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Economic feasibility of site-specific optical sensing for managing nitrogen fertilizer for growing wheat

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Abstract A site-specific nitrogen fertilizer application system that uses optical reflectance measurements of growing wheat plants to estimate N requirements has been developed. The machine enables unique applications of liquid N fertilizer at a grid level of 0.37 m^2. To achieve widespread adoption, the precision application system must be efficient enough to overcome the cost advantage of pre-plant applications of anhydrous ammonia (NH_3) relative to top-dress applications of either dry or liquid N sources on growing wheat. The objective of this research is to determine if the system is more profitable than conventional methods. Data from on-farm N fertilizer experiments were collected across three years and nine locations in the Southern Plains of the U.S.A. Net returns were calculated for each of eight treatments. The site-specific precision system was competitive economically, but it was not unambiguously superior to the conventional alternatives because it could not overcome the cost advantage of NH_3 pre-plant N sources relative to the cost of applying urea-ammonium nitrate (UAN) during the growing season. The value of the precision system is sensitive to the price of UAN relative to the price of NH_3.

Keywords Economic feasibility · Optical sensing · Nitrogen fertilizer · Site specific · Wheat

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Introduction

Nitrogen fertilizer is a primary nutrient that is typically applied each year in the fall prior to planting wheat in the southern Great Plains of the United States. Nitrogen accounts for 20 to 30% of the per hectare cash expenses, depending on the size of farm and location. A number of precision and site-specific technologies have been developed and introduced to the wheat farming community. These technologies are promoted as a means to improve farm profits. Such technologies include global positioning systems, geographic information systems, yield monitoring sensors and computer controlled within-field variable rate application equipment. Even though many of these precision technologies are commercially available (Whipker and Akridge 2007), widespread adoption has been slow with the exception of light bar guidance.

Several studies have focused on estimating the economic feasibility of soil-based precision fertilizer application technologies for wheat (Carr et al. 1991; Lambert et al. 2006; Swinton and Lowenberg-DeBoer 1998). The majority of this research, however, has concluded that precision fertilizer application technologies such as grid mapping and intensive soil testing are not economical for wheat. As an alternative to soil-based precision technologies, several research initiatives have focused on developing sensor-based systems to determine crop nutrient needs (Alchanatis et al. 2005; Ehlert et al. 2004; Phillips et al. 2004; Raun et al. 2002; Schachtl et al. 2005).

Haneklaus et al. (1999) evaluated different decision-making processes governing variable rate fertilizer application. They concluded that to accurately describe the variability of N, phosphorus and other plant nutrients in the soil, small grids are preferred to large grids. They found that 10 m^2 grids are more appropriate than the 1.2 ha average grid size often used as sample sites. Others report similar findings. For example, extensive soil testing as well as optical reflectance measurements of plants and yields collected on very small plots, have shown that the spatial scale of N availability to winter wheat can be as small as a 0.37 m^2 grid, and that economically optimal levels of N fertilizer may differ on adjacent 0.37 m^2 grids (Raun et al. 1998; Solie et al. 1999). A technology to sense growing wheat and apply N at a grid level of 0.37 m^2 (27,027 square grids ha^{-1}) has been developed. The system does not require mapping of soils, soil testing or yield monitors. However, it does require several steps.

First, in late summer, or early fall, N is applied to a narrow strip of the field prior to planting. The level of N applied to the strip must be sufficient so as not to limit plant growth. In other words, a non-limiting amount of N is applied to a strip across the field such that, in the N rich strip (NRS), yield will reach its plateau level (Frank et al. 1990; Grimm et al. 1987; Waugh et al. 1973). Wheat is planted in the fall after the strip has been fertilized. Second, in late winter after the crop is well established, optical reflectance readings are taken from the NRS area of the field. These measurements provide information that enable comparing N uptake from plants growing in the area of the field where N is not yield-limiting to plants growing elsewhere in the field. Third, the system uses a self-propelled UAN applicator equipped with optical reflectance sensors, on-board computers and a global positioning device that is used to assist with steering to prevent repeated applications on individual grids.

An N fertilizer optimization algorithm (NFOA) programmed into the system's computers uses the optical reflectance information taken from the NRS and optical reflectance information taken from each 0.37 m^2 grid to determine N treatment levels. The intent of the algorithm is to determine the quantity of N to apply to each individual 0.37 m^2 grid that is needed to achieve the plateau yield (Solie et al. 1996, 2002). As the applicator moves across the field, the machine optically senses, computes the level of N and treats individual 0.37 m^2 grids with UAN (28% liquid N solution). Rates of UAN vary. The NFOA does not consider the prices of N and wheat, and consequently may not estimate the economically optimal level of N, especially in circumstances when the yield plateau is estimated with error (Tembo et al. 2008).

The objective of the research reported here is to determine if the system is more profitable than conventional N fertilization strategies. Given the substantial investment needed to further develop the system, and the potential environmental benefits from lower N applications, estimates of its relative economic value are considered necessary to understand what is needed for the system to be adopted. Economic information would also provide engineers and manufacturers with a target cost to deliver the technology, would be of value to fertilizer distributors who must decide whether or not to purchase the system and would be useful to agricultural extension specialists who may be confronted with questions regarding the system. Although the system was designed specifically for managing N needs on winter wheat crops grown in the Southern Plains of the U.S.A., the algorithm and application system could be modified for use on other crops and in other regions.

