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Net Returns and Production Use Efficiency for Optical Sensing and Variable Rate Nitrogen Technologies for Cotton Production

M. Stefanini[1], J. Larson[1], D. Lambert[1], X. Yin[2], C. Boyer[1], J. Varco[3], P. Scharf[4], B. Tubaña[5], D. Dunn[4], H. Savoy[6], M. Buschermohle[6], and D. Tyler[6]

[1]Dept Ag & Res Econ, Univ. Tennessee, Knoxville TN; [2]Dept Plant Sci., Univ. Tennessee, Knoxville TN; [3]Dept Plant & Soil Sci., Mississippi State Univ., Mississippi State, MS; [4]Division of Plant Sci., Univ. Missouri, Columbia, MO; [5]School Plant, Environ & Soil Sci., Louisiana State Univ., Baton Rouge LA; [6]Dept Biosystems Engineering & Soil Sci., Univ. of Tennessee, Knoxville TN

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Abstract. *This research evaluated the profitability and N use efficiency of real time on-the-go optical sensing measurements (OPM) and variable-rate technologies (VRT) to manage spatial variability in cotton production in the Mississippi River Basin states of Louisiana, Mississippi, Missouri, and Tennessee. Two forms of OPM and VRT and the existing farmer practice (FP) were used to determine N fertilizer rates applied to cotton on farm fields in the four states. Changes in yields and N rates due to OPM and VRT were not enough to produce higher net returns and improve N use efficiency relative to the FP.*

Keywords. *Economics, nitrogen use efficiency, precision agriculture, variable rate technology*

Introduction

Fertilizer nitrogen (N) is an important and expensive input in the production of upland cotton (*Gossypium hirsutum* L.). Applying N uniformly across an entire field that has variability in soils and other field factors may result in sections of the field having more and less N fertilizer available to the crop than is necessary to maximize yields or profits (i.e., over- and under-application) and, in turn, decreasing crop yields and profits compared with economically optimal rates (Butchee et al. 2011). In addition, the over application of N fertilizer can increase excess N released into the environment from crop production (Butchee et al. 2011). Farmers can apply fertilizer more efficiently using precision agriculture (PA) technologies such as real time on-the-go optical sensing measurements (OPM) and variable rate technology (VRT) that can help farmers avoid over- or under- application of N (Boyer et al. 2011).

The N use efficiency (NUE) and profitability of OPM and VRT, has been evaluated in several North American locations for wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.), but not for cotton (Biermacher et al. 2006; Biermacher et al. 2009b; Boyer et al. 2011; Butchee et al. 2011; Ortiz-Monasterio and Raun 2007; Raun et al. 2002; Raun et al. 2005; Scharf et al. 2011). Raun et al. (2002) analyzed optical sensing and VRT in Oklahoma USA winter wheat production. The study examined four winter wheat experiments that compared these technologies with a uniform rate of N across the field (URT). The NUE, defined in the Raun et al. study as yield times total N concentration in the grain divided by the N application rate, on average increased by more than 15% when comparing VRT to URT. They found extra income due to an increase in NUE was able to cover the expected costs of the technology and that OPM and VRT would be most profitable in areas of high spatial variability. Raun et al. (2005) found N application rate reductions as well, measuring an increase of 15% in NUE via the adoption of optical sensing. Butchee et al. (2011) utilized the same technologies to assess NUE compared to farmer practice (FP) in Oklahoma. On average, using OPM to apply N produced similar wheat yields but reduced N by 22 kg ha^{-1} compared to the current FP. OPM and VRT technologies increased NUE and provided environmental benefits in the aforementioned Oklahoma studies.

Biermacher et al. (2006) assessed the profitability of OPM and VRT in wheat production using 65 site-years of data from two long term N management studies in Oklahoma. They used linear response plateau functions estimated from the data to evaluate the maximum economic value of sensor based N management compared with uniform rate N management. Overall, the two sites showed average profitability of \$21.80 to \$24.30 ha^{-1} over conventional practices and reduced pre-plant N by 59% to 82%. In another study, Biermacher et al. (2009b) evaluated data from experiments conducted at seven Oklahoma locations across nine years. Results from the yield response to N showed that the perfect information system (VRT application of N fertilizer based on OPM and an optimization algorithm generated \$16 ha^{-1} more and the uniform topdress-sensed system returned \$9 more ha^{-1}, respectively, in comparison with conventional practices. However, Boyer et al. (2011) in another Oklahoma study conducted at seven experiment locations found no statistical differences in net returns among 10 N treatments that included N applied using OPM and VRT. They concluded that the OPM technology did not apply enough N to maximize yields and profits relative to URT. The Oklahoma studies demonstrated mixed results about the economic benefits of OPM and VRT

