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Effects of Landscape, Soils, and Weather on Yields, Nitrogen Use, and Profitability with Sensor-Based Variable Rate Nitrogen Management in Cotton

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Abstract: Farmers may be reluctant to adopt variable rate nitrogen (VRN) management because of uncertain profits. This study assessed field landscape, soil, and weather effects on optical sensing (OS)-based VRN on cotton (*Gossypium hirsutum* L.) N rates, yields, and net returns (NRs). Field data were collected from 21 locations in Louisiana, Mississippi, Missouri, and Tennessee, USA, between 2011 and 2014. Data included yields, N rates, and NRs for the farmer practice (FP), OS-based VRN, and OS-based VRN supplemented with other information. Production data were augmented with landscape, soils, and weather data, and ANOVA and logistic regressions were used to identify field conditions where VRN was profitable, provided risk management benefits, and improved N efficiency. Key findings indicate that NRs were improved with VRN by applying additional N on more erodible soils. Higher organic matter soils also benefited from VRN through enhanced yields and NRs. VRN may also have provided risk management benefits by providing a lower probability of NRs below NRs for the FP on soils associated with greater water-holding capacity, higher organic matter levels, or deeper profiles. Results from this study may help identify farm fields with similar characteristics for adoption of VRN management.

Keywords: economics; normalized difference vegetation index (NDVI); on-the-go sensors; site-specific nutrient management

1. Introduction

Upland cotton (*Gossypium hirsutum* L.) is an important crop in the lower Mississippi River Basin (MRB) of the United States (US) that includes the states of Louisiana, Mississippi, Missouri, and Tennessee [1].

Cotton area planted in the four states was 700,405 ha in 2019 [2]. Nitrogen (N) is the plant nutrient most often applied in the largest amounts by farmers growing upland cotton [3,4]. Nitrogen is especially important for lint yield formation after the cotton plant's first bloom [5]. Under application of fertilizer N reduces lint yield and profit. However, over application of fertilizer N in cotton increases fertilizer costs and can also cause excessive vegetative plant growth rather than increased production of cotton bolls that contribute to lint yield and profit [6]. Excessive vegetative growth can decrease lint yield due to boll rot and insects, reduce lint fiber quality, and cause increased expenses due to additional applications of pesticides and plant growth regulators to prevent lint yield losses [6].

Over application of fertilizer N can also negatively affect water quality. Nitrogen, especially in the form of nitrates, can leach from farm fields into surface and ground water [7]. This may be especially true if farmers apply a uniform N rate across individual fields. Efficient N management on fields in the lower MRB is an important priority for the US Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) [1]. The goal of the USDA NRCS is to reduce nutrient and sediment loading to local and regional water bodies and to improve water use efficiency. The USDA NRCS promotes the use of variable rate N (VRN) management to apply different rates of fertilizer N across farm fields based upon soil N and crop needs through the Environmental Quality Incentives Program (EQIP) [8]. However, by 2017, only 9.5% of upland cotton growers adopted VRN [9]. Grower uncertainty about the profitability of managing soil N spatial and temporal variability may be an important factor influencing VRN adoption by farmers [10].

Optimal fertilizer N management depends on the amount of available N derived from the soil and fertilizer [11]. Complex interactions between land use, crop management, landscape characteristics, soil properties, and weather influence N soil availability to plants [12]. Soil properties and soil N can vary substantially within farm fields [11]. Alluvial soils in the floodplains of the lower MRB (USDA NRCS Major Land Resource Area 131) frequently exhibit significant variation in texture and N availability [6]. Loess soils are common on cotton fields located in the lower MRB (USDA NRCS Major Land Resource Area 134) and are subject to water-induced soil erosion because of the rolling landscapes upon which these soils occur in the region [13]. Soils redistributed by water-induced soil erosion cause variation in a field's soil properties and, consequently, field soil N [14].

Rainfall and temperature also interact with soil and landscape attributes to cause spatial and temporal variability of soil N that complicates cotton N management [15]. Soil testing for N is unreliable in the warm, humid climate of the lower MRB because soil N varies greatly with soil organic matter, soil texture, tillage, and other factors [16]. Consequently, lower MRB cotton growers generally do not completely rely on soil test information to manage N [6]. Growers and their crop consultants develop a single (uniform) rate for the field using Land Grant University fertility recommendations, their experience, and other considerations, including cotton variety, soil texture, and crop rotation.

Given the unreliability of N soil tests, plant-based measurements can be used to determine crop demand for N. For example, in-season N status can be assessed using visual inspection of plants for N deficiency symptoms, petiole NO^3-N or leaf tissue sampling, or chlorophyll meters to determine N status in the growing cotton for in-season fertilizer N applications up to the early bloom stage [16,17]. However, assessing plant N status using hand-held devices is labor intensive and may not provide sufficient information to determine N rates for VRN management. Ground-based optical sensing (OS) of the growing crop canopy facilitates assessment of crop N status throughout the field and provides growing spatial plant canopy data useful for determining VRN rates that vary across the field [11,17].

Most of the studies evaluating OS-based VRN reported crop yields similar to yields for the uniform fertilizer N rate (i.e., conventional or farmer practice) [18–25]. Thus, an important factor driving the profitability of OS-based VRN is lower fertilizer N rates relative to the uniform rate. Researchers have reported fertilizer N savings with OS-based VRN of as much as 69 kg ha^{-1} [22]. However, other studies have reported increased applications of fertilizer N relative to the uniform rate of as much as 84 kg ha^{-1} with OS-based VRN [24]. Researchers evaluating the economic feasibility of OS-based VRN have found mixed profitability results. Studies that reported a lack of profitability found similar yields but did not find sufficient fertilizer N cost savings to provide a profit [18–20,24]. Research reporting positive profitability through enhanced yields and N cost savings did not include the costs of OS information and VRN application [22,23,25]. Costs of information used to produce the VRN prescription and VRN application costs are also important factors influencing the profitability of the technology [26]. VRN management may also mitigate yield and profit risk compared to uniform N management by reducing the probability of yield or profit below a threshold level [27,28].

