Profitability of Site-specific Nitrogen Recommendations

for Michigan Corn

by

Yanyan Liu

A Plan B Paper

Submitted to

MICHIGAN STATE UNIVERSITY

in partial fulfillment of the requirements

for the degree of Master of Science

Department of Agricultural Economics

July 2003

ACKNOWLEGEMENTS

I owe great debt to my major advisor, Dr. Scott Swinton, who supervised the whole analysis and helped me greatly in every aspect during my master's study.

My sincere thanks also go to my committee members, Dr. Robert Myers, Dr. Peter Schmidt and Dr. Sasha Kravchenko, for their insightful suggestions and kind support.

I would also like to thank Dr. Eric Crawford, for his generous offers of admission and financial aid to my husband and me in 2000, and for his kind help thereafter.

I acknowledge the financial support for this study provided by Corn Marketing Program and the Michigan Department of Agriculture's Groundwater Stewardship Program (GWSP). Neil Miller, from Agri-Business Consultants, Inc, not only provided all the experimental data, but also gave me many valuable suggestions in this study. I owe a lot to him.

Last but not the least, thanks to my family: my husband Shanjun Li, my parents Guiying Liu and Shujun Chen, and my elder brother Weiwei Chen. I feel so blessed with their love and support.

ABSTRACT

Profitability of Site-specific Nitrogen Recommendations for Michigan Corn

by Yanyan Liu

Site-specific nitrogen application (SSNA) has been considered a potentially more efficient nitrogen (N) management than uniform N application (UNA), because it tailors the N application rate to meet crop needs. However, previous studies on the profitability of SSNA were inconclusive. This study examines the conventional N fertilizer recommendation as a possible reason for the poor profitability of previous SSNA studies. Most previous SSNA experiments followed state-level N recommendations based on yield goals and/or soil nutrient levels that assume corn yield response to N does not vary site-specifically. This study challenges that assumption. It examines a set of six continuous site characteristic variables, more than any previous study, in order to assess a wide range of site factors that could affect corn yield response to applied nitrogen. In examining three years of data on 14 fields in Central Michigan, this work looks at a longer time series and wider cross section than comparable research. For the first time, three years and 13 fields data are pooled together on the basis of irrigation status to provide an SSNA recipe. The results suggest that corn yield response to N does vary site-specifically, but at current prices, SSNA cannot generate enough benefits to cover its costs on most cornfields in this region.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

c or c_{ij} : Site characteristics

CEC: Cation exchange capacity

EC: Electrical conductivity

EPMNR: Expected profit maximizing nitrogen rate

IPI: Insolation potential index

N: Nitrogen

$N \times c$: Interaction term of nitrogen and site characteristics

N_credit: Plant-available soil N estimated from PSNT or previous legume crop

OM: Organic Matter

PSNT: Pre-sidedress nitrogen test (recommendation)

PSNT-UNA: Uniform nitrogen application based on PSNT recommendation

SSF: Site-specific farming

SSNA: Site-specific nitrogen application

SSI-SSNA: Site-specific nitrogen application based on site-specific information

SSI-UNA: Uniform nitrogen application based on site-specific information

TMT: Treatment

Tri-State: Tri-State nitrogen recommendation

Tri-State-UNA: Uniform nitrogen application based on Tri-State recommendation

UNA: Uniform nitrogen application

WET: Potential wetness index

Y: Corn yield

LIST OF TABLES

LIST OF FIGURES

Chapter 1 Introduction

1.1 Motivation for Site-Specific Nitrogen Management

Nitrogen (N) fertilizer is an important nutrient affecting corn growth and yield. As N prices have risen and nitrate (NO_{3}) leaching to groundwater has caused increasing concern in the US in recent years, improving N management in corn growth has become a critical problem to both farmers and researchers.

Site-specific N application (SSNA) has been considered a potentially more efficient N management practice than uniform N application (UNA), because it tailors the N application rate to meet crop needs. One basis for SSNA is the well-known observation that soil characteristics are heterogeneous across a field (Schnitkey, Hopkins et al. 1996), (McBratney and Whelan 1995). Compared with UNA, SSNA should offer two benefits:

1. Increasing profit by reducing N where less is needed and raising yield where more N is needed.
2. Decreasing residual N loadings by eliminating over-fertilization.

The idea of site-specific farming (SSF) is not new. Before machines took the place of draft animals in farming, farmers tilled small fields. They spent a lot of time on small pieces of land, treating plots site-specifically according to their special characteristics. SSF is still the typical farming style in most developing countries where labor is cheap relative to land, fertilizer inputs and machines. As labor saving tractors took over draft animals during the past century in the US, modern uniform management on large fields took over from traditional site-specific management in small fields. Recently, the advent of computer-based technologies, such as the global positioning system (GPS) and geographic information systems (GIS) have enabled detailed field information to become recorded in georeferenced form. Variable rate technology makes it possible to impose different treatments to different positions across a field without losing the advantage of mechanized management. Therefore, it is rational to expect that by using the new technologies, farmers could take advantage of both the efficiency of modern agriculture and the precision of traditional SSF. Some people have even predicted modern SSF to be another revolution in agriculture.

Despite the appealing idea of SSF, previous studies on the profitability of SSNA were inconclusive (see Swinton and Lowenberg-DeBoer 1998; and Doerge 2001). Several reasons are offered for the failure of SSNA to gain profitability, such as inaccurate yield goals and/or soil test values, miscalibrated variable rate equipment, and inaccurate fertilizer recommendations. This study examines the fertilizer recommendation as a possible reason for poor profitability of SSNA.

Virtually all prior SSNA experiments followed state-level N recommendations based on yield goals and/or soil tests. For example, two prevalent forms of N recommendations throughout the Corn Belt are the Tri-State N fertilizer recommendation for corn for Michigan, Illinois and Ohio and the pre-sidedress nitrate test (PSNT) recommendation used in Iowa. The Tri-state N recommendation takes the form:

$N(lb/acre) = -27 + (1.36 \times yield\_potential) - N\_credit$, where yield potential refers to the average yield achieved over the past years, N credit refers to plant-available soil N estimated from the PSNT or previous legume crop. This formula is based on the common-sense relationship between the expected corn yield and the amount of N the crop will need, which implies that high-yielding fields will respond to higher rates of N while low-yielding fields should require less N (Doerge 2001). The PSNT recommendation suggests an applied N level equal to a pre-determined target minus N credits on the PSNT. SSNA based on the Tri-State or PSNT recommendations thus assumes that the yield goal and soil N credit are site-specific, while corn yield response to N does not vary site-specifically. If that is not the case (i.e., corn yield response to N varies site-specifically), then the optimal N given by Tri-State or PSNT would be incorrect.

There has been some evidence that corn yield response to N varies site-specifically. A recent study in Central Minnesota indicated that there was significant variation in corn response to N for regions of the fields as small as 0.08ha (Hurley 2002). Another study in Argentina found that slope positions have a statistically significant while inconsistent influence on corn yield response to N in two years (Bongiovanni 2002). However, these results are only based on a few fields and/or single year experiments. Moreover, the Central Minnesota study did not identify significant site characteristic variables; and the Argentina study relied only upon dummy variables for slope position. Much more detailed representation of site characteristic variables is needed to fully assess the extent of site-specific N response and the factors that affect it.

To make it clear, we need to distinguish N application method from N recommendation. N recommendation refers to the formula following which to decide the N application level. Tri-state and PSNT are N recommendations. A new recommendation will be generated later in this paper based on the enlarged information set (Site-specific information N recommendation, SSI). SSNA and UNA are N application methods. SSNA applies variable N levels, while UNA applies a uniform N level within one field. Both UNA and SSNA can follow different N recommendations. Table 1 lists the combinations of three types of recommendations and two types of application methods considered in this study.

1.2 The Objectives

There are three objectives of this study:

1. To test whether site characteristics (*c*) interact with corn yield response to N. If *c* do interact with corn yield response to N, omitting them may lead to biased N response estimates.
2. To compare the performance of UNA based on Tri-State recommendation (Tri-State-UNA) with that of UNA based on PSNT recommendations (PSNT-UNA).
3. To provide a new N recommendation based on the enlarged information set (SSI) and test the profitability of SSNA based on SSI recommendations (SSI-SSNA), and UNA based on SSI recommendations (SSI-UNA) vs. Tri-State-UNA and PSNT-UNA.

1.3 Outline of the Paper

Chapter 2 outlines the conceptual framework in this study. Chapter 3 describes the experimental design and data structure. Chapter 4 reports analysis at both individual field- and pooled-field levels to fulfill the three study objectives. Summary and conclusions are made in Chapter 5.

Chapter 2 Conceptual Framework

2.1 A Whole-Field Model of Expected Profit Maximization

The expected profit maximization problem for whole-field N application is stated as

$$E(\pi) = T[E(p_Y Y - p_N N)] - FC - G_w$$

$$Y = g(N, \lambda, u)$$

π refers to profit,

$E(.)$ refers to the expectation of $(.)$,

p_y and p_N are prices of corn yield and nitrogen respectively,

Y refers to corn yield,

T refers to the total number of units of area in the field,

N refers to the uniform nitrogen rate used per unit of area based on whole-field recommendation,

FC refers to the fixed production cost,

G_w refers to the quasi-fixed cost related to generating whole-field nitrogen recommendation,

λ refers to weather effects,

u refers to other general stochastic effects,

$g(.)$ refers to yield function.

This model assumes corn yield response to N does not vary within the whole field. The yield function subdivides the unmanaged variables into two categories, weather effects (λ) and other general stochastic effects (u). The reason for separating weather effects from the other general stochastic effects is that weather significantly influences corn yield response to N while the other general stochastic effects are not considered in this whole-field model.

2.2 Biological Basis For Site-Specific Nitrogen Response[1]

Site characteristics (soil properties and terrain variables) may affect corn yield response to applied nitrogen (N) based on the biological N cycle in soils. Much of the naturally-occurring nitrogen available to corn plants is produced by the mineralization of soil organic matter (OM) to plant-available ammonium (NH_4^+) (roughly 20-30 lbs for every 1% OM in an acre-furrow slice) (Brady, 1974). Soil colloids fix ammonium N due to the negative charge of clay particles and soil OM. Soil cation exchange capacity (CEC) is an estimate of the ability of soil colloids to retain positive cations, including ammonium. Nitrogen losses in the light-textured soils of south-central Michigan are thought to occur largely through leaching of nitrate N through the soil profile. Losses of N occur when soils have more incoming water than the soil can hold. Soil electrical conductivity (EC) measurements are driven primarily by soil texture and soil moisture which are highly correlated to the soil's water-holding capacity. Therefore, EC could serve as a proxy for soil water-holding capacity (Lund 2000).

[1] Thanks to Neil R. Miller of Agri-Business Consultants Inc. of Birch Run, Michigan, for providing insightful suggestions in this part.

Aside from affecting water availability, topography also influences the redistribution (erosion and/or deposition) of soil particles, OM, and nitrogen through water movement. Kravchenko and Bullock (2000) detected higher OM contents at lower landscape position. They also found higher OM and phosphorus concentrations on concave surfaces than on convex surfaces. Water movement may also cause nitrogen losses through denitrification where water is ponded for significant periods of time.

The rate of photosynthesis affects a corn plant's ability to produce grain and its relative demand for nitrogen. While sunlight is a general stochastic variable, topography influences the propensity of plants to receive sunlight (Lee, 1978). Within a field, slope and aspect affect both total sunlight and the angle at which sunlight is received, and thus the relative demand for N.

2.3 A Site-specific Model of Expected Profit Maximization

The profit maximization problem for SSNA can be conceptualized as optimization of the individual cells in a farm field that has been divided into a Cartesian grid with i rows and j columns, such that any cell can be identified by its coordinates i,j. Using this framework, the expected profit-maximization of the variable rate fertilizer problem can be stated as a combination of 1) cell-specific yield revenue and variable-rate input costs and 2) field-level quasi-fixed and fixed costs (Lowenberg-DeBoer and Boehlje 1996),

$$\underset{\{N_{ij}\}\forall i,j}{Max}\, E(\pi) = \sum_{i=1}^{n}\sum_{j=1}^{m}[E(p_y Y_{ij} - p_N N_{ij})] - G_s - V - FC \qquad (2)$$

$$\text{s.t. } Y_{ij} = y(N_{ij}, x_{ij}, c_{ij}, \lambda, \varepsilon_{ij}) \qquad (3)$$

where,

p_y and p_N refer to prices of corn yield and fertilizer nitrogen respectively,

Y_{ij} refers to the corn yield in cell i,j,

N_{ij} refers to the nitrogen fertilizer rate applied to cell i,j,

x_{ij} refers to the vector of managed variables other than N in cell i,j,

c_{ij} refers to the vector of site characteristic variables in cell i,j,

λ refers to weather effects,

ε_{ij} refers to other general stochastic effects,

G_s refers to the quasi-fixed cost of intensive data collection and analysis in the field,

V refers to the quasi-fixed cost of SSNA in the field,

FC refers to all other costs, which are treated as fixed.

