IS YIELD RESPONSE SITE-SPECIFIC?

REVISITING NITROGEN RECOMMENDATIONS ON CORN

by

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Introduction

U.S. farmers have been slow to adopt variable rate applied (VRA) fertilizers in cereal grain crops (Daberkow and McBride, 2000). A major reason is the very uneven profitability results to date (Lambert and Lowenberg-DeBoer, 2000). Yield gains have been negligible (Doerge, 2001, Swinton and Lowenberg-DeBoer, 1998) and neither this nor fertilizer cost savings have outweighed the added costs of information (Hurley, et al., 2001) and VRA equipment. The failure of yield gains from VRA fertilization to achieve hoped-for levels has been blamed on poor prediction of soil fertility from interpolated soil test values, miscalibrated VRA equipment, inaccurate yield goals, and weather. Largely overlooked has been the possibility that the fertilizer recommendations might be unsuited to VRA management (Hergert, et al., 1997).

Field crop fertilizer recommendations in the United States were developed during a half century of multi-locational, small-plot experiments. Despite the celebrated efforts of agricultural economists like Earl Heady and his associates to develop fertilizer use rules based on production functions and economic marginality criteria (e.g., Heady and Dillon, 1961, Hexem and Heady, 1978), the variability of empirical crop yield functions across diverse landscapes and unpredictable weather was inconsistent with the need for simple extension recommendations. State-level fertilizer recommendations emerged as rough but serviceable compromise values, typically based on yield goals and/or soil tests, not relative prices of fertilizer and crop. With the advent of VRA technologies, farmers have set about making site-specific soil nutrient maps and fertilization plans following state-level fertilization recommendations. In so doing, they have assumed that while soil nutrient levels may vary site-specifically, the crop's yield response to any given nutrient level will be the same at any location in the state.

This paper challenges the assumption that yield response depends on nutrient levels alone and not other site characteristics. In so doing, it questions whether the dominant approach to fertilizer recommendations may be inappropriate for the information age. Formally, we test the null hypothesis that site characteristics do not interact with nitrogen (N) in affecting corn yield response. If they do, then site characteristic variables omitted from yield response models may have led to biased fertilizer response estimates. We further estimate the potential profitability foregone by not using site-specific N rates. These estimates indicate potential willingness to pay for the increased information costs of developing and implementing site-specific fertilizer response recommendations.

Conceptual Framework

A site-specific model of expected profit maximization

The profit maximization problem for site-specific (SS) nitrogen application 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 a) cell-specific yield revenue and variable-rate input costs and b) field- or farm-level quasi-fixed and fixed costs (Lowenberg-DeBoer and Boehlje, 1996), as in Equation (1).

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

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

where

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

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

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

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

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

G is the quasi-fixed cost of intensive data collection and analysis,

V is the quasi-fixed cost of VRA nitrogen ,

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

What makes this expected profit maximization problem special is the yield function. Following Bullock and Bullock (Bullock and Bullock, 2000) and Bullock, Lowenberg-DeBoer and Swinton (Bullock, et al., 2003), the yield function subdivides the unmanaged variables into two categories, site characteristics (c_{ij}) and general stochastic effects (ε_{ij}).

Biological basis for interaction between corn response to N and site characteristics

Site characteristics may affect corn yield response to applied nitrogen (N) both from the standpoint of nitrogen production and from the standpoint of nitrogen loss. Much of the naturally occurring nitrogen available to corn plants is produced by the mineralization of soil organic matter (OM) to plant-available ammonium (Brady and Weil, 2002).

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. This complex may represent either a source of plant available N or a mechanism for immobilizing free N depending on the clay mineralogy, the concentration of ammonium in the soil solution, and environmental conditions. As with OM, the spatial distribution of CEC is not random, and may therefore be expected to affect the spatial pattern of corn response to applied fertilizer N.

Nitrogen losses in the light-textured soils of south-central Michigan are thought to occur largely via the leaching of nitrate N through the soil profile. Nitrate is produced naturally in the soil through oxidation of ammonium or supplied directly by inorganic fertilizers. Because of their negative charge, nitrate ions are not fixed by soil CEC, and thus move freely with water. Any factors that affect water infiltration thus affect N losses and ultimately N availability to corn plants. Soil CEC as well as soil electrical and magnetic conductivity all are highly correlated with to soil texture, and thus provide some measurement of the distribution of nitrogen loss potential within fields.