Farmers are often unwilling to adopt technologies such as OS-based VRN unless they see the potential for positive profits [26]. This is especially a problem for N management in the lower MRB because plant response to N is influenced by landscape, soil, and weather characteristics. Quantifying how spatial and temporal factors affect yields, N use, profitability, and the risk management potential of VRN may be useful to cotton farmers in the lower MRB interested in adopting OS-based VRN. The objective of this research was to determine how landscape, soil, and weather influence fertilizer N use, lint yields, and profitability of OS-based VRN for cotton in the lower MRB.

2. Materials and Methods

2.1. Lint Yield and Fertilizer N Data

Lint yield and fertilizer N application rate data for the farmer practice (FP) and OS-based VRN management were from 21 study locations (Table 1). Farmers participating in the trials were eligible to receive payments to adopt VRN through USDA NRCS EQIP [8]. Stefanini et al. [24] previously reported differences in field-level fertilizer N use, lint yields, and profitability. The on-farm field trials were conducted between 2011 and 2014 at six locations in Tennessee, four locations in Mississippi, five locations in Louisiana, and six locations in Missouri. Most locations had only one year of data. However, several locations had two to three years of trials. Within each of the locations with multiyear trials, different fields were used for each year. A total of 29 site-years of data were collected in the study.

The field trial experimental design for each site-year was a randomized complete block design with three fertilizer N treatments and three replications. A strip-plot running the entire field length was used as the plot for each treatment in each replicate. Each strip-plot was further divided into sub-plots. The sub-plots were used to implement the two VRN treatments evaluated in this study. Cotton was planted on the nine strip-plots at each site, each with 8 to 10 sub-plots, that measured approximately 30.5 by 11.6 m. A different field on each participating farm was used for each site-year. While researchers attempted to choose similar field sizes in each year of the study, variation in field sizes resulted in different numbers of sub-plots within the strip-plots among the site-years (Table 1). However, the same number of sub-plots for each strip-plot within each site-year was maintained during the study.

The trials evaluated FP N management versus two OS-based VRN management regimes. The FP treatment was N application based on the farmer's current practice. Cotton farmers and their crop consultants often formulate their fertilizer N rate for the field using University recommendations, their experience, and agronomic and soil considerations [6]. Optical sensing-based VRN treatment 1 (VRN 1) was VRN management calculated using the normalized difference vegetation index (NDVI) readings collected with the GreenSeeker™ Crop Sensing System (Trimble, Sunnyvale, CA, USA) or Yara™ N-Sensor (Yara North America, Tampa, FL, USA) canopy optical-sensing. The configurations of sensor arrays were different in each state where the field trials took place. In Tennessee, a GreenSeeker™ RT200 system with six sensors (1.93 m apart and 0.76 m above the cotton canopy) covering 12 rows of cotton (11.58 m wide) was used to collect about two scans s^{-1} at a field speed of about 7.64 km h^{-1}. The second OS-based VRN treatment (VRN 2) was VRN management based on NDVI readings but augmented with additional information.

Table 1. State and county/parish locations of the farm fields.

State	County/Parish Field Locations	Years (Number of Field Sub-Plots) [A]		
Louisiana	Tensas Parish Res Station	2012 (89)		
Louisiana	Tensas Parish Middle	2012 (90)	2013 (90)	
Louisiana	Tensas Parish Middle Low	2014 (90)		
Louisiana	Tensas North	2012 (90)	2013 (100)	
Louisiana	Tensas Parish South	2012 (90)	2013 (90)	2014 (80)
Missouri	Dunklin	2013 (12)		
Missouri	New Madrid East	2012 (24)		
Missouri	New Madrid North	2012 (33)		
Missouri	New Madrid South	2012 (12)		
Missouri	Pemiscot North	2013 (6)		
Missouri	Pemiscot South	2013 (6)		
Mississippi	Adams	2012 (107)		
Mississippi	Leflore East	2014 (35)		
Mississippi	Leflore North	2013 (60)		
Mississippi	Leflore South	2013 (48)		
Tennessee	Carroll	2014 (72)		
Tennessee	Gibson	2011 (72)	2012 (88)	
Tennessee	Lauderdale	2012 (90)	2013 (90)	2014 (90)
Tennessee	Madison North	2012 (72)	2013 (72)	
Tennessee	Madison South	2014 (72)		
Tennessee	Tipton	2012 (72)		

[A] The number in parentheses indicates the total number of sub-plots at each field site. The field trials were conducted using a randomized complete block design at each site. Two variable rate nitrogen treatments were compared against the existing farmer practice. Each treatment was replicated three times in three strip-plots at each site. Strip-plots were divided into 8–10 sub-plots to implement the two variable rate nitrogen treatments in the field trials. Different fields with dissimilar sizes were used on each farm in each year of the study and resulted in a variable number of sub-plots at each site. However, the same number of sub-plots for each strip-plot within each site-year was maintained during the study. Yields were measured in Missouri at the strip-plot rather than the sub-plot level.

Two split applications of fertilizer N were made for the three fertilizer N management regimes. Starter fertilizer was applied at or before the planting of cotton and was determined by each farmer participating in the study. A uniform blanket rate of fertilizer N was applied to the entire field (covering all three treatment areas) with rates ranging from 33.6 to 78.4 kg N ha^{-1}, depending on the farm field location. A second side dress application of fertilizer N for the FP was made at approximately the early bloom stage. For the two VRN treatments, crop N status was determined using canopy optical-sensing at about the early bloom stage for each site-year of the trial and fertilizer N was side dressed variably on the sub-plots, thereafter based on the NDVI readings for the VRN 1 treatment and NDVI readings and either digital yield maps (Mississippi and Tennessee), soil productivity zones (Louisiana), or soil zones (Missouri) for VRN 2. Each state used different algorithms for the VRN 1 and VRN 2 treatments because each state has different soils, climates, and management practices for cotton. The unpublished algorithms were developed based on multiple-year and multiple-location data from previous research in each state.

