WHAT IS THE POTENTIAL FOR PRECISION AGRICULTURE BASED ON PLANT SENSING?

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Abstract

Plant-based precision nitrogen fertilizer application technologies have been developed as a way to predict nitrogen needs. This paper determines the expected profit from using plant sensing to determine nitrogen needs in winter wheat. The equipment necessary for precision application of nitrogen based on plant sensing is available commercially, but adoption has been slow. We find that plant sensing systems are roughly breakeven with current systems, which likely explains the slow rate of adoption.

Keywords: nitrogen, precision agriculture, stochastic plateau, wheat

What is the Potential for Precision Agriculture Based on Plant Sensing?

Past research suggests that most agricultural producers apply more nitrogen than is needed in most years. Precision application of nitrogen based on soil sampling and yield monitors has been developed to help producers decide how much nitrogen to apply. However, costs and measurement errors have limited usefulness of nitrogen recommendations based on yield monitors and soil sampling of small grids (Babcock, Carriquiry, and Stern, 1996; Arslan and Colvin, 2002). Soil sampling for nitrogen has always been marginal due to low levels of available nitrogen in the soil. Use of yield monitors has also been limited because while yields vary substantially across the field they do not vary in the same way every year. These limitations associated with use of soil sampling and yield monitors might explain why few producers use these technologies to determine how much nitrogen to apply (Daberkow and McBride, 2000).

More recently, plant sensing technologies have been introduced to agricultural crop producers. Plant sensing is promising since it is more precise than soil tests and yield monitors in predicting nitrogen response. However, adoption of such technologies has also been slow. Plant sensing is clearly an outstanding technical achievement, but it apparently faces some economic hurdles. One economic challenge to plant sensing is that it requires nitrogen be applied in liquid form whereas preplant nitrogen applications can use lower-priced anhydrous ammonia. Like soil tests and yield monitors, plant sensing technology is expensive. In addition, investment in plant sensing is irreversible in the sense that once the machines are bought the farmer cannot easily resell them to recoup the investment. When investment is irreversible there is an option value in postponing the decision to invest and search for new information. However, accurate information about producer benefits from using plant sensing is lacking. This lack of information may explain why adoption has been slow. Information about economic performance of plant sensing technologies is also valuable to agricultural manufacturers since it would provide them with a target cost needed to get producers to adopt these technologies.

The objective of this research is to determine the potential profitability of nitrogen recommendations based on whole field and variable rate wheat plant sensing relative to conventional practices. We develop a yield response to nitrogen function that is conditional on plant sensing. Using nine years of data containing wheat yield, optical reflectance, and levels of pre-plant nitrogen information, we find that plant sensing systems are roughly breakeven with current systems, which likely explains the slow rate of adoption.

Theory

Current plant sensing systems essentially require that a producer conduct a nitrogen response experiment in each field. The experiment consists of a single nitrogen-rich strip where enough nitrogen is applied so that nitrogen will not be the constraining input. Current plant sensing measures typically measure the normalized difference vegetative index, but the theory does not depend on what measure is used. With a nitrogen-rich strip, sensing is used to compare the fertilized and unfertilized plants and a formula is used to determine nitrogen needs. Nitrogen needs can vary across the field and systems have been developed to sense grids smaller than a square meter in an attempt to apply just the right amount of nitrogen to each grid.

We assume here that the nitrogen application system chosen does not affect the optimal quantity of other inputs. Nitrogen can either be applied preplant, in which case anhydrous ammonia can be used or nitrogen can be applied as a topdress application to growing plants. Assuming that price and yield are uncorrelated, the producer's optimization problem can be represented as

$$(2) \quad \max_{N^P, N^T, \boldsymbol{\lambda}} \mathrm{E}(R) = p\mathrm{E}(y) - r^P N^P - r^T N^T - \lambda_1 b^P - \lambda_2 b^{NRS} - \lambda_3((1-\lambda_2)b^T + \lambda_2 b^{N(ORI)}),$$

s.t.

