Improving Nitrogen Management Using Site-Specific Technology in the Virginia Coastal Plain

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Abstract

On a Virginia crop farm, alternative levels of information are evaluated for managing nitrogen applications based on soil properties and yield potential. Application of variable rates of nitrogen based on crop yield potential can increase profitability and reduce nitrogen pollution potential.

Keywords:

precision farming, pollution, cost, information, soil maps

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Introduction

Nitrogen (N) in crop production is not only the primary factor to manage in terms of importance to yields, but also one of the most important pollutants to the environment. Over 90% of the corn, cotton, potatoes, and rice acres and over 60% of the wheat acres in the United States receive commercial N fertilizers (Kellogg et al.). N loss from fertilizers forms a large share of soil nitrate-nitrogen (NO3-) contamination of groundwater, especially under irrigated cropping systems (Madison and Brunett). Up to 30% to 50% of applied N may not be taken up by the crop and much of it is lost to the environment (Keeney; Goolsby and Battaglin). Wasted N reduces farmers' income, while N pollution to water bodies accelerates eutrophication of lakes and estuaries (USEPA), threatens human health (Cantor), and degrades ecosystems (National Research Council (NRC), 1978). Two logical approaches to reducing N pollution from a farm are reducing application rates and altering application methods to increase uptake efficiency (Legg).

Current approach of treating the field as a homogeneous whole and applying a uniform rate of N may prevent the realization of application according to plant needs. Crop fields are often rather heterogeneous in terms of soil properties, slope, fertility, yield potential, pollution potential, pest distribution, and crop quality. These heterogeneities are actually the characteristics that make crop production distinctive from other industrial sectors (Wolf and Wood). As a result, in conventional uniform application, N is over-applied in some places but under-applied in other places, resulting in lost yields and potential N pollution (Carr et al.; Mostaghimi et al. 1997, 1998; Wolf and Wood; Nowak, 1998). Excessive N input may even reduce yield directly (Blackmer and White).

Incorporating soil variability into N management requires that information be generated about the within-field variability of yield and pollution potential. Variable rate application technology must also be used to respond fully to the information generated. Current advancement in site-specific management (precision agriculture) technology can be utilized to increase application efficiency.

Site-specific management (SSM), is a farm "strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production" (NRC, 1997, p.2). The objective of SSM is to monitor and respond to in-field variations on as fine a scale as allowed by available and economical means (Whelan and McBratney). The adoption of SSM can increase efficiency of conventional inputs like fertilizers (Nowak, 1997). Although profitability and environmental performance of current precision technology are not clear-cut (Lowenberg-DeBoer and Swinton, Lowenberg-DeBoer and Boehlje), some SSM practices may become standard in the United States (Lowenberg-DeBoer).

The current version of SSM can employ a global positioning systems (GPS), a geographic information systems (GIS), yield monitors, aerial photography and grid sampling for generating soil attribute maps, micro-meteorological condition maps, and crop yield maps. Variable rate applicators can be used to vary chemical and nutrient application rates across the field according to crop conditions (Lu et al.; Whelan and McBratney).

SSM, through targeting applications to plant requirements, does not necessarily reduce input use (Mostaghimi et al. 1997, 1998; Gupta, Mostaghimi, and McClellan; Wallace; Wolf and Wood; Harris). But SSM potentially can reduce N pollution, even though the magnitude of the reduction in N pollution remains site-specific (Larson et al.). Lowenberg-DeBoer and Boehlje note that environmental considerations need to be incorporated explicitly into the monitoring and decision making process, otherwise SSM can even increase pollution. The need of the crop should be balanced by the need to reduce damage to the environment (Nowak, 1998; Leiva, Morris, and Blackmore).

Current nutrient application recommendations (e.g. Simpson et al.) are generally based on soil types. When only soil types are used to base N application decisions, the best SSM that can be achieved is utilizing variable rate application for different soil zones within each field. Yield maps can provide additional information for N management (Hollands; Stein, Brouwer, and Bouma; Wollenhaupt, Mulla, and Crawford; Redulla et al.). Yield maps are developed by recording crop yield at a very fine spatial resolution throughout the field. Yield maps can be used to divide the field into functional zones with distinctive yield potentials and corresponding N application rates. Currently, yield maps are very likely the first thing farmers will utilize in managing input use with available SSM technologies (Alley; Lu et al.; Hergert et al.). The development of yield maps and provision of variable rate application can be done by fertilizer dealers (Alley).

Farmers have a number of site-specific alternatives for managing N applications including the use of soil zones and functional zones with variable and uniform N application rates. Alternatives which use more information, such as the functional zones, variable application strategy, may result in greater savings on N costs and greater reductions in N pollution but also have higher costs. More information is needed about the economic and environmental tradeoffs of alternative site-specific N management strategies.