Ortiz-Monasterio and Raun (2007) assessed N application efficiency in wheat utilizing OPM and VRT in Yaqui Valley, Mexico. Trials indicated an average savings of 69 kg ha^{-1} of N without a reduction in wheat yields. Across all field trials, OPM and VRT increased average profitability by \$56 ha^{-1}. Scharf et al. (2011) assessed OPM and VRT N application versus current FP uniform N rates in corn production in Missouri USA. Over four years, 55 replications were conducted to determine the profitability of PA. VRT N fertilizer applications increased yields by 110 kg ha^{-1} and reduced N by 15 kg ha^{-1}, increasing partial profits (value of corn grain less cost of N applied) by \$42 ha^{-1} over producer chosen uniform N rates. OPM and VRT increased NUE and provided environmental benefits in both of the aforementioned studies.

The review of literature indicates that OPM based VRT application of N may provide higher NUE and profitability in corn and wheat production. However, there is a lack of information about using OPM and VRT N fertilization technologies in cotton production in the Mississippi River Basin (MRB) states of Louisiana, Mississippi, Missouri, and Tennessee USA. The need for a cotton N utilization study using PA technologies such as OPM and VRT in the MRB was identified through surveys among producers in 12 southern states (Mooney et al. 2010). Managing N more efficiently on farm fields in the MRB is also an important USDA Natural Resources Conservation Service priority to reduce nutrient and sediment loading to local and regional water bodies (USDA 2016). If growers had access to information/studies specific to the MRB, they could make more informed decisions about adoption of OPM and VRT with regard to soil types, N fertilizer costs, profitability, labor/application efficiency, and excess N reaching groundwater. The aforementioned PA technologies may benefit cotton farms in the MRB by reducing the amount of N from cotton production released into the environment and increasing profit to the grower. Therefore, the objective of this research was to determine the lint yields, N fertilization rates, N production use efficiency, and profitability of OPM and VRT to manage spatial variability in cotton production.

Data and Methods

Demonstration Trial Data

The 29 site-years of data collected from demonstration trials on 21 farm fields in Louisiana, Mississippi, Missouri, and Tennessee USA from 2011 to 2014 included lint yields harvested and N rates calculated from three N rate management strategies (Table 1). Nine of the trials occurred in Louisiana, four in Mississippi, six in Missouri, and ten in Tennessee. The trials included a FP N application and two VRT N application methods on each cotton field. Each Environmental Quality Incentive Program (EQIP, USDA 2014b)-eligible farmers planted cotton across nine strip-plots (hereafter referred to as plots) containing 10 sub-plots, each measuring 30.5 m by 11.6 m with the exception of Missouri where the data were collected by plot. Pickers with yield monitors were not available to measure yields by subplot for the trials in Missouri.

The experiments were planned as a randomized complete block design with three N treatments and three replications. Treatment 1 was a uniform-rate N rate based on the current FP. Treatment 2 was a VRT N rate calculated via canopy optical-sensing with a Greenseeker™ RT200 Data Collection and Mapping System or a Yara™ N sensor. Treatment 3 was a VRT N rate based on vegetative index readings via canopy optical-sensing with a Greenseeker™ RT200 Data Collection and Mapping System or a Yara™ N sensor but adjusted based on any combination of historical yield productivity zones, soil imagery, and/or aerial imagery of crop growth. A uniform blanket rate of N was applied at (or before) planting to the entire field (covering all three treatment areas) that differed in the amount of before- or pre-planting N applied depending on the farm location. Each location provided harvested lint yields, N rates applied, type of N fertilizer used, and latitude and longitudes at the sub-plot or plot level for every participating year.

N Production Use Efficiency

VRT N use efficiency (NUE) has been measured in several ways, most of which comprise a zero-N application plot (omission plot) or an N-rich plot for comparison purposes. Butchee et al. (2011) calculated NUE from the following equation used to find the N rate: $N\ rate = \{(YP0 \times RI) - YP0\} \times \%grain\ N \times NUE\ factor$, where $YP0$ is yield potential for zero N applied. RI is a N response index

Table 1. 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	Obs	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
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
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
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

Obs is the number of observations.

