Profitability of Variable-Rate Technology in Cotton Production

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Abstract

Precision agriculture has the capability to reduce excess nitrogen (N) from crop production being released into the environment. This research evaluates the profitability and N use efficiency of utilizing real-time optical sensing with variable-rate technologies (VRT) to manage spatial variability in cotton production in the Mississippi River Basin states (Tennessee, Louisiana, and Mississippi). Two forms of VRT and the existing farmer technology (control) were used to determine N fertilizer rates applied to sub-plots within the fields. Cotton yields generated and N fertilizer rates determined by the sensor technology are used to determine the changes in yields and N rates due to VRT, thus N use efficiency and net returns. Results indicate no differences in control and VRT yields. Although N savings using VRT were identified in four fields, they were not enough to produce significant differences in net returns between VRT and control.

Introduction

Fertilizer nitrogen (N) is an expensive and important input in the production of crops such as cotton. The United States Department of Agriculture (USDA) estimated that farmers spent $7.2 billion[1] on anhydrous ammonia and N solutions in 2011 (USDA 2013). 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 increased use of N fertilizer has raised concerns about potential environmental damages due to the many ways N can be dispersed into the surrounding environment after application. 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).

Farmers have no easy way of containing the excess lost N but can apply the fertilizer more efficiently to limit N released to the environment. Current recommended rates of fertilizer N used by growers were developed in small individual fields with little spatial variability. Uniform N rates were applied across entire fields that likely have spatial variability in soils and other field factors that will result in sections of the field having more and less N fertilizer available to the crop that is necessary to maximize yields or profits (i.e., over- and under-application) (Scharf et al. 2005; Scharf et al. 2011; Vetch et al. 1995; Isik and Khanna 2003). Over- and under-application can increase excess N released into the environment and decrease crop yield compared with economically optimal rates and, in turn, reduce profits (Lambert, Lowenberg-DeBoer, and Malzer 2006). With precision agriculture technology, defined by the

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[1] In 2011, 4.2 million material short tons of anhydrous ammonia were consumed at $749 per material short ton. 11.4 million material short tons of nitrogen solutions were consumed at $351 per material short ton.

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 variable rate technology (VRT) applications of N fertilizer instead of uniform rate technology (URT) applications. VRT is used in crop production in an attempt to reach the optimal application rate by varying the rate based on variable field factors (Sawyer 1994), and can reduce the amount of wasted N, costs, labor (Raun et al. 2002; Tubaña et al. 2008), excess N pollution that collects in the groundwater (Biermacher et al. 2009b; Raun and Johnson 1999; Roberts et al. 2002; Watkins, Lu, and Huang 1998), and runoff that contributes to water pollution (Larkin et al. 2005; Raun and Johnson 1999; Scharf et al. 2005; Isik and Khanna 2003).

Zhang, Wang, and Wang (2002) categorized the spatial and temporal variability factors that influence the economic and environmental performance of precision agriculture technologies into: 1) yield variability, such as historical and present distribution, 2) field variability, such as topography, 3) soil variability, such as nutrients in the soil, density, and moisture, 4) crop variability, such as density, height, and nutrient stress, 5) anomalous factors, such as weed, insect, and disease infestation and wind damage, and 6) management variability, such as tillage, crop rotation, and fertilizer application. Yields can be affected by the anomalous factors such that rainfall and temperature cause yields to rise or fall below the same field’s potential by 20 percent (Bullock and Bullock 1994).

Early studies evaluating the economic and environmental aspects of precision application of fertilizer N using VRT were conducted via simulation. Watkins, Lu, and Huang (1998) and Roberts et al. (2002) used the Environmental Policy Integrated Climate model to simulate sweet potato and corn yields, respectively, and various soil processes (e.g., soil water balances and nutrient runoff). Both studies identified positive environmental impacts from adopting VRT N application but neither found economic benefits. These early studies did not specify the information technologies used to determine VRT N rates, nor did they use actual field data to evaluate the costs and benefits of VRT.

