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Maximum benefit of a precise nitrogen application system for wheat

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Abstract Research is ongoing to develop sensor-based systems to determine crop nitrogen needs. To be economic and to achieve wide adoption, a sensor-based site-specific application system must be sufficiently efficient to overcome both the cost disadvantage of dry and liquid sources of nitrogen relative to applications before planting of anhydrous ammonia and possible losses if weather prevents applications during the growing season. The objective of this study is to determine the expected maximum benefit of a precision N application system for winter wheat that senses and applies N to the growing crop in the spring relative to a uniform system that applies N before planting. An estimate of the maximum benefit would be useful to provide researchers with an upper bound on the cost of delivering an economically viable precision technology. Sixty five site-years of data from two dryland winter wheat nitrogen fertility experiments at experimental stations in the Southern Plains of the U.S.A. were used to estimate the expected returns from both a conventional uniform rate anhydrous ammonia (NH_3) application system before planting and a precise topdressing system to determine the value of the latter. For prices of \$0.55 and \$0.33 kg^{-1} N for urea-ammonium nitrate (UAN) and NH_3, respectively, the maximum net value of a system of precise sensor-based nitrogen application for

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winter wheat was about \$22–\$31 ha^{-1} depending upon location and assumptions regarding the existence of a plateau. However, for prices of \$1.10 and \$0.66 kg^{-1} N for UAN and NH_3, respectively, the value was approximately \$33 ha^{-1}. The benefit of precise N application is sensitive to both the absolute and relative prices of UAN and NH_3.

Keywords Economics · Nitrogen fertilizer · Precision farming · Site-specific · Wheat

Introduction

Nitrogen (N) fertilizer is a primary input for winter wheat production, accounting for approximately 15–25 % of total operating costs (USDA 2005a). Several studies have shown that the expected cost of implementing soil-based variable rate N fertilizer application systems for non-irrigated crops exceeds the expected returns (Hurley et al. 2005; Lambert and Lowenberg-DeBoer 2000). Lambert et al. (2006) found that returns from a soil-based variable rate N strategy were markedly less than those from a uniform application strategy. They concluded that spatial management of N over several growing seasons with soil based systems is difficult and expensive.

Research is ongoing to develop sensor-based systems to determine crop N needs (Alchanatis et al. 2005; Ehlert et al. 2004; Phillips et al. 2004; Raun et al. 2001; Schächtl et al. 2005). Such 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 U.S.A., 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 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 of applying a unit of N prior to planting is less than that of topdressing 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% more than a unit of N from NH_3. A second disadvantage of topdressing N on a growing crop relative to applications of N before planting is that the number of days available for topdressing is limited. Excessive precipitation during the window for topdressing might prevent N application in some years. By comparison, the window for applying N before planting is wider. Consequently, the conventional and most economic practice by farmers in the Southern Plains of the U.S.A. has been to apply NH_3 prior to planting.

To be economic, 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 possible losses if weather does not permit application during the growing season. The objective of this study is to determine the expected maximum benefit of a precision N application system for winter wheat that senses and applies N to the growing crop in the spring relative to a uniform system that applies N before planting. Such an estimate would provide agronomists and engineers with an upper bound on the cost of delivering an economically viable precision technology.

Theory

The expected maximum benefit of a precision application system may be calculated as the difference between the expected net return of a system that applies N precisely during the growing season minus the expected net return of the conventional uniform-application system that applies N prior to planting. It is assumed that wheat grain yield response to N is characterized as a plateau function (Frank et al. 1990; Grimm et al. 1987; Waugh et al. 1973, Kastens et al. 2003) and that a linear response plateau (LRP) function best describes wheat yield response to N. Perrin (1976) and Lanzer and Paris (1981) both concluded that the LRP functional form performed as well or better than polynomial specifications. Grimm et al. (1987) concluded that the LRP explained crop response to fertilizer at least as well as, if not better than, polynomial forms. The LRP function has the following form

$$y_t^{\mathrm{P}} = \begin{cases} a + bN_t + \theta_t, \text{if yield is less than the plateau,} \\ y^{\mathrm{PLT}} + \theta_t, \text{if yield is on the plateau,} \end{cases} \tag{1}$$

where y_t^{P} is yield obtained with the precise (P) 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 has a normal distribution with a mean of zero and variance σ_θ^2. Because of differences in weather from year to year, the plateau will vary from year to year.