The other production practices used to grow cotton on each field trial site were determined by the farmer cooperators in the study. Data collected for each sub-plot (strip-plot in Missouri) included harvested seed cotton yield, lint yields, applied fertilizer N rates, and latitude and longitudes for every field site, except in Missouri, where yield data were collected at the strip-plot level rather than by sub-plot (Table 2). In Louisiana, Mississippi, and Tennessee, cotton pickers with yield monitors were used to harvest cotton and determine sub-plot seed cotton and lint yields. Yield monitors were not available on cotton pickers at the Missouri sites so strip-plot yields rather than sub-plot yields were measured using a weigh wagon. A measure of nitrogen use efficiency (NEFF), defined as lint yield divided by fertilizer N rate, was also calculated for each N management regime (Table 2) [24].

Table 2. Field trial sub-plot mean, maximum, and minimum values and the number of sub-plot observations for lint yields, fertilizer nitrogen (N) rates, N efficiency (lint yield/fertilizer N rate), and net returns for the three fertilizer N treatments that were collected from the 2011–2014 field trials.

Variable Name/ Summary Statistics	Fertilizer N Treatment		
	FP [a]	VRN 1 [b]	VRN 2 [c]
Lint yield (kg ha^{-1})			
Mean	1332	1360	1349
Maximum	2397	2585	2565
Minimum	226	133	204
Observations	649	658	635
Fertilizer N rate (kg ha^{-1})			
Mean	107	109	114
Maximum	244	226	253
Minimum	34	54	34
Observations	660	659	635
Nitrogen efficiency (lint yield/fertilizer N rate, index)			
Mean	18	14	14
Maximum	120	54	40
Minimum	1	1	1
Observations	649	658	635
Net return (USD ha^{-1})			
Mean	2226	2315	2264
Maximum	4081	4233	4167
Minimum	481	239	333
Observations	649	658	635

[a] FP, farmer practice nitrogen management on each field in the study. [b] VRN 1, variable rate nitrogen management calculated using normalized difference vegetative index readings. [c] VRN 2, variable rate nitrogen management based on normalized difference vegetative index readings and either digital yield maps (Mississippi and Tennessee), soil productivity zones (Louisiana), or soil zones (Missouri).

2.2. Landscape, Soil, and Weather Data

Landscape, soil, and weather data were collected to determine differences within and between fields for each location-year. Georeferenced landscape, soil, and weather data were assembled from the center point of each sub-plot (strip-plot for Missouri locations) using ArcGIS 10.1 (ESRI, Redlands CA, USA). Sub-plot elevations (m above sea level) were collected from the National Elevation Dataset [29]. Soil water-holding capacity (volume fraction), soil organic matter (%), soil texture, soil depth (cm), field slope, and soil erosion factors were gathered from the Soil Survey Geographic (SSURGO) database [30]. Soil texture data in SSURGO were used to rank textures by coarseness—clay (finest), silt, loam, and sand (coarsest)—using the USDA soil texture calculator [31].

A soil erosion index (SEI) was created using SSURGO [30] data, USDA Revised Universal Soil Loss Equation, version 2 (RUSLE2) data [32], and a modified universal soil loss equation to account for the physical factors of the fields [24]:

$$SEI = (KF \times LS \times R)/TF \quad (1)$$

where *KF* is an erodibility factor due to water, *LS* is a soil length (*L*) and slope steepness (*S*) factor, *R* is the rainfall and runoff factor from USDA RUSLE2 version 2.5.2.11 [32]; and *TF* is a soil tolerance factor.

Weather was measured by temperature [33], expressed as seasonal growing degree days. To calculate seasonal growing degree days, the positive values of daily average temperature minus 15.6 °C was summed over 1 April through 31 October for each site-year.

2.3. Fertilizer N Management Net Returns

Net returns for the FP, VRN 1, and VRN 2 treatments were estimated using sub-plot lint yields, fertilizer N rates, lint and N fertilizer prices, and partial budgeting costs for OS and VRN technologies (Table 2). Price and budget data are in real 2013 US dollars indexed using the annual Gross Domestic Product Price Deflator Index [34]. Crop revenues were estimated by multiplying lint yields for each N management treatment by the national average marketing year cotton lint price of USD 1.86 kg^{-1} received for 2011 through 2014 [35]. EQIP cost-share payments (NRCS precision nutrient management practice code number 590) for each state for 2011 through 2014 were also added to crop revenues. Estimated payments were USD 68.21 ha^{-1} in Mississippi [36], USD 68.46 ha^{-1} in Louisiana [37], USD 65.85 ha^{-1} in Tennessee [38], and USD 32.64 ha^{-1} in Missouri [39].

Fertilizer N cost of USD 0.93 kg^{-1} was multiplied by the fertilizer N rate to determine fertilizer N cost for each N management regime. The fertilizer N price is the national average marketing year fertilizer N prices received for 2011 through 2014 [40]. Following Stefanini et al. [24], budgeted skilled operator labor and equipment operating and ownership costs of USD 2.14 ha^{-1} and USD 2.45 ha^{-1}, respectively, for OS of the crop canopy was assumed for GreenSeeker™ sensors retrofitted to a boom sprayer measuring 24.7 m wide. The cost of yield monitoring data identifying yield productivity zones in the field was assumed to be used to augment OS information for the VRN 2 prescription and had a budgeted cost of USD 2.73 ha^{-1}. In addition, the budgeted costs of a computer to manage yield monitor data of USD 0.31 ha^{-1} and reported cost of technical advice for incorporating yield monitor with OS information of USD 12.63 ha^{-1} [41], respectively, were included in the total cost for VRN 2. The cost of VRN application was estimated to be USD 6.60 ha^{-1} more than for the FP [41].