More recent studies have evaluated the profitability and the environmental consequences of VRT application of N on farm fields using different sensor based information technologies to gather soil, plant, and other data to determine N fertilization rates across the fields (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). Studies in Oklahoma and Missouri in corn and wheat production have shown some yield increases, increases in N application efficiency due to VRT of 6 to 15 percent relative to uniform N rates, and increased net returns of \$4 to \$42 ha^{-1} over producer chosen uniform N rates (Biermacher et al. 2006; Biermacher et al. 2009b; Butchee, May, and Arnall 2011; Raun and Johnson 1999; Raun et al. 2002; Raun et al. 2005; Scharf et al. 2011). A spring wheat study in Mexico exhibited lower N rates and higher profitability than current farmer practice due to optical sensing technologies, a savings of 69 kg ha^{-1} of N and increased profitability of \$56 ha^{-1} (Ortiz-Monasterio and Raun 2007). The aforementioned studies indicate increased economic and environmental benefits from the adoption of optical sensing and VRT. Currently, there is a lack of information in cotton production utilizing VRT N fertilization application and real-time optical sensing technologies in the Mississippi River Basin (MRB) states (Tennessee, Louisiana, and Mississippi), and whether these technologies can reduce losses of N to the environment.

If growers in the MRB states had access to information about the aforementioned precision technologies, they could have a better indication of the amount of N fertilizer needed to maximize profits while reducing environmental impacts. Growers in the south understand that the plants’ N needs vary within a field (Mooney et al. 2010). If they had access to information/studies specific to the MRB region, growers could make more informed decisions about adoption of VRT in N fertilization and real-time optical sensing with regard to reduced fertilizer costs, increased profitability, increased labor/application efficiency, and decreased excess N reaching groundwater (Biermacher et al. 2009b). Policy makers (Larkin et al. 2005; Roberts et al. 2002; Zhang, Wang, and Wang 2002), crop insurance companies (Lowenberg-DeBoer 1999), and technology manufacturers (Biermacher et al. 2009a) can also use economic information about precision technology to better assist producers.

Thus, the objectives of this research are: 1) to evaluate the profitability of optical sensing and variable-rate application technologies to manage spatial variability within individual fields of cotton in the MRB states, and 2) to assess how real-time optical sensing and VRT affect N use and N production use efficiency in cotton production.

Conceptual Framework

Producer Profits

A risk-neutral, profit-maximizing producer will adopt VRT N application if the net returns to using VRT N application are greater than the net returns to using URT N application. 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 farmer's profit equations for URT N application and VRT N application include the tradeoff factors listed above. The profit equation for URT N application decision for cotton can be written as:

$$NR_{URT} = P \times Y_{URT} - r^B N_{URT}^B - r^T N_{URT}^T - IC_{URT} - AC_{URT} - OCP, \qquad (1)$$

where *NR* is cotton net revenue (\$ ha^{-1}), P is cotton lint price (\$ kg^{-1}), Y is cotton lint yield (kg ha^{-1}), r^B is the pre-plant nitrogen price (\$ kg^{-1}), N^B is the pre-plant N fertilization rate (kg ha^{-1}), r^T is the top (or side) dress nitrogen price (\$ kg^{-1}), N^T is the top (or side) dress N fertilization rate (kg ha^{-1}), *IC* is the information cost used in the URT N fertilization process (\$ ha^{-1}), *AC* is the labor cost of applying N using URT (\$ ha^{-1}), and *OCP* represents the other costs of cotton production (\$ ha^{-1}) that do not change across N application technologies. Likewise, the producer's profit equation for the VRT N application decision for cotton can be written as:

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

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), to adopt VRT, and information costs (*IC*) include the ownership costs of VRT. USDA (NRCS) and the Environmental Protection Agency are interested in reducing the amount of excess N applied by incentivizing the adoption of conservation practices such as VRT N application (USDA 2014b). Considering the incentive payments in the net returns allows us to determine the effectiveness of these incentives in adoption of VRT N application.