Theory

Farmers must decide prior to planting their wheat in the fall whether or not they want to use the site-specific plant sensing technology. We use an expected profit maximizing framework so the analysis is done assuming either the producer is risk neutral or that any changes in the variability of farm profitability resulting from this decision would not substantively alter the optimal nitrogen rates for a risk averse producer. The decision rule for an expected profit maximizing producer can be written as:

$$\text{Producer decision} = \begin{cases} \text{adopt}, & \text{if } E(\max E(\pi^{\text{new}})) - E(\max E(\pi^{\text{old}})) > \tau, \\ \text{not adopt}, & \text{otherwise}, \end{cases} \tag{1}$$

where $\tau \geq 0$ represents the cost of change and $E(\pi^k)$ is the expected profit from using the kth technology ($k = \{\text{new, old}\}$). Adoption of precision technologies is driven by three key elements: (1) increased cost of sampling information and variable rate application; (2) change in cost of fertilizer applied; and (3) change in revenue from crop yield. The cost of information that is provided by precision technologies is central to analyzing profitability (Bullock et al. 2002). Plant sensing technology is no exception to this rule and as a result, it may provide value from increased yields, reduced costs or both.

The system requires that a producer conduct an N response experiment in each field. The experiment can consist of a single NRS. But it can also consist of a series of ramped strips where increasingly higher amounts of N are applied. The sensors measure the normalized difference vegetative index. With an NRS, sensing is used to compare the fertilized and unfertilized plants and the NFOA is used to determine N needs. With ramped N strips, a linear plateau model is estimated and the N level required to reach the plateau is determined.

It is assumed that the N application system does not affect the optimal quantity of other inputs. N can either be applied pre-plant via NH_3 or during the growing season as a top dress via UAN. Assuming that price and yield are uncorrelated, a producer's optimization problem can be represented as

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

s.t.

$$y = y(N),$$
$$N = N^P + \psi N^T,$$
$$\text{If } N^P > 0 \text{ then } \lambda_1 > 0$$
$$\text{If } N^T > 0 \text{ then } \lambda_3 > 0$$
$$\text{If } \lambda_2 > 0 \text{ then } N^T = N(ORI)$$
$$\lambda_i \in \{0,1\}\forall i, \text{ and}$$
$$N^{\mathrm{P}}, N^T \geq 0. \tag{2}$$

where R is net return above N fertilizer application costs; y is yield; N is the sum of pre-plant N (N^P) and top dress N (N^T); $\psi > 1$is the efficiency of top dress N relative to pre-plant NH_3; 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 NH_3 and UAN, respectively; b^P, b^{NRS}, $b^{N(ORI)}$, and b^T represent pre-plant N application costs, cost of the NRS, cost of top dressing with the precision system, and the cost of conventional top dressing, respectively; and the function *N(ORI)* is the NFOA based on NRS information. Note that λ_3 is selected conditionally on NRS being known.

A reduction in yield could result from the conventional systems applying either too much or too little N. The evidence regarding whether excess N causes yields to decline is mixed (Biermacher et al. 2006). The data suggest that, over a reasonable range, any yield decrease from applying excess N would be small. A system that applied too little N would result in lower yields than a system that applied exactly the amount of N needed. In practice, producers typically apply more N 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 N fertilizer rather than increased wheat yield. While the sensing system uses less total N, it faces a major economic hurdle because the cost per unit of N from NH_3 is less than the cost per unit of N from UAN ($r^P < r^T$).

For this study, experimental data were obtained from farm fields. This provides an opportunity to evaluate the system under environmental conditions and constraints encountered on farm fields. The expected profit is determined for each of the discrete choices considered in the field experiment. This restricts the choices in Eq. 2 such that $x^P \in \{0, 45, 90\}$ and $x^T \in \{0, 45, 90\}$ when sensing is not used.

Materials and methods

Procedures published by American Society of Agricultural Biological Engineers (2006) were used to estimate the annual ownership and operating costs for the sensor and computer equipped UAN applicator. The cost of implementing a NRS was also computed. Net returns are calculated for eight N management systems, including two precision systems.

Yield data were obtained from a series of randomized and replicated on-farm experiments conducted during the 2002, 2003 and 2004 growing seasons across nine locations in Oklahoma, U.S.A. Care was exercised in selecting co-operating farmers who would retain the integrity of the trials by not applying additional N (other than that administered via the treatment structure) and who would enable and facilitate harvest of individual plots. The trials were conducted on farms located close to the communities of Altus, Blackwell, Chickasha, Covington, Haskell, Hennessey, Lahoma, Perry, and Tipton, Oklahoma, U.S.A. Data describing differences in rainfall and soil characteristics across locations are reported in Tables 1 and 2. The N fertilizer application systems included in the on farm trials are described in Table 3.