2.4. Statistical Analysis

Two statistical models were used to evaluate OS-based VRN in-field fertilizer N rate, lint yield, and net return (NR) relationships with farm field characteristics. The first is a general linear model for the fertilizer N management mean differences. The sub-plot lint yields (YLD), fertilizer N rates (FNs), N efficiency (FNEFF), and NRs (FNRs) that are summarized in Table 2 were used to construct the regressions' dependent variables. The dependent variables were created using paired sub-plot observations in each strip-plot to measure differences between VRN 1 and the FP (VRN 1-FP) and VRN 2 and the FP (VRN 2-FP). For example, field 1, replication 1, and sub-plot 1 for the VRN 1 treatment versus field 1, replication 1, and sub-plot 1 for the FP treatment. This procedure resulted in 1263 observations available for each of the regressions (Table 3). Fixed effects included in the mean difference regressions are landscape, soil, and weather characteristics georeferenced to each sub-plot. To account for potential differences in landscape and soil characteristics between paired VRN and FP sub-plot observations within each replication, observations were omitted from the regressions if soil characteristics differed between the two sub-plots. For example, if soil texture differed across field 1, replication 1, and sub-plot 1 for the VRN treatment versus sub-plot 1 for the FP treatment, then the observation was omitted from the regressions; if not, the observation was retained for the estimation. The summary statistics for the landscape, soil, and weather variables used as fixed effects in the mean difference regressions are also presented in Table 3.

Table 3. Dependent and fixed-effect variable names, definitions, and statistics (mean, minimum, maximum, and number of available observations) for the mean difference and logit regression models.

Variable Name	Mean	Minimum	Maximum	Observations
Mean difference regression dependent variables				
ΔYLD [a]	37.05	−1941.20	2077.53	1263
ΔFN [b]	4.95	−67.59	125.36	1263
ΔFNEFF [c]	−3.21	−96.52	20.18	1263
ΔFNR [d]	102.37	−3630.32	3668.06	1263
Logit regression dependent variables				
YLDprob [e]	0.45	0	1	1263
FNprob [f]	0.55	0	1	1263
FNEFFprob [g]	0.47	0	1	1263
FNRprob [h]	0.37	0	1	1263
Fixed Effects				
Soil texture index [i]	2.14	1	4	1221
Elevation [j]	64.20	21.64	136.36	1262
WHC [k]	0.21	0.08	0.23	1168
SOM [l]	1.85	0.52	2.25	1166
SEI [m]	7.03	0.21	39.13	1158
Depth [n]	21.32	8.00	64.00	1152
GDD [o]	1574.3	1025.93	1943.27	1263
ν [p]	0.33	0	1	1263

[a] ΔYLD, difference in optical sensing-based variable rate nitrogen management and farmer practice nitrogen management lint yields (kg ha^{-1}). [b] ΔFN, difference in optical sensing-based variable rate nitrogen management and farmer practice nitrogen management fertilizer nitrogen rates (kg ha^{-1}). [c] ΔFNEFF, difference in optical sensing-based variable rate nitrogen management and farmer practice nitrogen management fertilizer nitrogen efficiency measured as lint yield divided by fertilizer nitrogen rate (index). [d] ΔFNR, difference in optical sensing-based variable rate nitrogen management and farmer practice nitrogen management net returns (USD ha^{-1}). [e] Yprob, if optical sensing-based variable rate nitrogen management lint yield is less than farmer practice nitrogen management lint yield, then 1; else 0. [f] Nprob, if optical sensing-based variable rate nitrogen management fertilizer nitrogen rate is less than farmer practice nitrogen management fertilizer nitrogen, then 1; else 0. [g] NEFFprob, if optical sensing-based variable rate nitrogen management nitrogen efficiency is less than farmer practice nitrogen management nitrogen efficiency, then 1; else 0. [h] NRprob, if optical sensing-based variable rate nitrogen management net return is less than farmer practice nitrogen management net return, then 1; else 0. [i] Soil texture index, 1 = Clay, 2 = Silt, 3 = Loam, and 4 = Sand. Sand is the reference variable in the regressions. Sources: [30,31]. [j] Elevation, vertical distance above sea level (m). Source: [29]. [k] WHC, water holding capacity (volume fraction). Source: [30]. [l] SOM, soil organic matter (%). Source: [30]. [m] SEI, soil erosion index. [n] Depth, soil depth (cm) from the top of the soil to the base of the soil horizon. Source: [30] [o] GDD, growing degree days, 1 April through 1 October, base 15.6 degrees Celsius: Source: [33]. ν [p], 0–1 variable indicating variable rate nitrogen treatment using normalized difference vegetative index and either digital yield maps (Mississippi and Tennessee), soil productivity zones (Louisiana), and soil zones (Missouri).

