A SYSTEMS APPROACH FOR EVALUATING ON-FARM SITE-SPECIFIC MANAGEMENT TRIALS: A CASE STUDY WITH VARIABLE RATE MANURE AND CROP QUALITY RESPONSE TO INPUTS

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Abstract

Site-specific application of manure has the potential to improve crop production and environmental quality. If manure is applied where it is needed, in the quantity required by the crop, over application, with attendant runoff and leaching problems can be reduced. To implement this approach growers need site-specific crop response information. Increasing availability of site-specific yield information offers a way to estimate such crop responses. The objective of this study is to develop a methodology for estimating site-specific response of corn and soybeans to manure given soil test information, and to use that methodology to analyze an on-farm manure management trial conducted near Sleepy Eye, Minnesota. Both quantity and quality of the crop is considered.

Keywords: Variable rate manure, grain quality premiums, site-specific management, profitability

Introduction

Variable Rate Manure (VRM) and Fertilizer Management

Animal waste can be a valuable commodity, but for some it is considered a liability, requiring time and money for disposal. Improper disposal or handling of manure may result in environmental degradation, hence many of the proposed changes in feedlot and manure management regulations (Ribaudo). Although many producers recognize the potential value of manure, few realize its maximum benefit.

Throughout the Midwest several approaches are utilized to assist producers with their manure management decisions. Although many of these approaches are good, the sheer diversity of management options often results in questions as to what producers should do for their fields. Site-specific approaches need to be established that will address both economic and environmental questions. Today, state-of-the-art manure applicators are available, capable of applying manure within a 2-8% range of delivery error (Ess *et al*., 2001). With older manure spreaders, application rates could vary between 2000 to 4000 gal acre^{-1} from start to finish (Olson, 20001, target levels not provided). Combined with other biophysical information about field production characteristics, site-specific manure recycling now has the potential to become an economically attractive and environmentally sound management strategy.

From a production standpoint, specific problems with manure as an alternative way to manage soil fertility prompt the following questions, including: (1) what is the nutrient value and uniformity of manure, (2) what is the amount of credit given that should be given to nutrients still in the organic portion of the manure, (3) what adjustments for nutrient loss should be made because of application methods or weather conditions, (4) does the producer have the ability to make uniform or variable rate application rates of manure, and (5) what are the economically optimal application rates for a given field or portion of a field. The last question integrates the four previous questions, and is the final factor in determining if the producer maximizes profit and minimizes environmental concern.

Grain Quality Premiums

Recent advances in plant breeding genetics have not only increased crop yields. Coupled with innovations in processing technologies, plant composition screening, and well-developed marketing channels, some producers now have the option to target production of grain *quality* as well as quantity. End-users such as seed companies, feed manufactures, processors, and grain elevators are willing to pay premiums for high extractable starch (HSC) corn, high-oil corn and soybean, and high-extractable protein soybean (HPS) and high-protein corn (HPC), and high-fermentable corn (HFC) for ethanol (Olson, 2004). Availability of on-the-go grain quality sensors (Lotz; Zhang, Wang, and Wang; Doerge) make precision monitoring of grain quality all the more attractive, especially with the prospects of managing not only quantity, but quality, site-specifically.

Contract production of HSC is not new (for example, Kliebenstein and Hill's 1971 report). Today, 100% of HSC is grown under contract (US Grains Council). These HSC hybrids mill more easily, resulting in greater returns of gluten meal and feed fraction (US Grains Council). The major export market for HSC is Japan, but domestic demand for HSC is also projected to increase as production efficiency of ethanol plants improves (Frerichs). Premiums for HSC generally range from \$0.07 to \$0.15 bu^{-1} for starch yields ranging between 69-72%.

Producers and processors have also long acknowledged the value of soybean as a feed supplement in general, and protein in particular. On average, soybean protein content is 34% (Theobold). HPS contains 37% to 41% more protein than conventional soybean varieties (Graef). In fall 2003, a Quality Premium Program was kicked off by the Minnesota Soybean Processors, a producer owned and controlled closed cooperative (MnSP). This company pays a protein premium based over a range of protein levels (35% to 37.5%) (figure 1). In figure 1, premiums are paid to HPS varieties when protein content exceeds 35%. For HSC, premiums are paid when starch levels exceed 69%. Below these thresholds, no premiums are received for HPS or HSC.

The objective of the protein and starch premium part of this study is to determine whether or not inclusion of grain quality premiums as an implicit choice variable in the producer's optimization problem will increase the value variable rate manure (VRM).

Empirical Methodology

Data and Experimental Design

The VRM experiment was conducted at Christensen Farms (Sleepy Eye, Minnesota). Corn grown during the 1999 season was followed by soybean. A randomized complete block design of four replications of four rates of liquid swine manure, including a check strip (0, 2000, 4000, 6000, and 8000 gal $acre^{-1}$) were applied on October 21 (1998) over a 10.7-acre field in constant rate strips utilizing a commercial state-of-the-art applicator (Terra-Gator 2505) equipped with computer assisted application controls, GPS, and a positive displacement pump. The applicator for this machinery is accurate within a 2-8% weighing error (Ess, Hawkins, and Morris). Each load of manure delivered was applied on a specific plot, taking into account how much manure was needed to complete two strips. A tank was used on 2 side-by-side strips. The field is managed in a corn-soybean rotation. Manure had not been applied to the field in recent years. Manure was only applied in fall 1998 before the 1999 corn-growing season. No manure was applied prior to planting soybean in spring, 2000. Nitrogen and other inorganic fertilizers were not applied to the field throughout the entire experiment. Soil tests were taken in 1998, prior to manure application.

Treatment strips were 24-ft wide (two passes with the applicator) and approximately 800-ft long. Manure was obtained from a nearby hog finishing building and was applied via surface broadcast and immediate incorporation with heavy double discs attached to the applicator. Manure was collected from the bottom of a pit where macronutrient concentration tends to be higher. Each manure load was sampled for nutrient content (average analysis was 46-57-28 pounds of N, P_2O_5, and K_2O 1000 gallons^{-1}, respectively).

