Maximum Value of a Precise Nitrogen Application System for Wheat

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Abstract

Nitrogen fertilizer is a primary input for winter wheat production. Research is ongoing to develop sensor-based systems to determine crop nitrogen needs. To be economical, and to achieve wide adoption, a sensor based precision application system must be sufficiently efficient to overcome both the cost disadvantage of dry and liquid sources of nitrogen relative to preplant applications of anhydrous ammonia and the additional risk associated with in season application. The objective of this study was to determine the expected maximum value of an in season precision nitrogen application system for winter wheat. An estimate of the maximum value would be useful to provide researchers with an upper bound on the cost necessary to deliver an economically viable precision technology. Sixty-seven site-years of data from two dryland winter wheat nitrogen fertility experiments conducted at experiment stations located in the U.S. Southern Plains were obtained and used to estimate the expected returns from both a conventional uniform rate preplant anhydrous ammonia application system and a precise in season topdress system to determine the value of a precise in season system. The maximum net value of an in season sensor based precision nitrogen application system for winter wheat was found to be approximately \$22 to \$24 ha^{-1} depending upon location. For a relatively low value per hectare crop such as dryland winter wheat, and for typical prices and application costs of nitrogen fertilizers, farmers could not afford to pay much more than \$20 ha^{-1} for a precision system.

Key Words: precision farming, site specific, economics, wheat, nitrogen fertilizer

Introduction

Nitrogen (N) fertilizer is a primary input for winter wheat production, accounting for approximately 15 to 25 percent of the total operating costs (USDA). Several studies have found that the expected cost of implementing soil-based variable rate N fertilization systems for non-irrigated crops exceed the expected returns (Hurley et al.; Lambert and Lowenberg-DeBoer). Research is ongoing to develop sensor-based systems to determine crop N needs (Alchanatis et al.; Ehlert et al.; Phillips et al.; Raun et al.; Schächtl et al.). Sensor based systems have several potential advantages especially for crops with a long growing season such as winter wheat. For example, in the Southern Plains of the United States winter wheat is planted in September or October. Peak N requirement for wheat grain production occurs in April and May. A system designed to sense N needs in late February or early March could take advantage of the early history (insect, disease, and weather) of the growing season. Yield potential could be estimated based upon the number and health of plants. A second advantage of a late in season application of N is that the probability of N loss either to the atmosphere or through leaching or runoff is reduced as the time between application and plant needs is reduced.

There are also several disadvantages associated with in season application of N to winter wheat. First, the cost to apply a unit of N prior to planting is less than the cost to topdress a unit in March. Anhydrous ammonia (NH_3) may be incorporated prior to planting. However, only dry (e.g. urea, ammonium nitrate) or liquid (e.g. aqueous solution of urea and ammonium nitrate (UAN)) sources of N may be topdressed. Historically, the cost of a unit of N fertilizer in a dry or liquid N solution that could be topdressed is 166% as much as a unit of N from NH_3. A second disadvantage of in season relative to preplant application of N is that the number of days available for topdressing is limited and excessive precipitation during the window for topdressing may in some years prevent fertilization. Relatively, the window for applying preplant N is rather wide. As a result of these issues the conventional and most economical farmer practice in the U.S. Southern Plains is to apply NH_3 prior to planting.

To be economical, and to achieve wide adoption, a sensor based precision application system must be sufficiently efficient to overcome both the cost disadvantage of dry and liquid sources of N and the additional risk associated with in season application. The objective of this study is to determine the expected maximum value of an in season precision N application system for winter wheat. An estimate of the maximum value would be useful to provide agronomists and engineers with an upper bound on the cost necessary to deliver an economically viable precision technology.