$$y = y(N),$$
$$N = N^P + \gamma N^T,$$
$$\text{If } N^P > 0 \text{ then } \lambda_1 > 0$$
$$\text{If } N^T > 0 \text{ then } \lambda_3 > 0$$
$$\text{If } \lambda_2 > 0 \text{ then } N^T = N(ORI)$$
$$\lambda_i \in \{0,1\} \forall i, \text{ and}$$
$$N^P, N^T \geq 0.$$

where R is net return above nitrogen fertilizer application costs; y is yield; N is the sum of preplant nitrogen (N^P) and topdress nitrogen (N^T); $\gamma > 1$ is the relative efficiency of topdress nitrogen relative to anhydrous; p represents the expected price of wheat; $\lambda = (\lambda_1, \lambda_2, \lambda_3)$ is a vector of binary choice variables; r^P and r^T represent the prices of preplant nitrogen and topdress nitrogen, respectively; b^P, b^{NRS}, $b^{N(ORI)}$, and b^T represent preplant nitrogen application costs, cost of the nitrogen-rich strip, cost of topdressing with optical sensing, and conventional topdress nitrogen application costs, respectively; and the function *N(ORI)* is the application rate algorithm based on precision sensing information (NRS). Note that λ_3 is selected conditional on NRS being known.

Increased yields with precision plant sensing could come about from conventional systems applying either too much or too little nitrogen. The evidence regarding whether excess nitrogen causes yields to decline is mixed (Biermacher et al.) but tends to suggest little or no yield decrease from applying excess nitrogen. A conventional system that applied too little nitrogen would clearly lead to lower yields than a precision sensing system that applied exactly the amount of nitrogen needed. In practice however, producers apply more nitrogen than is needed in most years. As a result, most of the advantage of precision sensing is expected to be due to reduced cost of nitrogen fertilizer rather than increased yield. While the optical sensing system clearly uses less total nitrogen, it faces a major economic challenge because plant sensing uses nitrogen in liquid form, which is more expensive than anhydrous ammonia used with conventional technologies (i.e. $r^P < r^T$).

Procedures

Past research and characteristics underlying plant sensing technology suggest that stochastic plateau functions are more appropriate to represent yield response to nitrogen than polynomial and switching regressions (Tembo, Brorsen, and Epplin, 2003; Katibie et al., 2003; Katibie et al., 2007). Thus, we use a linear response stochastic plateau function to represent wheat response to nitrogen. The linear response function with a stochastic plateau can be written as

(3) $$y_{it} = \min[\beta_0 + \beta_1 ORI_{it}^S(N_{it}^P) + \beta_2 N_{it}^T, \mu_M + v_t] + u_t + \varepsilon_{it},$$

where y_{it} is wheat yield in bushels per acre on grid i in year t; N^P is the level of preplant nitrogen; N^T is the level topdress nitrogen; $ORI_{it}^S(N_{it}^P)$ represents optical reflectance information taken in the spring on grid i in year t; μ_m is the average plateau yield, $\beta_0, \beta_1,$ and β_2, are parameters to be estimated; v_t represents the plateau year random effect; u_t is a year random effect that shifts the intercept, and ε_{it} is an i.i.d. normal error term.

Our data include preplant nitrogen and ORI readings for preplant nitrogen, but no topdress nitrogen. Therefore, equation (3) cannot be estimated. To circumvent this limitation, we assume that the marginal productivity of topdress nitrogen is the same (or at least proportional to) the marginal productivity of preplant nitrogen. Next, we estimate two separate regressions: wheat yield is regressed on optical reflectance information, and optical reflectance information is regressed on preplant nitrogen. The estimates from these regressions are then used to construct equation (3).

Let the relationship between wheat yield and optical reflectance information be written as

(4) $$y_{it} = a + bORI_{it}^S(N_{it}^P) + \theta_{it},$$

where y_{it} is wheat yield in bushels per acre on grid i in year t, a and b are the intercept and slope coefficients to be estimated, and the error term θ_{it} is partitioned into an independently and identically distributed random error term θ_{it}^* that has mean zero and variance $\sigma_{\theta^*}^2$, and year random effect ω_t that has mean zero and variance σ_ω^2.

Independence is assumed between the two variance components, and therefore the variance of the overall error term is $\sigma_\theta^2 = \sigma_\omega^2 + \sigma_{\theta^*}^2$. The symbol $ORI_{it}^S(N_{it}^P)$ is defined as the normalized difference vegetation index (NDVI) sensor reading taken in the spring on grid i in year t and is adjusted by the number of growing degree days. The optical reflectance index (ORI) measures the amount of nitrogen available to the plants at the time of sensing, which in turn helps in quantifying the amount of additional nitrogen needed to reach plateau yields.