Yield data was collected in 15-m segments for corn and soybean crops in 1999 and 2000 through each treatment. Grain yield was measured from the center row of each treatment strip using a Massey Ferguson plot combine equipped with a ground distance monitor and computerized Harvest Master weigh-all (Harvest Master, Logon UT). Every 15-m, the combine was stopped and the harvest grain weighed. Grain sub-samples were collected from each harvest segment and dried at 60^{o}C for moisture determination. Corn and soybean yield was adjusted to 15.5% and 13.5% moisture, respectively. Protein and starch content were assayed in each harvest segment (figure 2).

Choice of Management Zones in this Analysis

There are hundreds of classifications whereby management zones could be constructed. For example, management zone classifications could be organic matter, soil type, elevation, soil depth, or pH. In this study, phosphorus Bray (P-Bray) soil test values are used as a proxy to identify management zones (figure 3).

The reasoning behind using this classification is to identify potential management zones that respond differently to inputs. Strong correlation between P, Zn, %OM, and pH suggests at the study site exhibits SSM potential where management areas have exclusive edaphic features. In Minnesota, P soil tests are sometimes classified in five levels: 0-5, 6-10…to >20 ppm (Rehm *et al*., 1994). This classification is used to identify management areas at the site that exhibit distinct physical characteristics. Based on P-Bray soil test results, 3% of the field had P-Bray readings between 0-5 ppm (Z1), while 52%, 32%, 5%, and 8% of the field had readings of 6-10, 11-15, 16-20, and 20+ ppm P-Bray, respectively (zones Z2, Z3, Z4, and Z5) (table 1).

Identifying management zones is at most an intermediate objective. If the SSM objective is to better target input application, then a model based on this breakdown makes sense because: (1) the candidate management zones are supported by the University of Minnesota (UMN) extension literature; (2) P is a convenient proxy since it correlates strongly with zinc (Zn), pH, and % organic matter (%OM) soil tests (Lambert, Malzer, and Lowenberg-DeBoer); and (3) P is a manageable input that has been well-studied in extension and agronomic literature.

Descriptive Statistics for Soil Tests and Corn and Soybean Yield

Manure Heterogeneity

One issue facing producers who want to use manure as a fertilizer is product heterogeneity. For example, a study in Minnesota found that nutrient values for N, P, and K varied 300% from farm to farm for the same animal species (Olson). The VRM trial at Sleepy Eye is no exception for P (figure 4). On average, the 6000 gal acre^{-1} treatment also delivered more P_2O_5 than the 8000 gal acre^{-1} treatment. The amounts of P_2O_5 delivered by the 6000 and 8000 gal acre^{-1} treatments were not different from each other at the 5% level (Analysis of Variance, ANOVA). Additionally, the amounts of P_2O_5 delivered in the 4000 and 6000 gal acre^{-1} treatments were not different at the 5% level (ANOVA). However, the amount of available N and K_2O delivered by each treatment was significantly different at the 5% level, and on average K and N inputs increased with increasing manure quantity.

Yield and Quality

The average whole-field yield for corn (N = 300 yield observations for the entire field) was 166 ± 40 bu acre^{-1} (mean ± standard deviation) with a minimum and maximum yield of 51 and 220 bu acre^{-1} (table 1). The average whole-field yield for soybean (N = 300) was 48 ± 7 bu acre^{-1}, with minimum and maximum values of 24 and 62 bu acre^{-1}. In general, corn yield yields were highest in areas where soil test P levels were highest

(Zones 4 and 5, > 15 ppm). For soybeans, yield was highest in the Zone 5, followed by the low P zone (Zone 1).

The whole field (WF) average %starch level for corn was 73.46%. For soybean, the WF average %protein level was 37.69% (table 1). This is to be expected since the corn and soybean varieties planted were high-yield starch and protein varieties, respectively. At these average levels, the producer would receive a premium of $0.11 and $0.07 for starch and protein, respectively, based on the premium functions in figure 1.

Systems Model to Identify SSCR Functions

A second-degree polynomial response function (Dillon and Anderson) is assumed to describe corn and soybean response to liquid hog manure. Since inputs are economically quantifiable, response functions facilitate comparison between input changes and the cost of making those changes. Most of the recent work estimating SSCR function used single, quadratic equations to estimate plant response to inputs over space (Bongiovanni and Lowenberg-DeBoer; Hurley, Malzer, and Kilian; Lambert, Lowenberg-DeBoer, and Bongiovanni; Bruulsema et al.; Swinton et al.).

For crop production analyses, quadratic functions are suitable since they are concave functions with $f' > 0$ and $f'' < 0$, which permits diminishing marginal returns to inputs applied. This allows for the possibility that crop growth can be compromised by input applications above biophysical optimal levels (for example, nitrogen "burning" corn). The estimation of economically optimal input rates (EOR's) is also tractable since a closed-form solution to f' exists.

The system of equations used to estimate site-specific corn and soybean yield response and protein production is:

$$\mathbf{y} = \mathbf{XA} + \hat{\mathbf{C}}\boldsymbol{\gamma} + \boldsymbol{\varepsilon},\ \boldsymbol{\varepsilon} = \lambda\mathbf{W}\boldsymbol{\varepsilon} + \mathbf{u} \quad (1)$$

$$\mathbf{C} = \mathbf{F}\boldsymbol{\Phi} + \zeta,\ \zeta = \psi\mathbf{W}\boldsymbol{\zeta} + \mathbf{e} \quad (2)$$

$$\mathbf{Q} = \mathbf{Z}\boldsymbol{\Xi} + \hat{\mathbf{R}}\boldsymbol{\theta} + \boldsymbol{\eta},\ \boldsymbol{\eta} = \pi\mathbf{W}\boldsymbol{\eta} + \mathbf{g} \quad (3)$$

$$\mathbf{R} = \mathbf{P}\boldsymbol{\Delta} + \xi,\ \xi = \varphi\mathbf{W}\boldsymbol{\zeta} + \mathbf{o} \quad (4)$$

where **y** and **Q** are geo-referenced N x 1 vectors of yield and quality (starch and protein) unit^{-1} for corn and soybean, respectively; **X** is an N x k matrix of fixed effects (input levels unit^{-1}, their squares, and location dummy variables for field sites z); $\hat{\mathbf{C}}$ is an N x 1 vector of predicted yield values; **F** and **Z** are N x (s + s x k) matrix of instruments including the s-th soil test characteristic and k-th input by soil characteristic interaction; **W** is an N x N matrix identifying spatial relations between observations; **A** and $\boldsymbol{\Xi}$ are k x 1 vectors of fixed effects parameters; $\boldsymbol{\Phi}$ is a (s + s x k) x 1 matrix of linear and quadratic coefficients for a continuous yield response function; $\boldsymbol{\gamma}$ and $\boldsymbol{\theta}$ are s x 1 matrices of site locations; λ, π, φ and ψ are spatial autoregressive parameters; $\boldsymbol{\varepsilon}$, $\boldsymbol{\eta}$, $\boldsymbol{\xi}$ and $\boldsymbol{\zeta}$ are N x 1 vectors of (possibly) autocorrelated disturbances; **u**, **g**, **o** and **e** are N x 1 vectors of disturbances.