Surface water movement may also function to move nitrogen from higher to lower elevations within or beyond field borders, although it likely matters less on light textured soils. To the extent that water carries with it soil particles, it will move organic and ammonium nitrogen as well as nitrate. Water movement may also cause nitrogen losses through denitrification if water is ponded for significant periods of time. Given these links between water flows and N movement, surface water flows are expected to affect the spatial distribution of soil N. An index for achieving this is described under “Empirical Methods” below.

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. Hence, by affecting sunlight availability, these terrain features are expected to affect the spatial distribution of the crop’s photosynthetic activity , and thus its relative demand for N.

Hypothesis tests

Do site characteristics such as landscape position or soil traits change crop yield response to N? The first null hypothesis claims that corn yield response to N is completely separable in site characteristics, as follows:

$$\mathrm{H}_1\text{: } Y_{ij}^{ur} = y(N_{ij} \mid x_{ij}, c_{ij}, \varepsilon_{ij})$$

versus the alternative hypothesis that nitrogen and site characteristics interact nonseparably to effect a site-specific yield response, Y_{ij}^{sr} ,

$$\mathrm{H}_{1\mathrm{A}}\text{: } Y_{ij}^{sr} = y(N_{ij}, c_{ij} \mid x_{ij}, \varepsilon_{ij})$$

Assuming that the general stochastic term, ε_{ij} , is distributed i.i.d. normal and that the yield function is separable between variables *x* and other variables, then the first order conditions to this problem can be solved for each cell i,j as follows,

$$\partial E[y(N_{ij}, c_{ij} \mid x_{ij})]/\partial N_{ij} = p_N / p_Y$$

If the first hypothesis can be rejected and site characteristics do interact with nitrogen to affect corn yield response, then a second null hypothesis tests whether the value of profit-maximizing yields is large enough to cover the quasi-fixed costs *G* and *V*, and still leave a net gain that could cover the costs of developing site-specific fertilizer recommendations. Formally,

$$\text{H}_2\text{: } \sum_i \sum_j \{p_Y(Y_{ij}^{sr} - Y_{ij}^{ur}) - p_N(N_{ij}^{sr} - N_{ij}^{ur})\} \leq G + V$$

$$\text{H}_{2\text{A}}\text{: } \sum_i \sum_j \{p_Y(Y_{ij}^{sr} - Y_{ij}^{ur}) - p_N(N_{ij}^{sr} - N_{ij}^{ur})\} > G + V$$

where any excess on the left-hand side of $\text{H}_{2\text{A}}$ would represent potential willingness to pay for development of site-specific fertilizer recommendations.

Related research in Argentina found that one site characteristic, a dummy variable for field slope position, had a significant effect on within-field corn response to nitrogen (Bongiovanni and Lowenberg-DeBoer, 2001). The current research expands on this in two ways, 1) by developing continuous variables to measure terrain attributes associated with water movement and sunlight availability, and 2) by expanding the scope to a cross-sectional analysis of 14 fields.

Data and Empirical Methods

Experiments were conducted on 14 commercial corn fields during 1999-2001. The five farmer-cooperators were members of the Innovative Farmers of South Central Michigan who self-selected on the basis of their interest in optimizing N management and their ability to carry out spatially referenced on-farm experiments (including the use of a combine yield monitor equipped with a global positioning system, GPS). As such, they represent large, progressive producers in the area, not a typical cross-section.

The fields were located in Calhoun and Hillsdale counties, where agricultural soils are primarily sandy loams and 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 subsequently 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. Cooperators selected cultivars, planting dates, populations, in-row "starter" fertilizers, herbicides, and other inputs, just as they would for ordinary commercial grain production.

In each experiment year, planter passes were mapped with GPS after planting, and 300 ft plot areas were identified parallel to these passes in randomized complete blocks of 3-5 plots each. Plot width was either 30 ft for cooperators with 6-row combines or 60 ft for those with 8 row combines. This design allowed for 20-50 replications of each treatment in a typical 40 acre experiment.