The general linear model for the fertilizer N management mean differences was:

$$\Delta Y_{ijklt} \; = \; \mu + X_{lt}\beta + v + \varphi_j + \varphi_{k(j)} + e_{ijklt}, \tag{2}$$

where i = 1 (VRN 1 − FP), 2 (VRN 2 − FP); j = 1, ... , 21 farm field locations; k = 1, 2, and 3 replications on fields; l = 1, ... , 8 to 10 replication sub-plots within each strip-plot; t = 2011, 2012, 2013, and 2014; $\Delta Y_{ijklt} = Y^{VRN_i} - Y^{FP}$ is defined as the mean difference in the response variable Y (lint yields (ΔYLD, kg ha^{-1}), fertilizer N rates (ΔFN, kg ha^{-1}), YLD/FN (ΔFNEFF, index), and NR (ΔFNR, USD ha^{-1})) for VRN 1 or VRN 2 compared to the FP; μ is the conditional mean; X includes sub-plot measurements on soil texture (clay, silt, loam, and sand), elevation above sea level (m), soil water-holding capacity (volume fraction), soil organic matter (%), soil depth (cm), soil erosion index, and seasonal growing degree days (degrees Celsius); β is a vector of the estimated average landscape, soil, and weather effects on ΔY; and ν is a 0–1 variable indicating the VRN 2 treatment. The parameters φ_j and $\varphi_{k(j)}$ are the farm field location random effects and the nested random effects from replications in farm field locations, with $\varphi_j \sim N\left(0, \sigma^2_{\varphi_j}\right)$ and $\varphi_{k(j)} \sim N\left(0, \sigma^2_{\varphi_{k(j)}}\right)$. The model error is $e_{ijkt} \sim N\left(0, \sigma^2_e\right)$ [42].

The models using Equation (2) were estimated using the MIXED model procedure and restricted maximum likelihood in SAS 9.2 [43]. The sand soil texture 0–1 variable was dropped to estimate regressions and was included as the reference variable in the intercept term. The mean difference models were evaluated for multicollinearity using variance inflation factors (VIF) estimated using the REG model procedure in SAS 9.2 [43]. VIF exceeding 10 may indicate that multicollinearity is increasing the size of the parameters' standard errors [44]. Models estimated using Equation (2) tested the null hypotheses that mean yields, fertilizer N rates, NRs, and N efficiency were not different between VRN and FP, holding landscape, soil, and weather factors constant.

The second statistical model is estimated as a mixed logistic regression:

$$\Pr\left(VRN_{ijklt} > FP_{ijklt} \middle| X_{lt}\right) = \text{Logistic}\left(\mu + X_{lt}\beta + v + \varphi_j + \varphi_{k(j)} + e_{ijklt}\right) \tag{3}$$

where $\Pr(VRN_{ijklt} > FP_{ijklt}|X_{lt})$ is the probability that the response variable (lint yields (YLD, kg ha^{-1}), fertilizer N rates (FN, kg ha^{-1}), YLD/N (NEFF, index), and NRs (FNR, USD ha^{-1})) for VRN falls above or below the FP value. The sub-plot data summarized in Table 2 were used to construct the logit regressions' dependent variables and are presented in Table 3. The binary dependent variables using the paired sub-plot observations in each strip-plot were calculated as:

$$\text{If } YLD^{VRN_i} - YLD^{FP} < 0, \text{ then } YLDprob = 1; \text{ else, } YLDprob = 0; \tag{4}$$

$$\text{If } FN^{VRN_i} - FN^{FP} > 0, \text{ then } FNprob = 1; \text{ else, } FNprob = 0; \tag{5}$$

$$\text{If } FNEFF^{VRN_i} - FNEFF^{FP} < 0, \text{ then } FNEFFprob = 1; \text{ else,} FNEFFprob = 0, \text{ and} \tag{6}$$

$$\text{If } FNR^{VRN_i} - FNR^{FP} < 0, \text{ then } FNRprob = 1; \text{ else,} FNRprob = 0. \tag{7}$$

Equations (4)–(7) were estimated for each binary dependent variable with the same set of fixed effects summarized in Table 3 and the same random effects used for the mean difference regressions described above. The logit models were estimated using the GLIMIX model procedure and restricted maximum likelihood in SAS 9.2 [43]. Multicollinearity was also evaluated in the logit regressions with the same procedures used for the mean difference regressions [44]. The odds ratios calculated using the estimated coefficients β of these logistic regressions are used to test the hypotheses comparing FP and OS-based VRN. Each covariate's impact on the odds VRN < FP is $\exp(\beta)$. In percent terms, the change in the log odds probability that VRN lint yields, N rates, NEFF, or NRs exceeded those of the FP is $100 \times [\exp(\beta) - 1]$. The null hypotheses for Equations (4)–(7) was that the N management regime does not affect the probability that yields, N rates, N efficiency, and NRs differ for VRN versus the FP, holding soil, landscape, and weather variables constant.

3. Results and Discussion

3.1. VRN vs. FP Mean Differences

The VIFs were less than five for all covariates and all general linear regressions (lint yield, fertilizer N rate, N efficiency, and NR), suggesting that multicollinearity was not inflating the parameters' standard errors.

3.1.1. Lint Yields

The soil, landscape, and weather factors associated with lint yields in the estimated mean difference regressions were silt soil texture ($Pr \leq 0.01$), loam soil texture ($Pr \leq 0.05$), elevation ($Pr \leq 0.01$), organic matter ($Pr \leq 0.01$), soil depth ($Pr \leq 0.01$), soil erosion index ($Pr \leq 0.01$), and growing degree days (GDD) ($Pr \leq 0.01$) (Table 4). Soils classified as having a silty or loamy texture relative to sand (the intercept term) were negative in relation to VRN yields when compared to FP. Higher temperatures, as measured by seasonal GDD, or field sites at higher elevations also had a negative association with

VRN yields compared to FP. Therefore, soils with coarser textures, fields at higher elevations, or fields in locations with warmer temperatures were negatively related with VRN yields when compared to FP, all other factors equal. Thus, VRN management may not increase lint yields on fields with these conditions when compared to the FP. By contrast, soils with higher organic matter content, deeper profiles, or subject to more erosion were positively associated with VRN yields relative to FP, all else equal. Soils with more organic matter may have more natural N available to the plant [45]. Soils with a higher erosion index had a positive association with lint yields, potentially because more N was applied in areas of the field that were more eroded.

Table 4. Estimated average landscape, soil, and weather effects on lint yield, fertilizer nitrogen (N) rate, N efficiency (lint yield/fertilizer N rate), and net return.