What makes this expected profit maximization model special is the yield function. Following Bullock and Bullock (2000) and Bullock, et al. (2002), the yield function subdivides the unmanaged variables into two categories, site characteristics (c_{ij}) and general stochastic effects. The general stochastic effects are further divided into weather effects (λ) and other stochastic effects (ε_{ij}) in this study. Here site characteristics are separated from the other stochastic effects, because site characteristics interact with corn yield response to N in this site-specific model. This is the major difference between the site-specific model and the whole-field model.

The first order condition (FOC) to this problem gives the expected profit maximizing N rate (EPMNR) as follows:

$$\partial E[y(N_{ij}, z_{ij}, \lambda, \varepsilon_{ij})] / \partial N_{ij} = p_N / p_Y \tag{4}$$

Thus the maximum expected profit of SSNA is obtained by inserting the optimal nitrogen application level that solves (4).

Chapter 3 Data Description

Nitrogen fertilizer rate experiments were conducted on 14 commercial corn fields during 1999-2001 to test the profitability of SSNA. The five farmer-cooperators, members of the Innovative Farmers of South Central Michigan, were self-selected on the basis of their interest in the issue of optimizing N management and their ability to carry out on-farm experiments, including the use of a GPS-equipped combine yield monitor. As such, they represent the more progressive producers in the area, not a typical cross-section. Table 2 indicates soil type, irrigation condition and crop types of the 14 fields.

3.1 Experimental Design[2]

The fields were located in Calhoun and Hillsdale counties, where agricultural soils are primarily loams, some underlain by sand and gravel. An initial soil test was taken in each field in fall, 1998, and variable-rate phosphorus, potassium and lime were applied in subsequent years in order to eliminate these elements as possible factors limiting yields. Most fields were planted to corn in two out of the three project years, and soybeans in the off year. The farmer cooperators select cultivars, planting dates, populations, in-row "starter" fertilizers, herbicides, and other inputs, just as they would for ordinary commercial grain production.

[2] This part is provided by Neil Miller, partner in Agri-Business Consultants, Inc., Birch Run, MI. Besides Neil Miller, Fran Pierce, Oliver Shabenberger and Darryl Warncke from the MSU Dept. of Crop and Soil Science planned.

In each year, planter passes were mapped with GPS after planting, and plot areas were identified parallel to these passes and 300 feet in length in randomized complete blocks of 5 plots each. Plot width was either 30 feet for cooperators with 6-row combines or 60 feet for those with 8 row combines. This design allowed for 30-40 replications of each treatment in a typical 40 acre experiment.

One to two weeks prior to sidedressing, soil nitrate tests were taken to a depth of 12 inches within a 5-10 feet radius (12 cores) from the center of each block. Samples were analyzed for soil nitrate, and treatments were determined as follows:

1) No side-dress nitrogen
2) 33% less than treatment 3
3) The Tri-State recommended rate (Vitosh et al. 1995) based on the formula[3]
   yield goal*1.36 – 27- (mean PSNT N-credit)
4) 33% more than treatment 3
5) A non-limiting nitrogen rate (180-210 lbs/ac sidedress N)

The average treatment and corresponding average yield of each field are summarized in Tables 3 and 4. Nitrate credits were calculated using a conversion factor of 6 lbs/ac per 1 ppm soil nitrate (3.6 lbs for the measured top 12 in of soil + 2.4 lbs estimated as present in the lower soil profile). In fields where significant quantities of surface-applied nitrogen were present (e.g. manure or herbicide carrier) the estimate of lower soil-profile N was assumed to be less reliable, and that portion of the conversion factor was reduced

[3] Please notice that this formula is different from that of Tri-state recommendation described above.

accordingly. Experiments with 60-foot plots were assigned only 3 treatments in order to keep the block size small enough to encompass a relatively homogenous soil environment, and to maximize replication.

Nitrogen was applied when corn plants were 8-24 inches tall using 28% urea-ammonium nitrate solution delivered by a 12-row BLU-JET toolbar with a coulter-injection system on the inside 11 inter-rows. The "guess row" between treatments received no nitrogen in order to prevent plants from intercepting fertilizer intended for adjacent plots, while the adjacent injection units delivered a 50% greater volume to allow all 12 rows to receive the same total N. Flow control was achieved using a gate valve run by a Mid-Tech TASC 6200 controller, and continuously monitored with a Mid-Tech flow meter. Variable-rate application software, ArcView (GIS Solutions, Inc) in 1999 and SiteMate (Farm Works Software) in 2000-2001, also recorded as-applied data from the flow-meter.

Fields were harvested with combines equipped with yield monitors including 3 PF3000 units (AgLeader Technology), 1 PF2000, and one GreenStar (John Deere & Co.) and GPS systems. Yield point data were cropped from 50 feet at the end of each plot, and erroneous data were removed where appropriate (e.g. combine start/stop points, around obstacles, areas of equipment malfunction, etc.) Dry bushel yields (15.5% moisture) and moisture were summarized by plot. As-applied fertilizer data were summarized following the same cropping scheme used for yield point data.

Base data, including the 1998 soil test, PSNT results from each year, soil electrical or magnetic conductivity, digital elevation mapping, previous year soybean yields, and yield potential mapping were also summarized by plot as follows: Point data were first interpolated using inverse distance weighting to the 4th power except for zone-sampled data which were interpolated from sample points using a nearest neighbor technique. Interpolated values were then cropped and summarized following the same scheme used for yield point data in each field. Digital elevation data were further converted to terrain derivatives (slope, aspect, curvature, wetness index, and insolation potential) using ArcView Spatial Analyst[4] (Environmental Systems Research Institute, Inc.) All other GIS data manipulation and summarization was accomplished using SSToolbox software[5] (Site-Specific Technology Development Group, Inc.)

The 1999 growing season was characterized by limited rainfall and abundant heat units. Throughout the season, soils remained below field capacity, and overall water movement through the profile (and associated leaching of nitrate) was presumably minimal. This presumption is supported by the relatively high soil nitrate values and N credits measured in 1999. Crops were limited by moisture in non-irrigated experiment fields in 1999, though most produced average to slightly below average grain yields. Irrigated fields produced average to above-average crops.

[4] Thanks to John D. MeGuire of Spatial Agricultural Systems, Inc. of Sherwood, Ohio, who transformed the raw digital elevation data to create these variables in ArcView Spatial Analysis.

[5] Thanks to Neil R. Miller of Agri-Business Consultants Inc. of Birch Run, Michigan, who manipulated and summarized all other GIS data.

Near-record rainfall fell on much of South-Central Michigan in 2000, with totals of 18-22 inches recorded from May1-Aug 31. During May and early June, when nitrate leaching potential is presumably highest, most fields recorded a 4-day period with greater than 2 inches precipitation on at least 1 occasion. Soil nitrate test values were, not surprisingly, much lower than in 1999. Through the remainder of the growing season, rain was well-distributed and resulted in record yields on many non-irrigated fields.

Precipitation varied widely thorough the region in 2001. Fields in the northwest portion of the project area again received record levels of rain, similar to the 2000 season. Fields toward the southeastern portion of the project area received much less rainfall, and one experiment was not even considered harvestable due to drought injury. Monthly rainfall data for 1999 – 2001 obtained from the nearest weather stations are summarized in Table 5.

3.2 Variable Description

The variables are divided into three classes (as summarized in Table 6): The dependent variable is corn yield (Y); the controlled variable is applied fertilizer nitrogen (N); site characteristic variables (c) include OM, CEC, N-credit, EC, Potential Wetness index (Wet) and Insolation Potential Index (IPI). Among them, OM, CEC and N-credit were generated from a pre-sidedress soil nitrate test as described earlier. Soil electrical conductivity (EC) measures are taken with Veris electrical conductivity and/or EM38 electro-magnetic soil probes and also interpolated between sampled points. Because the EC measures used different equipment in different fields, and because EC can vary within a field from one date to another based on soil moisture, all measurements were normalized by field around 0 following the formula: $EC_{ij} = \frac{raw\_EC_{ij}}{Mean(EC)} - 1$.

Two variables, potential wetness index (Wet) and insolation potential index (IPI), need a little more explanation. According to biological theory (see section 2.2), topography affects corn yield response to N mainly by influencing water movement and sunlight reception. In order to capture these functions of topography, two index variables were developed from terrain variables as proxies for the potential soil wetness and sunlight reception. The potential wetness of soil in a given topographical grid cell was modeled as a logarithmic transformation of the ratio of specific upper catchment area (Speight, 1974), A_s, to the tangent of the cell slope, β (Moore, et al., 1991) (Eq. 18, p. 13),

$$Wet = \ln\left(\frac{A_s}{\tan\beta}\right)$$

The formula was implemented in ArcView Spatial Analyst using an ArcView Avenue script developed by Loesch[6].

Potential sunlight reception was modeled as a function of slope inclination (β), aspect (azimuth measured in degrees clockwise from north, α) and terrestrial latitude (λ) (Lee 1978 Eq. 3.31, p. 57),

$$IPI = (\sin\beta)(\cos\alpha)(\cos\lambda) + (\cos\beta)(\sin\lambda)$$

[6] Timothy N. Loesch, GIS Applications Coordinator, Minnesota Department of Natural Resources (tim.loesch@dnr.state.mn.us).

This formula gives the sine of the equivalent latitude of a horizontal surface on the Earth's surface that would get sunlight equivalent to the measured location.

Chapter 4 Analytical Approach and Results

4.1 Functional Form for Corn Yield Response to Nitrogen

An appropriate function form is important to this study because some functional forms may make the hypotheses very difficult or even impossible to test. Moreover, the expected profit maximizing N rate (EPMNR) derived from the conceptual model critically depends on the choice of functional form. A quadratic functional form was evaluated against two alternative forms, the linear response and plateau function and the quadratic response and plateau function. Based on Lau's five criteria for the selection of functional form (theoretical consistency, domain of application, flexibility, computational facility and factual conformity) (Lau 1986), the quadratic form was selected for the following reasons:

1. Unlike the plateau functions, the quadratic model takes a smooth and concave function form and does not suggest a growth plateau, which reflects the long-standing opinion of diminishing marginal return to inputs associated with microeconomic marginal analysis.
2. The quadratic model is linear in parameters, which makes it is easy to estimate in several software packages.
3. One of the objectives in this study is to determine whether the site characteristics interact with N application, which is easily tested in the quadratic model.
4. The quadratic model does not use many degrees of freedom. This is a desired property in this study, because the sample size of some data sets is not large with respect to the number of site characteristic variables under consideration.

5. The quadratic model has a long history representing corn response to nitrogen, so there are ample bases for comparison of results.

The full quadratic model[7] had the following structure:

$$Y_{ij} = y(N_{ij}, x_{ij}, c_{ij}, \lambda, \varepsilon_{ij}) = \alpha(\lambda) + \beta_1(\lambda)N_{ij} + \beta_2(\lambda)N_{ij}^2 + \delta(\lambda)c_{ij} + \theta(\lambda)(N \times c_{ij}) + \varepsilon_{ij}, \quad (5)$$

$$\text{where } E(\varepsilon_{ij} \mid N_{ij}, c_{ij}) = 0,$$

$$\varepsilon_{ij} \mid N_{ij}, c_{ij} \sim N(0, \sigma_\varepsilon)$$

Consequently, from Equations (2) and (5), we can derive the EPMNR is

$$N_{ij}^{sr} = (\beta_1 + \theta c_{ij} - p_N / p_Y)/(-2\beta_2) \quad (6)$$

It may be a little tricky that the weather effect (λ) is included Equation (5) by influencing the coefficients $(\alpha, \beta_1, \beta_2, \delta, \theta)$. In other words, all the coefficients are functions of λ.

4.2 Outline of Analytical Structure

The analysis of this study is first conducted at the level of individual field-year combinations. Sub-objectives of the field level analysis are:

1. To detect the effects of site characteristics (c);
2. To develop confidence intervals for posterior optimal nitrogen, using them as criteria to compare different recommendations;
3. To compare the performance of Tri-State vs. PSNT-based N recommendations;
4. To provide insights for pooled-field analysis.

---

[7] In order to keep enough degrees of freedom, higher order N values and c^2 terms are not included in the model.