Using the profit equations for URT and VRT, we can set $NR_{URT} = NR_{VRT}$ and rearrange the terms to analyze the sensitivity of changes in prices to profitability in VRT N application. The left-hand side of the equation becomes changes in the cost of the technology (cost of machinery ownership, fertilizer application, and labor), written as:

$$IC_{VRT} - OC_{URT} + AC_{VRT} - AC_{URT} =$$

$$P \times (Y_{VRT} - Y_{URT}) + IP_{VRT} + r^T \times (N_{URT}^T - N_{VRT}^T). \tag{3}$$

Equation (3) yields a partial budgeting net returns relationship, a common way to analyze the economic benefits of a technology (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 URT. The costs of VRT (C_{VRT}) on the left-hand side of Equation (3) can be denoted as

$$C_{VRT} = IC_{VRT} - IC_{URT} + AC_{VRT} - AC_{URT} \tag{4}$$

and Equation (3) can be rewritten as an inequality:

$$C_{VRT} <$$

$$P \times (Y_{VRT} - Y_{URT}) + r^T \times (N_{URT}^T - N_{VRT}^T) + IP_{VRT}, \tag{5}$$

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 the profitability of the technology. Changes in yields and N rates, and thus net returns and N use efficiencies, when switching from URT to VRT are of interest to the farmer.

N Production Use Efficiency

NUE has been measured in several different 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.

In this paper, we will use nitrogen production use (NPU) efficiency to measure N use by normalizing the yield for a given technology (Y) by dividing by the corresponding N rate applied (N_i) such that:

$$NUE_i = \frac{Y_i}{N_i}, \tag{6}$$

where i is either VRT or URT. Presenting this information will serve as a proxy for the environmental benefit of using VRT N application.

Methods and Procedures

Data

Eleven cotton N fertilizer experiments were conducted in 2012 and 2013 in Tennessee, Mississippi, and Louisiana. Five of the location-year trials occurred in Tennessee, three occurred in Mississippi, and six occurred in Louisiana. The trials tested URT N application versus two VRT N applications on each cotton field. Each EQIP eligible farmer planted cotton seeds across nine strip-plots (referred to as plot for the remainder of this paper) containing 10 sub-plots each that measure roughly 30.5 meters by 11.6 meters. Table 1 shows the average rainfall and growing degree days for each location-year in the study. Table 2 shows the soil types and characteristics for each location in the study.

The experiment was planned as a randomized complete block design with three N fertilizer treatments and three replications. The URT treatment (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 state. Each location provided yields harvested, N rate applied, type of N fertilizer used, and latitude and longitudes for the two years. Table 3 shows the average N rate, lint yield, NPU, and net returns by year, location, and treatment.

To evaluate the net returns inequality in Equations (4) and (5), price data, information costs, and application costs must be estimated. Price data included cotton lint prices received (USDA 2014a), N fertilizer prices paid (USDA 2014d), EQIP cost-share payment rates for the precision nutrient management system (personal communication with Patricia Turman, Tennessee State Agronomist, 2014, and Chris Coreil, Louisiana NRCS Conservation Agronomist; USDA 2014c), and budgeted costs of technology (equipment and labor). Prices are in real 2013 dollars, indexed using the Bureau of Economic Analysis annual Gross Domestic Product Price Deflator Index (U.S. Department of Commerce 2014).

Information cost budgets were estimated using partial budgeting methods (Larson et al. 2005) as demonstrated in Equations (4) and (5). Two budgets were developed to account for information: 1) for Greenseeker™ technology (treatment 2) and 2) for Greenseeker™ plus yield monitor information systems (treatment 3). Greenseeker™ was assumed to be retrofitted to an existing boom sprayer measuring 24.7 meters wide and the yield monitor information system was assumed to be retrofitted to an existing 6-row cotton picker measuring 5.8 meters wide. Ownership costs (OC) were estimated using the standards set forth by 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 ownership costs calculation techniques (Boehlje and Eidman 1984). OC were estimated in Table 4 using the equation:

$$OC_i = [CR_i + TIH_i + RM_i] * H_i, \tag{7}$$

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), Table 4.

Operating costs for treatment 3 included the estimated OC for Greenseeker™, estimated OC for yield monitor information system, and cost of a computer (\$ ha^{-1}), estimated in Table 4. The computer was assumed 100% use for 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 the field (Swinton and Lowenberg-DeBoer 1998). Here, we allocated the cost of a computer across the size of a cotton enterprise in each state (USDA 2012) (Table 4). Total operating cost for treatment 2 was \$2.24 ha^{-1} (2013 dollars), and costs for treatment 3 were \$5.25 ha^{-1} in Tennessee, \$5.31 ha^{-1} in Mississippi, and \$5.37 ha^{-1} in Louisiana.