Treatment yield means for each location were averaged across all replications for each year. Pre-plant N was applied as 33% ammonium nitrate (AN) and top dress N was applied

Table 1 Soil characteristics by location (250 mm depth)

Location	Texture	% Gravel	% Sand	% Silt	% Clay
L1: Lahoma	Clay loam	0	21	50	29
L2: Chickasha	Silt loam	0	19	42	40
L3: Blackwell	Clay loam	0	25	48	27
L4: Haskell	Silt loam	0	21	68	11
L5: Altus	Clay loam	1	24	40	36
L6: Covington	Silty clay loam	0	19	41	40
L7: Hennessey	Clay loam	0	21	50	29
L8: Tipton	Sandy loam	0	52	30	18
L9: Perry	Loam	0	36	42	22

Data provided by Oklahoma Mesonet (2007)

Table 2 Total rainfall (mm^{-1} water year) for each year and location classified by climate zone in Oklahoma

Climate zone	Locations	Oct 1 through Sep 30			Average
		2001–2002	2002–2003	2003–2004	
North central	L1, L3, L6, L7, and L9	650	740	740	710
Central	L2	800	780	800	800
East central	L4	1010	910	990	970
Southwest	L5 and L8	560	680	660	630

Data provided by the Oklahoma Climatology Survey (2007). L1 is Lahoma, L2 is Chickasha, L3 is Blackwell, L4 is Haskell, L5 is Altus, L6 is Covington, L7 is Hennessey, L8 is Tipton, and L9 is Perry

Table 3 Description of nitrogen fertilizer application systems used in the on-farm trials

N fertilizer application system	Pre-plant N application level (kg ha)	Top dress N application (kg ha)
0/0	0	0
0/45	0	45
0/90	0	90
45/45	45	45
45/0	45	0
90/0	90	0
0/NFOA	0	N^{NFOA}
45/NFOA	45	N^{NFOA}

Note that N level for the 0/NFOA and the 45/NFOA optical sensing systems is determined with the nitrogen fertilizer optimization algorithm (NFOA) and applied using the self propelled variable rate precision applicator as 28% UAN during Feekes Physiological Growth Stages 4–6 in early spring (Large 1954; Stone et al. 1996; Solie et al. 1996). Potential external environmental benefits of using the system were not measured.

Optimizing N using the NFOA

The NFOA developed by Raun et al. (2002) was used to determine the top dress N levels for the 0/NFOA and 45/NFOA treatments. The NFOA is designed to compare optical reflectance information obtained from the NRS with information obtained from each 0.37 m^2 grid of the field representing the farmer practice. Following Raun et al. (2002), the optimal level of N on grid i is defined as

$$N_i^{NFOA} = \frac{(YPN_i - YP0_i)}{\gamma}, \tag{3}$$

where γ is a constant that represents the level of N use efficiency (NUE) that is expected to be gained from applying only the level of N that is needed by the plants with none of it going unused (an NUE of 0.60 was used in the NFOA for the on-farm experiments), $YP0_i$ is yield response to ORI information taken on grid i and gives an estimate at the time of sensing for wheat yield potential when no additional N is applied. $YP0_i$ is defined as

$$YP0_i = c_0 \exp(ORI_i c_1), \tag{4}$$

where c_0 and c_1 are the intercept and slope parameters.[1] ORI_i denotes the optical reflectance information taken from the growing crop by the machine in late winter (March) on grid i, and YPN_i in Eq. 3 is defined as the yield potential when additional N is applied in late winter at a level necessary to bring plant growth to the maximum potential,

$$YPN = \begin{cases} \max((RI \times YP0), YP0), & \text{if } \max((RI \times YP0, YP0) < y^{\max}), \\ y^{\max}, & \text{otherwise}, \end{cases} \tag{5}$$

where RI is a response index that is calculated as

$$RI = \frac{\text{Average ORI from NRS}}{ORI \text{ from farmer practice}} = \frac{\overline{ORI}^{NRS}}{ORI_i} \tag{6}$$

$y^{\max}$ is the biological maximum yield for a specific crop, grown within a specific region, under defined management practices (e.g., $y^{\max} = 7$ Mg ha^{-1} for dryland winter wheat produced in central Oklahoma (Raun et al. 2002)). Substituting Eq. 6 into Eq. 5 gives

$$YPN_i = \begin{cases} \max\left(\left(\frac{\overline{ORI}^{NRS}}{ORI_i} \times 0.359 \exp(ORI_i \times 324.4)\right), 0.359 \exp(ORI_i \times 324.4)\right), \\ \qquad \text{if } \max((RI \times YP0, YP0) < y^{\max}), \\ y^{\max}, \qquad \text{otherwise.} \end{cases} \tag{7}$$

Sensors mounted at the front of the machine sense the growing plants and provide data to the onboard computers. The information is used by the NFOA to determine the level of N

[1] Parameter estimates were shifted one standard deviation to the left in an effort by Raun et al. (2002) to describe a yield boundary.

to apply. As the rear of the machine travels across the sensed grid, UAN is applied. Further details describing the algorithm are presented in Raun et al. (2002, 2005).

Machine costs

A custom fertilizer application industry exists in the wheat growing regions of Oklahoma, U.S.A. It could be assumed that this industry would be the primary provider of N application services including the precision sensing system. Procedures published by the American Society of Agricultural Biological Engineers (2006) were used to calculate ownership and operating expenses for the precision applicator. The custom rate for a uniform application of UAN fertilizer in the region is \$7.20 ha^{-1} (Kletke and Doye 2001). This rate includes the cost of transporting fertilizer and applicator to and from the field. The cost of modifying and equipping a self-propelled UAN applicator with optical reflectance technology is \$60,000. Based on an assumption of a rapid rate of obsolescence and deterioration of the computers that are integral to the technology, the expected useful life of the machine is five years with an annual interest rate of 8%. The applicator is expected to have a field operating speed of 24 km h^{-1}, 70% field efficiency and capacity of 335 ha day^{-1} when used 10 h day^{-1}. Workers in the region earn, on average, \$10 h^{-1} to operate a self-propelled sprayer. However, operators will require additional training to operate the precision applicator. The cost of this additional training is reflected in a higher wage rate (i.e., assumed to be \$12 h^{-1} rather than \$10 h^{-1}). This two-dollar difference is considered in the calculations of the cost of the technology.