Materials and methods

Data were obtained from two long-term N fertility experiments on winter wheat at experimental stations in the Southern Plains of the U.S.A. One site is near Lahoma and the other is 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 to 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. For both locations, the plot treatments were constant over time. That is, the zero N plots did not receive any N fertilizer after 1969 at Altus and after 1970 at Lahoma. Information about N applications to the plots prior to 1969–1970 is not available.

Wheat yields were averaged across replicates 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 fertilizer application of applying NH_3 before planting. They can also be used to estimate the expected returns from a system that senses N requirements in the spring and applies a precise quantity of UAN to achieve the plateau yield. The difference between these two estimates provides an estimate of the benefit of a precise application system.

The production of winter wheat in a continuous monoculture system typically begins in the summer with preparation of the soil. In the region of this study, N fertilizer is conventionally applied as NH_3 prior to planting because it is the least expensive source of N and timing of application is not critical. The USDA (2005b) conducts surveys of farming practices and reports the average N application to wheat on Oklahoma farms; it does not provide estimates for regions within the state. Over the time period of the study (1974–2003) the average reported application rate was 71 kg N ha^{-1}.

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 shown in Fig. 1. For these 29 years, the average yield from this treatment was 2840 kg ha^{-1} at Lahoma and 1694 kg ha^{-1} at Altus suggesting that yield potential is substantially greater at Lahoma than at Altus.

The 89.6 kg N ha^{-1} treatment was selected from the range available (0, 22.4, 44.8, 67.2, 89.6, and 112 kg N ha^{-1}) to represent the practice of those farmers that produce wheat on soil and under climate conditions similar to those found at the Lahoma station. For Altus, the 44.8 kg N ha^{-1} treatment was selected from the range available (0, 22.4, 44.8 and 89.6 kg N ha^{-1}) to represent those wheat producers that encounter similar soil and climate conditions to those at the Altus station. The state average of 71 kg N ha^{-1} fertilizer rate as reported by the USDA (2005b) is between these two levels. Anecdotal evidence from conversations with farm management specialists and farmers also suggests that given the available range of treatments, the rates of 89.6 kg N ha^{-1} at Lahoma and 44.8 kg N ha^{-1} at Altus, most closely approximate farmer practice in the two regions.

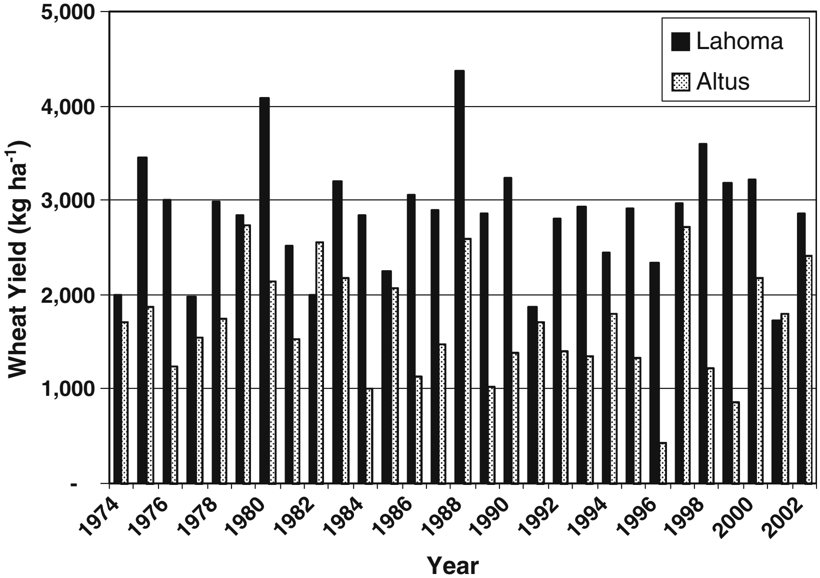

Fig. 1 Wheat grain yields from treatments that received annual applications of 89.6 kg N ha^{-1} at Lahoma and Altus from 1974 to 2002

