organic matter, and on how much of that N is lost before crop uptake. Release of N from soil organic matter is highest when both water and air are plentiful in the soil, and is limited by both lack of air (too wet) and lack of water (too dry). Nitrogen is also prone to loss from areas that are too wet. Areas that are too wet one year, and thus need high rates of N, may have ideal moisture the next and thus need low rates of N.

Approaches to vary N fertilizer rate

The factors mentioned in the previous paragraph mean that the most successful approaches to vary N fertilizer rate will be able to respond to weather. Zone approaches that do not allow different management in different weather years are limited in this regard.

In-season soil and plant samples can be used to guide N fertilizer rate in a way that is specific to the year's weather. However, even getting one good sample per field during the season is difficult due to the labor required and the time constraints. Managing spatial variability of N need with these tools is much more labor-intensive and could only be accomplished in a small minority of fields with the personnel currently available.

Optical sensors allow N rate decisions that are responsive to the weather conditions up to the time of fertilizer application. They can assess how weather has interacted with landscape and soil properties to influence soil N availability, and manage N accordingly. Everything is automated, so the labor limitations on other methods of managing spatial variability in fields are avoided.

REVIEW OF METHODS

Demonstrations were conducted in fields of EQIP-eligible cotton growers from 2012 to 2014. Each year, three fields using optical sensors for variable-rate nitrogen applications to cotton were carried out. Demonstrations covered the entire field; total area for the nine fields was 525 acres. All fields were on alluvial soils in the Mississippi River Delta.

All management practices except in-season N fertilizer applications were carried out using the farmer's equipment and normal practices. This includes pre-plant nitrogen fertilizer source and rate. All fields were furrow-irrigated.

A small high-N reference area was created in each demonstration field shortly after planting by hand-spreading ammonium nitrate at a rate of 150 pounds N per acre.

Only one of the cooperating farmers had a cotton picker with a yield monitor. On all of the other fields, each 'plot' on which a nitrogen management system was carried out was sized so that approximately one module of cotton would be produced on that plot (about 5 to 6 acres). Plots with different nitrogen management systems were alternated across the whole field. Module weights from the gin, along with turnout measurements, were then used to calculate cotton lint

yield from each plot. This allowed us to compare the yield outcomes of optical sensor-based nitrogen management to the farmer's normal nitrogen management.

In-season nitrogen fertilizer applications were carried out at the mid-square stage (about halfway between early square and early bloom) using fertilizer applicators owned either by the cooperating farmer or his service provider. A system for dribbling liquid nitrogen is shown below. Three Holland Scientific ACS-210 optical sensors (the small white objects in the photo below) were temporarily installed on a bar on the front of the applicator, and a tablet computer with custom software was mounted in the cab. Sensors were positioned directly over a cotton row and 20 inches above the canopy.

Before starting the in-season N fertilizer application, sensor measurements were taken from the high-nitrogen reference area and from bare soil in the demonstration field. The measurement from the high-nitrogen reference area served as a 'yardstick' for the appearance of cotton that was not N-limited. Cotton being fertilized was compared to this 'yardstick' to determine its level of N-sufficiency. The bare soil measurement allowed the computer to identify and discard sensor measurements from areas with skips in the cotton stand.

Nitrogen fertilizer rate was calculated once per second based on the measurements from the optical sensors, which were converted to nitrogen fertilizer rate using the equation published in the Soil Science Society of America Journal, volume 77, pages173-183. Calculated nitrogen fertilizer rates were sent to the applicator's controller, which activated the mechanism to make fertilizer rates go up and down as called for by the sensors.

Nitrogen management systems tested were:

1. Farmer's normal rate
2. Rate determined once per second by optical sensors
3. Rate determined once per second by optical sensors and modified by soil zone

Soil zones were chosen to be soil map units. Depending on the field, the soil zone adjustment was either:

1. Lower rate in soils with higher organic matter levels, or
2. Higher rate in soils with substantial amounts of clay

FINDINGS

Yield and N rate outcomes for sensor-based N management are shown in the table below. Our objectives in this project were both to demonstrate the use of the sensors to cotton growers, and to compare the performance of sensor-based N management with the farmer's current N management program.

Six similar demonstrations conducted on a previous project are also included in this table (fields 1-6).

Year	Field	N rate (pounds/acre) with:			Yield (pounds lint/acre) with:		
		Sensor rate	Farmer rate	Sensor + zone rate	Sensor rate	Farmer rate	Sensor + zone rate
2009	1	88	105		1334	1265	

2009	2	94	88		1310	1091	
2009	3	72	88		1140	1206	
2010	4	63	46		1167	1196	
2010	5	77	90		1439	1370	
2010	6	74	90		1320	1364	
2012	7	65	70	67	1174	1191	1166
2012	8	67	70	66	1122	1105	1116
2012	9	76	70	78	942	897	952
2013	10	63	100		1092	1047	
2013	11	85	100		952	969	
2013	12	85	101	80	771	844	762
2014	13	105	85		1063	1044	
2014	14	90	85		1011.2	974	
average all fields		79	85		1131	1112	
average 8 project fields		80	85		1016	1009	
average 4 fields with soil zones		73	78	73	1002	1009	999

Yield levels were generally good in the demonstration fields, with an average of over 1000 pounds of lint per acre.

Yield data were lost from one of the 2014 demonstration fields. Over the other 8 project fields, sensor-based N management resulted in small improvements in both N rate and yield: N rate was reduced by 6 pounds N per acre (appears to be 5 in the table due to rounding) and cotton lint yield was increased by 7 pounds per acre. These are modest improvements that are not going to motivate rapid and widespread adoption, but they are nonetheless a step in the right direction. They are also economically feasible. Using a N price of $0.65 per pound of N and a cotton price of $0.80 per pound of lint, the lower N rate and higher yield with sensor-based management produced an average value of slightly over $9 per acre. Given that the sensors cost roughly $20,000 for a set, they would be paid for after 2,200 acres with results similar to the 8 project fields. Most cotton farmers would reach this level of use after 1 to 5 years; sensor life is expected to be considerably greater than that, so they would begin accruing profit after that point.

When the 6 prior demonstration fields are included in the overall average, the estimated yield impact of sensor-based N management goes up to 19 pounds of lint per acre, and effect on N rate does not change. This larger yield response increases the estimated economic benefit of sensor-based N management to $19.50 per acre. Because more fields are included in this estimate, it is more robust and dependable than the estimate based on only the fields funded by this project. Sensors would be paid for after about 1000 acres of management with results like these, and acres above that would accrue profit.

Combining soil zones with sensors resulted in the same N rate as sensors alone, and 3 pounds lower lint yield. Use of soil zones did not improve sensor performance.

CONCLUSIONS AND RECOMMENDATIONS

Variable-rate N applications for cotton based on optical sensor readings were successfully carried out in 9 farm fields, demonstrating that this technology can reliably be deployed at the farm scale.

Compared to current N rates used by farmers, optical sensors gave small improvements in both N rate (lower) and cotton lint yield (higher). We estimate that, at current prices, it will take between 1,000 and 2,200 acres of use to reach the point at which the cost of the sensors has been covered, and after that profit will begin accruing.

Overall lower N use with optical sensors, and particularly lower N use targeted to areas of the field where soil N availability is high, will reduce the amount of N lost from cotton fields to water and air and reduce the proportion of the cotton crop that is too lush. Farmers may be able to save money on growth regulator and/or defoliant, and may sometimes have easier harvest conditions.

Technical, economic, and environmental outcomes are all modestly positive for the use of optical sensors to control variable-rate N applications on cotton. Based on our results, we endorse this approach for use by cotton growers in Missouri.

APPENDIX: Maps of nitrogen fertilizer rates in demonstration fields

The maps of N rate applied in demonstration fields give a sense of the scale of these demonstrations and the variability encountered in these fields. Adjacent rows of all one color are the places where the farmer’s chosen N fertilizer rate was applied uniformly. Rows with multiple colors have N fertilizer rate based on optical sensor measurements alone, or sensor measurements combined with soil zones.

Figure 1. Demonstration field 10 (in table) from 2013. The farmer's uniform N rate was applied about a week earlier and is not shown.

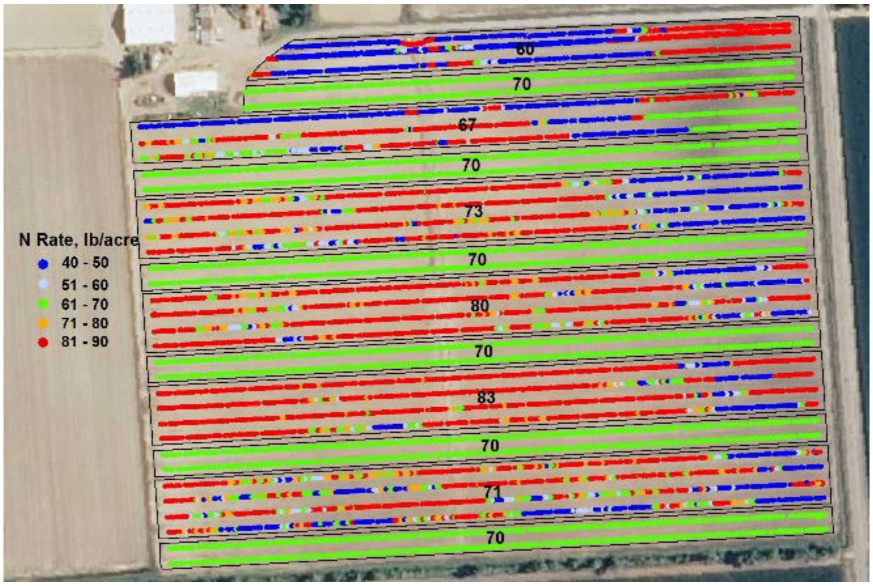

Figure 2. Demonstration field 9 (in table) from 2012.

Figure 3. Demonstration field 8 (in table) from 2012

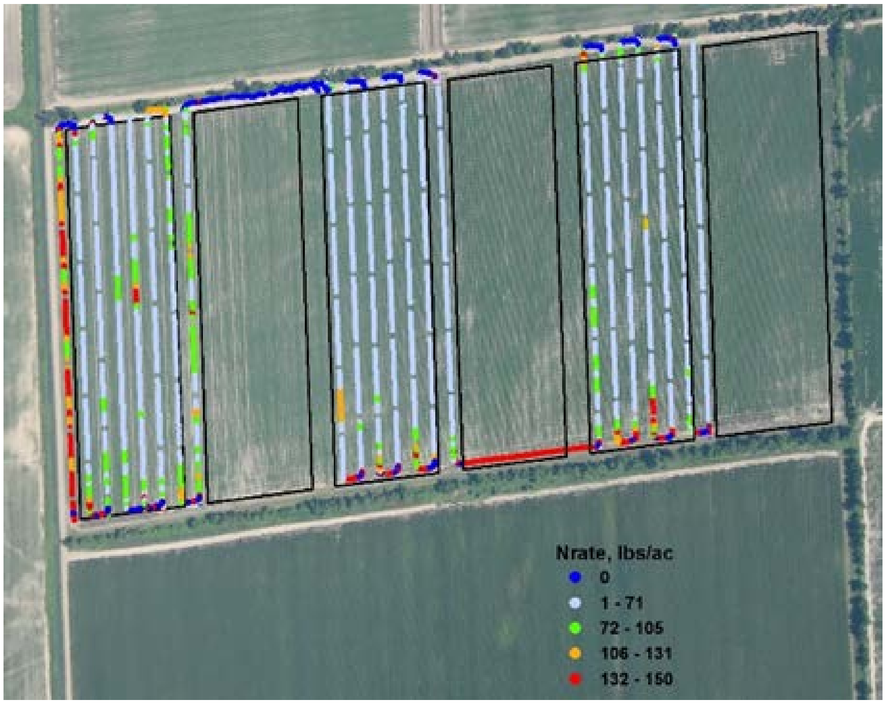

Figure 4. Demonstration field 7 (in table) from 2012.

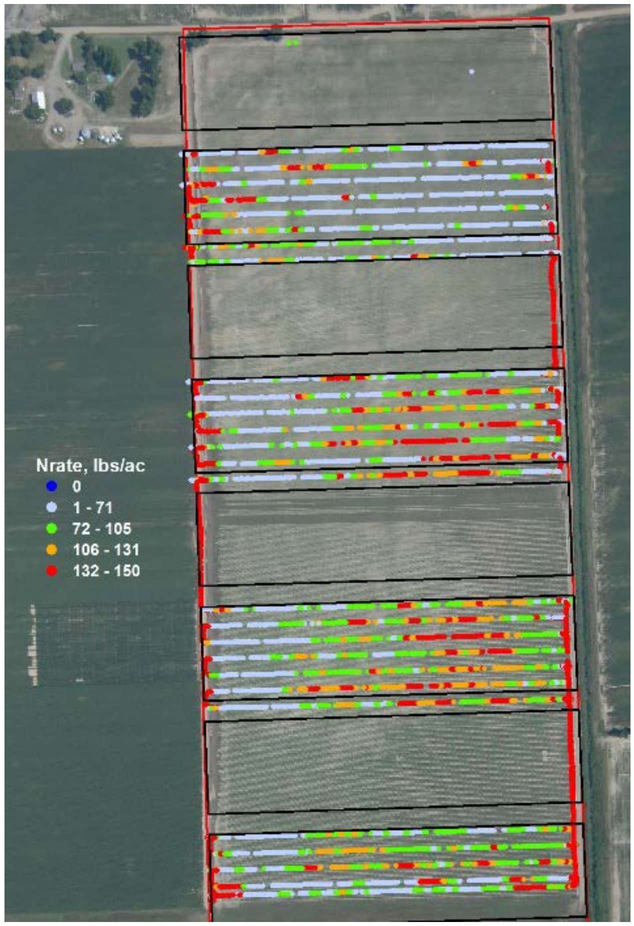

Figure 5. Demonstration field 11 (in table) from 2013. The farmer's uniform N rate was applied a week earlier and is not shown. Dark lines across the middle are a water leak from the irrigation pump; this area was excluded from the yield analysis.

Figure 6. Demonstration field 12 (in table) from 2013.

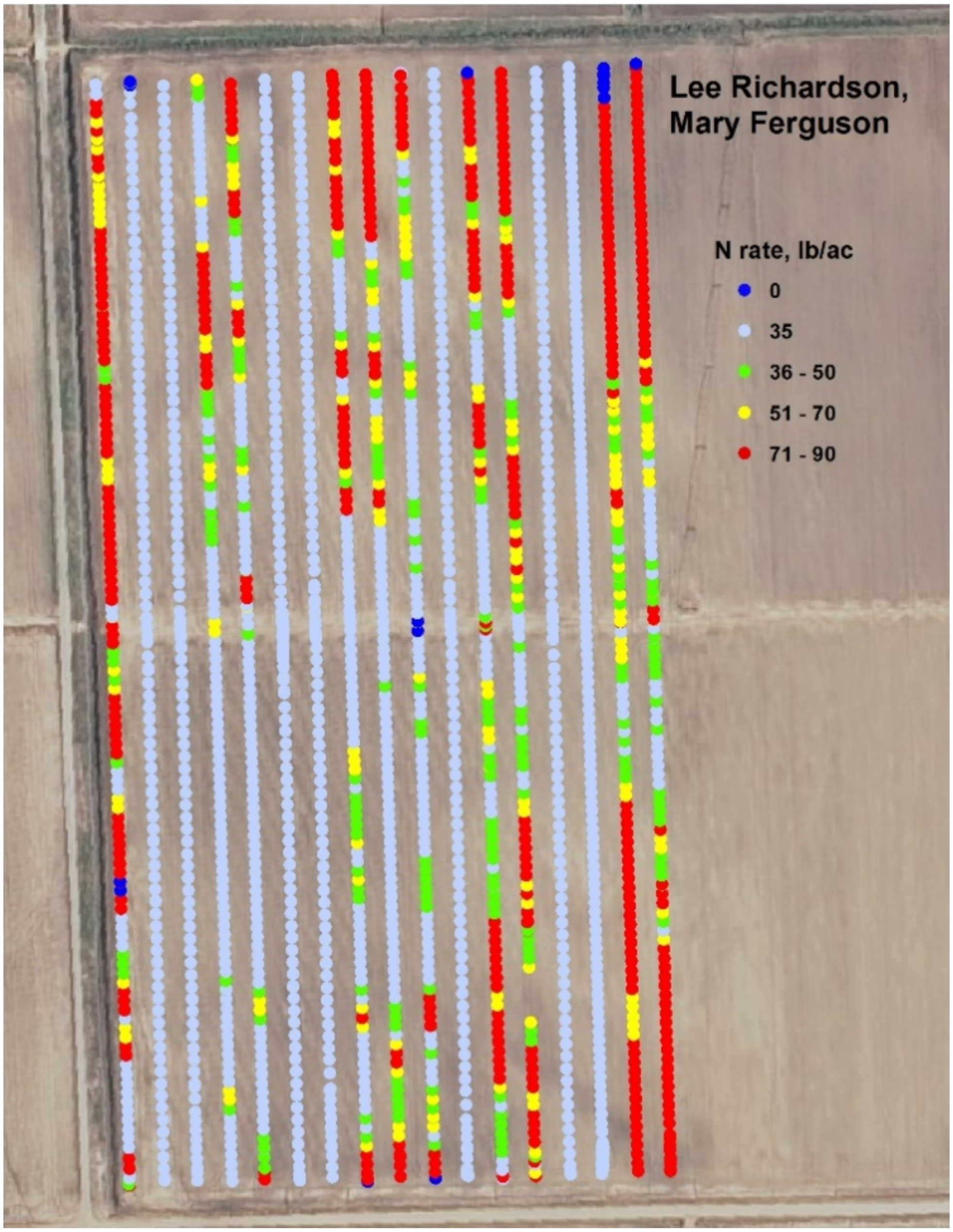

Figure 7. Demonstration field 13 (in table) from 2014.

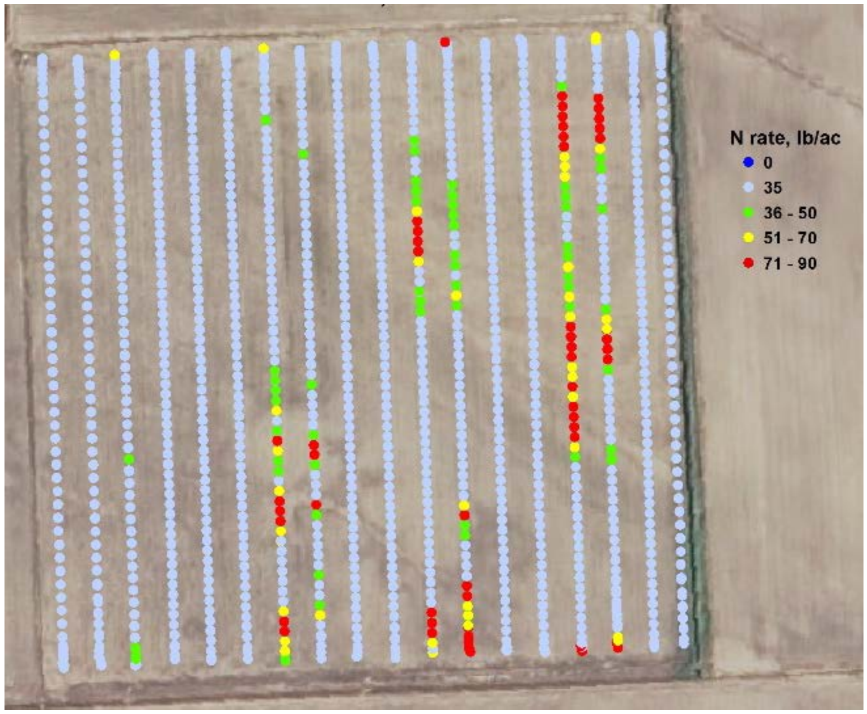

Figure 8. Third demonstration field in 2014. Yield data for this field was lost, so it is not presented in the table.

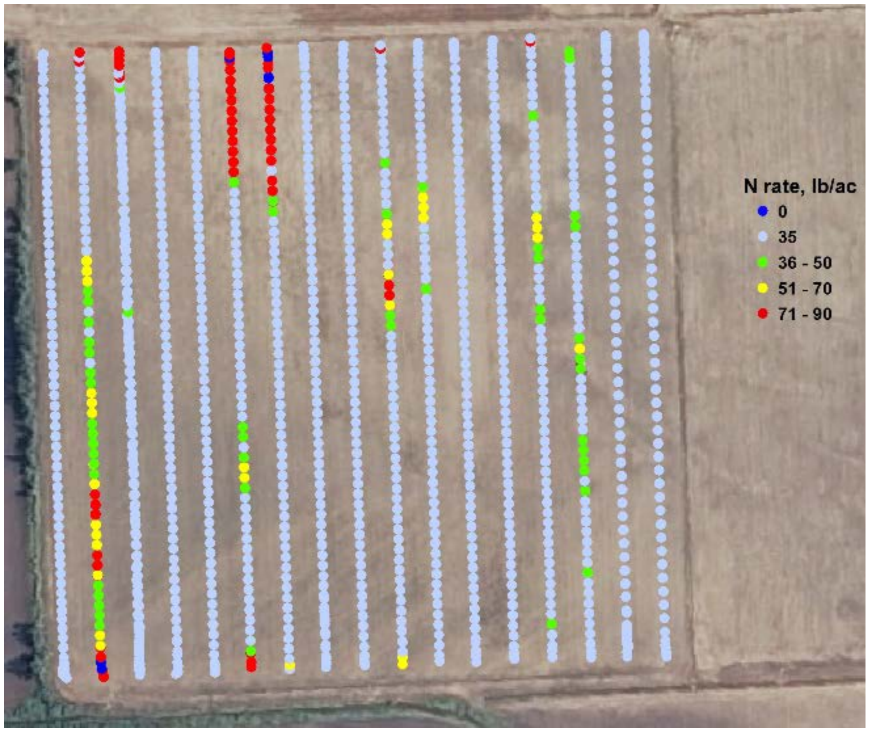

Figure 9. Demonstration field 14 (in table) from 2014.

Precision Nitrogen Injection Using Integrated Optical Sensing and Variable Rate Technologies

USDA NRCS Conservation Innovation Grant No. 69-3A75-11-177

September 2011 – December 2014

Final Report

Mississippi

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REVIEW OF METHODS

For the reported period, cotton was grown by producers while allowing the testing of a novel sensor based fertilizer N prescription application to four different fields. In 2012, the field was located south of Natchez Miss. in an alluvial bottom with mapped Convent and Morganfield soils and was not irrigated. In 2013, two experiments were set up in the same field northwest of Greenwood, Miss. with mapped soils of Dubbs-Dundee complex, Tensas and Alligator. In 2014, the field was located at Money, Miss. with mapped soils of Dubbs, Tensas, Alligator, and Tutwiler. Fields were grid soil sampled prior to cotton to determine spatial variations in residual soil N to a depth of 2 ft. The YARA N Sensor was mounted to a tractor 3-point hitch at each location and cotton canopy reflectance was collected with cotton at 4-5 nodes or pinhead square to first week of squaring. Based on a historically derived model, canopy reflectance data was converted using the Canopy Chlorophyll Content Index (CCCI) and a fertilizer application map was generated using the model with some grower adjustments. Treatments included comparison to the grower's established practice which was CEC soil test based VRN in 2012, and a constant rate of 120 lb N/acre in 2013 and 2014. A sensor based treatment adjusted for either crop productivity zones of low, medium, and high, derived from a previous year corn yield map was included in 2012, or zones differentiated with soil electrical conductivity of low, medium, and high were used in 2013. Each treatment was applied along a transect which ranged from 500 to greater than 1000 ft. depending on the field. All sites had 12 rows of cotton and treatments were replicated three to four times. Where available, the cooperators current liquid N applicator and in-cab technology were used (2012 and 2014) or a university owed 4-row rig equipped with the Capstan Nject LF system coupled to an Raven Envizio Pro field computer was used in 2013. In 2014, a Raven Envizio Pro was coupled to the grower's Raven SCS 440 rate controller console and 12 row liquid fertilizer N applicator. A GIS database was created for each field and variable rate prescriptions were generated by making shapefiles to be uploaded to the field computers attached to the liquid fertilizer N applicators. This system facilitated the capability of applying liquid fertilizer N at continuously variable rates as determined by a prescription based on canopy reflectance and perceived needs on spatially variable landscapes. Traditionally growers have applied fixed rates of fertilizer N across spatially variable landscapes resulting in both excess and less than optimum N rates applied. Each of the growers supplied yield monitor data for fields both current and the previous year, soil EC data collected by an independent provider, and conversion of the prescription on grower's software (first year only), and tractor drivers for fertilization and harvesting operations. Leaf samples were collected at four to five sub-plot locations within each treatment plot at early squaring, early flowering, and peak flowering to evaluate based on leaf tissue N sufficiency levels the performance of sensor based variable rate fertilization. All sites/fields were harvested with a 6-row spindle picker equipped with a round bale module builder. Lint yields were acquired both through weighing harvested modules and extracted from yield monitor data where available.

General schedule of events:

Prior to planting:
Soil EC and yield monitor data requested

Field grid sampled, plots delineated

At early cotton squaring:
Farmer tractor used to collect YARA canopy reflectance data
Data processed to a variable rate fertilizer N prescription
Variable rate prescription applied using grower's equipment (2011) or a combination of grower's equipment and university equipment.

A problem with coupling of grower's equipment to university equipment resulted in 2014 that negated a treatment of sensor based adjusted soil EC due to mis-application to designated plots. Yield monitor data was not produced on a second field in 2013 and it was not possible to determine as to why.

Better planning in terms of having a stated protocol or checklist to perform each operation may have helped facilitate a greater success rate in terms of data collection.

With thorough knowledge of equipment and technical skills or assistance all equipment worked as designed.

DISCUSSION OF QAULITY ASSURANCE

Each field was delineated using DGPS and soil samples were taken at accurate depths using probes with depth markings. Field maps to identify potential soil differences were acquired through the Soil Web. Requirements of the site were that soils were alluvial in nature. Part of the rationale for selecting sites was related to the co-operators ability to provide logistic support as well as have the necessary equipment and know-how to conduct somewhat controlled operations or field tests.

Each study site was performed in a grower's production field and row patterns or any other management strategy other than fertilization was not changed to simulate as closely as possible current production practices. Transects were used as what is referred to as "plots" and within each transect 4 to 5 sampling point were acquired to identify long range variability that occurred within these designated "plots." This includes multiple soil measurements which can be used to further sort out results and possible inferences as to why treatment differences or lack thereof differences were observed. Leaf tissue samples were collected from early squaring to peak bloom at locations marked during soil sampling with DGPS and flags. Six soil samples were collected to a depth of 2 ft in 6 in. increments for the surface ft. and 1 ft. for the second depth. Samples were immediately placed on ice in a cooler and stored frozen until analysed to preserve field levels of nitrate and ammonium. Six recently matured leaves (fifth node on main stem) were collected around marked sampling points and placed on ice in a cooler until they were put in a dryer at 65 ^{o}C to preserve the total N content for later analysis. All sample collection bags were labelled prior to field work and doubled checked at each sampling point. In general, all field work was conducted under my supervision while sample handling was performed by the same individuals from field, to freezer/dryers, to lab, sample preparation, and analysis. Data sheets with lab numbers are used and all samples are accounted for by checking data sheets and for their presence. Samples collected are never out of the custody of my lab personnel. All lab equipment is calibrated every time it is used with known analytical standards; field equipment was calibrated as need to compare rates indicated on controllers with actual rates applied. All total N analyses on leaf samples are run in duplicate and when the standard error of the mean exceeds 3% two more samples are run to improve accuracy. A standard method for extracting moist soil was used to determine nitrate and ammonium concentrations. As much as possible, once moist soil samples are defrosted they are physically crushed and homogenized to obtain the most representative results. All data is reviewed and periodically selected soil samples are re-extracted and analysed to ensure accuracy of the methods. All standards are lab certified and quality assurance is achieved by running quality control samples throughout all analytical procedures used in this study. Standard international units are used throughout this study but inevitably English units come into play when discussing results with growers. Leaf tissue values are accurate to 0.1% and extractable ammonium and nitrate values are accurate to 0.01 µg/g-soil. In general, sample point data was averaged across locations within designated “plots” and further averaged across replications. All data was subjected to an analysis of variance and regression analysis was used to determine response trends and the Least Significant Difference was calculated. All data is reviewed upon entry into spreadsheets and proofed for accuracy. Data are handled only by graduate students and myself. Final review and presentation of data is done by the PI, while graduate students are instructed on statistical analysis and provide initial synopsis.

FINDINGS

Sensor based variable rate fertilization resulted in multiple scenarios which suggest the method was flexible for different situations. For example, sensor based fertilization reduced fertilizer N use 21 lb N/acre, while increasing yield 60 lb lint/acre in 2012 when compared to the grower’s soil cation exchange capacity (CEC) based fertilization. Two different scenarios were tested in 2013 whereby one area of a field did not receive any pre-fertilizer N application while a 2^{nd} area received the grower’s broadcast 70 lb N/acre 39 days prior to planting. The sensor based rate averaged 92 lb N/acre compared to the grower constant rate of 120 lb N/acre, while lint was slightly less at 1576 lb/acre compared to 1609 lb/acre, respectively. Where a pre-N fertilization was practiced, sensor based resulted in 92 lb lint/acre more while applying an average of 10 lb N/acre more. These results suggested significant fertilizer N loss when applied 39 days prior to planting due to the high rainfall received during this period. In 2014, average fertilizer rate applied was 14 lb N/acre greater, while yield was increased 28.9 lb lint/acre. This was an important test of the sensitivity of the method as initial leaf samples taken at early square showed that a majority of the sites were highly deficient which caused the model to increase fertilizer N rates beyond the grower’s constant rate. Overall, sensor based variable fertilization maintained leaf tissue N levels equal to or greater than the grower standard practice suggesting spatial adjustments in fertilizer N rate were effective.

Available soil N sampled to a depth of 1-2 ft. showed widely varying results suggesting the need for spatially adjusted N fertilization. In 2012 south of Natchez, Miss. available N varied from 43 to 179 lb N/acre in the surface 2 ft. In 2013, available soil N to a depth of 2 ft. ranged from 11 to 167 lb N/acre with no pre-fertilization and 18 to 156 lb N/acre in the surface 1 ft. only where a pre-fertilization of 70 lb N/acre had been applied. In 2014, available soil N varied from 14 to 86 lb N/acre.

These results support the goals of adjusting fertilizer N rates across spatially variable fields to more closely match the soil supply and crop demand. Yield results demonstrate the potential for this technology to result in greater accuracy in meeting the fertilizer N needs to maximize crop yield across spatially variable fields.

CONCLUSIONS AND RECOMMENDATIONS

Sensor based adjustment of fertilizer N rates utilizing a vegetation index with known sensitivity to plant N status shows great promise to improve accuracy across spatially variable fields as compared to the standard practice of applying a constant rate. Although post-harvest available soil N was not sampled in this study it was obvious from the samples taken near planting that considerable variability in soil nitrate and ammonium existed in the fields utilized. Recommendations are to further refine the technology in terms of script writing to more easily facilitate the data processing steps and turnaround time from data acquisition to fertilization. Greater testing and development of algorithms is needed to make applicable across more regions.

APPENDICES

Figure 1.1 Mapped transects for 2012 research site south of Natchez, MS. White circles represent 5-m buffered points for data extraction centered on each soil and plant sampling site. Soil series are delineated.

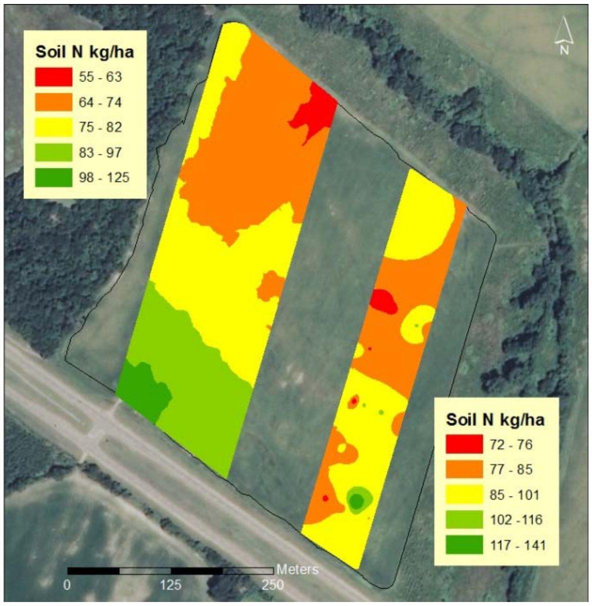

Figure 1.2 Soil N variability in 2012 near Natchez, MS.