The objective of this study is to develop and evaluate several site-specific N application strategies for the Virginia Coastal Plains in terms of their economic returns to farmers and N pollution potential. The N application strategies are based on varying levels of information about field soil characteristics and yield potential. Variable rate N applications are compared with uniform N applications. Specifically, five strategies are evaluated, namely, 1) the conventional strategy that applies N uniformly over the field according to agronomic recommendation for the predominant soil type of the field; 2) the soil zone-uniform strategy that applies a uniform rate of N over the field based on the distribution of soil types within the field; 3) the soil zone-variable strategy that applies a variable rate to each soil zone in the field; 4) the functional zone-uniform strategy that utilizes the observed yield potential pattern (functional zones) in the field and applies a uniform N rate over the field, and 5) the functional zone-variable strategy that applies a different N rate to each functional zone in the field.

Conceptual framework

The farmer's objectives

Suppose a field can be divided into *I* soil zones with area of A_i for each zone *i* and *J* functional zones with area of A_j for each zone *j* and $I \leq J$. A linear response and plateau (LRP) function, which is widely used by agronomists (Cox; Babcock; Babcock and Blackmer; Mallarino and Blackmer) is used as the form of production function for each zone.

$$y_t = \min\{\alpha + \beta x, y_p\} | SSI$$

where *t* is zone number, y_p is the plateau yield value, *x* is the N input, α and β are positive constants, and |*SSI* means "at given site-specific information level". It is assumed that only the functional information levels (based on actual observation of yields recorded by a yield monitor) give correct parameters for yield production function for a functional zone. Other levels of information are not based on observed yields but instead are based on soil distribution or the major soil type within the field.

Assuming profit-maximizing behavior, the farmer will adopt the strategy that gives him the highest net return for the field. The maximum net return for each strategy must be estimated. Then the strategy with the highest net return can be selected. For a given strategy, when the application is uniform, the farmer's decision is to choose an N rate that maximizes the field-level net return, i.e.,

$$\underset{X}{Max} \sum_{t=1}^{T} \{P \cdot y_t\} - C_0 - C_S - C_{SS}$$

where T is the total number of the zones, P is crop price, C_0 is total cost not related to the N application strategy or site specific productivity (e.g. seed cost), C_S is total cost related only to the N application strategy adopted (e.g. N application cost), and C_{SS} is the total cost related only to the site-specific productivity for a given strategy (e.g. the crop hauling cost which is determined by the total yield achieved on the field). For a given strategy, when the application is variable, then the farmer's decision is to choose an N rate that maximizes the net returns for each zone (soil or functional zone), i.e.,

$$\underset{X_t}{Max} \; P \cdot y_t - C_{0t} - C_{St} - C_{SSt}$$

and the total net return for the field is the sum of the above expression over all zones.

Using the naive strategy as the baseline, information value, which is the additional net return from a uniform application strategy which uses site-specific information, is calculated as $\pi_{IU} - \pi_C$ where π_{IU} is the field level net return for uniform application strategy at given information level (e.g. soil zone information), and π_C is field-level net return for the conventional strategy (Schnitkey, Hopkins, and Tweeten). The value of variable rate application is calculated as $\pi_{IV} - \pi_{IU}$ where π_{IV} is the field level net return for variable application strategy for given information level (e.g. soil zone information) (Schnitkey, Hopkins, and Tweeten). In estimating information value and value of variable rate application, C_0 and C_{0t} are cancelled out.

The evaluation of excess N

The "unrecovered N" (excess N) which equals zero or the difference between the amount of N applied and the amount of N in crop yield removed from field, whichever is greater (Kitchen et al.) is a good index of N pollution potential because the unrecovered N may eventually pollute the environment (Meisinger; Stevenson; Larson et al.). Considering the field heterogeneity, it is noted that a negative excess N in one functional zone does not cancel out the positive excess N in another functional zone from the perspective of water quality protection. Assuming a fixed N content in yield for each crop, the excess N is

$$EN_t = \max\{x_t - \rho f_t(x_t, W, M, R), 0\}$$

where EN_t is the excess N applied for functional zone t for the crop, x_t is applied N, W is other soil properties such as phosphorus and potassium levels, M is other management practices such as pest management, R is rainfall, and ρ is the proportion percentage of N content in yield. Total excess N from a field is the sum of the above expression over all functional zones.

Empirical Model

The study fields on the case farm

A case farm is selected in the Virginia Coastal Plains which produces corn and wheat double-cropped with soybean. Yield monitors were used in 1995 and 1996 to record corn and wheat yields. The N application method was uniform. Because the farm was well managed with fields generally well fertilized, the observed yield variability was not expected to be caused by insufficient N. Four fields on this farm are selected since they have yield data sets for a complete rotation. The acreage by soil type for each field is listed in Table 1.

Information levels and strategies for N application

Conventional strategy (baseline case of this study) applies N uniformly according to the predominant soil type in the field based on VALUES (Virginia Agronomic Land Use Evaluation System, Simpson et al.) recommendation. For example, for field E3&4, the farmer will apply 113 pounds per acre to wheat since the predominant soil type is 22A and 22B (identical for the purpose of this study because their yield potentials are equal).