The second regression used to construct equation (3) is the regression of optical reflectance information on preplant nitrogen. This relationship is defined as

(5) $$ORI_{it}^S(N_{it}^P) = \min(\alpha + \beta N_{it}^P, ORI^M + v_t) + u_t + \varepsilon_{it}$$

where $ORI_{it}^{S}(N_{it}^{P})$ is an optical reflectance index reading taken in the spring on grid *i* in year *t*; α and β are intercept and slope parameters to be estimated; N_{it}^{P} is any nitrogen in grid *i* at the time of planting in year *t*; ORI^{M} is the average sensor reading taken from the nitrogen rich strip; $v_t \sim N(0,\sigma_v^2)$ represents year random effects on the plateau ; $u_t \sim N(0,\sigma_u^2)$ represents year random effects; and $\varepsilon_{it} \sim N(0,\sigma_\eta^2)$ is the traditional random error term.

The estimates from equations (4) and (5) are used to construct equation (3). Again, the key assumption is that the marginal productivity of topdress nitrogen is the same as (or at least proportional to) the marginal productivity of preplant nitrogen; that is, $\beta_1 = b,$ and $\beta_2 = b\beta.$ So, with this assumption we set $\beta_0 = a$ from equation (4), equation (3) can be re-written as

(6) $$y_{it} = \min[a + b(\alpha + \beta N_{it}^{P}) + b\beta N_{it}^{T}, a + bORI^{M} + bv_t] + bu_t + b\varepsilon_{it} + \theta_{it},$$

which imposes $\partial y_{it} / \partial N_{it}^{T} = \partial y_{it} / \partial N_{it}^{P} = b\beta.$

Determining the optimum preplant level of nitrogen analytically using the stochastic plateau model (6) is not straightforward because year and spatial random effects enter equation (6) nonlinearly. The optimal level of nitrogen to apply with this functional form has been developed by Tembo et al. (2007). The optimum input level (N_{it}^{P*}) can be determined as

(7) $$N_{it}^{P*} = \min(0, \frac{1}{\beta}\left(ORI^{M} + Z_\delta \sigma_v - \alpha\right)),$$

where Z_δ is the critical Z-value where $\delta = 1 - \Phi = r/(pb\beta)$ is the observed probability in the right-hand tail of the *N*(0, 1) distribution, *r* is the price of nitrogen, and *p* is the price of wheat.

Parenthetically, if the variable rate plant sensing technology is applied, and we assume information from the NRS and each grid is sensed perfectly, then we can re-write equation (3) as

(8) $$y_{it} = \min[a + bORI_{it}^{S}(N_{it}^{P}) + b\beta N_{it}^{T}, a + bORI_{t}^{NRS}] + \theta_{it},$$

where ORI_{t}^{NRS} is the in-field experimental measure from a nitrogen-rich strip or some other measure. The model in (8) is a linear plateau model and the optimum is the level of nitrogen needed to reach the plateau on each grid, which is

(9) $$N_{it}^{T*} = \frac{ORI_{t}^{NRS} - ORI_{it}^{S}}{\beta}.$$

Note that we are implicitly assuming that none of the error in equation (5) represents measurement error. If we were to add measurement error, we would end up with the model developed by Berck and Helfand (1990) and Paris (1992). Adding measurement error would further reduce the value of sensing.

In the case of a whole field application, the ORI on each grid is no longer known. In the case of uniform application using sensing, only an average measure of ORI is obtained from the response, which implies that spatial variation on each grid is expected to be present. However, since sensor measurements are taken from the NRS, which covers such a large area in the field, no error in the plateau is assumed. This implicitly assumes that all variation across grids is due to differences in available nitrogen and thus the variation across grids in the nitrogen-rich strip should be zero (which is not entirely true and is yet another assumption that causes our results to favor sensing). The response portion of the plateau thus has an additional error and the production function becomes:

(10) $$y_{it} = \min[a + b\overline{ORI}_{it}^{S} + b\beta N_{it}^{T} + b\varepsilon_{it}, a + bORI_{t}^{NRS}] + \theta_{it}.$$

where $\overline{ORI}_{it}^{S}$ is an average ORI reading across an unfertilized portion of the field near the nitrogen-rich strip. The solution to the optimal level of nitrogen in (10) is analogous to (6) except that the upper rather than the lower tail of the distribution is needed. The optimal whole field (N_{it}^{W*}) can be determined as

$$(11) \qquad N_{it}^{W*} = \min(0, \frac{1}{\beta}\left(ORI_{t}^{NRS} + Z_{\delta_W}\sigma_{\varepsilon} - \overline{ORI}_{it}^{S}\right)).$$

where Z_{δ_W} is the critical Z-value, $\delta_W = \Phi = r/(pb\beta)$ is the observed probability in the right-hand tail of the $N(0, 1)$ distribution, r is the price of nitrogen, and p is the price of wheat. Note that in an actual field the plateau might also vary across grids and so again this is a simplification that could cause the value of sensing to be overstated, unless the sensing could also identify the grids with less yield potential.