Cost of NRS

Because the on-farm trials did not replicate exactly the scale of an actual field (i.e., the length of the experimental plots was less than the length of the fields), it was necessary to approximate the NRS cost. NRS size is a function of applicator width and field length. The width of the applicator and NRS used in the study was 19.8 m. For a representative field in the region of 64.7 ha, the NRS length would be 803 m. This gives a total area of 15,942 m^2, which translates into an NRS equal to approximately 2% of the field. For the 0/NFOA treatment, the UAN applicator is assumed to make one pre-plant pass across the center of the field applying 134 kg ha^{-1} N to define the NRS.[2] For the 45/NFOA treatment, the NRS is defined by one additional pass across the center of the field to apply an additional 90 kg ha^{-1} N. To account for the cost of the NRS, the machine ownership and operating cost are multiplied by 1.02.

Net return

Net return is calculated for each treatment at each location and for each year as the difference between gross revenue from the sale of wheat grain and the cost of N fertilization. Net returns are calculated under two pre-plant application scenarios: (1) a base model that reflects the pre-plant N fertilization source actually used in the experiment (i.e., ammonium nitrate (AN)), and (2) a model that reflects when the pre-plant N fertilizer source was assumed to be NH_3 and applied with an NH_3 applicator. Many wheat producers

[2] The level of N applied to the NRS (kg ha^{-1}) is equal to 0.0417 kg times the expected maximum potential yield of the field (kg ha^{-1}). In this study the average expected maximum potential yield was assumed to be 3,225 kg ha^{-1}.

in the southern Great Plains use NH_3 as a pre-plant source due to its cost advantage. For the region under study, it is assumed that wheat yield responds to the level but not the source of pre-plant N.

For both pre-plant application scenarios, an average of the historical prices received by farmers for wheat grain and paid by farmers for N fertilizer are used. The historical prices of wheat grain for 2002, 2003, and 2004 were \$0.10, \$0.12, and \$0.12 kg^{-1}, respectively (USDA 2007a). The prices for NH_3 in the fall of 2001, 2002, and 2003 were \$0.49, \$0.31, and \$0.44 kg^{-1} N, respectively. AN prices in the fall of 2001, 2002, and 2003 were \$0.85, \$0.62, and \$0.74 kg^{-1} N, respectively.

UAN prices in the spring of 2002, 2003, and 2004 were \$0.52, \$0.66, and \$0.72 kg^{-1} N, respectively (USDA 2007b). Application costs for NH_3, AN and non-site specific UAN were based upon average custom charges for the area of \$15.11, \$6.18, and \$7.20 ha^{-1} (Kletke and Doye 2001). The average relative price ratio of UAN to NH_3 over the three years of the study was 1.53:1. One unit of N from UAN cost 1.53 times the cost of a unit of N from the NH_3, providing a substantial cost advantage in favor of NH_3. An even greater cost advantage exists between pre-plant sources of N (i.e., the three year average price ratio of AN to NH_3 was 1.74). This cost advantage explains why many producers in the region use NH_3 as their primary source of pre-plant N.

Results

Wheat grain yields for each treatment, year, location and N rate applied for the 0/NFOA and 45/NFOA systems are presented in Table 4. Across all locations and years (19 site-years), the average amount of N applied via UAN in the spring with the 0/NFOA treatment was 28.8 kg ha^{-1} and the average response to N for this treatment was 336 kg ha^{-1}. For the 45/NFOA treatment, 45 kg ha^{-1} N was applied pre-plant followed by an average top dress application of 25.4 kg ha^{-1} N applied via UAN in the late winter which resulted in an average yield response of 625 kg ha^{-1}. The average yield response from the 45/NFOA system was 289 kg ha^{-1} greater than that of the 0/NFOA system. More total N (an average of 70 kg ha^{-1}) was applied with the 45/NFOA system. A joint F-test (F value = 1.47) was used to test the null hypothesis of no statistical differences in the mean yields between systems. The null hypothesis could not be rejected at a 95% level of confidence.