Model Estimation

Corn and soybean response curves may be considerably different, but many of the same factors such as weather, slope, and soil compaction affect the growth of both crops. For this study, this is an important assumption because any fertilizer effects manure has on soybeans are residual carry-over effects from the corn-growing season. The grain quantity system of equations for *t* crop rotations was estimated with a spatial error autoregressive model since (1) and (2) are correlated across growing seasons (Lambert, Malzer, Lowenberg-DeBoer, 2003). Spatial autoregressive parameters were estimated with the Iterated General Method of Moments approach of Kelejian and Prucha. The system of equations is a modification of Anselin's Seemingly Unrelated Regression spatial error model for panel data sets (Anselin, page 143). Carry-over effects between growing seasons are captured by stacking equations (1) and (2), and then estimating the system of equations with GM. The grain quality equations (3 and 4) are estimated using the same method.

Producer's Optimization Problem

Premium Price Function

The producer's optimization problem with respect to crop inputs ($\boldsymbol{x}$) changes with the option to produce for quality as well as quantity. Define the 'premium function' for grain quality *m* as $\wp^m\left(q^m\left(\boldsymbol{x}_t\right);\boldsymbol{\alpha}^m\right)$, where $\wp^m$ is the premium received for the amount (as %) produced of quality *m*; $\boldsymbol{\alpha}$ are parameters mapping the quality level (%) produced to the premium paid to the producer; and $\boldsymbol{x}_t$ is the input vector applied in season *t*. The price received for a given crop produced in season *t* is now a function of the competitive market price (P_t) for grain quantity, plus the premium function for quality *m*. Thus, the price received for crop *t* becomes an implicit choice variable for the producer $\left(\tilde{P}_t\right)$. If there is more than one quality in a given crop targeted by the producer (for example, oil and protein in soybean), then the price received for growing crop *t* is $\tilde{P}_t = P_t + \sum_m \wp^w\left(\boldsymbol{x}\right)$. The premium function is given by what the processor is willing to pay for a given level of quality *m*. The parameters $\boldsymbol{\alpha}^m$ used in this research were estimated using the premium price information taken from MnSP for HPS and the Illinois Specialty Farm Products Fact Sheet (Frerichs) for HSC (figure 1). The functions are included in the producer's profit maximization problem.

Producer's Maximization Restated with Quality Premiums

Site-specific management implies that a field can be partitioned into more than one area wherein profit maximization is achieved by applying input levels customized for those areas. Whole-field profit is then expressed as the weighted average of profits from these exclusive management areas. Bullock, Lowenberg-DeBoer, and Swinton's 'spatial optimization' model is modified to accommodate the premium function $\wp^m$. Restated, the producer's maximization problem including premiums and discounted over growing seasons is $\underset{\boldsymbol{x}}{NPV}^* = \sum_t \sum_z \omega_z \left(\beta^t \tilde{P}^*_{t,z} Y^*_{t,z} - \beta^{t-1}\left(F_t + I^g_{(t)} g_t + I^v_{(t)} v_t + \boldsymbol{r}'\boldsymbol{x}^*_{t,z}\right)\right)$, where $\beta^t = (1 + \rho)^{-t}$, and ρ is a discount rate (7.5%, Charialla *et al.*); *z* indicates a site-specific management area, *F* are fixed costs, *g* and *v* are quasi-fixed site-specific information and variable rate application costs, respectively; $\boldsymbol{r}$ is a *k* x 1 vector of costs for the *k* inputs applied in season *t*; $I^{(\bullet)}_{(t)}$ is an indicator variable equal to one when *g* and *v* costs are incurred by the producer; and ω_z are the portions of the field covered by management zone *z*. For example, soil test or maps (*g*) may be useful for four years (Swinton and Lowenberg-DeBoer), or *v* may be applied during corn years only (for example, nitrogen). Note when a producer manages inputs site-specifically and chooses to produce HSC or HPS, then $\tilde{P}^*_t \equiv \tilde{P}^*_{t,z}$, conditional upon quality level produced in site *z*.

Sensitivity Analyses and NPV Optimization Scenarios

Using the system regression results, the net present values (NPV) of seven manure management strategies are compared in a sensitivity analysis. The partial budget equations for each scenario are:

VRM: $$NPV = \beta^1 \tilde{p}^*_{corn} y^*_{corn} - r_{VRM} x^*_{VRM} - g + \beta^2 \tilde{p}^*_{soy} y^*_{soy} \quad (5)$$

VRM-WFF: $$NPV = \beta^1 \tilde{p}^*_{corn} y^*_{corn} - r_{VRM} x^*_{VRM} - g - \sum_{k=1}^{K} r_k s_k^{REC} + \beta^2 \tilde{p}^*_{soy} y^*_{soy} \quad (6)$$

VRM-VRF: $$NPV = \beta^1 \tilde{p}^*_{corn} y^*_{corn} - r_{VRM} x^*_{VRM} - g - v - \sum_{k=1}^{K} r_k s_k^* + \beta^2 \tilde{p}^*_{soy} y^*_{soy} \quad (7)$$

WFM: $$NPV = \beta^1 \tilde{p}^*_{corn} y^{REC}_{corn} - r_{UNI} x_{REC} + \beta^2 \tilde{p}^*_{soy} y^{REC}_{soy} \quad (8)$$