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 NUE: $PFP_i = (Y_0 + \Delta Y_i)/N_i$, where Y_0 is yield from an N omission plot, ΔY is change in yields from zero-N applied, and N_i is the N rate applied per treatment i. Raun et al. (2002) measured NUE by subtracting N removed (grain yield times total N concentration in grain) in the grain yield in the zero-N applied plots from the N removed in the grain yield found in the plots receiving added fertilizer N, divided by the rate of fertilizer N applied.

A N production use efficiency (NPU) is used in this study to measure NUE by normalizing the lint yield for a given technology (Y) by dividing by the corresponding N rate applied (N):

$$NPU_i = Y_i/N_i, \tag{1}$$

where *i* is N treatment 1, 2, and 3. NPU is a proxy for the environmental benefits from using VRT. Effects of VRT on NPU relative to the FP are evaluated at the field level (Table 1).

Net Returns

Net returns were calculated using lint yields and N rates for the three N treatments (Table 1). Price and budget data used to calculate net returns are in real 2013 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 for 2011 through 2014 (USDA 2014a), adjusted to real 2013 dollars of \$1.84 kg^{-1}. National prices paid for N fertilizer were collected for 2011 through 2014 marketing years (USDA 2014d), adjusted to real 2013 dollars of \$0.91 N kg^{-1}. EQIP cost-share payment were collected for each state in the study for precision nutrient management payment code 590 for 2011 through 2014 adjusted to real 2013 \$ ha^{-1}. Payments were \$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 and were added to crop revenue for treatments 2 and 3.

Information and application costs, including equipment/technology, labor, and other costs, were estimated using partial budgeting (AAEA 2000). Two budgets were developed to account for information and application costs: 1) for OPM and VRT N application (treatment 2) and 2) OPM and yield monitor information and VRT N application (treatment 3). The OPM and VRT technology was assumed to be retrofitted to an existing boom sprayer measuring 24.7 m wide. For treatment 3, the cost of obtaining yield monitor information was assumed to be used to augment the information provided by OPM to apply N on the field. The yield monitor was assumed to be retrofitted to an existing 6-row cotton picker measuring 5.8 m wide. Ownership costs of equipment/technology 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) and equipment costs calculation techniques outlined on the Agricultural and Applied Economics Association (AAEA) Commodity Costs and Returns Estimation Handbook (AAEA 2000). The total ownership cost of OPM and VRT was estimated to be \$2.29 ha^{-1} and the total ownership cost of yield monitoring was estimated to be \$2.73 ha^{-1}. In addition, the costs of a computer to manage yield monitor data and technical advice for incorporating yield monitor with sensing information were included in the total cost for treatment 3.

An average of 2009 cotton PA technical advice fees (Mooney et al. 2010) was normalized to real 2013 dollars, \$12.63 ha^{-1} and added to all years of applicable data. Added labor costs for VRT treatments were estimated using custom rate surveys produced by the extension service in each state. The 2013 PA fertilizer application labor cost was determined by taking the difference between PA fertilizer application in Tennessee and the average dry bulk fertilizer application in Tennessee, Missouri, and Mississippi. Tennessee, Mississippi, and Missouri rates were averaged and applied to all locations because Louisiana State University extension does not produce a custom rate survey. Therefore, VRT was assumed to cost \$6.60 more ha^{-1} in labor to relative to the FP N application. The respective information and operating costs ha^{-1} of treatment 3 for Louisiana, Mississippi, Missouri, and Tennessee were \$13.03, \$12.97, \$12.86, and \$12.91.

Soil Property, Landscape, and Weather Data

Given the importance of spatial variability in the profitability of PA (Raun et al. 2002; Scharf et al. 2002), soil properties, landscape, and weather from the field trials were examined to determine their effects on lint yields, N rates, NPU efficiency, and net returns, with VRT. 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 (Table 2). A soil erosion index (*SEI*) was estimated using a modified universal soil loss equation to account for the physical factors of the fields:

$$SEI = (KF \times LS \times R)/TF. \tag{2}$$

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×S+0.006541×S^2 at the standard slope length of 22.1 m (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). The 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 growing degree days (April 1 through October 31) (Wright et al. 2011). The daily average temperature minus 15.6 °C was summed over April 1 through October 31 per location-year for daily calculations greater than zero (Table 2).