Theory

Expected maximum value of a precision system may be calculated as the difference between the expected net return of a precise in season system minus the expected net return of the conventional uniform application preplant system. This value can be expressed as

$$\max_{\mathrm{N}^{\mathrm{P}}, N^{c}=\overline{N}} E(V) = \max_{N^P} \left\{ E(p) E\left[y_t^P\right] - r^P N^P - FC^P \right\} - \max_{N^C=\overline{N}} \left\{ E(p) E\left[y^C\right] - r^C N^C - FC^C \right\},$$

$$\text{where } y_t^P = y(N_t^P, \theta_t); \tag{1}$$

$$y^C = y(N^C = \overline{N}, u);$$

$E(\cdot)$ is the expectations operator; V is maximum value of a precise in season topdress technology; p is the price of wheat; N^P and N^C represent the level of N for a precision system and the conventional uniform rate system, respectively; r^P and r^C are prices per unit of N applied by the precision and conventional systems; FC^P and FC^C represent the fixed application costs for the precision and conventional systems; y_t^P and y^C are the yield response functions for the precision and conventional systems; $\overline{N}$ is the level of N assumed for the conventional system; and θ and u represent random disturbances that result from uncertain weather and uncertain changes in soil N mineralization.

Yield response data that are conditional on sensor information are not available. As a result, parameter estimates from a wheat grain yield response function cannot be estimated and used in traditional expected profit-maximizing methods. It is assumed that wheat grain yield response to N is characterized as a plateau function (Frank et al.; Grimm et al.; Waugh et al.) and that a linear response plateau (LRP) function best describes wheat yield response to N. The LRP function has the following form

$$y_t^P = \begin{cases} a + bN_t + \theta_t, & \text{if yield is less than the plateau,} \\ \mathrm{y}^{\mathrm{PLT}} + \theta_t, & \text{if yield is on the plateau,} \end{cases} \tag{2}$$

where y_t^P is yield obtained with the precision system in year t, a is the intercept, b is the slope, N is the level of N, y^{PLT} is the plateau yield, θ is a random error term that is distributed normal with mean zero and variance σ_θ^2.

Materials and Methods

Data were obtained from two long-term winter wheat N fertility experiments conducted at experiment stations located in the U.S. Southern Plains. One site is near Lahoma and the other near Altus, Oklahoma. The Lahoma experiment included N treatment levels of 0, 22.4, 44.8, 67.2, 89.6, and 112 kg N ha^{-1} that were replicated four times each year from 1971 through 2004 (except for 1973) for a total of 33 years. The experiment at Altus included treatment levels of 0, 22.4, 44.8 and 89.6 kg N ha^{-1} replicated six times each year from 1970 through 2002 (except for 1971) for a total of 32 years. Wheat yields were averaged across replications to obtain treatment means per year at both locations. These data provide 65 site-years of observations that can be used to estimate the expected return from the conventional N fertilization practice of applying NH_3 preplant.

Continuous monoculture winter wheat production typically begins in the summer with soil preparation. In the region, N fertilizer is conventionally applied as NH_3 prior to planting because it is the least expensive source of N and because the timing of application is not critical. Typical farmer practice in the region surrounding Lahoma is to apply NH_3 at a rate of approximately 89.6 kg N ha^{-1}. In the more arid region surrounding Altus, a rate of 44.8 kg N ha^{-1} is more common. Yields obtained from these treatments in the field experiments were used to represent the convention. In the region, wheat is harvested for grain in June.

Several steps were followed to obtain estimates of yields from a theoretical precision system. First, it was assumed that the yield obtained from the treatments that received the most N at each location represented the maximum precision yield. This was based upon the assumption that over the range of N levels used in the experiments; wheat grain yield response to N is characterized as a plateau function. Second, since soil testing in the region typically finds that fields have 22 kg ha^{-1} of available residual N prior to planting, it was assumed that yields from the treatments that received 22.4 kg N ha^{-1} preplant would be typical of yields from fields that received zero N fertilizer. Third, the difference in the yield of treatments that received the greatest level of N and those that received 22.4 kg N ha^{-1} was assumed to be the maximum yield increase attainable with a precision system. Fourth, parameters from a previously estimated wheat grain yield response to N function were used to estimate the quantity of N necessary to achieve the plateau yield.