One to two weeks prior to side-dress N application, 12 pre-side-dress nitrate test (PSNT) soil cores were taken to a depth of 12 inches in a 5-10 ft radius at the center of each block. Samples were analyzed for soil nitrate, and corresponding nitrate N credits were calculated using a conversion factor of 6 lbs/ac per 1 ppm soil nitrate (Vitosh et al., 1995). N fertilizer treatments were determined as follows:

1) No side-dress nitrogen,
2) A non-limiting nitrogen rate (180-210 lbs/ac sidedress N),
3) The Tri-State recommended N rate (Vitosh, et al., 1995) based on the formula

*(Yield goal*1.36) - 27- (field mean nitrate N-credit)*

4) 33% less than treatment #3,
5) 33% more than treatment #3,

Nitrogen was applied when corn plants were 8-24 inches tall using 28% urea-ammonium nitrate solution. Flow control was achieved using a gate valve run by a Mid-Tech TASC 6200 contoller, and continuously monitored with a Mid-Tech flow meter. Variable-rate application software, Agview (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. Yield point data were cropped from 50 ft 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 yield point data (15.5% moisture), which were very dense, were averaged over each trimmed experimental plot. The sparser data from the 1998 soil test, PSNT results from each year, soil electrical (Veris) or magnetic (EM38) conductivity, and digital elevation mapping, were first interpolated using inverse distance weighting to the 4th power (or, for the special case of zone-sampled soil data, 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.

Digital elevation data were further converted to terrain derivatives (slope, aspect, curvature, wetness index, and insolation potential) using ArcView Spatial Analyst (Environmental Systems Research Institute, Inc.) All other GIS data manipulation and summarization was accomplished using SSToolbox software (Site-Specific Technology Development Group, Inc.)

Development of site-characteristic variables

A principal innovation of this research is the development of continuous site-characteristic variables to capture the moisture flow and sunlight effects described above. Two prior studies have used binary variables to capture the potential effect of site-characteristics on crop yields. Bullock and Bullock (Bullock and Bullock, 2000) simulated the potential effect of soil depth on crop yields, characterizing the potential effects on input recommendations of omitting an unobserved binary soil depth variable. Bongiovanni and Lowenberg-DeBoer (2000, 2001) conducted a spatial regression analysis of corn yields in Argentina using binary variables to classify four slope positions: east slope, hilltop, west slope, and west toe slope. They found that slope position significantly affected profit-maximizing N recommendations.

The current study uses three classes of continuous variables describing site characteristics expected to affect crop yield. The first set of soil test point data were described above. These variables include N-credit from a PSNT, organic matter, and CEC. The second set contains soil conductivity measures taken with Veris electrical conductivity and EM38 electro-magnetic soil probes and also interpolated between sampled points.

The third class of site characteristic variables includes indexes of potential wetness and insolation developed from digital elevation data. The importance of water flow in affecting both nitrate leaching and moisture available for crop growth and associated N uptake called for a spatial variable to capture potential soil moisture. The potential wetness, w, 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),

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

This commonly used hydrological formula models potential soil moisture based on a) the total upper catchment area from which water can collect to flow over a given topographical grid cell and b) the slope of that cell, which influences the propensity of water to remain there or flow onward. The formula was implemented ArcView Spatial Analyst using an ArcView Avenue script developed by Loesch[1].

Potential sunlight reception was modeled based on the sunlight that would be received by an equivalent latitude on the Earth's sphere corresponding to the specific slope, aspect, and latitude of the plots in the farm fields studied. Potential solar radiation at a given point on the Earth's surface has been modeled by climatological geographers as function of solar declination, earth-sun distance, terrestrial latitude, and the slope and aspect of a specific site (Lee, 1978). Given the relative proximity of the fields studied in two adjacent Michigan counties, we simplified Lee's (1978) formula by dropping the solar distance and solar declination terms, such that the resulting insolation potential

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

index differs only in omitting a linear multiple that varies over the year but is constant across these fields at a moment in time. The insolation potential index, *IPI*, synthesizes slope, aspect and latitude as the sine of the equivalent latitude on the surface of the terrestrial sphere (Lee 1978, Eq. 3.31, p. 57),

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

where β remains slope inclination, α is aspect (azimuth measured in degrees clockwise from north), λ is terrestrial latitude, and λ' is the latitude of a horizontal surface on the Earth's surface that would get sunlight equivalent to the measured location.

