ECONOMIC FEASIBILITY OF SITE-SPECIFIC OPTICAL REFLECTANCE TECHNOLOGY AS AN ALTERNATIVE STRATEGY FOR MANAGING NITROGEN APPLICATIONS TO WINTER WHEAT

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PREFACE

This dissertation is comprised of three essays, each of which forms one of the main chapters or sections of the text. The first essay, “Maximum Value of Plant-Based Precision Fertilizer Technology for Winter Wheat” seeks to determine the expected maximum value of a precise in season nitrogen application system for winter wheat producers operating under different growing conditions in the southern Great Plains. 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.

The second essay is entitled, “Nitrogen Fertilization of Growing Wheat Based upon Site-Specific Optical Sensing”. Data from on farm experiments conducted over nine locations in Oklahoma are used to determine the economics of a plant-based site-specific nitrogen fertilizer application system that uses optical reflectance measurements of growing wheat plants to sense and estimate optimal nitrogen requirements. The net benefit from the site-specific system is compared with the net benefits from a number of conventional nitrogen fertilizer management systems that were included in the experiments to determine its economic feasibility for adoption.

The third and final essay, “Precision Nitrogen Fertilization Technology with Micro Grids” utilizes data from on farm experiments conducted at various locations in Oklahoma to estimate a linear response stochastic plateau wheat yield function conditional on optical reflective measurements. The estimated function is used within an expected profit-maximizing framework to estimate the upper bounds on the net returns from a number of precision nitrogen fertilizer application systems. The site-specific precision system that assumes perfect information was reported to have a higher average profit than the conventional systems. However, it was noted that the estimate of average profit for the perfect information system is likely unachievable in practice, and is therefore considered an upper bound for the technology.

It is a pleasure to express my appreciation to those who have influenced this work. I am sincerely grateful to Drs. Francis M. Epplin and B. Wade Brorsen for their advisement, encouragement, friendship, and everlasting patience with me in this research effort. In my eyes there is no quantifiable estimate of the value of the benefits they have imparted to me. I will forever be in their debt. I would also like to thank Dr. John Solie for his insightfulness and encouragement with this work. His intellect and ideas are embodied in every level of this research. I would like to extend my thanks and gratitude to Dr. Bill Raun for his willingness to allow me to participate in and make a contribution to this research effort. His vision and dedication to helping farm producers and ranchers achieve their financial and quality-of-life goals is forever ingrained in my spirit. I would also like to extend my sincere appreciation to Dr. R. Joe Schatzer for his willingness to sit on my dissertation committee, and for his comments and suggestions regarding this research effort. I would like also like to thank Dr. Kyle Freeman for his diligence in collecting, managing, and reporting the data used in this research effort. And lastly, but certainly not least, I would like to thank my family and friends for the never ending support and encouragement they provided me throughout my undergraduate and graduate studies.

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ESSAY I

MAXIMUM VALUE OF PLANT-BASED PRECISION FERTILIZER TECHNOLOGY FOR WINTER WHEAT

Abstract

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 possible losses if weather does not permit 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-five 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. For prices of \$0.25 and \$0.15 pounds per acre N for UAN and NH_3, respectively, the maximum net value of an in season sensor based precision nitrogen application system for winter wheat was found to be approximately $8.80 to $9.80 per acre depending upon location. However, for prices of $0.50 and $0.30 pounds per acre of N for UAN and NH_3, the value was found to be approximately $13.36 per acre. The value of precise N application is sensitive to both the absolute and relative prices of UAN and NH_3.

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

Introduction

Nitrogen fertilizer is a primary input for winter wheat production, accounting for approximately 15 to 25 percent of the total operating costs (USDA). The conventional whole field nitrogen fertilizer management strategy for continuous monoculture winter wheat is to apply nitrogen uniformly prior to planting in the fall. With this method, producers may apply more fertilizer than is required in a typical year as insurance against running out of nitrogen in the event of a better than average weather year. Research has found that nitrogen availability varies substantially within a field (Raun et al, 1998; Solie et al, 1999). This implies that when uniform applications are used some places in the field may receive too much nitrogen and other places may receive too little. In response to these issues, site-specific precision fertilizer management technologies based on sampling the soil have been developed and promoted as a means to increase profit. However, adoption of these technologies has been slow (Daberkow and McBride).

This slow rate of adoption was unexpected given that an extensive review of many of the published studies regarding the economics of site-specific soil-based precision application technologies indicated that these technologies were expected to be profitable (Lambert and Lowenberg-DeBoer). A major criticism of these studies is that some of the costs associated with site-specific information management and variable rate application were overlooked (Hurley, et al., 2001; Swinton and Lowenberg-DeBoer, 1998). The slow rate of adoption combined with the findings from the more comprehensive economic analyses, suggest that soil-based precision application technologies are very likely not unambiguously more economical than conventional uniform application systems for all soils, crops, and nutrients.

A precision nitrogen fertilizer application technology that is based on sampling the plants directly using NDVI measurement taken with optical reflectance sensors to detect plant performance and nitrogen need has been postulated and developed into a working system (Raun et al, 2001). Central to this plant-based system is the placement of a nitrogen rich strip (NRS) in the center of the wheat field prior to planting in the fall. The NRS is treated with a level of nitrogen that is expected to not limit wheat plant growth throughout the growing season. In other words, a non-limiting amount of nitrogen is applied to a strip across the field such that in that strip yield will reach its plateau level (Frank, Beattie and Embleton; Grimm, Paris, and Williams; Waugh, Cate, and Nelson).

Normalized difference vegetation index (NDVI) sensor readings are obtained from the growing wheat in late winter (Tucker; Hockheim and Barber; Raun et al, 1999). Yield response to nitrogen is computed as a response index (RI), or the ratio of sensor readings taken from the NRS to sensor readings taken from an adjacent strip that received either zero pre-plant nitrogen or a level of nitrogen less than that applied to the NRS. Parameter estimates from a yield response to optical reflectance information function describe yield potential with no added fertilizer. An estimate of the maximum yield is calculated from the response index and the yield function. Nitrogen requirements for the nonNRS region of the field are computed based upon the difference between estimated yield of the nonNRS region and the estimated yield of the NRS region adjusted for a gain in expected nitrogen use efficiency.[1]

Economic feasibility of this plant-based technology has not been determined. The purpose of this study is to determine the maximum value of the precision system to commercial winter wheat producers. An estimate of the maximum value is computed from data from two long-term winter wheat fertility experiments conducted at research stations in Oklahoma. An estimate of the maximum value would be useful to wheat producers in helping them decide whether or not to adopt this technology, and would provide engineers and manufacturers with a target cost to deliver the technology. In addition to commercial wheat producers, adoption of the technology would be of interest to the environmental and international communities who are concerned with problems associated with nitrogen use.

In the next section, a conceptual framework describing the means for determining the maximum expected value of the plant-based system is provided. The data are then described and discussed. The next section provides the primary assumptions for the analysis and describes a linear response plateau function and how it is used to obtain yield estimates and levels of nitrogen. Yield and net return results are then discussed. Finally, conclusions and limitations are provided.

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[1] Raun et al. define nitrogen use efficiency as the percentage of nitrogen that is applied to the plants that is actually used by the plants. For a late winter application of UAN to winter wheat, it is assumed that the plants will efficiently use between fifty and seventy percent of the total nitrogen applied.

Conceptual Framework

An *ex ante* approach is used to determine the maximum expected value of the system, where the maximum expected value is assumed to be the difference between the expected net return above nitrogen and nitrogen application expenses from the precision system and the expected net return above nitrogen and nitrogen application expenses from a conventional nitrogen application system. Conceptually, this value can be expressed mathematically as

$$
\begin{aligned}
\max_{N^P, N^c = \overline{N}} E(V) &= \max_{N^P} \left\{ E(p)E\left[y_t^P\right] - r^P N^P - FC^P \right\} \\
&\quad - \max_{N^C = \overline{N}} \left\{ E(p)E\left[y^C\right] - r^C N^C - FC^C \right\}, \\
\text{s.t. } y_t^P &= y(N_t^P, \theta_t), \\
y^C &= y(N^C = \overline{N}, u).
\end{aligned}
\tag{1}
$$

where $E(\cdot)$ is the expectations operator; V is maximum value of plant-based precision technology; p is the price of wheat; N^P and N^C represent the optimal level of nitrogen for the precision system and the conventional system, respectively; (For this study the nitrogen source for the precision system is assumed to be urea-ammonium nitrate (UAN). Anhydrous ammonia (NH_3) is assumed to be the nitrogen source for the conventional system.) r^P and r^C are prices of UAN and NH_3, respectively; FC^P and FC^C represent the fixed application costs for the precision system and the conventional system, respectively; y_t^P and y^C are the yield functions for the precision system and the conventional system, respectively; $\overline{N}$ is the level of nitrogen assumed for the conventional system; and θ and u represent random disturbances that result from uncertain weather and uncertain changes in soil nitrogen mineralization. The unique part of this framework is the yield response function used for the precision system, y_t^P.

Data

Data from two long-term winter wheat fertility experiments conducted at experiment stations at Lahoma and Altus, Oklahoma were obtained. The Lahoma experiment included nitrogen treatment levels of 0, 20, 40, 60, 80, and 100 pounds per acre that were replicated four times each year from 1971 through 2004 for a total of 33 years.[2] The experiment at Altus included nitrogen treatment levels of 0, 20, 40, and 80 pounds per acre replicated six times each year from 1970 through 2002 for a total of 32 years.[3] Wheat yields were averaged across replications to obtain treatment means per year at both locations.

Growing conditions including weather and soil, and hence yield potential, are different at the two locations. This provides the opportunity to test the hypothesis that plant-based precision sensing technology will have a greater value to producers operating in a region that has more favorable growing conditions, and hence an area that produces higher expected yields, than it does to those operating in less favorable growing conditions, and lower expected yields. To illustrate the diversity between locations, wheat grain yields from the treatments assumed to represent the NRS (i.e., 100-pound treatment at Lahoma, and the 80-pound treatment at Altus) averaged across individual treatments for each year of both of the long-term data sets are presented in Figure I-1. Note that the average of these NRS yields is substantially different across locations. At Lahoma, the average yield from the NRS was approximately 42 bushels per acre while at Altus the NRS yield was substantially lower at only approximately 25 bushels per acre, which indicates that yield potential at Lahoma is substantially higher than at Altus.

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[2] Yield data were not available at Lahoma in 1970 and 1973.

[3] Yield data were not available at Altus for 1971, 2003 and 2004.

All nitrogen at Lahoma was applied as ammonium nitrate (34-0-0) and incorporated prior to planting wheat in October. At Altus, ammonium nitrate was applied as a topdress in late winter. At both locations wheat seed was planted in 10-inch rows at a seeding rate of 60 pounds per acre. The Lahoma soil is a Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll). The Altus soil is a Tillman-Hollister clay loam (fine-mixed, thermic Typic Paleustoll). For additional information regarding the Lahoma experiment (E502) see Mullen et al., and a description of the experiment (E407) at Altus can be found at (http://nue.okstate.edu/Long_Term_Experiments/E407.htm).

Methods and Procedures

To implement equation (1), that is to determine the potential value of the system, several assumptions and parameter estimates are required. Equation (1) is used to determine the difference in monetary returns between a conventional uniform nitrogen application rate and an alternative that uses a variable nitrogen level depending upon optical sensing of growing plants. For our purposes it is assumed that the conventional uniform nitrogen application method is to apply NH_3 prior to planting at a rate of 80 pounds per acre at Lahoma and 40 pounds per acre at Altus. For the alternative system it is assumed that no nitrogen is applied pre-plant. A foliar application of UAN is made in late winter with the nitrogen rate based upon sensor readings taken from the NRS relative to those taken from unfertilized locations in the field.

Yield response data that are conditional on optical reflectance sensor information are not available. As a result, parameter estimates from a response function can not be estimated and used in traditional expected profit-maximizing methods. However, the concepts behind the proposed variable rate system can be applied to these long-term data via the treatments to obtain yield estimates and net returns that can be averaged over the span of each data set.

To begin, several assumptions are made concerning the precision variable rate system. First, it is assumed that plant nitrogen requirements are met by a foliar application in late winter during Feekes growth stages 4-6 (i.e., the beginning of the erection of the pseudo-stem, leaf sheaths beginning to lengthen and the development of the first node of the stem visible at base of the shoot) (Large) as a 28% UAN solution. Second, a key assumption is that the plant-based 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 the plant-based technology.

The technology assumes that the maximum wheat yield is expected, on average, to be obtained from the NRS. To maintain this assumption, it is assumed that the yield recorded in the experimental data for the 100-pound treatment at Lahoma and the 80-pound treatment at Altus represents the yield obtained from a NRS. Since an argument can be made that some residual nitrogen will be carried over from the previous year, the 20-pound treatment was used instead of the zero-pound treatment to represent a zero level of preplant nitrogen. It is assumed that a linear response plateau (LRP) function best describes yield response to nitrogen. The LRP function has the following form

$$(2) \qquad y_t^P = \begin{cases} a + bN_t + \theta_t, & \text{if below the plateau,} \\ \mathrm{y}^{\mathrm{NRS}} + \theta_t, & \text{if on or above the plateau,} \end{cases}$$

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 nitrogen, y^{NRS} is the plateau yield obtained from the NRS (i.e., the yield obtained from 100-pound treatments at Lahoma and the 80-pound treatments at Altus), θ is a random error term that is distributed normal with mean zero and variance σ_θ^2. Intercept and slope parameters were not estimated for this function. The intercept represents the yield without the application of nitrogen fertilizer, and was assumed in this paper to be the yield obtained from the 20-pound treatment for each dataset. An estimate of the slope parameter (*b* = 0.3075) was taken from Tembo, Brorsen, and Epplin. Alternatively, by this measure, over the range of observed yields, an average of 3.25 pounds of additional nitrogen (1/0.3075) is required to obtain an additional bushel of wheat. The LRP function was used to determine the level of yield that would be obtained from a perfect precision system for each treatment in each year.

The technology is not expected to provide a yield response above the plateau maximum, so any positive differences between average yield for the 20-pound treatment and the yield given by the LRP for the same year and location were removed from the analysis. Levels of nitrogen for each treatment were calculated as the difference between yield at the plateau (NRS) and yield for the 20-pound treatment divided by the marginal product of nitrogen, and can be expressed mathematically as

$$(3) \qquad N_t^P = \frac{y_t^P - a}{b},$$

where N_t^P is the optimal level of nitrogen to apply in year *t* with the plant-based precision system, y_t^P is the yield obtained with the LRP function that describes the perfect plant-based precision system (equation (2)), *a* is the intercept of equation (2) (i.e., the yield obtained from the 20-pound treatment), and *b* is the marginal product of nitrogen, or the variable that represents the slope of equation (2).

For example, if the yield difference for a given year and location between the precision system and the yield from the 20-pound treatment was 10 bushels per acre, it was assumed that the variable rate sensing system would apply 32.5 pounds of nitrogen per acre (10 bushels per acre/0.3075 bushels per pound of nitrogen).

The price of \$0.25 per pound (r^P in equation (1)) was charged for the UAN solution with an additional application cost of \$2.90 per acre (FC^P in equation (1)) (Kletke and Doye). The price of wheat was set equal to \$3 per bushel (*p* in equation (1)).

Conventional Preplant System

Continuous monoculture winter wheat production typically begins in the summer with soil preparation. For this paper, it is assumed that nitrogen fertilizer is applied as NH_3 prior to planting. Many producers in the region use NH_3 because it is the least expensive source of nitrogen and because the timing of application is not critical. Wheat is harvested for grain in June.

The primary interest is to determine what the per-acre net return is from fertilizing with 80-pounds of nitrogen per acre per year at Lahoma and with 50-pounds per acre at Altus. Both rates are based on extension recommendations of two pounds of N per bushel of yield goal. At Lahoma, the yield goal is assumed to be 40 bushels per acre, and at Altus the yield goal is assumed to be 25 bushels per acre.[4] The lower yield goal assumed at Altus reflects the differences in growing conditions relative to the growing conditions at Lahoma. Net return is calculated as the difference between value of wheat yield response and the cost of fertilizing, and is calculated for each year and location. An average price of \$0.15 per pound (r^C in equation (1)) was used for the anhydrous ammonia, and an application cost of \$6.12 (FC^C in equation (1)) was used in the analysis (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 I-1. On average, a ten bushel per-acre yield response above the yield obtained from the plots that had the 20-pound treatment was observed on the plots taken from the 100-pound treatment, which in this study represents yield obtained from the NRS. Results show that a sensor-based variable rate application system that applies UAN in late winter would, on average, require 59 percent less nitrogen than the conventional 80-pound preplant treatment. That is, only 33 pounds of nitrogen would have been needed on average to achieve the same response as the 80-pound preplant treatment (i.e., the difference between the yield obtained on the 20-pound treatment and the 100-pound treatment). This is so, because in nine of 33 years, the 20-pound treatment had a yield that was equal to the yield obtained from the 100-pound treatment, which implies that in those years there was no response to the 80-pound treatment.