Intercept and slope parameters were not estimated for equation (2). The intercept represents the yield without the application of N fertilizer, and was assumed to be the yield obtained from the 22.4 kg N ha^{-1} treatment for both locations. An estimate of the slope parameter (b = 18.6) was taken from Tembo et al. Alternatively, by this measure, over the range of observed yields, an average of 0.054 kg of additional N (18.6^{-1}) is required to obtain an additional kg of wheat. The LRP function was used to estimate the level of yield that would be obtained from a precise system for each year and location for which data were available.

Growing conditions including weather and soil, and hence yield potential, are different at the two locations. To illustrate the diversity between locations, wheat grain yields from the 89.6 kg N ha^{-1} treatments for those years for which data are available for both locations (1974-2002) are presented in Figure 1. For these 29 years, the average yield from the 89.6 kg N ha^{-1} treatment was 2,840 kg ha^{-1} at Lahoma and 1,694 kg ha^{-1} at Altus. Yield potential is substantially greater at Lahoma than at Altus.

Equation (1) was used to determine the difference in monetary returns between a conventional preplant uniform N application rate and an alternative that applies N late in season with a rate based upon sensing. To implement equation (1), that is to determine the potential value of a precision system, several assumptions and parameter estimates are required. It is assumed that the conventional uniform N application method is to apply NH_3 prior to planting at a rate of 89.6 kg N ha^{-1} at Lahoma and 44.8 kg N ha^{-1} at Altus. For the alternative system it is assumed that no N is applied preplant. A foliar application of UAN is made in late winter with the N rate based upon sensor readings.

It is assumed that the in season precision system senses and predicts plant needs perfectly, regardless of unpredictable exogenous conditions such as unforeseeable weather conditions that can affect yield (either positively or negatively) after the topdress application but prior to wheat grain harvest. This implies that the net return using the precision system when the unpredictable exogenous conditions affect yield negatively will be non-achievable in practice, but provides a maximum upper bound for plant-sensing and precision application technology.

Levels of N for each treatment were calculated as the difference between yield at the plateau (i.e., 112 kg N ha^{-1} treatment at Lahoma, and the 89.6 kg N ha^{-1} treatment at Altus) and yield for the 22.4 kg N ha^{-1} treatment divided by the marginal product of N. This can be expressed mathematically as

$$N_t^P = \frac{y_t^P - a}{b}, \tag{3}$$

where N_t^P is the level of N to apply in year *t* with the precision system, y_t^P is the yield obtained with the LRP function that describes the precise system (equation (2)), *a* is the intercept of equation (2) (i.e., the yield obtained from the 22.4 kg N ha^{-1} treatment), and *b* is the marginal product of N, assumed to be 18.6.

For example, if the yield difference for a given year and location between the precision system and the yield from the 22.4 kg N ha^{-1} treatment was 672 kg ha^{-1}, it was assumed that the variable rate sensing system would apply 36 kg N ha^{-1} (672 kg ha^{-1} 18.6 kg wheat kg^{-1} N). The price of \$0.55 kg^{-1} (r^P in equation (1)) was charged for the UAN solution with an additional application cost of \$7.16 ha^{-1} (FC^P in equation (1)) (Kletke and Doye). The price of wheat was set equal to \$0.11 kg^{-1} (*p* in equation (1)). An average price of \$0.33 kg^{-1} (r^C in equation (1)) and average application cost of \$15.12 (FC^C in equation (1)) was used for the NH_3 (Kletke and Doye).

Results

Yields, net returns, and expected differences in net returns between the two systems for each year for the Lahoma site are reported in Table 1. On average, 679 kg ha^{-1} wheat yield response above the yield obtained from the 22.4 kg N ha^{-1} treatment could be achieved with a precision system. Results show that a sensor-based variable rate precision application system that applies UAN in season, on average, require 59 percent less N than the conventional 89.6 kg N ha^{-1} preplant treatment. That is, only 36.4 kg N ha^{-1} of N would have been needed on average to achieve the same response as the 89.6 kg N ha^{-1} preplant treatment. This is so in part, because in eight of 33 years, the 22.4 kg N ha^{-1} treatment had a yield that was equal to the yield obtained from the plateau treatment, which implies that in those years there was no response to the conventional 89.6 kg N ha^{-1} treatment.