Fixed Effect [a]	Lint Yield (kg ha^{-1})	N Fertilizer Rate (kg ha^{-1})	N Efficiency (Index)	Net Return (USD ha^{1})
Intercept [b,c]	32.54	−7.77	−9.87	856.58
	(20.83)	(1.91) ***	(8.78)	(372.90) **
Clay [c]	−4.63	6.33	−12.41	−195.82
	(−6.61)	(0.61) ***	(2.77) ***	(118.31) *
Silt [c]	−24.45	−1.68	−2.67	−376.13
	(4.92) ***	(0.45) ***	(2.08)	(87.97) ***
Loam [c]	−14.00	−2.41	6.19	−190.16
	(6.15) **	(0.56) ***	(2.59) **	(110.02) *
Elevation	−1.98	−0.05	0.03	−3.80
	(0.53) ***	(0.05)	(0.02)	(0.95) ***
WHC [d]	6.74	1.92	6.54	929.64
	(−6.41)	(0.59) ***	(26.80)	(1148.78)
SOM [e]	1.71	−0.03	8.39	297.60
	(0.48) ***	−4.44	(2.01) ***	(86.15) ***
Depth	3.76	−0.27	0.08	6.58
	(1.26) ***	(0.12) **	(0.05)	(2.27) ***
SEI	5.89	0.90	−0.43	6.62
	(2.09) ***	(0.19) ***	(0.09) ***	(3.75) *
GDD	−0.34	0.04	−0.01	−0.71
	(0.05) ***	(0.00) ***	(0.00) ***	(0.09) ***
ν	24.82	5.81	0.02	26.02
	(−20.59)	(1.91) ***	(0.86)	(36.90)
Observations	1140	1140	1140	1140

Note: Standard errors are in parentheses. * Significant at the 0.10 probability level, ** significant at the 0.05 probability level, *** significant at the 0.01 probability level. [a] Variable names are defined in Table 3. [b] Intercept contains sand soil texture. [c] Soil texture coefficients scaled by 10%. [d] WHC coefficients scaled by 100. [e] SOM coefficients scaled by 100%.

3.1.2. N Fertilizer Rates

Many field soil, landscape, and weather characteristics were significantly related with N rate differences between VRN-generated N rates and the FP (Table 4). Fertilizer N rate differences were negatively associated with sand (the intercept term, Pr ≤ 0.01), silt (Pr ≤ 0.01), or loam (Pr ≤ 0.01) soil textures but positively related with clay (Pr ≤ 0.01) when VRN was compared to FP. Finer-textured soils required more fertilizer N applied due to the higher yield potential while coarser soils needed less applied N. Soils with greater water-holding capacity (Pr ≤ 0.01), larger soil erosion indexes (Pr ≤ 0.01), and higher GDD (Pr ≤ 0.01) were positive in relation to VRN N rates. All else equal, more N was applied using VRN compared to FP on fields with a greater water-holding capacity, more erodible soils, or warmer temperatures. Soils with deeper profiles (Pr ≤ 0.05) had a negative association to VRN N rate compared to FP. The estimated dummy variable for VRN 2 showed significantly higher N rates, indicating that OS plus yield monitor information calculated higher mean fertilizer N rates than the FP. However, the higher fertilizer N rates generated with the additional information embodied in the N management regime were not associated with higher lint yields (Table 4) and, therefore, limit the profit potential of VRN 2. In addition, the higher cost of information utilizing more expensive map-based information with VRN 2 also impedes its profit potential [28].

3.1.3. N Efficiency

Differences in N efficiency for VRN and the FP were negatively associated with the clay soil texture (Pr ≤ 0.01) compared to sand and positively associated with loam soil texture (Pr ≤ 0.05) (Table 4). Soils that were richer in organic matter (Pr ≤ 0.01) had a positive association with N efficiency for VRN compared to FP. More erodible soils (Pr ≤ 0.01) or fields with warmer temperatures (Pr ≤ 0.01) had negative associations with VRN efficiency. While higher organic matter content (Pr ≤ 0.01) soils had a positive relation to N efficiency of VRN compared to FP, all else equal, fields with more erodible soils (Pr ≤ 0.01) and warmer temperatures (Pr ≤ 0.01) had negative associations to N use efficiency, likely due to the need for higher N rates.

3.1.4. Net Returns

Soil, landscape, and weather factors also had significant impacts on mean NR differences (Table 4). Silt soil textures (Pr ≤ 0.01) had a negative impact on VRN NRs when compared to FP NRs. As noted above, the silt texture also had a negative association to VRN yields and VRN N rates. The N rates savings may not have been enough to increase NR for that soil type. The soil texture reference variable sand (Pr ≤ 0.05), however, had positive associations with VRN NRs compared to FP. Soils with higher organic matter (Pr ≤ 0.01) or deeper profiles (Pr ≤ 0.01) were positively associated with VRN NRs compared to FP. Higher elevation (Pr ≤ 0.10) fields had a negative association with VRN NRs compared to FP. Soils at higher elevations may be more exposed to erosion from wind and rain events. All else equal, warmer growing conditions as measured by GDDs were negatively associated with VRN 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 [46], which may cause the need for higher N rates because of increased volatilization of N to the atmosphere. However, the higher N applied was not sufficient to increase yields such that VRN NRs were increased relative to the FP.

3.2. VRN and Risk

The VIFs were less than five for all covariates and all logit regressions (lint yield, fertilizer N rate, N efficiency, and NR), suggesting that multicollinearity was not inflating the parameters' standard errors.

3.2.1. Lint Yields

Soil, landscape, and weather factors associated with lint yields in the estimated logit model were silt soil texture (Pr ≤ 0.01), loam soil texture (Pr ≤ 0.01), water-holding capacity (Pr ≤ 0.10), organic matter (Pr ≤ 0.05), soil depth (Pr ≤ 0.05), and growing degree days (Pr ≤ 0.01) (Table 5). Silt- or loam-textured soils or soils on fields with warmer growing conditions are positively attributed with the probability of lower VRN yields than FP (Table 6). Soils with greater water-holding capacity, higher organic matter content, or deeper profiles are negatively associated with the probability of lower VRN yields than FP. All else equal, higher organic matter in soils could potentially lower the probability of yield loss enough to warrant VRN adoption for some farmers through lower fertilizer N rates.