It was assumed that the yield from treatments that had the most N at each location represented the maximum potential yield from precise application. This was based on 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. Statistical analysis was done to test the validity of the plateau function hypothesis. For nine of the 32 years of the Altus experiment, the plateau was achieved by the 22.4 kg N ha^{-1} treatment. If applying more N reduces yields, then in these nine years lower yields could be expected from the 89.6 kg N ha^{-1} treatments than from the 44.8 kg N ha^{-1} treatments. The null hypothesis (no difference between the yield obtained from the 44.8 and 89.6 kg N ha^{-1} for these nine years) could not be rejected at the 0.05 level of probability. Therefore, for the Altus experiment the plateau hypothesis is reasonable and the largest rate of N used in the experiment did not reduce wheat yield. Thus, for a given year for the Altus site the yield from the 89.6 kg N ha^{-1} treatment was assumed to be on the plateau (y^{PLT} in Eq. 1).

A similar test was done on data from the Lahoma site. In 11 of the 33 years the plateau yield was achieved by the 67.2 kg N ha^{-1} treatment or less. The null hypothesis of no difference in yields between treatments that received 89.6 and 112 kg N ha^{-1} was rejected at the 0.05 level of probability. On average for these 11 years the average wheat yield was 208 kg ha^{-1} less from the 112 kg N ha^{-1} treatment than that of the 89.6 kg N ha^{-1} one. Over the 33 years, this is an average annual yield difference of 69 kg ha^{-1}. For the basic wheat price of \$0.11 kg^{-1}, this is \$7.59 ha^{-1} (69 kg × \$0.11 kg^{-1}). For a given year for the Lahoma site the yield resulting from the 112 kg N ha^{-1} treatment was assumed to be on the plateau. However, if the assumption regarding the existence of a plateau is not correct, there is a potential that the method used underestimates the upper bound on the value of precision at the Lahoma site by \$7.59 ha^{-1}.

The fertility level in the zero N treatment plots that had no N fertilizer after 1969–1970 would not be expected to approximate fields that are routinely fertilized. In general, soil analysis shows that cropped fields in the region that are routinely fertilized, typically have 20–25 kg ha^{-1} of available residual N prior to planting. Therefore, it was assumed that yields from treatments that received 22.4 kg N ha^{-1} before planting would be typical of yields from fields that had no N fertilizer applied in the current year but had routinely received applications of N in prior years.

These data were used to determine unique intercept and plateau values for each site for each year. The difference between the yield from treatments that had the largest level of N application (y^{PLT} in Eq. 1) and those that had 22.4 kg N ha^{-1} (a in Eq. 1) was assumed to be the maximum increase in yield attainable by a precise sensing system and N topdressing in the spring.

An estimate of the slope (b in Eq. 1) of the response function is necessary to determine an estimate of the level of spring N applied that is required to achieve the yield plateau. Previously, Tembo et al. (2003) used the Lahoma data to estimate an LRP function. They estimated a slope parameter value of 18.6. That is, over the range between the intercept yield and plateau yield, a yield response of 18.6 (kg wheat grain) is expected from each additional unit (kg) of applied N. This is referred to as the marginal product of N. 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 kilogram of wheat.

Kastens et al. (2003) found that both the Kansas State University agricultural extension service and the Olsen's Agricultural Laboratory assume a linear response with a marginal product of 34.3. The Oklahoma State University agricultural extension service assumes a linear response with a marginal product of 30. To determine how sensitive the estimates would be to alternative values for the marginal product of N, the analysis was done for marginal product values of 6, 30, 45, 60, and 75 as well as for the baseline value of 18.6.

Levels of N for the precise application system for each year and location were calculated as the difference between yield at the plateau (i.e., the 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

$$N_{\mathrm{ts}}^{\mathrm{P}} = \frac{y_{\mathrm{ts}}^{\mathrm{PLT}} - a_{\mathrm{ts}}}{b}, \tag{2}$$

where $N_{\mathrm{ts}}^{\mathrm{P}}$ is the level of N to apply in year t at location s with the precision system; $y_{\mathrm{ts}}^{\mathrm{PLT}}$ is the yield obtained at the assumed plateau in year t at location s; a_{ts} is the intercept of Eq. 1 in year t at location s (i.e., the yield obtained from the 22.4 kg N ha^{-1} treatment in year t at location s); and b is the marginal product of N, with an assumed baseline value of 18.6.