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[4] Based on a yield goal at Altus of approximately 25 bushels per acre, the preplant level of interest would be 50 pounds per acre; however, the experiment at this location did not have a 50-pound treatment included, so the 40-pound treatment was used.

For each state of nature (year) included in the data set, the nitrogen was assumed to be applied if the benefit from the additional nitrogen was greater than the cost of applying it. In addition, the maximum level of nitrogen that was allowed to be applied with the precision system was 100 pounds of N per acre. We are assuming that the precision system would not need to apply nitrogen in excess of the non- limiting level applied on the NRS. An additional argument could be made that nitrogen applied in excess of 100 pounds in late winter as a foliar application could burn the plants and hence reduce yields instead of increasing them. Figure I-2 provides a comparison of the magnitude of the differences in optimal levels of nitrogen to apply at the two locations under study. Note, that the optimal level of fertilizer needed at Lahoma using the plant-based technology is more than three and a half times the amount needed at Altus.

The data reported in Table I-1 show that the return over and above the cost of nitrogen expenses of a precision system would, on average, have been approximately \$118 per acre. This value is \$5.82 per acre greater than the net return to nitrogen expenses for the conventional preplant system. When fixed application charges were considered in the analysis for both systems the maximum expected value of the variable rate system averaged over the 33 years was equal to \$9.83 per acre 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 technology for this particular region ($E(V)$ of equation (1)).

The expected maximum value for the precision system at Lahoma was decomposed into quantity of nitrogen effect, price of nitrogen effect, fixed cost effect, and yield effect. As reported in Table I-2, on average, \$7.12 of the \$9.83 value was attributed to a savings in the quantity of nitrogen applied with the precision system. However, the price effect of $3.25 per acre can be subtracted from the quantity effect to yield the total effect of $3.87 per acre from using UAN and the precision system instead of the conventional preplant system that applies nitrogen as NH_3. The price effect is subtracted because the cost of using UAN instead of NH_3 reduces the value of precision. On average, the savings in fixed application expenses associated with not applying the NH_3 in the years when no nitrogen was required using the precision system was equal to $4.01 per acre. Lastly, there was a slight increase in yield at Lahoma from using the precision system in place of the convention. This response, on average, was equal to 0.65 bushels per acre. Assuming a wheat price of $3 per acre, this yield increase from using a precision system adds $1.95 per acre to the maximum value of the system.

A summary of yields, net returns, and expected differences in net returns between the two systems at Altus are presented in Table I-2. The yield response to nitrogen at Altus is substantially less than that of Lahoma. At Altus, average yield response between the plots that had the 20-pound per acre treatment and the plots that had the 80-pound application of nitrogen (i.e., the NRS) was only two bushels per acre. Assuming a sensor-based precision application technology could be used, the analysis shows that an average foliar application of approximately seven pounds of nitrogen per acre would be needed to obtain the same yield response as a preplant 40-pound application. This is approximately a 70 percent reduction in the total amount of nitrogen required, which would provide substantial savings in fertilizer expenses. In addition, there were 15 out of the 32 years that yield from the 20-pound treatment was at least as large as the yield obtained from the 80-pound treatment (i.e., the nitrogen rich strip). In these years, nitrogen would not have been needed, providing additional savings to the farm producers in this region.

Given the lower yields observed in the Altus experiment, average return to nitrogen was substantially less than observed in Lahoma. The net return above the cost of nitrogen was approximately $72 per acre, which is approximately $4 per acre greater than the net return to nitrogen expenses for the 40-pound per acre preplant convention. When the fixed application expenses for both systems are accounted for in the analysis, the plant-based precision system had an expected maximum value of $8.80 per acre above that of the conventional all-before-planting system. The estimated value of a sensor-based precision system was approximately 12 percent greater at Lahoma than Altus.

Similar to the analysis at Lahoma, the expected maximum value of the plant-based precision system at Altus was also decomposed into quantity of nitrogen effect, price of nitrogen effect, fixed cost effect, and yield effect. As reported in Table I-3, on average, $4.93 of the $8.80 value was attributed to a savings in the quantity of nitrogen applied with the precision system. The price effect of $0.71 per acre, when subtracted from the quantity effect, gives a total effect of $4.22 per acre from using UAN and the precision system as an alternative to the conventional preplant system. On average, there was approximately $5 of savings in fixed application expenses associated with not applying the NH_3 in the years when no nitrogen was required assuming a perfect system could be used. At Altus, no yield boost was observed from using the perfect plant-based precision system, and therefore none of the expected value at that location was attributed to gains in expected yield.

Sensitivity Analysis

Changes in the estimated value of the variable rate nitrogen application systems for both locations from changes in the marginal product of nitrogen, fertilizer prices, and fixed application costs are presented in Table I-3. The results show that, holding all other variables constant, an increase in the marginal product of nitrogen 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 143 percent increase in the marginal product of nitrogen (i.e., from .3075 to .75 (3.25 to 1.33 pounds of nitrogen per bushel)) results in a 27 percent increase in the value at Lahoma, but only an 6 percent increase in the value at Altus.

As would be expected, increases in the price of UAN relative to the price of NH_3 results in a reduction of the maximum value of the precision system. As the price of UAN increases from $0.25 to $0.40 per pound, the maximum value at Lahoma decreases from $9.38 per acre to $4.95 per acre, a 47 percent decrease. The same change at Altus results in a decrease in maximum value from $8.80 per acre to $7.74 per acre for a 12 percent decrease in value.

The opposite effect is observed when the price of NH_3 increases relative to UAN. As the price of NH_3 increases, the value of the system increases substantially. When the relative price is equal to 1 (i.e., the price of UAN and the price of NH_3 equal to $0.25 per pound of nitrogen) the maximum value of the precision system increases by 47 percent at Lahoma from $9.38 to $17.83 per acre, and at Altus it increases by 31 percent from $8.80 to $12.80 per acre.

As the fixed application costs for UAN are increased relative to the fixed application expenses for the NH_3, the value at Lahoma falls. If the application costs are increased to $6.12 per acre, which gives a relative fixed cost of 1, the maximum value at Lahoma decreases from $9.38 to $8.19 per acre. At this rate, though, the effect at Altus was a decrease in the expected maximum value of five percent. If the fixed cost of applying UAN exceeds the cost of applying NH_3, the benefit from applying nitrogen using the precision system at Altus does not outweigh the cost, which results in a zero level of nitrogen being applied.

Conclusions and Limitations

Precision technologies used to manage nitrogen fertilizer applications to winter wheat have been based on sampling the soil at sub-field grids. These technologies have been promoted as profitable, but have not been adopted in widespread fashion. An alternative plant-based precision fertilizer technology that uses optical reflectance sensor information from growing plants to determine plant performance and nitrogen need has been postulated and developed into a working system. The economics of the alternative system has not been researched. The objective of this paper was to determine the maximum potential value of the technology. Such a value would be useful to commercial wheat producers in helping them decide whether or not to adopt this type of technology, and would provide engineers and manufacturers with a target cost to deliver the technology.

Yield response data from long-term wheat fertility experiments conducted at two locations in Oklahoma were used to calculate estimates of yield response to nitrogen fertilizer application based on the underlying concept of the plant-based variable application precision system. Net returns above the cost of nitrogen and nitrogen application expenses from the precision system and the conventional pre-plant system used in the region were calculated.

Several points can be learned from this study. First, results indicate that managing nitrogen fertilizer on winter wheat using the concept of optical sensing of plants appears to offer additional value above the conventional practice, and this value, assuming perfect prediction of yields, differs depending on location. Second, in several years of the data, added nitrogen did not increase yields. Third, the value of the precision system is unachievable in practice due to unexplainable factors that affect yields after nitrogen application. The system as evaluated was assumed to predict perfectly so the maximum value is considered an upper bound on the technology.

The expected maximum value calculated in the paper does not include a fee or charge (per acre) for implementation of the precision technology. This implies that the farmer would not be able to extract the full amount of the expected per-acre maximum value even if it were fully achievable. In general a producer would only be interesting in adopting an alternative technology if it is unambiguously more profitable than the convention. This might imply, in some cases, the farm producer would only want to use this type of technology if it were provided to them in a custom service that they could just hire out to a crop consulting firm or rural cooperative service for a quoted per-acre payment.

In the case of custom sensing and application, the owners of the patent would not be the only entity that would want to extract a fee, but the agent who provides the custom services to the producer would want to extract a fee as well. The question, then, becomes: is this total expected maximum per-acre value of the precision technology large enough to satisfy the owners of the patent, the custom application agent, and the farm producer in such a way that it is adopted in widespread fashion?

A primary limitation for this research is the lack of data that reflects the actual technology. Better data describing actual yield response to nitrogen fertilization using the site-specific system is crucial in determining a better estimate of the value of the system. Better data could involve the implementation of a field experiment set up in a randomized split-plot design, where preplant applications and topdress applications are split on the same plots. A possible treatment structure for such an experiment is provided in the Appendix.

As development of the sensing and variable rate application system progresses, and better data become available, further research oriented at econometric estimation of yield response functions conditional on the optical sensor information should be conducted. In addition, due to the potential benefits that this type of optical sensing technology has for the environment in terms of improved water quality, additional research oriented at determining the value of this type of technology to society needs to be addressed.

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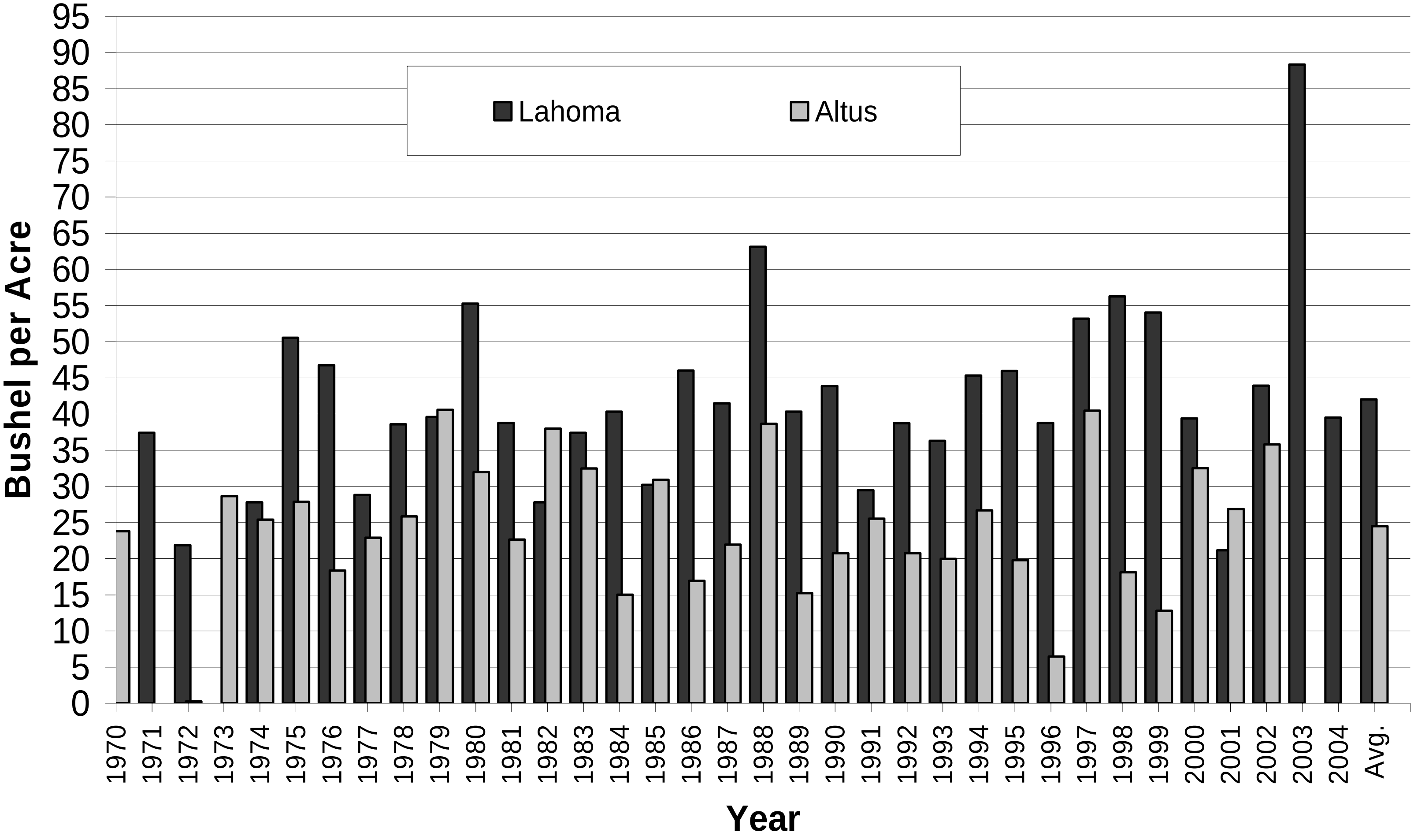

Figure I-1. **Annual wheat grain yields from treatments representing the nitrogen rich strip for Lahoma and Altus. Data were not available at Altus for 1971, 2003, and 2004. Data were not available for 1970 and 1973 at Lahoma.**

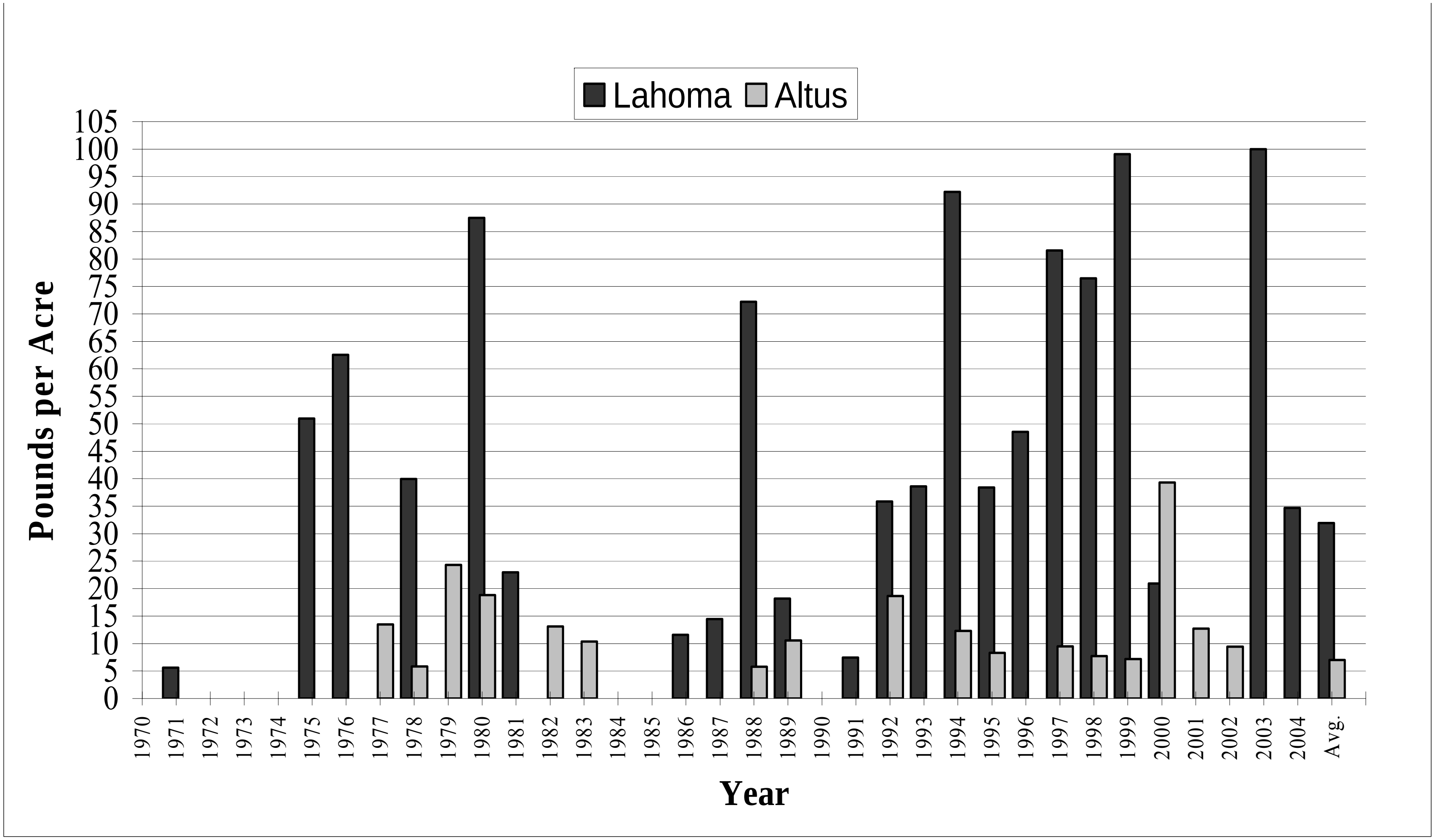

Figure I-2. **Optimal Levels of Nitrogen to Apply as Topdress in Late Winter Estimated Ex Post.**