Table 5. Estimated logit regression coefficients of landscape, soil, and weather effects on lint yield, fertilizer nitrogen (N) rate, N efficiency (lint yield/fertilizer N rate), and net return.

Fixed Effect [a]	Lint Yield	N Fertilizer Rate	N Efficiency	Net Return
Intercept [b,c]	−0.9069	−1.1892	−2.5115	−1.3077
	(1.2204)	(1.4787)	(1.3020) *	(1.3024)
Clay [c]	−0.2694	1.9090	4.1468	0.1044
	(0.4686)	(1.1793)	(1.0628) ***	(0.4491)
Silt [c]	1.7455	−3.8551	−0.1331	0.9767
	(0.3584) ***	(0.6889) ***	(0.2960)	(0.3522) ***
Loam [c]	1.2943	−3.7156	−0.9842	0.8824
	(0.3934) ***	(0.6505) ***	(0.3852) **	(0.4067) **
Elevation	0.0044	−0.0177	−0.0025	0.0050
	(0.0032)	(0.0041) ***	(0.00342)	(0.0033)
WHC [d]	−6.9961	17.7126	3.2916	−3.2100
	(3.9285) *	(5.3030) ***	(4.4964)	(4.0088)
SOM [e]	−0.6101	0.4142	−0.3834	−0.5137
	(0.2880) **	(0.3775)	(0.3052)	(0.2940) *
Depth	−0.01872	0.0040	−0.0174	−0.0121
	(0.0075) **	(0.0090)	(0.0080) **	(0.0077)
SEI	−0.0178	0.1221	0.0304	. 0.0003
	(0.01217)	(0.0166) ***	(0.0129) **	(0.0125)
GDD	0.0012	0.0002	0.0018	0.0010
	(0.0003) ***	(0.0003)	(0.0003) ***	(0.0003) ***
ν	0.1126	0.4640	0.0321	0.1378
	(0.1238)	(0.1398) ***	(0.1286)	(0.1262)
Observations	1140	1140	1140	1140

Note: Standard errors are in parentheses. * Significant at the 0.10 probability level. ** Significant at the 0.05 probability level. *** Significant at the 0.01 probability level. [a] Variable names defined in Table 3. [b] Intercept contains soil texture sand. [c] Soil texture coefficients scaled by 10%. [d] WHC coefficients scaled by 100. [e] SOM coefficients scaled by 100%.

Table 6. Odds ratios and percent changes in log odds probabilities for landscape, soil, and weather effects on lint yield, fertilizer nitrogen (N) rate, N efficiency (lint yield/fertilizer N rate), and net return calculated from logit regression estimated coefficients [a].

Fixed Effect [b]	Statistic	Lint Yield	N Fertilizer Rate	N Efficiency	Net Return
Intercept [c,d]	Odds ratio	NS	NS	0.0811 *	NS
	Percent change	NS	NS	−9.1885 *	NS
Clay [c]	Odds ratio	NS	NS	63.2313 ***	NS
	Percent change	NS	NS	622.3134 ***	NS
Silt [d]	Odds ratio	5.7287 ***	0.0212 ***	NS	2.6557 ***
	Percent change	47.2877 ***	−9.7883 ***	NS	16.5568 ***
Loam [d]	Odds ratio	3.6484 ***	0.0243 ***	0.3737 **	2.4167 **
	Percent change	26.4844 ***	−9.7566 ***	−6.2626 **	14.1669 **
Elevation	Odds ratio	NS	0.9825 ***	NS	NS
	Percent change	NS	−1.75443 ***	NS	NS
WHC [e]	Odds ratio	0.0009 *	4.9259×10^7 ***	NS	NS
	Percent change	−0.999 1*	4.9259×10^8 ***	NS	NS
SOM [f]	Odds ratio	0.5433 **	NS	NS	NS
	Percent change	−0.4567 **	NS	NS	NS
Depth	Odds ratio	0.9815 **	NS	0.9828 **	NS
	Percent change	−1.8546 **	NS	−1.7200 **	NS
SEI	Odds ratio	NS	1.1299	1.0309 **	NS
	Percent change	NS	12.9867 ***	3.0898 **	NS
GDD	Odds ratio	1.0012	NS	1.0018 ***	1.0010 ***
	Percent change	0.1248 ***	NS	0.1845 ***	0.0965 ***
ν	Odds ratio	NS	1.5904***	NS	NS
	Percent change	NS	59.0423 ***	NS	NS

*,**,*** 10, 5, and 1 percent significance for the estimated coefficient in the logit model, respectively. NS, not significant for the estimated coefficient in the logit model. [a] Odds ratios and the changes in the log odds probabilities were calculated using the estimated coefficients β of the logistic regressions reported in Table 5. [b] Variable names are defined in Table 3. [c] Intercept contains soil texture category sand. [d] Texture scaled by 10%. [e] WHC scaled by 100. [f] SOM scaled by 100%.

For the silt soil texture, the lint yield odds ratio indicated that VRN treatment yields were 5.73 ($e^{1.7455}$) times as likely to be lower than FP yields under these conditions. The percent change in the log odds of VRN yields lower than FP yields was 47.29%. A field with a silt soil texture had a high probability of lower yields with VRN and could potentially benefit from a keeping the current FP N rate instead of going with VRN management. Estimating the odds ratio for the loam soil texture indicated that VRN treatments on loam textured soils were 3.65 ($e^{1.2943}$) times likely to have lower yields than the FP. There was a 26.49% change in the log odds that VRN yields were lower than FP yields on loam textured soils. Loamy fields with the same mean landscape, soil, and weather characteristics would also likely benefit from keeping the FP instead of adopting VRN in terms of yields.