To illustrate differences in yield across sites, systems and years, consider two locations (Lahoma (L1) and Hennessey (L2)) that produced data for all three years (2002, 2003, and 2004). The sites are within 43.3 km of each other in north central Oklahoma, have similar soil characteristics and received (on average) similar amounts of rainfall in each of the three years of the study (Tables 1 and 2); however, grain production and yield response to N were mixed between the two locations. For instance, in 2002, at Hennessey, there was no response to N application for any of the systems, including the two OS systems. In the same year, a greater level of N (determined by the NFOA) was applied on the 0/NFOA and 45/NFOA systems at Hennessey than at Lahoma, even though no response was gained at Hennessey. In 2003, the 90/0 treatment at Lahoma realized a 131% response above the check treatment (0/0), but only a 38% response was obtained on the 0/NFOA system with 38 kg ha^{-1} N. The data suggest that for this year and location, the NFOA under-estimated yield response and applied too little N. At the Hennessey site in 2003, there was very little response to N on any of the treatments. Total grain yield was greater at Lahoma than at Hennessey in 2003, except for the check system (0/0). In 2004, both Lahoma and Hennessey showed little response to N. At Hennessey, the NFOA did recommend

Table 4 Wheat grain yields for each system, year and location (kg ha^{-1})

Year	System	L1	L2	L3	L4	L5	L6	L7	L8	L9	Avg.
2002	0/0	2046	3008	4170	1267			3474			2793
2002	0/45	2425	3081	4241	1371			3321			2888
2002	0/90	2442	1938	4081	1158			3859			2696
2002	45/45	2901	2141	3920	1311			3629			2780
2002	45/0	2517	2839	4209	1238			3968			2954
2002	90/0	2724	2191	4235	1169			3473			2758
2002	0/NFOA	2190 (8)	2625 (12)	4286 (8)	1287 (3)			3707 (15)			2819 (10)
2002	45/NFOA	2484 (10)	2375 (10)	4350 (10)	1382 (4)			3373 (17)			2793 (11)
2003	0/0	1960				2760	3422	2760	895	3334	2522
2003	0/45	3327				2773	4266	2987	1254	4134	3124
2003	0/90	4159				2477	4550	3120	1594	4796	3449
2003	45/45	4512				2899	4896	3378	1393	4449	3588
2003	45/0	3579				2753	4490	3264	993	4165	3207
2003	90/0	4518				2836	4688	3195	1465	4430	3522
2003	0/NFOA	2697 (39)				2836 (17)	3800 (19)	3162 (39)	1078 (25)	3781 (17)	2892 (26)
2003	45/NFOA	4751 (62)				2867 (18)	4550 (21)	3138 (10)	1519 (33)	4606 (22)	3572 (28)
2004	0/0	1949				1901	1949	4421	3386		2721
2004	0/45	2688				2217	2688	4576	4045		3243
2004	0/90	3091				2318	3091	4455	4099		3411
2004	45/45	3360				2600	3360	4663	4072		3611
2004	45/0	2822				2177	2822	4623	4038		3296
2004	90/0	2956				2479	2956	4347	3863		3321
2004	0/NFOA	3091 (72)				2143 (39)	3091 (61)	4710 (30)	3984 (30)		3404 (46)
2004	45/NFOA	3628 (29)				2137 (38)	3628 (69)	4522 (6)	4119 (22)		3607 (33)

Table 4 continued

Year	System	L1	L2	L3	L4	L5	L6	L7	L8	L9	Avg.
Avg.	0/0	1985	3008	4170	1267	2331	2685	3552	2141	3334	2679
Avg.	0/45	2813	3081	4241	1371	2495	3477	3628	2649	4134	3085
Avg.	0/90	3231	1938	4081	1158	2398	3820	3811	2846	4796	3185
Avg.	45/45	3591	2141	3920	1311	2750	4128	3890	2732	4449	3326
Avg.	45/0	2973	2839	4209	1238	2465	3656	3952	2516	4165	3153
Avg.	90/0	3399	2191	4235	1169	2658	3822	3672	2664	4430	3200
Avg.	0/NFOA	2659 (40)	2625 (12)	4286 (8)	1287 (3)	2490 (28)	3445 (40)	3860 (28)	2531 (28)	3781 (17)	3038 (27)
Avg.	45/NFOa	3621 (34)	2375 (10)	4350 (10)	1382 (4)	2502 (4)	4089 (45)	3678 (11)	2819 (28)	4606 (22)	3324 (24)

Note: Numbers in parentheses are levels of N applied as 28% urea-ammonium nitrate applied using the site-specific applicator equipped with optical sensing technology (kg ha^{-1}). L1 is Lahoma, L2 is Chickasha, L3 is Blackwell, L4 is Haskell, L5 is Altus, L6 is Covington, L7 is Hennessey, L8 is Tipton, and L9 is Perry substantially less N for the 0/NFOA system compared to the 90/0 system (i.e., 30 kg ha^{-1} versus 90 kg ha^{-1}). This result indicates that the sensor did detect that plants were not N stressed, which is what it was designed to do. Overall, the results suggest that the sensing system does a reasonable job detecting when N is not limited, but may not apply enough N when plants are N deficient.

Ownership and operating costs, including the cost of implementing the NRS, are reported in Table 5. Estimates for the 15-day window of application were used in the analysis to reflect the rate that producers would pay a custom application service to apply a pre-plant NRS (i.e., \$2.07 ha^{-1} and \$1.48 ha^{-1} for the 0/NFOA and 45/NFOA systems, respectively) and to reflect the rate to custom apply UAN (\$10.3 ha^{-1}).

Net returns above the cost of N fertilizer and application for each year, fertilizer system and location, assuming AN was used as the source of pre-plant N, are reported in Table 6. On average across all years and locations, the 45/0 system was the top performing system with an average net return of \$342 ha^{-1}. The two site-specific systems (0/NFOA and 45/NFOA) were economically competitive with net returns of \$340 ha^{-1}and \$338 ha^{-1}, respectively. The three-year (2001, 2002, and 2003) average price of AN (\$0.73 kg^{-1}) is higher than the three-year average price of UAN (\$0.64 kg^{-1}), giving the site-specific systems a cost advantage. A joint F-test was used to test the hypothesis of no differences in mean net returns across locations, years, and treatments. The null hypothesis could not be rejected at the 95% confidence level.