WFM-WFF: $$NPV = \beta^1 \tilde{p}^*_{corn} y^{REC}_{corn} - r_{UNI} x_{REC} - g - \sum_{k=1}^{K} r_k s_k^{REC} + \beta^2 \tilde{p}^*_{soy} y^{REC}_{soy} \quad (9)$$

WFM-VRF: $$NPV = \beta^1 \tilde{p}^*_{corn} y^{REC}_{corn} - r_{UNI} x_{REC} - g - v - \sum_{k=1}^{K} r_k s_k^* + \beta^2 \tilde{p}^*_{soy} y^{REC}_{soy} \quad (10)$$

WFM*-VRF: $$NPV = \beta^1 \tilde{p}^*_{corn} y^{*,WF}_{corn} - r_{UNI} x^*_{WF} - g - v - \sum_{k=1}^{K} r_k s_k^* + \beta^2 \tilde{p}^*_{soy} y^{*,WF}_{soy} \quad (11)$$

Equations 5-7 estimate the NPV of SSM manure. Equations 8-11 estimate the NPV of a uniform (WF) manure strategy. In the SSM strategies, the VRM fee (r_{VRM}) is \$0.008 gal^{-1}. The cost gal^{-1} of manure for the producer choosing the WF strategy is \$0.007 (r_{REC}). Yields, s_k^*, and x^*_{VRM} are weighted averages of the optimized values in management zone *z* (weights are in table 1). Other cost details are in Lambert, Lowenberg-DeBoer, and Malzer.

- VRM (Variable rate manure): In the first strategy (5), the producer has site-specific knowledge about corn and soybean yield respond to liquid hog manure.

The producer applies manure at economically optimal rates (EOR) for each site *z*. It is assumed that the producer has purchased soil test information (*g*) to identify management zones, but chooses not to use the information with respect to augmenting P and K levels, or adjusting pH. This is the SSM baseline scenario.

- VRM-WFF (Variable rate manure – whole-field fertilizer): The second strategy (6) considers a producer who has site-specific yield response information, and uses soil test information to bring P, K, and pH to levels recommended by extension agents to achieve target yield goals. Soil test information is used to develop management zones, and the producer is charged *g*. The producer practices VRM, but applies P, K, and pH uniformly. For example, if the WF average P-Bray level is 11 ppm and the average yield goal for the entire field is 183 bu acre^{-1} for corn, then a reasonable extension recommendation is to broadcast 45 lb acre^{-1} P_2O_5 to meet this yield goal (Rehm *et al*.). The VRA fee of \$5.64 acre^{-1} is avoided, but a charge (lbs acre^{-1}) for the P, K, and lime applied is incurred. The recommended WF rate is based on the average of the soil test values.
- VRM-VRF (Variable rate manure – variable rate fertilizer): This scenario (7) considers a producer who practices VRA and VRM simultaneously. Manure and P, K, and lime are applied at EOR levels according to each management zone. The producer is charged a VRA fee (*v*) for variable application of P, K, and lime, and *g* for the soil test information. The VRM application fee is charged (r_{VRM}).

- WFM: In this scenario (8), the producer chooses a WF manure application strategy. The producer uses a manure rate recommended by an extension agent. The recommended rate by UMN is 3500 gal acre^{-1}.
- WFM-WFF (Whole-field manure – whole-field fertilizer): The fifth strategy (9) considers a producer who opts to uniformly apply manure at the extension recommendations, but uses the soil test information to adjust P, K, and lime levels to recommended levels. These fertilizers are applied uniformly. Adjusted levels are based on the average of the soil tests and average WF yield goals. The producer is charged *g* for the soil test information.
- WFM-VRF (Whole-field manure – variable rate fertilizer): In this strategy (10) considers a producer who follows extension recommendations and applies liquid hog manure at a uniform rate, but manages P, K, and pH using VRA. The producer is charged *v* and *g*. Management zones are development using soil test information.
- WFM*-VRF (Whole-field manure at WF optimum– variable rate fertilizer): In the last strategy, NPV is evaluated at the WF optimal manure input level. This assumes the produce has information about yield response at the WF level. The producer applies manure at the optimal WF rate, and varies P, K, and lime.

The NPV for the producer using a VRF-P, K, and lime strategy (7 and 10) is based on the solution to the optimization problem $\max_{x_{k,t,z}, s_{k,z} \in [\underline{s}_{k,z}, \ldots, \bar{s}_{k,z}]} NPV$. The soil characteristics in each zone z ($s_{k,z}$) are bounded between the average of the soil test value for a given characteristic in zone z ($\underline{s}_{k,z}$), and the recommended level corresponding to a target yield level given by Rehm *et al*. ($\bar{s}_{k,z}$). The producer cannot choose to remove a nutrient from a given site. The $x_{k,t,z}$'s are the manure rates for zone Z.

The producer cannot apply more than the extension rate as determined by the soil characteristic level in a given site *z*. The upper and lower bound constraints on the optimized levels are applied to equations 7 and 10. The solution to the producer's problem choosing VRF is the optimal levels of P and K, or pH. These levels are converted to input rates applied to a specific site in the partial budget. Site-specific NPV's are weighted by the % of the field covered by zone *z* for producers choosing VRF-P, K, and lime (table 1).

Results and Discussion

Regression results for Yield Quantity Equations

Lambert, Malzer, and Lowenberg-DeBoer found significant spatial structure in the errors for the quantity system (equations 1 and 2). Site-specific yield response estimates for corn and soybean quantity are in table 2. Estimates for the soil fertility equations (equation 2) corresponding with the SSCR function equations are in table 3. For the corn equation, yield response in 4 out of the 5 management zones was significantly different from the WF average response. Additionally, the response function (**C**) channeling soil test information into the SSCR function equation was significant for all zones.

Regression results for Yield Quantity Equations

In a previous study, Lambert, Malzer, and Lowenberg-DeBoer found that P was the most significant variable affecting the VRM's effect on corn and soybean yield response.

Based on this information, the quality fertility function for starch and protein (equation 4) only included site-specific soil test information about P, along with manure, quadratic terms, and the interaction between P and manure. A system LM test for spatial error (Anselin, page 163) in the quality equations was rejected at the 5% level (LM = 31, df = 4). There was no significant site-specific response of starch with respect to manure (Table 2). However, the marginal response of protein response to manure did vary significantly between the management zones, excluding Zone 2. The soil fertility equations (equation 4) were significant in all zones, indicating that P management significantly influences quality response.