For each state of nature (year) included in the data set, N was assumed to be applied if the benefit from the additional N was greater than the cost of applying it. In addition, the maximum level of N application with the precision system was set at 112 kg N ha^{-1}. UAN applied in excess of 112 kg N ha^{-1} in late winter as a foliar application could burn the plants.

The data reported in Table 1 show that the maximum expected value of a precise system averaged over the 33 years was equal to \$24.3 ha^{-1} at Lahoma. Given the assumption of perfect prediction, this value is unachievable in practice. It does, however, provide an estimate of the maximum upper bound for the value of precision application of N for winter wheat for this region (*E(V)* of equation (1)).

A summary of yields, net returns, and expected differences in net returns between the two systems at Altus are presented in Table 2. The yield response to N at Altus was substantially less than at Lahoma. At Altus, average yield response between the plots that had the 22.4 kg N ha^{-1} treatment and the estimated precision treatment was only 154 kg ha^{-1}. Assuming a sensor-based precision application technology could be used, the analysis shows that an average in season foliar application of approximately 8 kg N ha^{-1} would be needed to obtain the same yield response as the conventional preplant application of 44.8 kg N ha^{-1}. This is approximately an 82 percent reduction in the total amount of N. In addition, there were 15 out of the 32 years that an in season precision system would have found that yield could not be increased by added N.

For the Altus data, the expected maximum value of \$21.8 ha^{-1} above that of the conventional uniform pre-plant system was estimated for the precision in season system. The estimated value of the precision system was approximately 12 percent greater at Lahoma (\$24.3 ha^{-1}) than Altus. Figure 2 provides a comparison of the magnitude of the differences in optimal levels of N to apply at the two locations. The optimal level of fertilizer needed at Lahoma using a precision system is more than four and a half times the amount needed at Altus.

Sensitivity Analysis

Changes in the estimated value of a precise N application system for both locations from changes in the marginal product of N, fertilizer prices, and fixed application costs are presented in Table 3. The results show that, holding all other variables constant, an increase in the marginal product of N results in an increase in the value of the precision system at both locations; however, the changes vary depending upon the location. For example, a 142 percent increase in the marginal product of N (i.e., from 18.6 to 45 kg wheat kg^{-1} N) results in a 47 percent increase in the value at Lahoma, but only an 11 percent increase in the value at Altus.

As expected, increases in the price of UAN relative to the price of NH_3 results in a reduction of the value of a precision system. As the price of UAN increases from \$0.55 to \$0.88 kg^{-1}, the value at Lahoma decreases from \$24.28 to \$12.23 ha^{-1}. The same change at Altus results in a decrease in value from \$21.74 to \$19.12 ha^{-1}. The opposite effect is observed when the price of NH_3 increases relative to UAN. As the price of NH_3 increases relative to the price of UAN, the value of an in season precision system would increase substantially. When the relative price is equal to 1 (i.e., the price of UAN and the price of NH_3 equal to \$0.55 kg^{-1}) the value of a precision system increases by 81 percent at Lahoma (from \$24.28 to \$ 44.04 ha^{-1}), and by 45 perecent at Altus (from \$21.74 to \$31.62 ha^{-1}).

As the fixed application costs for UAN are increased relative to the fixed application expenses for the NH_3, the value of a precision system that required UAN would decline. If the UAN application costs are increased to \$15.12 ha^{-1} (the same as budgeted for NH_3 application), the value at Lahoma decreases from \$24.28 to \$20.23 ha^{-1}. At this rate, though, the effect at Altus was a decrease in the expected maximum value of five percent. If the cost of applying UAN exceeds the cost of applying NH_3, the benefit from applying N using a precision system at Altus would not outweigh the cost, which results in a zero level of N being applied.