Differences in net return between systems and years were mixed. For instance, at Lahoma 45/NFOA was most profitable at \$364 ha^{-1} whereas at Hennessey 45/0 was most profitable at \$444 ha^{-1}. In all three years at Lahoma, a substantial response to N was achieved with the conventional systems. It appears that the 0/NFOA system did not apply enough N and did not benefit from the additional yield that may have been obtained if the NFOA would have recommended more N. At Hennessey, there was essentially no response to N over the three years of the study and the 0/NFOA system did apply a much lower quantity than the conventional systems.

Net returns, assuming that NH_3 was used as the source of pre-plant N, are reported in Table 7. On average across all years and locations, the 45/0 system had the highest average net return of \$351 ha^{-1} when the pre-plant source of N was assumed to be NH_3. The two site-specific systems (0/NFOA and 45/NFOA) realized net returns of \$340 and \$343 ha^{-1}, respectively. The average three-year (2001, 2002, and 2003) fall price of NH_3 (\$0.42 kg^{-1}) was \$0.22 kg^{-1} less than the three-year average spring price of UAN (\$0.64 kg^{-1}), providing the conventional pre-plant systems with a substantial cost advantage over the site-specific systems. The null hypothesis of no differences in mean net returns of the eight systems across locations and years was not rejected at the 95% confidence level.

Sensitivity analysis

Several factors that affect the economics across the treatments have changed since 2004, including the price of wheat grain and the price of N. In addition, the constant that represents the NUE level in the NFOA (γ in Eq. 3) has been adjusted downward (from 0.60 to 0.50) from the level used in the study so the site-specific systems will apply more N to wheat that has been sensed as N deficient. To simulate this change, the level of N applied by the 0/NFOA and 45/NFOA systems is adjusted upward by 17% and the yields for the 0/NFOA and 45/NFOA systems were set equal to those obtained with the 45/0 system. Sensitivity analysis was conducted to determine the consequences of these adjustments.

Table 5 Ownership and operating cost for a self-propelled applicator equipped with optical sensing technology ($ ha^{-1})

Hectares covered per hour	Hours used per day	Days used per Year	Hectares covered per year	Current cost of N application	Cost of optical sensing technology	Cost of N-rich strip for 0/NFOA	Ownership & operating cost for 0/NFOA	Cost of N-rich strip for 45/NFOA	Ownership & operating cost for 45/NFOA
33.6	10	5	1680	7.2	7.76	2.07	17.0	1.48	16.40
33.6	10	15	5040	7.2	3.10	2.07	12.4	1.48	11.78
33.6	10	25	8401	7.2	2.30	2.07	11.5	1.48	10.94
33.6	10	35	11761	7.2	1.98	2.07	11.2	1.48	10.62
33.6	10	45	15121	7.2	1.80	2.07	11.0	1.48	7.98
33.6	10	55	18482	7.2	1.73	2.07	11.0	1.48	7.90

Note: Cost of optical sensing technology assumes the cost of modifying a boom sprayer with computers, sensors and GPS is $60,000. Cost of the NRS includes the cost of fertilizer and application in the fall prior to planting. The self-propelled applicator has a 19.8 m operating width, a field speed of 24 km h^{-1} and a field efficiency level of 70%

Table 6 Net return to N fertilization for each year, system, and location assuming ammonium nitrate as the pre-plant source of N (\$ ha^{-1})

Year	System	L1	L2	L3	L4	L5	L6	L7	L8	L9	Avg.
2002	0/0	253	373	517	157			430			346
2002	0/45	270	351	495	139			381			327
2002	0/90	248	186	451	89			423			279
2002	45/45	283	189	410	86			374			268
2002	45/0	267	307	476	108			446			321
2002	90/0	253	187	441	61			346			258
2002	0/NFOA	255	306	514	145			438			331
2002	45/NFOA	246	230	476	112			351			283
2003	0/0	238				336	416	336	109	406	307
2003	0/45	368				301	482	327	116	466	343
2003	0/90	440				235	487	313	128	517	353
2003	45/45	478				281	524	340	98	470	365
2003	45/0	401				300	512	363	86	472	356
2003	90/0	487				282	508	326	115	476	366
2003	0/NFOA	290				320	436	343	100	435	320
2003	45/NFOA	490				289	491	328	114	498	368
2004	0/0	238				232	238	540	413		332
2004	0/45	288				231	288	519	454		356
2004	0/90	305				211	305	471	428		344
2004	45/50	330				237	330	489	417		361
2004	45/0	304				226	304	524	453		362
2004	90/0	287				229	287	457	397		331
2004	0/NFOA	312				217	314	538	449		366
2004	45/NFOA	369				177	335	495	432		362
Avg.	0/0	243	373	517	157	284	327	435	261	406	328[a]
Avg.	0/45	309	351	495	139	266	385	409	285	466	342[a]
Avg.	0/90	331	186	451	89	223	396	403	278	517	325[a]
Avg.	45/45	364	189	410	86	259	427	401	258	470	330[a]
Avg.	45/0	324	307	476	108	263	408	444	269	472	345[a]
Avg.	90/0	342	187	441	61	255	397	376	256	476	317[a]
Avg.	0/NFOA	285	306	514	145	268	375	440	274	435	340[a]
Avg.	45/NFOA	368	230	476	112	233	413	391	273	498	338[a]