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). The 2013 precision fertilizer application labor cost was found by taking the difference between precision fertilizer application in Tennessee and the average dry bulk fertilizer application in Tennessee and Mississippi[2] (precision fertilizer application such as VRT costs \$5.07 more ha^{-1} in labor to apply dry bulk than URT). The same calculation was estimated using liquid fertilizer application (\$2.31 ha^{-1} in labor costs).

Methods

In the econometric analysis, the farmer's decision to change his N application technology from URT to VRT will be measured by evaluating two aspects of the production decision: 1) net returns per location-year by treatment and 2) the NPU efficiency. Due to the randomized block design of N application in the field trials, the on-farm experimentation yield model described in Schabenberger and Pierce (2002) can be followed. The null hypothesis (H_0) that expected lint yields from the VRT treatments N application treatments (i) per trial [$E(Y_{VRT_i})$] will be equal to

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

the expected lint yields from the URT trials [$E(Y_{URT})$] will be tested: $H_0: E(Y_{VRT_i}) - E(Y_{URT}) = 0$, where *E* is the expectations operator and *i* represents the VRT treatments (*i*=treatment 2 or 3). Alternatively (H_A), expected VRT lint yields will be greater than expected URT lint yields: $H_A: E(Y_{VRT_i}) - E(Y_{URT}) > 0$. This hypothesis will be tested using a mixed model, estimated in SAS 9.2 (SAS Institute Inc. 2014), written mathematically as

$$Y_{ijkt} = \mu + \delta_t + \emptyset_k + \tau_i + \rho_{(j)k} + (\emptyset\tau)_{ik} + \varepsilon_{ijkt} \tag{8}$$

$$\delta_t \sim N(0, \sigma_\delta^2)$$

$$\emptyset_k \sim N(0, \sigma_\emptyset^2)$$

$$\rho_{(j)k} \sim N\left(0, \sigma_\rho^2\right)$$

$$(\emptyset\tau)_{ik} \sim N(0, \sigma_{\emptyset\tau}^2)$$

$$\varepsilon_{ijkt} \sim N(0, \sigma_\varepsilon^2),$$

where Y_{ijkt} represents cotton lint yield (kg ha^{-1}) by *i*th treatment (*i* = 1, 2, 3), *j*th replication (*j* = 1, 2, 3, 4), *k*th location or farm (*k* = 1, …, 9), and *t*th year (*t* = 2012, 2013), μ represents the true population cotton lint yield mean, δ_t is the effect of the *t*th year on yield, $\emptyset_k$ is the effect of the *k*th farm location on yield, τ_i is the effect of the *i*th treatment on yield, $\rho_{(j)k}$ is the *j*th replication (or block) effect nested within *k*th farm on yield, $(\emptyset\tau)_{ik}$ is the effect of the interaction between the *k*th farm and the *i*th treatment on yield, and ε_{ijkt} represents the random error associated with the *t*th year, *i*th treatment, *j*th replication, and *k*th farm. The treatment effect was a fixed effect, and random effects include location, year, and replication nested in location, and location-treatment interaction. Location was hypothesized to have a significant effect on yields 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.

VRT N applications were expected to reduce N use compared to URT. 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_i by treatment (i) created no added N use savings compared to URT will be tested: $H_0\colon E(N_{URT}) - E(N_{VRT_i}) = 0$, where E is the expectations operator, expected N applied using URT [$E(N_{URT})$] will be equal to expected N applied using VRT [$E(N_{VRT_i})$] by treatment (i). Alternatively, expected N applied using URT is greater than expected N applied using VRT application: $H_A\colon E(N_{URT}) - E(N_{VRT_i}) > 0$. This hypothesis will be tested using a mixed model, estimated in SAS 9.2, written mathematically as

$$N_{ijk} = \mu + \emptyset_k + \tau_i + \rho_{(j)k} + (\emptyset\tau)_{ik} + \varepsilon_{ijk}, \qquad (9)$$

where N rate applied (kg ha^{-1}) per treatment and location is a function of the same fixed and random effects as yields in Equation (8) with the exception of the random year effect. Year is not expected to be a significant random effect in this model.