Data and Empirical Procedures

Parameters of equations (4) and (5) are estimated using data from nine years of on-farm winter wheat experiments conducted at seven locations located on or near agronomic research stations throughout the state of Oklahoma from 1998-2006. The data include observations for wheat yield, optical reflectance information, and level of preplant nitrogen. Data were collected at locations near Stillwater every year. Data were collected at Haskell from 1999-2002. At Hennessey, data were collected for 2000 and 2002. At Lahoma data were collected in all years except 1998 and 2001. At Perkins, data from two experiments were used; one included data collected in 1998 only, and the other utilized data from 1998-2006. At the Tipton site, data were only collected in 1998. Winter wheat was planted for grain only at a 78 kg ha^{-1} seeding rate using a 0.19 meter row spacing at all locations, excluding one of the two experiments at Perkins where spacing ranged from 0.15 to 0.30 meters.

Nitrogen rich strips were placed in each experimental plot prior to planting wheat in late September or early October. All optical reflectance readings were taken during Feekes growth stages 4 (leaf sheaths beginning to lengthen) and 5 (pseudo-stem, formed by sheaths of leaves strongly erect) (Large, 1954). All reflectance readings from wheat collected from a 4.0 square-meter area between 10 a.m. and 4 p.m. were taken under natural lighting between January and March. Grain yield was measured from the same area where spectral reflectance data were collected. Additional information regarding the experiments can be found in Mullen, 2003.

Parameters in equation (4) are estimated using a linear mixed effects model (PROC MIXED in SAS). Year random effects are tested using a likelihood ratio test. The parameters of the stochastic plateau model represented by equation (5) are estimated using SAS NLMIXED (2002-2003). Then, the estimates from equation (4) and (5) are used to construct equation (6), which is then used to simulate expected net returns from each of the seven nitrogen application systems considered.

Nitrogen Levels

Equation (6) is used to compute the application levels of nitrogen fertilizer for each of several systems, including (1) an all-before-planting; (2) a whole field precision system; (3) a variable rate precision system; (4) the NFOA system developed by Raun et al., 2002; (5) the extension recommendation of 80 pounds per acre preplant system; and (6) an all-before-planting system that represents the average of what producers were actually found to be applying in the southern Plains (i.e., 63 pounds per acre) in a survey conducted in 2004 (Hossain et al., 2004). In addition, a check (system (7)) that has no nitrogen applied is included. Optimal application levels of nitrogen for systems 1, 2, and 3 are derived using the response function outlined in equation (3), and the optimal application level of nitrogen for system 4 is derived using the algorithm provided in Raun et al., 2002. Derivations of optimal levels of nitrogen for systems 1-4 are explained in detail in Biermacher, 2006.

Simulation of Expected Net Returns

Equation (6) is simulated to determine the expected net return from each of the alternative systems. Net returns on 250 sample grids within each of 250 sample years were simulated using the following steps. First, sample values for the error components in equation (6) are simulated using a random number generator. Errors are assumed normally distributed with mean zero and estimated variances provided from the regression procedures used to estimate equations (4) and (5). Intercepts, slopes, and expected value of optical reflectance information at the plateau are also provided from these regression procedures. In addition to the error components, values of ORI_{it}^{S} and ORI_{t}^{NRS} are simulated for each grid and year of the sample. Moreover, application costs, and prices for NH3 and 28% UAN are included. A zero level of N is assumed when expected net returns from application are negative.

The process for calculating sample values of optical reflectance information taken from the nitrogen rich strip is

(12) $$ORI_{t}^{NRS} = ORI^{M} + v_{t} + u_{t},$$

and the process for calculating sample values for the optical reflectance information on an individual grid and year is described by equation (5). Again, we note that since the NRS covers such a large area of the field, the plateau spatial variability is assumed to average to zero given that a substantial number of readings are taken from it.