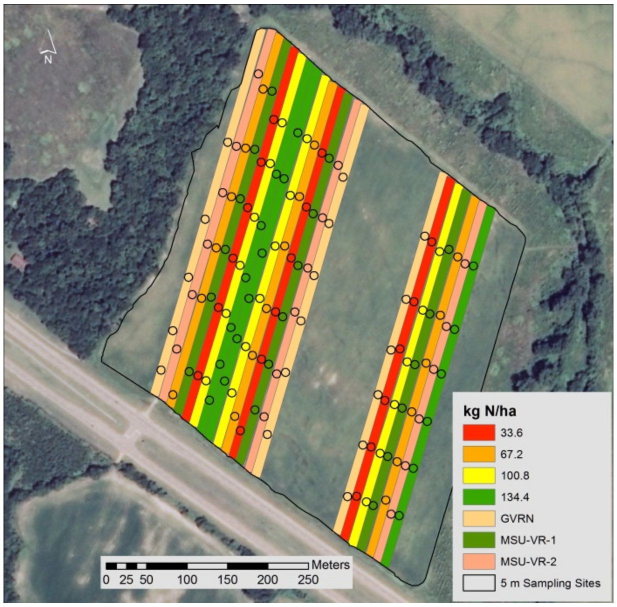

Figure 1.3 Map showing N treatments and three replications along with buffered sampling points south of Natchez, MS in 2012.

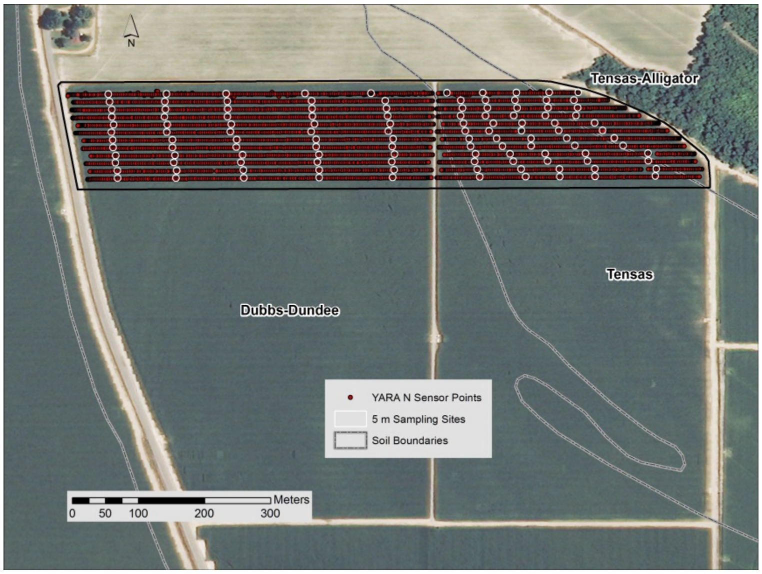

Figure 1.4 Mapped transects for 2013 research site northwest of Money, Miss. White circles represent 5 m buffered points for data extraction centered on each soil and plant sampling site. Soil series are delineated.

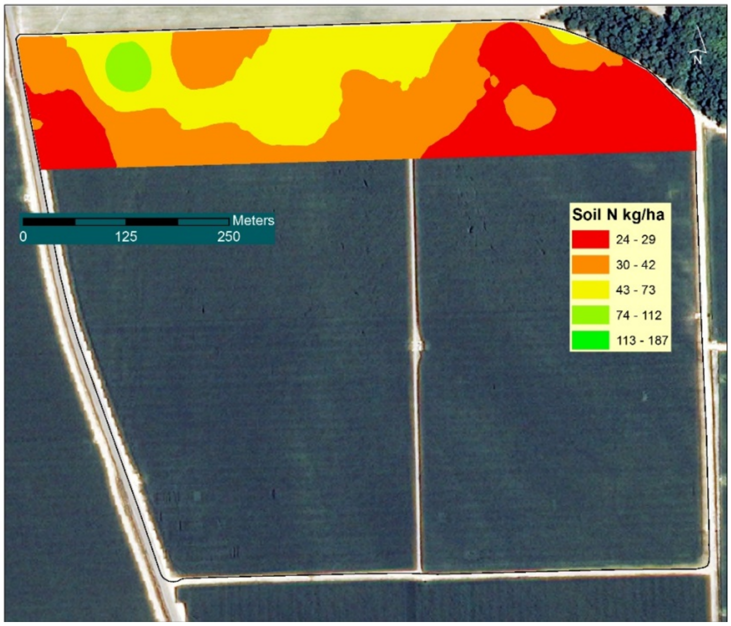

Figure 1.5 Soil N variability in 2012 near, Money, Miss.

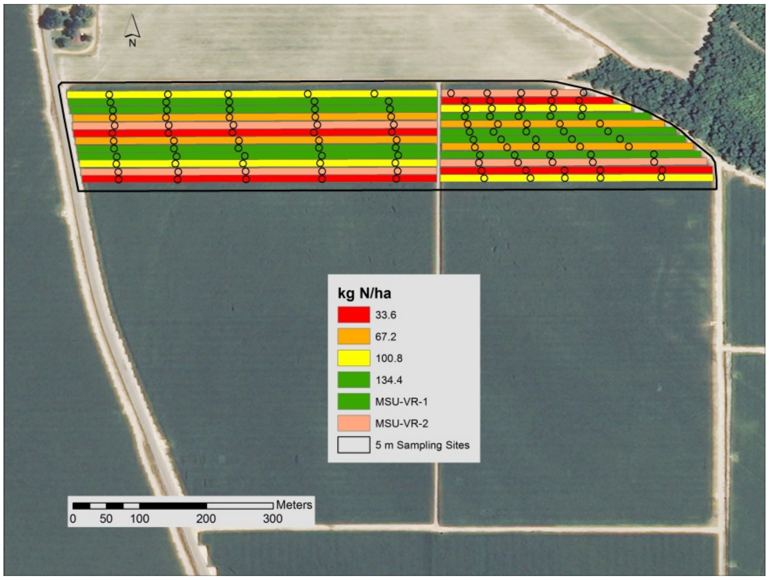

Figure 1.6 Map showing N treatments and four replications along with buffered sampling points northwest of Money, MS in 2013.

Presentations and Publications:

Raper, T., and J.J. Varco. 2014. Canopy-scale wavelength and vegetative index sensitivities to cotton growth parameters and nitrogen status. Prec. Agric. 15(5). DOI 10.1007/s11119-014-9383-4.

Raper, Tyson B., Jac J. Varco, and Derrick M. Oosterhuis. 2015. Remote sensing for nitrogen management. Reference Book Series, The Cotton Foundation, Cordova, TN. *In Press.*

Varco, J.J. 2014. On-farm evaluation of canopy sensor and soil conductivity driven variable rate nitrogen fertilization of cotton. P. 13. *In* Proc. 17th Annual National Conservation Systems Cotton & Rice Conf., 15-16 Jan. 2014. Tunica, MS. Mid-America Publications.

Varco, J.J., A.A. Fox, T.B. Raper, and K.J. Hubbard. 2013. Development of sensor based detection of crop nitrogen status for utilization in variable rate nitrogen fertilization. p. 145-150. *In* John V. Stafford (ed.) Proc. of 9th European Conf. on Precision Agriculture, Lleida, Catalonia, Spain, 7-11 July 2013. Wageningen Academic Publishers, The Netherlands.

Precision Nitrogen Injection Using Integrated Optical Sensing and Variable Rate Technologies

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Final Report

Tennessee

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EXECUTIVE SUMMARY

Ten field demonstration trials were conducted on cotton mostly on private farms with EQIP eligible producers in West Tennessee within the Mississippi River Basin during 2011 to 2014. Fields representative of land used for cotton production were used for this project. Four sensor-based variable-rate N management systems via side-dress during the early growing season were demonstrated in comparison with the local farmer's uniform-rate N application systems in large strip plots under a randomized complete block design with three replicates. Each strip plot was divided into various split-plots which received different N application rates under the in-season variable-rate N management systems but received the uniform N rate under the current uniform-rate N application systems. Initial soil inorganic N levels, leaf N concentrations , canopy Normalized Differential Vegetation Index (NDVI), lint yield and quality, seasonal fertilizer N consumption, fertilizer N use efficiency, and post-harvest residual soil N levels were determined on a sub-plot basis. This project used seasonal fertilizer N consumption, fertilizer N use efficiency (lint yield/fertilizer N applied), and post-harvest residual N levels in the soil profile to estimate its potential impacts on water quality in the Mississippi River Basin, which is scientifically sound and very cost-effective.

The goal of this project was to encourage producers' adoption of the in-season sensor-based variable-rate precision N management technologies and systems on their farms to reduce N fertilizer consumption and potential N losses, increase cotton productivity, and thus improve water quality and grower profitability in the Mississippi River Basin. The specific objectives for this project were to demonstrate to producers and other interested groups the integration of sensor-based variable-rate N fertilization into their current production systems, demonstrate the impacts of variable-rate precision N management systems based on optical sensing of crop canopy compared with the current uniform-rate N application systems in terms of fertilizer N use efficiency, post-harvest residual soil N subject to loss, potential improvements to water quality, cotton yield, and grower profitability, and show the benefits of incorporating yield maps and other field and soil information into the optical sensor-based variable-rate precision N management systems.

In the eight field trials on EQIP eligible farms, leaf N concentrations were generally comparable under the in-season sensor-based variable-rate N management systems relative to the current uniform-rate N application systems during early square to mid-bloom. Similarly, rare significant differences in canopy NDVI were observed because of in-season variable-rate N applications over the uniform-rate N applications. The in-season variable-rate N management systems via side-dress produced higher cotton lint yield at one location-year, similar lint yield at six location years, but lower lint yield at one location-year than the current uniform-rate N application systems. The in-season variable-rate N management systems did not affect post-harvest residual N levels in top 60 cm of the soil profile relative to the current uniform-rate N application systems. Averaged over the eight location-years, all the in-season variable-rate N management systems had significantly lower seasonal N fertilizer consumption, but higher N use efficiency than the current uniform-rate N application systems. Specifically, the in-season variable-rate N management systems reduced seasonal N fertilizer consumption by 9.3 to 14.8% (9.8 to 15. 6 kg N ha^{-1}), but increased higher N use efficiency by 9.2 to 11.0% compared with the current uniform-rate N application systems. No significant positive effect of in-season variable-rate N management systems was observed on post-harvest residual N levels in the top 60 cm of soil. The

benefits of incorporating yield maps of previous years into the optical sensor-based variable-rate N management systems were generally not noticeable in terms of cotton yield, seasonal N fertilizer consumption, N use efficiency, and post-harvest residual soil N level. Our results suggest that in-season sensor-based variable-rate N management systems use significantly less N fertilizer to produce comparable cotton yield via increasing N use efficiency relative to the current uniform-rate N application systems. The in-season sensor-based variable-rate N management systems are viable tools that can be used by producers on their farms to manage variations within the field. A variety of Extension and outreach activities were conducted to show the demonstration sites and precision equipment, and to disseminate the results to cotton producers and other interested groups.

Overall, the in-season sensor-based variable-rate management systems are reliable to be used to implement precision N management on cotton mostly with environmental or/and economic benefits. Cotton and other crop producers, private consultants, university Extension agents, government personnel, and industry agronomists in the four participating states and other adjacent states within the Mississippi River Basin are the customers that benefit from this grant.

INTRODUCTION

Twenty nine field demonstration trials were conducted on cotton (*Gossypium hirsutum* L.) mostly on private farms with EQIP eligible producers in West Tennessee, the Delta region of Mississippi, Missouri, and North Louisiana within the Mississippi River Basin during 2011 to 2014. Felds representative of land used for cotton production were used for this project. Historical cropping information was collected from the cooperative producers. The in-season sensor-based variable-rate N management systems were demonstrated in comparison with the local farmer's uniform-rate N application systems in large strip plots under a randomized complete block design with three replicates. A variety of Extension and outreach activities were conducted to show our demonstration sites and precision equipment, and to disseminate the results to cotton producers. This project used seasonal N fertilizer consumption, fertilizer N use efficiency (lint yield/fertilizer N applied), and post-harvest residual N levels in the soil profile to estimate its potential impacts on water quality in the Mississippi River Basin, which is scientifically sound and very cost-effective.

This project successfully demonstrated to producers and other interested groups the integration of sensor-based variable-rate N fertilization into their current production systems, the impacts of variable-rate precision N management systems based on optical sensing of crop canopy compared with the current uniform-rate N application systems in terms of fertilizer N use efficiency, post-harvest residual soil N subject to loss, potential improvements to water quality, cotton yield, and grower profitability; and the benefits of incorporating yield maps and other field and soil information into the optical sensor-based variable-rate precision N management systems.

The University of Tennessee, Mississippi State University, University of Missouri, and Louisana State University have strong teams of faculty working on precision agriculture, and have the optical sensing and variable-rate application equipment of commercial production scale. The researchers from different disciplines worked closely as an integrated team to carry out this project. The project team met and had conference calls frequently as needed to discuss the project progress and make improvements if necessary. Two semi-annual progress reports were developed and submitted each year. At the end of this project, a final report is developed.

Xinhua (Frank) Yin, Associate Professor of Systems Agronomy, University of Tennessee-Knoxville (UTK). Ph.D., Purdue University. He has over 20 years of experience in agronomic research and extension including precision agriculture. He was in charge of project coordination among the four states, and responsible for experimental design, trial establishment, data collection, conducting demonstration activities, writing summary reports and Extension publications and delivering extension talks in Tennessee.

Jac J. Varco, Professor of Agronomy, Mississippi State University. Ph.D., University of Kentucky. He has over 30 years of experience in nutrient management including precision agriculture utilizing remote sensing and canopy reflectance. For Mississippi locations, he was in charge of site selection and grower collaboration, experimental design, trial establishment, data collection, conducting demonstration activities, writing summary reports and Extension publications, and delivering extension talks.

Peter Scharf, Professor of Nutrient Management, University of Missouri. Ph.D., Virginia Tech University. He has over 30 years of experience in nutrient management and precision agriculture, and was in charge of site selection and grower collaboration, experimental design, trial establishment, data collection, conducting demonstration activities, writing summary reports and extension publications, and delivering Extension talks in Missouri.

Brenda S. Tubaña, Associate Professor of Soil Fertility, Louisiana State University. Ph.D., Oklahoma State University. She has over 10 years of experience in soil fertility and precision agriculture, and was in charge of experimental design, trial establishment, data collection, conducting demonstration activities, writing summary reports and Extension publications, and delivering extension talks in Louisiana.

James Larson, Professor of Ag. Economics, UTK. Ph.D., Oklahoma State University. He has 20 years of experience in production economics, farm management, and risk analysis, and was in charge of the economic analysis for this project.

David Verbree, Assistant Professor in Crop Physiology, UTK. Ph.D., Texas A and M University. He has over 5 years of experience in crop physiology research and Extension, and conducted Extension and outreach activities in Tennessee.

David Dunn, Professor of Soil Science, University of Missouri. Ph.D., University of Missouri. He has over 30 years of experience in soil testing and precision agriculture, and participated in demonstration and Extension activities in Missouri.

Hugh Savoy, Associate Professor in Soil Fertility Extension, UTK. Ph.D. University of Tennessee. He has 30 years of experience in soil fertility Extension and research, and conducted extension and outreach activities in Tennessee.

Michael Buschermohle, Professor and Extension Precision Agriculture Specialist, UTK. Ph.D., Clemson Univ. He has over 30 years of experience in conducting precision agriculture educational programs, and conducted Extension and outreach activities in Tennessee.

Don Tyler, Professor of Soil Science, University of Tennessee. Ph.D., University of Kentucky. He has about 40 years of experience in no-till production and precision farming, and participated in experimental design and trial evaluations in Tennessee.

Approximately fifteen EQIP eligible producers directly participated in this project from Tennessee, Mississippi, Missouri, and Louisiana. All these EQIP eligible producers were involved in the selection of trial locations, trial establishment and management, uses of the precision equiptment including optical sensors and variable-rate N applicators, data collection, and Extension and outreach activities.

Representatives of the local USDA NRCS offices in each state monitored and evaluated the results of this project. They were invited to visit the demonstration sites, participate in major Extension and outreach activities, and read semi-annual progress reports and the final report.

The purpose of this project was to demonstrate to producers and other interested groups the procedures and benefits of utilizing the innovative precision technologies: optical sensing and variable-rate application, to manage spatial variability within individual fields of cotton. The goal of this project was to encourage producers' adoption of these new precision N management technologies and systems on their farms to reduce N fertilizer consumption and potential N losses, improve cotton productivity, and thus improve water quality and grower profitability in the Mississippi River Basin. The specific objectives for this project included the follows:

1) To demonstrate to producers and other interested groups the integration of sensor-based variable-rate N fertilization into their current production systems;
2) To demonstrate the impacts of variable-rate precision N management systems based on optical sensing of crop canopy compared with the current uniform-rate N application systems

in terms of fertilizer N use efficiency, post-harvest residual soil N subject to loss, potential improvements to water quality, cotton yield, and grower profitability; and

3) To show the benefits of incorporating yield maps and other field and soil information into the optical sensor-based variable-rate precision N management systems.

There were 3,065,000 acres of cotton in 2006, and 1,375,000 acres in 2010 planted in Tennessee, Missouri, Mississippi, and Louisiana. Cotton is a major field crop in these four states. The majority of these cotton acres are located within the Mississippi River Basin. In addition, the results of this project can also be used in some other states such as Arkansas with some modifications. This project targeted thousands of cotton producers in the four participating states within the Mississippi River Basin via a variety of Extension and outreach activities.

This project adopted an innovative approach in several aspects. Firstly, it addressed fertilizer N use efficiency and related water quality issues by using the integration of two new precision technologies -- optical sensing and variable-rate application. No similar demonstrations had been conducted on cotton in the Mississippi River Basin. Secondly, it involved producers directly and meaningfully. Thirdly, the need for the project was identified through surveys among producers, county Extension agents, and private consultants at Extension events such as the Tennessee Cotton Focus Meeting. And finally, some producers and organizations had already been contacted, and the project was highly supported in the agricultural community.

This project was funded by the CIG proejct at less than 50% of the total costs. The University of Tennessee, Mississippi State University, University of Missouri, and Louisana State University funded this porject via providing scientists and supporting staff, optical snsors and variable-rate applicators, and analytical labs for soil testing and plant analyses. The participating producers provided land, seeds, chemicals, etc. for implementing this project. In addition, local relevant companies also provided support in various aspects to this project.

BACKGROUND

During the past several decades, the largest increase in the use of agricultural inputs was fertilizer N (Johnston, 2000). Nitrogen fertilization is a key production practice in most crops including cotton. Fertilizer N is one of the greatest cost inputs in cotton production. It is also the most difficult nutrient to manage, and has large potential adverse impacts on the environment. Due to substantially increased environmental concern and rising N prices (up to $1.00/lb N in 2008) during the last decade, there is an urgent need to develop and demonstrate innovative technologies and systems that can apply N more precisely so as to increase N use efficiency reduce N losses, enhance water quality, and increase crop yields and profitability.

Cotton is the largest source of natural fiber. Increasing cotton productivity and competitiveness in the global textile market remains a big challenge to the U.S. cotton industry. The recent decline in cotton acreage due to competition from grain crops and an increase in public concerns on environmental degradation necessitate greater productivity, improved sustainability, and environmentally-friendly cotton production systems. Apart from large input costs, the perennial growth habit of cotton requires an effective and refined fertilizer N management system. Under-application of N on cotton results in poor vegetative and reproductive growth, premature senescence, and reduced yields; while over-application can inhibit boll formation and retention, pose serious threats to the environment (Prasad and Power 1995), and reduce grower profitability due to greater expenses on fertilizer N, etc.

Due to security concern, urea and ammonium nitrate (UAN) and urea have been increasingly used to replace ammonium nitrate as the N source for cotton production in Tennessee. Presently, UAN is usually injected into the soil, while ammonium nitrate is broadcast on the soil surface. Traditionally, N fertilizer is applied around cotton planting, but split applications (a small portion of N as pre-plant plus a large portion of N as side-dress) have recently gained grower's attention. No-tillage systems are being widely used by producers in cotton production in Tennessee and throughout the southeastern USA. Under no-tillage, N fertilizer is often broadcast on soil surface without incorporation into the soil, while it is generally incorporated after surface application under conventional tillage systems (Howard et al., 2001). Overall, information on cotton responses to the application rate, timing, and method of alternate N sources such as UAN and urea is limited under no-till production systems.

Furthermore, current fertilizer N recommendations were developed by individual states on small fields where spatial variances were minimal. Although recommendations may account for soil variations, growers did not have the technology to manage spatial variability within individual fields. Under the current systems, producers use a uniform N fertilizer rate across the entire field, which often results in over- and under-applications of N because crop responses to N fertilization are often variable within an individual field (Vetch et al., 1995), and on some parts of the field more N should be applied or much less to none on other parts of the field (Raun and Johnson, 1999). Therefore, the presence of spatial variability within individual fields is a critical issue demanding careful management. In order to solve this problem, it is essential to develop and adopt innovative technologies and management systems that can generate and implement variable-rate fertilizer N recommendations based on spatial variances within individual fields.

Measuring crop N nutrition status during the growing season by optically sensing crop canopy has been developed into a viable precision N management tool during the past fifteen years (Raun et al., 2001, 2002). Researchers utilize on-vehicle, real-time optical sensing of crop canopy reflectance which can be used to develop indices such as the Normalized Difference Vegetation Index (NDVI) to assess crop growth, health, and/or N nutritional status and use these indices to adjust the fertilizer N rate accordingly. Integration of optical sensing and variable-rate application technologies enables on-the-go non-destructive diagnoses of crop N deficiency, sufficiency, or excesses without soil or plant tissue diagnostic testing, real-time application of N fertilizer at variable rates to correct those deficiencies or excesses, and precisely treating each part of the field sensed. Since this is real-time sensing, it is done without pre-processing of data or determining location within field beforehand. This innovative precision technology allows variable application of N fertilizers at very high resolutions. So far this system is the most efficient technology for precision N management as it can change uniform-rate N application to variable-rate N applications, minimizing time, labor, and cost of implementing variable-rate N applications (Raun et al., 2002; Tubaña et al., 2008), which is vastly different from the traditional N management system of uniform-rate N application across entire fields.

Investigations have shown significant environmental or/and economic benefits with optical sensor-based variable-rate precision N management technologies and systems. Research on corn and winter wheat have shown 10-15% increases in N use efficiency and some significant yield increases with these precision N management systems relative to the current uniform-rate N application systems (Raun and Johnson, 1999; Raun et al., 2002). Biermacher et al. (2006) in Oklahoma even reported as high as 59–82% reductions in N fertilizer use by winter wheat under the optical sensor-based variable-rate N management systems. Ortiz-Monasterio and Raun (2007) showed that optical sensor-based precision N management systems can save 63 lb/acre N on spring wheat and increase grower profitability by $60/acre. However, investigations on cotton responses to variable-rate N applications based on canopy NDVI were limited.

Overall, the optical sensing and variable-rate technologies were studied sufficiently by scientists at the four participating universities. Each participating state had adequate (at least three years of) research data of optical sensing on cotton to develop algorithms for variable-rate N applications in this project. However, these cutting-edge precision technologies were new to cotton producers. The delivery of these technologies to producers was highly needed. Since the total costs for purchasing the integrated optical sensing and variable-rate N application equipment for commercial production are approximately $30,000 to $40,000, and the equipment can be used on different crops for many years, and can also be rented to other producers, we believe this equipment is affordable for most producers and is a great investment tool.

This project was able to quantitatively determine seasonal fertilizer N consumption, fertilizer N use efficiency based on lint yield/fertilizer N applied (partial factor analysis), and post-harvest residual N level in the soil profile (2 to 3 ft. deep) for the variable-rate precision N management systems based on optical sensing, etc. and for the current N application systems of uniform-rate N application across entire fields as well in each year and on the averages of the three-year data. The three measurements mentioned above could all be used to estimate the potential impacts of this project on the environment, such as water quality. The uses of seasonal fertilizer N consumption, fertilizer N use efficiency, and post-harvest residual soil N level are scientifically sound and very cost-effective in estimating the impacts of this project on water quality in the Mississippi River Basin. Because we are able to calculate how many lbs/acre of fertilizer N that could be saved from using the variable-rate precision N management systems compared with the current uniform-rate N application systems, and if we know the total acreage of cotton fields using the variable-rate precision N management systems in the Mississippi River Basin, then we are able to figure out how many tons of fertilizer N will be saved each year in the Mississippi River Basin due to the use of these new precision technologies. The reduction in fertilizer N consumption is an estimate of the potential impacts of this project on the environment such as water quality in the Mississippi River Basin. Since cotton is a major crop with a total acreage ranging from 1,400,000 to 3,000,000 acres each year in Tennessee, Missouri, Mississippi, and Louisiana, the potential of using these new precision technologies in cotton production would be substantial in the Mississippi River Basin. In addition, the results of this project can also be used in some other states such as Arkansas with some modifications.

This project provides significant positive environmental or/and economical benefits of reducing fertilizer N consumption, lowering N losses, increasing crop yield, and thus improving water quality and grower profitibility. As cotton producers have realized the benefits of and shifted to these innovative sensor-based N management systems, the above benefits will be realized in the four participating states. Futhermore, the results of this project could be used by cotton producers in the other regions of the U.S. with some modifications. Producers will receive greater economic returns from cotton production using these innovative technologies and systems. Water quality in local streams and the Mississippi River could be gradually improved by reducing nitrate leaching from cotton fields to water because of the adoption of these new technologies and systems in all the states with cotton production in the Mississippi River Basin.

Overall, the optical sensor-based variable-rate precision N management technologies and systems have the potential to reduce fertilizer N consumption, lower N losses to water and atmosphere, and improve water and air quality in the Mississippi River Basin. Furthermore, the improved water quality with these innovative precision technologies will improve the conditions for fish production, tourism, and recreation in the region. There is no adverse impact of this project on the environment or society.

REVIEW OF METHODS

FIELD TRIALS ON EQIP ELIGIBLE FAMRS (2012-2014)

Eight field demonstration trials were conducted on cotton of private farms with EQIP eligible producers in west Tennessee within the Mississippi River Basin during 2012-2014. Fields representative of land used for cotton production were used for this project. Historical cropping information was collected from the cooperative producers. Although only three N management systems were proposed to be compared in the original proposal, the following five different N management systems were demonstrated and compared in large strip plots (about 40-ft wide run the entire field length, each strip plot was divided into various 100-ft long sub-plots) under a randomized complete block design with three replicates at all the eight location-years:

1. The current N application system -- uniform-rate application of granular or liquid N fertilizer within a field. Under this system, the N fertilizer rate was determined based on farmer experience and input, and was the same across the entire strip plot and all three replications. This system represents the current state of technology integrated with grower intuitive knowledge of field fertilizer N requirements.
2. A variable-rate precision N injection system utilizing canopy optical sensing (NDVI or other vegetation indices) and a fertilizer rate algorithm derived from multiple years of previous research data. The basic principle of the N management system is that the lower the vegetation index value was, the higher the amount of N fertilizer was applied, and vice versa. The N application algorithm for this treatment was developed using research data of previous years.
3. A variable-rate precision N injection system based on canopy optical sensing but adjusted for soil productivity zones derived from bare soil imagery and historical yield monitor data or aerial imagery of mid-season crop health. The N application algorithm for this system was developed as follows: The yield potentials of all sub-plots in the field were assessed using the methods mentioned above, and divided into three categories: low, medium, and high. For the medium yield potential category, the algorithm used in Treatment 2 was used without any adjustment. For the low and high yield potential categories, the algorithm used in Treatment 2 was used after adjusting for yield potentials. For instance, when cotton yield potential was in the low category, the N rate recommendation based on NDVI or other vegetation indices were scaled down by 30 lb N/acre; when the yield potential was high, the N rate recommendation was scaled up by 30 lb N/acre.

4. This treatment was the same as Treatment 2 but the in-season sensor-based variable N application rate ranged from 40 to 80 lb N/acre.
5. This treatment was the same as Treatment 3 but the in-season sensor-based variable N application rate ranged from 20 to 100 lb N/acre.

The above five N management systems were compared side by side on the same field. A uniform N rate was applied to all the sub-plots based on producer's current practice in Treatment 1. In Treatment 2, a uniform N rate of 30 lb N/acre was applied to each sub-plot at planting, and the in-season N application in late June to early July for each sub-plot was variable (ranging from 30 to 90 lb N/acre) based on the actual vegetation index from that sub-plot using the GreenSeeker® RT200 Data Collection and Mapping System (NTech Industries, Inc., CA) or the Yara® N sensing system. In Treatment 3, a uniform N rate of 30 lb N/acre was applied to each sub-plot at planting, and the in-season N application for each sub-plot was at a variable rate (ranging from 0 to 120 lb N/acre) according to the actual vegetation index but adjusted to the yield potential of that sub-plot.

The P and K fertilizers were broadcast applied uniformly across the entire test based on the soil testing results at each location-year. The soil types, dates of cotton planting, N treatment implementation, and other major field operations for these trials are presented in Table 1. The following sampling and measurements were taken on a sub-plot basis at each location-year for developing education materials: A composite soil sample was collected at a depth of 60-cm for nitrate N and ammonium N in the soil profile prior to treatment initiation. Canopy NDVI data were recorded at the early square, early bloom, and mid-bloom growth stages using the GreenSeeker® RT 200 Data Collection and Mapping System (NTech Industries, Inc., CA). A composite leaf sample (10 blades + 10 petioles) was collected three times at about the same dates when NDVI data were collected. All leaf samples were analyzed for N concentrations using a LECO Tru-Spec Analyzer. Pre-plant applied N, in-season applied N, and the total seasonal fertilizer N consumption were recorded for each sub-plot. Cotton harvest was completed timely for lint yield and gin turnout by harvesting the center 6 rows. In addition, fiber quality attributes were determined on a strip plot basis at each location-year. A post-harvest soil sample was taken for soil nitrate N and ammonium N at a 60-cm depth to estimate residual N levels in soil profile after harvest. Fertilizer N use efficiency based on lint yield/fertilizer N applied (partial factor analysis) was calculated. Both are good indices which could be used to estimate the potential impacts of this project on water quality. An economic analysis including grower profitability and risks with use of these new precision technologies was conducted. The procedures and benefits of utilizing optical sensor-based canopy reflectance, residual soil nitrate N analysis, and leaf tissue analysis to improve N management in cotton production on spatially variable soils were demonstrated to the producers.

Analysis of variance was conducted on each measurement with a randomized complete block model for each location-year and the combined data of the eight location-years using SAS statistical software (SAS Institute, Cary, NC). Treatment means were separated with the Fisher's protected LSD method if the F test was significant. Probability levels lower than 0.05 were designated as significant for all the analyses.

This project adopted an innovative approach in several aspects. Firstly, it addressed fertilizer N use efficiency and related water quality issues by using the integration of two new precision technologies -- on-vehicle, real-time optical sensing and variable-rate application. Integration of optical sensing and variable-rate application technologies enables on-the-go non-destructive diagnoses of crop N deficiency, sufficiency, or excesses without soil or plant tissue diagnostic testing, real-time application of N fertilizer at variable rates to correct those deficiencies or excesses, and precisely treating each part of the field sensed. Since this is real-time sensing, it is done without pre-processing of data or determining location within field beforehand. This innovative precision technology allows variable application of N fertilizers at very high resolutions. So far this system is the most efficient and cutting-edge technology for precision N management as it can change uniform-rate N application to variable-rate N applications, minimizing time, labor, and cost of implementing variable-rate N applications, which is vastly different from the traditional N management system of uniform rate N application across the entire field. No similar demonstrations were conducted on cotton in the Mississippi River Basin. Secondly, this project changed cotton N application timing form pre-planting and at-planting to in-season N application. Thirdly, a thorough economic analysis was conducted by agricultural economists. Fourthly, it involved producers directly and meaningfully. Fifthly, the need for the project was identified through surveys among producers, county Extension agents, and private consultants. And finally, the project was highly supported in the agricultural community.

The producers did not need to do much differently to accommodate this project since all the equipment for this project was provided the universities. However, if they want to adopt these technologies on their farms themselves, they need to buy the optical sensors and variable-rate applicators, and get the variable N rate algorithms for cotton from the universities or develop their own variable N rate algorithms.

Table 1. Major field operations performed on the trials of EQIP eligible farms during 2012-2014.