Given the expected interaction of weather with site characteristics, the three seasons over which the experiments were conducted offered a wide range of weather conditions. The 1999 growing season was hot and dry. Under such conditions, there is little water movement through the soil profile, an observation supported by the relatively high soil nitrate values and resultant N credits measured in 1999. Crops were limited by moisture in non-irrigated experiment fields in 1999. By contrast in 2000, near-record rainfall fell on much of South-Central Michigan. During May and early June, when nitrate leaching potential is presumably high, most fields recorded at least one 4-day period over 2 inches of precipitation. Soil nitrate test values were 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. In 2001, precipitation varied widely across the region, ranging from record levels in the northwest to droughty conditions in the southeastern part of the two-county project area.

Analytical approach

Specification of the regression models

In preliminary research, three different functional forms were reviewed for the yield response function, $Y_{ij} = y(N_{ij}, \varepsilon_{ij})$ at the field level. Upon discovering that the null hypothesis of quadratic yield response could not be rejected over those of a von Liebig-style linear or quadratic response and plateau, we adopted the maintained hypothesis of quadratic yield response for the sake of computational tractability (Lau, 1986).

As discussed above, weather – especially rainfall – was expected to interact with site characteristic variables (*c*) in effecting yield response. It was therefore inappropriate to pool the three years' data unless weather were explicitly modeled as a vector of explanatory variables. Instead, cross-field data were pooled to specify three different models of each year (1999, 2000 and 2001):

1. Full model: $Y^{sr} = y(N\ ,\ N^2, c,\ N \times c)$;
2. Final model: Full model minus jointly insignificant explanatory variables;
3. Simple model: Regress Yield on $Y^{ur} = y(N\ ,\ N^2)$ (omits site characteristics).

This approach assumes that (1) similar weather prevails across the different fields during the same year (reasonable, given the fields were in adjacent counties), and (2) site characteristics affect yield response to nitrogen similarly across different fields, conditional experiencing similar weather. 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*. The models were estimated separately by year as cross sectional data using ordinary least squares 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 were used in Stata 6.0 (Stata Corp. 1999), due to evidence of spatial autocorrelation in separate analyses (details not reported here). The fixed effect approach applied here has been shown to control for spatial error structure where model disturbances are correlated with defined zones (Case, 1991). Descriptive statistics for all variables included in the yield response models are presented in Table 1.

The test of the second hypothesis addresses the question: Can the value of the additional site-specific information cover the costs of site-specific data collection and VRA? Assuming the specified final model from the first hypothesis test is the true model, we evaluate the value of site-specific information using two different assumptions about the available information. The two informational assumptions both revolve around how rainfall or irrigation affects corn response to N. Moisture effects are 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 is expected to cause nitrate leaching from the crop root zone, making plant-available N scarcer. During the later period, from June 15 to August 15, precipitation is expected to contribute directly to crop growth. Weather from the early period is known at side-dress time. Weather for the mid-summer period is not known. However, farmers with irrigation can assure a minimum necessary water supply.

Two alternative assumptions emerge about the weather information available to a corn grower. The first assumption (for the irrigated corn grower) is that moisture availability for the crop year is known or controllable. By side-dress time, most nitrate leaching has taken place, and water necessary for crop growth can be assured through irrigation later in the season. The second assumption (for the rainfed corn grower) is that current year weather information is not available, only knowledge of long-term climate patterns in the area. From this perspective, the grower may ignore N leaching information prior to side-dress time and cannot predict late season rainfall.

Based on both assumptions, we compare the gross margin $(p_y Y - p_N N)$ of the three nitrogen management methods: (1) VR nitrogen application using the final yield response model with site characteristic variables (VRNA-SS), (2) uniform nitrogen application, also using the final, site-specific yield response model[2] (UNA-SS), (3) UNA based on simple yield response function without site characteristic variables, and (4) UNA based on the Tri-State nitrogen fertilizer recommendation for corn (Vitosh, et al., 1995) . Although VRNA and UNA use parallel information sets, the additional cost incurred by VRNA is $G+V$, while the additional cost incurred by UNA is G for the site-specific case and zero for the Tri-State case.