Once sample values for the errors and the optical reflectance information are simulated for each grid and year, then formulas for equations (7), (9), (11), and equation (17) in Biermacher, 2006 are used to generate samples of optimal nitrogen rates for each grid in each year for each system. The yield response function defined in equation (6) is then used to calculate sample values for wheat yield for each system, grid, and year in the sample. Net returns are then calculated as the difference between wheat revenue and cost of nitrogen and nitrogen application expenses for each grid in the year. The Monte Carlo integration is then completed by averaging net returns across the sample of years for each system.
For each system, a long run average price of $3 per bushel was used for the expected price of wheat grain and market prices of $0.15 and $0.25 per pound are used for anhydrous ammonia and 28% UAN, respectively (Oklahoma Department of Agriculture).

Gains in Efficiency

It is believed that some gain in efficiency will be obtained when the plant-based sensing technology is used instead of the traditional preplant systems. However, it is not assumed as in Raun et al., 2002 that a seventy percent gain (i.e., $\gamma = 0.70$) is achievable. For this study, we are assigning a twenty percent gain in efficiency to the marginal product of nitrogen, such that the slope parameter β is effectively multiplied by an efficiency parameter γ that is set equal to 1.2.

Results and Discussion

Regression estimates of equation (4) are presented in table 1. Rejection of the null hypothesis that no random effects exist were based on the likelihood ratio test. The slope parameter (*b*) is significant at the .05 level.

Table 1. Regression of Wheat Yield Response on Optical Reflectance Information

Statistic	Symbol	Estimates[a]
Intercept	a	-5.2268 (3.52)
Optical reflectance	b	6.7291 (.42)
Year random effect	σ^2_ω	103.81 (25.83)
Error variance	$\sigma^2_{\vartheta^*}$	105.31 (5.33)

[a] Asymptotic standard errors are in parentheses.
Note, that the parameter estimates for equation (2) were estimated using PROC MIXED in SAS.

The intercept parameter (*a*) was not significant at the .05 level; however, it was significant at the .10 level. Estimates of equation (5) are presented in table 2. The marginal product of nitrogen $(b\beta = (6.7291 \times 0.0297) = 0.20)$ suggests that approximately 2.27 kg of nitrogen should be applied to gain an additional bushel of wheat rather than the 0.65 kg suggested by the NFOA model.

Table 2. Stochastic Linear Plateau Model of Optical Reflectance Information as a Function of Nitrogen

Statistic	Symbol	Estimates[a]
Intercept	α	5.6882 (.0640)
Level of nitrogen	β	.0297 (.2022)
Average plateau ORI	ORI^{NRS}	6.8879 (.0599)
Nitrogen at expected plateau	N_t^{NRS}	57.8045 (.1958)
Variance of plateau yield	σ_v^2	0.5861 (.0936)
Variance of year random effect	σ_u^2	0.7563 (.0737)
Variance of error term	σ_η^2	0.5097 (.0263)

[a] Asymptotic standard errors are in parentheses.
Note, the parameter estimates for equation (3) were estimated using NLMIXED procedure in SAS.

Expected yield, optimal levels of nitrogen, and expected profits for each system are reported in table 3. The perfect (unachievable) information system had the largest expected profit of approximately \$271 ha^{-1}. Net return to nitrogen application for this system was approximately five percent greater than the average net return for the optimal preplant system determined using the TBE model, and was only approximately seven percent greater than the net return from the state recommendation of applying 90 kg ha^{-1} prior to planting in the fall, a value of \$15 ha^{-1} over the state recommended system.

Table 3. Average Yield, Nitrogen, and Expected Profits from Alternative Nitrogen Management Systems without Plateau Spatial Variability

	System						
Estimate	0/0[a]	80/0[b]	63/0[c]	0/HH[d]	TBE/0[e]	0/GS[f]	0/NFOA[g]
Average Yield (kg ha^{-1})	2196	2723	2696	2687	2693	2740	2476
Average Nitrogen (kg ha^{-1})	0.00	90	71	52	65	37	18
Average profit ($ ha^{-1})	242	256	259	265	260	271	255

[a] the check system with no nitrogen added.
[b] the system that represents the state extension recommendation of 90 kg ha^{-1}.
[c] the system that represents the average level of nitrogen applied in the state of Oklahoma that was reported by producers via a survey conducted in 2004.
[d] the system that represents the portable, handheld precision system where no nitrogen was applied prior to planting.
[e] the system that represents the analytical approach developed by Tembo, Brorsen, and Epplin (2007) to determine the optimal level of nitrogen to apply in the fall prior to planting.
[f] the system that represent the plant-based variable rate precision system that assumes perfect knowledge about the random processes.
[g] the system that represents the NFOA developed by Raun et al. (2002).