The second level analysis is to pool fields under different assumptions. The sub-objectives are:

1. To test the effect of interaction of N with c;
2. To evaluate the profitability of SSI-SSNA, SSI-UNA vs. Tri-State-UNA and PSNT-UNA;
3. To provide insights for future research.

In this study, three different models were specified at both levels:

1. Full model: Regression of corn yield on N, N^2, C, $N \times C$;
2. Final model: Full model minus jointly insignificant (at 10% significance level) explanatory variables;
3. Simple model: Regression of corn yield on N, N^2 (omits site characteristics).

The Full model and Final model are based on the information set including c, while the simple model is based on the information set without c.

Price sensitivity analysis is done at both the field and pooled-field levels. Because EPMNR is determined by the price ratio of nitrogen fertilizer to corn (Equation 4), three price scenarios were evaluated: P1 = 0.067 (for \$0.20/lb N and \$3.00/bu corn), P2 = 0.10 (for \$0.20/lb N and \$2.00/bu corn), and P3 = 0.15 (for \$0.30/lb N and \$2.00/bu corn).

4.3 Field Level Analysis

4.3.1 Site characteristics do affect corn yield but have little effect on EPMNR

In order to test the null hypothesis that site characteristics have no effect on corn yields, separate, field-level regressions with and without site characteristics were run on all 24 site-years of corn yield data. Table 8 summarizes the results of separate and joint F tests of site characteristic variables (c) and the interaction of nitrogen and site characteristic variables ($N \times c$) in the full model. c and ($N \times c$) are jointly significant at the 1% significance level in all of the 24 data sets. This provides strong evidence that site characteristics influence corn yield, reinforcing the findings of Kravchenko and Bullock (2000). However, the interaction terms ($N \times c$) are insignificant at $\alpha = 10\%$ in most data sets (21 out of 24). Thus we generally fail to reject the null hypothesis that c do not interact with nitrogen. Because c are significant at α = 10% in most data sets[8] (18 out of 24), we could conclude that c affects corn growth individually or through some unknown mechanism, but does not directly interact with nitrogen. These results suggest that the EPMNR derived from the simple model is consistent with (though less efficient than) the full model.

4.3.2. Yield response changes in same field in different years

The final models of corn yield response are summarized in Appendix Tables 9-11. These models omit all those variables that could be dropped under the criterion that a joint F-test would fail to reject the hypothesis of equal explanatory power with the full model at a 10% significance level. Yield is responsive to N in most cases, where both the N and N^2 coefficient estimates were significantly different from zero. In all cases where that was true, the coefficient estimates had the expected signs: positive for the linear term and negative for the quadratic term. Due to droughty conditions in 1999, 5 of the 8 fields showed no significant N response (Table 9). As expected, the PSNT N credit had a

[8] Each combination of field and year is a single data set in this part.

positive effect on corn yield (13 positive vs. 1 negative), and the interaction term of N and N credit is negative in all 5 cases where it was significant, which indicate that less N fertilizer should be applied where N credit is high. The wetness index also had a consistently positive effect on corn yield (17 positive vs. 1 negative). However, OM, CEC and EC did not demonstrate consistent effects on corn yield.

4.3.3 Confidence intervals for the posterior EPMNR

Table 12 summarizes the 80% confidence interval[9] around the posterior EPMNR from the final model for each field and year. It is called a "posterior" optimal rate because it is determined after realization of a stochastic process involving weather. The derived posterior EPMNRs are unknown at the time that N fertilizer decisions are taken, thus it is unjustified to compare them with N recommendations, but they can serve as a criterion to evaluate different recommendations. The advantage of using interval estimates instead of point estimates is that with interval estimates, it is very clear to what degree one recommendation is systematically different from the posterior EPMNR. For example, if the Tri-state recommendation is located outside the 80% confidence interval of posterior EPMNR, we can say we are 80% confident that the difference is systematic, not due to random chance.

Eighty percent confidence intervals were created around the observed EPMNR by Monte Carlo simulation of 3000 yield functions for each field using the final corn yield response to N model from Tables 7-9, According to (5),

[9] 80% was chosen because it is an approximate percentage normally acceptable to farmers.

$$Y_{ij} = \alpha + \beta_1 N_{ij} + \beta_2 N_{ij}^2 + \delta c_{ij} + \theta(N \times c_{ij}) + \varepsilon_{ij},$$

$$\text{where } E(\varepsilon_{ij} \mid N_{ij}, c_{ij}) = 0,$$

$$\varepsilon_{ij} \mid N_{ij}, c_{ij} \sim N(0, \sigma_\varepsilon)$$

Consequently, Estimates of β_1, β_2, δ and θ (denoted by $\hat{\beta}_1, \hat{\beta}_2, \hat{\delta}$ and $\hat{\theta}$) have a multivariate normal distribution with means μ_β, μ_θ and variance matrix Ω. Following from the OLS estimates (robust standard error adjustment allows the error term to be correlated and heteroskedastic) of $\mu_{\beta_1}, \mu_{\beta_2}, \mu_\delta, \mu_\theta$ and Ω, 3000 sets of $\hat{\beta}_1, \hat{\beta}_2, \hat{\delta}$ and $\hat{\theta}$ were simulated, permitting calculation of 3000 optimal nitrogen levels according to the first order condition for profit maximization. For the experiments where ($N\times c$) were insignificant in the final models, estimated EPMNR are computed following:

$$N^* = (\hat{\beta}_1 - p_N / p_Y)/(-2\hat{\beta}_2) \tag{7}$$

In the site-years where there were significant ($N\times c$) interactions, estimated EPMNR are computed following:

$$N^* = (\hat{\beta}_1 + \hat{\theta}\bar{c} - p_N / p_Y)/(-2\hat{\beta}_2)$$

(8)

where $\bar{c}$ is the vector of field-level mean values of the c variables.

Confidence intervals are relatively wider in 1999 than in the subsequent years due to low rainfall that caused weak and highly variable yield response to applied N. When both N and N^2 are significant, which was the case in most fields during 2000 and 2001, the interval estimates are very narrow and informative. In the cases of insignificant N or N^2, which typically occurred in 1999, the derived confidence intervals are unreliable and too wide to be informative.

In order to learn more about yield response to N on the five 1999 fields and one 2000 field where there was no significant N or N^2 coefficient estimate, one-way analysis of variance was conducted on these 6 data sets in order to see whether different nitrogen treatments had different effects on corn yield. The logic is as follows: if two treatments fail to generate significantly different yields, the optimal nitrogen application should be below the lower treatment level no matter what the prices may be, because extra nitrogen application cannot boost yield. Table 13 summarizes the analysis results and the inferred upper limit on a possible optimal nitrogen rate. For fields 1–A in 1999 and 1-B in 2000, yields were increasing over the range of the three N treatments applied, so it is not possible to identify an upper limit on an optimal rate, and therefore, the former derived confidence intervals are kept for use because they are the best estimates we can get.

Combining the results of Table 12 and Table 13, Table 14 indicates the estimated posterior EPMNR interval of each experiment. It was used to evaluate different pre-sidedress N recommendations.

4.3.4 Comparison of Tri-State vs. PSNT Recommendations

The Tri-State and PSNT recommendations were evaluated according to whether they fall inside the estimated interval of posterior EPMNR (as shown in Table 14). If not, the deviation was measured between the recommended N rate and the nearest side of the

80% confidence interval.

The experiments were classified into two groups based on irrigation status. Table 15 reports the amounts by which Tri-State and PSNT recommendations deviated from the observed EPMNR intervals in irrigated fields. The Tri-State outperformed the PSNT recommendations in 5 of the 9 experiments, while the PSNT outperformed the Tri-State in the other 4. The mean absolute deviations of the two recommendations did not differ much. We can conclude that the Tri-State and PSNT N recommendations have similar prediction performance for irrigated cornfields.

Table 16 reports the amounts by which Tri-State and PSNT recommendations deviated from the observed EPMNR intervals in non-irrigated fields. In the dry 1999 season, the PSNT outperformed the Tri-State in 6 of the 7 experiments. The mean absolute deviations of the PSNT formula at the all three price ratios were significantly lower than those of the Tri-State. This suggests that the PSNT outperformed the Tri-State in dry years for non-irrigated cornfields with these light soils. In the wet 2000 and moderate 2001 seasons, The Tri-State outperformed the PSNT recommendations in 5 of the 8 experiments, while PSNT outperform Tri-State in the other 3. The mean absolute deviations of the two recommendations did not differ significantly in either year. It seems that Tri-State and PSNT have similar performance for non-irrigated conditions in wet and moderate years. Therefore, given its superior performance in dry years, the PSNT generally outperforms the Tri-State for rain-fed corn production on these lightly textured soils.

In addition, the largest prediction deviation for each of the four situations (irrigated and rain-fed 1999, 2000 and 2001) was a Tri-State recommendation, which suggests that the PSNT may be a more consistent N recommendation than Tri-State.

As a summary, the Tri-State and PSNT N recommendation formulas had similar performance for irrigated fields, while the PSNT outperformed the Tri-State for rain-fed conditions based on the 24 $field \times year$ experiments. It is reasonable because water necessary for crop growth can be assured through irrigation, which eliminates drought condition such as that happened in 1999. The just-in-time nature of the PSNT allows it to compensate for nitrate leaching that may have occurred prior to sidedressing which is highly correlated with the pre-sidedress precipitation situation. This timely information accounts for the greater accuracy of the PSNT method.

However, what needs to be noted is that although the PSNT is more accurate in prediction for EPMNR than the Tri-State, it is not necessarily more profitable. The reason is that the PSNT tends to systematically under-predict EPMNR in irrigated fields and in all other fields in good rainfall years. The mean absolute deviation method used for comparison gives the same penalty for under-prediction as for over-prediction, while the economic loss incurred by under-prediction and over-prediction is asymmetric, i.e., with the same absolute deviation value, under-prediction of N needed undermines potential profit more than over-prediction. To see this clearly, from equation (2), we can derive the formula of marginal profitability of N:

$$\frac{\partial E(\pi)}{\partial N_{ij}} = p_Y \frac{\partial E(Y_{ij})}{\partial N_{ij}} - p_N \quad (9)$$

$\frac{\partial E(\pi)}{\partial N_{ij}}$ is diminishing, because $\frac{\partial E(Y_{ij})}{\partial N_{ij}}$ is diminishing, which is decided by the property of diminishing marginal productivity of N and was supported by empirical evidence (as shown in section 4.3.2).

The two characteristics of the PSNT recommendation (greater accuracy and systematic under-prediction for irrigated fields and for fields in "good" years) suggest that (1) PSNT recommendations need to be adjusted (for example, increase the base N rate for irrigated fields); (2) After proper adjustment, it is possible that the PSNT would become a more profitable N management strategy than the Tri-State.

4.4 Pooled-Field Analysis

4.4.1 Setup of the Pooled-Field Model

If SSNA recommendations are to be feasible on a regional basis, we need to identify consistent properties of corn yield response to N and set up a general model across fields and years. As discussed in earlier, weather – especially precipitation – was expected to interact with N and site characteristic variables (c) in affecting yield response. It was therefore inappropriate to pool the three years' data without any control of plant-available water.

As Figure 1 shows, corn yield response to N was quite different in 1999 and 2001 in the DEN10 (3–G) field. However, the HOM2 (3–H) field demonstrated a similar response pattern in 1999 and 2001 as shown in Figure 2. What also needs to be noted is that: (1) the two fields are so close that they experienced almost the same weather in the same year; (2) the two fields are owned by same farmer so that they are under the same management. The apparent reason that they demonstrated so different year pattern can be: HOM2 was an irrigated field, while DEN10 was not. In the dry 1999, plant-available water was the critical factor to corn growth, which masked the yield response to N. Irrigation could affect water status during corn growing season and assure enough water available for plant growth, in which case N became the critical factor to affect corn yield. Given this rationale, it seems reasonable to make the assumption that the response curve has same structure over years if enough water can be assured.

Theoretically, as was explained in section 2.2, water interacts with N to affect corn yield response via two mechanisms: nitrate leaching and moisture available for crop growth. Moisture effects can be divided into two periods, before and after side-dress N is applied in mid-June. During the early period, from March 1 to June 15, precipitation causes nitrate leaching from the crop root zone, making plant-available N scarcer. During the later period, from June 15 to August 15, precipitation contributes directly to crop growth. Farmers with irrigation can assure a minimum necessary water supply. The nitrate leaching effect can be considered captured by the N-credit variable that is calculated from the PSNT. So once moisture availability is assured, we can assume that the water effect has been included in the model. Therefore, we can safely pool three years' data together for the irrigated fields.