Table I-1. Summary of Yields, Level of Nitrogen, and Returns to Nitrogen to Plant Based Sensing at Lahoma

Year	Yield From 20-lb Treatment[a]	Yield From Precision System[b]	Yield From Convention System[c]	Nitrogen Applied Using Precision[d]	Return To N Using Precision[e]	Return To N Using Convention[f]	Return Change In Return[g]	Return To N Using Precision[h]	Return To N Using Convention[i]	Change In Net Return[j]	Quantity Nitrogen Effect[k]	Price Nitrogen Effect[l]	Fixed Cost Effect[m]	Yield Effect[n]
1971	35.70	37.43	37.43	5.63	110.88	100.29	10.59	107.98	94.17	13.81	11.16	-0.56	3.22	0.00
1972	21.84	21.84	21.84	0.00	65.52	53.52	12.00	65.52	47.40	18.12	12.00	0.00	6.12	0.00
1974	27.04	27.80	27.80	0.00	83.40	71.40	12.00	83.40	65.28	18.12	12.00	0.00	6.12	0.00
1975	34.88	50.55	50.55	50.96	138.91	139.65	-0.74	136.01	133.53	2.48	4.36	-5.10	3.22	0.00
1976	27.50	46.74	46.74	62.57	124.58	128.22	-3.64	121.68	122.10	-0.42	2.61	-6.26	3.22	0.00
1977	26.86	28.83	28.83	6.41	84.89	74.49	10.40	81.99	68.37	13.62	11.04	-0.64	3.22	0.00
1978	26.29	38.57	38.57	39.93	105.73	103.71	2.02	102.83	97.59	5.24	6.01	-3.99	3.22	0.00
1979	39.58	39.58	39.58	0.00	118.74	106.74	12.00	118.74	100.62	18.12	12.00	0.00	6.12	0.00
1980	28.41	55.30	53.01	87.45	144.04	147.03	-2.99	141.14	140.91	0.23	-1.12	-8.74	3.22	6.87
1981	31.71	38.78	38.78	22.99	110.59	104.34	6.25	107.69	98.22	9.47	8.55	-2.30	3.22	0.00
1982	27.80	27.80	27.80	0.00	83.40	71.40	12.00	83.40	65.28	18.12	12.00	0.00	6.12	0.00
1983	37.42	37.42	37.42	0.00	112.26	100.26	12.00	112.26	94.14	18.12	12.00	0.00	6.12	0.00
1984	40.35	40.35	40.35	0.00	121.05	109.05	12.00	121.05	102.93	18.12	12.00	0.00	6.12	0.00
1985	30.22	30.22	30.22	0.00	90.66	78.66	12.00	90.66	72.54	18.12	12.00	0.00	6.12	0.00
1986	42.44	46.01	46.01	11.61	135.13	126.03	9.10	132.23	119.91	12.32	10.26	-1.16	3.22	0.00
1987	37.06	41.50	41.50	14.44	120.89	112.50	8.39	117.99	106.38	11.61	9.83	-1.44	3.22	0.00
1988	40.96	63.16	63.16	72.20	171.43	177.48	-6.05	168.53	171.36	-2.83	1.17	-7.22	3.22	0.00
1989	34.73	40.32	40.32	18.18	116.42	108.96	7.46	113.52	102.84	10.68	9.27	-1.82	3.22	0.00
1990	41.83	43.86	43.86	6.60	129.93	119.58	10.35	127.03	113.46	13.57	11.01	-0.66	3.22	0.00
1991	27.20	29.49	29.49	7.45	86.61	76.47	10.14	83.71	70.35	13.36	10.88	-0.74	3.22	0.00
1992	27.73	38.75	38.75	35.84	107.29	104.25	3.04	104.39	98.13	6.26	6.62	-3.58	3.22	0.00
1993	24.44	36.32	36.32	38.63	99.30	96.96	2.34	96.40	90.84	5.56	6.20	-3.86	3.22	0.00
1994	16.95	45.31	41.55	92.23	112.87	112.65	0.22	109.97	106.53	3.44	-1.83	-9.22	3.22	11.28
1995	34.15	45.96	45.96	38.41	128.28	125.88	2.40	125.38	119.76	5.62	6.24	-3.84	3.22	0.00
1996	23.83	38.76	38.76	48.55	104.14	104.28	-0.14	101.24	98.16	3.08	4.72	-4.86	3.22	0.00
1997	28.10	53.17	52.70	81.53	139.13	146.10	-6.97	136.23	139.98	-3.75	-0.23	-8.15	3.22	1.41
1998	32.73	56.25	56.25	76.49	149.63	156.75	-7.12	146.73	150.63	-3.90	0.53	-7.65	3.22	0.00
1999	23.56	54.03	48.16	99.09	137.32	132.48	4.84	134.42	126.36	8.06	-2.86	-9.91	3.22	17.61
2000	32.96	39.40	39.40	20.94	112.96	106.20	6.76	110.06	100.08	9.98	8.86	-2.09	3.22	0.00
2001	21.16	21.16	21.16	0.00	63.48	51.48	12.00	63.48	45.36	18.12	12.00	0.00	6.12	0.00
2002	43.92	43.92	43.92	0.00	131.76	119.76	12.00	131.76	113.64	18.12	12.00	0.00	6.12	0.00
2003	54.71	88.33	79.31	100.00	239.99	225.93	14.06	237.09	219.81	17.28	-3.00	-10.00	3.22	27.06
2004	28.86	39.53	39.53	34.70	109.92	106.59	3.33	107.02	100.47	6.55	6.80	-3.47	3.22	0.00
Average	31.91	42.01	41.36	32.51	117.91	112.09	5.82	115.80	105.97	9.83	7.12	-3.25	4.01	1.95

[a] Yield (bushels per acre) is taken from the 20-pound treatment which represents the 0-pound treatment with residual nitrogen (equal to the intercept (a) of equation (1)).

[b] Yield (bushels per acre) for the precision system is obtained using the LRP function (equation (1)): (y = min[a+b100, yNRS]) where the intercept (a) is the yield from the 20-pound treatment, and yNRS is equal to the yield off the 100-pound treatment at Lahoma.

[c] Yield (bushels per acre) for the conventional system is obtained using the LRP function (equation (1)): (y = min[a+b80, yNRS]) where the intercept (a) is the yield from the 20-pound treatment, and yNRS is equal to the yield off the 100-pound treatment at Lahoma.

[d] Is the optimal level of nitrogen (pounds per acre) to apply with the precision system and is calculated as: (yield from precision system minus yield from 20-pound treatment divided by the marginal product of nitrogen (see equation (3)).

[e] Return to nitrogen expenses for the precision system ($ per acre).

[f] Return to nitrogen expenses for the conventional system ($ per acre).

[g] Change in returns to nitrogen between the precision system and the conventional system (V in equation (1)) ($ per acre).

[h] Net return to nitrogen and nitrogen application expenses for the precision system ($ per acre).

[i] Net return to nitrogen and nitrogen application expenses for the conventional system ($ per acre).

[j] Change in net return between the precision system and the conventional system ($ per acre). Note, average total change in net return ($9.83) represents the expected maximum value of the plant-based system (E(V) of equation (1)).

[k] Component of the total value of the precision system that is attributed to the savings in the quantity of nitrogen used ($ per acre).

[l] Component of the total value of the precision system that is attributed to the difference in the prices for the two sources of nitrogen ($ per acre). Since UAN is more expensive than NH3, the price effect is subtracted from the total value.

[m] Component of the total value of the precision system that is attributed to the savings in fixed application costs ($ per acre) from not applying NH3.

[n] Component of the total value of the precision system that is attributed to the value of a yield response over and above that obtained from the conventional system. (On average at Lahoma, the value of the yield response associated with the precision system was $1.95 per acre (0.65 bushels per acre times $3.00 per bushel).

Table I-2. Summary of Yields, Level of Nitrogen, and Returns to Nitrogen to Plant Based Sensing at Altus

Year	Yield From 20-lb Treatment[a]	Yield From Precision System[b]	Yield From Convention System[c]	Nitrogen Applied Using Precision[d]	Return To N Using Precision[e]	Return To N Using Convention[f]	Return Change In Return[g]	Return To N Using Precision[h]	Return To N Using Convention[i]	Change In Net Return[j]	Quantity Nitrogen Effect[k]	Price Nitrogen Effect[l]	Fixed Cost Effect[m]	Yield Effect[n]
1970	23.78	23.78	23.78	0.00	71.34	65.34	6.00	71.34	59.22	12.12	6.00	0.00	6.12	0.00
1972	0.17	0.23	0.23	0.00	0.69	-5.31	6.00	0.69	-11.43	12.12	6.00	0.00	6.12	0.00
1973	28.63	28.63	28.63	0.00	85.89	79.89	6.00	85.89	73.77	12.12	6.00	0.00	6.12	0.00
1974	25.38	25.38	25.38	0.00	76.14	70.14	6.00	76.14	64.02	12.12	6.00	0.00	6.12	0.00
1975	27.87	27.87	27.87	0.00	83.61	77.61	6.00	83.61	71.49	12.12	6.00	0.00	6.12	0.00
1976	18.37	18.37	18.37	0.00	55.11	49.11	6.00	55.11	42.99	12.12	6.00	0.00	6.12	0.00
1977	18.75	22.90	22.90	13.50	65.33	62.70	2.63	62.43	56.58	5.85	3.98	-1.35	3.22	0.00
1978	24.03	25.83	25.83	5.85	76.03	71.49	4.54	73.13	65.37	7.76	5.12	-0.59	3.22	0.00
1979	33.12	40.60	40.60	24.33	115.72	115.80	-0.08	112.82	109.68	3.14	2.35	-2.43	3.22	0.00
1980	26.20	31.98	31.98	18.80	91.24	89.94	1.30	88.34	83.82	4.52	3.18	-1.88	3.22	0.00
1981	22.65	22.65	22.65	0.00	67.95	61.95	6.00	67.95	55.83	12.12	6.00	0.00	6.12	0.00
1982	33.95	37.98	37.98	13.11	110.66	107.94	2.72	107.76	101.82	5.94	4.03	-1.31	3.22	0.00
1983	29.30	32.48	32.48	10.34	94.85	91.44	3.41	91.95	85.32	6.63	4.45	-1.03	3.22	0.00
1984	14.65	15.03	15.03	0.00	45.09	39.09	6.00	45.09	32.97	12.12	6.00	0.00	6.12	0.00
1985	30.92	30.92	30.92	0.00	92.76	86.76	6.00	92.76	80.64	12.12	6.00	0.00	6.12	0.00
1986	16.60	16.92	16.92	0.00	50.76	44.76	6.00	50.76	38.64	12.12	6.00	0.00	6.12	0.00
1987	20.75	21.93	21.93	0.00	65.79	59.79	6.00	65.79	53.67	12.12	6.00	0.00	6.12	0.00
1988	36.90	38.67	38.67	5.76	114.57	110.01	4.56	111.67	103.89	7.78	5.14	-0.58	3.22	0.00
1989	11.97	15.22	15.22	10.57	43.02	39.66	3.36	40.12	33.54	6.58	4.41	-1.06	3.22	0.00
1990	19.73	20.73	20.73	0.00	62.19	56.19	6.00	62.19	50.07	12.12	6.00	0.00	6.12	0.00
1991	25.53	25.53	25.53	0.00	76.59	70.59	6.00	76.59	64.47	12.12	6.00	0.00	6.12	0.00
1992	15.02	20.76	20.76	18.67	57.61	56.28	1.33	54.71	50.16	4.55	3.20	-1.87	3.22	0.00
1993	19.51	19.96	19.96	0.00	59.88	53.88	6.00	59.88	47.76	12.12	6.00	0.00	6.12	0.00
1994	22.92	26.69	26.69	12.26	77.00	74.07	2.93	74.10	67.95	6.15	4.16	-1.23	3.22	0.00
1995	17.25	19.81	19.81	8.33	57.35	53.43	3.92	54.45	47.31	7.14	4.75	-0.83	3.22	0.00
1996	6.47	6.47	6.47	0.00	19.41	13.41	6.00	19.41	7.29	12.12	6.00	0.00	6.12	0.00
1997	37.55	40.47	40.47	9.50	119.04	115.41	3.63	116.14	109.29	6.85	4.58	-0.95	3.22	0.00
1998	15.73	18.11	18.11	7.74	52.40	48.33	4.07	49.50	42.21	7.29	4.84	-0.77	3.22	0.00
1999	10.59	12.79	12.79	7.15	36.58	32.37	4.21	33.68	26.25	7.43	4.93	-0.72	3.22	0.00
2000	20.43	32.51	32.51	39.28	87.71	91.53	-3.82	84.81	85.41	-0.60	0.11	-3.93	3.22	0.00
2001	22.98	26.89	26.89	12.72	77.49	74.67	2.82	74.59	68.55	6.04	4.09	-1.27	3.22	0.00
2002	32.92	35.82	35.82	9.43	105.10	101.46	3.64	102.20	95.34	6.86	4.59	-0.94	3.22	0.00
Average	22.21	24.50	24.50	7.10	71.72	67.49	4.22	70.18	61.37	8.80	4.93	-0.71	4.58	0.00

[a] Yield (bushels per acre) is taken from the 20-pound treatment which represents the 0-pound treatment with residual nitrogen (equal to the intercept (a) of equation (1)).

[b] Yield (bushels per acre) for the precision system is obtained using the LRP function (equation (1)): ($y = \min[a+b80, yNRS]$) where the intercept (a) is the yield from the 20-pound treatment, and yNRS is equal to the yield off the 80-pound treatment at Altus.

[c] Yield (bushels per acre) for the conventional system is obtained using the LRP function (equation (1)): ($y = \min[a+b40, yNRS]$) where the intercept (a) is the yield from the 20-pound treatment, and yNRS is equal to the yield off the 80-pound treatment at Altus.

[d] Is the optimal level of nitrogen (pounds per acre) to apply with the precision system and is calculated as: (yield from precision system minus yield from 20-pound treatment divided by the marginal product of nitrogen (see equation (3)).

[e] Return to nitrogen expenses for the precision system ($ per acre).

[f] Return to nitrogen expenses for the conventional system ($ per acre).

[g] Change in returns to nitrogen between the precision system and the conventional system (V in equation (1)) ($ per acre).

[h] Net return to nitrogen and nitrogen application expenses for the precision system ($ per acre).

[i] Net return to nitrogen and nitrogen application expenses for the conventional system ($ per acre).

[j] Change in net return between the precision system and the conventional system ($ per acre). Note, average total change in net return ($8.80) represents the expected maximum value of the plant-based system (E(V) of equation (1)).

[k] Component of the total value of the precision system that is attributed to the savings in the quantity of nitrogen used ($ per acre).

[l] Component of the total value of the precision system that is attributed to the difference in the prices for the two sources of nitrogen ($ per acre). Since UAN is more expensive than NH3, the price effect is subtracted from the total value.

[m] Component of the total value of the precision system that is attributed to the savings in fixed application costs ($ per acre) from not applying NH3.

[n] Component of the total value of the precision system that is attributed to the value of a yield response over and above that obtained from the conventional system. Note that no yield response was observed between the precision system and the conventional system at this location.

Table I-3. Sensitivity Values for Independent Relative Changes in MPN, Prices of Nitrogen, and Fixed Costs at Lahoma and Altus Locations

Lahoma		Altus					
Maximum Value to Nitrogen	Total Maximum Value	Maximum Value to Nitrogen	Total Maximum Value	MPN	Price UAN	Price NH3	FC UAN
Change in Marginal Product of Nitrogen							
0.00	3.79	4.79	10.73	0.10			
5.82	9.83	4.22	8.80	0.31[a]	0.25[a]	0.15[a]	2.90[a]
8.90	12.92	4.89	9.38	0.50			
10.58	14.50	5.26	9.75	0.75			
11.42	15.34	5.44	9.93	1.00			
11.93	15.85	5.56	10.04	1.25			
Change in Price of UAN							
4.19	8.20	3.87	8.45		0.30		
0.94	4.95	3.16	7.74		0.40		
-2.31	1.70	2.63	7.39		0.50		
Change in Price of NH_3							
9.82	13.83	6.22	10.80			0.20	
11.42	15.43	7.02	11.60			0.22	
13.82	17.83	8.22	12.80			0.25	
17.82	21.83	10.22	14.80			0.30	
Change in Fixed Application Cost of UAN							
5.82	9.03	4.31	8.56				4.00
5.96	8.19	4.50	8.32				6.12
6.10	6.10	†	†				10.63

[a] Represents the actual values for the parameters used prior to sensitivity analysis.