For example, if the yield difference for a given year and site between the plateau 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 divided by 18.6). The cost was \$0.55 kg^{-1} for the UAN solution, with an additional application cost of \$7.16 ha^{-1} (Kletke and Doye 2001). The price of wheat was assumed to be \$0.11 kg^{-1}. An average cost of \$0.33 kg^{-1} was used for NH_3, with an average application cost of \$15.12 ha^{-1} (Kletke and Doye 2001).

Results

Yields, net returns, and expected differences in net returns between the conventional pre-plant system and the precision in-season system for each year for the Lahoma site are given in Table 1. On average, a yield response of 679 kg ha^{-1} of wheat above the yield obtained from the 22.4 kg N ha^{-1} treatment could be achieved with a precise management system. The results show that a sensor-based precise application system that applies UAN during the growing season, requires on average 59% less N than the conventional 89.6 kg N ha^{-1} treatment before planting. Thus, only 36.4 kg N ha^{-1} would have been needed on average to achieve the same response in yield as the 89.6 kg N ha^{-1} pre-plant treatment. This is partly because in eight of 33 years the 22.4 kg N ha^{-1} treatment had a yield that was equal to that obtained from the plateau treatment. In those years there was no response to the conventional 89.6 kg N ha^{-1} treatment.

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

The data given in Table 1 show that the maximum expected benefit of a precise system averaged over the 33 years with expected fertilizer prices, application costs, and the expected yield response function, was equal to \$24.28 ha^{-1} at Lahoma. However, as noted, there is a potential that the plateau yield assumption could underestimate the upper bound of the benefit of precise application at the Lahoma site by \$7.59 ha^{-1}. By the adding the potential underestimate of (\$7.59 ha^{-1}) to the expected benefit (\$24.28 ha^{-1}) the upper bound on the estimated benefit of precise N

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

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	2399	2515	6.3	267	233	34.1
1972	1467	1467	0.0	162	117	44.8
1974	1817	1868	0.0[a]	206	161	44.8
1975	2344	3396	57.1	336	330	6.1
1976	1848	3140	70.1	301	302	–1.0
1977	1805	1937	7.2	203	169	33.6
1978	1766	2592	44.7	254	241	12.9
1979	2659	2659	0.0	293	249	44.8
1980	1909	3716	97.9	349	348	0.6
1981	2131	2606	25.7	266	243	23.4
1982	1868	1868	0.0	206	161	44.8
1983	2514	2514	0.0	277	233	44.8
1984	2711	2711	0.0	299	254	44.8
1985	2030	2030	0.0	224	179	44.8
1986	2852	3091	13.0	327	296	30.4
1987	2490	2788	16.2	291	263	28.7
1988	2752	4244	80.9	416	423	–7.0
1989	2334	2709	20.4	280	254	26.4
1990	2811	2947	7.4	314	280	33.5
1991	1828	1981	8.3	207	174	33.0
1992	1863	2604	40.1	258	242	15.5
1993	1642	2440	43.3	238	224	13.7
1994	1139	3044	103.3	272	263	8.5
1995	2295	3088	43.0	310	296	13.9
1996	1601	2604	54.4	250	242	7.6
1997	1888	3572	91.3	336	346	–9.3
1998	2199	3779	85.7	362	372	–9.6
1999	1583	3630	111.0	332	312	19.9
2000	2215	2647	23.5	272	247	24.7
2001	1422	1422	0.0	157	112	44.8
2002	2951	2951	0.0	325	281	44.8
2003	3676	5935	112.0	586	543	42.7
2004	1939	2656	38.9	264	248	16.2
Average	2144	2823	36.4	286	262	24.3[b]

[a] Given the fixed cost of application, assumed prices and marginal product of N, the estimated yield gain from precise application must be at least 89 kg ha^{-1} for the benefits of application to exceed the cost

[b] There is a potential that the plateau yield assumption could result in an underestimate of the upper bound on the value of a precision approach at the Lahoma site of \$7.59 ha^{-1}. If the plateau assumption is incorrect the upper bound on the average estimated change in net return is \$31.87 ha^{-1} (\$24.28 + \$7.59)

fertilizer application to winter wheat during the growing season at Lahoma relative to a conventional uniform rate applied prior to planting is \$31.87 ha^{-1}. This benefit is unachievable in practice since perfect sensing and perfect N application to each plant would not be practical. However, \$31.87 ha^{-1} is the estimate of the upper bound for the value of precise application of N for winter wheat for this region.