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 (\$ ha^{-1}) from VRT N applications by treatment (i) [$E(NR_{VRT_i})$] were the same as expected net returns (\$ ha^{-1}) from URT N application [$E(NR_{URT})$]]: $H_0\colon E(NR_{VRT_i}) - E(NR_{URT}) = 0$. Alternatively, expected net returns (\$ ha^{-1}) from VRT N applications were greater than expected net returns (\$ ha^{-1}) from URT application:

$H_A: E\left(NR_{VRT_i}\right) - E(NR_{URT}) > 0$. Net returns (\$ ha^{-1}) for URT will be estimated using a mixed model in SAS 9.2, written as

$$NR_{ijkt} = \mu + \delta_t + \emptyset_k + \tau_i + \rho_{(j)k} + (\emptyset\tau)_{ik} + \varepsilon_{ijkt}, \tag{10}$$

where net return by treatment (*i*), location (*k*), replication (*j*), and year (*t*) is a function of site specific factors and other effects mentioned above, Equation (8).

N Production Use Efficiency

NPU was calculated for each by treatment (*i*), location (*k*), replication (*j*), and year (*t*). The null hypothesis was the expected NPU for VRT N application treatments will be equal to expected NPU efficiency for the URT treatment. Alternatively, expected NPU efficiency for VRT N application will be greater than expected NPU for URT N application. This will be estimated using a mixed model in SAS 9.2, written as

$$NPU_{ijkt} = \mu + \delta_t + \emptyset_k + \tau_i + \rho_{(j)k} + (\emptyset\tau)_{ik} + \varepsilon_{ijkt}, \tag{11}$$

where NPU_{ijkt} efficiency by treatment (*i*), location (*k*), replication (*j*), and year (*t*) is a function of treatment and the same random effects as in Equation (8).

Results and Discussion

Profits

The cotton lint yield model, Equation (8), was estimated with and without the location-treatment interaction term. The -2 Res Log Likelihood was lower with the interaction term (17633.7) than without (17636.5). Neither model, however, was significant (Table 5); yields did not differ across treatments at the 5% level of significance. A pair-wise comparison of the treatments showed the yields for either of the VRT treatments were not higher than the yields for the URT treatment at the 5% level (Table 7).

The mixed model for N rates applied, Equation (9), showed significant differences between treatments. The mixed model on N rates applied by treatment with the interaction term showed no significant differences across treatments (Table 5) but indicated that the farm variance estimate ($\sigma_{\emptyset}^{2}$ = 385.17) was substantially higher than the variance between farms ($\sigma_{\emptyset}^{2}$ = 14.58), similar to Schabenberger and Pierce's (2002) yield findings. This means that there was more N rate variation between farms than within farms. The model was estimated again without the interaction term to see if any effects were being masked. The model without the interaction term was significant (Table 5) and showed the two VRT treatments to be respectively significantly different from the URT treatment (Table 6). The -2 Res Log Likelihoods, however, indicated that the model including the interaction term was a better fit (10298.5) than without (10778.0). Thus, the interaction term was significant but the treatment effects were being masked.

Estimates of VRT treatments (2 and 3) versus treatment 1 by location will tease out any masked treatment effects. Results demonstrated treatments 2 and 3 had significantly lower N rates applied in Lauderdale, TN, Northern Leflore County, MS, and Middle Tensas Parish, LA. Tipton County, TN, had N rates lower than URT for only treatment 3. This could be for a number of reasons but it is likely due to some spatial variability in the field, i.e. soil type or field slope. Madison County, TN, and Northern Tensas Parish, LA, showed N rates significantly lower using URT than either VRT treatment (2 and 3). Adams County, MS, and Southern Tensas Parish, LA, experienced lower N rates using URT than VRT treatment 3 (Table 7).

Both net return mixed models, Equation (10), indicated that there was no significant difference between net returns across treatments (Table 5). In both models, the Dunnett's test showed no difference between the respective VRT treatments and URT treatment (Table 6). Estimating the difference between treatments VRT and URT by farm showed no significant difference by farm (Table 7).