† Fixed costs for UAN above $6.12 per acre at Altus results in a zero-pound solution for the perfect system each year, and is therefore non-meaningful to the sensitivity analysis.

Note, average maximum values are reported as dollars per acre, and all prices for fertilizer are reported as dollars per pound of actual nitrogen. In addition, fixed costs are reported as dollars per acre.

Appendix

Table I-4. Treatment recommendations for a randomized split-plot wheat fertility experiment using site-specific optical sensing technology (pounds per acre).

Treatment	Preplant Nitrogen	Topdress Solution
1	0	0, 12, 24, 36, 48, 60, 72, 84
2	20	0, 12, 24, 36, 48, 60, 72, 84
3	40	0, 12, 24, 36, 48, 60, 72, 84
4	60	0, 12, 24, 36, 48, 60, 72
5	65	0, 12, 24, 36, 48, 60
6	70	0, 12, 24, 36, 48
7	75	0, 12, 24, 36, 48
8	80	0, 12, 24, 36

ESSAY II

NITROGEN FERTILIZATION OF GROWING WHEAT BASED UPON SITE-SPECIFIC OPTICAL SENSING

Abstract

A plant-based site-specific nitrogen fertilizer system that uses NDVI reflectance measurements of growing wheat plants to sense and estimate nitrogen requirements is under development. The variable rate applicator is designed to enable unique applications of liquid nitrogen fertilizer at a grid level of four square feet. The objective is to determine if the system is more economical than alternative systems. Data from on-farm nitrogen fertilizer experiments were collected across four years and ten locations. Net returns were calculated for each of eight treatments. The site-specific system is competitive economically, but not unambiguously superior to the conventional alternatives.

Key Words: optical sensing, NDVI, nitrogen fertilizer, precision farming, site specific, wheat

Introduction

A number of precision and site-specific technologies have been developed and introduced to the farming community, including global positioning systems, geographic information systems, yield monitoring sensors, and computer controlled within-field variable rate application equipment. Many agronomists, engineers, and economists posit that precision technology will be a driving force behind production agriculture in the future. Even though the profitability of some precision technologies appears promising, widespread adoption has been slow (Daberkow and McBride).

Nitrogen fertilizer is a primary nutrient that is typically applied each year in the fall prior to planting wheat in the southern Great Plains, and accounts for 20 to 30% of the per acre cash expenses, depending on the size of farm and location. Precision technologies for fertilizer application on wheat have relied on grid soil sampling, soil testing, and mapping on a three-acre grid basis. Haneklaus, Shroeder, and Schnug evaluated different decision-making processes governing variable rate fertilizer application. They concluded that to accurately describe the variability of nitrogen, phosphorus, and other plant nutrients in the soil, small grids are preferred to large grids. They found that 108 square foot grids (10 square meters) are more appropriate than the three-acre average grid size normally used as sample sites. Others report similar findings. For example, extensive soil testing, optical reflectance measurements of plants, and yields collected on very small plots, have shown that the spatial scale of nitrogen availability to winter wheat can be as small as a four square feet grid, and that economically optimal levels of nitrogen fertilizer may differ on adjacent four-square-foot grids (Raun et al.; Solie, Raun and Stone.).

Practical implementation of a management strategy to sense growing wheat and apply nitrogen at a grid level of four-square-feet (10,890 square grids per acre) is challenging. A prototype site-specific variable rate nitrogen application system that uses optical reflectance information obtained from growing winter wheat plants has been developed. The system does not require mapping of soils, soil testing, or yield monitors. However, it does require several steps. First, in the late summer, or early fall, nitrogen is applied to a narrow strip of the field prior to planting. The level of nitrogen applied to the strip must be sufficient so as not to limit plant growth throughout the growing season. In other words, a non-limiting amount of nitrogen is applied to a strip across the field such that in that strip yield will reach its plateau level (Frank, Beattie and Embleton; Grimm, Paris, and Williams; Paris; Waugh, Cate, and Nelson). This is referred to as a nitrogen rich strip (NRS). 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 nitrogen rich strip area of the field. These measurements provide information that enable comparing nitrogen uptake from plants growing in the area of the field where nitrogen is not yield limiting to plants growing elsewhere in the field.

Third, the system uses a self-propelled boom sprayer equipped with a mix of optical reflectance sensors, on-board computers, and a global positioning device that is used to assist with steering the sprayer to prevent repeated applications on individual grids throughout the field. An algorithm programmed into the system's computers uses the sensor information from the NRS and sensor information from each four-square-foot grid of the field to determine the nitrogen treatment levels. The intent of the algorithm is to determine the quantity of nitrogen to apply to each individual four-square-foot grid necessary to achieve the plateau yield (Solie et al.). As the applicator moves across the field, the machine optically senses, computes the level of nitrogen, and treats individual four-square-foot grids with 28% liquid nitrogen solution on the go.

The prototype does not consider either the price of nitrogen or the price of wheat. The objective of the research is to determine if the system is more economical than alternative nitrogen fertilization strategies. The system is in commercial production, but few sales have been made. Given the substantial investment needed to further develop the system, and the potential environmental benefits from lower nitrogen 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 and promote the new equipment, and would be useful to agricultural extension specialists who may be confronted with questions regarding the system.

Economics of Variable Rate Precision Technology (VRPT)

Several studies have focused on estimating the economic feasibility of precision technologies for agricultural production. Lambert and Lowenberg-DeBoer reviewed 108 studies that provided estimates of the economics of site-specific variable rate precision technologies for agriculture. They found that 63% of the studies reported positive economic benefits for the precision technology evaluated. However, Bullock, Lowenberg-DeBoer, and Swinton found that of those 63% reporting economic benefits, many had omitted important costs, made unrealistic yield advantage estimates, or used simulation methods that might overestimate the value. The economics of variable rate fertilizer application are driven by three elements: (1) increased cost of sampling information and variable rate application; (2) change in cost of fertilizer applied; and (3) change in revenue due to crop yield. The cost of information that is provided by precision technologies is central to analyzing profitability. However, cost estimates are not included in some studies (Bullock, Lowenberg-DeBoer, and Swinton).

VRPT for Wheat

Some studies have reported positive economic returns to VRPT for wheat. For example, Fiez, Miller, and Pan reported that managing nitrogen on wheat using VRPT was more profitable than a uniform management strategy, but they did not consider some of the costs associated with using VRPT, reported data from only one year, and did not consider risk. Long, Carlson, and Nielsen also reported that net returns from VRPT were greater than the uniform strategy. Godwin et al. evaluated nitrogen application rates and systems for wheat and barley fields in a one-year three-site on-farm experiment located in the United Kingdom. They reported that net returns from VRPT across all sites were greater than uniform rate systems, and that net returns varied by site and method used. However, they did not consider the cost of information collection, fixed costs for application, and did not consider risk.

Other studies of VRPT for commercial wheat production have found that the economics is questionable. Wibawa et al., Lowenberg-DeBoer and Aghib, and Carr et al. found that whole field management strategies realized higher net returns than managing fertilizer using VRPT based on soil mapping information and grid soil sampling and testing information. The reasons for these findings are related to the high costs of implementing the precision technologies, such as consulting fees, costs of training, and costs of information gathering.

Wollenhaupt and Buchholtz summarized the results of four field trials that investigated the marginal returns of VRPT for wheat in Montana. They concluded that site-specific management techniques including grid and soil sampling tests, map-making, variable rate fertilizing, and data management were not profitable compared to conventional soil fertility management techniques. They found that special application equipment, additional soil sampling and analysis, data management and map making incurred higher costs than the benefits incurred from the site-specific management strategy.

Swinton and Lowenberg-DeBoer evaluated the profitability of VRPT on nine farms in the western United States. They found that VRPT was not profitable for wheat and barley. They concluded that high value, high yielding crops are more economically responsive to VRPT than lower value per acre crops such as wheat and barley. Hennessy, Babcock, and Fiez concluded that site-specific information is a low-value commodity, and that returns from VRPT did not outweigh implementation costs. For the conditions of their study they found little incentive for producers to adopt VRPT.

The majority of studies have concluded that VRPT such as grid mapping and intensive soil testing are not economical for wheat. However, to-date the economics of site-specific nitrogen fertilizer application to wheat using optical sensing technology has not been evaluated. This plant-based precision technology does not require soil mapping, soil sampling, or soil testing. The optical sensing technology samples (senses) the growing plant directly.

Procedures and Data

The annual per acre ownership and operating costs for the sensor and computer equipped nitrogen fertilizer applicator are estimated. The cost of implementing the NRS prior to planting wheat is also estimated. Net returns are computed for eight nitrogen fertilizer management systems, including two systems that use site-specific four-square-foot grid technology.

Yield data were obtained from a series of on-farm wheat experiments with alternative nitrogen treatments conducted during the 2002, 2003, and 2004 growing seasons across ten locations in Oklahoma. The farms were located near the communities of Altus, Blackwell, Chickasha, Covington, Haskell, Hennessey, Lahoma, Perkins, Perry, and Tipton. Wheat grown on these on-farm experiments are managed for a grain-only crop. The nitrogen fertilization treatments are as follows: 0/0 is a check treatment that received a 0-pound per acre level of nitrogen prior to planting in September and a 0-pound per acre level of topdress in March; 0/40 received a 0-pound per acre level of preplant and a 40-pound per acre level of actual nitrogen as a topdress in March; 0/80 received a 0-pound per acre level of preplant and an 80-pound per acre level of topdress; 40/40 received a 40-pound per acre level of both preplant and topdress; 40/0 received a 40-pound per acre level of preplant and a 0-pound per acre level of topdress; 80/0 included an 80-pound per acre level of preplant with no topdress; 0/OS received no preplant nitrogen with the level of topdress determined by the optical sensing (OS) system; and 40/OS included a 40-pound per acre level of preplant with topdress levels determined by the optical sensing system.

Treatment yield means for each location were averaged across all replications for each year. Treatments 0/OS and 40/OS are the two alternative treatments for managing nitrogen application to winter wheat using the prototype site-specific optical sensing applicator. For the experiments, preplant nitrogen was applied as 33% ammonium nitrate (AN) prior to planting wheat in the fall, and topdress nitrogen was applied as 28% urea-ammonium nitrate (UAN) during Feekes Physiological Growth Stages 4-6 (i.e., the beginning of the erection of the pseudo-stem and the leaf sheaths beginning to lengthen and the development of the first node of the stem visible at base of the shoot in early spring) (Large, 1954; Stone et al., 1996; Solie et al., 1996). However, there are currently many wheat producers in the southern Great Plains who apply anhydrous ammonia (NH_3) prior to planting, primarily due to its lower cost. Net returns are estimated for each of the eight treatments under the assumption that AN was used as the source of preplant nitrogen and then again under the assumption that NH_3 was used as the source of preplant nitrogen. For the region under study it is assumed that wheat yield responds to the level but not the source of preplant nitrogen.

The levels of 28% UAN applied with treatments 0/OS and 40/OS in the on-farm experiments were determined using a nitrogen fertilizer optimization algorithm that compares optical reflectance information obtained from the NRS and with information from an adjacent strip of the field that is nitrogen stressed. The algorithm is programmed into the computers on the prototype machine. Sensors mounted at the front of the machine sense the growing plants and provide a reading to the onboard computers. The information is used to determine the level of nitrogen to apply. As the rear of the machine travels across the sensed grid it is fertilized. A description of the algorithm used for the on-farm trails used in this research is presented in Raun et al. 2002.

Machine Costs

Custom application charges for applying 28% UAN fertilizer in the southern Great Plains in the spring is, on average, $2.90 per acre (Kletke and Doye). This includes ownership and operating costs including the cost of transporting fertilizer and applicator to and from the field. The ownership and operating expenses associated with equipping a field applicator with optical sensing technology is computed using MACHSEL (Kletke and Sestak). The cost of modifying and equipping a self-propelled fertilizer applicator with optical reflectance technology is $60,000. The expected useful life of the equipment is five years. This is assumed because of the rapid rate of obsolescence and wear and tear of the many computers that are included with the technology. The applicator equipped with optical sensing technology is expected to have a field operating speed of 15 miles per hour with 70% field efficiency. By these measures, the applicator can cover 82.7 acres per hour for a total of 827 acres per day when used 10 hours per day. The window of opportunity for applying liquid nitrogen to winter wheat during the optimal application time may be relatively small due to weather conditions, so machine managers could be expected to use the machine as many hours per day as possible.

Workers in the region earn, on average, ten dollars per hour to operate a self-propelled boom-sprayer. However, with the enhanced site specific applicator the operator is expected to have additional interaction with the machine's computers that will require additional training. The cost of this additional training is reflected in the wage rate. To reflect this cost of additional training, a wage rate of $12 rather than $10 per hour was assumed. This two-dollar difference is considered when determining the ownership and operating cost of the optical sensing technology. An annual interest rate of eight percent is assumed.

Cost of Nitrogen Rich Strip

Implementing the NRS is an essential part of the optical sensing technology. The NRS is placed in the center of the field. Its size is a function of the applicator boom width and the length of the field. For this study the width of the NRS is assumed to be 65 feet, which is the same as the width of the site-specific variable rate applicator. Field area is assumed to be 160 acres (0.5 mile square). Hence, NRS length is assumed to be 2,640 feet. This gives a total area of 171,600 square feet, which translates into a NRS equal to 3.94 acres. For the 0/OS treatment, the applicator is assumed to make one pass across the center of the field applying 120 pounds of nitrogen in the form of 28% UAN per acre, and for the 40/OS treatment the applicator will make one pass across the center of the field, but it will only apply 80 pounds of nitrogen. The NRS encompasses approximately two percent of the 160-acre field. To account for the cost of the NRS, the per-acre machine ownership and operating cost is multiplied by 1.02.

Net Return

Net return is calculated for each treatment and year as the difference between gross revenue from the sale of wheat grain and the cost of nitrogen fertilization. Average prices for wheat grain and nitrogen fertilizer sources are based on long-term (32-year) averages (USDA). The budgeted price of wheat grain is $3 per bushel, anhydrous ammonia (82-0-0) is $0.15 per pound of nitrogen ($246 per ton), ammonium nitrate (33-0-0) is $0.25 per pound of nitrogen ($170 per ton), and UAN liquid solution (28-0-0) is $0.25 per pound of nitrogen ($140 per ton). In addition to using the 32-year average price of $0.15 per pound for anhydrous ammonia, net returns for each treatment that requires preplant nitrogen were also calculated using the 2002 price of anhydrous ammonia of $0.22 per pound ($361 per ton) to reflect a possible structural change in the production and marketing of this type of nitrogen fertilizer.

Results

Wheat grain yields for each treatment, year, and location and levels of 28% UAN applied for the two treatments using optical sensing technology are presented in Table II-1. Across all locations and years of the study, the average amount of nitrogen applied as 28% UAN in the spring with the 0/OS treatment was 25.7 pounds per acre, and the average response to nitrogen for this treatment was 5 bushels per acre. For the 40/OS treatment, an average of 22.7 pounds of nitrogen was applied as 28% UAN in the spring that resulted in an average response of 9.3 bushels per acre. The yield response from the 40/OS system is 4.3 bushels greater than that of the 0/OS system. This is due to the fact that 40 pounds of nitrogen was applied as a preplant in the fall with the 40/OS system in addition to the 22.7 pounds applied on average for the 0/OS system for an average of 62.7 pounds per acre. 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 percent level of confidence.

During the 2002 season, the average yield from the 0/0 treatment was 42 bushels per acre. In the same year, the 0/OS treatment applied, on average, eight pounds per acre of nitrogen as UAN in the spring and also yielded 42 bushels per acre. The 40/OS treatment received 40 pounds of actual nitrogen preplant and ten pounds of nitrogen topdressed as UAN and also yielded 42 bushels per acre. During 2002, it would have been more economical not to apply any nitrogen in the spring.

In 2003, the average yield obtained from the 0/0 treatment was 38 bushels per acre. The 0/OS treatment received an average of 23 pounds per acre of nitrogen in the spring and yielded 43 bushels per acre. The 40/OS treatment received 40 pounds per acre of nitrogen preplant and an average of 25 pounds per acre in the spring and yielded 53 bushels per acre.   These data suggest that for 2003 the site-specific system did not apply sufficient nitrogen to the 0/OS treatments. The results suggest that additional research may be warranted to either improve the algorithm used to determine the site-specific application rates or to improve the applicator.

Estimated annual ownership and operating costs, including the cost of implementing the NRS for the site-specific system are reported in Table II-2. Results indicate, as expected, that an inverse relationship exists between the annual cost per acre and the number of days per year the machine is used. Since the window for machine use in the spring for applying nitrogen to wheat is expected to be about 15 days per year due to likeliness of unfavorable weather, the cost of $5.01 acre was used to estimate net returns above the cost of fertilizer application for the 0/OS treatment, and $4.77 for the 40/OS treatment. These costs are based on (1) the cost of non site-specific nitrogen fertilizer application ($2.90/acre), (2) an estimated cost of $60,000 to equip the fertilizer applicator with optical sensing technology, and (3) the cost of treating the NRS in the fall prior to planting wheat. Application costs for anhydrous ammonia, ammonium nitrate, and non-site specific UAN were based upon average custom charges for the area of $6.12, $2.50, and $2.90 per acre (Kletke and Doye, 2002).