Optimization Results

The VRM-VRF strategy produced the highest corn and soybean yields, and the highest NPV ($605 acre^{-1}) in the baseline case (table 4). The WFM*-VRF strategy followed closely with similar yields for corn and soybean, but an NPV of $603 acre^{-1}. The most gallons of manure acre^{-1} was applied (on average) under the VRM management scenario (5595 gal acre^{-1}), followed by WFM*-VRF (4852 gal acre^{-1}), VRM-VRF (4629 gal acre^{-1}), and VRM-WFF (4576 gal acre^{-1}). Any strategy using a variable strategy for manure, P, K, and lime, or a combination of these inputs was more profitable than WF strategies alone.

In the premium scenarios, NPV is determined as a trade-off between yield quantity and grain quantity (table 5). In all scenarios, NPV increased when inputs can be managed to reflect this trade-off. The profitability rankings of the management strategies changed with the addition of protein and starch premiums (table 6). When the premium is introduced, the WFM*-VRF shows a slight advantage in NPV over the VRM-VRF scenario ($1.10 acre^{-1}). The amount of manure applied on a per acre basis decreases with the addition of protein and starch premiums for the VRM-WFF scenario, but increases in the WFM*-VRF and VRM-VRF. There is no difference in the amount of manure applied in the VRM case on average, but the site-specific amounts change. Corn yield is slightly higher in the WFM*-VRF and VRM-VRF scenarios with protein and starch premiums. Soybean yields are higher in the VRM-VRF scenario with premiums, decrease in the WFM*-VRF scenario, and remain generally the same in the other scenarios compared to the baseline yields.

When starch and protein premiums are included in the optimization problem, the largest gain over the baseline NPV is observed under the VRM scenario ($23.81 acre^{-1} over the baseline case), followed by the WFM*-VRF strategy ($22.09 acre^{-1}), and then the WFM scenario ($21.44 acre^{-1}, table 6). With the quality premiums in place, the producer's profit is higher than the base case of no premium. Alternatively, the producer could forego grain quality premiums for yield. However, this does not seem to be the case. That is, in all scenarios with the premium in place, there was incentive for the producer to capture some level of the premium (compared to just managing for quantity yield).

In general, increases to corn and soybean prices were very modest compared to the baseline premium levels in table 1. For the %protein premiums, the biggest gain over the baseline value was to the WFM*-VRF (0.0774 – 0.0738 = $0.0036), followed by the WFM-WFF and WFM-VRF strategies ($0.0035). For starch, the biggest boost in corn price occurred under the WFM-VRF scenario (0.1106 – 0.1062 = $0.0044), followed by the WFM-WFF strategy (0.1099 – 0.1062 = 0.0037). It is worthwhile noting that the larger gains from premiums accrued to the management strategies that used WFM strategies. This suggests that the VRM strategies target grain yield more so than the WFM strategies.

Conclusions

Much work remains to be done to optimize manure management. Producers need better information and management tools to maximize the economic benefit of manure and at the same time minimize environmental concerns. Site-specific improvements can be made not only with variability between fields but potentially with variability within fields. Considering the many benefits associated with manure application, it may not be economically or environmentally prudent to determine application rates based solely on the agronomic need of a single nutrient. Supplemental applications of inorganic nutrient sources could be made to compliment manure applications and provide more flexibility to the producer to adjust nutrient application for field and weather variability. This approach would address both application and environmental questions simultaneously.

Additionally, the inclusion of grain quality response in the analysis facilitates evaluation of input management with respect to optimization of crop characteristics such as starch or protein. The possibility managing inputs for grain quality and quantity is a new dimension that needs to be addressed in agricultural production economics with the advent of specialty crops, high protein soybean, high starch corn, and other specialty crops designed for the production of characteristics, and not necessarily bulk yield.

To tackle these issues, a systems regression model that incorporated soil test information into crop quantity and quality response function was proposed. The advantage of this model is that soil test information is automatically incorporated into first order conditions used to solve optimal manure rates. The system of equations combined a yield response zone function and a continuous yield response function. The objective behind the yield-zone production function was to identify candidate management zones delimited using P-Bray as a proxy for those zones. The objective of the continuous yield response equation was to model corn and soybean response to liquid hog manure, conditional upon latent soil characteristics identified by soil tests.

SSM profitability was tested under several assumptions. In most cases, the value of soil test information increases when manure is applied site-specifically, especially in conjunction with variable rate manure application. In the baseline scenario (excluding premiums), the best strategy is a VRM-WFM strategy, followed closely by the WFM*-VRF strategy where a WF optimal manure rate (4852 gal acre^{-1}) is applied. The next best strategy is the WFM-VRF program following extension manure rates (3500 gal acre^{-1}). These rankings switch when premiums are allowed. The WFM*-VRF strategy posts a slight advantage over the VRM-VRF strategy.

These results should be put into perspective and interpreted with some care, especially with the cause-effect relationship between soil test information and crop yield. For example, in the low P areas, some control plot yields (no manure applied) were above 180 bu acre^{-1}, which is unusual. In other years in similar experimental designs studying variable rate nitrogen, high P areas with no N treatment have produced corn yields of 125 bu acre^{-1}, which is also above average. The soil test, topography, and other information available for this field clearly do not capture all the sources of yield variability.

Another issue with interpretation of the results is that of manure heterogeneity (figure 4). The gallons applied per treatment are known, but the manure N, P, and K content varies. The precision of within-field variable rate application may be an illusion. This argues in favor of a whole-field manure management strategy as opposed to VRM. With current technology, good agitation and careful calibration, a uniform application of whatever the nutrient contents turns out to be may be a more achievable goal than variable rate application of the nutrient in manure.

At the higher, WF optimal manure rate of 4852 gal acre^{-1}, there is less than a 2$ acre^{-1} in NPVs compared to the VRM-VRF strategy. With premiums, the WFM*-VRF strategy has about a \$1 acre^{-1} advantage over the VRM-VRF strategy. Given the variability of the nutrient content of manure, it is difficult to argue that the VRM-VRF strategy is a better strategy than the WFM strategy combined with variable rate fertilizer program.