To find some statistical evidence supporting this assumption and to provide some insights for future analysis, an F test was conducted on data from the HOM2 field to test whether there was structure change of the corn yield response curve between 1999 and 2001. The procedure and result are:

1. Regress corn yield on $N, N^2, C, N \times C, D, D \times N, D \times N^2, D \times C, D \times N \times C$, where D is year dummy.
2. Test the joint significance of $D \times N, D \times N^2, D \times C, D \times N \times C$.

   Result: F(14, 378) = 1.22, Prob > F = 0.2549.
3. Test the joint significance of $D, D \times N, D \times N^2, D \times C, D \times N \times C$.

   Result: F(15, 378) = 2.54, Prob > F = 0.0013

The test result suggests: (1) failure to reject the null hypothesis that there was no structure change excluding the intercept between 1999 and 2001 at the 10% significance level; (2) rejection of the null hypothesis that there was no structure change including the intercept between 1999 and 2001 at the 1% significance level.[10]

The pooled-field model was then set up based on the assumption that given enough plant-available water, the corn response to N has same structure (except for the intercept) across fields and years. The data from 13 experiments were pooled to specify Full model, Final model and Simple model (as explained in 4.1). The selected experiments include 3-H 1999, 1-B 2000, 2-D 2000, 2-E 2000, 3-I 2000, 4-K 2000, 5-M 2000, 5-N 2000, 1-C 2001, 2-F 2001, 3-G 2001, 4-J 2001 and 4-L 2001. The selection criteria were: (1)

---

[10] The other two fields with two years' data and in which moisture was not limiting, R5&7W and 1N were tested in the same way. The F test results failed to reject that there was no structure change including the intercept between two different years for one field at the 10% significance level.

enough plant-available water, either from precipitation or from irrigation; (2) only keeping one of the two experiments if they are of same field in different years in order to avoid correlation between them; (3) trying to keep the data balanced across years while doing (2).

The models are estimated as cross sectional data using ordinary least squares (OLS) with a dummy variable assigned to each field to model the fixed effect across fields. Robust standard errors using the Huber/White sandwich estimator of variance for fields as clusters are used in Stata 6.0, due to evidence of spatial autocorrelation in separate analyses (not reported here). Descriptive statistics for all variables included in the yield response models are presented in Table 17.

4.4.2. Do Site Characteristics Interact With Corn Yield Response to N?

The joint significance of the $N \times c$ interaction terms was tested with F test of the Full model compared with the one without interaction terms (Table 4.2). The result was to reject the null hypothesis at 5% significance level ($F(6, 12) = 3.60$), so we conclude that site characteristics *do* interact with corn yield response to nitrogen in the Full model. Equation (5) states that site-specific information is relevant and potentially valuable in N management. This test result is different from that of 4.3.1, where $N \times c$ was not significant in most of the individual experiments. However, it is possible that even if $N \times c$ is relevant in the true model, it may fail to demonstrate significance in field-level models due to small sample size and small variation of site characteristics. By contrast, in the pooled data set, much larger sample size and data variability made it easier to discriminate deterministic factors from random factors and hence specify the true model.

The two interaction terms kept in the Final model (Table 16) are the interaction terms for N-credit with N ($N \times Ncredit$) and potential wetness index interact with N ($N \times WET$). Their coefficient estimates are both negative, which suggests that (1) less N should be applied where the N credit is higher, ceteris paribus, and (2) less N should be applied where potential wetness is higher, ceteris paribus. Result (1) is consistent to what derived in field level analysis (refer to 4.3.2). Result (2) is also consistent with the Final models of individual experiments where $N \times WET$ was significant (though only 2 out of 24, it is not surprising with respect to the narrow variation of wetness variable listed in Table 5).

4.4.3 Comparison of N Prediction Accuracy of SSI-UNA vs. Tri-State and PSNT

Table 18 summarizes the deviations of the SSI-UNA recommendations based on the pooled yield model from the posterior EPMNR intervals derived in section 4.2.3. The SSI-UNA recommendation fell into the posterior EPMNR interval in most of the experiments. The mean absolute deviation are merely 4, 4 and 5 (lb/ac) at the three price ratios. This result also supports the rationality of the model design that controls for moisture availability.

As shown in Table 19, the SSI-UNA recommendations obviously outperformed the Tri-State and PSNT approaches in both stability and accuracy of prediction.

4.4.4 Profitability Analysis

From sections 4.4.2 and 4.4.3, we learned that site-specific information is potentially valuable in N management, and the SSI-UNA recommendation outperforms the Tri-State and PSNT ones. In this section, we want to see whether the expected profit increase of SSI-SSNA is large enough to cover the quasi-fixed costs G and V in Equation (2), and still leave a net gain that could cover the costs of developing site-specific fertilizer recommendations. The null hypothesis, H_0, states that expected benefits from SSI-SSNA do not exceed its quasi-fixed costs of information (G_s) and variable rate application (V):

$$H_0: \sum_i \sum_j \{p_Y(Y_{ij}^{sr} - Y_{ij}^{ur}) - p_N(N_{ij}^{sr} - N_{ij}^{ur})\} \leq G_s + V$$

$$H_A: \sum_i \sum_j \{p_Y(Y_{ij}^{sr} - Y_{ij}^{ur}) - p_N(N_{ij}^{sr} - N_{ij}^{ur})\} > G_s + V$$

where any excess on the left-hand side would represent potential willingness to pay for development of SSI-SSNA recommendation.

Assuming the specified Final model of pooled-field analysis (as shown in Table 17) is the true model, we compare the gross margins $(P_y Y - P_N N)$ of the four nitrogen management strategies: (1) SSI-SSNA using the final yield response model with site characteristic variables, (2) SSI-UNA, also using the final yield response model but evaluated at mean values of c; (3) Tri-State-UNA; and (4) PSNT-UNA. Although SSI-SSNA and SSI-UNA use the same information set, the additional cost incurred by SSI-SSNA is $G_s + V$, while the additional cost incurred by SSI-UNA is G_s only.

Tables 20-22 compare field-level expected gross margins $[P_y E(Y) - P_N N]$ among the SSI-SSNA, SSI-UNA, Tri-State-UNA and PSNT-UNA strategies for the fields where moisture was not limiting, given the three price ratios. Tables 23-25 further calculate the 80% confidence intervals of the difference of field-level expected gross margins among the four strategies, based on 3000 Monte Carlo simulations.

Apart from the N fertilizer cost and fixed cost, the other costs of the four strategies are:

- SSI-SSNA: $G_s + V$;
- SSI-UNA: G_s ;
- Tri-State-UNA: the cost of generating yield goal (G_1);
- PSNT-UNA: the cost of the pre-sidedress soil nitrate test for determining the N credit (G_2).

From Tables 20-22, we can see that the difference in expected gross margin between SSNA and SSI-UNA is very small (less than 40cents/acre) in all the fields at each price ratio. Tables 23-25 suggest that all of the upper limits of the 80% confidence intervals are less than \$1/acre. Compared to the cost of variable rate application of a single fertilizer (V) averaged over \$5.00/acre in a 2001 dealer survey (Whipker and Akridge 2001), we can conclude that SSI-SSNA is less profitable than SSI-UNA.

Now Consider SSI-UNA and PSNT-UNA. Because the potential wetness index (WET) and N credit are the only site characteristics relevant to generating SSI-UNA, the cost difference between SSI-UNA and PSNT-UNA comes solely from generating the potential wetness index, which is easy to calculate from digital elevation data that can be collected with one pass of a yield monitor or electrical conductivity sensor. Since the wetness index, once developed, can be used for several years, the averaged yearly cost could be very small. Compared with the difference of expected gross margin between SSI-UNA and PSNT-UNA ($9.64/ac at P1, $4.51/ac at P2, $2.51 at P3 on average, as shown in Tables 17-19), it seems SSI-UNA is more profitable than the PSNT-UNA strategy. But as explained in section 4.2.4, the current PSNT recommendation may not be properly calibrated for Michigan conditions. Given a modified PSNT, whether SSI-UNA is more profitable than PSNT-UNA would depend upon whether the information value of the potential wetness index exceeds the cost of generating it.

As to comparing the SSI-UNA and Tri-State-UNA strategies, the quasi-fixed cost of generating the SSI recommendation is estimated to be about $3.80/ac[11] while the quasi-fixed cost of generating the Tri-State recommendation is close to zero. Compared with the difference of expected gross margin between SSI-UNA and Tri-State-UNA ($4.20/ac at P1, $2.18/ac at P2, $2.12/ac at P3 on average as shown in Tables 14-16), the SSI-UNA strategy is no more profitable than the Tri-State. Tables 17-19 further confirm this conclusion: The upper limit of 80% confidence interval is less than $3.80/acre (which suggests SSI-UNA is less profitable than Tri-State) in 8 fields at P1, 9 fields at P2, and 8 fields at P3. The 80% confidence interval includes $3.80/acre (which suggests no significant difference of profitability) in only 2 fields at P1 and P2, and 3 fields at P3; the

[11] Labor fee ($1.00/acre) + laboratory fee ($2.80/acre) = Total expense ($3.80/acre), Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

lower limit of 80% confidence interval exceeds $3.80/acre (which suggests SSI-UNA is more profitable than Tri-State) in merely 3 fields at P1, and 2 fields at P2 and P3.

Chapter 5 Summary and Conclusions

This study examines the conventional nitrogen (N) fertilizer recommendation as a possible reason for the poor profitability of previous site-specific nitrogen application (SSNA) studies. Most previous SSNA experiments followed state-level N recommendations based on yield goals and/or soil nutrient levels that assume corn yield response to N does not vary site-specifically. This study challenges that assumption. It examines a set of six continuous site characteristic variables, more than any previous study, in order to assess a wide range of site factors that could affect corn yield response to applied nitrogen. In order to capture the biological functions of topography, two index variables were first developed from terrain variables as proxies of the potential soil wetness and sunlight reception. In examining three years of data on 14 fields in Central Michigan, this work looks at a longer time series and wider cross section than comparable research. In addition, three years and 13 field-years of data are pooled together to provide an SSNA recipe for conditions where moisture is not limiting.

5.1 Summary of the Findings

- Corn yield response to N does vary site-specifically. The potential soil moisture index (Wetness) and N credit are the two site characteristics that were statistically significant in determining the expected profit maximizing N rate.
- The PSNT-based recommendation outperformed the yield-goal-based Tri-State recommendation in predictive accuracy, but failed to generate more profit than the Tri-State due to its systematic under-prediction of profit-maximizing N levels. This

result suggests that the PSNT formula for fertilizer recommendation base on estimated N credit should be adjusted.

- For irrigated fields, SSI-SSNA was not profitable compared to SSI-UNA, because the in-field variation of site characteristics was too small for variable rate N application to cover its cost.
- For irrigated fields, SSI-UNA predicted the EPMNR better than did the Tri-State and PSNT strategies, but the expected average gain in gross margin was not very large.
- For non-irrigated fields, the inter-seasonal weather effect appears to overcome the intra-seasonal spatial effects on corn yields, making it difficult to provide a reliable SSI-SSNA or SSI-UNA recommendation without some control on plant-available water.

5.2 Limitations and Future Research Needs

Certain site variables, such as the insolation potential index, do not have much variation. As a result, may lead to the problems of omitting relevant variables and failing to give more precise estimates. Fields of greater variability are desired in future researches.

The data are correlated in three interacted layers: (1) plots in the same year are correlated because they share similar weather condition; (2) same plots of different years are correlated because they have similar site characteristics; (3) plots within the same field of the same year are correlated because the neighbor plots within one field may share similar site characteristics. In the pooled-field model, the above correlation structures are not fully modeled. Only water status is considered in the model based on rough category.

In order to avoid the second type of correlation, I did not include all the experiments in which moisture was not limiting (see section 4.4.1). However, in doing so, some valuable information was discarded. Moreover, spatial structure was not fully modeled in this study. The use of robust standard error adjustment could eliminate the spatial error problem to some degree, but it had no effect on the possible lag problem (Anselin 1988).

Perhaps the biggest lesson was how important are seasonal weather differences. For rain-fed fields, the inter-seasonal rainfall variation dwarfed the intra-seasonal spatial effects in affecting EPMNR. Even for irrigated fields, the lack of information about within-field moisture levels was a big obstacle to further profitability analysis.