Net returns above the cost of nitrogen fertilizer and application for each year and treatment, assuming ammonium nitrate was used as the source of preplant nitrogen, are reported in Table II-3. The eight treatments performed about the same for each of the three years; no statistically significant differences were found across the eight treatments. The 40/0 system had the highest averaged net return over the years of the study of $128 per acre. The next highest system was the 40/OS system, which had a mean net return of $126 per acre. Two treatments (0/40, and 0/OS) had an average net return above the cost of nitrogen fertilizer and application of $125 per acre. Net returns for 2002 were mixed. However, the check system (0/0) did have the highest net return of $125 per acre. The average net returns for 2003 were high due to better than average growing conditions. In this year, the top performing system was the 40/OS system, which had a average net return of $136 per acre, which is approximately two percent higher than the next best system for that year. In 2004, the top ranking system was the 0/OS system with an average net return of $137 per acre.

Net returns for each year and treatment, assuming that anhydrous ammonia was used as the source of preplant nitrogen fertilizer are reported in Table II-4. When the price of anhydrous ammonia was set equal to $0.15 per pound, the top performing treatment, on average, was the 40/0, which had a net return of $128 per acre. The next best system for this scenario was the 40/OS system with an average net return of $126 per acre. For this scenario, however, all systems were, on average, about the same. In fact, no statistically significant differences in net returns were found between the systems over the span of the data.

When the price of anhydrous ammonia was set equal to $0.22 per pound, the top performing treatment was the 40/0, realizing an average net return of $126 per acre. The 0/OS system was slightly lower at $125 per acre. The average net return for the 40/OS was also competitive with the 40/0 system at $124 per acre. As was the case for the other two scenarios, no statistical differences were found between the systems for this scenario.

Conclusions

Several things can be learned from this study. First, the average ownership and operating costs of using the optical sensing technology is sensitive to the number of acres on which the machine is used per year. However, it is relatively inexpensive. With a zero level of preplant nitrogen application, and an expected 15 days of use per year, these costs, including the cost of the NRS, are approximately $5.01 per acre. This is approximately 73% greater than the $2.90 per acre charged for applying UAN as a topdress with conventional non-site specific technology. However, potential benefits from reductions in the cost of the technology (approximately $2 per acre) such as reducing the number of sensors and increasing the grid size are not great.

A second finding is that the economics of the technology depends critically upon the price of UAN relative to the price of NH_3. For the historic price ratio of 1.67 ($0.25 per pound of nitrogen as UAN to $0.15 per pound of nitrogen as NH_3) and application costs, 61 pounds of nitrogen applied as UAN has the same cost as 80 pounds applied as

NH_3. Given that the technology requires UAN, the cost difference reduces the value of precision.

A third finding is that the results from use of the technology on farm fields were disappointing. For example, during the 2002 season, the average yield from the 0/0 treatment was the same as that obtained from both site-specific treatments. However, the technology applied nitrogen that, in hindsight, should not have been applied. In 2003, the technology did not apply enough nitrogen. These results suggest that additional research will be required to either improve the algorithm used to determine the site-specific application rates or to improve the efficiency of the applicator.

The technology is in the early development stages and as the cost of computers and sensors declines over time, and engineering improvements are made that lower the cost of production, the net benefits may increase. The algorithm used to estimate nitrogen requirements did not consider economics. Fine-tuning the nitrogen fertilizer optimization algorithm in a way that incorporates prices of nitrogen and wheat might improve nitrogen recommendations, which could translate into additional net benefits to the farm operation. That is, in good years, more would be applied than that of current recommendations, and in poor years less would be applied. Additionally, in some years and fields where a zero level should be applied, it might be economical to pay an operator the per acre custom charge for that information. This would provide additional savings on unnecessary application expenses. Another potential benefit from this technology stems from the idea that not all fields would necessarily require a nitrogen rich strip. Producers throughout the region could take advantage of region-wide samples of sensor readings taken from nitrogen rich strips that are selectively placed on fields throughout the region.

As the development of the site-specific sensing and application system progresses, and better data become available, further research oriented at econometric estimation of yield response functions conditional on the optical reflectance information could be conducted in an effort to improve the nitrogen fertilizer optimization algorithm. Further development and refinement of the technology including improvements to the application algorithm, combined with an increase in the price of anhydrous ammonia relative to the price of UAN could alter the economics to favor the technology. The potential benefits to the environment from reducing nitrogen application clearly favor the technology.

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Table II-1. Wheat Grain Yields for Each System, Year, and Location (bushels per acre)

Year	System	Preplant Level	Topdress Level	Yield L1	Yield L2	Yield L3	Yield L4	Yield L5	Yield L6	Yield L7	Yield L8	Yield L9	Yield L10	Average
2002	0/0	0	0	30	45	62	19				52			42
2002	0/40	0	40	36	46	63	20				49			43
2002	0/80	0	80	36	29	61	17				57			40
2002	40/40	40	40	43	32	58	20				54			41
2002	40/0	40	0	37	42	63	18				59			44
2002	80/0	80	0	41	33	63	17				52			41
2002	0/OS	0	OS	33 (7)	39 (11)	64 (7)	19 (3)				55 (14)			42 (8)
2002	40/OS	40	OS	37 (9)	35 (11)	65 (9)	21 (3)				50 (15)			42 (10)
2003	0/0	0	0	29				41	51		41	13	50	38
2003	0/40	0	40	50				41	63		44	19	62	46
2003	0/80	0	80	62				37	68		46	24	71	51
2003	40/40	40	40	67				43	73		50	21	66	53
2003	40/0	40	0	53				41	67		49	15	62	48
2003	80/0	80	0	67				42	70		48	22	66	52
2003	0/OS	0	OS	40 (35)				42 (15)	57 (17)		47 (35)	16 (22)	56 (15)	43 (23)
2003	40/OS	40	OS	71 (55)				43 (16)	68 (19)		47 (9)	23 (29)	69 (20)	53 (25)
2004	0/0	0	0	22				28	29		66	50		41
2004	0/40	0	40	42				33	40		68	60		48
2004	0/80	0	80	52				35	46		66	61		51
2004	40/40	40	40	54				39	50		69	61		54
2004	40/0	40	0	39				32	42		69	60		49
2004	80/0	80	0	54				37	44		65	58		49
2004	0/OS	0	OS	47 (64)				32 (35)	46 (55)		70 (27)	59 (27)		51 (46)
2004	40/OS	40	OS	57 (34)				32 (34)	54 (61)		67 (5)	61 (20)		54 (33)

Note: Numbers in parentheses are levels of nitrogen applied as 28% urea-ammonium nitrate applied using the site-specific applicator equipped with optical sensing technology (pounds per acre). L1 is Lahoma, L2 is Chickasha, L3 is Blackwell, L4 is Haskell, L5 is Altus, L6 is Covington, L7 is Perkins, L8 is Hennessey, L9 is Tipton, and L10 is Perry.

Table II-2. Ownership and operating cost for the self-propelled applicator equipped with optical sensing technology ($ per acre)

Acres Covered Per Hour	Hours Used Per Day	Days Used Per Year	Acres Covered Per Year	Current Cost of Nitrogen Application	Cost of Optical Sensing Technology	Cost of N-Rich Strip for 0/OS	Ownership & Operating Cost for 0/OS	Cost of N-Rich Strip for 40/OS	Ownership & Operating Cost for 40/OS
83	10	5	4,150	$2.90	$3.14	$0.84	$6.88	$0.60	$6.64
83	10	15	12,450	2.90	1.27	0.84	5.01	0.60	4.77
83	10	25	20,750	2.90	0.93	0.84	4.67	0.60	4.43
83	10	35	29,050	2.90	0.80	0.84	4.54	0.60	4.30
83	10	45	37,350	2.90	0.73	0.84	4.47	0.60	3.23
83	10	55	45,650	2.90	0.70	0.84	4.44	0.60	3.20

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 N-Rich strip includes the cost of fertilizer and application in the fall prior to planting. The self-propelled applicator has a 65-foot operating width, a field speed of 15 miles per hour, and a field efficiency level of 70%.

Table II-3. Net returns for each Year and System Assuming Ammonium Nitrate as the Preplant Nitrogen Source ($ per acre at $0.25 per pound of N)

Year	0/0	0/40	0/80	40/40	40/0	80/0	0/OS	40/OS
2002	125	116	97	98	119	100	119	105
2003	113	127	131	134	130	134	118	136
2004	122	132	129	136	134	125	137	136
Mean	120	125	119	123	128	120	125	126

Table II-4. Net returns for each Year and System and Assuming Anhydrous Ammonia as the Preplant Nitrogen Source ($ per acre)

Year	0/0	0/40	0/80	40/40	40/0	80/0	0/OS	40/OS
Anhydrous Ammonia price of $0.15 per pound								
2002	125	116	97	99	119	105	119	105
2003	113	127	131	135	131	139	118	136
2004	122	132	129	136	135	130	137	137
Mean	120	125	119	123	128	124	125	126
Anhydrous Ammonia price of $0.22 per pound								
2002	125	116	97	96	117	99	119	102
2003	113	127	131	132	128	133	118	133
2004	122	132	129	133	132	124	137	134
Mean	120	125	119	120	126	119	125	123

[a] Price for 28% urea-ammonium nitrate held constant at $0.25 per pound.

ESSAY III

PRECISION NITROGEN FERTILIZATION TECHNOLOGY WITH MICRO GRIDS

Abstract

Sensor-based precision fertilizer technologies are being developed and researched by production scientists. One such technology uses normalized difference vegetation index (NDVI) reflectance measurements of growing winter wheat plants and a nitrogen fertilizer optimization algorithm (NFOA) to determine nitrogen requirement necessary for plants to reach their yield plateau. A number of precision fertilizer application systems that use this technology are considered in this paper. A linear response stochastic plateau wheat yield function conditional on NDVI reflectance measurements is estimated and used within an expected profit-maximization framework to estimate upper bounds on the returns from the precision nitrogen application systems. The on-the-go precision system that assumes perfect information was approximately $7 per acre more profitable than the convention of applying 80 pounds of nitrogen prior to planting in the fall. The whole-field precision system was break-even with conventional methods.

Key Words: expected profit, NDVI, nitrogen fertilizer, precision farming, site specific, wheat

Introduction

Nitrogen fertilizer is a primary input for winter wheat production, accounting for between 15 and 25 percent of total operating expenses (USDA). A conventional approach to wheat production involves applying nitrogen requirements uniformly to a whole field prior to planting wheat in the fall. Substantial variations in soil nutrient availability both within and across fields and the cost associated with over-application of nitrogen with a whole field management strategy provide justification for using variable rate precision application technologies for wheat production. Since the 1990's, precision application technologies using soil sampling to determine soil nitrogen availability have been proposed. However, adoption of precision soil sampling for nitrogen has been limited (Daberkow and McBride).

Early published studies on the costs and benefits of soil-based precision technologies mostly reported that the benefits from theses technologies were greater than the costs (Lambert and Lowenberg-DeBoer). More recent research argued that technologies and strategies such as combine yield monitors, soil sampling and mapping, and fertilizer applicators equipped with global positioning systems have not been adopted in widespread fashion because significant costs associated with site-specific information management and variable rate application were overlooked (Hurley et al., Swinton and Lowenberg-DeBoer; Bullock and Bullock). Economic theory suggests that if a new technology is unambiguously economical it will be adopted by profit maximizing producers. As a result, alternative techniques for applying fertilizers variably are being explored to solve the problem of over applying fertilizer in some parts of the field, and under applying fertilizer in other parts.

One alternative to soil sampling that has gained substantial interest from the production agriculture community uses reflective sensor measurements of growing wheat plants to determine nitrogen need (Alchanatis et al.; Ehlert et al.; Phillips et al.; Raun et al., 2001; Schachtl et al.). The technology developed by Raun et al., 2001 uses NDVI reflectance measurements of growing wheat plants and a nitrogen fertilizer optimization algorithm (NFOA) to determine plant performance and nitrogen needs on micro grids as small as four square-feet. Two individual systems using this technology have been developed by engineers.

The first system is a precision-based, whole field application system, and the second system is a site-specific variable rate application system that can sample and treat plants on individual four square-foot micro grids instead of the three-acre grids commonly used with soil testing and mapping strategies (Raun et al 1998; Solie et al., 1999). Both systems are commercially available for use in winter wheat production, but adoption has been slow.

Public and private sector investment into this technology, including the two systems described, has been substantial, but an economic analysis of the expected producer benefits from the adoption of these systems is lacking. The objectives of this research are to determine the maximum expected net returns for the whole field system and two special cases of the variable rate system relative to the maximum expected net return from conventional all-before-planting systems. The net value of the plant-based systems above that of the conventional systems would be useful to farm producers in helping them decide whether or not to adopt this technology, and would provide engineers and manufacturers with a target cost to deliver the systems. Data for wheat yield, optical reflectance information, and levels of preplant nitrogen have been collected from on-farm in-season trials over six years and across eight locations in Oklahoma. These data provide the opportunity to develop a yield response to nitrogen function that is conditional on in-season sensor readings taken from growing winter wheat plants in the late winter or early spring. The NDVI reflectance reading obtained with the optical reflectance sensor is believed to reveal information about plant nutrient availability and hence plant performance.

We first develop a conceptual framework of the producer's optimization problem that describes the interaction between independent variables (such as nitrogen, optical reflectance readings, and stochastic variables) and the dependent variable (wheat yield). Using the panel data set, a wheat yield response to optical reflectance information function and a response function that describes the relationship between optical reflectance information and the level of nitrogen are estimated. Optimal levels of nitrogen for the alternative systems are then derived. Monte Carlo integration is then used to determine whether or not farmers should consider adopting a plant-based precision nitrogen fertilizer application technology. Sensitivity analysis is used to provide insight into how the results change to slight changes in the model's parameters.

Conceptual Framework

<u>Expected profit maximization</u>

The plant-based precision technology requires placing a nitrogen rich strip (NRS) in the field in the fall. The NRS is fertilized with a non-limiting level of nitrogen fertilizer; that is, a level that will ensure that the yield of wheat growing in that strip will reach its plateau level (Frank, Beattie and Embleton; Grimm, Paris, and Williams; Waugh, Cate, and Nelson).

Normalized difference vegetation index (NDVI) sensor measurements of plants growing in the NRS and in nonNRS regions of the field are obtained in late winter (Tucker; Hockheim and Barber; Raun et al., 1999) and used within a nitrogen fertilizer optimization algorithm (NFOA) to compute the optimal level of nitrogen to apply to the growing wheat. A concern regarding the NFOA is that it does not consider the price of nitrogen or the price of wheat. In addition, this particular technology faces a high economic hurdle because it was designed to use urea-ammonium nitrate (UAN), which is historically a more expensive form of nitrogen fertilizer than anhydrous ammonia.

The whole-field precision system uses a portable sensing device that collects NDVI sensor measurements of growing plants that is then entered into the NFOA to obtain the average whole field recommendation of nitrogen fertilizer. Alternatively, the plant-based technology has been incorporated into a site-specific system that has the NFOA stored in a computer on board a self-propelled boom applicator that is equipped with a mix of optical reflectance sensors, computers, and spray nozzles. The applicator assesses plant nitrogen need and applies discrete quantities of liquid nitrogen fertilizer on individual four square-foot grids on the go.

Economic theory suggests that for a precision technology to be adopted into the on-farm production process, the adopters need to be convinced that it is substantially more profitable than the conventional system they are accustomed to using (Lowenberg-DeBoer). Conceptually, the expected farm-level net return associated with the proposed precision technology is the difference between expected crop revenue (expected price times expected yield) and the total cost of nitrogen application (cost of nitrogen plus fixed application costs), or mathematically

$$
\begin{aligned}
& \max_{N^T} \mathrm{E}(\pi_t) = \sum_{i=1}^{n}\sum_{t=1}^{m} \mathrm{E}(p)\mathrm{E}(y_{it}(N_{it}^T)) - r^P \sum_{i=1}^{n}\sum_{t=1}^{m} N_{it}^P - r^R \sum_{i=1}^{n}\sum_{t=1}^{m} N_{it}^R - c^P - c^R, \\
& \quad \text{s.t. } y_{it} = y(N_{it}^T, ORI_{it}, ORI_t^{NRS}, \phi), \\
(1) \qquad & \qquad N_{it}^T = N_{it}^P + N_{it}^R, \\
& \quad N_{it}^P, N_{it}^R \geq 0, \\
& \quad c^P, r^P > 0 \text{ if } N_{it}^P > 0, \\
& \quad c^R, r^R > 0 \text{ if } N_{it}^R > 0.
\end{aligned}
$$

where π_t is net return to nitrogen application in field-year *t*; y_{it} is wheat yield on grid *i* in field-year *t*, N_{it}^T is the amount of nitrogen on grid *i* in field-year *t*, N_{it}^P is the level of preplant nitrogen on grid *i* in field-year *t*, N_{it}^R is the level of topdress nitrogen on grid *i* in year *t*, the symbol ORI_{it} represent optical reflectance readings taken on each grid and field-year, the symbol ORI_t^{NRS} represents optical reflectance readings taken off the NRS in year *t*, symbols r^P and r^R are the price of preplant and topdress nitrogen sources, respectively, symbols c^P and c^R are fixed costs for preplant application and topdress application, respectively, and ϕ represents a vector of random error terms.