Summary and Conclusions

Research is ongoing to develop sensor-based systems to determine crop N needs. To be economical a sensor based precision application system must be sufficiently efficient to overcome both the cost disadvantage of dry and liquid sources of N relative to preplant applications of NH_3 and the additional risk associated with in season application. The objective of this study was to determine the expected maximum value of an in season precision N application system for winter wheat.

Sixty-seven site-years of data from two dryland winter wheat nitrogen fertility experiments conducted at experiment stations located in the U.S. Southern Plains were obtained. They were used to estimate the expected returns above the cost of N and N application from both a conventional uniform rate preplant NH_3 application system and a precise in season topdress UAN system to determine the potential value of a precise in season system. It was found that a precise in season system could reduce the overall N application level from preplant conventional levels by 59 to 82 percent depending upon location. However, since the typical price per unit of

N from UAN is 166 percent as much as the price per unit N from NH_3, the value of this savings is less than might be expected.

Based upon the assumptions regarding the prices of wheat, UAN, NH_3, the assumed cost to apply UAN and NH_3, and the assumed marginal product of N, the maximum net value of an in season sensor based precision N application system for winter wheat was found to be approximately \$22 to \$24 ha^{-1} depending upon location. By this measure farmers could not afford to pay much more than \$20 ha^{-1} for a precision system. N sensing and delivery systems that cost more than this are not likely to be adopted by wheat producers in the region. For perspective, Whipker and Akridge report that dealers charged an average of \$15.22 ha^{-1} for soil sampling with a global positioning system (GPS), \$8.80 ha^{-1} for field mapping with a geographic information system, and \$13.12 ha^{-1} for a controller-driven GPS single nutrient fertilizer application.

Based upon sensitivity analysis, it was determined that at one of the two locations the results are relatively insensitive to changes in the marginal product of N, changes in the price of UAN and changes in the cost to apply UAN. However, the value of a precision system is sensitive to the price of NH_3. If the price per unit N of NH_3 and UAN were equal, a precise system would be worth \$32 to \$44 ha^{-1} depending upon location.

A primary limitation for this research is the lack of data that reflects an actual technology. Another shortcoming is that the potential weather risk associated with in season application was not considered. A third limitation is that the potential environmental benefits for reducing N applied were not considered.

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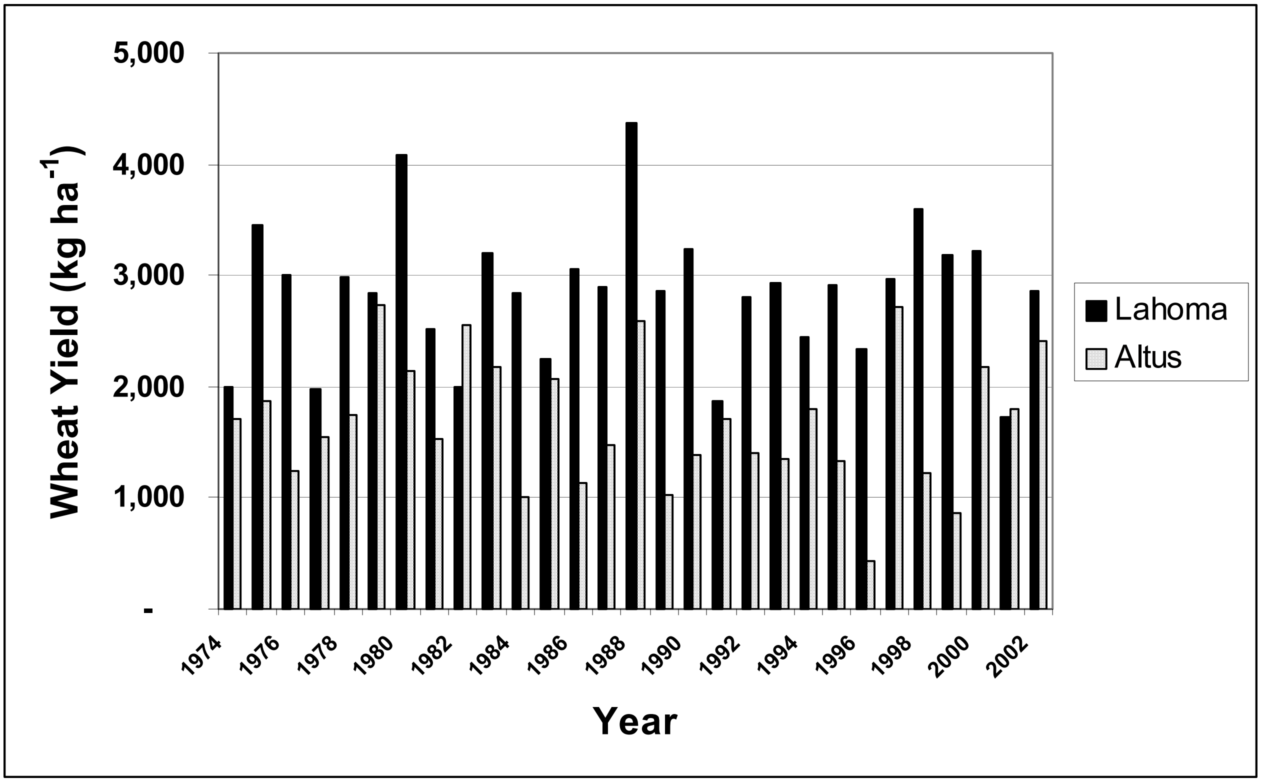