Year		Major Operations Performed	Date Performed
2012	Lauderdale	Farmer applied 30 lb N a^{-1}, 20 lb S a^{-1} and 1 lb B a^{-1} plus a uniform rate of P and K to all plots	05/08/12
		Planted DPL 912	05/11/12
		Collected pre-treatment soil samples to 60 cm deep (2 cores sub-$plot^{-1}$)	05/17/12
		Recorded canopy NDVI prior to N treatment	06/28/12
		Side-dressed fluid N treatments by sub-plot	07/06/12
		Collected early square canopy NDVI and leaf samples (10 leaves sub-$plot^{-1}$)	07/10/12
		Collected early bloom canopy NDVI and leaf samples (10 leaves sub-$plot^{-1}$)	07/19/12
		Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-$plot^{-1}$)	07/27/12
		Hand-picked seed cotton samples from 50 open bolls sub-$plot^{-1}$ for gin turnout and fiber quality	10/22/12
		Harvested center 6 rows of each 12 row sub-plot & collected seed cotton samples by strip plot	10/30/12
		Collected post-harvest soil samples to 60 cm deep (2 cores $plot^{-1}$)	11/02/12
	Madison	Planted PHY 499	04/26/12
		Collected pre-treatment soil samples to 60 cm deep (2 cores sub-$plot^{-1}$)	05/16/12
		Farmer applied 30 lb N a^{-1}, 40 lb P_2O_5 a^{-1}, and 80 lb K_2O a^{-1} to all plots plus 60 lb N a^{-1} to Treatment 1	05/25/12
		Recorded canopy NDVI prior to N treatment	06/15/12
		Side-dressed fluid N treatments by sub-plot	06/29/12
		Collected early square canopy NDVI and leaf samples (10 leaves sub-$plot^{-1}$)	07/11/12
		Collected early bloom canopy NDVI and leaf samples (10 leaves sub-$plot^{-1}$)	07/25/12
		Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-$plot^{-1}$)	08/08/12

		Hand-picked seed cotton samples from 50 open bolls sub-plot^{-1} for gin turnout and fiber quality	10/08/12
		Harvested center 6 rows of each 12 row plot & collected seed cotton samples by strip plot	10/19/12
		Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	11/05/12
	Tipton	Farmer applied 30 lb N a^{-1}, 40 lb P_2O_5 a^{-1}, 100 lb K_2O a^{-1}, and 10 lb S a^{-1} to all plots	04/07/12
		Planted DPL 912	05/18/12
		Collected pre-treatment soil samples to 60 cm deep (2 cores sub-plot^{-1})	06/14/12
		Recorded canopy NDVI prior to N treatment	07/05/12
		Collected early square canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/11/12
		Side-dressed fluid N treatments by sub-plot	07/12/12
		Collected early bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/23/12
		Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/30/12
		Hand-picked seed cotton samples from 50 open bolls sub-plot^{-1} for gin turnout and fiber quality	10/09/12
		Harvested center 6 rows of each 12 row plot & collected seed cotton samples by strip plot	10/23/12
		Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	11/05/12
2013	Lauderdale	Farmer applied 30 lb N a^{-1}, 20 lb S a^{-1} and 1 lb B a^{-1} plus a uniform rate of P and K to all plots	NR†
		Planted DPL 1321	06/04/13
		Collected pre-treatment soil samples to 60 cm deep (2 cores sub-plot^{-1})	06/14/13
		Collected early bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/26/13
		Side-dressed fluid N treatments by sub-plot	07/27/13

		Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	08/14/13
		Collected late bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	08/27/13
		Hand-picked seed cotton samples from 50 open bolls sub-plot^{-1} for gin turnout and fiber quality	11/27/13
		Harvested center 6 rows of each 12 row plot & collected seed cotton samples by strip plot	11/29/13
		Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	12/02/13
	Madison	Planted PHY 499	05/14/13
		Farmer applied 30 lb N a^{-1} and a uniform rate of P and K to all plots plus 60 lb N a^{-1} to Treatment 1	06/14/13
		Collected early square canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/10/13
		Side-dressed fluid N treatments by sub-plot	07/18/13
		Collected early bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/24/13
		Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	08/07/13
		Hand-picked seed cotton samples from 50 open bolls sub-plot^{-1} for gin turnout and fiber quality	11/04/13
		Harvested center 6 rows of each 12 row plot & collected seed cotton samples by strip plot	11/14/13
		Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	11/15/13
2014	Lauderdale	Farmer applied 30 lb N a^{-1}, 20 lb S a^{-1} and 1 lb B a^{-1} plus a uniform rate of P and K to all plots	NR
		Planted DPL 1321	05/10/14
		Collected early square canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/11/14
		Side-dressed fluid N treatments by sub-plot	07/17/14
		Collected early bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/28/14

	Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	08/11/14
	Hand-picked seed cotton samples from 50 open bolls sub-plot^{-1} for gin turnout and fiber quality	10/31/14
	Harvested center 6 rows of each 12 row plot & collected seed cotton samples by strip plot	11/12/14
	Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	11/19/14
Madison	Farmer applied 30 lb N a^{-1} plus a uniform rate of P and K to all plots pre-plant plus 60 lb N a^{-1} to Treatment 1	NR
	Planted PHY 499	05/05/14
	Collected pre-treatment soil samples to 60 cm deep (2 cores sub-plot^{-1})	05/21/14
	Collected early square canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/08/14
	Side-dressed fluid N treatments by sub-plot	07/10/14
	Collected early bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/21/14
	Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	08/01/14
	Hand-picked seed cotton samples from 50 open bolls sub-plot^{-1} for gin turnout and fiber quality	10/01/14
	Harvested center 6 rows of each 12 row plot & collected seed cotton samples by strip plot	10/21/14
	Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	10/24/14
Carroll	Farmer applied 30 lb N a^{-1} plus a uniform rate of P and K to all plots pre-plant	NR
	Planted PHY 333	05/05/14
	Collected pre-treatment soil samples to 60 cm deep (2 cores sub-plot^{-1})	05/22/14
	Collected early square canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/02/14
	Side-dressed fluid N treatments by sub-plot	07/07/14
	Collected early bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/18/14

	Collected mid-bloom canopy NDVI and leaf samples (10 leaves sub-plot^{-1})	07/30/14
	Hand-picked seed cotton samples from 50 open bolls sub-plot^{-1} for gin turnout and fiber quality	10/09/14
	Harvested center 6 rows of each 12 row plot & collected seed cotton samples by strip plot	10/22/14
	Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	10/23/14

NR: Date not recorded.

FIELD TRIALS ON A UNIVERSITY RESEARCH AND EDUCATION CENTER (2011-2012)

Another two field trials were conducted on cotton on the University of Tennessee Research and Education Center at Milan in 2011 and 2012 with the following six in-season side-dress UAN treatments evaluated in strip plots. Each strip plot was divided into 8 sub plots (7.5 m wide × 15 m long).

1. Zero N
2. Low uniform-rate N application of 56 kg N ha^{-1} (50 lb N a^{-1}) over each strip plot
3. High uniform-rate N application rate of 78.4 kg N ha^{-1} (70 lb N a^{-1}) over each strip plot
4. Ordinary variable-rate N application algorithm in the range of 33.6 to 100.8 kg ha^{-1} (30 to 90 lb a^{-1}) of N for each sub plot based on the average NDVI value in that sub plot
5. Reversed variable-rate N application algorithm in the range of 33.6 to 100.8 kg ha^{-1} (30 to 90 lb a^{-1}) of N for each sub plot based on the average NDVI value in that sub plot
6. Nitrogen application rate based on the average NDVI value in each strip plot

No side-dress UAN fertilizer was applied in any strip or sub plot in Treatment 1. Nitrogen fertilizer of 56 kg N ha^{-1} was applied to all sub plots in each strip plot in Treatment 2. Nitrogen fertilizer at 78.4 kg N ha^{-1} was applied to all sub plots in each strip plot in Treatment 3. The N applicate rates in Treatments 2 & 3 roughly represented the lower and higher limits of side-dress N applications used by cotton producers after approximately 22 to 34 kg N ha^{-1} (20 to 30 lb N a^{-1}) was pre-plant applied as monoammonium phosphate or diammonium phosphate. Nitrogen applications in Treatments 4 to 6 were based on NDVI readings. In Treatment 4, when the NDVI reading was lower, more N fertilizer was applied. However, in Treatment 5, when the NDVI reading was lower, less N fertilizer was applied. In-season fluid N application rate ranged from 33.6 to 100.8 kg ha^{-1} for both Treatments 4 and 5. In Treatment 6, the N application rate was identical for all sub-plots within a strip plot, but it might be different among the three strip plots of the three replicates since it was based on the average NDVI value in each strip plot. Fluid N fertilizer UAN (32-0-0) was injected 3.8 cm deep into the soil and 25.4 cm to one side of the row with a KBH 8-row pull-type coulter injector for all the in-season applied N treatments (Treatments 2 to 6). In addition to the above in-season N treatments, all the plots received 26 kg N ha^{-1} and 67 kg P_2O_5 ha^{-1} as diammonium phosphate and 67 kg K_2O ha^{-1} as muriate of potash regardless of treatment in fall 2010. In March 2012, 26 kg N ha^{-1}, 67 kg P_2O_5 ha^{-1}, and 101 kg K_2O ha^{-1} were applied to all the plots irrespective of the treatment. The P and K fertilizers were broadcast applied uniformly on the soil surface across the test based on the soil testing results each year.

The test field had four different soil types: Calloway, Falaya, Grenada, and Lexington. The initial soil nitrate- and ammonium-N content within the top 60 cm of soil varied substantially ranging from 3 to 57 mg kg^{-1}. All these suggest that the test field is spatially variable.

The dates of cotton planting, N treatment implementation, and other major field operations for these two trials are presented in Table 2. The following sampling and measurements were taken from each sub-plot each year: A composite soil sample was collected at a depth of 60-cm for nitrate N and ammonium N in the soil profile on a sub-plot basis prior to treatment initiation. Canopy NDVI data were recorded at the early square and early, mid, and late bloom growth stages using the GreenSeeker® RT 200 Data Collection and Mapping System (NTech Industries, Inc., CA). A composite leaf sample (10 blades + 10 petioles) was collected four times at about the same dates when NDVI data were taken. All leaf samples were analyzed for N concentrations using a LECO Tru-Spec Analyzer. Cotton harvest was completed timely for lint yield and gin turnout by harvesting the center 4 rows. In addition, fiber quality attributes were determined on a strip plot basis each year. A post-harvest soil sample was taken for soil nitrate N and ammonium N at a 60-cm depth.

Analysis of variance was conducted for each measurement with a randomized complete block model using SAS statistical software (SAS Institute, Cary, NC). Treatment means were separated with the Fisher's protected LSD method. In addition, nonorthogonal contrasts were conducted in order to compare means of treatment combinations. Probability levels lower than 0.05 were designated as significant for all analyses.

Table 2. Major field operations performed on the trials on a university research and education center in 2011 and 2012.

Year	Operations Performed	Date Performed
2011	Planted DPL 0912 with a 8-row planter	05/11/11
	Collected pre-treatment soil samples to 60 cm deep (2 cores sub-plot^{-1})	05/26/11
	Recorded canopy NDVI prior to N treatment	06/24/11
	Side-dressed fluid N treatments by sub-plot	07/12/11
	Collected early square leaf samples (10 leaves sub-plot^{-1})	07/12/11
	Recorded canopy NDVI at early bloom	07/21/11
	Collected early bloom leaf samples (10 leaves sub-plot^{-1})	07/22/11
	Recorded canopy NDVI at mid-bloom	08/01/11
	Collected mid bloom leaf samples (10 leaves sub-plot^{-1})	08/02/11
	Recorded canopy NDVI at late bloom	08/15/11
	Collected late bloom leaf samples (10 leaves sub-plot^{-1})	08/12/11
	Harvested center 4 rows of each 8 row plot & collected seed cotton samples by strip plot	10/11/11
	Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	11/07/11
2012	Planted DPL 0912 with a 8-row planter	05/10/12
	Recorded canopy NDVI prior to N treatment	07/11/12
	Collected early square leaf samples (10 leaves sub-plot^{-1})	07/11/12
	Side-dressed fluid N treatments by sub-plot	07/18/12
	Recorded canopy NDVI at early bloom	07/19/12
	Collected early bloom leaf samples (10 leaves sub-plot^{-1})	07/19/12
	Recorded canopy NDVI at mid bloom	07/26/12

Collected mid bloom leaf samples (10 leaves sub-plot^{-1})	07/26/12
Recorded canopy NDVI at late bloom	08/08/12
Collected late bloom leaf samples (10 leaves sub-plot^{-1})	08/08/12
Harvested center 4 rows of each 8 row plot & collected seed cotton samples by strip plot	10/25/12
Collected post-harvest soil samples to 60 cm deep (2 cores sub-plot^{-1})	11/09/12

DISCUSSION OF QUALITY ASSURANCE

All ten field demonstration trials were conducted in west Tennessee within the Mississippi River Basin. Fields representative of land used for cotton production were used for this project. Historical cropping information was collected from the collaborators.

All the field demonstration trials were conducted under a randomized complete block design with three replicates. Except the N treatments, all other field operations for this project were based on the standard practices for no-till cotton production recommended by University of Tennessee Extension Service.

Almost all sampling and measurements were taken on a sub-plot basis from each location-year for developing education materials based on the normal sampling and measuring procedures.

A post-harvest soil sample was taken for soil nitrate N and ammonium N at a 60-cm depth to estimate residual N levels in soil profile after harvest. Fertilizer N use efficiency based on lint yield/fertilizer N applied (partial factor analysis) was calculated. Both are good indices which could be used to estimate the potential impacts of this project on water quality.

The analyses of soil, plant, and fiber samples were conducted by licensed commercial laboratories with the standardized procedures.

Analysis of variance was conducted on each measurement with a randomized complete block model for each location-year and the combined data of the eight location-years using SAS statistical software (SAS Institute, Cary, NC). Treatment means were separated with the Fisher's protected LSD method if the F test was significant. Probability levels lower than 0.05 were designated as significant for all the analyses. All the statistical methods used in this project are widely used for technology and development projects.

FINDINGS

FIELD TRIALS ON EQIP ELIGIBLE FAMRS (2012-2014)

Initial Soil N Fertility

In 2012, the initial inorganic NO_3^--N, NH_4^+-N, and total N (NO_3^--N + NH_4^+-N) contents in the top 60 cm of soil did not differ among the 15 strip plots which were assigned to the five treatments randomly within each replicate before the N treatments were implemented at Lauderdale, Madison, and Tipton except the total N content at Tipton (Table 3). The total N content was higher under the plots assigned to Treatments 1 and 4 than those with Treatments 2 and 3 at Tipton in 2012. The identical plots and treatment layout on the field used in 2012 was also used for 2013 and 2014 at Lauderdale. The same plots and treatment layout on the field used in 2012 was also used in 2013 at Madison. No significant differences were observed in soil initial inorganic N contents on the two new fields that were used at Madison and Carroll in 2014 (Table 3). Obviously some of the fields used for this study had high initial inorganic N levels in the soil profile from the previous crop production. High initial inorganic N levels in the soil profiles have been increasingly observed in cotton and corn production in Tennessee and other states.

Table 3. Initial soil NO_3^--N, NH_4^+-N, and total N (NO_3^--N + NH_4^+-N) contents in top 60 cm in the field trials of EQIP eligible farms during 2012-2014.

Year	Location	Treatment	NO_3^--N	NH_4^+-N	Total N
			kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
2012, 2013, & 2014	Lauderdale	1	102.8	91.5	194.3
		2	102.3	102.2	204.5
		3	116.9	109.4	226.3
		4	109.4	127.4	236.8
		5	115.7	116.0	231.7
		Significance	0.5382	0.4740	0.3195
2012 & 2013	Madison	1	44.7	52.7	97.4
		2	43.8	33.5	77.3
		3	46.0	82.4	128.4
		4	42.3	155.9	198.2
		5	47.8	229.9	277.7
		Significance	0.8418	0.6525	0.6519
2012	Tipton	1	53.6	39.8	93.4a†
		2	41.1	30.6	71.7b
		3	43.6	27.0	70.7b
		4	51.5	35.4	86.9a
		5	43.6	37.9	81.6ab
		Significance	0.4623	0.2207	**0.0325**
2014	Madison	1	38.2	39.9	78.1
		2	41.6	39.5	81.1

		3	37.8	34.0	71.8
		4	37.9	34.0	71.9
		5	34.8	36.6	71.4
		Significance	0.7470	0.2366	0.4616
2014	Carroll	1	60.3	202.4	262.7
		2	45.2	90.2	135.5
		3	45.7	85.3	131.0
		4	41.3	86.6	127.9
		5	42.4	64.3	106.7
		Significance	0.3305	0.4301	0.4095
Average	Average	1	59.4	82.0	141.4
		2	53.9	58.2	112.2
		3	57.8	65.3	123.0
		4	56.6	84.7	141.4
		5	55.9	93.5	149.5
		Significance	0.7624	0.7946	0.7800

† Values in a column within each location-year or the averages of the location-years followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.

Effects of In-season Variable-rate N Applications on Leaf N Concentrations

In 2012, leaf N concentrations were statistically similar among Treatments 1, 2, 3, 4, and 5 at early square shortly after the in-season N treatments were applied at Lauderdale, Madison, and Tipton (Table 4). No significant differences were observed in leaf N levels among the five treatments at the early or mid-bloom stage either at any location (Table 4), which meant leaf N nutrition was not improved by the variable-rate N treatments based on NDVI only or NDVI and yield maps relative to the uniform-rate N treatment at any of the three locations in 2012.

In 2013, leaf N concentrations were similar at Lauderdale but different at Madison among the plots assigned to the five treatments at early square before the in-season N treatments were imposed (Table 4), which indicated there were some variations in initial leaf N levels at Madison.

Leaf N levels at early square were higher in the plots assigned to Treatment 1 than those allocated to the other four treatments. Leaf N concentrations did not differ among the five treatments at the early and mid-bloom stages at either location after the imposition of the N treatments (Table 4), which suggests leaf N nutrition is improved by the variable-rate N treatments compared with the uniform-rate N application system.

In 2014, leaf N concentrations did not differ among the plots allocated to Treatments 1, 2, 3, 4, and 5 at early square before the in-season N treatments were implemented at Lauderdale, Madison, and Carroll (Table 4). After the implementation of the N treatments, the differences in leaf N levels were not significantly different among the five treatments at the early or mid-bloom stage (Table 4), which meant leaf N concentrations were not improved by the variable-rate N treatments relative to the uniform-rate N treatment at any location.

Overall, the variable-rate N applications generally resulted in comparable cotton N nutrition relative to the uniform-rate N applications in this study.

Table 4. Effects of in-season variable-rate N applications on leaf N concentrations at major growth stages in the field trials of EQIP eligible farms during 2012-2014.

Year	Location	Treatment	Early Square	Early Bloom	Mid-Bloom
			g kg^{-1}	g kg^{-1}	g kg^{-1}
2012	Lauderdale	1	39.1	41.4	41.6
		2	40.0	41.1	41.6
		3	39.5	42.1	42.1
		4	39.3	41.5	40.5
		5	39.7	40.9	41.7
		Significance	0.7920	0.5050	0.7100
	Madison	1	43.3	47.1	43.5
		2	40.8	47.3	43.4
		3	38.4	45.4	42.7
		4	38.6	46.2	43.6
		5	41.0	46.1	42.2
		Significance	0.0694	0.0690	0.5952

	Tipton	1	40.3	44.3	44.8
		2	40.5	42.9	44.7
		3	41.2	44.0	43.3
		4	41.0	43.3	44.3
		5	41.2	44.4	44.6
		Significance	0.6504	0.5981	0.7480
2013	Lauderdale	1	39.2	40.1	39.2
		2	39.4	40.1	39.0
		3	39.1	38.6	38.4
		4	38.7	39.9	37.6
		5	40.1	40.0	38.6
		Significance	0.5911	0.2306	0.4561
	Madison	1	43.6a†	43.7	44.0
		2	34.9b	39.8	47.9
		3	35.3b	39.9	48.5
		4	34.0b	39.6	47.5
		5	34.7b	39.9	49.3
		Significance	**<0.0001**	0.1215	0.2013
2014	Lauderdale	1	42.1	43.9	51.0
		2	43.0	43.7	48.0
		3	42.2	44.6	48.3
		4	42.7	44.0	47.3
		5	42.5	44.5	47.9
		Significance	0.9718	0.9161	0.3292

	Madison	1	40.4	39.6	41.6
		2	39.2	38.8	41.3
		3	36.8	39.7	41.9
		4	35.9	39.2	41.6
		5	38.6	38.8	43.2
		Significance	0.7266	0.9864	0.6819
	Carroll	1	40.2	38.4	39.3
		2	40.2	38.2	40.1
		3	40.6	38.9	41.7
		4	39.5	37.5	39.5
		5	38.6	37.0	41.8
		Significance	0.4071	0.5455	0.2202
Average	Average	1	41.0a	42.3	43.1
		2	39.8b	41.5	43.2
		3	39.2b	41.6	43.3
		4	38.7b	41.4	42.7
		5	39.6b	41.4	43.7
		Significance	**0.0046**	0.4214	0.4522

† Values in a column within each location-year or the averages of the location-years followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.

Leaf N concentration was adequate under the uniform-rate N systems regardless of growth stage, which might relate to the fact that initial inorganic N levels were high in the top 60 cm of soil profiles before cotton planting at most location-years in this study. All these suggest that variable-rate N treatments may not increase cotton N nutrition and yields compared with the current uniform-rate N application systems in this study.

The sensitivity of cotton leaf N to N application is greater at early bloom than at any other growth and developmental stages (Bell et al., 2003; Fritschi et al., 2004). This trend indicates monitoring of leaf N nutrition status at early bloom is especially helpful in deciding whether supplemental N application is required. Campbell and Plank (2011) recommended that the range of adequate leaf N concentration be 30 to 45 g kg^{-1} at early bloom for cotton grown in the southern United States. According to this criterion, leaf N concentration at early bloom was obviously greater than the lower limit of the sufficiency range in the uniform-rate N treatments at all the eight location-years of this study. Similarly, the range of adequate leaf N concentration is recommended to be 30 to 45 g kg^{-1} at mid-bloom for cotton (Campbell and Plank, 2011). According to this standard, leaf N at mid-bloom was also above the lower limit of the sufficiency range in the uniform-rate N treatment. Therefore, cotton yield responses to variable-rate N applications might not be expected, based on the adequate leaf N nutrition under the uniform-rate N treatment, if the recommended sufficiency leaf N ranges during early to mid-bloom are indicative of final cotton yield since the in-season variable-rate N applied treatments mostly did not result in higher N concentrations than the uniform-rate N treatment in this study.

Effects of In-season Variable-rate N Applications on Canopy NDVI Readings

Canopy NDVI is a viable vegetation index that can be used to assess plant N nutrition and plant growth status. In 2012, NDVI readings were statistically similar among the five treatments at early square shortly after the in-season N treatments were implemented at Lauderdale, Madison, and Tipton (Table 5). No significant difference was observed in NDVI among the five treatments at early or mid-bloom stage except early bloom at Madison (Table 5), where NDVI readings were lower under Treatments 2, 4, and 5 than that with Treatment 1.

In 2013, NDVI readings were similar at Lauderdale but different at Madison among the five treatments at early square prior to the imposition of the in-season N treatments (Table 5). No significant difference was observed in NDVI among the five treatments at early or mid-bloom stage except early bloom at Madison (Table 5). NDVI readings were lower under Treatments 2, 3, and 4 than Treatment 1at both early square and early bloom at Madison.

In 2014, NDVI readings did not differ among the five treatments at early square before the N treatments were implemented at Lauderdale, Madison, or Carroll (Table 5). No significant difference was observed in NDVI among the five treatments at early or mid-bloom stage regardless of location (Table 5).

Table 5. Effects of in-season variable-rate N applications on canopy NDVI at major growth stages in the field trials of EQIP eligible farms during 2012-2014.

Year	Location	Treatment	Early Square	Early Bloom	Mid-Bloom
2012	Lauderdale	1	0.860	0.859	0.874
		2	0.861	0.857	0.880

		3	0.860	0.855	0.883
		4	0.857	0.855	0.877
		5	0.863	0.857	0.875
		Significance	0.8539	0.9810	0.6746
	Madison	1	0.756	0.796a†	0.807
		2	0.715	0.732b	0.785
		3	0.742	0.767ab	0.824
		4	0.731	0.757b	0.812
		5	0.723	0.748b	0.809
		Significance	0.5351	**0.0403**	0.7623
	Tipton	1	0.799	0.833	0.862
		2	0.797	0.836	0.872
		3	0.780	0.832	0.872
		4	0.775	0.829	0.869
		5	0.769	0.827	0.863
		Significance	0.4262	0.8216	0.3657
2013	Lauderdale	1	0.826	0.881	0.870
		2	0.800	0.888	0.882
		3	0.843	0.885	0.879
		4	0.846	0.884	0.875
		5	0.849	0.876	0.866
		Significance	0.5227	0.5733	0.3128
	Madison	1	0.748a	0.855a	0.885

		2	0.684b	0.810b	0.855
		3	0.671b	0.819b	0.862
		4	0.665b	0.825b	0.862
		5	0.722a	0.836ab	0.871
		Significance	**0.0027**	**0.0386**	0.2574
2014	Lauderdale	1	0.771	0.840	0.847
		2	0.788	0.828	0.838
		3	0.762	0.825	0.864
		4	0.777	0.830	0.843
		5	0.776	0.834	0.851
		Significance	0.4046	0.5016	0.2183
	Madison	1	0.755	0.826	0.850
		2	0.725	0.807	0.833
		3	0.775	0.838	0.859
		4	0.756	0.842	0.859
		5	0.749	0.808	0.833
		Significance	0.6028	0.3339	0.4268
	Carroll	1	0.791	0.871	0.848
		2	0.774	0.874	0.853
		3	0.795	0.875	0.853
		4	0.795	0.868	0.853
		5	0.785	0.864	0.851
		Significance	0.4627	0.7927	0.9632

Average	Average	1	0.788	0.845	0.856
		2	0.768	0.829	0.850
		3	0.779	0.837	0.862
		4	0.775	0.836	0.856
		5	0.780	0.831	0.852
		Significance	0.2783	0.1193	0.4665

† Values in a column within each location-year or the averages of the location-years followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.

Effects of In-season Variable-rate N Applications on Lint Yield, Gin Turnout, and Fiber Quality

In 2012, lint yield responses to in-season variable-rate N treatments were not significant at Lauderdale or Madison, but significant at Tipton (Table 6). Lint yields were higher under Treatments 4 and 5 than that with Treatment 1 at Tipton. In 2013, lint yield did not respond significantly to the in-season N treatments at Lauderdale but responded significantly at Madison (Table 6). Lint yields were lower under Treatments 2, 3, 4, and 5 than with Treatment 1 at Madison. In 2014, lint yield responses to in-season variable-rate N treatments were not significant at Lauderdale, Madison, or Carroll (Table 6). Averaged over the eight location-years, lint yields were statistically similar among the five treatments (Table 6). Gin turnout was not significantly affected by the in-season N treatments regardless of location and year in this study (Table 6).

Table 6. Effects of in-season variable-rate N applications on lint yield and gin turnout in the field trials of EQIP eligible farms during 2012-2014.

Year	Location	Treatment	Yield	Gin turnout
			kg ha^{-1}	%
2012	Lauderdale	1	1605.6	37.2
		2	1517.3	37.3
		3	1525.3	37.2
		4	1566.6	37.4
		5	1594.8	37.1
		Significance	0.5963	0.8161

	Madison	1	997.2	40.4
		2	956.0	40.9
		3	1047.9	40.9
		4	1026.8	41.0
		5	1020.5	40.7
		Significance	0.8165	0.1273
	Tipton	1	1301.3bc†	37.9
		2	1312.4ab	37.8
		3	1250.4c	37.7
		4	1372.4a	38.0
		5	1369.1a	38.0
		Significance	**0.0084**	0.7888
2013	Lauderdale	1	890.7	38.0
		2	892.6	38.2
		3	1001.7	38.6
		4	924.4	38.8
		5	826.5	38.9
		Significance	0.6639	0.5319
	Madison	1	1562.3a	42.0
		2	1270.0b	42.5
		3	1279.3b	41.9
		4	1244.0b	42.3
		5	1347.6b	42.4
		Significance	**0.0204**	0.5212

2014	Lauderdale	1	715.4	41.0
		2	763.4	40.9
		3	690.7	40.6
		4	763.7	40.6
		5	762.4	40.7
		Significance	0.4745	0.7536
	Madison	1	1241.0	40.6
		2	1157.3	40.8
		3	1175.4	40.6
		4	1262.9	41.0
		5	1183.3	40.8
		Significance	0.6432	0.8481
	Carroll	1	782.6	41.2
		2	813.3	44.7
		3	917.7	41.6
		4	970.1	41.9
		5	950.3	41.4
		Significance	0.3397	0.4369
Average	Average	1	1137.0	39.8
		2	1085.3	40.5
		3	1111.0	39.9
		4	1141.4	40.1
		5	1131.8	41.3

	Significance	0.4724	0.5412

† Values in a column within each location-year or the averages of the location-years followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.

In 2012, fiber quality attributes were statistically similar among the five treatments at Lauderdale, Madison, and Tipton except fiber strength at Lauderdale and fiber micronair at Madison (Table 7). Fiber strength was greater under Treatments 1, 2, and 4 than that with treatment 5 at Lauderdale. Fiber micronair was higher with Treatment 3 than Treatments 1, 2 and 5 at Madison. In 2013 or 2014, none of the fiber quality attributes was affected by the in-season variable-rate N treatments at any location (Table 7). Averaged over the eight location-years, the staple, length, and uniformity of fiber responded significantly to the in-season variable-rate N treatments (Table 7). Treatment 5 had greater staple, length, and uniformity then Treatment 1 on the averages over the eight location-years.

Table 7. Effects of in-season variable-rate N applications on fiber quality in the field trials of EQIP eligible farms during 2012-2014.

Year	Location	Treatment	Micronair	Strength	Staple	Length	Uniformity
				g tex^{-1}	32nds of an inch	inch	%
2012	Lauderdale	1	5.43	31.9a†	36.7	1.14	84.3
		2	5.43	32.0a	36.7	1.15	84.0
		3	5.53	31.3 ab	36.7	1.14	84.1
		4	5.40	31.8 a	36.7	1.14	84.2
		5	5.33	30.9 b	37.3	1.16	85.1
		Significance	0.1610	**0.0372**	0.5977	0.4609	0.3712
	Madison	1	5.17bc	33.2	36.0	1.12	83.6
		2	5.10c	34.9	36.3	1.13	83.6
		3	5.30a	33.9	36.7	1.14	84.8
		4	5.27ab	33.3	35.7	1.12	83.6
		5	5.13c	34.7	36.3	1.13	84.3
		Significance	**0.0170**	0.2447	0.4609	0.7659	0.3551
	Tipton	1	5.47	31.0	35.3	1.10	83.3

		2	5.50	31.9	35.3	1.10	83.7
		3	5.50	32.3	35.7	1.12	84.3
		4	5.57	32.7	35.7	1.11	83.6
		5	5.50	33.3	35.7	1.10	84.2
		Significance	0.8386	0.2644	0.9018	0.6976	0.5253
2013	Lauderdale	1	4.40	29.3	38.0	1.20	84.5
		2	4.27	29.1	38.3	1.20	85.6
		3	4.43	28.5	38.0	1.19	84.7
		4	4.50	29.1	38.3	1.19	85.3
		5	4.20	29.2	39.3	1.23	86.1
		Significance	0.1444	0.9143	0.3521	0.2293	0.1705
	Madison	1	5.13	29.7	36.3	1.13	84.6
		2	5.27	30.4	36.7	1.13	84.9
		3	5.07	30.5	36.0	1.12	85.6
		4	5.07	30.3	36.3	1.13	85.5
		5	5.10	29.9	36.7	1.14	85.6
		Significance	0.1976	0.8223	0.8714	0.8454	0.2435

2014	Lauderdale	1	5.37	32.1	37.7	1.17	86.3
		2	5.37	32.1	37.3	1.16	86.2
		3	5.37	32.4	37.0	1.16	85.6
		4	5.40	32.9	37.0	1.16	86.2
		5	5.33	31.5	37.0	1.16	86.2
		Significance	0.9357	0.0960	0.4609	0.7892	0.2397
	Madison	1	5.00	34.8	38.0	1.19	86.3
		2	5.17	35.4	38.3	1.19	86.0
		3	5.10	35.2	38.0	1.18	85.6
		4	5.20	34.5	37.7	1.19	85.8
		5	5.17	35.1	38.7	1.21	86.4
		Significance	0.0639	0.8783	0.2115	0.2677	0.4128
	Carroll	1	4.70	32.6	37.7	1.18	82.8
		2	4.97	32.0	38.0	1.20	84.0
		3	4.83	32.9	38.3	1.20	83.8
		4	4.70	32.0	37.7	1.18	84.1

		5	4.77	32.0	38.7	1.21	84.5
		Significance	0.5454	0.9261	0.4204	0.1506	0.4187
Average	Average	1	5.08	31.8	37.0b	1.15b	84.5b
		2	5.13	32.2	37.1ab	1.16ab	84.8b
		3	5.14	32.1	37.0b	1.16ab	84.8b
		4	5.14	32.1	36.9b	1.15b	84.8b
		5	5.07	32.1	37.5a	1.17a	85.3a
		Significance	0.1614	0.7724	**0.0401**	**0.0199**	**0.0040**

† Values in a column within each location-year or the averages of the location-years followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.

Effects of In-season Variable-rate N Applications on In-season Side-dress N Fertilizer Consumption, Total Seasonal N Fertilizer Consumption, and N Use Efficiency

In 2012, both in-season side-dress N and total seasonal N fertilizer (pre-plant N + in-season side-dress N) consumptions were similar among the five treatments at Lauderdale but statistically different at Madison and Tipton (Table 8). In-season side-dress N fertilizer consumption was higher under Treatments 2, 3, 4, and 5 than that with Treatment 1 at Madison. Treatment 3 consumed less in-season side-dress N and total seasonal N fertilizer than Treatment 1 at Tipton.