5.3 Suggestions for Future Research

The Tri-State N recommendation formula assumes average weather conditions. It does not consider season-specific weather, which is partially known at the time of pre-sidedress N fertilization. As explained in section 4.3.4, the early season precipitation situation is highly correlated with nitrate leaching that occurs prior to sidedress N application. This effect accounts for the more accurate EPMNR prediction of PSNT than that of Tri-State. Soil testing is costly, which may eat up the potential benefits of PSNT and SSI-UNA (as shown in section 4.4.4).

One alternative to explore is to try to model nitrate leaching as a function of precipitation, thereby estimating N credits without doing costly soil tests. As noted in section 4.4.4, the cost of generating a potential wetness index is very low. Therefore, without annual

PSNT's, SSI-UNA could potentially become a consistently more profitable strategy for N management in corn than the Tri-State approach. In order to make the most of spatial yield response models in future, within-field precipitation and irrigation information should be carefully modeled.

APPENDIX

Table 1: The combinations of N recommendations and N application methods

	Tri-state	**PSNT**	**SSI**
UNA	Tri-state-UNA	PSNT-UNA	SSI-UNA*
SSNA	Tri-state-SSNA	PSNT-SSNA	SSI-SSNA

* SSI-UNA uses the same information set as SSI-SSNA to gain field-specific information, while still applying a uniform N rate to avoid the cost of the variable rate technique. Schnitkey et al. have shown that site-specific soil nutrient information can be used to improve upon a naïve model of whole-field average response for uniform rate fertilizer application Schnitkey, G., J. Hopkins, et al. (1996). An Economic Evaluation of Precision Fertilizer Applications on Corn-Soybean Fields. Precision Agriculture: Proceedings of the 3rd International Conference. W. E. Larson. Madison, WI, ASA/CSSA/SSSA: 977-988.

Table 2: Field characteristics and crop, 14 fields with corn nitrogen experiments, south-central Michigan, 1998-2000

Field ID	Field Name	Irri-gation	Soil Type	Crop 1998	1999	2000	2001
1 - A	V1&2N		Boyer SL, Kalamazoo L, Hillsdale SL	Soy	Corn*	Soy	Corn*
1 - B	C2&3S		Oshtemo SL, Kalamazoo L, Hillsdale SL	Wheat	Corn*	Corn*	Corn
1 - C	R5&7W	irr	Kalamazoo L, Kibbie L	Corn	Soy	Corn*	Corn*
2 - D	OFF		Brady SL, Matherton L, Gilford fine SL	Wheat	Corn*	Corn*	Soy
2 - E	CHY-E	irr	Spinks LS, Bronson SL, Gilford fine SL	Corn	Soy	Corn*	Soy
2 – F	MEY-N	irr	Boyer SL	Soy	Corn	Soy	Corn*
3 - G	DEN10		Palms muck, Edwards muck, Osthemo SL, Kalamazoo L, Sleeth L, Sebewa L	Soy	Corn*	Soy	Corn*
3 - H	HOM2	irr	Oshtemo SL, Leoni gravelly L, Brady SL	Soy	Corn*	Soy	Corn*
3 - I	HOM1	irr	Oshtemo SL, Leoni gravelly L, Brady SL	Soy	Soy	Corn*	Soy
4 - J	BRY-E		Oshtemo SL, Boyer SL, Kalamazoo L	Soy	Corn*	Soy	Corn*
4 - K	OUT		Kalamazoo L, Riddles L, Morley L	Wheat	Corn*	Corn*	Soy
4 - L	HOM-W		Bronson SL, Oshtemo SL, Kalamazoo L, Hillsdale SL, Brady SL,	Corn	Soy	Corn*	Corn*
5 - M	1N	Irr[1]	Riddles SL	Soy	Corn*	Corn*	Soy
5 - N	20N		Hillsdale SL, Riddles L	Corn	Soy	Corn*	Corn

* Corn nitrogen experiment

[1] This field is non-irrigated in 1999, while irrigated in 2000

NB: L = loam; SL = sandy loam

Data source: Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Table 3: Fields and N treatments by year, 14 fields in south-central Michigan, 1999-2001

Field ID	Field Name	Year	Average Nitrogen Treatment (Pound/Acre)				
			TMT 1	TMT 2	TMT 3	TMT 4	TMT 5
1 - A	V1&2N	1999	-	92	112	170	-
1 - B	C2&3S	1999	-	88	115	157	-
2 - D	OFF	1999	-	103	138	191	-
3 - G	DEN10	1999	34	103	128	158	194
3 – H	HOM2	1999	33	116	153	185	213
4 – J	BRY-E	1999	57	110	130	153	197
4 - K	OUT	1999	55	129	154	184	220
5 - M	1N	1999	19	111	150	185	206
1 - B	C2&3S	2000	-	81	112	163	-
1 - C	R5&7W	2000	27	90	124	157	216
2 - D	OFF	2000	-	99	140	200	-
2 - E	CHY-E	2000	24	131	163	199	223
3 - I	HOM1	2000	34	125	164	200	238
4 - K	OUT	2000	25	101	146	190	230
4 - L	HOM-W	2000	25	116	155	197	232
5 – M	1N	2000	19	107	149	195	226
5 - N	20N	2000	21	101	140	178	217
1 - A	V1&2N	2001	-	63	108	150	-
1 - C	R5&7W	2001	27	118	166	210	233
2 – F	MEY-N	2001	5	81	111	165	206
3 - G	DEN10	2001	30	112	151	188	235
3 - H	HOM2	2001	28	121	163	208	232
4 - J	BRY-E	2001	26	118	165	209	233
4 - L	HOM-W	2001	25	131	167	204	233

Data source: Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Table 4: Mean corn yields (15.5% moisture) by treatment and field, 1999-2001

Field ID	Field Name	Year	Average Yield (bu/ac) TMT 1	TMT 2	TMT 3	TMT 4	TMT 5
1 - A	V1&2N	1999	-	127	136	142	-
1 - B	C2&3S	1999	-	152	157	156	-
2 - D	OFF	1999	-	152	155	157	-
3 - G	DEN10	1999	110	120	124	121	122
3 – H	HOM2	1999	105	157	168	175	177
4 – J	BRY-E	1999	121	128	125	128	132
4 - K	OUT	1999	113	117	118	119	117
5 - M	1N	1999	72	102	102	102	104
1 - B	C2&3S	2000	-	115	127	138	-
1 - C	R5&7W	2000	86	125	139	146	150
2 - D	OFF	2000	-	140	155	162	-
2 - E	CHY-E	2000	80	133	140	146	145
3 - I	HOM1	2000	85	136	142	144	147
4 - K	OUT	2000	120	180	188	191	193
4 - L	HOM-W	2000	136	164	163	163	165
5 – M	1N	2000	37	111	129	137	135
5 - N	20N	2000	47	115	126	129	132
1 - A	V1&2N	2001	-	130	140	139	-
1 - C	R5&7W	2001	47	95	111	116	116
2 – F	MEY-N	2001	94	153	160	167	169
3 - G	DEN10	2001	115	160	168	168	168
3 - H	HOM2	2001	92	148	158	161	164
4 - J	BRY-E	2001	105	142	147	150	151
4 - L	HOM-W	2001	77	170	184	192	193

Data source: Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Table 5: Total monthly rainfall (mm) during March-August in 1999, 2000 and 2001 at Battle Creek and Hillsdale, Michigan

	Battle Creek			Hillsdale		
	1999	**2000**	**2001**	**1999**	**2000**	**2001**
March	27	40	12	54[2]	47	11[2]
April	159	102	68	170[2]	128	104[2]
May	51	227	197	97	171	134[3]
June	88	95	98	53[2]	168	107
July	69	109	51[1]	197[2]	99	107[2]
August	50[1]	88	148[1]	68	115	140[2]

[1] Data from Gull Lake replace missing data for Battle Creek

[2] Data from Coldwater replace missing data for Hillsdale

[3] Data from Jackson replace missing data for Hillsdale

Data source: Battle Creek, Hillsdale, Gull Lake, Cold Water and Jackson weather stations

Table 6: Variable category

Dependent variable	**Treatment variable**	**Site Characteristics variables (C)**		
		Soil test data	**Sensor data**	**Derived var.**
Corn yield (Y)	Nitrogen applied (N)	Organic matter (OM) Caption exchange capacity (CEC) N credit (Ncre)	Electrical conductivity (EC)	Potential wetness index (Wet) Potential sunshine reception index (IPI)

Table 7: Definitions and summary statistics for variables included in corn yield response to nitrogen regressions that include site characteristics.

Variable name	Units	Mean	Min	Max
Corn dry yield[1]	bu/ac	137	16	229
Nitrogen applied[1]	lbs. actual N/ac	140	5	330
Soil test characteristics - N credit[2]	lbs. actual N	42	4.5	148
- Organic matter (OM) [2]	percent	2.59	0.87	59.13
- Cation exchange capacity (CEC)[2]	meq/100 gr	6.36	2.65	23.53
Soil electrical conductivity (EC)[2]	Veris & EM38 0.3m (interpolated, standardized)	0	-.62	2.90
Wetness index[1]	ln ratio	10.56	7.88	15.07
Insolation Potential Index[1]	Sine of equiva-lent latitude	0.67	0.60	0.73

[1] Average value per plot

[2] Average of interpolated values in plot

Data source: Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Table 8: F test results of the significance of site characteristic variables (c) and the interaction of site characteristic variables and nitrogen ($N \times c$)

Field ID	Field Name	Yr	Test of c and $N \times c$		Test of c		Test of $N \times c$	
			F statistics	Prob>F	F statistics	Prob>F	F statistics	Prob>F
1 - A	V1&2N	1999	F(12,90) =12.58	0.0000	F(6,90)=2.31	0.0404	F(6,90)=1.71	0.1274
1 - B	C2&3S	1999	F(12,87)=3.56	0.0003	F(6,87)=1.49	0.1908	F(6,87)=.82	0.5570
2 - D	OFF	1999	F(12,45)=2.77	0.0067	F(6,45)=.37	0.8924	F(6,45)=.22	0.9673
3 - G	DEN10	1999	F(12,163)=17.49	0.0000	F(6,163)=5.85	0.0000	F(6,163)=1.54	0.1688
3 – H	HOM2	1999	F(12,189)=6.78	0.0000	F(6,189)=2.61	0.0186	F(6,189)=.36	0.9010
4 – J	BRY-E	1999	F(12,125) =12.79	0.0000	F(6,125)=1.31	0.1389	F(6,125)=.91	0.3620
4 - K	OUT	1999	F(12,195)=8.73	0.0000	F(6,195)=2.25	0.0403	F(6,195)=.37	0.8958
5 - M	1N	1999	F(12,145)=6.25	0.0000	F(6,145)=4.76	0.0002	F(6,145)=1.57	0.1606
1 - B	C2&3S	2000	F(12,89)=7.69	0.0000	F(6,89)=1.42	0.2153	F(6,89)=.98	0.4435
1 - C	R5&7W	2000	F(12,221)=43.48	0.0000	F(6,221)=47.37	0.0000	F(6,221)=15.60	0.0000
2 - D	OFF	2000	F(12,39)=4.32	0.0002	F(6,39)=.43	0.8552	F(6,39)=.54	0.7729
2 - E	CHY-E	2000	F(12,142)=3.71	0.0001	F(6,142)=4.26	0.0006	F(6,142)=2.33	0.0352
3 - I	HOM1	2000	F(12,172)=31.85	0.0000	F(6,172)=18.39	0.0000	F(6,172)=1.65	0.1365
4 - K	OUT	2000	F(12,211)=8.08	0.0000	F(6,211)=3.11	0.0061	F(6,211)=.38	0.8935
4 - L	HOM-W	2000	F(12,269)=17.05	0.0000	F(6,269)=16.07	0.0000	F(6,269)=1.26	0.2744
5 – M	1N	2000	F(12,145)=4.70	0.0000	F(6,145)=2.34	0.0347	F(6,145)=.94	0.4650
5 - N	20N	2000	F(12,87)=17.25	0.0000	F(6,87)=16.67	0.0000	F(6,87)=1.41	0.2185
1 - A	V1&2N	2001	F(12,90)=18.31	0.0000	F(6,90)=3.26	0.0060	F(6,90)=1.08	0.3807
1 - C	R5&7W	2001	F(12,228)=15.93	0.0000	F(6,228)=5.14	0.0001	F(6,228)=1.34	0.2389
2 – F	MEY-N	2001	F(12,112)=6.13	0.0000	F(6,112)=2.20	0.0472	F(6,112)=.73	0.6249
3 - G	DEN10	2001	F(12,153)=4.55	0.0000	F(6,153)=3.98	0.0010	F(6,153)=3.16	0.0059
3 - H	HOM2	2001	F(12,189)=4.18	0.0000	F(6,189)=1.63	0.1404	F(6,189)=.98	0.4409
4 - J	BRY-E	2001	F(12,122)=7.82	0.0000	F(6,122)=1.83	0.0981	F(6,122)=.40	0.8809
4 - L	HOM-W	2001	F(12,244)=3.11	0.0004	F(6,244)=4.22	0.0005	F(6,244)=1.58	0.1545