The second alternative information set assumes that if long-term weather conditions are known, then particular states of nature can be associated with probabilities. Suppose there are M possible states of nature, each with probability $q_m, m = 1,2,...,M$. If a model of yield response to N and c could be specified for each weather condition, then an optimal nitrogen rate could be derived to maximize expected profit. Since we only have three years' data, such analysis must be done under the assumptions that the three years represent three distinct states of nature and that no other states of nature are possible. Given that 1999 was a dry year, 2000 a wet year, and 2001 a mixed year, yield response for these three years was associated with probabilities of comparable states of

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[2] This approach includes information cost G but not variable rate application cost V. Schnitkey et al. (1996) showed 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.

nature occurring. Based on 42 years of daily precipitation data from the nearest weather stations, annual precipitation data from 1960 to 2001 were divided into three categories: 17 dry years, 7 wet years, and 18 moderate years. Thus the probability of facing a dry year, a wet year and a moderate year is roughly 40%, 20% and 40%, and these probabilities were associated with yield response following patterns estimated for 1999, 2000 and 2001, respectively. Returns to N recommendations based upon such average weather conditions were estimated using yield response functions for the 1999 year.

Results

Do site characteristics affect corn yield response to nitrogen fertilizer?

Results of the three statistical models of years 1999, 2000 and 2001 are summarized in Table 2. The explanatory variables included in the final model and their coefficient estimates differ considerably from year to year, providing evidence that the effect of site characteristics on yield response to nitrogen depends on the weather condition. N credit systematically increased yields in all three years, and the $N \times Ncredit$ interaction term decreased yields, indicating that the N credit works like N itself, as it should. The *Wetness* index increased yields in the two drier years (1999, 2001), but had no significant yield effect in rainy 2000. Organic mater and EC significantly influenced yields in two years but changed sign, increasing yield in dry 1999 but reducing it in moderate 2001. Cation exchange capacity (CEC) and several of the N interaction terms with site characteristics were significant in individual years. The Insolation Potential Index (IPI) and had no significant effect on corn yields.

The joint significance of the $N \times c$ interaction terms was tested with F tests of the full model compared with the one without interaction terms for each of the three years. The results lead to rejection of the first null hypothesis at the one percent significance level in 2000 and 2001, but failure to reject in 1999 (p = 0.122). Although not conclusive, the weight of the evidence indicates that site characteristics *do* interact with corn yield response to nitrogen in the full model for all three years.

Based on the final model, the site-specific optimal nitrogen rate N_{ij}^{sr} can be derived:

$$\partial E[y(N_{ij}, c_{ij} \mid x_{ij}, \varepsilon_{ij})] / \partial N_{ij} = p_N / p_Y$$

$$\text{s.t. } E[y(N_{ij}, c_{ij} \mid x_{ij}, \varepsilon_{ij})] = \alpha + \beta N_{ij} + \theta N_{ij}^2 + \gamma c_{ij} + \delta (N_{ij} \times c_{ij})$$

$$\Rightarrow N_{ij}^* = (\beta + \delta c_{ij} - p_N / p_Y) / (-2\theta)$$

The last equation states that site-specific information is relevant and potentially valuable in nitrogen management.

Can site-specific N response functions add enough value to cover their costs?

<u>1) Comparing the nitrogen management strategies with moisture conditions known</u>

Table 3 compares field-level expected gross margins $[P_y E(Y) - P_N N]$ among the VRNA-SS, UNA-SS, UNA-Simple and Tri-State strategies for the years 1999, 2000 and 2001, given a nitrogen fertilizer price of \$0.21 per pound N and corn at \$2.00 per bushel. As a result of year-to-year differences in weather, the optimal N rates vary accordingly. Since the simple N response model is based on an information set containing average yield response to known weather, the difference between the expected gross margins of

VRNA-SS and UNA-Simple models is the value of site-specific information, given that weather conditions are known. These values are $0.01, $0.45 and $0.37 per acre in 1999, 2000 and 2001 respectively. Given that the cost of site-specific soil testing and mapping (*G*) averaged over $6.00/acre and VR application of a single fertilizer (*V*) averaged over $5.00/acre in a 2001 dealer survey (Whipker and Akridge, 2001), the values of the benefits estimated here do not come close to covering typical costs of VRNA-SS. By contrast, although the differences were small ($0.01 and $1.38) in 1999 and 2000, in the uneven rainfall year of 2001, VRNA-SS had a gross margin $24.58 higher than the Simple Model, more than enough to cover a *G* of $6.00/acre either. Thus, at these prices, we fail to reject the second null hypothesis in two of the three years – obtaining site-specific information is not profitable – even with prior knowledge of weather conditions.