In 2013, in-season side-dress N and total seasonal N consumptions differed significantly among the five treatments at Lauderdale (Table 8), where in-season and total seasonal N consumptions were lover under Treatments 2, 3, 4, and 5 than with Treatment 1. In-season side-dress N consumption was different among the five treatments at Madison (Table 8), where Treatment 1 had lower in-season side-dress N consumption than the other four treatments.

In 2014, in-season side-dress N and total N seasonal fertilizer consumptions were statistically different among the five treatments at Lauderdale and Carroll (Table 8). In-season and total seasonal N consumptions were lower under Treatments 2, 3, 4, and 5 than that with Treatment 1 at Lauderdale. Treatment 4 had lower in-season side-dress N and total seasonal N consumptions than Treatment 1 at Carroll.

Averaged over the eight location-years, all the variable-rate N management systems (Treatments 2, 3, 4, and 5) had lower total seasonal N fertilizer consumption, but higher N use efficiency than the current uniform-rate N application systems (Treatment 1) (Table 8). Specifically, the four variable-rate N application systems reduced the total seasonal N fertilizer consumption by 9.3 to 14.8% (9.8 to 15. 6 kg N ha^{-1}), but increased higher N use efficiency by 9.2 to 11.0% compared with the current uniform-rate N application systems.

Table 8. Effects of in-season variable-rate N applications on in-season side-dress N consumption, total seasonal N consumption, and N use efficiency in the field trials of EQIP eligible farms during 2012-2014.

Year	Location	Treatment	In-season N Consumption	Total N Consumption	N Use Efficiency
			kg ha^{-1}	kg ha^{-1}	kg kg^{-1}
2012	Lauderdale	1	78.5	112.1	14.3
		2	77.3	111.0	13.7
		3	86.3	119.9	12.8
		4	77.0	110.6	14.2
		5	93.0	126.7	12.7
		Significance	0.0832	0.0824	0.3130

	Madison	1	0.0b†	100.9	9.9
		2	53.3a	86.9	11.2
		3	45.4a	79.0	13.6
		4	56.1a	89.7	11.6
		5	46.3a	79.9	12.8
		Significance	**0.0019**	0.2269	0.2406
	Tipton	1	67.3a	100.9a	12.9
		2	60.8ab	94.4ab	13.9
		3	53.3b	86.9b	14.5
		4	68.7a	102.9a	13.4
		5	62.6a	96.2a	14.3
		Significance	**0.0283**	**0.0285**	0.2976
2013	Lauderdale	1	78.5a	112.1a	7.9
		2	62.0b	95.7b	9.4
		3	53.8c	87.5c	11.5
		4	67.3b	100.9b	9.2
		5	63.9b	97.5b	8.5
		Significance	**0.0006**	**0.0006**	0.1677
	Madison	1	0.0c	100.9a	15.5
		2	51.8b	85.5b	14.9
		3	65.9a	99.5a	12.8
		4	58.9ab	92.5ab	13.5
		5	56.1ab	89.7ab	15.0
		Significance	**<0.0001**	0.0718	0.1428

2014	Lauderdale	1	78.5a	112.1a	6.4b
		2	40.0c	73.6c	10.4a
		3	59.0b	92.3b	7.5b
		4	50.1bc	83.7bc	9.1a
		5	49.3bc	82.9bc	9.2a
		Significance	**0.0005**	**0.0005**	**0.0008**
	Madison	1	67.3	100.9	12.3
		2	54.7	88.3	13.2
		3	51.4	85.0	13.9
		4	53.7	87.4	14.5
		5	60.3	93.9	12.8
		Significance	0.1009	0.0997	0.6038
	Carroll	1	67.3a	100.9a	7.8
		2	50.4b	84.1b	9.7
		3	61.7a	95.3a	9.6
		4	50.9b	84.6b	11.5
		5	62.2a	95.8a	9.9
		Significance	**0.0032**	**0.0033**	0.1357
Average	Average	1	54.7c	105.1a	10.9b
		2	56.3bc	89.5c	12.0a
		3	59.6ab	93.2bc	12.0a
		4	60.3a	94.0b	12.1a
		5	61.7a	95.3b	11.9a

	Significance	**0.0021**	**<0.0001**	**0.0224**

† Values in a column within each location-year or the averages of the location-years followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.

Effects of In-season Variable-rate N Applications on Post-harvest N Contents in the Soil Profile

An important focus of N management strategies should be the reduction of soil residual N. Reducing N application rates for cotton, when appropriate, likely will reduce post-harvest residual N levels in the soil profile, and thus decrease the potential of N losses from soil to ground and surface waters.

No significant difference was observed in post-harvest residual N (NO_3^--N + NH_4^+-N) level in the top 60 cm soil profile among the five treatments at any location-year or on the averages of the eight location-years (Table 9). Overall, our results suggest that the imposition of in-season variable-rate N applications do not significantly affect the post-harvest residual N levels in soil compared with the current uniform-rate N application systems, which may relate to the possibility that the applied N was either taken up by cotton plants, lost out of the soil via nitrate leaching to deeper layers, or/and lost via ammonium volatilization to the atmosphere during the growing season. Therefore, regardless how large the differences were in the N application rates among the five N management systems, the post-harvest residual N levels were similar among the treatments in the top 60 cm soil profile.

Similarly, Boquet and Breitenbeck (2000) reported that N fertilization on cotton for optimal yield was exceptionally efficient and probably did not result in N losses to nearby surface and ground waters. In contrast, soil samples collected after 3 years of continuous N fertilization resulted in a significant increase in NO_3^--N concentration at the 15-45 cm depth only in the plots treated with the highest N rate of 224 kg N ha^{-1} annually (McConnell et al., 1993). Results of a 5-yr study showed excessive N buildup in many California cotton soils due to the high N application rates for previous cotton or other rotational crops (Hutmacher et al., 2004). Bronson et al. (2001) found that residual soil NO_3^--N accumulated to high levels in the low irrigation, high N fertilizer treatments, but remained stable in the high irrigation, low N treatments.

Table 9. Effects of in-season variable-rate N applications on post-harvest residual soil N contents (0-60 cm) in the field trials of EQIP eligible farms during 2012-2014.

Year	Location	Treatment	NO_3^--N	NH^+-N	Total N
			kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
2012	Lauderdale	1	21.0	38.3	59.3
		2	40.0	49.3	89.3

		3	34.9	37.4	72.3
		4	17.3	36.8	53.8
		5	23.3	41.9	65.2
		Significance	0.4275	0.2090	0.0812
	Madison	1	14.9	24.1	39.0
		2	40.4	34.1	74.5
		3	17.4	23.8	41.2
		4	43.0	26.1	69.1
		5	32.4	23.9	56.3
		Significance	0.3218	0.6238	0.2850
	Tipton	1	29.3	34.6	63.9
		2	19.3	30.6	49.9
		3	13.1	31.7	44.8
		4	17.9	31.3	49.2
		5	12.8	30.0	42.7
		Significance	0.6341	0.9193	0.7182
2013	Lauderdale	1	29.6	25.2	54.8
		2	34.7	22.8	57.5
		3	30.2	24.0	54.2
		4	29.1	21.4	50.5
		5	26.7	24.7	51.4
		Significance	0.7988	0.9755	0.9581
	Madison	1	16.4	14.3	30.7

		2	23.3	13.2	36.5
		3	17.0	13.4	30.4
		4	23.3	12.3	35.6
		5	23.6	13.1	36.7
		Significance	0.6304	0.9795	0.8952
2014	Lauderdale	1	24.6	37.8	62.4
		2	18.8	33.0	51.8
		3	18.1	13.2	31.3
		4	21.1	21.4	42.5
		5	26.8	48.0	74.8
		Significance	0.2166	0.4432	0.3233
	Madison	1	16.9	17.5	34.4
		2	15.2	18.1	33.3
		3	15.1	12.9	28.0
		4	14.5	14.1	28.6
		5	15.7	17.5	33.2
		Significance	0.9235	0.3836	0.6283
	Carroll	1	27.0	12.6	39.6
		2	28.7	8.8	37.5
		3	25.6	15.5	41.1
		4	27.6	11.2	38.8
		5	29.3	12.3	41.6
		Significance	0.9456	0.1551	0.9019

Average	Average	1	22.5	25.6	48.1
		2	27.6	26.2	53.8
		3	21.4	21.5	42.9
		4	24.2	21.8	46.0
		5	23.8	26.4	50.2
		Significance	0.5834	0.4194	0.3326

FIELD TRIALS ON A UNIVERSITY RESEARCH AND EDUCATION CENTER (2011-2012)

Initial Soil N Fertility

Initial inorganic N (NO_3^--N + NH_4^+-N) content in the top 60 cm of soil varied substantially among the 144 sub plots with a range of the minimum 3 mg kg^{-1} to the maximum 57 mg kg^{-1} prior to treatment imposition in spring 2011 in this study (data not presented). These variations might relate to the soil types in this field. The average initial inorganic N level in the top 60 cm of soil was 6.8, 7.4, 9.8, 8.0 10.4, and 8.8 mg kg^{-1}, equivalent to 60.8, 66.4, 88.0, 71.6, 93.2 and 78.8 kg ha^{-1}, for the plots allocated to Treatments 1, 2, 3, 4, 5, and 6, respectively, before treatment application in spring 2011. Obviously this field had pretty high residual inorganic N level in the soil profile from the previous crop production. High residual inorganic N level in soil profile has been increasingly observed in cotton and corn production in Tennessee and other states.

Effects of In-season Variable-rate N Applications on Leaf N Concentrations

Leaf N concentrations were similar among the plots allocated to Treatments 1, 2, 3, 4, 5, and 6, respectively, at early square before the in-season side-dress N treatments were applied when the results of 2011 and 2012 were combined (Table 10). However, significant differences in leaf N were observed among the six treatments at the early, mid, and late bloom stages (Table 10). Leaf N concentrations were mostly significantly higher under the five N applied treatments than that with the zero N treatment (Treatment 1) during early bloom to late bloom. Treatments 3, 4, and 5 had significantly higher leaf N concentrations than Treatment 1, and significantly or numerically higher leaf N levels than Treatments 2 and 6 at the early, mid, and late bloom stages.

Under nonorthogonal contrasts, Applied N, Uniform N, and Variable N all resulted in significantly higher leaf N concentrations than Zero N at the early, mid, and late bloom stages (Table 10). However, Variable N had similar leaf N level as Uniform N regardless of growth stage.

Both ANOVA and nonorthogonal contrast analyses of this study indicate that in-season side-dress N application improve cotton N nutrition irrespective of the application method (uniform-rate or variable-rate); but variable-rate N applications do not improve cotton N nutrition compared with the uniform-rate N applications on this upland field with high initial soil N fertility.

Table 10. Effects of in-season variable-rate N applications on leaf N concentrations at major growth stages on a university research and education center averaged over 2011 and 2012.

Treatment	Early Square	Early Bloom	Mid-Bloom	Late Bloom
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}
1	40.5	38.3c†	35.8c	34.4b
2	40.4	40.8ab	36.8bc	36.9ab
3	40.7	41.7ab	38.4a	38.8a
4	41.3	41.4ab	37.6ab	37.3a
5	41.8	42.3a	37.7ab	38.4a
6	39.6	40.2bc	37.0bc	36.5ab
Significance	ns‡	**	**	*
Contrast				
Applied N vs. Zero N§	ns	***	**	**
Uniform N vs. Zero N	ns	**	**	**
Variable N vs. Zero N	ns	**	**	**
Variable N vs. Uniform	ns	ns	ns	ns

† Values within a column followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.
‡*, significant at P<0.05; **, significant at P<0.01; ***, significant at P<0.001; ns, not significant at P<0.05.
§ Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

It was expected that leaf N concentration was pretty high under the zero N treatment regardless of growth stage, which might relate to the fact that the initial inorganic N level was high in the top 60 cm of soil profile and 26 kg N ha^{-1} was applied across the treatments as diammonium phosphate before cotton planting in both years.

Campbell and Plank (2011) recommended that the range of adequate leaf N concentration be 30 to 45 g kg^{-1} at early bloom for cotton grown in the southern United States. According to this criterion, leaf N concentration at early bloom was greater than the lower limit of the sufficiency range in the zero N treatment of this study. Similarly, the range of adequate leaf N concentration is recommended to be 30 to 45 g kg^{-1} at late bloom for cotton (Campbell and Plank, 2011). According to this standard, leaf N at late bloom was also above the lower limit of the sufficiency range in zero N. Therefore, cotton yield responses to N applications might not be expected, based on the adequate leaf N nutrition under the zero N treatment, if the recommended sufficiency leaf N ranges during early to late bloom are indicative of final cotton yield, although the in-season N applied treatments mostly resulted in higher N concentrations than the zero N treatment in this study.

Effects of In-season Variable-rate N Applications on Canopy NDVI Readings

Canopy NDVI readings were statistically similar among the six treatments at early square before the N treatments were implemented averaged over 2011 and 2012 (data not presented). Unlike leaf N concentrations, no significant difference in NDVI was observed among the six treatments at early, mid, or late bloom stage (data not presented). Similarly, nonorthogonal contrasts did not show any beneficial effect of Applied N, Uniform N, or Variable N on NDVI over Zero N at any growth stage (data not presented).

Effects of In-season Variable-rate N Applications on Lint Yield, Gin Turnout, and Fiber Quality

Lint yield responses to in-season side-dress N treatments were not significant on the averages of 2011 and 2012 (Table 11). Numerically, lint yields were higher under Treatments 2 and 5 than those with the other treatments. Gin turnout was not significantly affected by the N treatments (data not presented). None of the fiber quality attributes was influenced by the N treatments (Table 11).

Table 11. Effects of in-season variable-rate N applications on lint yield, gin turnout, and fiber quality on a university research and education center averaged over 2011 and 2012.

Treatment	Yield	Micronair	Strength	Length	Uniformity
	kg ha^{-1}		g tex^{-1}	cm	%
1	1037.0	4.95	32.9	2.84	83.2
2	1127.7	4.90	33.3	2.82	83.3
3	1076.4	4.95	32.2	2.77	82.3
4	1089.2	4.95	33.0	2.82	82.9
5	1155.5	4.85	33.1	2.82	83.7
6	1075.5	5.00	32.2	2.77	82.7
Significance	ns†	ns	ns	ns	ns

Contrast					
Applied N vs. Zero‡	ns	ns	ns	ns	ns
Uniform N vs. Zero N	ns	ns	ns	ns	ns
Variable N vs. Zero N	ns	ns	ns	ns	ns
Variable N vs.	ns	ns	ns	ns	ns

† ns, not significant at P<0.05.
‡ Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

Similarly, Main et al. (2013) [15] reported only 11 of 20 site-years across the Cotton Belt region in which there was a cotton lint yield response to applied N. They observed when 45 kg N ha^{-1} was applied, yields were greater than when no N was applied, but were less than yields where 90 to 134 kg N ha^{-1} was applied on the N responsive site-years; however, when all the site-years, both N responsive and non-responsive, were considered, 45 kg N ha^{-1} increased yields above no applied N, but additional N above 45 kg N ha^{-1} did not improve lint yield.

Effects of In-season Variable-rate N Applications on In-season N Fertilizer Consumption

The in-season side-dress N fertilizer consumption was 0, 56.0, 78.4, 68.7, 63.5, and 67.2 kg N ha^{-1} for Treatments 1 to 6, respectively, averaged over 2011 and 2012 in this study (Table 12). The three variable-rate N application algorithms (Treatments 4, 5, and 6) consumed 7.8 to 12.3 kg ha^{-1} more N than the low uniform-rate application of 56.0 kg N ha^{-1}, but used 10.1 to 14.6 kg ha^{-1} less of N than the high uniform rate application of 78.4 kg N ha^{-1}. Under nonorthogonal contrasts, Applied N, Uniform N, and Variable N all consumed more in-season side- dress N fertilizer than the Zero N treatment, but Variable N used similar in-season side-dress N fertilizer as Uniform N (Table 12).

Table 12. Effects of in-season variable-rate N applications on in-season side-dress N consumption and post-harvest soil residual N (0-60 cm) on a university research and education center averaged over 2011 and 2012.

Treatment	Side-dress N Consumption	Soil Residual N
	kg ha^{-1}	mg kg^{-1}
1	0c†	7.65

2	56.0b	7.28
3	78.4ab	8.58
4	68.7ab	8.95
5	63.5ab	9.36
6	67.2ab	7.78
Significance	***‡	ns
Contrast		
Applied N vs. Zero N§	***	ns
Uniform N vs. Zero N	***	ns
Variable N vs. Zero N	***	ns
Variable N vs. Uniform N	ns	ns

† * Values within a column followed by the same letter are not significantly different with Fisher's protected LSD at the 0.05 probability level.
‡ ***, significant at P<0.001; ns, not significant at P<0.05.
§ Applied N vs. Zero N refers to the comparison of average over the five N applied treatments (Treatments 2, 3, 4, 5, and 6) with the zero N treatment (Treatment 1); Uniform N vs. Zero N refers to the comparison of average over the two uniform-rate N treatments (Treatments 2 and 3) with the zero N treatment; Variable N vs. Zero N refers to the comparison of average over the three variable-rate N treatments (Treatments 4, 5, and 6) with the zero N treatment; Variable N vs. Uniform N refers to the comparison of average over the three variable-rate N treatments with the two uniform-rate N treatments.

Effects of In-season Variable-rate N Applications on Post-Harvest Soil Residual N Contents

An important aspect of N management strategies should be the reduction of soil residual N. Reducing N application rates for cotton, when appropriate, will reduce post-harvest residual N levels in the soil profile, and thus decrease the loss of N from soil to ground and surface waters.

No significant differences were observed in post-harvest soil residual N (NO_3^--N + NH_4^+-N) level in the top 60 cm soil profile among the six treatments on the averages of 2011 and 2012 (Table 12). Numerically, soil residual N level was higher under Treatments 3, 4, and 5 than those with the other treatments after cotton harvest. Overall, our results suggest that the application of in-season side-dress N ranging from 0 to 78.4 kg N ha^{-1} do not significantly affect the post-harvest residual N levels in the soil profile, which may relate to the possibility that applied N was either taken up by cotton plants or lost out of the soil via nitrate leaching to deeper layers or ammonium volatilization to the atmosphere during the growing season.

CONCLUSIONS AND RECOMMENDATIONS

In the eight field trials on EQIP eligible farms, leaf N concentrations were generally comparable under the in-season sensor-based variable-rate N management systems relative to the current uniform-rate N application systems during early square to mid-bloom. Similarly, rare significant differences in canopy NDVI were observed because of in-season variable-rate N applications over the uniform-rate N applications. The in-season variable-rate N management systems via side-dress produced higher cotton lint yield at one location-year, similar lint yield at six location-years, but lower lint yield at one location-year than the current uniform-rate N application systems. The in-season variable-rate N management systems did not affect post-harvest residual N levels in top 60 cm of the soil profile relative to the current uniform-rate N application systems. Averaged over the eight location-years, the in-season sensor-based variable-rate N management systems had significantly lower seasonal N fertilizer consumption, but higher N use efficiency than the current uniform-rate N application systems. Specifically, the in-season variable-rate N management systems reduced the seasonal N fertilizer consumption by 9.3 to 14.8% (9.8 to 15. 6 kg N ha^{-1}), but increased higher N use efficiency by 9.2 to 11.0% compared with the current uniform-rate N application systems. No significant positive effect of in-season variable-rate N management systems was observed on post-harvest residual N levels in the top 60 cm of soil. The benefits of incorporating yield maps of previous years into the in-season sensor-based variable-rate N management systems were generally not noticeable in terms of cotton yield, seasonal N fertilizer consumption, N sue efficiency, and post-harvest residual soil N level. Our results suggest that in-season sensor-based variable-rate N management systems use less N fertilizer to produce comparable cotton yield via increasing N use efficiency relative to the current uniform-rate N application systems. The in-season sensor-based variable-rate N management systems are viable tools that can be used by producers on their farms to manage variations within the field.

APPENDICES

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Presentations

Below are some selected presentations about this project mainly at international, national, and regional conferences. Many other talks about this project were given at various local and state Extension meetings and other outreach activities.

Yin, X., and S. Schaeffer. 2014. Variable rate nitrogen application on cotton. UT No-Till Field Day. *Oral.* Milan, TN, Jul. 24 (20 min., 6 sessions, 125 attendees in total).

Stefanini, M.R., J.A. Larson, C.N. Boyer, S.H. Cho, D. Lambert, and X. Yin. 2015. Profitability of variable-rate technology in cotton production. 2015 Southern Agricultural Economics Association (SAEA) Annual Meeting. *Abstract.* Atlanta, GA. Jan. 31-Feb. 3.

Yin, X. 2014. Precision nitrogen management for cotton. Visitors from Argentina. *Oral.* Milan, TN, Sep. 5 (20 min., 32 attendees).

Griffin, T.W., E.M. Barnes, P.A. Allen, P. Andrade-Sánchez, D.B. Arnall, K. Balkcom, L.T. Barber, P. Bauer, K.F. Bronson, M.J. Buschermohle, A.P. Jones, Y. Ge, G. Roberson, R.K. Taylor. B.S. Tubana, J.J. Varco, G. Vellidis, E.D. Vories, J.B. Wilkerson, and X. Yin. 2014. Pooled Analysis of Combined Primary Data across Multiple States and Investigators for the Development of a NDVI-Based On-the-Go Nitrogen Application Algorithm for Cotton. ASABE Paper No. 1900279. St. Joseph, MI: ASABE.

Yin, X., C.L. Main, C.O. Gwathmey, and D.D. Tyler. 2013. Variable-rate precision injection of fluid nitrogen fertilizer for cotton. Proceedings of Fluid Fertilizer Foundation Forum. Phoenix, AZ. Feb. 18-19 (20 min., 150 attendees).

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Economic Analysis of Precision Nitrogen Injection Using Integrated Optical Sensing and Variable Rate Technologies

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Final Report

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EXECUTIVE SUMMARRY

This project addresses USDA NRCS priority to accelerate conservation in the Mississippi River Basin (MRB) to continue to reduce nutrient and sediment loading to local and regional water bodies and to improve efficiency in using water supplies, particularly in the southern states. The goal of this project was to encourage producer adoption of new precision nitrogen (N) management technologies and systems on their farms to reduce N fertilizer consumption and potential N losses, improve cotton productivity, and thus improve water quality and grower profitability in the MRB states of Louisiana, Missouri, Mississippi, and Tennessee. Precision agriculture (PA) may benefit cotton farms in the MRB by reducing the amount of excess N from cotton production released into the environment, increasing net returns to the grower, and reducing the risk of profit losses due to spatial and temporal variability. The objectives of the demonstration project economic analysis were to determine the profitability, risk management potential, and N production use efficiency of using real-time optical sensing and variable-rate technologies (VRT) to manage spatial variability in cotton production.

Data collected from 29 field demonstration trials in Tennessee, Louisiana, Mississippi, and Missouri from 2011 to 2014 included lint yields harvested and N rates calculated from three N rate management strategies. The first N treatment was the existing farmer practice, the second was a VRT treatment using optical sensing technology information, and the third was a VRT treatment using optical sensing and yield monitor information. The two PA strategies were compared to the existing farmer practice. In addition, soil properties, landscape, and weather were examined to determine their effects on lint yields, net returns, N rates, and N production use efficiency. Three statistical models were used in the project to evaluate the lint yields, N rates, net returns, and N production use efficiency from the strip-plots on the 29 fields. The first model was an analysis of variance (ANOVA) model used to identify treatment mean differences while controlling for soil, landscape, and weather factors. The second model was an ANOVA model that measured soil and climate effects on mean differences between the optical sensing and VRT technologies and the farmer practice. The third model was a logistic model to determine the risk (probability) of lint yield and net return losses using optical sensing and VRT relative to the current farmer practice. The statistical and economic analysis with the models was used to identify conditions where optical sensing and VRT was profitable, provided potential risk management benefits, and improved N production use efficiency.

The two key findings of the statistical and economic analysis were as follows. First, the real-time optical sensing and VRT treatments indicated some N fertilizer savings but were not more profitable on average than the existing farmer N management practices. There was some evidence of significantly higher mean net returns using VRT to manage N compared to the current practice at the sub-plot level, but the field level showed no difference. Second, there were risk management benefits identified at the field level using VRT compared to the farmer practice. Fields with lower lint yields tended to produce higher net returns with optical sensing and VRT than with the farmer practice which may help farmers manage risk on fields with this characteristic. Three additional inferred conclusions may aid in cotton farmers' decisions about the precision N management technologies evaluated in this project. First, the optical sensing and VRT treatments may not apply enough N to significantly increase lint yields relative to the existing farmer practice. Second, changes in the N rate for optical sensing and VRT relative to the farmer practice were field/farm specific. Four locations (Tensas Middle, LA, Gibson, TN, Lauderdale, TN, and Leflore, MS) realized significantly lower N rates applied in at least one form of VRT N fertilizer application. Four locations had higher N rates with optical sensing and

VRT (Madison North, TN, Adams, MS, Tensas North, LA, and Tensas South, LA). Finally, the N rates across the 29 field demonstrations were not low enough to increase N use efficiency and encourage environmental benefits. Even though the fields in the demonstration project represented a range of soils, landscapes, and weather in the southern MRB locations used in the project, there was likely not enough spatial and temporal variability within the fields that optical sensing VRT treatments did not make a difference in field level mean net returns.

INTRODUCTION

This project addressed the USDA NRCS priority to accelerate conservation in the Mississippi River Basin (MRB) to continue to reduce nutrient and sediment loading to local and regional water bodies and to improve efficiency in using water supplies, particularly in the southern states. The goal of this project was to encourage producer adoption of new precision nitrogen (N) management technologies and systems on their farms to reduce N fertilizer consumption and potential N losses, improve cotton productivity, and thus improve water quality and grower profitability in the Mississippi River Basin (MRB). The overall project objectives were:

1) To demonstrate to producers and other interested groups the integration of sensor based variable rate technology (VRT) N fertilization into their current production systems;

2) To demonstrate the impacts of VRT precision N management systems based on optical sensing of crop canopy compared with the current uniform-rate N application system in terms of fertilizer N use efficiency, post-harvest residual soil N subject to loss, and potential improvements to water quality, cotton yield, and grower profitability; and

3) To show the benefits of incorporating yield maps and other field and soil information into an optical sensor-based VRT precision N management system based on vegetation indices.

Therefore, the purpose of this project was to demonstrate to producers and other interested groups the procedures and benefits of utilizing these innovative precision technologies: optical sensing and VRT N application, to manage N spatial variability within individual fields of cotton. The two specific objectives related to the statistical and economic evaluation of the optical sensing and VRT N technologies demonstrated in the project were:

1) To determine the profitability and risk management potential of using real-time optical sensing and VRT to manage spatial variability in N in cotton fields in the MRB states (Louisiana, Mississippi, Missouri, and Tennessee), and

2) To ascertain how real-time optical sensing and VRT affect N use and N production use efficiency in cotton production.

To accomplish the aforementioned project goals and objectives, twenty-nine cotton N fertilizer field demonstration trials were conducted from 2011 to 2014 in Tennessee, Mississippi, Louisiana, and Missouri. Ten of the trials occurred in Tennessee, four in Mississippi, nine in Louisiana, and six in Missouri. The county/parish locations of the farmer fields in each state that were used in the project are presented in Figure 1. The trials on each cotton field tested the existing farmer practice (FP) N application versus two VRT N applications based on optical sensing and optical sensing and yield monitoring information. Each EQIP eligible farmer planted cotton across nine strip-plots containing 10 sub-plots each that measure roughly 30.5 meters by 11.6 meters with the exception of Missouri where the data was collected by plot. Lint yields and N rates for each treatment for the 29 site-years were used for the statistical and economic analysis. The farm field dataset was augmented with soil, landscape, and weather data collected to determine differences within and between fields that may influence the profitability, risk management, and N use efficiency of the alternative N management practices. The soils, landscape, and weather characteristics included elevation, soil texture, soil erosion factors, soil water holding capacity, organic matter, soil depth, and growing degree days.

Three statistical models were developed to evaluate the lint yields, N rates, net returns, and N production use efficiency from the strip-plots on the 29 fields. The first model was an analysis of variance (ANOVA) model used to identify treatment mean differences while controlling for soils, landscape, and weather factors. The second model was an ANOVA model that measured soils, landscape, and weather effects on mean differences between the optical sensing and VRT technologies and FP. The third model was a logistic model to test for the risk (probability) of lint yield and net return losses using optical sensing and VRT relative to the current FP. The statistical and economic analysis with the models was used to identify field conditions where optical sensing and VRT was profitable, provided risk management benefits, and provided improvements in N production use efficiency.

The key personnel who implemented the farmer field demonstrations and conducted the statistical and economic analyses and the descriptions of their qualifications are as follows.

- Frank Yin, Associate Professor of Systems Agronomy, University of Tennessee Institute of Agriculture (UTIA). Ph.D., Purdue University. He has over 20 years of experience in agronomic research and extension including precision agriculture. He was in charge of project coordination among the four states, and was responsible for experimental design, trial establishment, data collection, and conducting demonstration activities in Tennessee.

- Jac J. Varco, Professor of Agronomy, Mississippi State University. Ph.D., University of Kentucky. He has over 30 years of experience in nutrient management including precision agriculture utilizing remote sensing and canopy reflectance. For Mississippi locations, he was in charge of site selection and grower collaboration, experimental design, trial establishment, data collection, and conducting demonstration activities.

- David Dunn, Professor of Soil Science, University of Missouri. Ph.D., University of Missouri. He has over 30 years of experience in soil testing and precision agriculture, and was in charge of site selection and grower collaboration, experimental design, trial establishment, data collection, and conducting demonstration activities in Missouri.

- Brenda S. Tubaña, Assistant Professor of Soil Fertility, Louisiana State University. Ph.D., Oklahoma State University. She has over 10 years of experience in soil fertility and precision agriculture, and was in charge of experimental design, trial establishment, data collection, and conducting demonstration activities in Louisiana.

- James A. Larson, Professor of Ag. Economics, UTIA. Ph.D., Oklahoma State University. He has over 20 years of experience in production economics, farm management, and risk analysis, and he was responsible for the statistical and economic analysis for this project. Dr. Larson supervised the Master's thesis project (http://trace.tennessee.edu/utk_gradthes/3515/) by Melissa Stefanini (MS degree awarded August 2015) that analyzed the lint yield and nitrogen application data from the field demonstrations supported by the project.

- Chris Main, Associate Professor in Cotton and Wheat Extension, UTIA. Ph.D., University of Tennessee. He has over 10 years of experience in cotton and wheat extension and research, and conducted Extension and outreach activities in Tennessee.

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- Hugh Savoy, Associate Professor in Soil Fertility Extension, UTIA. Ph.D. University of Tennessee. He has 30 years of experience in soil fertility Extension and research, and conducted Extension and outreach activities in Tennessee.

- Michael Buschermohle, Professor and Extension Precision Agriculture Specialist, UTIA. Ph.D., Clemson Univ. He has over 15 years of experience in conducting precision agriculture educational programs, and conducted Extension and outreach activities in Tennessee.

- Don Tyler, Professor of Soil Science, UTIA. Ph.D., University of Kentucky. He has over forty years of experience in no-till production and precision farming, and participated in experimental design and trial evaluations in Tennessee.

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BACKGROUND

Fertilizer N is an expensive and important input in the production of crops such as upland cotton. Crop nutrient N consumption more than doubled, from 6.0 million to 13.7 million short tons, from 1967 to 2007 in the United States (USDA 2013). The United States Department of Agriculture (USDA) estimated that farmers spent $7.2 billion on anhydrous ammonia and N solutions in 2011 (USDA 2013). The increased use of N fertilizer has raised concerns about high production cost and potential environmental damages due to that N can be dispersed into the surrounding environment in different ways. N is unstable after it is applied (Raun and Johnson 1999) and can be lost into the environment through gaseous emissions, leaching, runoff, and soil denitrification (Peng et al. 2006). Waterways such as the Mississippi River and the Chesapeake Bay have experienced changes in water quality due to increased fertilizer use (Turner and Rabalais 1991; Roberts and Prince 2010).

It is very difficult for farmers to handle the excess lost N. However, they can apply the fertilizer more efficiently to limit the amount of N released to the environment and reduce the cost. Conventional rates of fertilizer N used by growers were developed in small individual fields with little spatial variability (Isik and Khanna 2003). Uniform N rates were applied across entire fields that likely varied in soils and other field factors, resulting in more or less N fertilizer (i.e., over- or under-application) to the crop than necessary (Scharf et al. 2005; Scharf et al. 2011; Vetsch et al. 1995; Isik and Khanna 2003). Compared with economically optimal rates, over-application can increase production cost and excess N released into the environment, and under-application can decrease crop yield and revenue. Both over- and under- application reduces profits (Lambert, Lowenberg-DeBoer, and Malzer 2006).