Statistical Analysis

The methods and procedures used to examine the VRT treatments are based on a modified version of the Schabenberger and Pierce (2002, pp. 474-479) on-farm experimentation model:

$$x^{a}_{ijktd} = \mu + \delta_t + \lambda_k + \tau_i + \rho_{(j)k} + (\lambda\tau)_{ik} + \omega_{kjid} + \theta_{kjid} + \gamma_{kjid} + \varphi_{kjid} + \beta_{kjid} + \psi_{kjid} + \chi_{\mathrm{kt}} + \varepsilon_{\mathrm{ijkt}}, \tag{3}$$

where x is the dependent variable; a is 1=cotton lint yield (kg ha^{-1}), 2=N rate applied (kg ha^{-1}), 3=net returns ($ ha^{-1}), and 4=NPU efficiency; i is N rate treatment (i=1, 2, 3); j indexes replications; k is farm location (k=1,…,21); t is year (t = 2011, 2012, 2013, 2014), d is sub-plot, μ is the overall mean; δ is the year random effect; λ is the farm location random effect; ρ is replication nested within farm location random effect; ($\lambda\tau$) is the farm location-treatment interaction random effect; τ is the fixed treatment effect; ω is the fixed effect of water holding capacity in cm of water per cm of soil depth (cm cm^{-1}); θ is the fixed effect of organic matter (%); γ is the fixed effect of SEI; φ is the fixed effect of soil depth (cm); β is the fixed effect of soil texture; ψ is the fixed effect of elevation (m); and χ is the fixed effect of growing degree days.

The explanatory variables were hypothesized to affect the dependent variables as follows: location because the farms are physically different, time because the experiments span more than one year, treatment because the treatments differ within a farm and among farms, and sub-plot because sub-plots physically differ within a farm and among farms. The location-treatment interaction was expected to affect the dependent variables but to mask treatment differences. 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 from yield differences will not be a factor in net returns. N rates become the driver. The null hypothesis that VRT by treatment is not different from the FP was tested for lint yields, N rates, NPU efficiency, and net returns.

The cotton lint yield, N rate, NPU efficiency, and net return equations 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 adjust degrees of freedom.

Table 2. 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 (°C) by county/parish and state

County/Parish	State	Obs	Elevation (m)[4]	Soil Texture(s)[2]	Soil Erosion Index	Water Holding Capacity (cm cm^{-1})[1]	Organic Matter (%)[1]	Soil Depth (cm)[1]	Growing Degree Days (°C)[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
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
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
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).
Obs is the number of observations.

To determine if the treatments produced significantly different lint yields, N rates, NPUs and net returns, Dunnett's tests were estimated using SAS 9.2 (Littell et al. 2006). This test performs multiple comparisons while holding the familywise error rate at or below an alpha level. The reference category was FP.

Because the interaction term is random, contrasts between farms were estimated via best linear unbiased predictions using SAS 9.2 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 VRT outperformed FP. 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 $\alpha = 0.10/21 = 0.0047$. The Type I error rate becomes 0.0047 for each hypothesis at the field level. The models were checked for multicollinearity by estimating a regression using SAS 9.2 (PROC REG) and the VIFs. The random effects listed for Equation (2) apply here as well.

The null hypotheses that mean yields, N rates, NPU efficiency, and net returns do not differ between VRT N management strategies and FP due to variability in soils characteristics and climate were tested. Alternatively, soils and climate do generate differences using VRT when compared to FP.

Results and Discussion

Using VIFs as a measure of multicollinearity, all variables in the estimated models for lint yields, N rates, NPU efficiency, and net returns were under a VIF value of five. The four statistical models were first estimated with only treatment as the explanatory variable. The added soil and climate characteristics generated models that were better fitting using the AIC and 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

The estimated cotton lint yield model produced a better fitting model based on AIC and BIC than re-estimating the model without the location-treatment interaction term (Table 3, 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 4). A Dunnett's test with the interaction term indicated that treatment 3 was significantly different than the FP but there were no differences in either VRT treatment versus FP with the interaction term (Table 5).

Soil and climate attributes were significant (Table 6). All else equal, soils with more 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.