NPU Efficiency

Results from the NPU mixed model, Equation (11), including the interaction term indicated that the model was not significant and the treatment means did not differ (Table 5). Like Schabenberger and Pierce (2002), the variation between farms ($\sigma_{\emptyset}^{2}$ = 25.21) was greater than within the farms ($\sigma_{\emptyset}^{2}$= 0.33). The model was estimated without the interaction term to determine if farm effects were being masked and was significant (Table 5). VRT treatments were respectively different from the control URT treatment as estimated by the Dunnett's test (Table 6). The -2 Res Log Likelihoods indicated that the model including the interaction term (8402.0) was a better fit than without (8480.3). Thus, the interaction term was significant to the model but was masking the treatment effect.

Treatment effect of VRT by farm resulted in significantly higher URT NPU efficiency than VRT treatments 2 and 3 in Madison County, TN, and Northern Tensas Parish, LA. Adams County, MS, experienced a URT NPU efficiency that was higher than VRT for treatment 3. No farms exhibited higher VRT NPU efficiencies than URT at the 5% level of significance (Table 7). Because NPU is a ratio of yields to N rates, the same yield with a lower N rate produces a larger NPU ratio; therefore, in this case it was preferred for VRT to 'outperform' URT to show environmental benefits using the NPU efficiency measure. While these results do not indicate positive net returns with VRT, they are expected because farms in the Madison County, TN, and Northern Tensas Parish, LA, locations experienced more benefit from URT treatment N rates applied.

Conclusion

The objective of this study was to determine the effect of optical sensing and VRT on profitability and N use/NPU efficiency in cotton production. Field trials were conducted in Tennessee, Mississippi, and Louisiana in 2012 and 2013 that provided cotton yield and N rates applied per technology. Three conclusions inferred from this study can aid cotton farmers in decision making and are important to the cotton industry as a whole: 1) the VRT treatments did not apply enough N to significantly increase yields; 2) 4 of the 9 locations (44.4%) realized significantly lower N rates applied in at least one form of VRT N fertilizer application; 3) net returns did not differ across treatments. The fields tested in the experiments likely had limited enough variability in field factors that VRT treatments did not make a difference in net returns. One county (Madison County, TN) actually experienced higher yields at the 10% level, lower N rates at the 1% level, and higher NPU efficiency at the 1% level (Table 7) using URT when compared to VRT treatment 2.

Cotton farmers in the MRB states can use this information as a decision aid when considering switching to VRT. It is not recommended based on the findings in this study for cotton farmers in the MRB states to adopt VRT. While mean net returns were positive across locations (for all technologies), Table 3, N savings and EQIP incentive payments did not offset the cost of the technology enough to justify the adoption of VRT in Tennessee, Mississippi, and Louisiana. 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, and Louisiana.

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Tables

Table 1. Total rainfall (millimeters) and growing degree days (Celsius) for the cotton growing season (April 1-October 31) per year

	Rainfall (millimeters)[2]		Growing Degree Days (Celsius)[1,2]	
County/Parish, State	2012	2013	2012	2013
Lauderdale, TN	477.0	880.1	1555.1	1361.1
Madison, TN	595.0	970.4	1490.8	1319.2
Tipton, TN	513.8	895.0	1584.4	1411.4
Adams, MS	849.1	889.1	1856.3	1811.9
North Leflore, MS	789.3	915.4	1743.7	1648.8
South Leflore, MS	789.3	915.4	1743.7	1648.8
Middle Tensas, LA	733.4	812.0	1882.8	1810.3
South Tensas, LA	630.2	755.3	1943.3	1874.8
North Tensas, LA	734.8	872.1	1870.3	1794.8

[1] Growing Degree Days= ∑ (average daily temperature – 15.6) or 0 if negative

[2] Source: PRISM (2014)

Table 2. Soil types and characteristics by location (average mineral particles 0.05 to 2.0mm in equivalent diameter as a weight percentage of the less than 2mm fraction)[1]

Farm	County/Parish, State	Soil Types in Farm	Total Sand	Total Silt	Total Clay
1	Lauderdale, TN	Fine-silty, Coarse-silty	13.2	71.7	15.2
2	Madison, TN	Fine-silty	3.0	83.4	13.6
3	Tipton, TN	Fine-silty	5.7	77.8	16.5
4	Adams, MS	Coarse-silty	25.3	68.8	6.0
5	North Leflore, MS	Fine, fine-silty	31.6	46.0	22.3
6	South Leflore, MS	Coarse-silty, fine, fine-silty	34.5	45.9	19.5
7	Middle Tensas, LA	Coarse-silty, fine-silty	11.8	68.5	19.8
8	South Tensas, LA	Coarse-silty, very-fine	13.2	69.0	17.8
9	North Tensas, LA	Clayey over loamy, fine-silty, very-fine	11.9	47.3	40.8