Precision agriculture (PA) technology can help farmers more efficiently apply the fertilizer, avoiding over- or under- application. PA was defined by the National Research Council (1997) as "a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production (p. 17)," growers can utilize several technologies to better manage N fertilizer application. PA allows producers to use within-field, site-specific information about soil and plant input requirements to apply the right amount of input in the right place at the right time (Bongiovanni and Lowenber-Deboer, 2004). PA technologies have been developed to identify variability within a field and provide site-specific input applications that match varying crop and soil needs (Cochran et al., 2006; Roberts et al., 2004; Zhou et al., 2015). VRT manifests the concept of PA and accomplishes those goals. For example, switching N application from a uniform rate technology (URT) to a variable rate technology (VRT) by varying the rate based on variable field factors (Sawyer 1994) can reduce the amount of wasted N, costs, labor (Raun et al. 2002; Tubaña et al. 2008), excess N pollution leaching in the groundwater (Biermacher et al. 2009b; Raun and Johnson 1999; Roberts et al. 2002; Watkins, Lu, and Huang 1998), and surface N runoff contributing to water pollution (Larkin et al. 2005; Raun and Johnson 1999; Scharf et al. 2005; Isik and Khanna 2003). A literature summary is in Appendix Table 1.

Managing N using PA technologies has the potential to increase profits and decrease N losses to the environment as well as risk in cotton production. The pertinent literature has progressed over time along with the technology. Early literature begins with simulation analysis using the Environmental Policy Integrated Climate (EPIC) model to estimate the economic and environmental benefits from VRT (Roberts et al. 2002; Watkins, Lu, and Huang 1998). Their studies found positive environmental impacts of adopting VRT N application but no economic benefits.

Later studies analyzed the impacts of VRT (N, phosphorus, and lime) compared to URT on production of rice (Oryza sativa L.) (Hu et al. 2007; Peng et al. 2006), corn (Bongiovanni and Lowenberg-DeBoer, 2000; Lambert et al. 2004; Lambert et al. 2006; Maine et al. 2010; Wang et al. 2003), and wheat (Biermacher et al. 2006; Biermacher et al. 2009b; Raun et al. 2002; Raun et al. 2005) using experiments and farm field trial data. Peng et al. (2006) and Hu et al. (2007) used experimental data on irrigated rice in four Chinese provinces to compare current farming practices with alternative N management systems to evaluate the potential of N efficiency improvement. Peng et al. (2006) compared current practices with two site specific management systems: real-time N management and fixed-time adjustable-dose N management. Their study found that site specific N management systems reduced N applied, increased NUE (nitrogen use efficiency), and produced similar or higher yields than current farming practices. Hu et al. (2007) had similar findings using three N application management techniques: current N practices, site specific management, and a modified site specific management plan. Both Peng et al. (2006) and Hu et al. (2007) found that NUE increased by reducing the N rate applied without reducing yields.

In corn production, Lambert et al. (2004), Lambert et al. (2006), Wang et al. (2003), and Maine et al. (2010) examined the economic benefits of adopting VRT. Lambert et al. (2004) did an economic analysis of VRT in corn response to N by comparing four spatial regression methods on data from an experiment conducted in 1999 in Córdoba Province, Argentina. Their study found that net returns to N use were found to be \$1 to \$2 ha^{-1} more profitable using VRT compared to URT. Lambert et al. (2006) did a spatial analysis on yield response to VRT using N and/or phosphorus on a 5 year corn-soybean rotation in Windom, Minnesota. Their results found that average returns to VRT (including both N and phosphorus) were \$28 ha^{-1} more profitable than the URT management system. Wang et al. (2003) found profitability and environmental benefits through VRT N application versus two different URT N applications using data collected from four claypan soil fields in Missouri. Bongiovanni and Lowenberg-DeBoer (2000) estimated the profitability of VRT lime application to corn and soybean production in 18 sites spanning the Eastern and Midwestern United States and one in Canada. Their results found that using VRT increased profits. Maine et al. (2007) and Maine et al. (2010) analyzed the profitability of VRT phosphorus and N fertilizer applications on corn production in South Africa and found that VRT was more profitable over conventional methods.

The most recent literature involves optical sensing, sensor based technology such as GreenSeeker™, with VRT for analysis of profitability, NUE, and environmental benefits for production of wheat (Triticum aestivum L.) and corn (Zea mays L.) in experiments and farm field trials (Biermacher et al. 2006; Biermacher et al. 2009b; Butchee, May, and Arnall 2011; Ortiz-Monasterio and Raun 2007; Raun et al. 2002; Raun et al. 2005; Scharf et al. 2011). Scarf et al. (2011) assessed sensor based, VRT N application versus current farmer uniform N rates in corn production in Missouri. Their study found that VRT N fertilizer applications increased yields by 110 kg ha^{-1}, reduced N by 15 kg ha^{-1}, and increased partial profits (value of corn grain minus cost of N applied) by \$42 ha^{-1} over producer chosen uniform N rates. Raun et al. (2002) analyzed optical sensing and VRT compared with URT for winter wheat production in Oklahoma. They found that NUE on average increased by at least 15% with extra income (\$4.00 to \$5.00 ha^{-1}) for VRT compared with URT and optical sensing would be most beneficial in areas of high spatial variability. Also, Raun et al. (2005) found N reductions and an increase of 15% in NUE through the adoption of optical sensing. Biermacher et al. (2006) estimated net returns of adopting sensor based precision agriculture in wheat production using 30 years of data in Oklahoma. Their study found that the adoption reduced pre-plant N by 59% to 82% and achieved an average profitability of \$21.80 to \$24.30 ha^{-1}. Ortiz-Monasterio and Raun (2007) assessed VRT using N-rich strips with GreenSeeker™ sensing technology compared with conventional practices for wheat production in an eight-field-trial experiment in Yaqui Valley, Mexico. Their study found that using optical sensing technologies achieved an average saving of 69 kg ha^{-1} of N without reducing yields and an average increase by \$56 ha^{-1} in profitability. Butchee, May, and Arnall (2011) utilized the same GreenSeeker™ optical sensing technology for wheat production in Oklahoma and found a reduction of N by 22 kg ha^{-1} without yield reduction relative to conventional practices.

In addition to increasing profitability and reducing N loss to environments, PA has the potential to reduce production risk by creating a more homogenous growing environment within the farm field (Lowenberg-DeBoer and Swinton 1997; Lowenberg-DeBoer 1999; Larson et al., 2002). Production risks usually involve in yield and net return affected by anomalous factors such as rainfall and temperature causing yields to rise or fall (Bullock and Bullock 1994; Isik and

Khanna 2003; Elms, Green, and Johnson 2001; Carr et al. 1991; Vetsch et al. 1995; Wibawa et al. 1993).

Several articles have assessed the risk management benefits of VRT including Lowenberg-DeBoer (1999), Isik and Khanna (2003), and Larson et al. (2002). Lowenberg-DeBoer (1999) examined risk management benefits of using VRT application of phosphorus and potassium using data from on-farm trials in Indiana, Ohio, and Michigan from 1993 to 1995 on either corn-soybean or corn-soybean-wheat crop rotations. Their study found a reduction in the probability of low net returns and VRT application of fertilizer preferred by risk-averse farmers. Larson et al. (2002) conducted a simulation model for VRT N application using soil management zones for three soil types. They found that VRT could provide risk management benefits on corn fields with large spatial variability but URT would be preferred by risk-averse farmers. Lowenberg-DeBoer (1999) found that human implementation or interpretation error or risk of technology obsolescence on VRT could cause yield and net return losses and prevent the adoption.

Previous research showed mixed results in terms of profitability from the adoption of PA. A lack of information in cotton production utilizing real-time optical sensing technologies and VRT N fertilization application need experiment studies especially in the Mississippi River Basin (MRB) states (Tennessee, Louisiana, Mississippi, and Missouri). Also, research based on the field data in MRB need to conducted to assess whether these technologies can reduce losses of N to the environment. The need for a cotton N utilization study using PA technologies in the MRB area was identified through surveys among producers in twelve southern states (Mooney et al. 2010). If cotton growers had access to information/studies specific to the MRB region, they could make more informed decisions about adoption of real-time optical sensing and VRT in N fertilization with regard to soil types, reduced fertilizer costs, increased profitability, increased labor/application efficiency, and decreased excess N reaching groundwater (Biermacher et al. 2009b).

Policy makers, crop insurance companies, and technology manufacturers can also use economic information about PA technology to assist producers. Policy makers would have the resources to create incentive programs for farmers to adopt site-specific technologies like VRT. Externalities can be examined to determine a program that would either reduce N by charging a tax of sorts on excess fertilizer use or incentivize growers to adopt VRT with a subsidy for the technology (Larkin et al. 2005; Roberts et al. 2002; Zhang, Wang, and Wang 2002). This information is useful for crop insurance companies because they could potentially provide lower rates to those who adopt a site-specific technology (Lowenberg-DeBoer 1999). Technology manufacturers could better pinpoint a target cost for the technology for the end consumer (Biermacher et al. 2009a).

REVIEW OF METHODS

Conceptual Framework

Treatment Effect for Net Returns and N Production Use Efficiency

A risk-neutral, profit-maximizing producer will adopt VRT N application if the profitability of VRT is greater than the profitability of the current FP N application. The typical FP is to apply the same rate of N across the farm field. The profitability of VRT involves tradeoffs among: 1) cost of information, 2) cost of VRT application, 3) changes in yield, and 4) changes in N use (Biermacher et al. 2009a; Lowenberg-DeBoer 1999). In addition, site-specific factors, such as soil variability within fields and weather can influence the producer’s decisions of how much N to apply and whether to use a new technology (Bullock and Bullock 1994; Isik and Khanna 2003; Lowenberg-DeBoer 1999; Whelan and McBratney 2000; Zhang, Wang, and Wang 2002).

The profit equations for FP N application and VRT N application include the tradeoff between the factors listed above. The profit equation for FP N application decision for cotton is:

$$NR_{FP} = P \times Y_{FP} - r^B \times N_{FP}^B - r^T \times N_{FP}^T - IAC_{FP} - OCP, \quad (1)$$

where *NR* is cotton net returns (\$ ha^{-1}), *P* is cotton lint price (\$ kg^{-1}), *Y* is cotton lint yield (kg ha^{-1}), r^B is the pre-plant N price (\$ kg^{-1}), N^B is the pre-plant N fertilization rate (kg ha^{-1}), r^T is the top (or side) dress N price (\$ kg^{-1}), N^T is the top (or side) dress N fertilization rate (kg ha^{-1}), *IAC* is the information and application cost used in the FP N fertilization process (\$ ha^{-1}) including labor and equipment, and *OCP* represents the other costs of cotton production (\$ ha^{-1}) that do not change across N application technologies.

The profit equation for the VRT N application decision for cotton is:

$$NR_{VRT} = P \times Y_{VRT} + IP_{VRT} - r^B \times N_{VRT}^B - r^T \times N_{VRT}^T - IAC_{VRT} - OCP, \quad (2)$$

where *IP* is an incentive payment received from a government agency, such as the USDA Natural Resource Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP)[1], to adopt VRT, and information costs (*IC*) include the ownership and labor costs of VRT. USDA (NRCS) and the Environmental Protection Agency are interested in reducing the amount of N applied by incentivizing the adoption of conservation practices such as VRT N application (USDA 2014b). Considering the incentive payments in net returns allows the effectiveness of these incentives in adoption of VRT N application to be determined.

Using the profit equations for FP (1) and VRT (2), NR_{FP} can be set equal to NR_{VRT} and the terms rearranged to analyze the sensitivity of changes in prices to profitability in VRT N application. The left-hand side of the equation is the change in the cost of the technology (cost of machinery ownership, fertilizer application, and labor):

$$IAC_{VRT} - IAC_{FP} = P \times (Y_{VRT} - Y_{FP}) + IP_{VRT} + r^B \times (N_{FP}^B - N_{VRT}^B) + r^T \times (N_{FP}^T - N_{VRT}^T). \quad (3)$$

Equation 3 yields a partial budgeting net returns relationship, a common way to analyze the economic benefits of a technology (Boehlje and Eidman 1984; Thrikawala et al. 1999; Koch et al. 2004; Biermacher et al. 2009a; Boyer et al. 2011).

Equation 3 assumes that the VRT costs are more expensive than FP. The costs of VRT (C_{VRT}) on the left-hand side of Equation 3 can be denoted as

$$C_{VRT} = IAC_{VRT} - IAC_{FP} \quad (4)$$

and Equation 3 can be rewritten as an inequality:

$$C_{VRT} < P \times (Y_{VRT} - Y_{FP}) + r^B \times (N_{FP}^B - N_{VRT}^B) + r^T \times (N_{FP}^T - N_{VRT}^T) + IP_{VRT}, \quad (5)$$

where the cost of using VRT (\$ ha^{-1}) is on the left-hand side and three sources of potential cash inflows to offset the cost are on the right-hand side, i.e., higher yields, N savings, and incentive payments. If C_{VRT} is less than the cash flows on the right-hand side, VRT is profitable; otherwise, not.

Based on the implications drawn from Equation 5, changes in yields and N rates are the driving factors influencing technology profitability holding lint cotton and N prices constant. Changes in net returns and N use efficiency due to changes in yields and N rates with the adoption of VRT are of interest to the farmer. Given that crop production is affected by managerial and growing environment factors such soils and weather (Bullock and Bullock 1994;

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[1] NRCS precision nutrient management practice code number 590 used for incentive payment in Equation 2.

Isik and Khanna 2003; Lowenberg-DeBoer 1999; Whelan and McBratney 2000; Zhang, Wang, and Wang 2002), yield for the N fertilizer management decision can be written as a function of crop management and exogenous environment factors:

$Y_{a,d} = f(N_d, Z_d, W_d, S_d, O_d)$,(6)

where *Y* is yield (kg ha^{-1}) , *a* is the N fertilizer management strategy (FP or VRT), *d* is a sub-field area (e.g., management zone) within a field used to apply N at the rate (kg ha^{-1}) determined by management strategy *a*, *Z* is a vector of other crop inputs applied by the farmer, *W* is a vector of weather parameters such as precipitation and temperature, *S* is a vector of farm field soil properties and landscape characteristics, and *O* is a vector of other random factors affecting production such as pests. The N management decision can be written as a function of the previously mentioned exogenous environmental factors:

$N_{a,d} = g(Z_d, W_d, S_d, O_d)$. (7)

Average yields and N rates at the field level for the FP and VRT N management strategies are:

$Y_{FP} = \sum_{d=1}^{D} Y_{d,FP}/D,$ and $N_{FP} = \sum_{d=1}^{D} N_{d,FP}/D$, and(8)

$Y_{VRT} = \sum_{d=1}^{D} Y_{d,VRT}/D,$ and $N_{VRT} = \sum_{d=1}^{D} N_{d,VRT}/D$,(9)

where *D* is the total number of management zones in the field as indicated by the N management studies.

In this research, the effects of optical sensing and VRT on average yields, N rates, and net returns relative to the FP are evaluated at the field level. In addition, the effects of exogenous weather, soil properties, and landscape characteristics on differences in yields, N rates, and net returns for VRT versus the FP are evaluated at the sub-field level.

VRT NUE has been measured in several ways, most of which comprise a zero-N applied plot (omission plot) or N-rich plot for comparison purposes. Butchee et al. (2011) found the N rate using the NUE factor: $N\ rate = \{(YPO \times RI) - YPO\} \times \%grain\ N \times NUE\ factor$, where *YPO* represents the yield potential for zero N, *RI* represents response index measured by a sensor based N-rate calculator, and the grain is winter wheat. Cassman et al. (1998) and Cassman et al. (1996) employed partial factor productivity (PFP) as a measure of nutrient-use efficiency: $PFP = \frac{(Y_0 + \Delta Y)}{N_t}$ where Y_0 is the yield from a N omission plot, ΔY represents the change in yields from zero-N applied, and N_t is the N rate applied per treatment (*t*). Raun et al. (2002) measured NUE by subtracting N removed (grain yield times total N) in the grain in zero-N plots from that found in plots receiving added N, divided by the rate of N applied.

A nitrogen production use (NPU) efficiency is used here to measure N use by normalizing the yield for a given technology (*Y*) by dividing by the corresponding N rate applied (*N)* such that:

$NPU_a = \frac{Y_a}{N_a}$,(10)

where *a* is N management strategy used (VRT or FP). This variable is a proxy for the environmental benefits from using VRT. The effects of VRT on average NPU relative to the FP are evaluated at the field level. In addition, the effects of exogenous weather, soil properties, and landscape characteristics on differences in NPU for VRT versus the FP is evaluated at the sub-field level.

Risk Management Benefits

Besides expected profit, farmers may be interested in the potential risk management benefits of VRT fertilizer management. Assuming farmers are risk-averse, the potential for yields and net returns to fall below a target value is a main concern; i.e., farmers are particularly concerned about reducing the probability of yields and NR in the lower tail of the probability distribution

(Binswanger 1981; Selley 1984; Antle 1987; Lowenberg-DeBoer 1999; Chavas 2004). Physical soil properties (e.g., soil organic matter content and depth) and topography (e.g., slope and elevation) of farm fields that can limit yields remain relatively fixed over time (Larson, Roberts, and English 2002). One potential risk management benefit of VRT is reducing the variability of growing environment factors across a field, making the field more homogenous (Lowenberg-DeBoer and Swinton 1997). Another potential risk management benefit may come from reducing the field average temporal yield variability across soil types under VRT compared to applying the same rate of inputs across the farm field (Larson, Roberts, and English 2002).

Stochastic dominance and lower partial moment criteria can be useful for evaluating the risk management benefits of optimal sensing and VRT fertilizer management. The risk-neutral farmer will choose the treatment that produces the highest mean net return. The decision cannot solely be made on mean net returns when there is a level of risk involved. Stochastic dominance is a helpful tool in evaluating the decision between random variables (Post and Kopa 2013; Dhompongsa, Nguyen, and Sriboonchita 2010). When making a decision between VRT and FP, for instance, first degree stochastic dominance states that VRT would dominate FP if $F_{VRT}(NR) \leq F_{FP}(NR)$ for all observations (π) where $F_{VRT}(NR)$ is some function of VRT and $F_{FP}(NR)$ represents a function of FP (Dhompongsa, Nguyen, and Sriboonchita 2010), here cumulative distribution functions.

Lower partial moment measures the downside risk, i.e., yields, N rates, net returns, and NPU that fall below a target level (Fishburn 1977):

$$LPM_n = \frac{1}{m}\sum_{i=1}^{m} Max[0, Y_{FP,i} - Y_{VRT,i})]^n, \quad (11)$$

$$LPM_n = \frac{1}{m}\sum_{i=1}^{m} Max[0, N_{VRT,i} - N_{FP,i})]^n, \quad (12)$$

$$LPM_n = \frac{1}{m}\sum_{i=1}^{m} Max[0, NR_{FP,i} - NR_{VRT,i})]^n, \quad (13)$$

$$LPM_n = \frac{1}{m}\sum_{i=1}^{m} Max[0, NPU_{FP,i} - NPU_{VRT,i})]^n \quad (14)$$

where *LPM* is the lower partial moment, *m* is the number of observations (*i*), *FP*, *VRT*, *Y*, *N*, *NR*, and *NPU* were defined previously, and *n* is the degree of the moment. The classifications of the degree of the moment (*n*) are *n* = 0 is the probability of a loss, *n* = 1 is the target shortfall, *n* = 2 is the target semi-variance, and *n* = 3 is the target skewness. The probability of a loss, where *n* = 0, provides the probability of VRT yields, net returns, and N use efficiency being lower than the current FP.

Hypothesis Testing

Given the potential effects of optical sensing and VRT on crop yields, N rates, net returns, NPUs, and crop risk management, the three hypotheses that are tested in this study are:

1) Optical sensing and VRT treatments versus the FP: The null hypothesis is that using optical sensing and VRT for N management do not generate yields, N rates, NPU, and net returns that are different from FP yields, N rates, net returns, and NPUs. The alternate hypothesis is that the aforementioned factors differ with N management using optical sensing and VRT when compared with the FP.

2) Weather, soil, and landscape characteristic effects on optical sensing and VRT versus FP: The null hypothesis is that yields, N rates, net returns, and NPUs from N management using optical sensing and VRT relative to the FP are not influenced by weather and farm field soil and landscape characteristics. The alternative hypothesis is that weather and farm field soil

properties and landscape characteristics influence differences in the aforementioned factors when using optical sensing and VRT as compared with the FP.

3) Risk management benefits of optical sensing and VRT: The null hypothesis is that optical sensing and VRT do not provide a higher (lower for N rates) probability of yields, N rates, net returns and NPU being in the lower tail compared to the respective FP yields and net returns as influenced by weather and farm field soil properties and landscape characteristics. The alternative hypothesis is that optical sensing and VRT do provide a higher (lower for N rates) probability of yields, N rates, net returns and NPU above FP yields and net returns as influenced by weather and farm field soil properties and landscape characteristics.

Data and Methodology

Data

Twenty-nine cotton N fertilizer field demonstration trials were conducted from 2011 to 2014 in Tennessee, Mississippi, Louisiana, and Missouri. Ten of the trials occurred in Tennessee, four in Mississippi, nine in Louisiana, and six in Missouri. The county/parish locations of the farmer fields in each state that were used in the study are presented in Figure 1. The trials tested FP N application versus two VRT N applications on each cotton field. Each EQIP eligible farmer planted cotton across nine strip-plots (referred to as plot for the remainder of this report) containing 10 sub-plots each that measure roughly 30.5 meters by 11.6 meters with the exception of Missouri where the data was collected by plot, Figure 2.

The experiment was planned as a randomized complete block design with three N fertilizer treatments and three replications. The FP treatment (1) was a uniform-rate N application based on the farmer's current practice. Treatment 2 was a VRT N application calculated using the normalized difference vegetation index (NDVI) via canopy optical-sensing with the Greenseeker™ RT200 Data Collection and Mapping System (NTech Industries, Inc., CA). Treatment 3 was a VRT N application based on actual NDVI readings via canopy optical-sensing with the Greenseeker™ RT200 Data Collection and Mapping System but adjusted based on any combination of historical yield productivity zones, soil imagery, and/or aerial imagery of mid-season crop health. A uniform blanket rate ranging from 33.6 to 78.4 kg N ha^{-1} was applied at (or before) planting to the entire field (covering all three treatment areas) depending on the experiment. Each location provided lint yields harvested, N rates applied, type of N fertilizer used, and latitude and longitudes at the sub-plot level for every participating year. Table 2 includes the average N rate, lint yield, NPU, and net returns by location and year.

To evaluate the net returns inequality in Equation 5, price data, information costs, and application costs were used. Price and budget data are in real 2013 dollars ($), referred to as real dollars, and were indexed using the Bureau of Economic Analysis annual Gross Domestic Product Price Deflator Index (U.S. Department of Commerce 2014). Price data included national average marketing year (August 1-July 31) cotton lint prices received, marketing years 2011 through 2014 (USDA 2014a), adjusted to real $ kg^{-1}, $1.84 kg^{-1} in 2014. National prices paid for N fertilizer urea (32% N) were collected for 2011 through 2014 marketing years (USDA 2014d), adjusted to real $ kg^{-1}, $0.91 kg^{-1} in 2014. EQIP cost-share payment rates were collected for each of the four states in the experiments for the precision nutrient management payment code 590 for 2011 through 2014 adjusted to real $ ha^{-1}. Payments for 2014 included $68.21 ha^{-1} in

Mississippi, \$68.46 ha^{-1} in Louisiana, \$65.85 ha^{-1} in Tennessee, and \$32.64 ha^{-1} in Missouri (personal communication with Patricia Turman, Tennessee State Agronomist, 2014, Chris Coreil, Louisiana NRCS Conservation Agronomist, 2014, and Jodie Reisner, Missouri NRCS Conservation Agronomist, 2014; USDA 2014c).

Information and application costs (IAC), including equipment/technology, labor, and other costs, were estimated using partial budgeting methods (Larson et al. 2005) as demonstrated in Equations 4 and 5, Table 3. Two budgets were developed to account for information and application costs: 1) for Greenseeker™ technology (treatment 2) and 2) for Greenseeker™ plus yield monitor information systems (YMIS) (treatment 3). Greenseeker™ was assumed to be retrofitted to an existing boom sprayer measuring 24.7 meters wide and the YMIS was assumed to be retrofitted to an existing 6-row cotton picker measuring 5.8 meters wide. Ownership costs (OC) of equipment/technology for inclusion in IAC for treatments 2 and 3 were estimated using the standards of the American Society of Agricultural and Biological Engineers (ASABE) (ASABE 2011) similar to Biermacher et al. (2009a), the Agricultural and Applied Economics Association (AAEA) Commodity Costs and Returns Estimation Handbook (AAEA 2000), and equipment costs calculation techniques (Boehlje and Eidman 1984). OC were estimated in Table 3 using the equation:

$$OC_i = [CR_i + TIH_i + RM_i] \times H_i, \quad (15)$$

where ownership costs (\$ ha^{-1}) by treatment (i = 2 or 3) were composed of hourly capital recovery (CR_i) by treatment (\$ $hour^{-1}$), hourly taxes, insurance, and housing (TIH_i) by treatment (\$ $hour^{-1}$), hourly repairs and maintenance (RM_i) by treatment (\$ $hour^{-1}$), and hours ha^{-1} (H_i) by treatment. For Greenseeker™, the useful life was assumed to be 5 years or 1500 hours (Gandonou et al. 2006) and the yield monitor information system assumed a useful life of 5 years or 3000 hours (Gandonou et al. 2006; Biermacher et al. 2009a), Table 3. Total Greenseeker™ OC was multiplied by 1.02 to account for calibration using N rich strips (Biermacher et al. 2009a). Information and application cost (real \$ ha^{-1}) for treatment 2 in 2014 was \$2.32 ha^{-1}.

Information and application costs for treatment 3 included the estimated OC for Greenseeker™, estimated OC for yield monitor information system, the cost of a computer, and a consulting fee for technical advice (\$ ha^{-1}), Table 3. The computer was assumed 100% use for the yield monitor system, GPS signal was assumed to be free, and a \$687.08 (2013 real dollars) custom installation fee for retrofitting each technology to existing machinery was assumed for both Greenseeker™ and the yield monitor system (Larson et al. 2005; Gandonou et al. 2006). Computer list price costs were an average of costs for a desktop computer with 8GB memory, 1TB hard drive, and 21" to 23" screen (informal internet survey 2014). In partial budgeting, if information costs were not available ha^{-1} (such as the cost of a computer), costs were spread across the size of a field (Swinton and Lowenberg-DeBoer 1998). Here, the cost of a computer was allocated across the size of a cotton enterprise in each state (USDA 2012), Table 3. The consulting fee was included due the necessary technical assistance to correctly implement and interpret the technology (McBratney, Whelan, and Ancev 2005). To account for such assistance, an average of 2009 cotton technical advice fees including yield monitor, grid soil sampling, zone soil sampling, and soil survey map fees (Mooney et al. 2010) was normalized to real 2013 dollars, \$12.63 ha^{-1} and added to all years of applicable data. Costs for treatment 3 were \$18.00 ha^{-1} in Tennessee, \$18.06 ha^{-1} in Mississippi, \$18.12 ha^{-1} in Louisiana, and \$17.94 ha^{-1} in Missouri. The 2011, 2012, 2013, and 2014 partial budgets were in real 2013 dollars, 2013 budget example in Table 3.

VRT requires more skilled labor to correctly interpret the technology and compute appropriate N rates. Thus, labor costs for VRT treatments were estimated using custom rate surveys produced by their respective agricultural extension offices (Bowling 2013; Mississippi State University Extension Services 2013; University of Missouri Extension 2012). The 2013 precision fertilizer application labor cost was determined by taking the difference between precision fertilizer application in Tennessee and the average dry bulk fertilizer application in Tennessee, Missouri, and Mississippi[2] (precision fertilizer application such as VRT costs $6.60 more ha^{-1} in labor to apply dry bulk than FP). The 2013 labor costs were applied to all years of data, 2011-2014. Application costs as well as the other pieces to Equation 5 are included in a partial net returns summary in Table 4.

For each location-year, soil and climate characteristics were collected to determine differences within and between fields (variable names, definitions, and units can be found in Table 5). Soil water holding capacity, organic matter, soil texture, soil depth, field slope, and soil erosion factors were collected from the SSURGO database (USDA 2014f) at the center point of each sub-plot (plot for Missouri locations) using ArcGIS 10.1. A soil erosion index (*SEI*) was estimated using a modified universal soil loss equation to account for the physical factors of the fields:

$$SEI = \frac{KF \times LS \times R}{TF}, (15)$$

where *KF* is erodibility factor due to water (USDA 2014f) , *LS* is a soil length (*L*) and slope steepness (*S*) factor, calculated as $LS = (0.065 + 0.0456 \times S + 0.006541 \times S^2)$ at the standard slope length of 22.1 meters (Stone and Hilborn 2012) and percent slope steepness (*S*) (USDA 2014f). *R* is the rainfall and runoff factor from USDA RUSLE2 version 2.5.2.11 (2014), and *TF* is a soil tolerance factor (USDA 2014f). Soil texture percent sand, silt, and clay from SSURGO (USDA 2014f) were used to find the general soil texture name via the USDA soil texture calculator (USDA 2014e). Textures were then narrowed down to four major soil textures and ranked by coarseness: clay (finest), silt, loam, and sand (coarsest). Field elevation was collected from the National Elevation Dataset (U.S. Geology Survey 2014). Climate was measured by temperature (PRISM 2014) as seasonal growing degree days (April 1 through October 31) (Larson et al. 2007; Wright et al. 2011). To calculate seasonal growing degree days, the daily average temperature minus 15.6 degrees Celsius was summed over April 1 through October 31 per location-year if the daily calculation was greater than zero. Mean farm soil and climate characteristics are presented in Table 6.

Methodology

In addition to soil and weather fixed effects, Equations 16-19 included random variables based on the Schabenberger and Pierce (2002) on-farm experimentation model. Due to the experimental design, Equations 20-23 and 28-31 were each treated like as a meta-analysis similar to Tolliver et al. (2012).

Treatment Effects

The farmer's decision to change his N application technology from FP to VRT is measured by evaluating two aspects of the production decision: 1) net returns per location-year by treatment as driven by yields and N rates and 2) the NPU efficiency.

The following models are estimated with an (ANOVA) using SAS 9.2 (SAS Institute Inc. 2014):

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[2] Tennessee, Mississippi, and Missouri rates were averaged and applied to all locations because Louisiana State University extension office does not produce a custom rate survey.

$$Y_{ijktd} = \mu + \delta_t + \lambda_k + \tau_i + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \varepsilon_{ijkt}, \quad (16)$$

$$N_{ijktd} = \mu + \delta_t + \lambda_k + \tau_i + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \varepsilon_{ijkt}, \quad (17)$$

$$NR_{ijktd} = \mu + \delta_t + \lambda_k + \tau_i + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \varepsilon_{ijkt}, \quad (18)$$

$$NPU_{ijktd} = \mu + \delta_t + \lambda_k + \tau_i + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \varepsilon_{ijkt}. \quad (19)$$

The following is consistent for all models included for the remainder of this report:

Dependent Variables:

Y_{ijktd} is cotton lint yield (kg ha^{-1}),

N_{ijktd} is N rate applied (kg ha^{-1}),

NR_{ijktd} is net returns ($ ha^{-1}),

NPU_{ijktd} is NPU efficiency,

Explanatory Variables:

μ is the overall mean,

Random Effects:

δ_t is the effect of the t^{th} year (t=2011, 2012, 2013, 2014),

λ_k is the effect of the k^{th} farm location (k=1,…,21),

$\rho_{(j)k}$ is the j^{th} replication (or block) effect nested within k^{th} farm,

$(\lambda\tau)_{ik}$ is the effect of the interaction between the k^{th} farm and the i^{th} treatment,

Fixed Effects:

τ_i is the effect of the i^{th} treatment (i=1, 2, 3),ω_{kjid} is effect of water holding capacity (cm cm^{-1}) by k^{th} farm, j^{th} replication, i^{th} treatment, and d^{th} sub-plot,

θ_{kjid} is effect of organic matter (%) by k^{th} farm, j^{th} replication, i^{th} treatment, and d^{th} sub-plot,

γ_{kjid} is the effect of soil erosion index by k^{th} farm, j^{th} replication, i^{th} treatment, and d^{th} sub-plot,

φ_{kjid} is the effect of soil depth (cm) by k^{th} farm, j^{th} replication, i^{th} treatment, and d^{th} sub-plot,

β_{kjid} is the effect of soil texture by k^{th} farm, jth replication, i^{th} treatment, and d^{th} sub-plot,

ψ_{kjid} is the effect of elevation (meters) by k^{th} farm, j^{th} replication, i^{th} treatment, and d^{th} sub-plot,

χ_{kt} is the effect of seasonal growing degree days by k^{th} farm and t^{th} year,

ε_{ijktd} is the random error associated with the k^{th} farm, j^{th} replication, i^{th} treatment, t^{th} year, and d^{th} sub-plot,

$\delta_t \sim iid(0, \sigma_\delta^2)$ (*iid* refers to independent and identical distribution),

$\lambda_k \sim iid(0, \sigma_\lambda^2)$,
$\rho_{(j)k} \sim iid(0, \sigma_\rho^2)$,
$(\lambda\tau)_{ik} \sim iid(0, \sigma_{\lambda\tau}^2)$,
$\varepsilon_{ijkt} \sim iid(0, \sigma_\varepsilon^2)$.