The yield response function

A key element in equation (1) is the yield response to nitrogen function. Because of the data limitations, the yield response function had to be developed and estimated in two parts.[5] The key assumption is that nitrogen is assumed to have the same influence

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[5] The available data have preplant applications of nitrogen, mid-season readings of ORI, and wheat yield. An ideal experiment would record ORI before applications of varying levels of nitrogen. To-date, such an experiment has not been conducted.

(except for an efficiency adjustment) on ORI and in turn yield whether it is applied preplant or at time of sensing. So, for the first part in developing our yield response function we define wheat yield response to optical reflectance information to be

$$y_{it} = a + bORI_{it} + \theta_{it}, \tag{2}$$

where y_{it} is wheat yield in bushels per acre on grid i in field-year t, symbols a and b are the intercept and slope coefficient to be estimated, and the error term θ_{it} is partitioned into an independently and identically distributed random error term θ^*_{it} that has mean zero and variance $\sigma^2_{\theta^*}$, and year random effect ω_t that has mean zero and variance σ^2_{ω}.[6]

Independence is assumed between the two variance components, and therefore the variance of the overall error term is $\sigma^2_{\theta} = \sigma^2_{\omega} + \sigma^2_{\theta^*}$. The symbol ORI_{it} is defined as the NDVI reflectance reading taken on grid i in field-year t and is adjusted by the number of growing degree days. It is assumed that ORI_{it} is quantifiable information that relates how much nitrogen is available to the plants at the time of sensing, which in turn provides information that is useful in quantifying how much additional nitrogen is needed to reach full yield potential.

The wheat yield response to the optical reflectance information was defined in equation (2). However, the relationship of primary interest for this study is the relationship between wheat yield and the total level of nitrogen, regardless of where it comes from (i.e., residual from previous year, released through soil mineralization, fertilizer application, rain, or lightning). Research suggests that a linear response plateau

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[6] The hypothesis of linear functional form could not be rejected at a 95% level of confidence in favor of an exponential functional form based on the J-test for nonnested models $\left(H_0 : \alpha = 0, t = 1.33, \Pr > |t| = .7899\right)$ (Greene, p. 302).

(LRP) function performs as well, if not better, than polynomial forms (Perrin; Lanzer and Paris), and that the LRP explained crop response to fertilizer at least as well, if not better, than polynomial forms (Grimm, Paris, and Williams; Heady, Pesek, and Brown; Paris; Frank, Beattie, and Embleton; Chambers and Lichtenberg).

A study conducted by Tembo, Brorsen and Epplin used data from a long-term winter wheat experiment (32-years) conducted in Oklahoma to estimate a LRP and a proposed alternative estimated as a linear response stochastic plateau (LRSP), where the plateau is assumed to be a year random variable that is distributed normally. In their paper, they found that the LRSP function improved on the statistical accuracy of the estimates for the optimal level of nitrogen to apply to wheat. Katibie et al. (2003) also utilized both LRP and LRSP functional forms to determine the effect of stocking density on wheat grain yield and average daily gain of steers using seven years of experimental data from a stocking density experiments conducted in Oklahoma. They used a likelihood ratio test and rejected the conventional LRP in favor of the LRSP function.

Katibie et al. (2005) point out that the primary difference between the LRP and the LRSP forms regards the nonrandom assumption for the plateau. With an LRP the effect is treated as fixed and has often been specified using dummy variables. Tembo, Brorsen, and Epplin argue that when estimating yield response functions using long-term panel data, it is more plausible to assume that the plateau is stochastic due to certain unknown factors over time such as differences in weather patterns, level of rainfall, and mineralization of the organic matter. In addition to the assumption of a stochastic plateau, the Tembo, Brorsen, and Epplin model is a predictive model that allows for identifying unusually low or high yields by estimating random effects for each field-year.

In the case of variable rate nitrogen application, such as the system that Raun et al. (1999) developed, each grid or space in the field is treated as an independent farm with each grid having its own plateau. The plateau on each grid has two random components: a year random effect that is measured with the NRS and an element unique to the grid which is unknown unless measured using the sensors. It is assumed that the plateau in each grid is random due to one or more unknown factors such as weather patterns, rainfall, and/or soil mineralization that all vary across years. Additionally, the plateaus have randomness that results from unknown factors across space, such as uneven rainfall across grids, unequal levels of drainage, poor plant stand, and/or differences in the soil mineralization process that vary across grids within the field (mainly due to different soil types). The nitrogen fertilizer optimization algorithm (NFOA) developed by Raun et al., (2002) implicitly assumes a LRSP function.

The second part, then, uses the approach provided by Tembo, Brorsen, and Epplin to develop and estimate a LRSP function that relates the level of nitrogen to optical reflectance information collected from growing wheat in late winter. This relationship is defined as[7]

$$(3)\qquad ORI_{it}^{S}=\begin{cases}\alpha+\beta(N_{it}^{A}+N_{it}^{R})+u_t+\eta_{it}, & \\ \qquad \text{if } \alpha+\beta(N_{it}^{A}+N_{it}^{R})+u_t\le E\left(ORI_{t}^{NRS}\right)+v_t+\tau_{it}+u_t, & \\ E\left(ORI_{t}^{NRS}\right)+v_t+\tau_{it}+u_t+\eta_{it}, & \\ \qquad \text{if } \alpha+\beta(N_{it}^{A}+N_{it}^{R})+u_t> E\left(ORI_{t}^{NRS}\right)+v_t+\tau_{it}+u_t, & \end{cases}$$

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[7] Note that equation (3) can not be estimated in its present state because observations for N_{it}^{R} are not available. That is, the spatial random component τ_{it} can not be estimated because data are not available from experiments in which nitrogen treatments were applied after sensing. Consequently, equation (3) is estimated using observations for preplant nitrogen only for N_{it}^{A}, and assuming that the plateau spatial error component τ_{it} is equal to zero.

where ORI_{it}^{S} is optical reflectance information observed in late winter on grid *i* in field-year *t*; α and β are the intercept and slope parameters to be estimated; N_{it}^{A} is the level of nitrogen that is available to the plant at the time of planting (this could be residual N from the previous year, from preplant fertilizer, soil mineralization, or from other possible sources such as rainfall and lightning); N_{it}^{R} is the post-sensing level of nitrogen required in the spring that is necessary for the plants to produce the plateau level of yield; the symbols u_t and η_{it} represent the year random effect and traditional random error component, respectively, and are both assumed to be distributed normal with a mean of zero and variances equal to σ_u^2 and σ_η^2, respectively; and the plateau is defined as $E\left(ORI_t^{NRS}\right)+v_t+\tau_{it}$, which is equal to a constant average of sensor readings taken from the NRS plus a field-year random effect, v_t, and a spatial plateau random effect, τ_{it}, that varies by grid. The plateau random variables are assumed to be independently and identically distributed with means equal to zero and variances equal to, σ_v^2 and σ_τ^2, respectively.

As previously mentioned, an important component of this paper is to develop a response equation that sufficiently describes the relationship between wheat yield and the total level of nitrogen that is necessary for the plants to reach their plateau yield. The theoretical derivation of such a relationship can be accomplished in the following steps. The first step is to develop an equation that relates the level of preplant nitrogen to optical reflectance information observed in the late winter. This equation can be expressed as

$$(4) \qquad ORI_{it}^{S} = \begin{cases} \alpha + \beta N_{it}^{P} + u_t + \eta_{it}, \\ \qquad \text{if } \alpha + \beta N_{it}^{P} + u_t \le E\left(ORI_t^{NRS}\right) + v_t + \tau_{it} + u_t, \\ E\left(ORI_t^{NRS}\right) + v_t + \tau_{it} + u_t + \eta_{it}, \\ \qquad \text{if } \alpha + \beta N_{it}^{P} + u_t > E\left(ORI_t^{NRS}\right) + v_t + \tau_{it} + u_t, \end{cases}$$

where N_{it}^{P} is the level of preplant applied nitrogen on grid *i* in year *t*. Equation (4) can be solved for the level of preplant nitrogen, which in this paper is simplified by assuming that the total amount of nitrogen available to the plants at the time of sensing in late winter comes from a preplant source only (i.e., $N_{it}^{A} = N_{it}^{P}$). The solution for this step is written as

$$(5) \qquad N_{it}^{P} = \frac{ORI_{it}^{S} - \alpha - \eta_{it} - u_t}{\beta}.$$

The next step is to derive the relationship between the total level of nitrogen available to the plants and optical reflectance information observed post-topdressing. The challenge here is that that post-topdressing sensor information is never observed with available data. However, it seems reasonable to assume that optical reflectance information taken after topdressing nitrogen in late winter would be the same as the optical reflectance information would be (with an adjustment reflecting an expected gain in nitrogen use efficiency) if the same amount of nitrogen had been applied before planting. With this assumption, the solution obtained in equation (5) can be substituted into equation (4) and simplified. Doing so yields the following

$$(6) \qquad ORI_{it}^{T}\left(N_{it}^{T}\right) = \begin{cases} ORI_{it}^{S}(N_{it}^{P}), \\ \qquad \text{if } ORI_{it}^{S} + \beta N_{it}^{R} - \eta_{it} \le E\left(ORI_t^{NRS}\right) + v_t + \tau_{it} + u_t, \\ E\left(ORI_t^{NRS}\right) + v_t + \tau_{it} + u_t + \eta_{it}, \\ \qquad \text{if } ORI_{it}^{S} + \beta N_{it}^{R} - \eta_{it} > E\left(ORI_t^{NRS}\right) + v_t + \tau_{it} + u_t, \end{cases}$$

where ORI_{it}^{T} represents post-topdressing optical reflectance information on grid *i* in field-year *t* in late winter, which is a function of the optical reflectance information taken prior to topdressing and hence represents the level of nitrogen available to the plants at that time. However, the process is not complete because we are interested in a function that relates total nitrogen level (level of N available plus the level of N required for plants to yield at the plateau) to optical reflectance information. This requires the addition of the variable representing the level of N required back into equation (6). Completion of this step provides a function that relates the total level of nitrogen to optical reflectance information, or more formally

$$(7)\qquad ORI_{it}^{T}\left(N_{it}^{T}\right)=\begin{cases} ORI_{it}^{S}(N_{it}^{P})+\beta N_{it}^{R}, \\ \quad \text{if } ORI_{it}^{S}+\beta N_{it}^{R}-\eta_{it}\leq E\left(ORI_{t}^{NRS}\right)+v_{t}+\tau_{it}+u_{t}, \\ E\left(ORI_{t}^{NRS}\right)+v_{t}+\tau_{it}+u_{t}+\eta_{it}, \\ \quad \text{if } ORI_{it}^{S}+\beta N_{it}^{R}-\eta_{it}> E\left(ORI_{t}^{NRS}\right)+v_{t}+\tau_{it}+u_{t}. \end{cases}$$

The final step requires substituting equation (7) into the original yield function described by equation (2) to obtain the desired LRSP function. This LRSP function is expressed as

$$(8)\qquad y_{it}=\begin{cases} a+bORI_{it}^{S}(N_{it}^{P})+b\beta N_{it}^{R}+\theta_{it}, \text{ if} \\ \quad a+bORI_{it}^{S}(N_{it}^{P})+b(\beta N_{it}^{R}-\eta_{it})\leq a+bE\left(ORI_{t}^{NRS}\right)+bv_{t}+b\tau_{it}+bu_{t}, \\ a+bE\left(ORI_{t}^{NRS}\right)+bv_{t}+b\tau_{it}+bu_{t}+b\eta_{it}+\theta_{it}, \text{ if} \\ \quad a+bORI_{it}^{S}(N_{it}^{P})+b(\beta N_{it}^{R}-\eta_{it})\leq a+bE\left(ORI_{t}^{NRS}\right)+bv_{t}+b\tau_{it}+bu_{t}. \end{cases}$$

Equation (8) represents the production function that will be used to generate yields, levels of nitrogen, and expected profit estimates for the alternative nitrogen fertilizer management systems that are being compared in this study.

Data and Estimation

Parameter estimates for equation (2) and equation (4) (assuming that τ_{it} is equal to zero) are estimated using data gathered from eight on-farm winter wheat experiments conducted at six locations located on or near research stations throughout Oklahoma from 1998-2003. The data set includes observations for wheat yield, optical reflectance information, and level of preplant nitrogen for a total of 624 site years useful for analysis. Locations for each of the experiments included Haskell (Exp. #801), Hennessey (Hennessey AA), Lahoma (Exp. #508), Perkins (Exp. N x P, and Exp. N x S), Stillwater (Exp. #222 and Efaw AA), and Tipton (Exp. N x S). The N rate by spacing (N x S) experiment at Perkins included only nitrogen and was initiated in 1996; however, only data for 1998 was used in this study. The N rate by P rate (N x P) experiment at Perkins included both nitrogen and phosphorus from 1998 to 2003. The Hennessey AA and Efaw AA experiments were designed as anhydrous ammonia fertility experiments. Data were collected at Haskell (Exp. #801) from 1999 to 2002, and at Stillwater (Exp. #222 and Efaw AA) for five years from 1999-2003. At Hennessey data were collected for 2000 and 2002. At Lahoma, data were collected in 1999, 2000, 2002, and 2003, and at Tipton data were only collected in 1998.

Soil types for each locations are: Haskell, Taloka silt loam (fine, mixed, thermic Mollic Albaqualfs); Hennessey, Shellabarger sandy loam(fine-loamy, mixed, thermic Udic Paleustolls); Lahoma, Grant silt loam (fine-silty, mixed, thermic Udic Argiustolls; Perkins, Teller sandy loam (fine-loamy, mixed, thermic Udic Argiustolls); Stillwater, Kirkland silt loam(fine, mixed, thermic Udertic Paleustoll); Stillwater-Efaw, Norge silt loam (fine-silty, mixed, thermic Udic Paleustoll); and Tipton, Tipton silt loam (fine-loamy, mixed, thermic Pachic Argiustolls).

In each of the experiments, winter wheat was planted at a 70 pounds per acre seeding rate using a 7.5 inch row spacing, excluding the S*N experiment at Perkins where spacing ranged from six inches to ten inches. It was not reported in the paper how spacing affected yields for the Tipton (N x S) and Perkins (N x S) experiments. In addition, the paper did not provide information regarding how phosphorus affected yield for the Perkins (N x P) experiment. All field experiments where sensor and yield data were collected employed randomized complete block designs with 3 to 4 replications (depending on site).

Nitrogen rich strips were placed in each experimental plot prior to planting wheat in late September or early October. All optical reflectance readings were taken during Feekes growth stages 4 (leaf sheaths beginning to lengthen) and 5 (pseudo-stem, formed by sheaths of leaves strongly erect) (Large). Sensor measurements were taken from treatments with varying levels of N nutrition within each replication. NDVI spectral reflectance was measured using a handheld sensor that included two upward and downward directed photodiode sensors that received light through cosine corrected Teflon windows fitted with red (671 ± 6 nm) and near-infrared (NIR) (780 ± 6 nm) interference filters developed by (Stone et al.).

Consistent with different planting times and growing conditions, spectral reflectance readings were from wheat were collected from a 43.03 square-feet (4.0 square-meters) area under natural lighting either in January, February, March, April, or May. Plots were harvested with a self-propelled combine and grain yield was determined from the same 43.03 square-feet area where spectral reflectance data were collected. Additional information regarding the experiments can be found in Mullen et al. (2003).

Parameters in equation (2) are estimated using a linear mixed effects model (PROC MIXED in SAS). The presence of year random effects is tested using a likelihood ratio test. The LRSP described in equation (3) is estimated using a nonlinear mixed effects model (PROC NLMIXED in SAS). This is required because the randomness associated with year random effects (i.e., v_t in equation 3) enters the response function non-linearly (Tembo, Brorsen, and Epplin). The model illustrated in equation 3 is sufficiently designed to allow for the presence of plot-level plateau spatial randomness, which is denoted by τ_{it} in equation 3. A lack of data prohibits direct estimation of the plot-level plateau randomness; however, an alternative model will be simulated that allows for spatial random effects. In the alternative model, a percentage of the random variation contained in the general error component (η_{it} in equation 3) is subtracted and given to the plateau spatial error component (τ_{it} in equation 3). The two models are compared to determine the effects of spatial variability on profitability.