[1] Source: SSURGO (USDA 2014e)

Table 3. Means of total N applied (kg ha^{-1}), cotton lint yield harvested (kg ha^{-1}), N production use efficiency, and net returns (kg ha^{-1}) by year, location and treatment

		Total N applied (kg ha^{-1})		Cotton Lint Yield (kg ha^{-1})		N Production Use (kg kg^{-1})		Net Returns (\$ ha^{-1})	
County/Parish, State	Treatment Number	2012	2013	2012	2013	2012	2013	2012	2013
Lauderdale, TN	1	112.0	112.0	1539.7	2160.9	13.7	19.3	2485.0	3799.9
Lauderdale, TN	2	110.9	95.6	1455.1	2158.9	13.2	23.1	2403.8	3880.0
Lauderdale, TN	3	119.8	87.3	1462.8	2400.0	12.4	27.7	2399.9	4325.1
Madison, TN	1	100.8	33.6	956.4	3447.8	9.5	102.6	1492.8	6240.5
Madison, TN	2	86.8	85.4	916.7	2766.0	11.3	35.1	1529.6	4993.2
Madison, TN	3	78.9	99.4	1005.2	2825.0	14.5	28.9	1689.0	5077.1
Tipton, TN	1	100.8		1299.9		12.9		2096.4	
Tipton, TN	2	94.2		1311.0		14.1		2185.7	
Tipton, TN	3	86.8		1249.0		14.8		2089.6	
Adams, MS	1	70.4		971.2		18.6		1587.3	
Adams, MS	2	76.8		1057.7		14.1		1786.4	
Adams, MS	3	88.0		1002.2		12.0		1671.8	
North Leflore, MS	1		134.4		1768.1		13.2		3057.1
North Leflore, MS	2		103.3		1745.2		17.3		3122.4
North Leflore, MS	3		119.9		1713.9		15.2		3039.2
South Leflore, MS	1		134.4		1905.0		14.2		3368.6
South Leflore, MS	2		145.7		2008.1		14.0		3601.8
South Leflore, MS	3		147.6		1944.0		13.6		3479.9
Middle Tensas, LA	1	146.0	145.6	1768.1	1871.1	12.1	12.9	2818.5	3227.7
Middle Tensas, LA	2	98.9	140.5	1737.4	1848.8	17.6	13.2	2903.3	3257.4
Middle Tensas, LA	3	122.5	140.6	1722.5	1832.3	14.2	13.1	2838.0	3224.3
South Tensas, LA	1	112.0	112.0	1206.2	1944.8	10.8	17.4	1920.2	3408.7
South Tensas, LA	2	133.7	101.0	1199.6	2001.2	9.0	19.9	1937.8	3589.4
South Tensas, LA	3	160.2	115.8	1186.5	1994.1	7.5	17.4	1871.1	3552.5
North Tensas, LA	1	47.0	84.0	2246.1	1239.9	47.8	14.8	3783.3	2172.6
North Tensas, LA	2	125.0	164.5	2359.2	1401.1	19.3	8.5	3915.7	2413.1
North Tensas, LA	3	135.0	164.7	2316.8	1376.3	17.9	8.4	3825.1	2364.8

Table 4. Ownership Cost Budgets for Greenseeker™, Yield Monitor Information Systems (YMIS), and a Computer

	Greenseeker™	YMIS	Computer	
Ownership Cost	Dollars	Dollars	Dollars	Cost by State
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	$ -	
CR 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})	1000	1000		
Efficiency (%)[3]	65%	70%		
Sq m per Hectare	10000	10000		
Hours per Hectare	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
Total ownership costs hour^{-1}	$ 37.81	$ 4.97	$ 78.31	
Total machine costs (2013 dollars ha^{1})	$ 2.24	$ 2.73		

[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)

[4A] merican 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)

Table 5. Type 3 fixed effects with (With) and without (Without) the location-treatment interaction term