Figure 1. Wheat grain yields from treatments that received annual applications of 89.6 kg N ha^{-1} at Lahoma and Altus from 1974 to 2002.

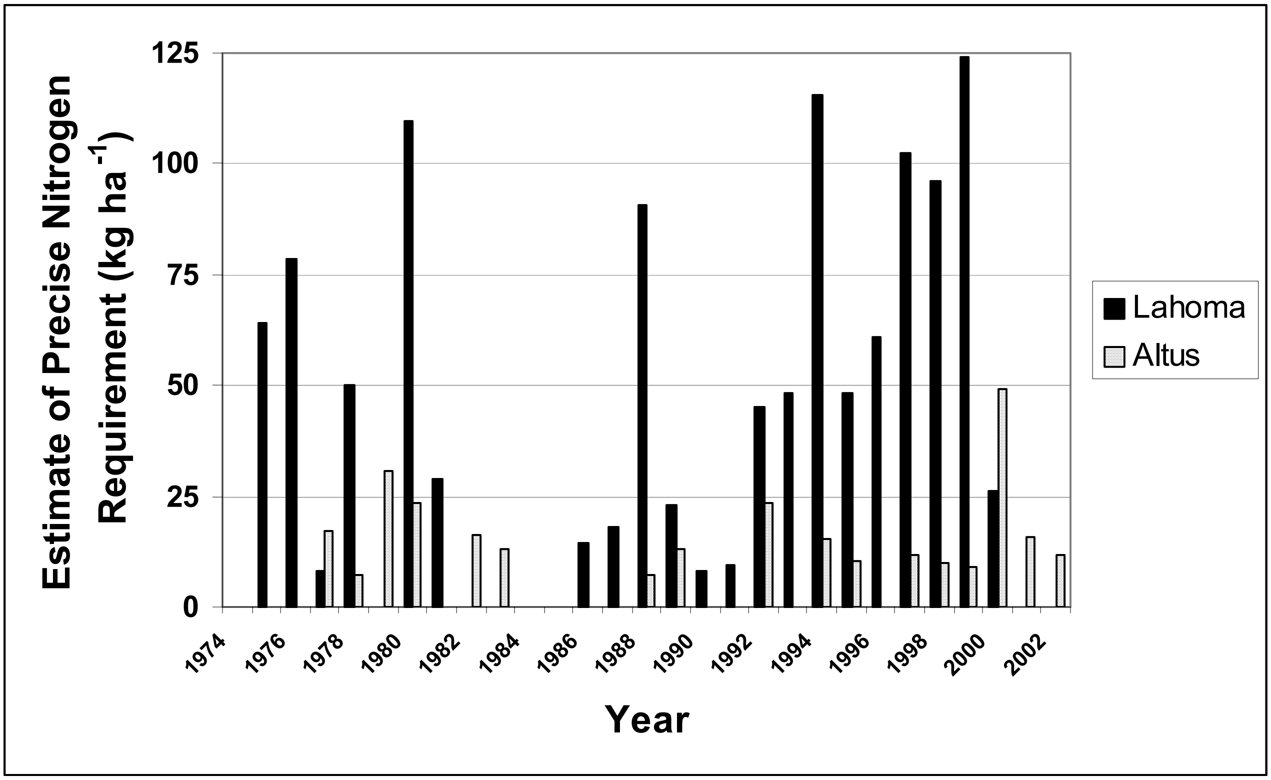

Figure 2. Estimate of precise nitrogen requirement at Lahoma and Altus from 1974 to 2002.

Table 1. Yield from the 22.4 kg N ha^{-1} treatment at Lahoma, an estimate of the potential yield from a precision system, N level required to achieve precision, returns above the cost of N fertilization and the expected change in net return resulting from a precision system (1971 to 2004).

Year	Yield from 22.4 kg N ha^{-1} treatment (kg ha^{-1})	Estimated yield from precision system (kg ha^{-1})	Estimate of N required to achieve precision (kg ha^{-1})	Estimated return above the cost of N using precision system (\$ ha^{-1})	Estimated return above the cost of N using conventional system (\$ ha^{-1})	Estimated change in net return (\$ ha^{-1})
1971	2,399	2,515	6.3	267	233	34.1
1972	1,467	1,467	0.0	162	117	44.8
1974	1,817	1,868	0.0[a]	206	161	44.8
1975	2,344	3,396	57.1	336	330	6.1
1976	1,848	3,140	70.1	301	302	-1.0
1977	1,805	1,937	7.2	203	169	33.6
1978	1,766	2,592	44.7	254	241	12.9
1979	2,659	2,659	0.0	293	249	44.8