3.2.2. N Fertilizer Rates

The landscape, 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 ($Pr \leq 0.01$), soil erosion index ($Pr \leq 0.01$), and VRN 2 treatment dummy variable ($Pr \leq 0.01$) (Table 5). Evaluating the percentage changes in the log odds probabilities of landscape, soil, and weather attributes indicated that silt- or loam-textured soils or soils at higher elevations are negatively associated with the probability that FP generates lower N rates than VRN (Table 6). Greater water-holding capacity, more erodible soils, or VRN 2 were positively associated with the probability that FP generates lower N rates than VRT.

The fertilizer N rate odds ratio for silt indicated that FP N rates were 0.0212 ($e^{-3.8551}$) times as likely to be lower than VRT N rates. There was a 9.79 percent change in the log odds that the FP N rates were lower than VRN N rates. Fields with silt textures with the mean soil conditions would likely benefit from VRN in terms of N cost savings and environmental benefits due to significant chances of VRN generating lower N rates than the FP. Evaluating the odds ratio at the loam soil texture indicated that the FP N rates were 0.0243 ($e^{-3.7156}$) times as likely to be lower than the VRT N rates. The percentage change in the log odds of FP N rates being lower than VRN N rates was 9.76 percent. Under these conditions, there was a relatively large chance that the VRN practice would be applied less N than the FP technology. A field with these conditions may benefit from VRN use for environmental benefits.

3.2.3. N Efficiency

Soil, landscape, and weather variables related with N efficiency 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 ($Pr \leq 0.01$) (Table 5). The percentage changes in the log odd probabilities of landscape, soil, and weather attributes in relation to NEFF indicated that finer soil textures or warmer temperatures were positively associated with the probability of a lower VRN N efficiency compared to FP (Table 6). Deeper soils or soil with coarser textures were negatively related to the probability of lower N efficiency of VRN compared to FP.

Fertilizer N efficiency on the clay soil texture indicated that VRN N efficiency was 63.2 ($e^{4.1468}$) times as likely to be lower than FP. There was a 622% change in the log odds of VRN N efficiency, lower than FP. Using VRN on clay fields, these may be inefficient in terms of N use relative to the FP. At the loam soil texture, the odds ratio indicated that VRN N efficiency was 0.3737 ($e^{-0.9842}$) times as likely to be lower than FP. Evaluating the odds ratio for the loam soil texture, there was a 6.26 percent change in the log odds of lower VRN N efficiency compared to the FP on loamy textured fields with these conditions. This finding indicates that there is a significant chance of obtaining higher N efficiency using VRN on loam soil textures.

3.2.4. Net Returns

The landscape, soil, and weather variables associated with NRs 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 ($Pr \leq 0.01$) (Table 5). Evaluating the aforementioned soil texture and weather attributes in relation to NRs indicated that coarser soil textures and warmer temperatures were positively associated with the probability of lower NRs using VRN compared to FP (Table 6). Evaluating the NR odds ratio for the silt soil texture indicated that VRN NRs were 2.66 ($e^{0.9767}$) times as likely to be lower than FP NRs. There was a 16.56% change in the log odds that had lower NRs than the FP. Fields with these conditions would likely not benefit from VRN adoption in terms of profits. The odds ratio evaluated at the loam soil texture indicated that VRN NRs were 2.42 ($e^{0.8824}$) times as likely to be lower than FP. The change in the log odds of lower NRs under these conditions was 14.17%. Fields with these soil conditions may be better suited, from a profitability standpoint, to continue using the current FP N management in place.

4. Conclusions

Many field landscape, soil, and weather factors impacted the performance of VRN in the farm MRB fields analyzed in this study. Soils with higher organic matter content, deeper profiles, and that are more erodible produced higher lint yields using VRN compared to the FP. In contrast, coarser soils, fields at higher elevations, or fields in locations with warmer temperatures were negatively associated with VRN yields compared to the FP. More N was applied using VRN compared to the FP on fields associated with greater water-holding capacity, more erodible soils, or warmer temperatures. In contrast, deeper profiled soils had a negative association to VRN N rate compared to FP. Soil, landscape, and weather had less of an impact on VRN NRs than on lint yields and fertilizer N rates. Most notable was the positive association with greater NRs with VRN relative to the FP for soils that were deeper and had higher organic matter. Soils with more organic matter had a positive relation to N efficiency of VRN compared to the FP. More erodible fields and warmer climates had negative associations to N efficiency, likely due to the need for higher N rates to account for lower available N in soils. Supplementing OS information with other map-based information resulted in higher VRN N rates but not yields and NRs. In addition, the additional expense of map-based information also impeded VRN profitability.

VRN may provide downside risk management benefits on fields with greater water-holding capacity, higher organic matter, or deeper profile soils by being associated with a smaller probability of low yields relative to the FP. Fields with silt and loam soils would likely benefit from VRN fertilizer N cost savings and environmental benefits because of a high probability of VRN resulting in lower N rates than the FP. In addition, the probability of enhanced N efficiency is more likely on a loam texture soil. However, the potential environmental benefits on these two soil textures may be obtained at the cost of a higher probability of lower NRs.

Key findings can be used by extension educators and cotton farmers to determine if adopting OS-based VRN on fields with certain characteristics would likely provide positive benefits. However, an important caveat of this study is that the profitability of OS and VRN were evaluated at the sub-field level to identify the conditions where the technology may provide an advantage over the FP. Notwithstanding the potential benefits of VRN, farmers are interested in the profitability of the technology at the field and farm levels. Future analyses should assess the profitability and risk management potential of the technology at the field level and farm levels as influenced by landscape, soil, and weather.

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