Table 9: Final corn yield response models for 1999, 8 fields, south-central Michigan

	1 - A V1&2N	**1 – B C2&3S**	**2 – D OFF**	**3 – G DEN10**	**3 – H HOM2**	**4 – J BRY-E**	**4 – K OUT**	**5 – M 1N**
Obs. No.	105	102	60	178	204	140	210	160
F stat.	17.67	6.19	4.73	34.05	160.55	23.50	18.45	68.61
Prob>F	0.0000	0.0002	0.0012	0.0000	0.0000	0.0000	0.0000	0.0000
R-squared	0.5369	0.2677	0.3193	0.5584	0.8684	0.4964	0.1938	0.6892
Variables								
n	1.03[2]	.401	.261	.406[1]	.956[1]	-.00245	.0411	.4551[1]
n2	-.00143	-.00144[1]	-.000725	-.000758[1]	-.00228[1]	.000282	-.0000721	-.00143[1]
om				.568[1]	13.0[1]	-24.8[1]	-17.1[1]	-14.9[1]
cec					-4.72[1]	12.9[1]	9.41[1]	3.94[2]
ec	-36.5		-5.04[3]	9.85[1]		58.6[1]	-18.8[1]	30.3[1]
ncredit	1.71[1]	-.0763[2]		.735[1]	.122[2]	.378[1]	.199[1]	
wet	5.27[1]	3.34[1]	2.91[2]		1.97[1]	3.47[1]		5.83[1]
ipi	288[1]		-520[1]	390[1]				.0971[2]
nxom								
nxcec								
nxec	.445[2]							
nxncre	-.0107[2]			-.00267[2]				
Nxwet								
nxipi								

[1] Significant at 1% significance level

[2] Significant at 5% significance level

[3] Significant at 10% significance level

Table 10: Final corn yield response models for 2000, 9 fields, south-central Michigan

	1 – B	1 – C	2 – D	2 – E	3 – I	4 – K	4 – L	5 – M	5 – N
	C2&3S	R5&7W	OFF	CHY-E	HOM1	OUT	HOM-W	1N	20N
Obs.	104	236	54	157	187	226	284	160	102
F stat.	44.26	156.93	20.68	57.55	354.42	161.02	57.90	920.18	209.37
Prob>F	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R-squ.	0.6728	0.8800	0.6738	0.6852	0.9078	0.8059	0.5999	0.9539	0.8873
Var.									
n	.642[2]	1.03[1]	.917[1]	.950[1]	.965[1]	1.05[1]	.454[1]	1.22[1]	1.09[1]
n2	-.00151	-.00217[1]	-.00230[1]	-.00181[1]	-.00194[1]	-.00281[1]	-.00128[1]	-.00307[1]	-.00267[1]
om	3.98[2]			8.30[2]	20.2[1]	17.7[1]	-1.41[1]		-13.5[1]
cec		-1.10					1.01[1]	2.06[1]	
ec	6.26[3]	25.4[1]	-11.2[1]			19.5[1]	28.0[2]	9.25[3]	23.5[1]
ncredit		1.22[1]		2.21[1]	.197[2]	.460[1]			.897[1]
wet	5.72[1]	3.03[2]			4.76[1]	2.78[3]	-4.09[1]		5.74[1]
ipi			-407[2]		123[2]	492[1]			
nxom									
nxcec		.0396[2]							
nxec		-.101[2]					-.155[3]		
nxncre		-.00535[1]		-.0104[1]					
nxwet		-.0197[3]			-.0144[2]				
nxipi									

[1] Significant at 1% significance level

[2] Significant at 5% significance level

[3] Significant at 10% significance level

Table 11: Final corn yield response models for 2001, 7 fields: south-central Michigan

	1 - A V1&2N	1 - C R5&7W	2 - F MEY-N	3 - G DEN10	3 - H HOM2	4 - I BRY-E	4 - L HOM-W
Obs. No.	105	243	127	168	204	137	259
F stat.	36.35	310.70	96.42	255.52	143.79	50.91	435.70
Prob>F	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R-squ.	0.6506	0.8564	0.7576	0.9336	0.8395	0.7294	0.8996
Variables							
n	.574[1]	.805[1]	.891[1]	1.03[1]	.891[1]	.591[1]	1.33[1]
n2	-.00215[1]	-.00179[1]	-.00261[1]	-.00215[1]	-.00212[1]	-.00144[1]	-.00307[1]
om	-16.1[1]	12.1[1]		-2.72[1]	7.85[1]	-22.7[1]	-.895[2]
cec	10.2[1]		19.1[1]	3.65[2]	-4.99[1]	9.68[1]	
ec	10.5			9.27[1]		106[1]	
ncredit		1.20[1]		.648[1]	.534[1]		.287[1]
wet	5.15[1]	1.37[2]	3.46[2]		2.01[2]	5.33[1]	1.75[3]
ipi	152[1]			213[2]		672[1]	
nxom				.0164[1]			
nxcec				-.0248[2]			
nxec							
nxncre				-.00343[2]			
Nxwet							
Nxipi							

[1] Significant at 1% significance level

[2] Significant at 5% significance level

[3] Significant at 10% significance level

Table 12: 80% confidence interval of optimal nitrogen (kg/ha) calculated at 3 price ratios (P1, P2 and P3) of nitrogen ($/lb) and corn yield ($/bu) by field and year based on 3000 Monte Carlo simulations

Field ID	Field Name	Year	80% C.I. of Optimal Nitrogen			Note
			P1 = 0.2/3	P2 = 0.2/2	P3 = 0.3/2	
1 - A	V1&2N	1999	[87, 240]	[104, 210]	[120, 164]	N^2 insignificant, NXC significant
1 - B	C2&3S	1999	[100, 135]	[81, 129]	[44, 120]	N^2 insignificant
2 - D	OFF	1999	[94, 192]	[49, 223]	Too large*	N, N^2 jointly insig.
3 - G	DEN10	1999	[89, 119]	[53, 98]	[0, 73]	NXC significant
3 – H	HOM2	1999	[189, 210]	[182, 202]	[172, 189]	
4 – J	BRY-E	1999	[55, 189]	[29, 262]	Too large*	N, N^2 individually insig.
4 - K	OUT	1999	Too large*	Too large*	Too large*	N, N^2 jointly insig.
5 - M	1N	1999	[135, 152]	[125, 139]	[109, 120]	
1 - B	C2&3S	2000	[143, 264]	[140, 240]	[134, 206]	N^2 insignificant
1 - C	R5&7W	2000	[179, 191]	[172, 182]	[161, 170]	NXC significant
2 - D	OFF	2000	[170, 216]	[164, 202]	[155, 181]	
2 - E	CHY-E	2000	[178, 222]	[171, 210]	[160, 192]	NXC significant
3 - I	HOM1	2000	[188, 200]	[180, 190]	[168, 176]	NXC significant
4 - K	OUT	2000	[170, 182]	[165, 176]	[156, 166]	
4 - L	HOM-W	2000	[145, 159]	[133, 144]	[113, 124]	NXC significant
5 – M	1N	2000	[184, 194]	[179, 188]	[171, 179]	
5 - N	20N	2000	[170, 195]	[165, 188]	[157, 178]	
1 - A	V1&2N	2001	[103, 130]	[99, 119]	[82, 107]	
1 - C	R5&7W	2001	[198, 228]	[190, 217]	[177, 199]	
2 – F	MEY-N	2001	[151, 166]	[145, 159]	[137, 149]	
3 - G	DEN10	2001	[171, 178]	[164, 170]	[153, 158]	NXC significant
3 - H	HOM2	2001	[189, 209]	[182, 200]	[170, 185]	
4 - J	BRY-E	2001	[169, 205]	[159, 189]	[144, 165]	
4 - L	HOM-W	2001	[201, 218]	[196, 212]	[189, 203]	

* Lower limit less than zero; upper limit exceeds reasonable level.

Table 13: Probabilities of yield difference from alternative N treatments based on one-way analysis of variance in the data sets with insignificant N or N^2 coefficients estimates

Field ID	Field Name	Year	Pr>|t| TMT 1, 2	TMT 2, 3	TMT 3, 4	TMT 4, 5	Optimal N (lb/ac)
1 - A	V1&2N	1999	n.a.	0.0017	0.056	n.a.	-
1 - B	C2&3S	1999	n.a.	0.015	0.41	n.a.	< 115
2 - D	OFF	1999	n.a.	0.31	0.45	n.a.	< 103
4 – J	BRY-E	1999	0.020	0.45	0.55	0.30	< 110
4 – K	OUT	1999	0.041	0.77	0.81	0.36	< 129
1 – B	C2&3S	2000	n.a.	< .0001	< .0001	n.a.	-

n.a.: Only 3 treatments used

Table 14: Estimated posterior EPMNR interval calculated at 3 price ratios (P1, P2 and P3) of nitrogen ($/lb) and corn yield ($/bu) by field and year based on the results of Table 10 and Table 11

Field ID	Field Name	Year	80% C.I. of Optimal Nitrogen			Note
			P1 = 0.2/3	P2 = 0.2/2	P3 = 0.3/2	
1 - A	V1&2N	1999	[87, 240]	[104, 210]	[120, 164]	N^2 insignificant, NXC significant
1 - B	C2&3S	1999	< 115	< 115	< 115	N^2 insignificant
2 - D	OFF	1999	< 103	< 103	< 103	N, N^2 jointly insig.
3 - G	DEN10	1999	[89, 119]	[53, 98]	[0, 73]	NXC significant
3 – H	HOM2	1999	[189, 210]	[182, 202]	[172, 189]	
4 – J	BRY-E	1999	< 110	< 110	< 110	N, N^2 individually insig.
4 - K	OUT	1999	< 129	< 129	< 129	N, N^2 jointly insig.
5 - M	1N	1999	[135, 152]	[125, 139]	[109, 120]	
1 - B	C2&3S	2000	[143, 264]	[140, 240]	[134, 206]	N^2 insignificant
1 - C	R5&7W	2000	[179, 191]	[172, 182]	[161, 170]	NXC significant
2 - D	OFF	2000	[170, 216]	[164, 202]	[155, 181]	
2 - E	CHY-E	2000	[178, 222]	[171, 210]	[160, 192]	NXC significant
3 - I	HOM1	2000	[188, 200]	[180, 190]	[168, 176]	NXC significant
4 - K	OUT	2000	[170, 182]	[165, 176]	[156, 166]	
4 - L	HOM-W	2000	[145, 159]	[133, 144]	[113, 124]	NXC significant
5 – M	1N	2000	[184, 194]	[179, 188]	[171, 179]	
5 - N	20N	2000	[170, 195]	[165, 188]	[157, 178]	
1 - A	V1&2N	2001	[103, 130]	[99, 119]	[82, 107]	
1 - C	R5&7W	2001	[198, 228]	[190, 217]	[177, 199]	
2 – F	MEY-N	2001	[151, 166]	[145, 159]	[137, 149]	
3 - G	DEN10	2001	[171, 178]	[164, 170]	[153, 158]	NXC significant
3 - H	HOM2	2001	[189, 209]	[182, 200]	[170, 185]	
4 - J	BRY-E	2001	[169, 205]	[159, 189]	[144, 165]	
4 - L	HOM-W	2001	[201, 218]	[196, 212]	[189, 203]	

Table 15: Deviations of Tri-State and PSNT recommendations (lb/ac) from the posterior EPMNR for 9 irrigated field-years, south-central Michigan, 1999-2001

			Tri-State				PSNT			
Field ID	**Field Name**	**Year**	**Recs.**	**Devs. (P1)**	**Devs. (P2)**	**Devs. (P3)**	**Recs.**	**Devs. (P1)**	**Devs. (P2)**	**Devs. (P3)**
3 – H	HOM2	1999	181	-8	-1	0	110	-79	-72	-62
1 - C	R5&7W	2000	106	-73	-66	-55	167	-12	-5	0
2 - E	CHY-E	2000	188	0	0	0	163	-15	-7	0
4 - L	HOM-W	2000	174	15	30	50	143	-2	0	19
5 – M	1N	2000	184	0	0	5	167	-17	-12	-4
1 - C	R5&7W	2001	163	-35	-27	-14	181	-17	-9	-4
2 – F	MEY-N	2001	201	35	57	52	137	-14	-8	0
3 - H	HOM2	2001	181	-8	-1	0	156	-33	-26	-14
4 - L	HOM-W	2001	204	0	0	1	168	-33	-28	-21
Mean Abs Dev's				**19**	**20**	**20**		**24**	**19**	**14**