[a] Average net returns across all locations and years were not statistically different at the 95% confidence level

L1 is Lahoma, L2 is Chickasha, L3 is Blackwell, L4 is Haskell, L5 is Altus, L6 is Covington, L7 is Hennessey, L8 is Tipton, and L9 is Perry. Note that data for only 2002 are available for locations L2, L3, and L4; and data for only 2003 were available for L9. Data for 2002, 2003, and 2004 were available for L1 and L7

Results of the sensitivity analysis conducted on prices of wheat, prices of N sources, level of NUE and cost of UAN application are reported in Table 8. Net returns for the two pre-plant base models with the base (2001–2004) prices are reported in model scenarios 1 and 5 (MS1-base AN and MS5-base NH_3). The wheat price is increased from \$0.11 kg^{-1} to \$0.19 kg^{-1} for all alternatives to the base.

Table 7 Net return to N fertilization for each year, system, and location assuming NH_3 ammonia as the preplant source of N (\$ ha^{-1})

Year	System	L1	L2	L3	L4	L5	L6	L7	L8	L9	Avg.
2002	0/0	253	373	517	157			430			346
2002	0/45	270	351	495	139			381			327
2002	0/90	248	186	451	89			423			279
2002	45/45	291	197	417	94			381			276
2002	45/0	274	314	484	116			454			328
2002	90/0	277	211	465	85			370			282
2002	0/NFOA	255	306	514	145			438			331
2002	45/NFOA	253	237	483	119			358			290
2003	0/0	238				336	416	336	109	406	307
2003	0/45	368				301	482	327	116	466	343
2003	0/90	440				235	487	313	128	517	353
2003	45/45	483				286	529	345	103	475	370
2003	45/0	406				305	517	368	91	477	361
2003	90/0	506				301	527	345	134	495	385
2003	0/NFOA	290				320	436	343	100	435	320
2003	45/NFOA	495				294	496	333	119	502	373
2004	0/0	238				232	238	540	413		332
2004	0/45	288				231	288	519	454		356
2004	0/90	305				211	305	471	428		344
2004	45/50	335				242	335	494	421		365
2004	45/0	309				230	309	528	457		367
2004	90/0	305				247	305	475	416		349
2004	0/NFOA	312				217	314	538	449		366
2004	45/NFOA	374				182	339	499	437		366
Avg.	0/0	243	373	517	157	284	327	435	261	406	328[a]
Avg.	0/45	309	351	495	139	266	385	409	285	466	342[a]
Avg.	0/90	331	186	451	89	223	396	403	278	517	325[a]
Avg.	45/45	369	197	417	94	264	432	406	262	475	337[a]
Avg.	45/0	330	314	484	116	268	413	450	274	477	351[a]
Avg.	90/0	363	211	465	85	274	416	397	275	495	338[a]
Avg.	0/NFOA	285	306	514	145	268	375	440	274	435	340[a]
Avg.	45/NFOA	374	237	483	119	238	418	397	278	502	344[a]

[a] Average net returns across all locations and years were not statistically different at the 95% confidence level

L1 is Lahoma, L2 is Chickasha, L3 is Blackwell, L4 is Haskell, L5 is Altus, L6 is Covington, L7 is Hennessey, L8 is Tipton, and L9 is Perry. Note that data for only 2002 are available for locations L2, L3, and L4; and data for only 2003 were available for L9. Data for 2002, 2003, and 2004 were available for L1 and L7

For MS2, the prices of AN and UAN were adjusted from the base levels to \$1.10 and \$1.19 kg^{-1}, respectively. This adjustment increases the relative economic advantage of the 45/0 to the 0/NFOA system by \$11 ha^{-1}. This change is due to changes in the price of AN relative to UAN; that is, the 2007 spring price of UAN was greater than the 2006 fall price

Table 8 Sensitivity of average net return for each system to changes in the assumptions regarding price of wheat, price of N source, nitrogen use efficiency, and cost of precision system

Model scenario	Prices				NUE γ	Cost	System							
	Wheat ($ kg^{-1})	NH_3	AN	UAN		Precision system	0/0 ($ ha^{-1})	0/45	0/90	45/45	45/0	90/0	0/NFOA	45/NFOA
MS1 (Base AN)[a]	0.11		0.73	0.64	0.6	10.31	328	342	325	330	**345**	317	340	338
MS2	0.19		1.10	1.19	0.6	10.31	498	509	471	496	**528**	486	512	514
MS3	0.19		1.10	1.19	0.5	10.31	498	513	479	500	528	486	**541**	527
MS4	0.19		1.10	1.19	0.5	7.73	498	513	479	500	528	486	**543**	530
MS5 (Base NH_3)[b]	0.11	0.42		0.64	0.6	10.31	328	342	325	337	**351**	338	340	344
MS6	0.19	0.66		1.19	0.6	10.31	498	509	471	508	**541**	519	512	526
MS7	0.19	0.66		1.19	0.5	10.31	498	513	479	512	**541**	519	**541**	539
MS8	0.19	0.66		1.48	0.6	10.31	498	499	451	499	**541**	519	528	529
MS9	0.19	0.66		1.19	0.5	7.73	498	513	479	512	541	519	**543**	542