A summary of yields, net returns, and expected differences in net returns between the two systems at Altus are given 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 received the 22.4 kg N ha^{-1} treatment and the plateau treatment was 154 kg ha^{-1}. Assuming that a sensor-based precision application technology could be used, the analysis shows that an average foliar application of approximately 8 kg N ha^{-1} would be needed to obtain the same yield response as the conventional application of 44.8 kg N ha^{-1} before planting. This is about an 82% reduction in the total amount of N applied. In addition, there were 15 of the 32 years for which a precise application system would not have increased yield with added N.

For the Altus data, the expected maximum benefit of \$21.8 ha^{-1} above that of the conventional uniform pre-plant system was estimated for the precise system. The estimated benefit of the precise system was 11–46% greater at Lahoma (\$24.3–\$31.9 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 precise application system is >4.5 times the amount needed at Altus.

Sensitivity analysis

Changes in the estimated benefit of a precise N application system for both sites due to changes in the marginal product of N, fertilizer prices, and fixed application costs are given in Table 3. The results show that when all other variables are constant, an increase in the marginal product of N results in an increase in the benefit of the precise system at both sites. However, the magnitude of the increases depend upon the site. For example, a 142% increase in the marginal product of N (i.e., from 18.6 to 45 kg wheat kg^{-1} N) results in a 47% increase in benefit at Lahoma, but only an 11 % increase at Altus.

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

As the fixed application costs for UAN are increased relative to those for NH_3, the benefit of a precise system that required UAN would decline. Increasing UAN application costs to \$15.12 ha^{-1} (as budgeted for NH_3), decreases the benefit of a precise application system at Lahoma from \$24.28 to \$20.23 ha^{-1} (17% less). For Altus, however, this rate led to a decrease in the expected maximum benefit of only 5%. If the cost of applying UAN exceeds that of applying NH_3, the benefit from

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 fertilizer required to achieve precision, returns above the cost of N fertilizer application and the expected change in net return resulting from a precision system (1970–2002)

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	1598	1598	0.0	176	146	29.9
1972	11	15	0.0[a]	2	–28	29.9
1973	1924	1924	0.0	212	182	29.9
1974	1705	1705	0.0	188	158	29.9
1975	1873	1873	0.0	207	177	29.9
1976	1234	1234	0.0	136	106	29.9
1977	1260	1539	15.1	154	140	14.4
1978	1615	1736	6.6	181	161	19.2
1979	2225	2728	27.2	279	271	7.8
1980	1760	2149	21.1	218	207	11.2
1981	1522	1522	0.0	168	138	29.9
1982	2281	2552	14.7	266	251	14.7
1983	1969	2182	11.6	227	211	16.4
1984	984	1010	0.0[a]	111	81	29.9
1985	2078	2078	0.0	229	199	29.9
1986	1115	1137	0.0[a]	125	95	29.9
1987	1394	1473	0.0[a]	163	133	29.9
1988	2479	2598	6.5	276	257	19.2
1989	804	1023	11.8	99	83	16.3
1990	1326	1393	0.0[a]	154	124	29.9
1991	1715	1715	0.0	189	159	29.9
1992	1009	1395	20.9	135	124	11.2
1993	1311	1341	0.0[a]	148	118	29.9
1994	1540	1793	13.7	183	168	15.2
1995	1159	1331	9.3	134	117	17.6
1996	435	435	0.0	48	18	29.9
1997	2523	2719	10.6	287	270	16.9
1998	1057	1217	8.7	122	104	18.0
1999	712	859	8.0	83	65	18.4
2000	1373	2184	44.0	209	211	–1.5
2001	1544	1807	14.2	184	169	14.9
2002	2212	2407	10.6	252	235	16.9
Average	1492	1646	8.0	173	152	21.8

[a] Given the fixed cost of application, assumed prices and marginal product of N, the estimated yield gain from precision must be at least 89 kg ha^{-1} for the benefits of application to exceed the cost

applying N using a precise system at Altus would not outweigh the cost, which would result in no N being applied.