Data source: Tri-State and PSNT recommendations provided by Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Table 16: Deviations of Tri-State and PSNT recommendations (lb/ac) from the posterior EPMNR for 15 non-irrigated field-years, south-central Michigan, 1999-2001

			Tri-State				PSNT			
Field ID	**Field Name**	**Year**	**Recs.**	**Devs. (P1)**	**Devs. (P2)**	**Devs. (P3)**	**Recs.**	**Devs. (P1)**	**Devs. (P2)**	**Devs. (P3)**
1 - A	V1&2N	1999	120	0	0	0	161	0	0	0
1 - B	C2&3S	1999	127	> 12	> 12	> 12	113	0	0	0
2 - D	OFF	1999	191	> 88	> 88	> 88	126	> 23	> 23	> 23
3 - G	DEN10	1999	147	28	49	74	110	0	12	37
4 – J	BRY-E	1999	147	> 37	> 37	> 37	155	> 45	> 45	> 45
4 - K	OUT	1999	177	> 48	> 48	> 48	157	> 28	> 28	> 28
5 - M	1N	1999	154	2	15	34	132	-3	0	12
Mean Abs Dev's				**31**	**36**	**42**		**14**	**15**	**21**
1 - B	C2&3S	2000	177	0	0	0	177	0	0	0
2 - D	OFF	2000	191	0	0	10	156	-14	-8	-1
3 - I	HOM1	2000	181	-7	0	5	153	-35	-27	-15
4 - K	OUT	2000	177	0	1	11	146	-24	-19	-10
5 - N	20N	2000	127	-43	-38	-30	163	-7	-2	0
Mean Abs Dev's				**10**	**8**	**11**		**16**	**11**	**5**
1 - A	V1&2N	2001	120	0	1	13	130	0	11	23
3 - G	DEN10	2001	147	-24	-17	-6	151	-20	-13	-2
4 - J	BRY-E	2001	147	-22	-12	0	166	-3	0	1
Mean Abs Dev's				**15**	**10**	**6**		**8**	**8**	**9**

Data source: Tri-State and PSNT recommendations provided by Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Table 17: Three models* of pooled fields in which moisture was not limiting

	Full Model		Final Model		Simple Model	
Obs. No.	2128		2128		2128	
F stat.	F(11, 12) = 14888		F(6, 12) = 2901		F(1, 12) = 105	
Prob>F	0.0000		0.0000		0.0000	
R-squ.	0.8674		0.8652		0.8451	
Variables	Estimates	S. E.	Estimates	S. E.	Estimates	S. E.
n	.371	.561	1.30	.174	.972	.0758
n2	-.00240	.000182	-.00239	.000182	-.00240	.000192
om	-.420	.860				
cec	-1.43	1.17				
ec	12.7	5.24	6.46	2.54		
ncredit	.371	.136	.363	.129		
wet	7.23	1.08	7.42	1.20		
ipi	-132	121				
nxom	.00224	.00528				
nxcec	.00937	.00683				
nxec	-.0412	.0344				
nxncre	-.000686	.000838	-.000657	.000739		
Nxwet	-.0282	.00893	-.0291	.00972		
Nxipi	1.27	.848				

* Field dummy variables are not reported here

Table 18: Deviations of SSI-UNA recommendations (lb/ac) from the posterior EPMNR for the fields in which moisture was not limiting

Field ID	Field Name	Year	P1 = 0.2/3		P2 = 0.2/2		P3 = 0.3/2	
			Recs.	Devs.	Recs.	Devs.	Recs.	Devs.
3 – H	HOM2	1999	186	-3	179	-3	168	-4
1 - B	C2&3S	2000	189	0	182	0	172	0
2 - D	OFF	2000	186	0	179	0	168	0
2 - E	CHY-E	2000	190	0	183	0	172	0
3 - I	HOM1	2000	191	0	184	0	173	0
4 - K	OUT	2000	184	2	177	1	167	1
5 – M	1N	2000	193	0	186	0	175	0
5 - N	20N	2000	194	0	187	0	176	0
1 - C	R5&7W	2001	189	-9	182	-8	172	-5
2 – F	MEY-N	2001	185	19	178	19	167	18
3 – G	DEN10	2001	186	8	179	9	168	10
4 - J	BRY-E	2001	189	0	182	0	171	6
4 - L	HOM-W	2001	192	-9	185	-11	174	-15
Mean Abs Dev's				**4**		**4**		**5**

Table 19: Deviations of SSI-UNA, Tri-State and PSNT recommendations (lb/ac) from the posterior EPMNR for the fields in which moisture was not limiting

			P1 = 0.2/3			P2 = 0.2/2			P3 = 0.3/2		
Field ID	Field Name	Year	SSI-UNA	Tri-State	PSNT	SSI-UNA	Tri-State	PSNT	SSI-UNA	Tri-State	PSNT
3 – H	HOM2	1999	-3	-8	-79	-3	-1	-72	-4	0	-62
1 - B	C2&3S	2000	0	0	0	0	0	0	0	0	0
2 - D	OFF	2000	0	0	-14	0	0	-8	0	10	-1
2 - E	CHY-E	2000	0	0	-15	0	0	-7	0	0	0
3 - I	HOM1	2000	0	-7	-35	0	0	-27	0	5	-15
4 - K	OUT	2000	2	0	-24	1	1	-19	1	11	-10
5 – M	1N	2000	0	0	-17	0	0	-12	0	5	-4
5 - N	20N	2000	0	-43	-7	0	-38	-2	0	-30	0
1 - C	R5&7W	2001	-9	-35	-17	-8	-27	-9	-5	-14	-4
2 – F	MEY-N	2001	19	35	-14	19	57	-8	18	52	0
3 – G	DEN10	2001	8	-24	-20	9	-17	-13	10	-6	-2
4 - J	BRY-E	2001	0	-22	-3	0	-12	0	6	0	1
4 - L	HOMW	2001	-9	0	-33	-11	0	-28	-15	1	-21
Mean Abs Dev's			**4**	**13**	**19**	**4**	**12**	**16**	**5**	**10**	**9**

Table 20: Expected gross margins over N fertilizer costs at P1= 0.067 (for $0.20/lb N and $3.00/bu corn), in fields where moisture was not limiting for four N recommendations: (1) SSI-SSNA; (2) SSI-UNA; (3) Tri-State-UNA; (4) PSNT-UNA.

Field ID	Field Name	Year	Expected Partial Profits ($/acre)				Differences ($/acre)		
			(1)	(2)	(3)	(4)	(1)-(2)	(1)–(3)	(1)–(4)
3 – H	HOM2	1999	484.69	484.37	484.22	443.46	0.32	0.47	41.23
1 - B	C2&3S	2000	400.26	399.92	398.83	398.83	0.34	1.43	1.43
2 - D	OFF	2000	452.14	451.81	451.62	445.46	0.33	0.52	6.68
2 - E	CHY-E	2000	405.78	405.32	405.30	400.20	0.46	0.48	5.58
3 - I	HOM1	2000	408.06	407.74	407.06	397.53	0.32	1.00	10.53
4 - K	OUT	2000	547.05	546.91	546.53	536.39	0.14	0.52	10.66
5 – M	1N	2000	359.93	359.74	359.21	355.05	0.19	0.73	4.69
5 - N	20N	2000	364.25	363.92	332.02	357.16	0.33	32.23	7.09
1 - C	R5&7W	2001	309.26	308.82	303.93	308.35	0.44	5.33	0.91
2 – F	MEY-N	2001	491.55	491.22	489.34	474.85	0.33	2.21	16.70
3 – G	DEN10	2001	487.56	487.33	476.65	478.75	0.23	10.91	8.81
4 - J	BRY-E	2001	435.24	435.02	422.59	431.35	0.22	12.65	3.89
4 - L	HOMW	2001	510.35	509.99	508.87	506.03	0.36	1.48	4.32
Mean Values			**439.19**	**438.89**	**434.69**	**429.25**	**0.30**	**4.50**	**9.94**

Table 21: Expected gross margins over N fertilizer costs at P2 = 0.10 (for $0.20/lb N and $2.00/bu corn) in fields where moisture was not limiting for four N recommendations: (1) SSI-SSNA; (2) SSI-UNA; (3) Tri-State-UNA; (4) PSNT-UNA.

Field ID	Field Name	Year	Expected Partial Profits ($/acre)				Differences ($/acre)		
			(1)	(2)	(3)	(4)	(1)-(2)	(1)–(3)	(1)–(4)
3 – H	HOM2	1999	310.99	310.78	310.75	288.31	0.21	0.24	22.68
1 - B	C2&3S	2000	254.45	254.22	254.09	254.09	0.23	0.36	0.36
2 - D	OFF	2000	289.28	289.06	288.34	286.57	0.22	0.94	2.71
2 - E	CHY-E	2000	258.11	257.80	257.66	255.93	0.31	0.45	2.18
3 - I	HOM1	2000	259.56	259.34	259.31	254.82	0.22	0.25	4.74
4 - K	OUT	2000	352.64	352.55	352.55	347.86	0.09	0.09	14.78
5 – M	1N	2000	227.35	227.22	227.21	225.57	0.13	0.14	1.78
5 - N	20N	2000	230.15	229.93	212.88	227.24	0.22	12.27	2.91
1 - C	R5&7W	2001	193.80	193.50	191.75	193.50	0.30	2.05	0.30
2 – F	MEY-N	2001	315.61	315.39	312.83	307.43	0.22	2.78	8.18
3 – G	DEN10	2001	312.90	312.75	307.97	309.10	0.15	4.93	3.8
4 - J	BRY-E	2001	277.82	277.67	271.93	276.50	0.15	5.89	1.32
4 - L	HOMW	2001	327.70	327.46	325.65	326.15	0.24	2.05	1.55
Mean Values			**280.46**	**280.25**	**278.07**	**275.74**	**0.21**	**2.39**	**5.49**

Table 22: Expected gross margins over N fertilizer costs at P3 = 0.15 (for $0.30/lb N and $2.00/bu corn) in fields where moisture was not limiting for four N recommendations: (1) SSI-SSNA; (2) SSI-UNA; (3) Tri-State-UNA; (4) PSNT-UNA.

Field ID	Field Name	Year	Expected Partial Profits ($/acre)				Differences ($/acre)		
			(1)	(2)	(3)	(4)	(1)-(2)	(1)–(3)	(1)–(4)
3 – H	HOM2	1999	293.66	293.44	292.65	277.31	0.22	1.01	16.35
1 - B	C2&3S	2000	236.74	236.51	236.39	236.39	0.23	0.35	0.35
2 - D	OFF	2000	271.92	271.70	269.24	270.97	0.22	2.68	0.95
2 - E	CHY-E	2000	240.35	240.04	238.86	239.63	0.31	1.49	0.72
3 - I	HOM1	2000	241.71	241.49	241.21	239.52	0.22	0.50	2.19
4 - K	OUT	2000	335.43	335.34	334.85	333.26	0.09	0.58	2.17
5 – M	1N	2000	209.31	209.19	208.81	208.87	0.12	0.50	0.44
5 - N	20N	2000	212.00	211.78	200.18	210.94	0.22	11.82	1.06
1 - C	R5&7W	2001	176.10	175.81	175.45	175.40	0.29	0.61	0.66
2 – F	MEY-N	2001	298.35	298.14	292.73	293.73	0.21	5.62	4.62
3 – G	DEN10	2001	295.56	295.41	293.27	294.00	0.15	2.29	1.56
4 - J	BRY-E	2001	260.18	260.03	257.23	259.90	0.15	2.95	0.28
4 - L	HOMW	2001	309.77	309.53	305.25	309.35	0.24	4.52	0.42
Mean Values			**262.82**	**262.61**	**260.49**	**260.10**	**0.21**	**2.33**	**2.72**

Table 23: 80% confidence interval of expected gross margins over N fertilizer costs at P1= 0.067 (for $0.20/lb N and $3.00/bu corn), in fields where moisture was not limiting for four N recommendations: (1) SSI-SSNA; (2) SSI-UNA; (3) Tri-State-UNA; (4) PSNT-UNA, based on 3000 Monte Carlo simulations.