The fixed effects are N treatment, soil attributes, and weather, and the random effects are location, year, replication nested in location, and location-treatment interaction. Location was hypothesized to have a significant effect on the dependent variables because every farm was physically different from the next, time in years because the data spans more than one year, treatment because the treatments differ within a farm and between farms, and effects that are within the same farm due to the physical difference between sub-plots from farm to farm. The location-treatment interaction term was expected to be significant but to mask the treatment differences.

The null hypothesis for Equation 16 is that expected lint yields from the VRT N application treatments (*i* = 2 or 3) per trial will be equal to the expected lint yields from the FP trials was tested in Equation 16. Alternatively, expected VRT lint yields will be greater than expected FP lint yields.

VRT N applications were expected to reduce N use compared to FP. In the special case that the yields are not significantly different across treatments per location-year, revenues (price of cotton times lint yield) will no longer be a factor in net revenues, Equations 1 and 2. The cost side of the equation becomes the driver, as seen in Equation 5. The null hypothesis that VRT by treatment generated no additional N use savings compared to FP, was tested in Equation 17. Alternatively, expected N applied using FP is greater than expected N applied using VRT application.

If yields were not significantly different across treatments per location, N applied was the driving factor. In this case, net returns can be estimated in a similar way to Equations 4 and 5. The null hypothesis that expected net returns from VRT N applications by treatment were the same as expected net returns from FP N application was tested in Equation 18. Alternatively, expected net returns from VRT N applications were greater than expected net returns from FP application.

N rate was also the driver in N use efficiency if yields did not differ. For the same cotton lint yield, a lower N rate would increase the NPU efficiency. The null hypothesis that the expected NPU for VRT N application treatments were equal to expected NPU efficiency for the FP treatment was tested using Model 4. Alternatively, expected NPU efficiency for VRT N application was expected to be greater than NPU for FP N application.

Equations 16, 17, 18, and 19 were first estimated with only treatment as the explanatory variable and again with added soil and weather characteristics. The better fitting models were chosen based on the Akaike information criterion (AIC) and Bayesian information criterion (BIC). Multicollinearity was checked by estimating the variance inflation factor (VIF) using SAS 9.2. The Satterthwaite approximation was used to deal with degrees of freedom.

To determine if the treatments produced significantly different lint yields, N rates, net returns, and NPUs, Dunnett's tests were estimated using SAS 9.2 for Equations 16-19 (Littell et al. 2006). This two-tailed test is useful because multiple treatments can simultaneously be compared to one control while holding the familywise error rate at or below alpha; here, if VRT treatment 2 is significantly different than FP (control) and if VRT treatment 3 is significantly different than FP. This test performs multiple comparisons while holding the familywise error rate at or below an alpha level.

Because the interaction term is random, contrasts between farms were estimated via best linear unbiased predictions using SAS 9.2 for Equations 16-19 to measure the treatment effect at the farm level (Schabenberger and Pierce 2002; Littell et al. 2006). Both VRT treatments were measured separately against FP to see if technology outperformed the current practice. The null hypothesis is that VRT treatments do not differ from FP at the farm level. Alternatively, treatments do differ at the farm level. A Bonferroni correction is a conservative way to handle multiple comparisons and deal with the familywise error rate. Because there are 21 farms, there are 21 separate hypotheses to test for VRT treatment 2 versus FP and VRT treatment 3 versus FP. At a 10% confidence level, the Bonferroni correction is calculated as $\alpha = \frac{0.10}{21} = 0.0047$. Alpha becomes 0.0047 for each hypothesis; at the field level.

Soil, Landscape, and Weather Impacts on Mean Treatment Differences

The soil and climate impacts on mean differences were evaluated by estimating a mixed model ANOVA using SAS 9.2. The mean difference models are:

$$Y\Delta_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (20)$$

$$N\Delta_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (21)$$

$$NR\Delta_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (22)$$

$$NPU\Delta_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (23)$$

where ν_i is a dummy variable by treatment (*i*); if N management strategy treatment 3 was used in that sub-plot (*d*), then 1; otherwise, 0. Refer to Equations 16-19 for all other explanatory variables. The dependent variable was defined as the difference between *VRT* and *FP* in terms of yields, N rates, NR, and NPU:

$$Y\Delta_{dijkt} = Y_{VRT_i} - Y_{FP} \quad (24)$$

$$N\Delta_{dijkt} = N_{VRT_i} - N_{FP} \quad (25)$$

$$NR\Delta_{dijkt} = NR_{VRT_i} - NR_{FP} \quad (26)$$

$$NPU\Delta_{dijkt} = NPU_{VRT_i} - NPU_{FP} \quad (27)$$

where *Y*Δ is the mean difference in cotton lint yields (kg ha^{-1}), *N*Δ represents the mean difference in total N rates (kg ha^{-1}), *NR*Δ is the mean difference in net returns ($ ha^{-1}), and *NPU*Δ is the mean difference in NPU efficiencies, each between *VRT* technology treatment 2 or 3 and *FP* by the d^{th} sub-plot, i^{th} treatment, j^{th} replication, k^{th} location, and t^{th} year.

The manner in which Equations 20-23 were estimated did not take the FP sub-plot soil explanatory variables into consideration. If the soil characteristics differ from the optical sensing and VRT treatment sub-plots, the integrity of the model may be compromised and what is being measured may not be accurate. To account for this, Equations 20-23 were estimated using a restructured database where a balanced set of replicates for the FP and VRT treatments were used. For example, if the soil texture differed across field 1, replication 1, and sub-plot 1 in treatment 2 versus sub-plot 1 in treatment 1, Figure 1, then the observation was omitted from the dataset; if not, the original observation was used. The models in Equations 20-23 were estimated using the original and restructured datasets and the outputs were evaluated using AIC and BIC statistics to choose the better fitting model. The number of observations omitted ranged from 42 to 105 depending on the variable.

The models were checked for multicollinearity by estimating a regression using SAS 9.2 (PROC REG) and the VIFs. The random effects listed for Equations 16-19 apply here as well.

Models in Equations 20-23 tested the null hypotheses that mean yields, N rates, net returns, and NPUs do not differ between VRT N management strategies and FP due to variability in soils characteristics and climate. Alternatively, soils and climate do generate differences using optical sensing and VRT when compared to FP.

Risk Management Benefits

First degree stochastic dominance of N management treatments was evaluated using the cumulative probability distributions of each treatment. The distributions were calculated by ordering the yields, N rates, NRs, and NPUs from lowest to highest by treatment. The histogram feature in Microsoft Office Excel 2010 was then used to count the number of observations in each pre-determined bin category for every treatment which were used to calculate the respective cumulative probability distributions.

The Kolmogorov-Smirnov (KS) test is a nonparametric test based on the empirical cumulative distribution function and can be used to compare two distributions. The KS statistic D represents the goodness of fit and is based on the vertical difference between the two cumulative probability distributions (Chakravarti et al., 1967). The KS test was estimated using SAS 9.2 as a supplement to the first degree stochastic dominance results due to the criteria that at least one point has to be to the right to show dominance (all others could be equal). The null hypotheses for the KS tests are that the treatment distributions are similar.

Risk management benefits were also assessed using the lower partial moment to evaluate how soil and weather factors affected the probability of the outcomes from the optical sensing and VRT N management treatments being different from the FP N management. The probability of a loss, $n = 0$, Equations 11-14, was measured using a mixed logistic model, and estimated using SAS 9.2:

$$Yprob_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (28)$$

$$Nprob_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (29)$$

$$NRprob_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (30)$$

$$NPUprob_{ijktd} = \mu + \delta_t + \lambda_k + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{kt} + \nu_i + \varepsilon_{ijkt} \quad (31)$$

where *Yprob* is the estimated probability of a VRT treatment producing lower yields than FP, *Nprob* is the estimated probability of the VRT treatment calculating higher N rates than FP, *NRprob* is the probability of VRT net returns being lower than FP, and the *NPUprob* is the probability of VRT treatments calculating lower NPUs than FP. The binary dependent variables are defined in Table 5 as:

If $Y_{VRT} - Y_{FP} < 0$, then $Yprob = 1$; else, $Yprob = 0$;(32)

If $N_{VRT} - N_{FP} > 0$, then $Nprob = 1$; else, $Nprob = 0$;(33)

If $NR_{VRT} - NR_{FP} < 0$, then $NRprob = 1$; else, $NRprob = 0$;(34)

If $NPU_{VRT} - NPU_{FP} < 0$, then $NPUprob = 1$; else, $NPUprob = 0$;(35)

where Y_{VRT} is the VRT yield, Y_{FP} is the current practice yield, N_{VRT} is the VRT N rate applied, N_{FP} is the current practice N rate applied, NR_{VRT} is the VRT net return, NR_{FP} is the current practice net return, NPU_{VRT} is the VRT N use efficiency, and NPU_{FP} is the current practice N use efficiency. If VRT lint yields, net returns, or NPU by treatment (*i*), replication (*j*), farm (*k*), year (*t*), and sub-plot (*d*) were less than the respective FP value, the dependent variable was represented by a 1; otherwise, 0. N rates applied were represented by a 1 if the VRT value was greater than FP; otherwise 0. Equations 28-31 were estimated using the restructured database. Multicollinearity was checked for the models by estimating the VIF using SAS 9.2. The random variables for these models are specified for Equations 16-19.

A proxy for the estimated marginal probability for each explanatory variable was calculated using the respective odds ratio parameter estimates from SAS 9.2 code ODDSRATIO. The proxy formula used was $100 \times [exp(OR) - 1]$ where exp is the exponential and OR is the odds ratio parameter estimate.

Odds ratios were estimated at the restructured database means of the significant variables using the following equation:

$ODDs = \exp[\widehat{\eta_0} + \widehat{\eta_1}X_1 + \widehat{\eta_2}X_2 + \cdots + \widehat{\eta_e}X_e]$(36)

where *ODDs* is the yield, N rate, net return, or NPU odds ratio, *exp* represents exponential, $\hat{\eta}$ represents the expected coefficient, X is the significant explanatory variable, and e is the last significant explanatory variable for that odds ratio. The odds ratios estimates are used to predict the probability of downside risk, measured by:

$VRTprob(a = 1) = \frac{ODDs}{1+ODDs}$(37)

where *VRTprob* is the probability of VRT lint yields, N rates, net returns, or NPU having a higher chance of being in the lower tail when compared to FP.

The null hypotheses for Equations 28-31 are that N management strategy does not provide yields, N rates, net returns, and NPUs that differ due to soil properties and temperature. Alternatively, soils and temperature do have an effect on yields, N rates, net returns, and NPUs.

DISCUSSION OF QUALITY ASSURANCE

A total of 21 farm field sites and 29 total site-years were used for the demonstration of optical sensing and VRT management of N in the project (Table 6). The county/parish locations of the farmer fields in in Missouri, Mississippi, and Tennessee that were used in the project are presented in Figure 1. Soil, landscape, and weather of each farm field are summarized in Table 6. The soil, landscape, and weather variables used to describe the characteristics of each field site include elevation, soil texture, soil erosion potential, soil water holding capacity, organic matter, soil depth, and growing degree days. The summary of mean field characteristics suggest that a diversity of geographic locations within the southern MRB and a range of soil properties, landscape, and weather were attained for the demonstration of the optical sensing and VRT N management technologies.

The lint yield and N fertilization data for each treatment in the project were used for a statistical and economic analysis developed in a Master's thesis project by Melissa Stefanini:

Stefanini, Melissa Reynolds, "Effects of Optical Sensing and Variable Rate Technology on Nitrogen Fertilizer Use, Lint Yields, and Profitability in Cotton Production. " Master's Thesis, University of Tennessee, 2015 (http://trace.tennessee.edu/utk_gradthes/3515).

The statistical and economic analysis by Ms. Stefanini was supervised Dr. James A. Larson and is the basis for this final project report. The data, methods, results, and conclusions of her analysis were critically reviewed and approved by her Master's thesis committee that included three economists who were not co-principal investigators on the grant project. The thesis committee members were Dr. Christopher N. Boyer (Farm Management and Production Economist, University of Tennessee, Knoxville), Dr. Seong-Hoon Cho (Spatial Econometrics Economist, University of Tennessee, Knoxville), Dr. Dayton Lambert (Spatial Econometrics Economist, University of Tennessee, Knoxville), Dr. Xinhua (Frank) Yin (Systems Agronomist), and Dr. James A. Larson (Major Professor).

FINDINGS

Treatment Effects

Using VIF as a measure of multicollinearity, all variables in Equations 16-19 were under a VIF value of five. Equations 16, 17, 18, and 19 were first estimated with only treatment as the explanatory variable. The added soil and climate characteristics generated models that were better fitting using the Akaike information criterion (AIC) and Bayesian information criterion (BIC) best fit criteria without compromising the integrity of the estimation, i.e., the treatment effect for each model did not change when soil properties and temperature were added.

Lint Yields, N Rates, and Net Returns

The estimated cotton lint yield model, Equation 16, produced a better fitting model based on best fit criteria (AIC and BIC), Table 7, than re-estimating the model without the location-treatment interaction term (Schabenberger and Pierce 2002). This indicated that the interaction term was significant. Neither estimation suggested treatment effects. A contrast comparison of the treatments indicated FP lint yields (treatment 1) were not significantly different than VRT treatment 2 or 3, Table 8. A Dunnett's test with the interaction term indicated that treatment 3 was significantly different than the control (FP) but there were no differences in either VRT treatment versus FP with the interaction term, Table 9.

Soil and climate attributes were significant, Table 10. All else equal, soils with a higher percentage of organic matter, greater water holding capacity, coarser soil texture, or deeper soils were positively associated with lint yields. Layers of soil below the surface are more fertile, carrying more organic matter and N available to the plant (Tiessen, Cuevas, and Chacon 1994), and potentially increase yields. Warmer temperatures (i.e., higher growing degree days) were negatively associated with lint yields. Soil texture significantly impacted yields, meaning that coarser soils were positively related to yields.

The mixed model for N rates applied, Equation 17, showed no significant differences between treatments but indicated that the variance between farms (σ_λ^2 = 242.33) was substantially higher than the variance within farms (σ_λ^2 = 86.83). This means that there was more N rate variation between farms than within farms. Model 2 was re-estimated without the interaction term to see if any effects were being masked, and a Dunnett's test indicated that the VRT treatment 3 was significantly different from the FP treatment, Table 9. Based on the model's best fit criteria, Table 7, the interaction term was significant to the model.

Estimates of VRT treatments (2 and 3) versus FP by location revealed masked treatment effects. Results demonstrated treatments 2 and 3 had significantly lower N rates applied in Lauderdale, TN, Gibson County, TN, and Middle Tensas Parish, LA, using a Bonferroni correction of 0.0047. Northern Leflore County, MS, had N rates lower than FP for only treatment 2. Northern Madison County, TN, and both the northern and southern locations in the Tensas Parish, LA, had estimated N rates that were significantly lower using FP than either VRT treatment (2 and 3). Adams County, MS, experienced lower N rates with FP than VRT treatment 3, Table 8.

The current FP was to apply less N in the locations where FP was significantly lower than VRT by respective state. Tennessee and Louisiana fields have less organic matter as a percentage of the soil where N rates were lower using FP. This could potentially mean that optical sensing of the plant canopy was associated with low organic matter areas in the field and applied more N to the soil. Organic matter, however, was not significant to the N rate model, Table 10. Holding all else constant, soils that were more erodible or had warmer temperatures were positively associated with N rates. All else equal, more erodible soils or warmer average temperatures had more applied N. Warmer temperatures are correlated with less precipitation (Madden and Williams 1978) and fields with these conditions may get more wind exposure, erosion, and have the potential to lose applied N. Holding all else constant, fields at higher elevations or with coarser soil textures were negatively related to N rates.

On average, farms requiring significantly higher VRT N rates relative to FP (northern Madison County, TN, Adams County, MS, and the northern and southern Tensas Parish locations, LA) had lower elevations, had higher SEI, higher percentages of organic matter, deeper soils, and warmer temperatures than those that had lower VRT N rates (middle Tensas Parish, LA, Gibson and Lauderdale Counties, TN, and northern Leflore County, MS), Table 11. Fields with more erodible soils and warmer temperatures likely require more N because they have the potential to lose N more easily. Fields requiring significantly lower N rates using VRT compared to FP were on average at higher elevations and had lower SEI indexes, lower water holding capacity, lower percentage organic matter, shallower soils, and cooler temperatures.

The net returns Equation 18 estimated with and without the interaction term identified significant treatment differences between net returns, Table 12. Estimating the difference between treatments by farm, however, indicated no treatment differences at Bonferroni correction of 0.0047, Table 8. A Dunnett’s test showed net returns to be different between VRT treatment 2 and FP when estimating Equation 18. When re-estimating the model without the interaction term, the Dunnett’s test revealed significant differences between VRT treatment 2 versus the control (FP) and VRT treatment 3 versus control, Table 9.

All else equal, coarser soil textures, soils with a higher percentage of organic matter, or deeper soils were positively associated with net returns. The significant and positive soil texture coefficient estimate indicates that coarser soil textures had a positive effect on net returns. Greater water holding capacity was negatively associated with net returns. *Ceteris paribus*, fields with higher percentages of organic matter, coarser soils, or deeper soils had positive associations with yields and, in turn, profits. In the same respect, fields at higher elevations or that were warmer had negative associations with yields and profits.

N Production Use Efficiency

Results from the NPU mixed model, Equation 19, indicated that the treatment means were not significantly different, Table 12. The variation between farms (σ_{λ}^{2} = 131.75) was greater than within the farms (σ_{λ}^{2}= 0.92). Equation 19 was re-estimated without the interaction term to determine if farm effects were being masked and results indicated treatment differences, Table 12. NPU means were significantly different between both VRT treatments and the control FP treatment as estimated by the Dunnett's test, Table 9. The AIC and BIC criteria indicated that the original model was a better fit than dropping the interaction term, Table 7. Thus, the interaction term was significant to the model but was masking the treatment effect.

Estimating the mean treatment differences at the farm level resulted in significantly higher FP N use efficiency than either of the VRT treatments in northern Madison County, TN, and northern Tensas Parish, LA. Adams County, MS, experienced a FP N use efficiency that was significantly higher than VRT treatment 3. These three farms experienced more efficient N use when determining their own rates than when using VRT. No farms exhibited more efficient N use with VRT when compared to FP, Table 8.

Elevation, water holding capacity, organic matter, soil texture, soil depth, and growing degree days had significant effects on NPU, Table 10. Fields at higher elevations, with greater water holding capacity, or warmer temperatures, all else equal, were negatively associated with N use efficiency. Fields with a higher percentage of organic matter, coarser soil textures, or deeper soils had positive effects on N use efficiency. Soil texture also had a positive association with NPU, meaning that coarser soils in reference to sand promoted more efficient use of N. Holding all else constant, soils with relatively more organic matter, coarser soils, and deeper soils were associated with low enough N rates to increase N efficiency. *Ceteris paribus*, high elevation fields with greater water holding capacity, or warmer average days had a negative relationship with N use efficiency. Soils with these conditions may have higher tendencies for erosion and, therefore, may require more N applied.

Soil, Landscape, and Weather Impacts on Mean Treatment Differences

The VIF test for multicollinearity indicated all factors were under a value of five when estimated for equations 20-23. In each case, the model estimated from the restructured database was the better fitting model than using the entire database, i.e. had lower AIC and BIC values.

Lint Yields, N Rates, and Net Returns

Several soil attributes were statistically significant in the lint yield mean difference model, Equation 20 and Table 13. Soils classified as having a silt or loam soil texture relative to sand (intercept) were negative in relation to VRT yields when compared to FP. Deeper soils or more erodible soils were positively associated with VRT yields relative to FP. Higher temperatures or fields at higher elevations had a negative relationship with VRT yields compared to FP. Coarser soils, fields at higher elevations, or fields in locations with warmer temperatures were negatively associated with VRT yields when compared to FP, all other factors being equal. Thus, VRT may not be a good option on fields with these conditions. Soils that have a higher percentage of organic matter, deeper soils, and more erodible soils had positive associations with lint yields using VRT compared to FP, all else equal. This could be due to organic matter carrying natural N and has nutrients available to the plant (Tiessen, Cuevas, and Chacon 1994). Soils with a higher erosion index had a positive association to lint yields potentially because more N was applied, Table 13.

Many of the soil attributes had a significant impacts on N rate differences between technology generated N rates and FP, Equation 21. N rate differences were significantly and negatively associated with sand (intercept), silt, or loam soil textures and positively with clay when VRT was compared to FP. Finer textured soils tend to need more N applied due to the lack of natural N while coarser soils need less applied N. Greater water holding capacity, more erodible soils, and higher growing degree days were positive in relation to VRT N rates. Deeper soils had a negative association to VRT N rate compared to FP. All else equal, more N was applied using VRT compared to FP on fields with a greater water holding capacity, more erodible soil, or warmer temperatures. The estimated VRT treatment 3 dummy variable indicated significantly higher N rates, indicating that Greenseeker™ plus YMIS calculated higher mean N rates than FP. While soil attributes had significant impacts on mean differences in lint yields and N rates between N management strategies, they had less of an impact on net returns Equation 22. Silt soil textures had a negative impact on VRT net returns when compared to FP. As noted above, the silt texture also had a negative association to VRT yields and VRT N rates. The N rates savings may not have been enough to increase the net return for that soil type, holding all else constant. The soil texture reference variable sand, however, experienced positive associations with VRT net returns compared to FP, Table 13. A higher percentage of organic matter or deeper soils were positively associated with VRT net returns compared to FP. Higher elevation fields had a negative association with VRT net returns compared to FP. Higher elevations may be more exposed to wind and rain and therefore have more erosion. Higher temperatures had a negative relation to VRT net returns. All else equal, warmer climates were negatively associated with VRT yields compared to FP, positively with N rates and, thus, negatively with NR. Warmer temperatures are correlated with dryer climates, particularly during the summer months in the United States (Madden and Williams 1978), which may cause the need for higher N rates. N applied was not high enough to increase yields such that net returns were increased.

N Production Use Efficiency

Results from Equation 23 indicated that soil and climate characteristics play a significant role in N use efficiency. NPU was negatively associated with clay soil texture compared to sand and positively associated with loam soil texture. Soils that were richer in organic matter had a positive association with VRT N use efficiency compared to FP. More erodible soils or fields with warmer temperatures had negative associations to VRT N efficiency. While a higher percentage of organic matter had a positive relation to N use efficiency of VRT compared to FP, all else equal, the more erodible fields and warmer climates had negative associations to N use efficiency, likely due to the need for higher N rates.

Risk Management Benefits

Stochastic Dominance

Results presented above for mean differences among the N management treatments are applicable to risk-neutral producers who makes decisions based on expected net returns. Risk averse farmers are not only concerned about expected net returns but also the dispersion of net returns—particularly net returns that fall below the expected value. The cumulative probability distributions for net return displayed at the sub-plot level and at the location-year (also referred to as field) level in Figure 2 were used to evaluate the risk management benefits of optical sensing and VRT for N management in cotton. In addition, cumulative probability distributions for yield, N rate, and N use efficiency at the sub-plot and field levels are presented in Figures 3-10.

At the sub-plot level, the net return distributions crossed when all treatments were examined together, but treatment 2 compared to FP exhibited first degree stochastic dominance, Figure 7. However, the net return distribution for treatment 2 was not first degree stochastic dominant over the FP at the field level. Thus, a farmer using first degree stochastic dominance as the decision rule for field level data could not make a decision on whether to adopt VRT based on first degree stochastic dominance criterion. At the sub-plot and field levels, yield, N rate, and

NPU distributions crossed at least once, indicating that VRT did not provide consistently higher yields, lower N rates, or higher NPU across the different field locations in the study, respective Figures 3-4, 5-6, and 9-10.

Based on the mean-variance rule, the farmer could not make a decision as the highest mean net return occurred in treatment 2 and the lowest variance occurred in treatment 3, Table 14. Further investigation was needed to know if the treatments were significantly different. The lint yield KS statistics indicated that the treatments did not differ at the sub-plot or field level, Table 15. Both VRT net return distributions were respectively different when compared to the FP at the sub-plot level. When tested to see if the two VRT treatments were different from each other, the KS results indicated that net return distributions were not significantly different between the two VRT treatments at both the sub-plot and field levels.

Downside Risk – Lint Yields, N Rates, and Net Returns

When equations 28-31 were tested for multicollinearity, the VIF for each variable was under a value of five. The significant explanatory variables were evaluated at their means to determine the potential risk management benefit of using VRT. Table 16 includes the estimated coefficients for Equations 28-31. Marginal effects of soil characteristics and weather on VRT risk management benefits are shown in Table 17.

The significant soil and weather factors associated with lint yields in the estimated logit model were silt soil texture ($Pr \leq 0.01$), loam soil texture ($Pr \leq 0.01$), water holding capacity ($Pr \leq 0.10$), organic matter ($Pr \leq 0.05$), soil depth ($Pr \leq 0.05$), and growing degree days ($Pr \leq 0.01$). Yield marginal changes indicate coarser soils or warmer temperatures are positively attributed with the probability of lower VRT yields than FP. Greater water holding capacity, higher percentages of organic matter, or deeper soils are negatively associated with the probability of lower VRT yields than FP. All else equal, increases in organic matter could potentially lower the probability of yield loss enough to warrant VRT adoption for some.

Odds ratios were evaluated at the means of the significant variables in the cotton lint yield model for the two significant soil texture variables, Equation 36. At the silt soil texture, the lint yields odds ratio indicated that VRT treatment yields were 3.6 times as likely to be lower than FP yields under these conditions. There was a 78.11% probability of VRT yields being lower than FP yields, Equation 37. A field with a silt soil texture had a high probability of lower yields with VRT and could potentially benefit from a keeping the farmer’s current practice N rate.

Estimating the odds ratio at the loam soil texture indicated that VRT treatments on loam fields were 2.3 times as likely to have lower yields than with FP. Evaluating Equation 36 for the loam soil texture, there was a 69.44% probability that VRT yields were lower than FP yields. Loamy fields with the same mean soil conditions and climate would also likely benefit from FP in terms of yields.

The significant soil and weather variables related with N rates in the estimated logit model were silt soil texture ($Pr \leq 0.01$), loam soil texture ($Pr \leq 0.01$), elevation ($Pr \leq 0.01$), water holding capacity ($Pr \leq 0.01$), treatment 3 dummy variable ($Pr \leq 0.01$), and soil erosion index ($Pr \leq 0.01$). Evaluating the marginal changes in soil and weather attributes at the means indicated that coarser soils or soils at higher elevations are negatively associated with the probability that FP generates lower N rates than VRT, Table 17. Greater water holding capacity, more erodible soils, or treatment 3 were positively associated with the probability that FP generates lower N rates than VRT.

N rate odds ratios were estimated at the means of the significant variables for the soil textures silt and loam. N rate odds ratio for silt indicated that FP N rates were 0.32 times as likely to be lower than VRT N rates. There was a 24.21% probability that the FP N rates were lower than VRT N rates. Silt fields with the mean soil conditions would likely benefit from VRT in terms of N cost savings and environmental benefits due to the 75.79% chance of VRT generating lower N rates than FP.

Evaluating the odds ratio at the loam soil texture indicated that the FP N rates were 0.27 as likely to be lower than the VRT N rates, Equation 36. The probability of FP N rates being lower than VRT N rates, Equation 37, was 26.68%. Under these conditions, there was a relatively small chance that FP was applying less N than the VRT technology calculated as necessary. A field with these conditions may benefit from VRT use for environmental benefits.

Parameter estimates from the net returns logit model Equation 30 are in Table 16. The significant soil and weather variables associated with net returns in the estimated logit model were silt soil texture ($Pr \leq 0.01$), loam soil texture ($Pr \leq 0.06$), organic matter ($Pr \leq 0.10$), and growing degree days ($Pr \leq 0.01$). Evaluating soil property and weather marginal changes in relation to net returns indicated that coarser soil textures and warmer temperatures were positively associated with the probability of lower net returns using VRT compared to FP, Table 17.

Evaluating the NR odds ratio at the means of the significant variables for the soil texture silt indicated that VRT net returns were 3.3 times as likely to be lower than FP net returns There was a 76.6% chance that VRT had lower net returns than FP. Field with these conditions would not benefit from VRT adoption in terms of profits.

The odds ratio evaluated at the loam soil texture indicated that VRT net returns were 3.0 times as likely to be less than FP. The probability of downside risk under these conditions was 74.91%, Equation 27. Fields with these soil conditions would be better suited to continue using the current FP N management in place.

Downside Risk – N Production Use Efficiency

Significant soil and weather variables related with N production use were sand soil texture ($Pr \leq 0.10$), clay soil texture ($Pr \leq 0.01$), loam soil texture ($Pr \leq 0.05$), soil depth ($Pr \leq 0.05$), soil erosion index ($Pr \leq 0.05$), and growing degree days ($Pr \leq 0.01$).The marginal changes in soil properties and weather in relation to NPU indicated that finer soil textures or warmer temperatures were positively associated with the probability of a lower VRT N use efficiency compared to FP, Table 17. Deeper soils or coarser soil textures were negatively related to the probability of lower N use efficiency of VRT compared to FP.

NPU efficiency odds ratio estimated at the clay soil texture indicated that VRT N use efficiency was 79.9 times as likely to be lower than FP. There was a 98.76% probability of VRT NPU being lower than FP, Equation 37. Using VRT on clay fields with the mean depth, erosion index, and temperature such as these would be inefficient in terms of N use relative to the FP.

At soil texture loam the odds ratio indicated that VRT N use efficiency was 0.5 times as likely to be lower than FP. Evaluating Equation 37 at this odds ratio, there was a 32.08% probability that VRT N efficiency was lower than FP on loam fields with these conditions. This means there is a 67.92% chance of higher N use efficiency using VRT compared to FP.

CONCLUSIONS AND RECOMMENDATIONS

Two main conclusions were drawn from this study. First, the real-time optical sensing and variable rate technologies (VRT) treatments indicated some N savings but were not more profitable on average compared to the existing farmer practices. There was some evidence of significantly higher mean net returns using optical sensing and VRT to manage N compared to the current practice at the sub-plot level, but the field level showed no difference. Second, there were risk management benefits identified at the field level using optical sensing and VRT compared to the farmer practice. Fields with lower lint yields were found to likely produce higher net returns with optical sensing and VRT than with the farmer practice which may help farmers manage risk on fields with this characteristic, Figure 5.

Other inferred conclusions that can aid in the cotton farmer's decision making are: 1) the VRT treatments may not apply enough N to significantly increase lint yields; 2) four locations realized significantly lower N rates applied in at least one form of VRT N fertilizer application (Tensas Middle, LA, Gibson, TN, Lauderdale, TN, and Leflore, MS) and four had higher N rates(Madison North, TN, Adams, MS, Tensas North, LA, and Tensas South, LA), Table 11; and 3) N rates were not low enough to increase N use efficiency and encourage environmental benefits. The farm fields used in this demonstration project represented a range of soils and climates in the MRB, Table 6; however, the fields tested in the experiments likely had limited enough spatial and temporal variability within the field that VRT treatments did not make a difference in field level mean net returns.

Cotton farmers in Tennessee, Louisiana, Mississippi, and Missouri states can use this information as a decision aid when considering switching to VRT. Mean net returns were positive across locations (for all technologies), Table 2, but N savings and EQIP incentive payments did not offset the cost of the technology enough to justify the adoption of VRT based on mean net returns alone in the MRB states. Policy makers are also interested in these results as EQIP payments did not increase net returns enough to justify the adoption of VRT. This can be considered when deciding nutrient management cost-share payments for the future in Tennessee, Mississippi, Missouri and Louisiana.

Areas for potential further research on net returns with this data include incentive payments and price sensitivity. Determining the precision nutrient management EQIP payment that would make optical sensing and VRT more profitable than FP by state would be of interest to policy makers. Additional studies on fields with more in field spatial variability could also be evaluated to further identify the conditions under which optical sensing a VRT may provide profitability, risk management, and nitrogen production use efficiency benefits.