The difference between the expected gross margins of VRNA-SS and Tri-State can be explained as the information value of both year-specific weather pattern and site characteristics. This difference turns out to be larger during the wetter years, which at $4.95 in 2000 and $3.75 in 2001 were well above the $1.26 gain in dry 1999 (Table 3). Although the data do not permit separation of the year effect from the site-characteristics effect, it is likely that early season leaching led to N deficiency that the VRNA-SS model corrected by factoring in nitrate leaching prior to side-dress time.

2) Comparing the nitrogen management strategies with moisture conditions unknown

Table 4 compares expected gross margins between VRNA-SS, UNA-SS and Tri-State fertilization strategies for 8 fields, given relative prices of nitrogen fertilizer at $0.21/lb and corn at $2.00/bu. Note that the information set here differs from that under the perfect information case above, because it substitutes long-term weather expectations for current year weather information. Based on these weather expectations at the individual field level and the yield functions estimated for 1999, it would be profitable only in 1 of the 8 fields to obtain and use site-specific information if that cost $11.00/acre. Hence, based on expected values for seasonal weather, it is not possible to reject the null hypothesis that variable rate N application based on site-specific response functions is unprofitable. Only one of the site-specific methods here appears more profitable than management based on the Tri-State fertilizer recommendations when the costs of information acquisition and VRA are included.

Conclusions

This research finds that corn yield response to nitrogen varies spatially with quantifiable field characteristics. Potential soil moisture (wetness index) is especially important. Such an index is easy to calculate from digital elevation data that can be collected with a pass of a GPS-equipped yield monitor or electrical conductivity sensor.

The significant site-characteristic variables are fairly consistent from field to field within each year. However, the effect organic matter seems to vary from one season to another. This could well be associated with rainfall, such that organic matter mineralization without nitrate leaching could have caused it to be a significant source of N in a dry year but a sink for N in a wet one.

Although the site-characteristic variables are significant statistically, they appear to be economically insignificant. The added revenue from site-specific nitrogen application was generally insufficient to cover the costs of site-specific data acquisition and variable rate fertilizer application, leaving no surplus that could pay for the development of site-specific fertilizer recommendations. This is true even with current high nitrogen and low corn prices, leading to a nitrogen-corn price ratio of over 1/10. Such a price ratio is relatively high for corn, so the failure to find VRNA profitable at these prices means it is unlikely to generate more valuable yield gains or fertilizer cost savings.

If interpreted as breakeven prices, the gross margin gains over fertilizer costs reported here are slightly higher than those reported by Bongiovanni and Lowenberg-DeBoer (2001) for Argentina. The increased gain may be attributable to the site-specific N recommendations. However, the mean gain of $2-3 per acre is small enough that it cannot compensate for typical soil testing and variable rate fertilization charges over $10 per acre – far short of paying for the cost of developing site-specific recommendations.

Perhaps the biggest lesson was how important are seasonal weather differences. The interseasonal weather effect appears to overcome the intraseasonal spatial effects on corn yields. In order to make the most of spatial yield response models in future, scientists and farmers will need to find \ways to incorporate better weather predictions.

Table 1: Variable names and definitions for 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	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 normalized to 0	0	-0.62	2.90
Wetness index[1]	ln ratio	10.56	7.88	15.07
Insolation Potential Index[1]	Sine of equivalent latitude	0.67	0.60	0.73

[1] Average value per plot
[2] Average of interpolated values in plot

Table 2: Corn yield response to nitrogen regression models with and without site characteristic variables, 14 Michigan fields, 1999- 2001.