The portable handheld system had an average net return that was only $9 ha^{-1} greater than that obtained from the state extension system. Although, the TBE system realized a slightly higher yield, the gain from the reduction in fertilizer cost was the primary factor accounting for the difference. Note that using portable sensing provides the chance that some areas of the field could receive less nitrogen than actually needed, which will likely keep some yield in the field from reaching its potential plateau.

A noteworthy comparison is the $16 ha^{-1} difference in net return between the perfect information system and the system that utilized the NFOA. This could be viewed as an indication that further improvements could be made to the NFOA. However, it is unlikely that the NFOA could ever perform as well as the perfect information system described in this paper. Note that the marginal product of nitrogen for the NFOA is too high and, adjusting it down to the size of that found using the data, the NFOA outcome would be similar to that given by the profits for the 90 kg ha^{-1} system.

Sensitivity values for independent relative changes in the price of wheat, price of anhydrous ammonia, and the price of 28% Urea-ammonium nitrate are reported in table 4. The expected value of the perfect information system is not very sensitive to either below average or above average prices of wheat. In the extreme case where wheat price increases to $0.074 kg^{-1}, the additional value of the perfect information system above that of the state recommendation is only about $3.75 ha^{-1}.

Table 4. Sensitivity Values for Independent Relative Changes in Price of Wheat, Price of Anhydrous Ammonia, and Price of 28% Urea-Ammonium Nitrate

		System						
Parameter	Price	0/0[a]	80/0[b]	63/0[c]	0/HH[d]	TBE/0[e]	0/GS[f]	0/NFOA[g]
Price of Wheat ($/kg)	.030	161	155	160	168	162	171	165
	.045	242	256	259	265	260	271	255
	.060	323	356	358	363	360	372	346
	.074	404	456	457	461	459	473	437
Price of NH3 ($/kg)	0.07	242	256	259	265	260	271	255
	0.11	--------	236	243	--------	248	--------	--------
	0.18	--------	206	220	--------	234	--------	--------
	0.23	--------	186	204	--------	229	--------	--------
Price of UAN ($/kg)	0.11	242	256	259	265	260	271	255
	0.16	--------	--------	--------	257	--------	263	251
	0.20	--------	--------	--------	248	--------	255	248
	0.23	--------	--------	--------	244	--------	251	247

[a] the check system with no nitrogen added.
[b] the system that represents the state extension recommendation of 80 pounds per acre. .
[c] the system that represents the average level of nitrogen applied in the state of Oklahoma that was reported by producers via a survey conducted in 2004.
[d] the system that represents the portable, handheld precision system where no nitrogen was applied prior to planting.
[e] the system that represents the analytical approach developed by Tembo, Brorsen, and Epplin to determine the optimal level of nitrogen to apply in the fall prior to planting.
[f] the system that represent the plant-based variable rate precision system that assumes perfect knowledge about the random processes.
[g] the system that represents the NFOA developed by Raun et al. (2002).

As expected, the value of perfect sensing technology increases relative to the state system as the price of NH3 increases relative to the price of UAN. When the price of NH3 is increased to the point where it is equal to the price of UAN, the value of the variable rate system increased to approximately \$40 ha^{-1} over that of the state-recommended system. The opposite relationship exists when the price of UAN increases relative to the price of NH3. If the price of UAN increases to \$0.27 kg^{-1} , holding the price of NH3 constant at \$0.07 kg^{-1}, then the value of the state recommended system is approximately \$10 ha^{-1} more profitable than the perfect variable rate system. In this situation, a typical producer would not be interested in adopting the plant-based precision system.

Currently, this plant-based precision sensing technology is available on a commercial basis, and is being promoted to increase net returns to nitrogen fertilization by \$25-\$75 ha^{-1}. However, the findings of this study do appear to explain why adoption has been slow. These findings also indicate that the optical sensing technology, including the nitrogen fertilizer optimization algorithm (NFOA), in many cases, does not apply enough nitrogen fertilizer, and therefore could be improved upon.

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