If the baseline prices of \$0.55 and \$0.33 kg^{-1} N for UAN and NH_3, respectively, are doubled to \$1.10 and \$0.66, the maximum net benefit of an in-season precise application system increases by 34% to \$32.6 ha^{-1} at Lahoma and by 52% to \$33.07 ha^{-1} at Altus. As the price of N increases relative to the cost of other inputs, precise application of N becomes more valuable. If the price of NH_3 is doubled from to \$0.33 to \$0.66 kg^{-1} N and if the price of UAN increases from \$0.55 to \$0.88 kg^{-1} N, which is 133% as much as the price per unit N from NH_3 (rather than the baseline 166%), the value of precision increases to \$40.48 ha^{-1} at Lahoma and to \$33.94 ha^{-1} at Altus. The benefit of precise N application will increase if the price

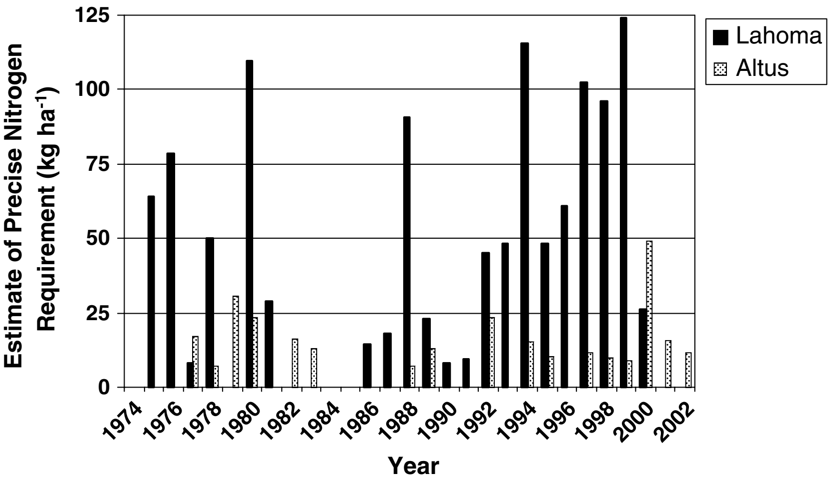

Fig. 2 Estimate of precise nitrogen requirement at Lahoma and Altus from 1974 to 2002

per unit of spring applied N declines relative to that of NH_3 applied in late summer prior to planting.

Summary and conclusions

Research is ongoing to develop sensor-based systems to determine crop N needs. A precise application system for winter wheat must be sufficiently efficient to overcome both the cost disadvantage of dry and liquid sources of N relative to applications of NH_3 before planting, and the additional risk associated with application during the growing season. The objective of this study was to determine the expected maximum benefit of a precise N application system for winter wheat that senses and applies N to the growing crop in the spring relative to a uniform system that applies N before planting.

The results showed that a precise system could reduce the overall N application level from conventional levels before planting by 59–82% depending on the site. However, since the typical price per unit of N from UAN is 166% as much as that from NH_3, the benefit of this savings is less than might be expected.

Based upon the assumptions regarding the prices of wheat, the costs of UAN and NH3, the cost of applying UAN and NH_3, and the marginal product of N, the maximum net benefit of a sensor-based precise N application system for winter wheat was found to be \$22–\$31 ha^{-1} depending on the site. However, when the baseline prices of UAN and NH_3 are doubled, the benefit of the precise application system increases to \$33 ha^{-1}. Nitrogen sensing and delivery systems that cost more than this are unlikely to be adopted by wheat producers in the region.

Based on sensitivity analysis, the results at one of the two sites are relatively insensitive to changes in the marginal product of N, changes in the price of UAN and changes in the cost of applying UAN. However, the value of a precise application 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 on the site.

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

Marginal product of N kg^{-1} Wheat (kg^{-1} N)	Price of UAN (\$ kg^{-1})	Price of NH_3 (\$ kg^{-1})	Cost to apply UAN (\$ ha^{-1})	Lahoma maximum return to precision (\$ ha^{-1})	Altus maximum return to precision (\$ 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[b]	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
Increase in price of UAN					
18.6[a]	0.55 [a]		7.16[a]	24.28[b]	21.74
	0.66			20.25	20.87
	0.88			12.23	19.12
	1.10			4.20	18.25
Increase in price of NH_3					
18.6[a]	0.55[a]	0.33[a]	7.16[a]	24.28[b]	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
Increase in UAN application cost					
18.6[a]	0.55[a]	0.33a	7.16[a]	24.28[b]	21.74
			9.88	22.30	21.14
			15.12	20.23	20.55
			26.26	15.07[c]	
Increase in price of UAN and NH_3					
18.6[a]	0.55[a]	0.33[a]	7.16[a]	24.28[b]	21.74
	1.10	0.66		32.60	33.07
	0.88	0.66		40.48	33.94