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APPENDICES

Tables

Table 1. Literature review summary

				Profitability			Excess N			Risk Management Benefits
Author	Year	Fertilizer	Crop	VRT	URT	FP	VRT	URT	FP	VRT
Watkins, Lu, and Huang	1998	N	seed potato	$1 per ha	$2 per ha		same to reduced	same to reduced		
Roberts et al.	2002	N	corn				reduced more	Reduced		
Hu et al.	2007	N	rice	$63 to $82 per ha			+NUE			
Peng et al.	2006	N	rice	similar to higher		X	- N/+ NUE		X	
Lambert, Lowenberg-DeBoer, and Bongiovanni	2004	N	corn	0 or $1 to $2 per ha	X					
Wang et al.	2003	N	corn	++	X		reduced	X		
Maine et al.	2010	N	corn	++ overall	X					
Biermacher et al.	2006	N	winter wheat	$21.80 to $24.30 per ha	X		N by -59% by -82%	X		
Biermacher et al.	2009	N	winter wheat	$16 per ha	$9 per ha					
Butchee, May, and Arnall	2011	N	spring wheat				-22.4 kg N per ha		X	
Ortiz-Monasterio and Raun	2007	N	spring wheat	$56 per ha		X	-69 kg N per ha		X	
Raun et al.	2002	N	winter wheat	$4 to $5 per ha			NUE +15%			
Raun et al.	2005	N	winter wheat				NUE +15%			
Scharf et al.	2011	N	corn	$42 per ha	X		- 15 kg N per ha	X		
Lowenberg-DeBoer	1999	P&K	corn*							X
Isik and Khanna	2003	N&P	corn							X
Larson, English, and Roberts	2002	N	corn							X

*Corn-soybean or corn-soybean-wheat rotation.
X represents VRT in relation to either URT or FP.
++ represents that VRT was overall more profitable than either URT or FP.

Table 2. Mean cotton lint yields (kg ha^{-1}), N rates (kg ha^{-1}), NPU efficiency, and net returns ($ ha^{-1}) by location and year

County/Parish	State	Year	N	Cotton Lint Yield (kg ha^{-1})	N rates (kg ha^{-1})	NPU Efficiency	Net Returns ($ ha^{-1})
Research Station	LA	2012	89	941.14	101.65	9.44	1476.63
Tensas Parish Middle	LA	2012	90	1742.67	122.48	14.63	2787.45
		2013	90	1850.73	142.23	13.06	3162.93
Tensas Parish Middle low	LA	2014	90	1524.16	113.43	14.00	2675.18
Tensas Parish North	LA	2012	90	2307.38	102.33	28.33	3789.34
		2013	100	1329.18	132.35	10.97	2235.61
Tensas Parish South	LA	2012	90	1197.45	135.29	9.07	1835.10
		2013	90	1980.03	109.57	18.23	3463.60
		2014	80	1755.68	125.27	13.92	3077.85
Dunklin	MO	2013	12	887.22	99.29	9.29	1484.72
New Madrid East	MO	2012	24	1318.00	75.12	17.68	2151.04
New Madrid North	MO	2012	33	1247.82	75.62	16.67	2031.05
New Madrid South	MO	2012	12	1042.00	83.33	12.55	1665.04
Pemiscot North	MO	2013	6	1313.41	91.08	15.46	2273.55
Pemiscot South	MO	2013	6	1180.49	103.58	11.58	2007.44
Adams	MS	2012	107	1010.71	78.49	14.86	1647.00
Leflore East	MS	2014	35	1761.77	143.45	12.33	3047.17
Leflore North	MS	2013	60	1742.37	119.19	15.23	3013.67
Leflore South	MS	2013	48	1952.37	142.55	13.93	3437.51
Carroll	TN	2014	72	836.96	93.32	9.25	1451.90
Gibson	TN	2011	72	760.35	179.23	4.82	1570.31
		2012	88	1160.80	93.96	13.00	1849.92
Lauderdale	TN	2012	90	1485.86	114.22	13.09	2369.38
		2013	90	869.03	98.29	23.37	1474.07
		2014	90	722.41	92.69	8.28	1242.81
Madison North	TN	2012	72	959.41	88.81	11.77	1543.11
		2013	72	1168.91	72.79	55.53	2068.93
Madison South	TN	2014	72	1189.96	91.29	13.61	2104.08
Tipton	TN	2012	72	1286.63	93.94	13.93	2077.64

N represents the number of observations.

Table 3. 2013 Ownership Cost Budgets for Greenseeker™, Yield Monitor Information Systems (YMIS), a Computer, and Technical Assistance

	Green-seeker™	YMIS	Computer		Technical Advice[10]
Ownership Cost	Dollars	Dollars	Dollars	Cost by State	Dollars
Capital Recovery (annual)[2]	$13,622.38	$ 3,232.99	$ 224.90		
Purchase/list price[1,6,7] (2013 dollars)	$60,684.08	$14,421.08	$1,001.24		
Salvage value[3] (2013 dollars)	$ 48.27	$ 34.52	$ -		
Capital recovery factor	0.22	0.22	0.22		
Real interest rate[4] (%)	4%	4%	4%		
Useful life (years)[5]	5	5	3		
Average hours of use per year[5]	300	600			
Taxes, Insurance, and Housing[2]	$ 606.36	$ 143.87	$ 10.01		
Interest rate (%)	2%	2%	2%		
Repairs and Maintenance[2]	$42,478.86	$11,536.86	$ 0.00		
Repairs as % of list price[3] (%)	70%	80%			
Useful life[5] (hours)	1500	3000			
Hectares per Hour[2]	16.86	1.82			
Speed (km $hour^{-1}$)[3]	10.5	4.5			
Width (m)[3]	24.7	5.7912			
Meters per kilometer (m km^{-1})	1,000	1,000			
Efficiency (%)[3]	65%	70%			
$Meters^2$ ha^{-1}	10,000	10,000			
Hours ha^{-1}	0.059	0.548			
Cotton Enterprise Size[8]					
Tennessee farm (ha)			279.42	$ 0.28	
Mississippi farm (ha)			231.10	$ 0.34	
Louisiana farm (ha)			196.47	$ 0.40	
Missouri farm (ha)			347.08	$ 0.23	
Total ownership costs $hour^{-1}$	$ 37.81	$ 4.97	$ 78.31		
Total costs (2013 dollars ha^{-1})	$ 2.25	$ 2.73			$ 12.63
Greenseeker™ costs * 1.02[9]	$ 2.29				

[1]Includes $500 (684.08 in 2013 dollars) to retrofit (Larson et al. 2005)
[2]Formula given in Boehlje and Eidman (1984)
[3]ASABE Standards (2011)
[4]American Agricultural Economics Association (2000)
[5]Gandonou et al. (2006)
[6]List Price for Yield Monitoring is the average of Case IH and John Deere plus $500 (684.08 in 2013 dollars) (Larson et al. 2005)
[7]Average cost for desktop computer and color printer (informal survey 2014)
[8]Average area (ha) in cotton on a farm categorized as a cotton farm per state as given by 2012 Census of Agriculture (USDA 2012)
[9]Greenseeker™ multiplied by 1.02 to account for N rich strip calibration (Biermacher et al. 2009a).
[10]Mooney et al. 2010

Table 4. Partial budget summary for VRT treatments: Greenseeker™ (treatment 2) and Greenseeker™ plus YMIS (treatment 3)

Net Return Component		Treatment 2		Treatment 3
Revenue ($ ha^{-1})				
Cotton Revenue ($ ha^{-1})	$	2,530.27	$	2,509.08
Cotton lint price[1] ($ kg^{-1})	$	1.86	$	1.86
Cotton lint yield[1] (kg ha^{-1})		1360.36		1348.97
2013 EQIP Payment ($ ha^{-1})				
Tennessee	$	63.99	$	63.99
Louisiana	$	66.53	$	66.53
Mississippi	$	66.28	$	66.28
Missouri	$	33.61	$	33.61
Costs ($ ha^{-1})				
N applied ($ ha^{-1})	$	66.55	$	71.51
Urea N price[1] ($ kg^{-1})	$	0.93	$	0.93
In-season N rate[1] (kg ha^{-1})		71.56		76.89
N fertilizer application[3] ($ ha^{-1})	$	6.60	$	6.60
Information/operating costs[2] ($ ha^{-1})				
Tennessee	$	2.29	$	12.91
Louisiana	$	2.29	$	13.03
Mississippi	$	2.29	$	12.97
Missouri	$	2.29	$	12.86
Net Returns ($ ha^{-1})				
Tennessee	$	2,518.82	$	2,508.20
Louisiana	$	2,521.36	$	2,510.62
Mississippi	$	2,521.11	$	2,510.43
Missouri	$	2,488.44	$	2,477.87

[1]Prices, yields, and N rates are averages of the years included in this study (2013 real $).

[2]Operating costs for treatment 3 include cost of computer and technical assistance (see table 3).

[3]N fertilizer application is the labor cost for dry bulk only.

Table 5. Dependent and explanatory variable names, definitions, and means

Variable Name	Variable Definition	Mean	Min	Max	N
Dependent Variable					
Y	Cotton lint yields (kg ha^{-1})	1347.07	133.25	2585.06	1942
N	Total nitrogen rates applied (kg ha^{-1})	109.74	33.59	252.83	1953
NR	Net returns ($ ha^{-1})	2268.57	239.25	4232.64	1942
NPU	Nitrogen production use efficiency (Y/N)	13.43	0.61	119.56	1942
YΔ	VRT_i-FP yields (kg ha^{-1})	37.05	-1941.20	2077.53	1263
NΔ	VRT_i-FP N rates (kg ha^{-1})	4.95	-67.59	125.36	1263
NRΔ	VRT_i-FP NR ($ ha^{-1})	102.37	-3630.32	3668.06	1263
NPUΔ	VRT_i-FP NPU	-3.21	-96.52	20.18	1263
Yprob	If VRT_i<FP, 1; otherwise, 0	0.45	0	1	1263
Nprob	If VRT_i>FP, 1; otherwise, 0	0.55	0	1	1263
NRprob	If VRT_i<FP, 1; otherwise, 0	0.37	0	1	1263
NPUprob	If VRT_i<FP, 1; otherwise, 0	0.47	0	1	1263
Explanatory Variables					
Treatment	Treatment dummy 1 Farmer practice 2 VRT Greenseeker™ 3 VRT Greenseeker™ + yield monitor information systems (YMIS)[1]				
Soil texture index	Soil texture ranked by coarseness (4 being the coarsest) 1 Clay 2 Silt 3 Loam 4 Sand[1]	2.13	1	4	1935
Elevation	Vertical distance above sea-level (meters)	64.40	21.64	136.36	1953
Water holding capacity[2]	Water holding capacity (cm cm^{-1}) – "the amount of water that an increment of soil depth, inclusive of fragments, can store that is available to plants"	0.21	0.08	0.23	1935
Organic matter[2]	Organic matter (%) – "the amount by weight of decomposed plant and animal residue expressed as a weight percentage of the less than 2 mm soil material"	1.84	0.52	2.50	1935
Soil erosion index	Soil erosion index	7.35	0.21	39.13	1935
Depth[2]	Soil depth (cm) – "Distance from the top of the soil to the base of the soil horizon"	21.53	8.00	64.00	1935
Growing degree days	Seasonal growing degree days (Celsius)	1574.3	1025.93	1943.27	1953
Treatment 3	If treatment 3 (Greenseeker™ plus YMIS), then 1; otherwise, 0	0.33	0	1	1953

[1]Reference variable

[2]Definition taken directly from SSURGO (USDA 2014f).

Table 6. Mean elevation (meters), soil texture(s), mean SEI, mean water holding capacity (cm cm^{-1}), mean organic matter (%), mean soil depth, and mean growing degree days (Celsius) by county/parish and state

County/Parish	State	N	Elevation (meters)[4]	Soil Texture(s)[2]	SEI	Water Holding Capacity (cm cm^{-1})[1]	Organic Matter (%)[1]	Soil Depth (cm)[1]	Growing Degree Days (Celsius)[3]
Research Station	LA	90	21.64	Sand	7.53	0.22	2.20	18.00	1938.34
Tensas Middle	LA	180	21.64	Silt	3.59	0.21	2.23	22.29	1846.54
Tensas Middle low	LA	90	21.64	Silt	3.69	0.22	2.20	28.00	1346.87
Tensas North	LA	190	23.46	Clay; Silt	3.15	0.18	2.15	15.96	1830.56
Tensas South	LA	270	21.64	Clay; Silt	7.26	0.22	2.20	28.00	1731.71
Dunklin	MO	12	82.09	Loam; Sand	0.31	0.09	1.01	19.67	1439.52
New Madrid East	MO	24	92.99	Loam; Sand	2.06	0.21	1.35	22.75	1682.86
New Madrid North	MO	33	89.74	Loam	1.92	0.21	1.23	19.61	1682.86
New Madrid South	MO	12	89.74	Sand	1.00	0.17	0.75	20.00	1682.86
Pemiscot North	MO	6	85.12	Silt; Sand	2.53	0.19	1.13	17.33	1377.81
Pemiscot South	MO	6	83.86	Silt	3.85	0.23	2.00	18.00	1377.81
Adams	MS	107	55.17	Silt	6.87	0.22	1.89	27.03	1856.31
Leflore East	MS	35	43.07	Clay; Silt; Loam	6.91	0.20	1.49	20.00	1211.69
Leflore North	MS	60	43.07	Silt; Loam	6.59	0.19	1.75	23.00	1648.79
Leflore South	MS	48	43.07	Silt; Loam	6.86	0.20	1.60	21.54	1648.79
Carroll	TN	72	123.22	Silt	11.41	0.21	1.45	17.49	1025.93
Gibson	TN	160	130.72	Silt	19.60	0.22	1.38	21.32	1464.16
Lauderdale	TN	270	90.32	Silt	3.22	0.21	1.93	13.18	1337.34
Madison North	TN	144	117.25	Silt	16.12	0.22	1.33	20.06	1404.96
Madison South	TN	72	136.36	Silt	12.79	0.22	1.41	18.72	1063.23
Tipton	TN	72	89.70	Silt	5.02	0.22	1.25	40.51	1584.43

[1] Source: SSURGO (USDA 2014f).

[2] Source: Soil texture triangle (USDA 2014e).

[3] Source: PRISM (PRISM 2014).

[4] Source: National Elevation Data (U.S. Geology Survey 2014).

N represents number of observations.

Table 7. Best fit criteria for treatment effect models, Equations 16-19

	Yields		N Rate		NPU		NR	
	With	Without	With	Without	With	Without	With	Without
-2 LL	27181.0	27187.8	17617.0	18274.3	12695.8	12886.7	29433.0	29435.2
AIC	27195.0	27199.8	17625.0	18280.3	12709.8	12898.7	29447.0	29447.2
BIC	27190.7	27196.1	17629.2	18283.5	12705.5	12895.0	29442.7	29443.6
N used	1924	1924	1935	1935	1924	1924	1924	1924

N represents number of observations.
AIC is the Akaike information criterion, BIC is the Bayesian information criterion, and the -2LL is the -2 Log Likelihood.

Table 8. Treatment effect estimates of VRT treatments 2 and 3 versus FP by location on lint yield (kg ha^{-1}), N rate (kg ha^{-1}), NPU, and net returns (NR) (\$ ha^{-1})

			Cotton Lint Yield (kg ha^{-1})		Total N Rates (kg ha^{-1})		NPU Efficiency (kg kg-^{1})		Net Returns (\$ ha^{-1})	
County/Parish	State	N	2 vs 1	3 vs 1	2 vs 1	3 vs 1	2 vs 1	3 vs 1	2 vs 1	3 vs 1
Research Station	LA	30	211.71	271.85	37.54	32.26	-1.11	-0.33	339.48	446.59
			(284.71)	(237.62)	(17.91)	(16.69)	(3.66)	(2.76)	(471.11)	(394.46)
Tensas Middle	LA	60	-26.53	-42.19	-26.10	-14.23	2.91	1.18	73.13	15.77
			(183.39)	(171.05)	(21.71)*	(13.73)*	(2.95)	(2.06)	(335.51)	(313.35)
Tensas Middle low	LA	30	67.05	19.65	-45.90	-50.52	5.45	5.72	276.87	195.90
			(103.57)	(126.16)	(5.90)	(6.06)	(1.21)	(1.40)	(190.26)	(232.52)
Tensas North	LA	60	153.95	120.37	79.22	84.33	-17.15	-17.91	163.19	90.22
			(119.97)	(181.58)	(12.57)*	(19.52)*	(11.69)*	(12.43)*	(226.68)	(332.13)
Tensas South	LA	90	234.03	219.22	9.50	24.69	1.50	-0.08	452.83	390.41
			(593.14)	(574.53)	(16.89)*	(24.76)*	(4.93)	(5.22)	(1031.12)	(1010.62)
Dunklin	MO	4	-82.30	-92.51	-18.48	-23.80	0.95	1.88	-84.03	-94.68
			(44.57)	(73.65)	(13.11)	(21.10)	(1.18)	(3.39)	(62.69)	(136.49)
New Madrid East	MO	8	-18.59	-27.52	-6.02	-3.78	1.33	0.67	8.23	-14.94
			(37.84)	(35.32)	(6.69)	(6.80)	(1.43)	(1.56)	(59.65)	(63.17)
New Madrid North	MO	11	19.02	12.00	-3.97	-4.72	1.28	1.45	67.30	54.11
			(71.34)	(81.91)	(9.26)	(10.46)	(2.27)	(2.26)	(121.03)	(132.36)
New Madrid South	MO	4	51.00	61.57	6.44	8.40	-0.29	-0.50	98.01	108.52
			(26.14)	(34.75)	(7.94)	(5.67)	(1.53)	(1.10)	(60.66)	(66.31)
Pemiscot North	MO	3	55.27		-41.81		7.95		212.60	
			(129.95)		(8.40)		(4.06)		(250.70)	
Pemiscot South	MO	3	-20.94		-16.80		1.89		23.61	
			(288.35)		(16.95)		(3.07)		(510.74)	
Adams	MS	29	117.77	57.66	17.25	26.71	-6.74	-8.58	222.35	96.12
			(58.26)	(75.84)	(39.40)	(54.08)*	(8.87)	(11.30)*	(27.51)	(30.40)
Leflore East	MS	17	20.10		17.38		-1.33		64.03	
			(306.27)		(6.85)		(2.09)		(559.30)	

Table 8. Continued

County/Parish	State	N	Cotton Lint Yield (kg ha^{-1}) 2 vs 1	Cotton Lint Yield (kg ha^{-1}) 3 vs 1	Total N Rates (kg ha^{-1}) 2 vs 1	Total N Rates (kg ha^{-1}) 3 vs 1	NPU Efficiency (kg kg^{-1}) 2 vs 1	NPU Efficiency (kg kg^{-1}) 3 vs 1	Net Returns ($ ha^{-1}) 2 vs 1	Net Returns ($ ha^{-1}) 3 vs 1
Leflore North	MS	20	-22.93	-54.22	-31.07	-14.47	4.16	2.04	81.82	-11.77
			(54.67)	(132.68)	(18.95)*	(25.57)	(3.06)	(3.82)	(101.80)	(236.09)
Leflore South	MS	16	103.06	38.91	11.27	13.24	-0.14	-0.61	223.42	100.24
			(98.79)	(92.19)	(18.12)	(23.81)	(2.18)	(2.80)	(177.21)	(193.01)
Carroll	TN	24	30.69	134.90	-16.80	-5.60	2.31	2.16	149.39	315.32
			(246.94)	(150.60)	(15.84)	(20.36)	(3.60)	(2.87)	(462.84)	(285.18)
Gibson	TN	48	-11.03	-4.42	-14.65	-16.42	1.20	1.56	-2.92	-15.29
			(303.57)	(286.92)	(19.42)*	(22.30)*	(3.94)	(3.04)	(576.54)	(532.59)
Lauderdale	TN	90	-12.88	45.84	-18.66	-12.07	2.45	2.86	76.83	165.33
			(391.78)	(360.03)	(18.84)*	(20.85)*	(5.03)	(5.54)	(718.42)	(657.46)
Madison North	TN	48	-360.74	-286.99	18.90	21.93	-32.88	-34.34	-641.41	-521.44
			(608.74)	(533.45)	(38.80)*	(49.86)*	(37.10)*	(40.98)*	(1148.18)	(1010.12)
Madison South	TN	24	-83.65	-65.59	-12.60	-15.86	1.33	2.59	-68.93	-32.30
			(301.44)	(231.69)	(15.60)	(21.88)	(4.33)	(5.00)	(573.11)	(424.55)
Tipton	TN	24	11.04	-50.89	-6.53	-14.00	1.20	1.89	92.83	1.70
			(182.06)	(194.22)	(10.40)	(14.11)	(2.15)	(3.05)	(305.61)	(327.91)

* Significant differences using the Bonferroni correction to deal with multiple comparisons.

Standard errors are in parentheses.

N is the number of observations; the Pemiscot, MO, locations did not have a treatment 3.

Table 9. Differences of least squares means and Dunnett's test results, with (With) and without (Without) the location-treatment interaction term

		F Observed Estimate	
Variable	Effect	With	Without
Yield	Treatment 2 vs 1	29.96	28.68
		(21.50)	(15.69)
Yield	Treatment 3 vs 1	38.39	35.82
		(21.92)	(15.84)$^{++}$
N rate	Treatment 2 vs 1	-2.20	2.32
		(5.50)	(1.46)
N rate	Treatment 3 vs 1	1.35	7.95
		(5.73)	(1.50)$^{+++}$
NPU	Treatment 2 vs 1	-1.86	-3.21
		(1.72)	(0.67)$^{+++}$
NPU	Treatment 3 vs 1	-2.15	-3.70
		(1.77)	(0.66)$^{+++}$
Net Returns	Treatment 2 vs 1	90.73	89.59
		(34.33)$^{++}$	(28.27)$^{+++}$
Net Returns	Treatment 3 vs 1	76.03	72.09
		(34.92)$^{+}$	(28.56)$^{++}$

Note: Standard error in parentheses.

$^{+,++,+++}$ Dunnett's adjusted probability significant at the 10%, 5%, or 1% level.

Table 10. Treatment, soil attribute, and climate effects on lint yields (kg ha^{-1}), N rates (kg ha^{-1}), NPU, and net returns (NR) ($ ha^{-1})

	Cotton lint yields (kg ha^{-1})	N rates (kg ha^{-1})	NPU	NR ($ ha^{-1})
N	1924	1935	1924	1924
Intercept[1] (μ)	1872.41	133.85	159.15	2730.60
	(467.32)***	(15.82)***	(14.68)***	(739.26)***
Treatment 1 (τ_1)	-38.39	-1.35	2.15	-76.86
	(21.92)*	(5.73)	(1.77)	(48.83)**
Treatment 2 (τ_2)	-8.42	-3.55	0.29	-14.27
	(21.62)	(5.73)	(1.66)	(34.67)
Elevation (ψ)	-5.53	-0.35	-0.27	-8.30
	(2.66)*	(0.12)***	(0.07)***	(4.62)*
WHC[2] (ω)	29.72	0.98	-0.51	-53.20
	(5.10)***	(0.38)***	(0.09)***	(9.19)***
OM[3] (θ)	1.64	-0.05	0.03	3.01
	(0.36)***	(0.03)*	(0.01)***	(0.65)***
Soil Texture[4,1] (β)	26.44	-1.52	0.69	48.64
	(3.78)***	(0.27)***	(0.72)***	(6.78)***
SEI (γ)	0.78	0.87	-0.04	1.33
	(2.18)	(0.18)***	(0.04)	(3.93)
Depth (φ)	5.33	-0.01	0.05	9.58
	(1.01)***	(0.08)	(0.02)***	(1.83)***
GDD (χ)	-0.44	0.01	-0.09	-0.52
	(0.21)**	(0.00)***	(0.00)***	(0.32)

*,**,*** Significant at the 10%, 5%, and 1% level.

Standard error in parentheses.
WHC is water holding capacity, OM is organic matter, SEI is soil erosion index, GDD is growing degree days, and N is number of observations.

[1]Treatment 3 and soil texture ‘sand’ are in intercept.

[2] WHC scaled by 100 cm cm^{-1}.

[3] OM scaled by 100%.

[4] Soil texture scaled by 10%

Table 11. Soil and climate property means by farm with significant N rate differences using VRT versus FP

N Rate	County/Parish	State	Elevation (meters)[4]	Soil Texture(s)[2]	SEI	Water Holding Capacity (cm cm^{-1})[1]	Organic Matter (%)[1]	Soil Depth (cm)[1]	Growing Degree Days (Celsius)[3]
VRT<FP	Tensas Middle	LA	21.64	Silt	3.59	0.21	2.23	22.29	1846.54
	Gibson	TN	130.72	Silt	19.6	0.22	1.38	21.32	1464.16
	Lauderdale	TN	90.32	Silt	3.22	0.21	1.93	13.18	1337.34
	Leflore North	MS	43.07	Silt; Loam	6.59	0.19	1.75	23.00	1648.79
	Average		*71.44*		*8.25*	*0.21*	*1.82*	*19.95*	*1574.21*
VRT>FP	Madison North	TN	117.25	Silt	16.12	0.22	1.33	20.06	1404.96
	Adams	MS	55.17	Silt	6.87	0.22	1.89	27.03	1856.31
	Tensas North	LA	23.46	Clay; Silt	3.15	0.18	2.15	15.96	1830.56
	Tensas South	LA	21.64	Clay; Silt	7.26	0.22	2.20	28.00	1731.71
	Average		*54.38*		*8.35*	*0.21*	*1.89*	*22.76*	*1705.89*

[1] Source: SSURGO (USDA 2014f).

[2] Source: Soil texture triangle (USDA 2014e).

[3] Source: PRISM (PRISM 2014).

[4] Source: National Elevation Data (U.S. Geology Survey 2014).

Table 12. Type 3 fixed effects, Equations 16-19, (With) and without (Without) the location-treatment interaction term

	Treatment F Value Estimate	
Variable	With	Without
Yield[1,2]	1.71	2.84*
N rate[1]	0.2	14.8***
NPU[1,2]	0.86	16.44***
Net Returns[1,2]	3.90**	5.52***

*** Significant at the 1% level.

[1]Model included Satterthwaite approximation to deal with degrees of freedom.

[2]Model included a repeat statement with group treatment to deal with unequal variances.

Table 13. Soil and climate attribute effects on lint yield (kg ha^{-1}), N rate (kg ha^{-1}), net returns (NR) ($ ha^{-1}), and NPU mean differences

Effect	Yield (kg ha^{1})	N rate (kg ha^{1})	NR ($ ha^{1})	NPU
Intercept[1,2] (μ)	32.54	-7.77	856.58	-9.87
	-20.83	(1.91)***	(372.90)**	(8.78)
Clay[2] (β_1)	-4.63	6.33	-195.82	-12.41
	-6.61	(0.61)***	(118.31)*	(2.77)***
Silt[2] (β_2)	-24.45	-1.68	-376.13	-2.67
	(4.92)***	(0.45)***	(87.97)***	(2.08)
Loam[2] (β_3)	-14	-2.41	-190.16	6.19
	(6.15)**	(0.56)***	(110.02)*	(2.59)**
Elevation (ψ)	-1.98	-0.05	-3.80	0.03
	(0.53)***	-0.05	(0.95)***	(0.02)
WHC[2] (ω)	6.74	1.92	929.64	6.54
	-6.41	(0.59)***	(1148.78)	(26.80)
OM[3] (θ)	1.71	-0.03	297.60	8.39
	(0.48)***	-4.44	(86.15)***	(2.01)***
Depth (φ)	3.76	-0.27	6.58	0.08
	(1.26)***	(0.12)**	(2.27)***	(0.05)
VRT3 (ν)	24.82	5.81	26.02	0.02
	-20.59	(1.91)***	(36.90)	(0.86)
SEI (γ)	5.89	0.90	6.62	-0.43
	(2.09)***	(0.19)***	(3.75)*	(0.09)***
GDD (χ)	-0.34	0.04	-0.71	-0.01
	(0.05)***	(0.00)***	(0.09)***	(0.00)***

*,**,*** 10, 5, and 1 percent significance.

Standard error in parentheses.
WHC is water holding capacity, OM is organic matter, VRT3 is the variable rate dummy for treatment 3, SEI is soil erosion index, and GDD is growing degree days.

The number of observations for each model is 1140.

[1] Intercept contains soil texture sand.

[2] Textures scaled by 10%.

[3] WHC scaled by 100 cm cm^{-1}.

[4] OM scaled by 100%.

Table 14. Treatment summary statistics for lint yields (kg ha^{-1}), N rates (kg ha^{-1}), net returns (NR) (\$ ha^{-1}), and NPU efficiency

Variable	Summary Statistics	Treatment 1	Treatment 2	Treatment 3
Lint Yield (kg ha^{-1})				
	Max	2,397	2,585	2,565
	Min	226	133	204
	Mean	1,332	1,360	1,349
	Std Dev	463	472	457
	CV	34.75	34.72	33.91
	N	649	658	635
N Rate (kg ha^{-1})				
	Max	244	226	253
	Min	34	54	34
	Mean	107	109	114
	Std Dev	35	31	35
	CV	32.48	28.73	30.93
	N	660	659	635
NR (\$ ha^{-1})				
	Max	4,081	4,233	4,167
	Min	481	239	333
	Mean	2,226	2,315	2,264
	Std Dev	805	816	782
	CV	36.14	35.25	34.56
	N	649	658	635
NPU				
	Max	120	54	40
	Min	1	1	1
	Mean	18	14	14
	Std Dev	19	7	6
	CV	107.38	46.07	44.86
	N	649	658	635

Table 15. Kolmogorov-Smirnov Statistics, D Statistic (D Stat) and P value (P) by lint yield, N rate, net returns (NR), and NPU and treatment at the sub-plot and field levels

			Cotton Lint Yield		N Rate		NR		NPU	
Comparison Level	Treatment Comparison	N	D Stat	P value	D Stat	P value	D Stat	P value	D Stat	P value
Sub-plot	2 versus 1	1307	0.0576	0.2275	0.2128	<0.0001	0.0852	0.0173	0.1107	0.0007
	3 versus 1	1284	0.0675	0.1075	0.1895	<0.0001	0.0798	0.0334	0.0832	0.0235
	2 versus 3	1293	0.0392	0.7035	0.0849	0.0190	0.0692	0.0906	0.0946	0.0062
Field	2 versus 1	58	0.1379	0.9455	0.3103	0.1224	0.1379	0.9455	0.1724	0.7818
	3 versus 1	55	0.1896	0.7075	0.2626	0.3009	0.1605	0.8719	0.1631	0.8589
	2 versus 3	55	0.0981	0.9994	0.1260	0.9815	0.1256	0.9815	0.1552	0.8961

Note: The null hypothesis is that the treatments are similar.
N represents the number of observations.

Table 16. Soil and climate attribute effects on lint yield, N rate, net returns (NR), and NPU, logistic coefficient estimates

Effect	Yield (kg ha^{-1})	N rate (kg ha^{-1})	NR ($ ha^{-1})	NPU
Intercept[1,2] (μ)	-0.91	-1.19	-1.31	-2.51
	(1.22)	(1.48)	(1.30)	(1.30)*
Clay[2] (β_1)	-0.27	1.91	0.10	4.15
	(0.47)	(1.18)	(0.45)	(1.06)***
Silt[2] (β_2)	1.75	-3.86	0.98	-0.13
	(0.36)***	(0.69)***	(0.35)***	(0.30)
Loam[2] (β_3)	1.29	-3.72	0.88	-0.98
	(0.39)***	(0.65)***	(0.41)**	(0.39)**
Elevation (ψ)	0.00	-0.02	0.00	0.00
	(0.00)	(0.00)***	(0.00)	(0.00)
WHC[2] (ω)	-7.00	17.71	-3.21	3.29
	(3.93)*	(5.30)***	(4.01)	(4.50)
OM[3] (θ)	-0.61	0.41	-0.51	-0.38
	(0.29)**	(0.38)	(0.29)*	(0.31)
Depth (φ)	-0.02	0.00	-0.01	-0.02
	(0.01)**	(0.01)	(0.01)	(0.01)**
VRT3 (ν)	0.11	0.46	0.14	0.03
	(0.12)	(0.14)***	(0.13)	(0.13)
SEI (γ)	-0.02	0.12	0.00	0.03
	(0.01)	(0.02)***	(0.01)	(0.01)**
GDD (χ)	0.00	0.00	0.00	0.00
	(0.00)***	(0.00)	(0.00)***	(0.00)***

[1] Intercept contains soil texture category ‘sand’

*,**,*** 10, 5, and 1 percent significance

Standard error in parentheses.

Number of observations per model is 1140.

Table 17. Marginal effects of soil and climate properties in yields, N rates, net returns (NR), and NPU

Effect	Lint Yield Estimate	N Rate Estimate	NR Estimate	NPU Estimate
Intercept[1,2]	-5.9623	-6.9554	-7.2956	-9.1885*
Clay[2]	-2.3616	57.4634	1.1004	622.3134***
Silt[2]	47.2877***	-9.7883***	16.5568***	-1.2462
Loam[2]	26.4844***	-9.7566***	14.1669**	-6.2626**
Elevation	0.4425	-1.75443***	0.498338	-0.24969
WHC[2]	-0.9991*	0.0000***	-0.9596	25.8859
OM[3]	-0.4567**	0.5132	-0.4017	-0.3185
Depth	-1.8546**	0.3996	-1.2057	-1.7200**
VRT3	11.9184	59.0423***	14.7746	3.2590
SEI	-1.7672	12.9867***	0.0348	3.0898**
GDD	0.1248***	0.0249	0.0965***	0.1845***

*,**,*** 10, 5, and 1 percent significance to logit models.