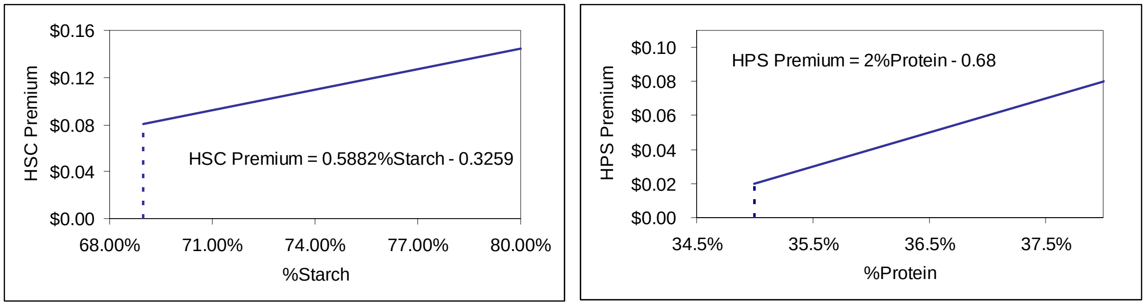

Figure 1. Interpolated protein and starch premium functions

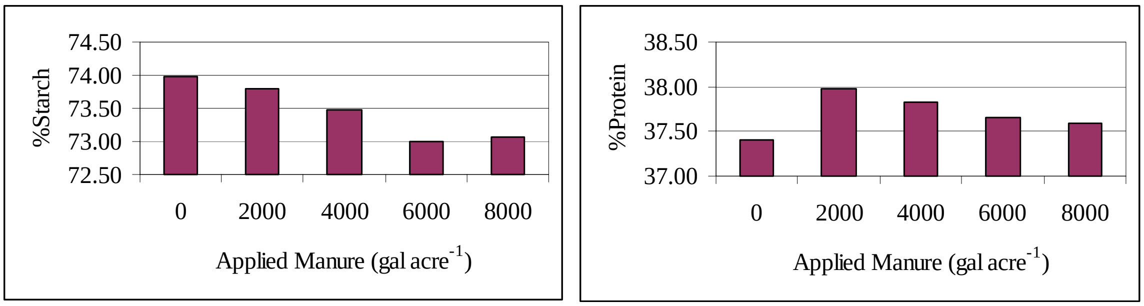

Figure 2. Treatment effects on %starch and %protein grain content

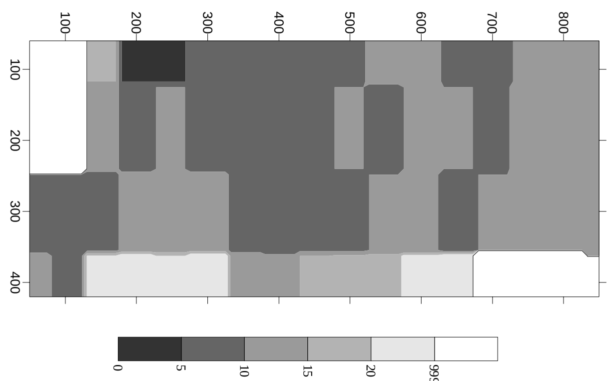

Figure 3. Management zones using P-Bray soil test levels (ppm) as a proxy. Key: Z1 ≤ 5 ppm; 5 ppm < Z2 ≤ 10 ppm; 10 ppm < Z3 ≤ 15 ppm; 15 ppm < Z4 ≤ 20 ppm; Z5 > 20 ppm. The blank areas (999) indicates sections of the field not included in the experiment

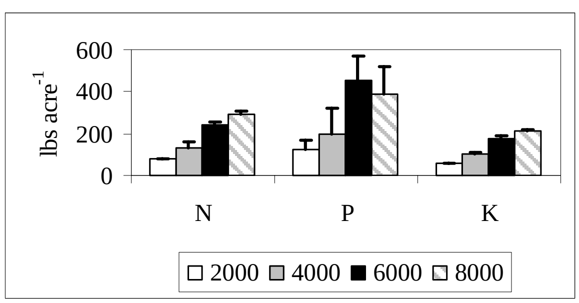

Figure 4. Nutrient content heterogeneity of manure

Table 1. Descriptive statistics for grain quality and quantity, and base premiums*

	< 5 ppm P	5 - 10 ppm P	10-15 ppm P	15-20 ppm P	20+ ppm P	WF Average
---Quality---						
%Corn Starch	73.35%	73.50%	73.47%	73.39%	73.32%	73.46%
%Soy Protein	37.61%	37.71%	37.67%	37.79%	37.64%	37.69%
---Baseline Premium received ($)---						
%Corn Starch	0.1055	0.1064	0.1063	0.1058	0.1054	0.1062
%Soy Protein	0.0722	0.0742	0.0734	0.0758	0.0728	0.0738
---Yield (bu acre^{-1})---						
Corn	163	160	170	179	180	166
Soybean	51	48	49	50	52	48
%Of field	3%	52%	32%	5%	8%	.

*Overall averages of treatment effects are in figure 2.