Field ID	Field Name	Year	Difference of expected gross margins ($/acre)		
			(1)-(2)	(1)–(3)	(1)–(4)
3 – H	HOM2	1999	[0.13, 0.67]	[0.61, 2.72]	[34.73, 48.43]
1 - B	C2&3S	2000	[0.13, 0.67]	[0.61, 2.72]	[0.61, 2.72]
2 - D	OFF	2000	[0.12, 0.64]	[0.23, 1.22]	[4.44, 9.36]
2 - E	CHY-E	2000	[0.15, 0.91]	[0.24, 1.20]	[3.17, 8.48]
3 - I	HOM1	2000	[0.11, 0.64]	[0.35, 2.14]	[7.31, 14.18]
4 - K	OUT	2000	[0.05, 0.29]	[0.20, 1.41]	[7.98, 13.89]
5 – M	1N	2000	[0.07, 0.37]	[0.18, 1.89]	[2.51, 7.77]
5 - N	20N	2000	[0.11, 0.64]	[24.49, 40.43]	[4.14, 10.67]
1 - C	R5&7W	2001	[0.15, 0.85]	[3.24, 7.84]	[0.36, 1.93]
2 – F	MEY-N	2001	[0.11, 0.65]	[1.01, 3.84]	[13.42, 20.50]
3 – G	DEN10	2001	[0.09, 0.46]	[7.97, 14.22]	[6.24, 11.77]
4 - J	BRY-E	2001	[0.08, 0.45]	[9.34, 16.30]	[2.31, 5.91]
4 - L	HOMW	2001	[0.13, 0.67]	[0.61, 2.72]	[34.73, 48.43]

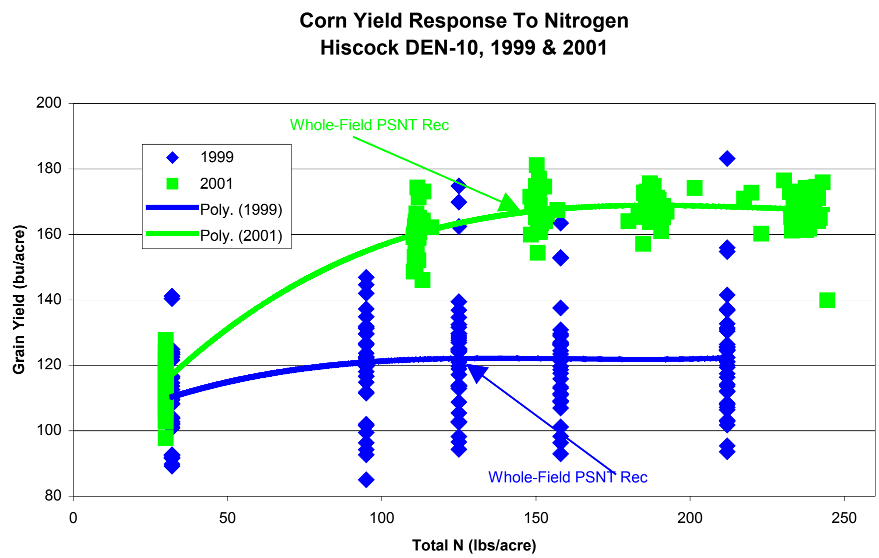
Table 24: 80% confidence interval of expected gross margins over N fertilizer costs at P2 = 0.10 (for $0.20/lb N and $2.00/bu corn) in fields where water was not limiting for four N recommendations: (1) SSI-SSNA; (2) SSI-UNA; (3) Tri-State-UNA; (4) PSNT-UNA, based on 3000 Monte Carlo simulations

Field ID	Field Name	Year	Difference of expected gross margins ($/acre)		
			(1)-(2)	(1)–(3)	(1)–(4)
3 – H	HOM2	1999	[0.09, 0.43]	[0.15, 0.73]	[18.75, 27.04]
1 - B	C2&3S	2000	[0.09, 0.45]	[0.15, 0.90]	[0.15, 0.90]
2 - D	OFF	2000	[0.08, 0.43]	[0.44, 1.75]	[1.56, 4.12]
2 - E	CHY-E	2000	[0.10, 0.61]	[0.25, 0.97]	[0.98, 3.74]
3 - I	HOM1	2000	[0.07, 0.43]	[0.12, 0.69]	[2.96, 6.82]
4 - K	OUT	2000	[0.03, 0.19]	[0.07, 0.37]	[3.37, 6.55]
5 – M	1N	2000	[0.04, 0.24]	[0.08, 0.56]	[0.68, 3.31]
5 - N	20N	2000	[0.07, 0.43]	[12.55, 22.35]	[1.40, 4.89]
1 - C	R5&7W	2001	[0.10, 0.57]	[1.03, 3.39]	[0.15, 0.72]
2 – F	MEY-N	2001	[0.07, 0.43]	[1.63, 4.19]	[6.28, 10.36]
3 – G	DEN10	2001	[0.06, 0.31]	[3.32, 6.80]	[2.41, 5.44]
4 - J	BRY-E	2001	[0.05, 0.30]	[4.03, 8.01]	[0.60, 2.33]
4 - L	HOMW	2001	[0.08, 0.48]	[1.24, 3.21]	[0.66, 2.79]

Table 25: 80% confidence interval of expected gross margins over N fertilizer costs at P2 = 0.15 (for $0.30/lb N and $2.00/bu corn) in fields where water was not limiting for four N recommendations: (1) SSI-SSNA; (2) SSI-UNA; (3) Tri-State-UNA; (4) PSNT-UNA, based on 3000 Monte Carlo simulations

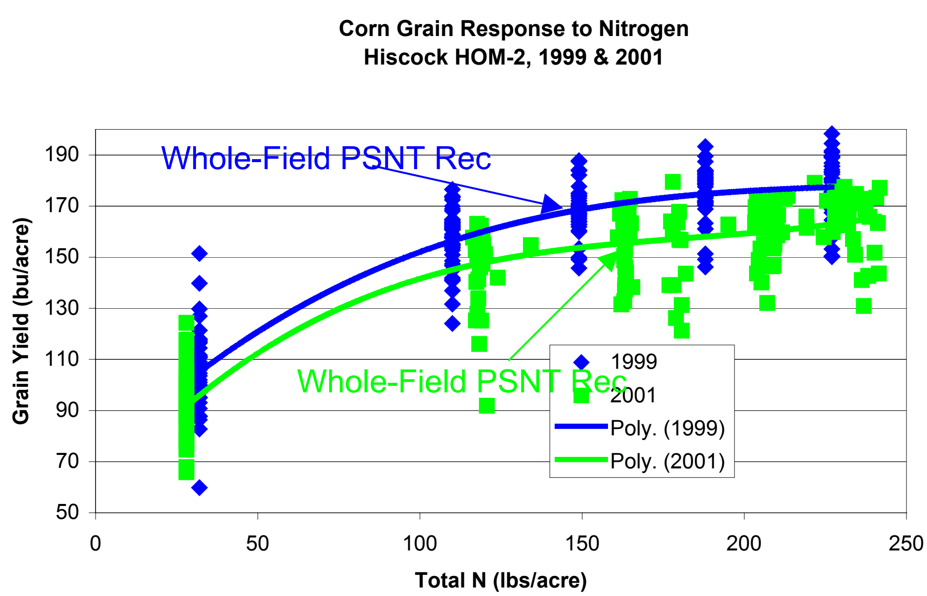
Field ID	Field Name	Year	Difference of expected gross margins ($/acre)		
			(1)-(2)	(1)–(3)	(1)–(4)
3 – H	HOM2	1999	[0.09, 0.43]	[0.42, 2.06]	[13.01, 20.13]
1 - B	C2&3S	2000	[0.09, 0.45]	[0.20, 0.80]	[0.20, 0.80]
2 - D	OFF	2000	[0.08, 0.43]	[1.66, 4.05]	[0.36, 1.84]
2 - E	CHY-E	2000	[0.10, 0.61]	[0.85, 2.63]	[0.21, 1.71]
3 - I	HOM1	2000	[0.07, 0.43]	[0.28, 1.08]	[1.02, 3.75]
4 - K	OUT	2000	[0.03, 0.19]	[0.18, 1.28]	[1.27, 3.39]
5 – M	1N	2000	[0.04, 0.24]	[0.20, 1.34]	[0.11, 1.32]
5 - N	20N	2000	[0.07, 0.43]	[7.85, 16.27]	[0.27, 2.39]
1 - C	R5&7W	2001	[0.10, 0.57]	[0.22, 1.47]	[0.38, 1.39]
2 – F	MEY-N	2001	[0.07, 0.43]	[3.98, 7.51]	[3.20, 6.32]
3 – G	DEN10	2001	[0.06, 0.31]	[1.22, 3.65]	[0.73, 2.68]
4 - J	BRY-E	2001	[0.05, 0.30]	[1.64, 4.58]	[0.10, 0.79]
4 - L	HOMW	2001	[0.08, 0.48]	[3.17, 6.28]	[0.14, 1.12]

Figure 1:



Data source: Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Figure 2:



Data source: Miller, Neil R., Agri-Business Consultants Inc., Birch Run, Michigan, personal communication, May, 2002.

Bibliography

Anselin, L. (1988) Spatial Econometrics: Methods and Models. Boston: Kluwer Academic Publishers.

Bongiovanni, R. and J. Lowenberg-Deboer (2002). "Economics of Nitrogen Response Variability Over Space and Time: Results from the 1999-2001 Field Trials in Argentina." Paper presented at the 6th International Conference on Precision Agriculture and Other Precision Resource Management, Bloomington, MN, July 14-17, 2002. (Forthcoming on CD-ROM.)

Brady, N. C. (1974). The Nature and Properties of Soils. 8th ed. New York: Macmillan.

Bullock, D. S. and D. G. Bullock (2000). "From Agronomic Research to Farm Management Guidelines: A Primer on the Economics of Information and Precision Technology." Precision Agriculture **2**(1): 71-101.

Bullock, D. S., J. Lowenberg-Deboer and S. M. Swinton (2002). "Spatial Input Management for Agriculture: Making Better Use of Precision Farming Data." Agricultural Economics 27: 233-245.

Case, A. C. (1991). "Spatial Patterns in Household Demand." Econometrica **59**(4): 953-965.

Doerge, T. (2001). "Variable-rate nitrogen management for corn production -- success proves elusive." Crop Insights **11**(11): 1.

Hurley, T. M., G.L.Malzer and B. Kilian (2002). "A Test of Within Field Variation For Corn Response to Nitrogen in Central Minnesota." Paper presented at the 6th International Conference on Precision Agriculture and Other Precision Resource Management, Bloomington, MN, July 14-17, 2002. (Forthcoming on CD-ROM.)

Kravchenko, A. N. and D. G. Bullock (2000). "Correlation of Corn and Soybean Grain Yield with Topography and Soil Properties." Agronomy Journal **92**(1): 75-83.

Lau, L. J. (1986). "Functional Forms in Econometric Model Building." Handbook of Econometrics **III**. M. D. Intrilligator. Amsterdam, Elsevier.**:** 1515-1564.

Lee, R. (1978). Forest Microclimatology. New York, Columbia University Press.

Lowenberg-DeBoer, J. and M. Boehlje (1996). "Revolution, Evolution or Dead-End: Economic Perspectives on Precision Agriculture." In P. C. Robert, R. H. Rust and W. E. Larson, eds., Precision Agriculture: Proceedings of the 3rd International Conference. Madison, WI, ASA/CSSA/SSSA**:** 923-944.

Lund, E. D., C. D. Christy, and P. E. Drummond (2000). "Using yield and soil electrical conductivity (EC) maps to derive crop production performance information." In P. C.

Robert, ed. Preceedings of the Fifth International Conference on Precision Agriculture. Bloomington, MN.

McBratney, A. B. and B. M. Whelan (1995). "The Potential for Site-Specific Management of Cotton Farming Systems." Discussion Paper No. 1. Co-operative Research Center for Sustainable Cotton Production, Australian Cotton Research Institute, Narrabri, NSW.

Schnitkey, G., J. Hopkins and L. Tweeten. (1996). An Economic Evaluation of Precision Fertilizer Applications on Corn-Soybean Fields. In P. C. Robert, R. H. Rust and W. E. Larson, eds., Precision Agriculture: Proceedings of the 3rd International Conference. Madison, WI, ASA/CSSA/SSSA**:** 977-988.

Swinton, S. M. and J. Lowenberg-DeBoer (1998). "Evaluating the Profitability of Site-specific Farming." Journal of Production Agriculture **11**: 439-446.

Vitosh, M. L., J. W. Johnson and D. B. Mengel (1995). "Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa." MSU Extension Bulletin E-2567, East Lansing: Michigan State University.

Whipker, L. D. and J. T. Akridge (2001). More Profit Taking. CropLife. **164:** 14-16.