Numbers highlighted in bold correspond to the system that realized the greatest net return for each model scenario

[a] MS1 (Base AN) uses the base (2001–2004) prices to compute average net returns with the assumption that ammonium nitrate is the pre-plant source of N as reported in Table 5

[b] MS5 (Base NH_3) uses the base (2001–2004) prices to compute average net returns with the assumption that anhydrous ammonia is the pre-plant source of N as reported in Table 6

of AN, giving AN a small cost advantage over UAN. The affect of this cost advantage was displaced with the simulated change in the level of NUE (γ in Eq. 3) as reflected in the results for MS3. Changing the NUE estimate from 0.6 to 0.5 provided an increase in net return of \$29 ha^{-1} and \$13 ha^{-1} for the 0/NFOA and 45/NFOA systems, respectively, over that of the 45/0 system. Under this AN pre-plant scenario, the 0/NFOA system outperformed the 45/0 conventional system by \$13 ha^{-1}. When the estimated cost of the precision system is decreased by 25%, (MS4) the \$2.58 benefits accrue to the 0/NFOA and 45/NFOA systems, as expected.

Similar analysis was conducted for the NH_3 pre-plant system. MS5 (Base NH_3) includes the base (2001–2004) prices to compute the average returns as reported in Table 7. When more recent wheat and N prices are used (MS6), the estimated value of the 45/0 conventional system increases relative to the site-specific systems. This results because the NH_3 to UAN price ratio declined from 0.65 (\$0.42 kg^{-1}/\$0.64 kg^{-1}) to 0.55 (\$0.66 kg^{-1}/\$1.19 kg^{-1}). The cost advantage of NH_3 increased from 2004 to 2007; \$0.55 spent on NH_3 provides as much N as \$1 spent on UAN.

MS7 illustrates the results of changing the NUE parameter in the system's algorithm from 0.6 to 0.5. This change increases the expected net returns by \$29 ha^{-1} for the 0/NFOA system and by \$13 ha^{-1} for the 45/NFOA system. The practical effect of changing the NUE parameter is that the system will apply more N to N-deficient plants. The change is economically justified even with the increase in the cost of UAN. The change in the NUE parameter value from 0.6 to 0.5 makes the precision system more competitive economically with the conventional systems.

Conclusions

A prototype site-specific variable rate nitrogen (N) application system that uses optical reflectance information obtained from growing winter wheat plants has been developed. The system requires that a producer conduct an N response experiment in each field using a single nitrogen-rich strip (NRS) where enough N is applied so that N will not be the constraining input. Information is obtained using a sensor that detects red and near-infrared spectral reflectance measurements of fertilized plants in the NRS and unfertilized plants in the field. The sensor information is used by the applicator's on-board computers and algorithm to determine N needs on each 0.37 m^2 grid in the field on-the-go. The objective of this study was to determine if the precision system is economically competitive with conventional N fertilization strategies for winter wheat.

On average, across all years and locations, net returns with the precision N system were not statistically different from net returns using conventional systems. Net returns from precision sensing were slightly above the 90/0 system that is closest to what most producers use, but were slightly below the 45/0 conventional system. Using anhydrous ammonia (NH_3) as the pre-plant nitrogen source favors the conventional systems. With historical prices and with ammonium nitrate (AN) as the pre-plant source of N, a conventional system that applied 45 kg N ha^{-1} pre-plant realized, on average across all locations and years, \$5 ha^{-1} more net returns than the precision system that only applied urea-ammonium nitrate (UAN) top dress N. With the assumption that anhydrous ammonia (NH_3) would be used as the pre-plant N source, the average net returns from the site-specific system (0/NFOA) were \$11 ha^{-1} less than the conventional system that applied 45 kg N ha^{-1} pre-plant.

Further analysis revealed that the average net return to N fertilizer and application were sensitive to several factors, including the price of wheat, prices of N sources, the level of nitrogen use efficiency (NUE), and the cost of the system. The precision sensing system that applied no pre-plant nitrogen did use considerably less nitrogen than conventional systems, but it experienced a yield loss. Based on this experiment and others, the 2008 system applies more nitrogen. Sensitivity analysis showed that if this additional nitrogen is enough to remove the yield reductions, then the precision sensing systems are substantially better than pre-plant urea-ammonium nitrate (UAN) and roughly equal to pre-plant anhydrous ammonia (NH_3). The results were not as sensitive to changes in prices. The key to adoption of these systems appears to be adjusting the algorithm so that there is no yield loss (which may have already been done) and to use the system when pre-plant anhydrous ammonia (NH_3) cannot be used.

The algorithm used by the precision system to estimate N requirements does not consider the price of wheat or the prices of fertilizer. Adjusting the algorithm by incorporating current price information might improve N recommendations, which could translate into additional net benefits to the system. Additional research is warranted to determine the effect of weather risk on ability to top dress N in the spring. The top dress window is relatively small. Weather preventing top dressing could be costly in years when plants are N stressed, and would reduce the benefits of the precision system relative to conventional pre-plant application practices. Lastly, the study did not include a measure of the environmental benefits that could accrue to society from more precise N application.

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