[a] Represents the baseline parameter values

[b] There is a potential that the plateau yield assumption could result in an underestimate of the upper bound on the value of precision at the Lahoma site of \$7.59 ha^{-1}. If the plateau assumption is incorrect the upper bound on the average estimated change in net return given base prices and base marginal product of N is \$31.87 ha^{-1} (\$24.28 + \$7.59)

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

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References

Alchanatis V, Scmilivitch Z, Meron M (2005) In-field assessment of single leaf nitrogen status by spectral reflectance measurements. Precis Agric 6:25–39

Ehlert D, Schmerler J, Voelker U (2004) Variable rate nitrogen fertilisation of winter wheat based on a crop density sensor. Precis Agric 5:263–273

Frank MD, Beattie BR, Embleton ME (1990) A comparison of alternative crop response models. Am J Agric Econ 72:597–603

Grimm SS, Paris Q, Williams WA (1987) A von Liebig model for water and nitrogen crop response. Western J Agric Econ 12:182–192

Hurley TM, Oishi K, Malzer GL (2005) Estimating the potential value of variable rate nitrogen applications: A comparison of spatial econometric and geostatistical models. J Agric Resour Econ 30:231–249

Kastens TL, Schmidt JP, Dhuyvetter KC (2003) Yield models implied by traditional fertilizer recommendations and a framework for including nontraditional information. Soil Sc Soc Am J 67:351–364

Kletke D, Doye D (2001) Oklahoma Farm and Ranch Custom Rates, 2001–2002. Oklahoma Cooperative Extension, Current Report CR–205

Lambert D, Lowenberg-Deboer J (2000) Precision Agriculture Profitability Review. Site-Specific Management Center, Purdue University. Found at: http://www.agriculture.purdue.edu/ssmc/Frames/newsoilsX.pdf

Lambert DM, Lowenberg-Deboer J, Malzer GL (2006) Economic analysis of spatial-temporal patterns in corn and soybean response to nitrogen and phosphorus. Agron J 98:43–54

Lanzer EA, Paris Q (1981) A new analytical framework for the fertilization problem. Am J Agric Econ 63:93–103

Perrin RK (1976) The value of information and the value of theoretical models in crop response research. Am J f Agric Econ 58:54–61

Phillips SB, Keahey DA, Warren JG, Mullins GL (2004) Estimating winter wheat tiller density using spectral reflectance sensors for early-spring, variable-rate nitrogen applications. Agron J 96:591–600

Raun WR, Solie JB, Johnson GV, Stone ML, Lukina EV, Thomason WE, Schepers JS (2001) In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron J 93:131–138

Schächtl J, Huber G, Maidl F-X, Stickse E, Schulz J, Haschberger P (2005). Laser-induced chlorophyll fluorescence measurements for detecting the nitrogen status of wheat (Triticum aestivum L.) canopies. Precis Agric 6:143–156

Tembo G, Brorsen BW, Epplin FM (2003) Linear response stochastic plateau functions. J Agric Appl Econ 35:445

USDA (2005a) Commodity Costs and Returns. The Economics of Food, Farming, Natural Resources, and Rural America, Economic Research Service. Found at: http://www.ers.usda.gov/Data/costsandreturns/testpick.htm.

USDA (2005b) Fertilizer Use and Price. Nitrogen used on wheat, rate per fertilized acre receiving nitrogen, selected States for 1964–2003. Found at: http://www.ers.usda.gov/Data/FertilizerUse/Tables/Fert%20Use%20Table%2028.xls

Waugh DL, Cate RB, Nelson LA (1973) Discontinuous Models for Rapid Correlation, Interpretation and Utilization of Soil Analysis and Fertilizer Response Data. North Carolina State University Technical Bulletin No. 7, Soil Fertility Evaluation and Improvement Program, Raleigh