	F Value Estimate	
Variable	With	Without
Yield[1,2]	0	0.02
N rate[1]	1	39.1***
NPU[1,2]	1.96	19.53***
Net Returns[1,2]	0.17	0.28

*** 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 6. 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	-3.51	-2.15
		(46.34)	(35.71)
Yield	Treatment 3 vs 1	-2.13	3.90
		(46.26)	(35.55)
N rate	Treatment 2 vs 1	5.32	9.92
		(8.79)	(1.94)+++
N rate	Treatment 3 vs 1	12.41	17.77
		(8.81)	(2.04)+++
NPU	Treatment 2 vs 1	-5.01	-5.98
		(3.18)	(1.13)+++
NPU	Treatment 3 vs 1	-5.91	-6.85
		(3.17)	(1.11)+++
Net Returns	Treatment 2 vs 1	43.67	44.52
		(77.64)	(64.17)
Net Returns	Treatment 3 vs 1	34.62	41.44
		(77.36)	(63.77)

Note: Standard error in parentheses.

+++ Dunnett's Adjusted P Value Significant at the 1% level.

Table 7. Treatment effect estimates of treatments 2 and 3 versus treatment 1 by location for yield, N rate, NPU, and net returns (NR)

Location		Estimate			
County, State	Treatment	Yield	N Rate	NPU	NR
Lauderdale, TN	2 vs. 1	24.389	8.5069	-0.9398	-22.2059
		(66.298)	(3.5592)**	(2.3828)	(109.99)
Lauderdale, TN	3 vs. 1	-40.389	8.0081	-2.8544	-109.8
		(66.172)	(3.5592)**	(2.3393)	(109.63)
Madison, TN	2 vs. 1	146.520	-18.5809	29.1633	155.75
		(70.119)*	(3.971)***	(2.6374)***	(115.18)
Madison, TN	3 vs. 1	112.190	-21.7078	30.6332	117.67
		(69.997)	(3.971)***	(2.589)***	(114.84)
Tipton, TN	2 vs. 1	-0.806	5.9902	0.1632	-52.6535
		(80.212)	(5.5586)	(3.5572)	(128.1)
Tipton, TN	3 vs. 1	16.730	12.7931	-0.4949	-23.9751
		(80.107)	(5.5586)**	(3.4908)	(127.81)
Adams, MS	2 vs. 1	-25.755	-6.4379	4.4737	-81.8485
		(74.903)	(4.6016)	(3.028)	(121.44)
Adams, MS	3 vs. 1	-4.971	-17.5308	6.5822	-40.7657
		(74.788)	(4.6016)***	(2.9735)**	(121.13)
North Leflore, MS	2 vs. 1	7.948	29.0987	-1.8043	-46.8102
		(82.344)	(6.0646)***	(3.8284)	(130.69)
North Leflore, MS	3 vs. 1	15.178	13.0134	0.2524	-23.1962
		(82.245)	(6.0646)**	(3.7564)	(130.41)
South Leflore, MS	2 vs. 1	-17.354	-10.8787	2.1003	-70.215
		(84.651)	(6.7398)	(4.1733)	(133.43)
South Leflore, MS	3 vs. 1	-4.346	-13.1862	2.6169	-43.0745
		(84.559)	(6.7398)*	(4.094)	(133.17)
Middle Tensas, LA	2 vs. 1	12.864	25.5121	-2.1123	-50.4294
		(66.298)	(3.5592)***	(2.3828)	(109.99)
Middle Tensas, LA	3 vs. 1	20.269	13.7352	-0.4044	-24.5751
		(66.172)	(3.5592)***	(2.3393)	(109.63)
South Tensas, LA	2 vs. 1	-9.281	-5.3454	0.1825	-63.9392
		(66.300)	(3.5595)	(2.3829)	(109.99)
South Tensas, LA	3 vs. 1	-4.869	-25.7332	2.191	-37.0894
		(66.172)	(3.5592)***	(2.3393)	(109.63)
North Tensas, LA	2 vs. 1	-106.960	-76.0933	13.8587	-160.63
		(65.085)	(3.4705)***	(2.2423)***	(108.27)
North Tensas, LA	3 vs. 1	-90.596	-81.2433	14.6304	-126.81
		(64.954)	(3.4705)***	(2.1957)***	(107.9)

Note: Standard error in parentheses.

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