Table 2. Iterated SARE-GM quantity and quality site-specific response estimates

Variable	*Corn*	*T*	*Soybean*	*T*	*Starch*	*T*	*Protein*	*T*
Intercept	17.83	6.63	-1.36	-2.22	-105.88	-5.78	37.40	589.43
G*	-0.01	-6.65	-0.00132	-9.84	-1.91E-04	-1.55	1.89E-04	6.11
G^2	7.96E-07	6.85	1.28E-07	8.36	1.03E-08	0.74	-2.24E-08	-6.07
d_1**	16.77	11.42	6.92	18.38	-0.85	-0.03	-1.44E-03	-0.12
d_2	-31.96	-15.32	-4.31	-15.04	0.29	0.01	2.90E-04	0.05
d_3	-1.57	-0.65	-0.10	-0.33	0.23	0.01	3.58E-04	0.06
d_4	14.06	4.05	0.61	1.33	0.57	0.01	1.73E-03	0.13
d_5	2.70	0.50	-3.12	-4.34	-0.23	-0.01	-9.41E-04	-0.13
G x d_1	0.01	-3.52	2.25E-03	2.72	1.38E-04	0.37	5.31E-07	5.05
G x d_2	0.02	19.34	0.00253	19.23	3.93E-05	0.28	-9.29E-08	-1.03
G x d_3	5.17E-05	0.05	-2.99E-04	-2.01	1.86E-05	0.12	-2.03E-07	-2.29
G x d_4	-0.02	-9.78	-3.03E-03	-12.79	-1.12E-04	-0.40	-6.70E-07	-4.78
G x d_5	-0.01	-6.09	-1.45E-03	-7.15	-8.40E-05	-0.38	4.35E-07	3.05
G^2 x d_1	-1.4E-06	0.47	-4.1E-07	-8.53	8.73E-10	0.39	-7.03E-11	-4.21
G^2 x d_2	-2E-06	-17.88	-2.8E-07	-18	-8.42E-09	-0.54	-5.20E-12	-0.54
G^2 x d_3	-1.1E-07	-0.86	5.31E-08	3.04	-6.09E-09	-0.36	7.58E-12	0.73
G^2 x d_4	2.05E-06	9.91	4.14E-07	14.41	4.47E-09	0.15	7.72E-11	4.66
G^2 x d_5	1.45E-06	8.36	2.21E-07	9.08	9.16E-09	0.37	-9.27E-12	-0.64
Γ x d_1	0.88	25.62	0.95	54.47	2.45	3.23	2.10E-03	5.02
Γ x d_2	0.99	41.56	1.09	70.17	2.44	12.86	2.07E-03	23.23
Γ x d_3	0.98	42.47	1.08	74.39	2.45	9.71	2.09E-03	16.23
Γ x d_4	0.96	31.13	1.09	63.58	2.45	3.08	2.07E-03	5.07
Γ x d_5	0.94	24.8	1.14	61.03	2.46	5.18	2.08E-03	10.37
λ*	0.04		0.06		0.14		0.40	

*Standard errors are not estimated for AR coefficients when estimated with GM (Kelejian and Prucha).

Table 3. Iterated SARE-GM estimates for the soil fertility and quality functions

Variable	*Corn*	*T*	*Soybean*	*T*	*Starch*	*T*	*Protein*	*T*
Intercept	-487.03	-3.85	-178.12	-19.81	73.98	447.51	37.48	591.26
G	0.02	13.04	-1.11E-03	-8.12	-1.82E-04	-5.63	1.89E-04	6.06
P	36.00	11.45	8.82	36.11	0.02	0.72	-1.27E-04	-1.89
Om	-87.34	-3.10	20.43	10.02				
Zn	-115.48	-3.15	-28.59	-10.57				
K	1.96	4.99	1.28	42.39				
pH	185.70	3.43	28.08	7.18				
G^2	-2.55E-06	-94.71	-2.82E-07	-131.72	6.07E-09	1.89	-2.24E-08	-6.06
G x P	-3.87E-04	-14.19	-8.90E-05	-41.69	4.53E-07	0.29	4.61E-08	6.09
G x OM	-8.28E-04	-4.11	3.84E-04	25.11				
G x Zn	-9.43E-04	-3.09	-2.41E-04	-10.66				
G x K	7.19E-07	0.17	2.27E-05	70.15				
G x pH	2.68E-03	7.42	5.78E-05	2.15				
P^2	-0.08	-3.33	-0.04	-20.17	-8.82E-04	-1.26	-3.19E-07	-0.16
OM x P	-4.89	-10.68	-0.76	-22.14				
Zn x P	6.61	11.38	0.63	14.18				
P x K	0.03	4.88	0.01	37.02				
pH x P	-4.61	-8.87	-1.33	-33.64				
OM^2	6.10	4.45	0.26	2.75				
Zn x OM	25.43	4.11	5.96	13.73				
OM x K	0.51	10.20	0.14	36.29				
OM x pH	-3.77	-0.77	-8.73	-25.40				
Zn^2	-33.89	-7.16	-3.89	-11.41				
Zn x K	-1.40	-15.01	-0.54	-78.86				
Zn x pH	49.76	7.18	18.06	34.96				
K^2	1.93E-03	3.22	1.04E-03	24.64				
pH x K	-0.51	-7.51	-0.30	-59.63				
pH^2	-11.66	-1.98	3.34	7.81				
λ*	0.19		0.77		0.02		0.39	

*Standard errors are not estimated for AR coefficients when estimated with GM (Kelejian and Prucha).

Table 4. Baseline (no premium) results (SARE-GM)

	Corn*	Soybean*	NPV^^	EOMR&	App. P@	App. K@
Mgmt. Zone			VRM			
1	178	51	559	4360		
2	201	52	601	5267		
3	190	53	583	5248		
4	203	58	614	8000		
5	199	52	575	8000		
Weighted avg.-->	197	53	593	5595		
Mgmt. Zone			WFM			
1	171	51	559	3500		
2	183	51	579	3500		
3	180	52	578	3500		
4	174	51	563	3500		
5	177	48	554	3500		
Weighted avg.-->	181	51	575	3500		
Mgmt. Zone			WFM/VRF			
1	172	53	560	3500	11	0
2	187	53	583	3500	12	4
3	208	55	634	3500	27	0
4	178	51	561	3500	9	0
5	177	48	545	3500	0	0
Weighted avg.-->	192	53	594	3500	16	2
Mgmt. Zone			WFM/WFF			
1	160	50	517	3500	45	
2	182	51	562	3500	45	
3	204	56	628	3500	45	
4	178	51	556	3500	45	
5	178	48	543	3500	45	
Weighted avg.-->	187	52	580	3500	45	
			VRM/WFF			
Mgmt. Zone	159	50	515	3214	45	
	188	51	564	4359	45	
	205	56	624	3756	45	
	194	55	574	7219	45	
	202	54	574	8000	45	
Weighted avg.-->	194	53	583	4576	45	
			VRM/VRF			
1	176	53	559	3952	9	0
2	201	53	599	5012	7	0
3	205	55	630	2656	30	0
4	203	58	608	8000	0	0
5	199	52	569	8000	0	0
Weighted avg.-->	201	54	605	4629	13	0
			WFM*/VRF			
1	180	52	559	4852	7	0
2	198	54	604	4852	7	0
3	211	56	626	4852	22	0
4	181	51	566	4852	4	0
5	183	49	555	4852	0	0
Weighted avg.-->	199	54	603	4852	11	0

^^In dollars.
*Bu./ac.
&Economically optimal manure rate (3500 gal/ac at WFM)
@lbs/acre P applied.