N Rates

The mixed model for N rates applied showed no significant differences between treatments but indicated that the variance between farms ($\sigma_{\lambda}^{2} = 242.33$) was substantially higher than the variance

Table 3. Best fit criteria for treatment effect models with (With) and without (Without) the location–treatment interaction term

	Yields		N Rate		NPU		NR	
Statistic	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
Obs	1924	1924	1935	1935	1924	1924	1924	1924

Obs is the number of observations.

AIC is the Akaike information criterion, BIC is the Bayesian information criterion, and 2LL is the -2 Log Likelihood.

within farms (σ_{λ}^{2} = 86.83). This means that there was more N rate variation between farms than within farms. The N rate model 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 5). Based on the model's best fit criteria (Table 3) the interaction term was significant to the model.

Estimates of VRT treatments 2 and 3 versus the 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 Tensas Parish, LA, had estimated N rates that were significantly lower using the FP than either VRT treatment (2 and 3). Adams County, MS, experienced lower N rates with FP than VRT treatment 3 (Table 4).

The results indicated that for some of the fields in the study the current FP applied less N than VRT. Tennessee and Louisiana fields have less organic matter as a percentage of the soil where N rates were lower using FP (Table 2). 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 was significant at the 10% level in the N rate model potentially lending support to this proposition (Table 6). 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 N applied. 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 N applied. 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 7). 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.

Table 4. 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})

County/			Cotton Lint Yield (kg ha^{-1})		Total N Rates (kg ha^{-1})		NPU Efficiency		Net Returns ($ ha^{-1})	
Parish	State	Obs	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	LA	30	211.71	271.85	37.54	32.26	-1.11	-0.33	339.48	446.59
Station			(284.71)	(237.62)	(17.91)	(16.69)	(3.66)	(2.76)	(471.11)	(394.46)
Tensas	LA	60	-26.53	-42.19	-26.10	-14.23	2.91	1.18	73.13	15.77
Middle			(183.39)	(171.05)	(21.71)*	(13.73)*	(2.95)	(2.06)	(335.51)	(313.35)
Tensas	LA	30	67.05	19.65	-45.90	-50.52	5.45	5.72	276.87	195.90
Middle low			(103.57)	(126.16)	(5.90)	(6.06)	(1.21)	(1.40)	(190.26)	(232.52)
Tensas	LA	60	153.95	120.37	79.22	84.33	-17.15	-17.91	163.19	90.22
North			(119.97)	(181.58)	(12.57)*	(19.52)*	(11.69)*	(12.43)*	(226.68)	(332.13)
Tensas	LA	90	234.03	219.22	9.50	24.69	1.50	-0.08	452.83	390.41
South			(593.14)	(574.53)	(16.89)*	(24.76)*	(4.93)	(5.22)	(1031.12)	(1010.62)
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	MS	17	20.10		17.38		-1.33		64.03	
East			(306.27)		(6.85)		(2.09)		(559.30)	
Leflore	MS	20	-22.93	-54.22	-31.07	-14.47	4.16	2.04	81.82	-11.77
North			(54.67)	(132.68)	(18.95)*	(25.57)	(3.06)	(3.82)	(101.80)	(236.09)
Leflore	MS	16	103.06	38.91	11.27	13.24	-0.14	-0.61	223.42	100.24
South			(98.79)	(92.19)	(18.12)	(23.81)	(2.18)	(2.80)	(177.21)	(193.01)
North										
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	MO	8	-18.59	-27.52	-6.02	-3.78	1.33	0.67	8.23	-14.94
East			(37.84)	(35.32)	(6.69)	(6.80)	(1.43)	(1.56)	(59.65)	(63.17)
New Madrid	MO	11	19.02	12.00	-3.97	-4.72	1.28	1.45	67.30	54.11
North			(71.34)	(81.91)	(9.26)	(10.46)	(2.27)	(2.26)	(121.03)	(132.36)
New Madrid	MO	4	51.00	61.57	6.44	8.40	-0.29	-0.50	98.01	108.52
South			(26.14)	(34.75)	(7.94)	(5.67)	(1.53)	(1.10)	(60.66)	(66.31)
Pemiscot	MO	3	55.27		-41.81		7.95		212.60	
North			(129.95)		(8.40)		(4.06)		(250.70)	
Pemiscot	MO	3	-20.94		-16.80		1.89		23.61	
South			(288.35)		(16.95)		(3.07)		(510.74)	
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	TN	48	-360.74	-286.99	18.90	21.93	-32.88	-34.34	-641.41	-521.44
North			(608.74)	(533.45)	(38.80)*	(49.86)*	(37.10)*	(40.98)*	(1148.18)	(1010.12)
Madison	TN	24	-83.65	-65.59	-12.60	-15.86	1.33	2.59	-68.93	-32.30
South			(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 adjust p-values for multiple comparison.
Standard errors are in parentheses.
Obs is the number of observations.