Levels of Nitrogen

Equation (8) is used to compute the application levels of nitrogen fertilizer for each of several systems, including (System 1) an all-before-planting system based on an economically optimal level of nitrogen computed using the analytical approach provided by Tembo, Brorsen, and Epplin; (System 2) the portable plant-based precision system that gives a uniform, whole field recommendation; (System 3) the on-the-go variable rate precision system; (System 4) the plant-based NFOA system developed by Raun et al.

(2004); (System 5) an all-before-planting system that represents the agricultural extension recommendation of 80 pounds per acre preplant system (i.e., two pounds of N per acre based on a 40 bushel per acre yield goal), and (System 6) an all-before-planting system that represents the average of what producers were actually found to be applying in the southern Plains (i.e., 63 pounds per acre) in a survey conducted in 2000 (Hossain et al., 2004). In addition, a check system (System 7) that has no nitrogen applied is included. Optimal application levels of nitrogen for systems 1, 2, and 3 are derived using the response function described by equation (3).

Optimal level of preplant nitrogen

The approach used by Tembo, Brorsen, and Epplin is used to obtain the optimal level of nitrogen to apply in the fall prior to planting wheat, which is the traditional system for applying nitrogen fertilizer in the southern Great Plains region of the United States. This process requires several steps. To account for all nitrogen requirements applied in the fall prior to planting, we need to rewrite equation (3) as

$$(9) \qquad ORI_{it} = \begin{cases} \alpha + \beta N_{it}^{P} + u_t + \eta_{it}, \\ \quad \text{if } N_{it}^{P} \le N_{it}^{NRS} \Rightarrow ORI_{t}^{NRS} > \alpha + \beta N_{it}^{P}, \\ E\left(ORI_{t}^{NRS}\right) + v_t + \tau_{it} + u_t + \eta_{it}, \\ \quad \text{if } N_{it}^{P} > N_{t}^{NRS} \Rightarrow ORI_{t}^{NRS} \le \alpha + \beta N_{it}^{NRS}, \end{cases}$$

where N_{it}^{P} is the level of nitrogen applied to grid i in field-year t in the fall prior to planting (assumed to be the total level of nitrogen in this case), the symbols α and β represent intercept and slope coefficients to be estimated, N_{t}^{NRS} is the plateau level of nitrogen.

Note, after the sample reflectance readings from the NRS have been taken with the sensors, and an average computed, then N_t^{NRS} will be known.

The next step is to substitute equation (9) into the yield function given by equation (2), which gives the following conditional wheat yield response to nitrogen function

$$(10)\qquad y_{it} = \begin{cases} a + b\alpha + b\beta N_{it}^{P} + bu_t + b\eta_{it} + \theta_{it}, \\ \quad \text{if } N_{it}^{P} \le N_t^{NRS} \Rightarrow \text{(below plateau)} \\ a + bE\left(ORI_t^{NRS}\right) + bv_t + b\tau_{it} + bu_t + b\eta_{it} + \theta_{it}, \\ \quad \text{if } N_{it}^{P} > N_t^{NRS} \Rightarrow \text{(on plateau).} \end{cases}$$

Using the yield function described in equation (10) and following the analytical approach of Tembo, Brorsen, and Epplin, the optimal level of nitrogen to apply as a preplant in the fall $\left(N_{it}^{P*}\right)$ is

$$(11)\qquad N_{it}^{P*} = \frac{1}{b\beta}\left[F^{-1}\left(1 - \frac{r}{pb\beta}\right) - a - \alpha b\right],$$

where $F^{-1}(\cdot)$ is the inverse of the normal cumulative distribution function. To complete the computation, the market price for preplant nitrogen (r) and the expected price of wheat (p) are required, and the parameters, $a, b, \alpha,$ and β can be replaced by their statistical estimates. Because N_{it}^{P*} cannot be negative and $b,\ \beta \ge 0,$ equation (11) is valid only if

$$(12)\qquad \frac{F^{-1}\left(1 - \dfrac{r}{pb\beta}\right) - a}{b\beta} \ge \frac{\alpha}{\beta}.$$

An optimal solution can be determined analytically only if a unique inverse exists for the prescribed cumulative distribution function. First, we define

(13) $$y_{it}^{NRS} = a + bORI_t^{NRS},$$

where y_{it}^{NRS} represents the yield that is generated on the NRS, which is expected to be the yield on the plateau. Next, if we assume that $ORI_t^{NRS} \sim N(E(ORI_t^{NRS}), \sigma_v^2 + \sigma_\tau^2)$ then $y_{it}^{NRS} \sim N\left(a + bE(ORI_t^{NRS}), b^2\sigma_v^2 + b^2\sigma_\tau^2\right)$. Furthermore, if we assume the maximum optical reflectance reading is related to the level of nitrogen necessary to achieve the plateau yield

(14) $$ORI_t^{NRS} = \alpha + \beta N_t^{NRS},$$

then $N_t^{NRS} \sim N\left(\frac{E(ORI_t^{NRS}) - \alpha}{\beta}, \frac{\sigma_v^2 + \sigma_\tau^2}{\beta^2}\right)$.

The next step is to obtain an approximate of the inverse in equation (11). However, first convert $E(y_t^{NRS} \mid N_t^{NRS} = N_{it}^P)$ into a standard normal variant defined as Z_δ, or more formally as

(15) $$Z_\delta = \frac{a + b\alpha + b\beta N_{it}^{P*} - (a + bE(ORI_t^{NRS}))}{b\sigma_v + b\sigma_\tau},$$

where $\delta = 1 - F(a + b\alpha + b\beta N_{it}^{P*}) = \frac{r}{pb\beta}$ is the observed probability in the right-hand tail of the $N(0,1)$ distribution and $F(a + b\alpha + b\beta N_{it}^{P*})$ which is the cdf of y_t^{NRS} evaluated at $a + b\alpha + b\beta N_{it}^{P*}$. The optimal level of preplant nitrogen to apply in the fall prior to planting is obtained by solving (15) for N_{it}^{P*}, which gives

(16) $$N_{it}^{P*} = \frac{Z_\delta(\sigma_v + \sigma_\tau) - \alpha + E(ORI_t^{NRS})}{\beta}.$$

As an example, assume *r* = \$0.15 and *p* = \$3.00. Further, assume that the slope estimate for *b* in equation 2 is equal to 7.5793 and that the slope estimate for β in equation 3 is equal to 0.031. Using these values we can see that $\delta = \dfrac{.15}{(3.00 \times 7.5793 \times 0.031)} = 0.2128.$

Because we are interested in a one-tailed test, we must subtract the $\delta = 0.2128$ from 0.5, which is equal to 0.2872. Unfortunately, the normal distribution function cannot be expressed in an easily invertible form; however, entering the one-tailed version δ into the NORMINV function in Excel provides us with an approximation of the unique inverse desired. After Z_δ is known, solving equation (16) is straightforward. Assuming that $Z_\delta = 0.79,$ and that statistical estimates for $\sigma_v = 0.38, \sigma_\tau = 0.20, \alpha = 5.99, \beta = 0.031, \text{and } E(ORI_t^{NRS}) = 7.1947,$ then the optimal level of preplant nitrogen in equation (16) is equal to 58.52 pounds per acre.

Optimal level of nitrogen for the portable handheld precision system

In this section of the paper we derive a function that describes the uniform level of nitrogen fertilizer that is necessary for plants to produce at the yield plateau. This system makes use of a portable, sensor that obtains average reflectance readings on both the NRS and on individual nonNRS grids throughout the field. After sensing and the optical reflectance information is known, including information from the NRS, the plateau is no longer considered stochastic (assuming as we have that τ_{it} is equal to zero), and therefore optimal levels of nitrogen can be determined using the standard formula for a deterministic plateau. Intuitively, the optimal level of topdress nitrogen required in the late winter is the amount required to achieve the plateau yield.

Under this system, the level of nitrogen required to reach the plateau yield can be thought of as the difference between the level of nitrogen in the NRS and the level of nitrogen applied prior to planting, or

$$N_{it}^{R} = N_{t}^{NRS} - N_{it}^{P}, \tag{17}$$

where the level of nitrogen available in the NRS can be solved using equation (14) and written as

$$N_{t}^{NRS} = \frac{ORI_{t}^{NRS} - \alpha}{\beta}, \tag{18}$$

and the level of preplant nitrogen can be solved using equation (9) and written as

$$N_{it}^{P} = \frac{ORI_{it}^{S} - \alpha}{\beta}. \tag{19}$$

Subtracting equation (19) from equation (18) gives the optimal level of additional nitrogen required in the spring using the portable sensing system, and is written as

$$N_{it}^{R} = \frac{ORI_{t}^{NRS} - ORI_{it}^{S}}{\beta}. \tag{20}$$

Since the optical reflectance information given by the sensor measures the value of the plateau, the plateau is no longer thought of as stochastic and the deterministic solution is appropriate.

Optimal level of nitrogen for variable rate application with perfect information

Determining the optimal level of nitrogen to apply on each grid for each field-year for the variable rate system is an important and challenging task. One of the primary assumptions regarding the on-the-go system is that the cause of any low optical reflectance reading, whether it is from low nitrogen or from another physical factor such as poor soil or a poor stand, can be perfectly identified. This is not achievable in practice at this time, but the NFOA is continually being tweaked based on ongoing research (e.g., Raun et al., 2005).

If all information about plant nitrogen need is known with certainty (i.e., an unachievable, perfect information scenario) then the level of nitrogen required in the spring is thought of as the difference between the plateau yield and the yield at the intercept adjusted by the marginal product of nitrogen. This solution is expressed more formally as

$$N_{it}^{T} = \frac{\text{Plateau Yield - Yield with no N}}{\text{Adjusted Marginal Product of N}}$$

(21)

$$= \frac{a + bORI_{t}^{NRS} + b\tau_{it} - (a + bORI_{it}^{S}) + \eta_{it}}{b\beta}$$

$$= \frac{ORI_{t}^{NRS} - ORI_{it}^{S} + \tau_{it} + \eta_{it}}{\beta}.$$

This result can also be derived directly from the condition outlined in equation (8), and is considered optimal under a situation where perfect information about the random processes is known.

The above result does not assume away uncertainty associated with unfavorable weather that may take place between the time of topdressing and the time of harvesting. However, unknowns associated with soil mineralization, technological problems with the sensors or computers on the system, and other potential problems such as weed and insect problems present at the time of sensing are assumed away. It is unreasonable to assume certainty concerning the random processes, and therefore the results obtained from equation (21) are unachievable in practice. However, the result does place a maximum threshold value on the on-the-go system, barring unusual weather events between topdressing and harvest. Such a value would be useful to producers deciding whether or not to adopt the system.

Optimizing nitrogen using the nitrogen fertilizer optimization algorithm (NFOA)

The nitrogen fertilizer optimization algorithm (NFOA) developed by Raun et al. (2002) is used to determine how much nitrogen is needed in late winter during the topdress application season. Following their work, the optimal level of nitrogen to apply using the plant-based precision technology, N_{it}^{NFOA}, is defined as

$$N_{it}^{NFOA} = \frac{(YPN_{it} - YP0_{it})}{\lambda}, \tag{22}$$

where λ is a constant that represents the level of nitrogen use efficiency (NUE) that is expected to be gained from applying only the level of nitrogen that is needed by the plants in the spring with none of it going unused as opposed to applying nitrogen prior to planting in the fall (Raun et al., 2002 used an NUE of 0.70 in the NFOA), $YP0_{it}$ is yield response to optical reflectance information and gives an estimate at the time of sensing for wheat yield potential when no additional nitrogen is added to the plants. Mathematically, $YP0_{it}$ has the following exponential functional form

$$YP0_{it} = c_0 \exp(ORI_{it} c_1), \tag{23}$$

where c_0 and c_1 are the intercept and slope parameters.[8] The symbol ORI_{it} denotes the optical reflectance information taken in the spring on grid *i* in field-year *t*, and the symbol YPN_{it} in equation (22) is defined as the yield potential when additional nitrogen fertilizer

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[8] Note that parameter estimates have been shifted one standard deviation out to the left in an effort by Raun et al. (2004) to describe a yield frontier. Current estimates of c_0 equal to 0.359 and c_1 equal to 324.4 describe the frontier.

is applied in the spring at a level necessary to bring plant growth to the maximum potential. More formally, it is written as

$$(24) \qquad YPN = \begin{cases} \min\big(\big(RI \times YP0\big), YP0\big), & \text{if } \min((RI \times YP0, YP0) < y^{\max}), \\ y^{\max}, & \text{otherwise,} \end{cases}$$

where RI is a response index that is calculated as the ratio of optical sensor readings taken from the NRS to optical senor readings taken from an adjacent nonNRS strip of the field that represents growing wheat when nitrogen is limiting, or defined mathematically as

$$(25) \qquad RI = \frac{ORI \text{ from NRS}}{ORI \text{ from farmer practice}} = \frac{ORI_t^{NRS}}{E(ORI_{it}^{S})} = \frac{ORI_t^{NRS}}{\alpha + u_t};$$

and according to Raun et al. (2002), $y^{\max}$ is the maximum yield that is determined by the farmer, or previously defined as a biological maximum for the specific crop, and grown within a specific region, and under defined management practices (e.g., dryland winter wheat produced in central Oklahoma would be 104 bushels per acre. Substituting equation (25) into equation (24) gives

(26)

$$YPN_{it} = \begin{cases} \min\left\{ \left(\left(\frac{ORI_t^{NRS}}{\alpha + u} \right) \times 0.359 \exp(ORI_{it} \times 324.4) \right), 0.359 \exp(ORI_{it} \times 324.4) \right\}, & \\ \qquad \text{if } \min((RI \times YP0, YP0) < y^{\max}), & \\ y^{\max}, \qquad \text{otherwise.} & \end{cases}$$

The NFOA is very similar to equation (8). The main differences are that *YP0* and *YPN* are based on an exponential function, the plateau level is reduced when YP0 is low, and the value of λ is more than double. In equation (22), λ corresponds to the marginal product of nitrogen $(b\beta \text{ in equation } 8)$ which can be estimated from the data.

Simulation of Expected Net Returns

Equation (8) is simulated in two separate models to determine the expected net return from each of the alternative systems. The first model assumes that no plateau spatial variability exists (i.e., τ_{it} equal to zero), and the second model allows for plateau spatial variability by subtracting variance from the general error component η_{it} and allocating it to the spatial error component τ_{it}. Although this method is crude, it does provide us with an idea of how sensitive net returns are to the presence of spatial variability within the field-year.

Net returns on 250 sample grids within each of 250 sample field-years were simulated using the following steps. First, sample values for the error components in equation (8) are simulated using a random number generator. Errors are assumed normally distributed with mean zero and estimated variances provided from the regression procedures used to estimate equations (2) and (3). Intercepts, slopes, and expected value of optical reflectance information at the plateau are also provided from these regression procedures. In addition to the error components, values of ORI_{it}^{S} and ORI_{t}^{NRS} are simulated for each grid and field-year of the sample. Moreover, application costs, and prices for 82% NH_3 and 28% UAN are included. A zero level of N is assumed when expected net returns from application are negative on average over the entire field.

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

$$(25) \qquad ORI_{t}^{NRS} = E(ORI_{t}^{NRS}) + v_{t} + u_{t},$$

and the process for calculating sample values for the optical reflectance information on an individual grid and field-year is described by equation (3). Note, τ_{it} has not been included in equation (25). Because the NRS is assumed to cover a sufficiently large area of the field, the plateau spatial variability is assumed to average to zero given that a substantial number of readings are taken from it.

After sample values for the errors and the optical reflectance information are simulated for each grid and field-year, then the formulas for the optimal levels of nitrogen (i.e., equations (16), (20), (21), and (22)) for each of the alternative systems can be used to generate samples of optimal nitrogen rates for each grid in each field-year. The yield response function defined in equation (8) is then used to calculate sample values for wheat yield for each system, grid, and field-year in the sample. Net returns are then calculated as the difference between wheat revenue and cost of nitrogen and nitrogen application expenses for each grid in the field-year. The Monte Carlo integration is then completed by averaging net returns across the sample of field-years for each system. The differences in the average profits between the precision systems and the conventional systems provide an estimate for the value of the plant-based precision systems (e.g., the difference between the expected profit from the perfect information system and the expected profit from a uniform application of 80 pounds of nitrogen per acre provides an approximation for how much a winter wheat producer could pay for a variable rate application system).

For each system, a long run average price of \$3 per bushel was used for the expected price of wheat grain (USDA), and market prices of \$0.15 and \$0.25 per pound are used for anhydrous ammonia and 28% UAN, respectively (Oklahoma Department of Agriculture).