1980	1,909	3,716	97.9	349	348	0.6
1981	2,131	2,606	25.7	266	243	23.4
1982	1,868	1,868	0.0	206	161	44.8
1983	2,514	2,514	0.0	277	233	44.8
1984	2,711	2,711	0.0	299	254	44.8
1985	2,030	2,030	0.0	224	179	44.8
1986	2,852	3,091	13.0	327	296	30.4
1987	2,490	2,788	16.2	291	263	28.7
1988	2,752	4,244	80.9	416	423	-7.0
1989	2,334	2,709	20.4	280	254	26.4
1990	2,811	2,947	7.4	314	280	33.5
1991	1,828	1,981	8.3	207	174	33.0
1992	1,863	2,604	40.1	258	242	15.5
1993	1,642	2,440	43.3	238	224	13.7
1994	1,139	3,044	103.3	272	263	8.5
1995	2,295	3,088	43.0	310	296	13.9
1996	1,601	2,604	54.4	250	242	7.6
1997	1,888	3,572	91.3	336	346	-9.3
1998	2,199	3,779	85.7	362	372	-9.6
1999	1,583	3,630	111.0	332	312	19.9
2000	2,215	2,647	23.5	272	247	24.7
2001	1,422	1,422	0.0	157	112	44.8
2002	2,951	2,951	0.0	325	281	44.8
2003	3,676	5,935	112.0	586	543	42.7
2004	1,939	2,656	38.9	264	248	16.2
Average	2,144	2,823	36.4	286	262	24.3

[a]

Table 2. Yield from the 22.4 kg N ha^{-1} treatment at Altus, an estimate of the potential yield from a precision system, N level required to achieve precision, returns above the cost of N fertilization and the expected change in net return resulting from a precision system (1970 to 2002).