Table 5. 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, respectively.

N Production Use Efficiency

Results from the NPU efficiency mixed model indicated that the treatment means were not significantly different. The variation between farms (σ_λ^2 = 131.75) was greater than within the farms (σ_λ^2= 0.92). The model was re-estimated without the interaction term to determine if farm effects were being masked and results indicated treatment differences (F-value=16.44; Prob $\leq$ 1%). NPU means were significantly different between both VRT treatments and the control FP treatment as estimated by the Dunnett's test (Table 5). The AIC and BIC criteria indicated that the original model was a better fit than dropping the interaction term (Table 3). 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 4).

Elevation, water holding capacity, organic matter, soil texture, soil depth, and growing degree days had significant effects on NPU efficiency (Table 5). Fields at higher elevations, with greater water holding capacity, or warmer temperatures, all else equal, were negatively associated with NPU 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

Table 6. 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})
Observations used	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, respectively.

Standard errors are in parentheses.

WHC is water holding capacity, OM is organic matter, SEI is soil erosion index, and GDD is growing degree days.

[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%

efficiency, 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 NPU efficiency. *Ceteris paribus*, high elevation fields with greater water holding capacity, or warmer average days had a negative relationship with NPU efficiency. Soils with these conditions may have higher tendencies for erosion and, therefore, may require more N applied.

Table 7. Soil and climate property means by farm with significant N rate differences using VRT versus FP

County/ Parish	State	Elevation (meters)[4]	Soil Texture[2]	Soil Erosion Index	Water Holding Capacity (cm cm^{-1})[1]	Organic Matter (%)[1]	Soil Depth (cm)[1]	Growing Degree Days (°C)[3]
----------VRT<FP----------								
Tensas Middle	LA	21.64	Silt	3.59	0.21	2.23	22.29	1846.54
Leflore North	MS	43.07	Silt; Loam	6.59	0.19	1.75	23.00	1648.79
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
average		*71.44*		*8.25*	*0.21*	*1.82*	*19.95*	*1574.21*
----------VRT>FP----------								
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
Adams	MS	55.17	Silt	6.87	0.22	1.89	27.03	1856.31
Madison North	TN	117.25	Silt	16.12	0.22	1.33	20.06	1404.96
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).

Net Returns

The net returns model estimated with and without the interaction term identified significant treatment differences between net returns (F-value=5.52; Prob $\leq$ 1%). Estimating the difference between treatments by farm, however, indicated no treatment differences at Bonferroni correction of 0.0047 (Table 4). A Dunnett's test showed net returns to be different between VRT treatment 2 and the FP when estimating the net returns model. When re-estimating the model without the interaction term, the Dunnett's test revealed significant differences between VRT treatment 2 versus the FP and VRT treatment 3 versus the FP (Table 5).

All else equal, coarser soil textures, soils with a higher percentage of organic matter, or deeper soils were positively associated with net returns (Table 6). 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 lint yields and profits.

Conclusions

This research determined the lint yields, N fertilization rates, NPU efficiency and profitability of using OPM and VRT to manage spatial variability in cotton production using 29 site years of data from field trials in Louisiana, Mississippi, Missouri, and Tennessee. The VRT N management indicated some N savings but were not more profitable on average than existing FP N management. Three additional inferred conclusions may aid in farmers' decisions about precision N management. First, VRT may not apply enough N to significantly increase yields relative to the FP. Second, changes in the N rate for VRT relative to the FP were field/farm specific. Four locations (Tensas Middle, LA, Gibson, TN, Lauderdale, TN, and Leflore, MS) realized lower N rates applied in at least one form of VRT N application. Four locations had higher N rates with VRT (Madison North, TN, Adams, MS, Tensas North, LA, and Tensas South, LA). Finally, the N rates across the 29 site-years were not low enough to increase NPU efficiency. Even though the fields in the study represented a range of soils, landscapes, and weather in the locations used in the project, there was likely not enough spatial variability within the fields that the VRT treatments did not make a difference in field level net returns.

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