Gains in efficiency

It is believed that some gain in efficiency will be obtained when the plant-based sensing technology is used instead of the traditional preplant systems. However, it is not assumed as is by Raun et al. (2002) that a seventy percent gain (i.e., $\lambda = 0.70$) is achievable. For this study, we are assigning a twenty percent gain in efficiency to the marginal product of nitrogen, such that the slope parameter β is multiplied by an efficiency parameter ψ that is set equal to 1.2. Sensitivity analysis on the efficiency parameter and its effect on expected profits are presented later in the paper. The efficiency parameter is assigned to equation (8) as well as for the optimal levels of nitrogen in equations (20), (21), and (22).

Results and Discussion

Regression estimates of equation (2) are presented in Table III-1. Rejection of the null hypothesis that no random effects exist were based on the likelihood ratio test. Each of the parameters is significant at the .05 level. Estimates of equation (3) are presented in Table III-2. The marginal product of nitrogen $\left(b\beta = (7.5793 \times .031) = .2349\right)$ was smaller than that found by Tembo, Brorsen, and Epplin (0.3075), and is considerably smaller than the 0.7 assumed in the NFOA. This result suggests that approximately 4.3 pounds of nitrogen should be applied to gain an additional bushel of wheat rather than the 3.25 pounds suggested by the Tembo, Brorsen and Epplin model.

Expected yield, optimal levels of nitrogen, and expected profits for each system and without spatial variability are reported in Table III-3. As expected, the perfect information variable rate system had the largest expected profit of approximately $114 per acre. Net return to nitrogen application for this system was approximately $3 greater than the average net return for the Tembo, Brorsen and Epplin system. A better comparison might be made between the perfect information variable rate system and the state recommendation of applying 80-pounds per acre prior to planting in the fall. The net return to nitrogen and nitrogen application for the state recommendation system was approximately $107 per acre, which is approximately $7 per acre lower than the perfect variable rate system.

The portable system had an average net return of approximately $109 per acre, which was approximately $2 per acre more profitable than the state extension recommendation of applying 80-pounds per acre. The portable system averaged $2 per acre less than that of the Tembo, Brorsen and Epplin system. In this case, the cost saving of the precision technology could not outweigh the gains in additional yield predicted with the Tembo, Brorsen and Epplin system. The portable system used 42% less N on average than the Tembo, Brorsen and Epplin preplant system, but the cost of N for the precision system was only $0.28 less than the cost of N for the Tembo, Brorsen and Epplin preplant system. However, the additional yield obtained with the Tembo, Brorsen and Epplin preplant system relative to the portable system results from using a larger average uniform level of nitrogen (i.e., 57.35 pounds versus 33.3 pounds). Using the average from a set of sensor readings taken from the farmer's field to approximate the uniform level of nitrogen needed to achieve the yield plateau, some areas of the field will still receive less nitrogen than actually needed, keeping some yield in the field from reaching its potential plateau.

Another interesting comparison is the approximate $8 difference in net return between the perfect information variable rate system and the NFOA system. This could be viewed as indication that further improvements could be made to the NFOA. However, it is unlikely that the NFOA could be improved to the point that it performs as well as the perfect information system described in this paper. Note that the marginal product of nitrogen for the NFOA is too high, and adjusting it down to the size of that found using the data, the NFOA outcome would be similar to that given by the profits for the 80 pounds per acre system. Also, note that the production function assumed in the simulation does not exactly match the production function assumed by the NFOA so the NFOA could do relatively better in real-world applications.

Plateau spatial variability is expected to exist within each of the field years resulting from random weather within a field and varying soil type. Table III-4 reports average yield, nitrogen, and expected profit for each of the alternative systems assuming that plateau spatial variability is present. In this instance, 50 percent of the variability estimated in the general error component (η_{it} in equation 3) has been subtracted and added to the plateau spatial error component (τ_{it} in equation 3). The presence of plateau spatial variability does not have a large effect on the yields, levels of nitrogen, and expected profits.

Sensitivity values for independent relative changes in the exogenous variables are reported in Table III-5. Note that the sensitivity analysis has been conducted on results that were calculated assuming that plateau spatial variability is equal to 25 percent of the total variability estimated for the general error component (η_{it} in equation 3). Sensitivity results indicate that as the marginal product of nitrogen increases (implying that the total level of nitrogen applied decreases) the value of the perfect variable rate system increases relative to the value of the state recommended system that applies 80-pounds of N per acre. In addition, as the marginal product of nitrogen increases, the value of the NFOA system becomes more profitable relative to all other systems. That is, a situation when less nitrogen is needed to obtain an additional unit of yield, the NFOA system becomes the preferred system.

As expected, the value of the perfect variable rate system increases relative to the state recommended system as the price of NH_3 increases relative to the price of UAN. When the price of NH_3 is increased to the point where it is equal to the price of UAN, the value of the variable rate system increased to approximately $11 per acre over that of the state recommended system. The opposite relationship exists when the price of UAN increases relative to the price of NH_3. If the price of UAN increases to $0.50 per pound, holding the price of NH_3 constant at $0.15 per pound, then the value of the state recommended system is approximately $1 per acre more profitable than the perfect variable rate system. In this situation, a typical producer would not be interested in adopting the plant-based precision system.

As the nitrogen use efficiency adjustment variable is increased, the value of the perfect variable rate system increases over the value of the state recommended system. Note that when the NUE is adjusted upwards from 1.20 to 1.50, the average return of the portable system increases from approximately $106 per acre to $107.50, which is a value larger than the average net return for the state recommended system. Also notice that the estimate for the NUE adjustment factor positively affects the expected profitability of the NFOA system.

As the custom application cost for NH_3 increases relative to the custom application rates for the alternative systems, then the value for the preplant systems is reduced. Similarly, increases cost of custom applying uniform levels of UAN relative to the alternative systems would reduce the value of the portable system relative to the alternative systems. Likewise, if custom variable rate application of UAN increases relative to the custom rates for the alternative systems, then the value of the perfect variable rate system will decline relative to the alternative systems.

Summary and Conclusions

Panel data covering six years and seven locations in Oklahoma were used to estimate wheat yield response to nitrogen conditional on optical reflectance information taken from growing wheat plants in the spring. A linear response stochastic plateau function was assumed to best fit the data. Yield and net return were simulated on a large sample of independent grids and field-years. Under the assumption that the random processes are known perfectly, a maximum, unachievable value for the plant-based precision technology, over and above that of the conventional system, was found to be approximately \$7 per acre. The portable precision system was found to be approximately breakeven with the nitrogen application system that represents the 80-pound per-acre state extension recommendation.

Previous economic research has shown that variable rate application technologies that are based on sampling the soil have not been profitable when all economic costs associated with the technology are included in the analysis. A perfect information plant-based precision application technology had a value approximately $7 per acre above that of the conventional preplant system. The implications of this finding would be more promising if the relative prices of nitrogenous fertilizers increase. Currently, the plant-based precision sensing technology is available on a commercial basis, and is being promoted to increase net returns to nitrogen fertilization. However, the findings of this study explain why adoption has been slow. These findings also indicate that the optical sensing technology, including the nitrogen fertilizer optimization algorithm (NFOA), in many cases, does not apply enough nitrogen fertilizer, and therefore could be improved.

In addition to the lack of substantial increases in producer net return, other factors may impede the adoption of this technology such as timing. This specific technology applied all nitrogen in the spring as a topdress. However, during this time adverse weather conditions can limit application to only a few days, and possibly prevent application altogether.

Limitations and Further Research

A limitation to the widespread adoption of this technology in the southern Plains regards the large number of acres that are grazed with stocker cattle in the winter months. In the case of grazing, nitrogen rich strips would have to be fenced off from livestock. Plus, the technology requires a 14 day re-growth period before sensors measurements can be taken. If livestock are not removed at the appropriate time, the window of opportunity for topdressing can narrow or become nonexistent. This too, increases the risk of not being able to apply the necessary level of nitrogen when the plants use it the most efficiently. As a result of these impediments, and the fact that the technology is only marginally profitable may explain the limits of its adoption.

Further research oriented at evaluating the possible economic benefits from using the site-specific system for nitrogen application and application of additional chemicals such as insecticides and herbicides needs to be investigated.

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

Statistic	Symbol	Estimates[a]
Intercept	a	-12.25 (3.52)
Optical reflectance	b	7.57 (0.42)
Year random effect	σ_{ω}^{2}	9.65 (2.58)
Error variance	$\sigma_{\vartheta^*}^{2}$	103.79 (5.57)

[a] Asymptotic standard errors are in parentheses.

Note, that the parameter estimates for equation (2) were estimated using PROC MIXED in SAS.

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

Statistic	Symbol	Estimates[a]
Intercept	α	5.99 (.1609)
Level of nitrogen	β	.031 (.3458)
Expected plateau ORI	$E\left(ORI_t^{NRS}\right)$	7.19 (.1958)
Nitrogen at expected plateau	$N_t^{NRS} \cdot$	58.52 (.1958)
Variance of plateau yield	σ_{v}^{2}	0.39 (.1378)
Variance of year random effect	σ_{u}^{2}	0.55 (.1614)
Variance of error term	σ_{η}^{2}	0.66 (.0385)

[a] Asymptotic standard errors are in parentheses.

Note, the parameter estimates for equation (3) were estimated using NLMIXED procedure in SAS.

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

	System						
Estimate	0/0[a]	80/0[b]	63/0[c]	0/Port[d]	TBE/0[e]	0/GS[f]	0/NFOA[g]
Average Yield	32.54	41.61	41.23	40.11	41.79	42.11	38.29
Average Nitrogen (lbs)	0.00	80	63	33.38	57.53	31.77	17.73
Average profit ($)	97.63	106.72	108.13	108.88	110.64	113.79	106.28

[a] the check system with no nitrogen added.

[b] the system that represents the state extension recommendation of 80 pounds per acre, or 2 pounds of nitrogen for each bushel of yield goal.

[c] the system that represents the average level of nitrogen applied in the state of Oklahoma that was reported by producers via a survey conducted in 2000.

[d] the system that represents the portable precision system where no nitrogen was applied prior to planting.

[e] the system that represents the analytical approach developed by Tembo, Brorsen, and Epplin to determine the optimal level of nitrogen to apply in the fall prior to planting.

[f] the system that represent the plant-based variable rate precision system that assumes perfect knowledge about the random processes.

[g] the system that represents the NFOA developed by Raun et al. (2004).

Table III-4. Average Yield, Nitrogen, and Expected Profits from Alternative Nitrogen Management Systems with Plateau Spatial Variability

	System						
Estimate	0/0[a]	80/0[b]	63/0[c]	0/Port[d]	TBE/0[e]	0/GS[f]	0/NFOA[g]
Average Yield	32.54	41.61	41.23	38.87	41.57	42.10	39.95
Average Nitrogen (lbs)	0.00	80	63	33.27	57.35	32.40	17.65
Average profit ($)	97.63	106.72	108.13	105.01	109.15	113.92	105.25

Note that plateau spatial variability of 50% is assumed to come from the general error component, η_{it}.

[a] the check system with no nitrogen added.

[b] the system that represents the state extension recommendation of 80 pounds per acre, or 2 pounds of nitrogen for each bushel of yield goal.

[c] the system that represents the average level of nitrogen applied in the state of Oklahoma that was reported by producers via a survey conducted in 2004.

[d] the system that represents the portable precision system where no nitrogen was applied prior to planting.

[e] the system that represents the analytical approach developed by Tembo, Brorsen, and Epplin to determine the optimal level of nitrogen to apply in the fall prior to planting.

[f] the system that represent the plant-based variable rate precision system that assumes perfect knowledge about the random processes.

[g] the system that represents the NFOA developed by Raun et al. (2004).

Table III-5. Sensitivity Values for Independent Relative Changes in MPN, Prices of Nitrogen, NUE Adjustment, and Custom Application Costs

		System						
Parameter	Coefficient/ Price	0/0[a]	80/0[b]	63/0[c]	0/Port[d]	TBE/0[e]	0/GS[f]	0/NFOA[g]
Marginal Product of Nitrogen	0.114	97.63	100.48	99.68	97.00	101.99	105.43	99.75
	0.189	--------	105.74	106.30	103.81	107.87	111.96	103.15
	0.234*	--------	106.72	108.13	105.80	109.86	113.88	105.97
	0.303	--------	106.99	109.31	107.67	111.86	115.69	110.34
	0.531	--------	107.00	109.55	110.44	115.11	118.35	125.13
	0.682	--------	107.00	109.55	111.26	116.15	119.14	135.01
Price of NH3 ($/lb)	0.15*	97.63	106.72	108.13	105.80	109.86	113.88	105.97
	0.20	--------	102.72	104.98	--------	107.14	--------	--------
	0.25	--------	98.72	101.83	--------	104.66	--------	--------
	0.30	--------	94.72	98.68	--------	102.41	--------	--------
Price of UAN ($/lb)	0.20	--------	--------	--------	107.46	--------	115.49	106.85
	0.25*	97.63	106.72	108.13	105.80	109.86	113.8	105.97
	0.30	--------	--------	--------	104.14	--------	112.28	105.09
	0.40	--------	--------	--------	100.83	--------	109.10	103.38
	0.50	--------	--------	--------	97.55	--------	105.95	101.78
Nitrogen Use Efficiency Adjustment	1.20*	97.63	106.72	108.13	105.80	109.86	113.88	105.97
	1.50	--------	--------	--------	107.46	--------	115.55	109.73
	2.00	--------	--------	--------	109.43	--------	117.16	116.08
Custom, Uniform NH_3 Application Rates	6.11*	97.63	106.72	108.13	105.80	109.86	113.88	105.97
	7.00	--------	105.84	107.25	--------	108.98	--------	--------
	8.00	--------	104.84	106.25	--------	107.98	--------	--------
Custom, Uniform UAN Application Cost ($/acre)	3.74*	97.63	106.72	108.13	105.80	109.86	113.88	105.97
	4.00	--------	--------	--------	105.58	--------	--------	--------
	5.00	--------	--------	--------	104.75	--------	--------	--------
Custom, Variable Rate Application Cost ($/acre)	5.01*	97.63	106.72	108.13	105.80	109.86	113.88	105.97
	6.00	--------	--------	--------	--------	--------	113.02	105.17
	7.00	--------	--------	--------	--------	--------	112.16	104.42
	8.00	--------	--------	--------	--------	--------	111.33	103.74

Note, sensitivity analysis has been conducted on the results that were calculated assuming that plateau spatial variability τ_{it} is equal to 25% of the total variability estimated for the general error component η_{it}.

[a] the check system with no nitrogen added.

[b] the system that represents the state extension recommendation of 80 pounds per acre, or 2 pounds of nitrogen for each bushel of yield goal.

[c] the system that represents the average level of nitrogen applied in the state of Oklahoma that was reported by producers via a survey conducted in 2004.

[d] the system that represents the portable precision system where no nitrogen was applied prior to planting.

[e] the system that represents the analytical approach developed by Tembo, Brorsen, and Epplin to determine the optimal level of nitrogen to apply in the fall prior to planting.

[*] the baseline values for parameters.

f the system that represent the plant-based variable rate precision system that assumes perfect knowledge about the random processes.

g the system that represents the NFOA developed by Raun et al. (2004).

VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: ECONOMIC FEASIBILITY OF SITE-SPECIFIC OPTICAL REFLECTANCE TECHNOLOGY AS AN ALTERNATIVE STRATEGY FOR MANAGING NITROGEN APPLICATIONS TO WINTER WHEAT

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Title of Study: ECONOMIC FEASIBILITY OF SITE-SPECIFIC OPTICAL REFLECTANCE TECHNOLOGY AS AN ALTERNATIVE STRATEGY FOR MANAGING NITROGEN APPLICATIONS TO WINTER WHEAT

Pages in Study: 89 Candidate for the Degree of Doctor of Philosophy

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Scope and Method of Study: This dissertation is comprised of three essays, each of which examines the economics of plant-based precision nitrogen fertilizer application technologies relative to conventional fertilizer application methods for winter wheat. Partial budgeting techniques are used in all three essays to determine the net returns to nitrogen fertilizer and fertilizer application expenses for a number of precision systems and conventional systems.

Findings and Conclusions: In the first essay, it was found that a precise in season fertilizer application system would be worth approximately $8 to $10 per acre to a wheat farm producer operating in the southern Plains, depending upon location. A perfect precision system, then, would have to be developed and offered to farm producers for less than that amount in order for them to adopt it into their production practices. Results from the second essay suggest that two individual site-specific precision systems were not unambiguously more profitable than conventional methods. Results also indicate that the precision systems evaluated could be improved upon so as to increase their profitability relative to conventional methods. In the third essay, results suggest that the site-specific, perfect information precision system was approximately $7 more profitable than that of convention methods. It was pointed out that the perfect information system is unlikely in practice, and therefore the site-specific system was essentially breakeven with conventional methods. Contrasting the first essay results with the results found in the last two essays, it was concluded that the precision systems that were tested against the conventions could be improved to enhance their profitability.

ADVISER’S APPROVAL: Francis M. Epplin