Year	Yield from 22.4 kg N ha^{-1} treatment (kg ha^{-1})	Estimated yield from precision system (kg ha^{-1})	Estimate of N required to achieve precision (kg ha^{-1})	Estimated return above the cost of N using precision system (\$ ha^{-1})	Estimated return above the cost of N using conventional system (\$ ha^{-1})	Estimated change in net return (\$ ha^{-1})
1970	1,598	1,598	0.0	176	146	29.9
1972	11	15	0.0[a]	2	-28	29.9
1973	1,924	1,924	0.0	212	182	29.9
1974	1,705	1,705	0.0	188	158	29.9
1975	1,873	1,873	0.0	207	177	29.9
1976	1,234	1,234	0.0	136	106	29.9
1977	1,260	1,539	15.1	154	140	14.4
1978	1,615	1,736	6.6	181	161	19.2
1979	2,225	2,728	27.2	279	271	7.8
1980	1,760	2,149	21.1	218	207	11.2
1981	1,522	1,522	0.0	168	138	29.9
1982	2,281	2,552	14.7	266	251	14.7
1983	1,969	2,182	11.6	227	211	16.4
1984	984	1,010	0.0	111	81	29.9
1985	2,078	2,078	0.0	229	199	29.9
1986	1,115	1,137	0.0[a]	125	95	29.9
1987	1,394	1,473	0.0 [a]	163	133	29.9
1988	2,479	2,598	6.5	276	257	19.2
1989	804	1,023	11.8	99	83	16.3
1990	1,326	1,393	0.0 [a]	154	124	29.9
1991	1,715	1,715	0.0	189	159	29.9
1992	1,009	1,395	20.9	135	124	11.2
1993	1,311	1,341	0.0 [a]	148	118	29.9
1994	1,540	1,793	13.7	183	168	15.2
1995	1,159	1,331	9.3	134	117	17.6
1996	435	435	0.0	48	18	29.9
1997	2,523	2,719	10.6	287	270	16.9
1998	1,057	1,217	8.7	122	104	18.0
1999	712	859	8.0	83	65	18.4
2000	1,373	2,184	44.0	209	211	-1.5
2001	1,544	1,807	14.2	184	169	14.9
2002	2,212	2,407	10.6	252	235	16.9
Average	1,492	1,646	8.0	173	152	21.8

Table 3. Estimated maximum return to precision application of N to wheat for alternative levels of the marginal product of N, prices of UAN and NH_3, and application cost of UAN for both Lahoma and Altus environments.

Marginal product of N kg^{-1} Wheat (kg^{-1} N)	Price of UAN ($\$\ \text{kg}^{-1}$)	Price of NH_3 ($\$\ \text{kg}^{-1}$)	Cost to apply UAN ($\$\ \text{ha}^{-1}$)	Lahoma maximum return to precision ($\$\ \text{ha}^{-1}$)	Altus maximum return to precision ($\$\ \text{ha}^{-1}$)
Change in marginal product of N					
6.0				$ 9.36	$ 26.50
18.6[a]	$ 0.55[a]	$ 0.33[a]	$ 7.16[a]	$ 24.28	$ 21.74
30.0				$ 31.91	$ 23.17
45.0				$ 35.82	$ 24.08
60.0				$ 37.89	$ 24.53
75.0				$ 39.15	$ 24.80
Change in price of UAN					
18.6	$ 0.55	$ 0.33	$ 7.16	$ 24.28	$ 21.74
	$ 0.66			$ 20.25	$ 20.87
	$ 0.88			$ 12.23	$ 19.12
	$ 1.10			$ 4.20	$ 18.25
Change in price of NH_3					
18.6	$ 0.55	$ 0.33	$ 7.16	$ 24.28	$ 21.74
		$ 0.44		$ 34.16	$ 26.68
		$ 0.48		$ 38.11	$ 28.65
		$ 0.55		$ 44.04	$ 31.62
		$ 0.66		$ 53.92	$ 36.56
Change in UAN application cost					
18.6	$ 0.55	$ 0.33	$ 7.16	$ 24.28	$ 21.74
			$ 9.88	$ 22.30	$ 21.14
			$ 15.12	$ 20.23	$ 20.55
			$ 26.26	$ 15.07	[b]

[a] Represents the base line parameter values.

[b] Application costs for UAN above $15.12 ha^{-1} at Altus results in no applications for the time period.