	1999			**2000**			**2001**		
	Full Model	**Final Model**	**Simple Model**	**Full Model**	**Final Model**	**Simple Model**	**Full Model**	**Final Model**	**Simple Model**
Regression diagnostics									
No. of obs.	1159	1159	1159	1510	1510	1510	1243	1243	1243
Prob > F	.0000	.0000	.0000	.0000	.0000	.0005	.0001	.0000	.0624
R-squared	.7645	.7488	.7118	.8351	.8250	.7707	.8491	.8431	.8173
Variables									
N-applied	.379	.450	.457	2.00	1.01	.872	-.409	1.23	.897
	(.731)	(.168)	(.162)	(.473)	(.088)	(.115)	(1.11)	(.300)	(.129)
N^2	-.000999	-.00116	-.00118	-.00217	-.00217	-.00224	-.00220	-.00220	-.00214
	(.000407)	(.000395)	(.000347)	(.000279)	(.000282)	(.000291)	(.000285)	(.000277)	(.000301)
OM[a]	2.93	1.06		-1.01	-.347		-.146		
	(1.75)	(.314)		(.175)	(.302)		(.640)		
CEC[b]	-4.57	-.395		1.85			-2.31		
	(3.66)	(.757)		(.940)			(1.36)		
EC[c]	12.1	4.43		2.26			6.78	-3.30	
	(8.01)	(1.95)		(7.53)			(9.81)	(7.51)	
Ncredit*	.291	.142		.783	1.01		.985	.918	
	(.119)	(.0684)		(.171)	(.213)		(.285)	(.208)	
Wetness	7.08	2.90		3.40			5.67	5.91	
	(1.21)	(.468)		(2.84)			(1.72)	(2.14)	
Insolation	-.399			211			-230		
	(141)			(139)			(276)		
N×OM	-.0142			-.00160	-.00485		.00119		
	(.0116)			(.000808)	(.00162)		(.00385)		
N×CEC	.0324			.0106			.0149		
	(.0246)			(.00597)			(.00782)		
N×EC	-.0620			-.0604			-.0148	.0512	
	(.0685)			(.0540)			(.0482)	(.0426)	
N×Ncredit	.00108			.00372	-.00412		-.00477	-.00433	
	(.000736)			(.00153)	(.00152)		(.00194)	(.00164)	
N×Wet	-.0303			-.0117			-.0173	-.0185	
	(.0108)			(.0120)			(.0143)	(.0166)	
N×Insolation	.384			-1.22			2.28		
	(.920)			(.850)			(1.84)		

NB: Field-level fixed effect coefficients estimated for all models but not shown .

*Standard error in parenthesis.

[a] OM: Organic matter

[b] CEC: Caption exchange capacity

[c] EC: Electrical conductivity or electromagnetic conductivity

Table 3: Expected gross margins over N fertilizer costs for four corn fertilization strategies with weather known.

Year	**Expected gross margins ($/acre)**				**Difference of expected gross margins ($/acre)**		
	VRNA-SS (1)	**UNA-SS (2)**	**UNA-Simple (3)**	**UNA-Tri-State (4)**	**(1) - (2)**	**(1) – (3)**	**(1) – (4)**
1999	238.00	237.99	237.99	236.74	0.01	0.01	1.26
2000	275.16	274.71	273.78	270.21	0.45	1.38	4.95
2001	326.25	325.88	301.67	322.50	0.37	24.58	3.75

(1) Site-specific nitrogen application using site-specific yield response (VRNA-SS);
(2) Uniform nitrogen application using the same information set (UNA-SS);
(3) UNA using the simple N response (UNA-Simple);
(4) UNA based on Tri-State recommendation.

Table 4: Expected gross margins over N fertilizer costs for three fertilization strategies based on longterm weather expectations, 8 fields, south-central Michigan, 1999.

Field	**Difference of expected partial profits ($/acre)**		
	(1) – (2)	**(1) - (4)**	**(2) – (4)**
Field A	0.36	0.51	0.15
Field B	0.49	2.01	1.52
Field C	0.69	0.69	0.00
Field D	0.25	0.30	0.05
Field E	0.37	3.65	3.28
Field F	0.10	10.34	10.24
Field G	0.29	4.39	4.10
Field H	0.09	6.54	6.45

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