[1] Intercept contains soil texture category sand.

[2] Texture scaled by 10%.

[3] WHC scaled by 100 cm cm^{-1}.

[4] OM scaled by 100%.

Figures

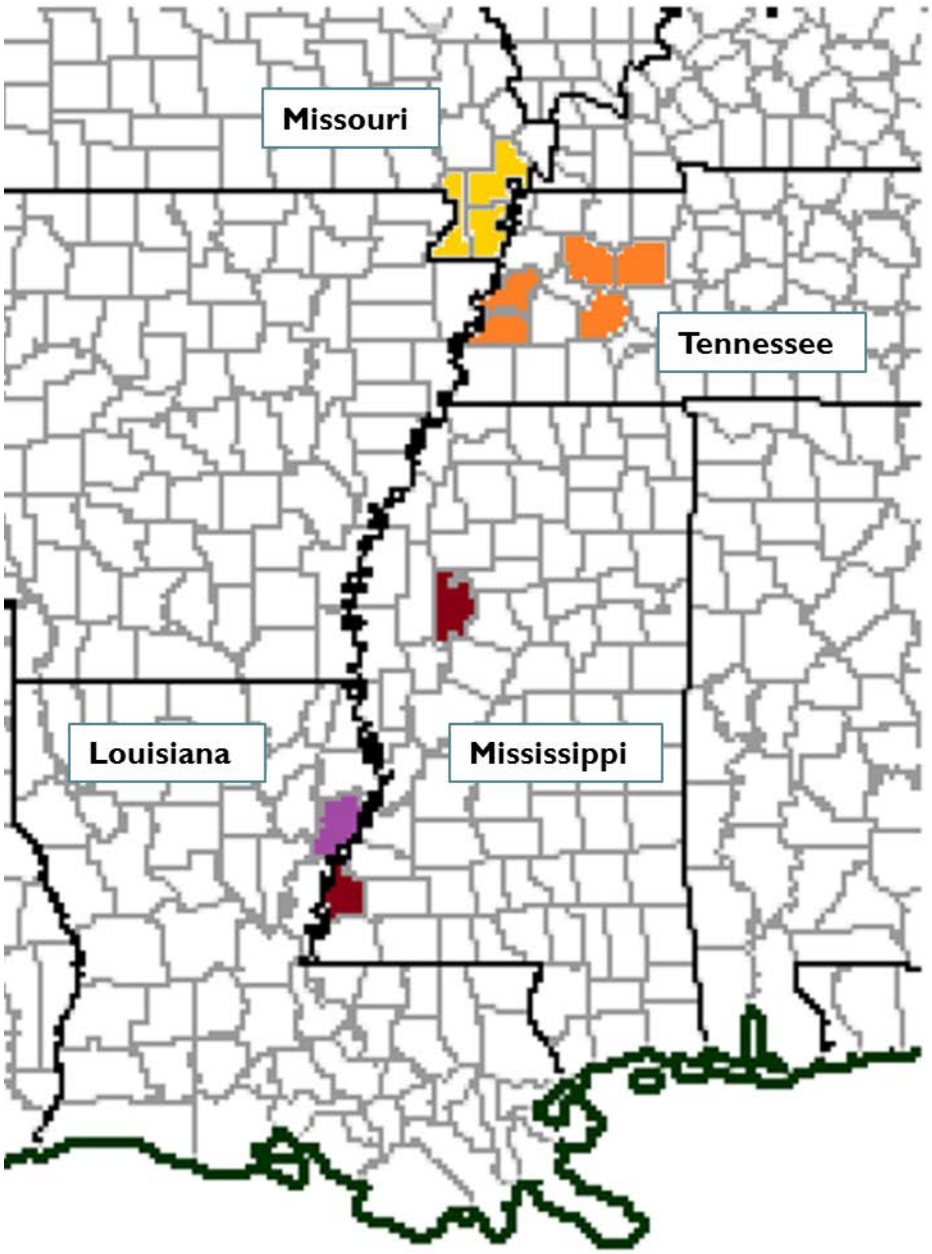

Figure 10. County/Parish locations of the experiment fields designated by color

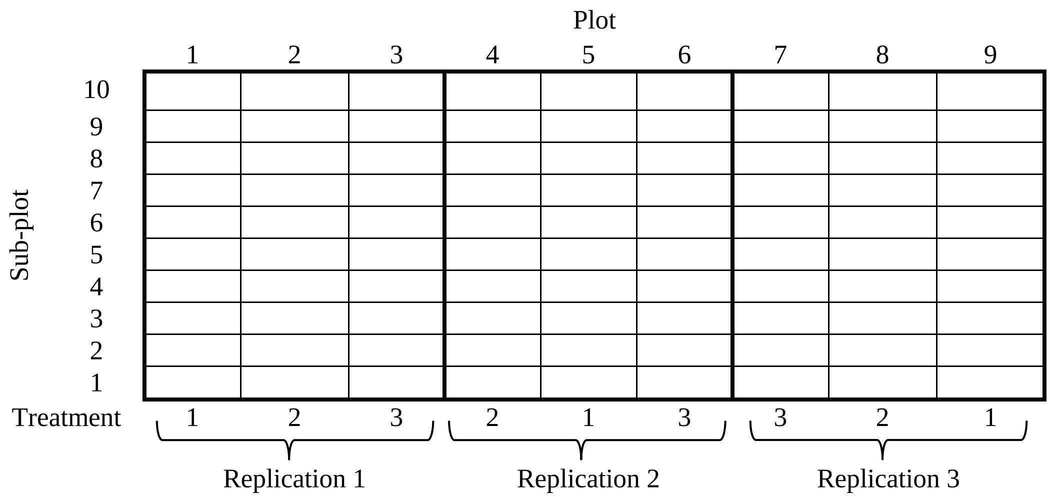

Figure 11. Example of a location's randomized complete block design: 9 plots, 10 sub-plots per plot (totaling 90), and 3 replications of random treatments

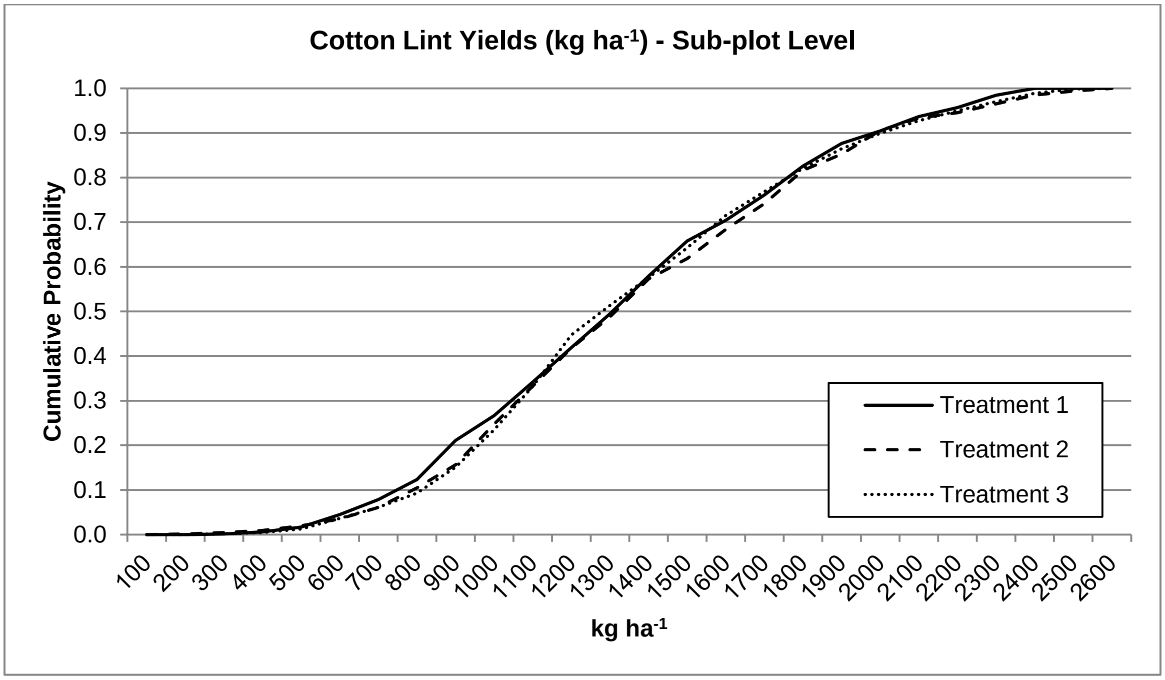

Figure 12. Sub-plot level cotton lint yields (kg ha^{-1}) cumulative probability distributions

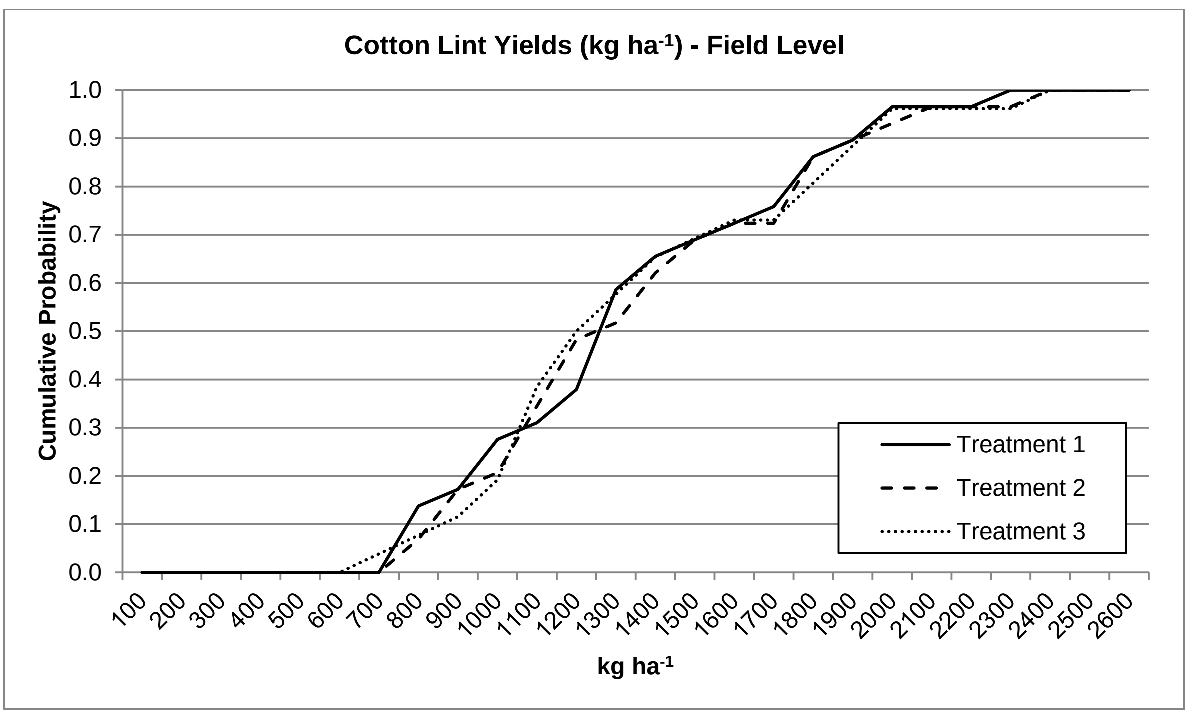

Figure 13. Field level cotton lint yields (kg ha^{-1}) cumulative probability distributions

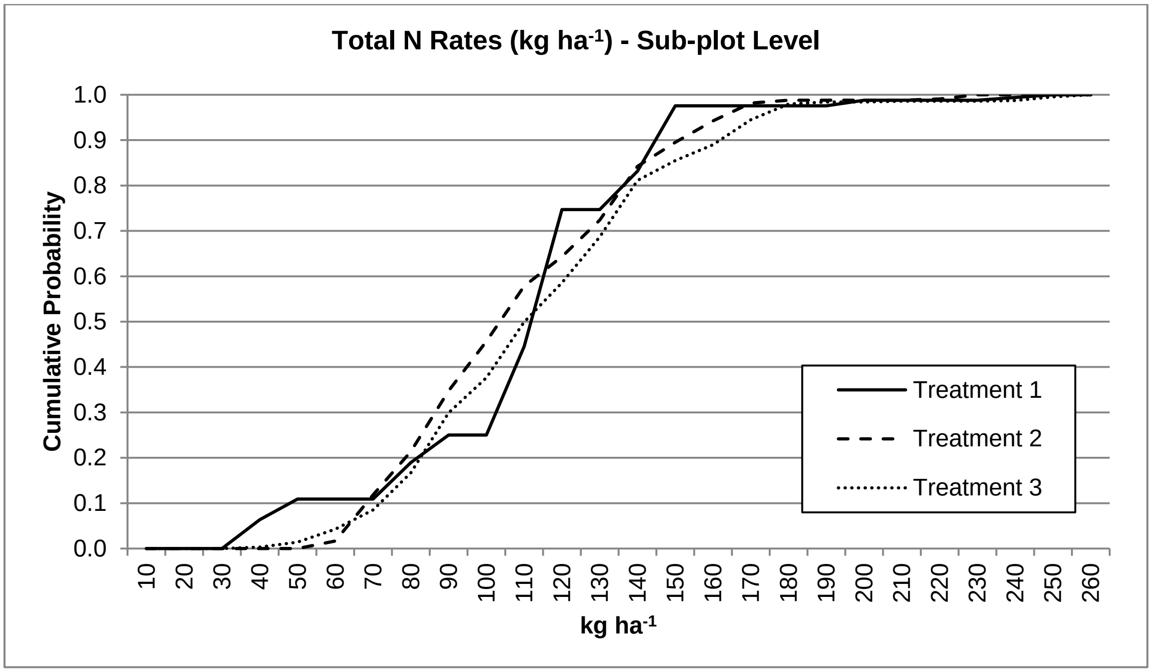

Figure 14. Sub-plot level total N rate (kg ha^{-1}) cumulative probability distributions

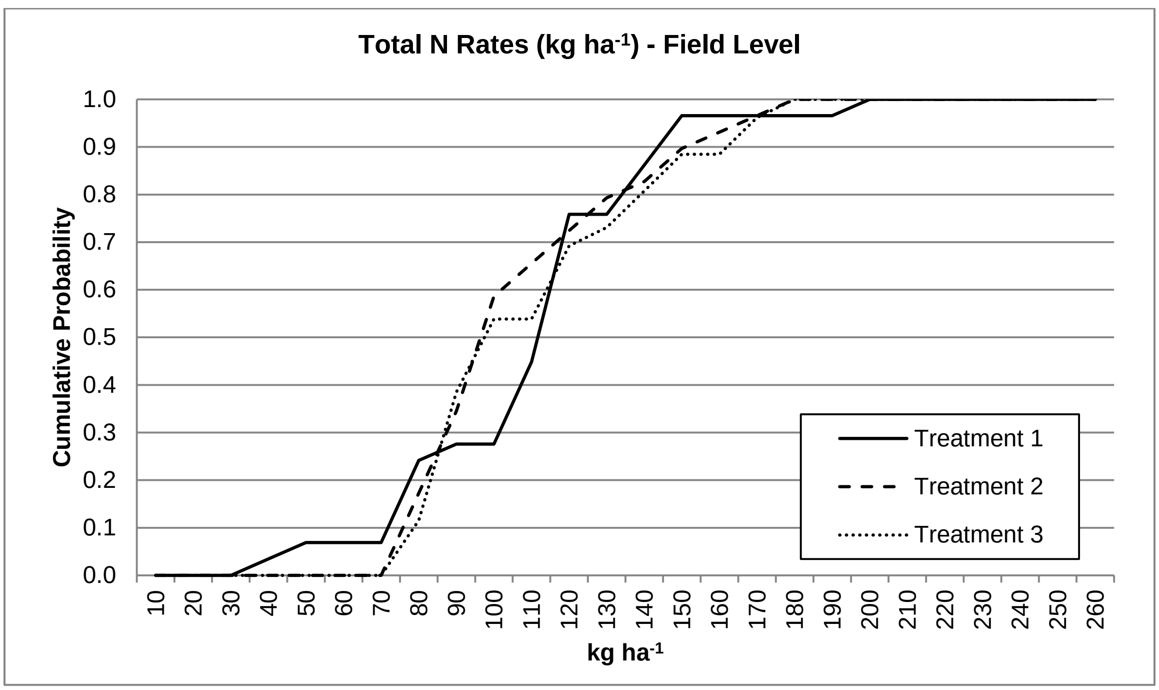

Figure 15. Field level total N rates (kg ha^{-1}) cumulative probability distributions

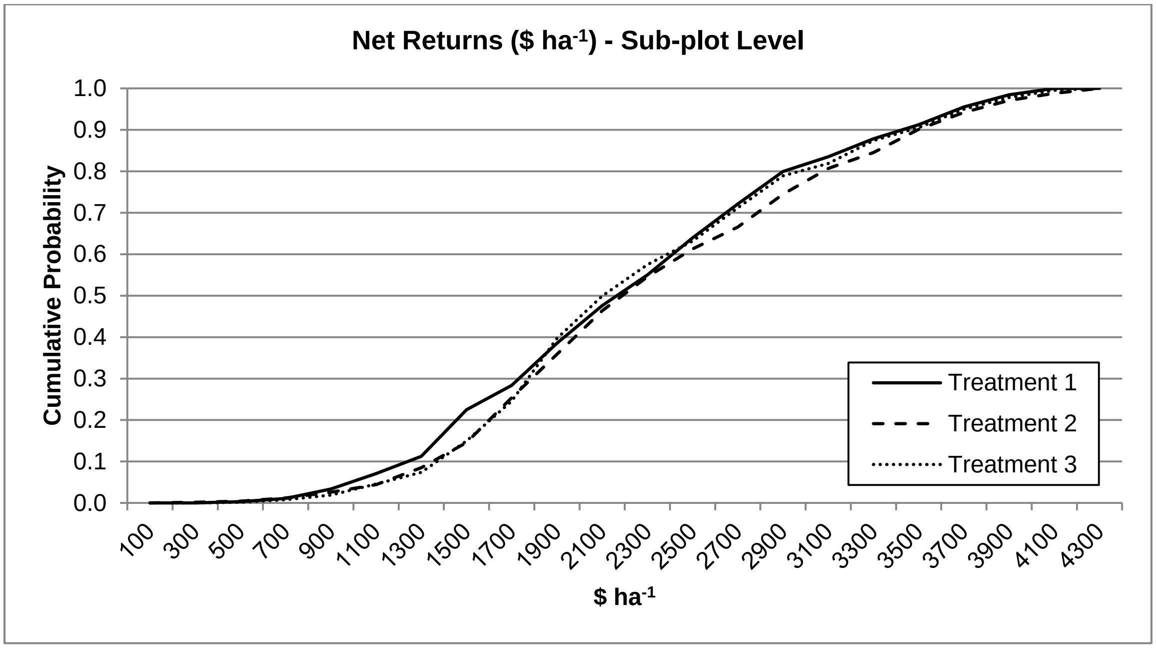

Figure 16. Sub-plot level net return ($ ha^{-1}) cumulative probability distributions

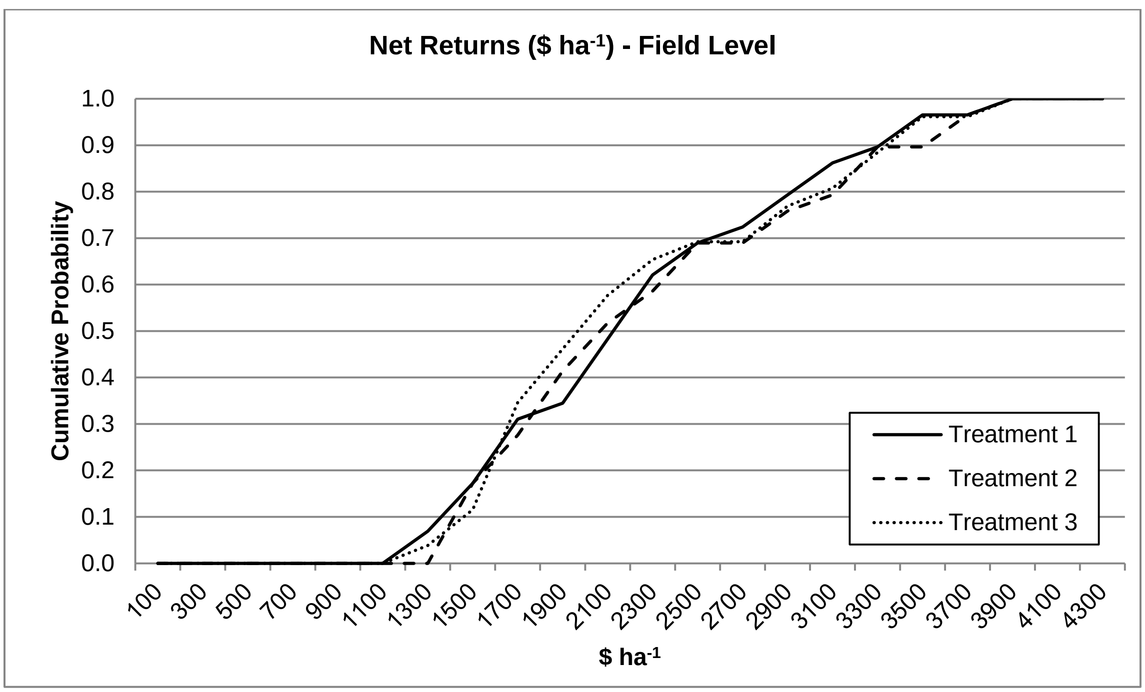

Figure 17. Field level net return ($ ha^{-1}) cumulative probability distributions

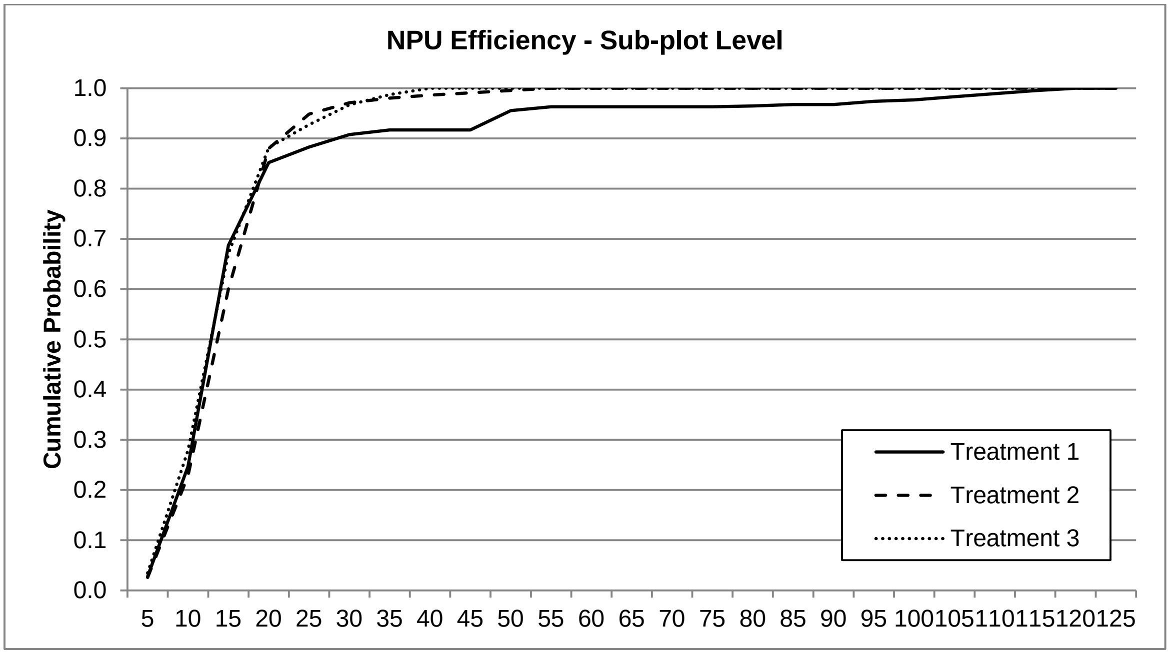

Figure 18. Sub-plot level NPU efficiency cumulative probability distributions

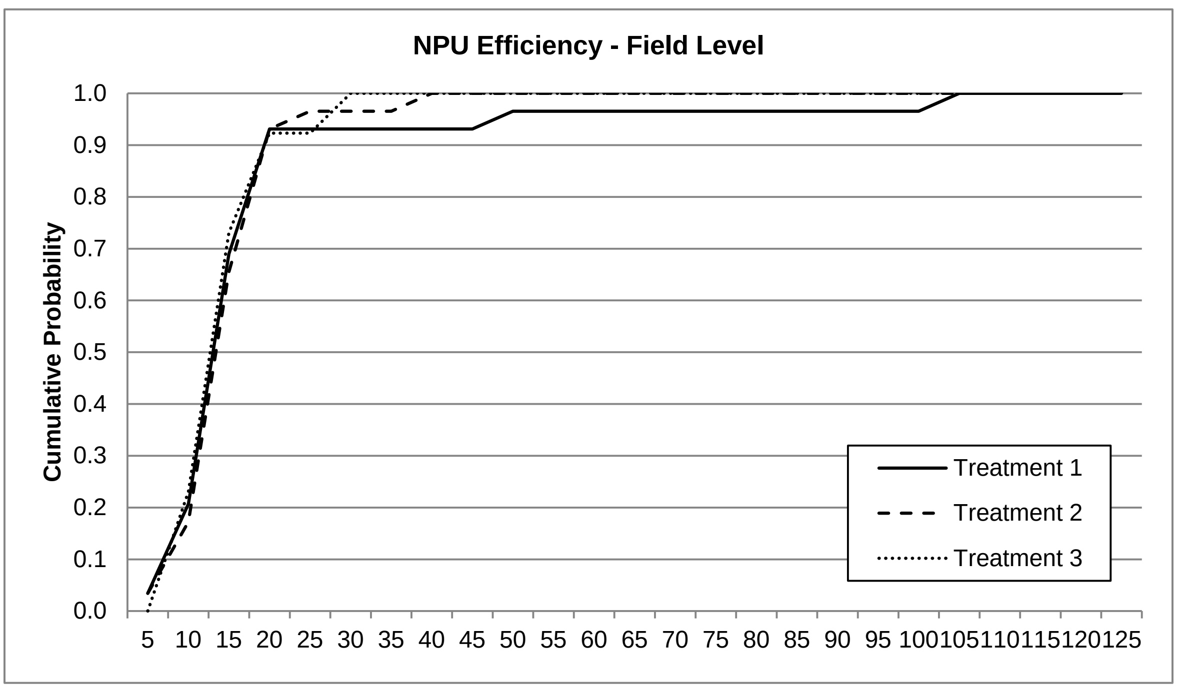

Figure 19. Field level NPU efficiency cumulative probability distributions

CONCLUSIONS AND RECOMMENDATIONS

This project involved four states of TN, LA, MO, and MS. Twenty nine field demonstration trials were conducted on cotton mostly on private farms with EQIP eligible producers in West Tennessee, the Delta region of Mississippi, Missouri, and North Louisiana within the Mississippi River Basin during 2011 to 2014. The in-season sensor-based variable-rate N management systems were demonstrated in comparison with the local farmer's uniform-rate N application systems in large strip plots under a randomized complete block design with three replicates. The conclusions and recommendations from each state and the economic analyses on all the data from the four participating states are summarized as follows.

In Louisiana, the results obtained from this project thus far demonstrated that VRT/Sensor systems as another effective approach in managing N in cotton production in the region. For future projects, it will be ideal to have the participating producers to implement the VRT/Sensor systems themselves. For this team, the three producers involved in this project alone can significantly contribute in extending this technology to other producers. This is under the stipulation that they (producers) are convinced about the use of this technology. In addition to this, bringing this technology to the field can be enhanced with continued extension and education outreach program through field day demonstrations, workshops, and even personal visit by the researchers and extension agents with the producers.

In Missouri, variable-rate N applications for cotton based on optical sensor readings were successfully carried out in 9 farm fields, demonstrating that this technology can reliably be deployed at the farm scale. Compared to current N rates used by farmers, optical sensors gave small improvements in both N rate (lower) and cotton lint yield (higher). We estimate that, at current prices, it will take between 1,000 and 2,200 acres of use to reach the point at which the cost of the sensors has been covered, and after that profit will begin accruing. Overall lower N use with optical sensors, and particularly lower N use targeted to areas of the field where soil N availability is high, will reduce the amount of N lost from cotton fields to water and air and reduce the proportion of the cotton crop that is too lush. Farmers may be able to save money on growth regulator and/or defoliant, and may sometimes have easier harvest conditions. Technical, economic, and environmental outcomes are all modestly positive for the use of optical sensors to control variable-rate N applications on cotton. Based on our results, we endorse this approach for use by cotton growers in Missouri.

In Mississippi, sensor based adjustment of fertilizer N rates utilizing a vegetation index with known sensitivity to plant N status shows great promise to improve accuracy across spatially variable fields as compared to the standard practice of applying a constant rate. Although post-harvest available soil N was not sampled in this study it was obvious from the samples taken near planting that considerable variability in soil nitrate and ammonium existed in the fields utilized. Recommendations are to further refine the technology in terms of script writing to more easily facilitate the data processing steps and turnaround time from data acquisition to fertilization. Greater testing and development of algorithms is needed to make applicable across more regions.

In Tennessee, the sensor-based variable-rate N management systems via side-dress during the early growing season produced higher cotton lint yield at one location-year, similar lint yield at six location years, but lower lint yield at one-location-year than the current uniform-rate N application systems. The in-season variable-rate N management systems did not affect post-harvest residual N levels in top 60 cm of the soil profile relative to the current uniform-rate N application systems. Averaged over the eight location-years on EQIP eligible farms, all the four in-season variable-rate N management systems had significantly lower seasonal N fertilizer consumption, but higher N use efficiency than the current uniform-rate N application systems. Specifically, the in-season variable-rate N management systems reduced the seasonal N fertilizer consumption by 9.3 to 14.8% (9.8 to 15. 6 kg N ha^{-1}), but increased higher N use efficiency by 9.2 to 11.0% compared with the current uniform-rate N application systems. No significant effect of in-season variable-rate N management systems was observed on post-harvest residual N levels in the top 60 cm of soil. The benefits of incorporating yield maps of previous years into the optical sensor-based variable-rate precision N management systems were generally not noticeable in terms of cotton yield, seasonal N fertilizer consumption, N sue efficiency, and post-harvest residual soil N level. Our results suggest that in-season sensor-based variable-rate N management systems via side-dress use significantly less N fertilizer to produce comparable cotton yield via increasing N use efficiency relative to the current uniform-rate N application systems. The in-season sensor-based variable-rate N management systems are viable tools that can be used by producers on their farms to manage variations within the field.

Two main conclusions were drawn from the economic analyses of the data from all the four states in this study. First, the real-time optical sensing and variable rate technologies (VRT) treatments indicated some N savings but were not more profitable on average compared to the existing farmer practices. There was some evidence of significantly higher mean net returns using optical sensing and VRT to manage N compared to the current practice at the sub-plot level, but the field level showed no difference. Second, there were risk management benefits identified at the field level using optical sensing and VRT compared to the farmer practice. Fields with lower lint yields were found to likely produce higher net returns with optical sensing and VRT than with the farmer practice which may help farmers manage risk on fields with this characteristic. Other inferred conclusions that can aid in the cotton farmer's decision making are: 1) the VRT treatments may not apply enough N to significantly increase lint yields; 2) four locations realized significantly lower N rates applied in at least one form of VRT N fertilizer application (Tensas Middle, LA, Gibson, TN, Lauderdale, TN, and Leflore, MS) and four had higher N rates (Madison North, TN, Adams, MS, Tensas North, LA, and Tensas South, LA), and 3) N rates were not low enough to increase N use efficiency and encourage environmental benefits. The farm fields used in this demonstration project represented a range of soils and climates in the MRB; however, the fields tested in the experiments likely had limited enough spatial and temporal variability within the field that VRT treatments did not make a difference in field level mean net returns. Cotton farmers in Tennessee, Louisiana, Mississippi, and Missouri states can use this information as a decision aid when considering switching to VRT. Mean net returns were positive across locations (for all technologies), but N savings and EQIP incentive payments did not offset the cost of the technology enough to justify the adoption of VRT based on mean net returns alone in the MRB states. Policy makers are also interested in these results as EQIP payments did not increase net returns enough to justify the adoption of VRT. This can be considered when deciding nutrient management cost-share payments for the future in Tennessee, Mississippi, Missouri and Louisiana. Areas for potential further research on net returns with this data include incentive payments and price sensitivity. Determining the precision nutrient management EQIP payment that would make optical sensing and VRT more profitable than the farmer's practice (FP) by state would be of interest to policy makers. Additional studies on fields with more in field spatial variability could also be evaluated to further identify the conditions under which optical sensing a VRT may provide profitability, risk management, and nitrogen production use efficiency benefits.