Table 5. Premium included for High Starch Corn and High Protein Soybean (SARE-GM)

	Corn*	Soybean*	NPV	Starch+	Protein++	Starch Premium&&	Protein Premium&&	EOMR&	App. P@	App. K@
Mgmt. Zone						----VRM----				
1	176	51	579	73.38%	37.88%	0.1057	0.0776	4055		
2	201	52	625	73.80%	37.85%	0.1082	0.0771	5268		
3	190	53	606	73.49%	37.85%	0.1063	0.0771	5259		
4	203	58	637	73.14%	37.56%	0.1043	0.0712	8000		
5	199	52	596	72.41%	37.56%	0.1000	0.0712	8000		
Weighted avg.-->	197	53	616	73.54%	37.82%	0.1066	0.0763	5589		
Mgmt. Zone						----WFM----				
1	171	51	580	73.29%	37.89%	0.1052	0.0778	3500		
2	183	51	600	73.52%	37.87%	0.1066	0.0775	3500		
3	180	52	599	73.50%	38.18%	0.1064	0.0836	3500		
4	174	51	583	73.40%	37.94%	0.1059	0.0788	3500		
5	177	48	574	73.30%	37.92%	0.1053	0.0784	3500		
Weighted avg.-->	181	51	596	73.48%	37.98%	0.1063	0.0796	3500		
Mgmt. Zone						----WFM/VFF----				
1	172	53	581	73.54%	37.87%	0.1067	0.0774	3500	11	0
2	187	53	605	74.22%	37.87%	0.1106	0.0773	3500	12	4
3	208	55	659	74.27%	37.87%	0.1109	0.0773	3500	27	0
4	178	51	583	74.26%	37.87%	0.1109	0.0773	3500	9	0
5	177	48	566	74.14%	37.87%	0.1102	0.0774	3500	0	0
Weighted avg.-->	192	53	617	74.21%	37.87%	0.1106	0.0773	3500	16	2
Mgmt. Zone						----WFM/WFF----				
1	160	50	537	73.54%	37.87%	0.1067	0.0774	3500	45	
2	182	51	585	74.22%	37.87%	0.1106	0.0773	3500	45	
3	204	56	652	74.11%	37.87%	0.1100	0.0773	3500	45	
4	178	51	578	73.93%	37.87%	0.1089	0.0773	3500	45	
5	178	48	564	73.59%	37.87%	0.1070	0.0774	3500	45	
Weighted avg.-->	187	52	602	74.09%	37.87%	0.1099	0.0773	3500	45	
Mgmt. Zone						----VRM/WFF----				
	159	50	533	72.99%	37.86%	0.1034	0.0772	3250	45	
	188	51	585	73.55%	37.88%	0.1067	0.0776	4371	45	
	205	56	648	73.52%	37.87%	0.1066	0.0775	3793	45	
	173	53	603	73.22%	37.48%	0.1048	0.0696	0	45	
	202	54	595	71.79%	37.56%	0.0964	0.0712	8000	45	
Weighted avg.-->	193	53	605	73.36%	37.83%	0.1056	0.0766	4234	45	
Mgmt. Zone						----VRM/VRF----				
1	177	53	580	73.01%	37.88%	0.1036	0.0776	4115	9	0
2	201	53	622	73.45%	37.86%	0.1061	0.0772	5086	6	0
3	207	55	655	73.79%	37.85%	0.1081	0.0770	3059	29	0
4	182	52	581	72.92%	37.87%	0.1030	0.0775	4691	5	0
5	195	51	586	72.51%	37.69%	0.1006	0.0738	7136	0	0
Weighted avg.-->	201	54	626	73.44%	37.84%	0.1061	0.0769	4563	13	0
Mgmt. Zone						----WFM*/VRF----				
1	180	52	580	73.60%	37.87%	0.1070	0.0774	4866	6	0
2	200	53	628	74.03%	37.87%	0.1095	0.0774	4866	7	0
3	209	55	651	73.93%	37.87%	0.1089	0.0774	4866	23	0
4	183	52	588	73.74%	37.87%	0.1079	0.0774	4866	4	0
5	184	49	577	73.41%	37.87%	0.1059	0.0774	4866	0	0
Weighted avg.-->	200	53	627	73.92%	37.87%	0.1089	0.0774	4866	11	0

^^In dollars.
*Bu./ac.
&Economically optimal manure rate (3500 gal/ac at WFM), && Sum of Corn and Starch Premiums
+% starch for corn (WF avg. Soybean protein content = 37.69%)
++ % protein for soybean (WF avg. Corn starch content = 73.46%)
@lbs/acre applied.

Table 6. NPV ($ acre^{-1}) comparison of VRM, VRF, and WFM management strategies (SARE-GM)

Strategy	NPV	WFM	WFM-WFF	WFM-VRF	VRM-WFF	VRM-VRF	WFM*-VRF	Rank
Without Premium								
VRM	592.66	17.45	13.04	-1.09	9.83	-12.72	-10.77	4
WFM	575.21		-4.41	-18.53	-7.62	-30.16	-28.21	7
WFM-WFF	579.62			-14.12	-3.21	-25.75	-23.80	6
WFM-VRF	593.75				10.91	-11.63	-9.68	3
VRM-WFF	582.83					-22.55	-20.60	5
VRM-VRF	605.38						1.95	1
WFM*-VRF	603.43							2
With Premium								
Strategy	NPV	WFM	WFM-WFF	WFM-VRF	VRM-WFF	VRM-VRF	WFM*-VRF	Rank
VRM	615.65	19.48	13.36	-1.37	10.58	-10.50	-11.60	6
WFM	596.18		-6.12	-20.84	-8.90	-29.98	-31.08	7
WFM-WFF	602.30			-14.72	-2.78	-23.86	-24.96	5
WFM-VRF	617.02				11.94	-9.13	-10.24	3
VRM-WFF	605.08					-21.08	-22.18	4
VRM-VRF	626.15						-1.10	2
WFM*-VRF	627.26							1

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