Soil zone-uniform strategy and soil zone-variable strategy apply N according to soil type distribution in the field. When the uniform application method is used, the N rate is determined by the weighted average of the recommended rates for each soil zone (as suggested by Simpson et al.). Further research is underway to determine the rate that equates field level marginal cost of N application and marginal value from increased yield from N application. When variable application is used, an optimal N rate which is equal to that needed to achieve yield potential is applied to each soil zone.

Functional zone-uniform strategy and functional zone-variable strategy are similar to soil zone strategies. The difference is that functional zones are developed from observed yield patterns directly. The functional zone represents the highest level of information in this study.

Yield potentials, N application rate, and excess N

The Virginia Agronomic Land Use Evaluation System (VALUES) (Simpson et al.) is used to direct the recommended N application rates for the case farm. VALUES gives realistic yield potential for each soil type based on soil productivity and management requirements. For example, wheat yield potentials are 64 bushels for standard wheat and 90 bushels for intensive management wheat for Pamunkey soil (VALUES). Since the observed wheat yield on the case farm is well above that of standard wheat (the farm-level average is around 86 bushels), in this study, wheat potential yields are those of intensive wheat in VALUES.

VALUES assumes that all soil in corn production, the N requirement for corn is one pound per bushel. Corn follows soybeans in the rotation and the credit for N carryover from soybeans is 20 pounds. Since wheat N removal is higher, 1.25 pounds per bushel, it is assumed that 1.25 pounds N application is needed for each bushel of wheat harvested. Table 2 reports the yield potential and N application rates based on VALUES and expert opinions. Soil type 22A and 22B differ only by slope and have identical yield rating.

Because corn grain at a moisture level of 15.5% contains 0.9 of a pound of N per bushel (Virginia Coorperative Extension Service (VCES), 1984) and the seeding rate is 1.3 bushels (73 pounds)(VCES, 1995), the excess N from corn production is calculated as the sum of N carryover plus N applied plus N contained in seeds minus crop removal:

$$Max\left[(20+N+1.3*.9-yield*.9),0\right]$$

where *N* is N applied to the field, 1.3 are the bushels of seed, and 20 is N carryover from the soybean crop. When applied correctly, the only excess N from wheat is assumed to come from seed. Thus, at a seeding rate of 135 pounds (2.2 bushels), the excess N is

$$Max\,[N+2.2*1.25-yield*1.25,0]$$

In both corn and wheat production, it is assumed that all overapplied N becomes part of excess N. Similarly, when N is under-applied, a yield penalty results for both corn and wheat. For corn, the yield penalty is 1 bushel per pound N underapplied. For wheat, the yield penalty is 0.8 of a bushel per pound N underapplied since each bushel of wheat contains 1.25 pounds N (VCES, 2000).

Crop prices and production costs

Crop prices are estimated from Food and Agricultural Policy Research Institute (FAPRI) forecasts for 2000 to 2007, deflated by the GDP deflators projected by FAPRI. After forecast prices for each future year are deflated, expected national prices are obtained by averaging the deflated prices for each of the years. Then based on the historical price differences between Virginia and national level (USDA) the expected national prices are further adjusted to Virginia level. The crop prices thus calculated are $2.10 per bushel for corn and $2.87 per bushel for wheat.

The costs related to the N application strategy (C_s) are costs related to N application (base and/or additional cost from variable rate application), information generation, and related interest cost (Table 3). The cost related to site-specific productivity (C_{ss}) is the cost of N applied and crop hauling cost[1]. The price of N fertilizer is $0.25 per pound and hauling cost is $0.15 per bushel (Virginia Cooperative Extension Farm Management Staff, 1999).

The information cost of $3.50 per acre in the above table is for yield map generation and record keeping (Lowenberg-DeBoer, Hawkins, and Nielsen; Alley). Additional cost for variable rate application is $1.00 for soil zone variable application and $3.00 for functional zone variable application. The cost for variable rate application is higher for the functional zone strategy because the layout of functional zones within a field is much more complicated than that of the soil zone pattern and would require a fully functioning variable rate applicator, whereas it is possible to carry out soil zone variable application with simpler equipment (Thrikawala et al.).

[1] It is assumed that P, K, and lime are applied uniformly all over the case farm. One reason for this assumption is that P, K, and pH variability on the farm generally is not large enough to justify variations in P, K, and lime applications.

The functional zones.

Clustering analysis (Everitt) is used to generate functional zones which are groups of grids in the field having similar yield levels while yield levels between two clusters are rather different. The fundamental clustering criterion is from the matrix equation (Everitt):

$$\mathbf{T} = \mathbf{W} + \mathbf{B}$$

where **T** is the total dispersion matrix, **W** is the matrix of within-groups dispersion, and **B** is the between-groups dispersion matrix. Because **T** is fixed for a given data set, clustering criteria should be functions of **B** and **W**. When only one variable is involved in grouping (as in the case for the farmer who only uses yield data to do the grouping), then it is straightforward to minimize **W** or maximize **B**. In this study, only one variable (observed yield) is involved in grouping. The number of groups needed can be chosen as the range of yields (in bushels) divided by 10 because ten bushels are usually the minimum difference of yield that is required to generate a different fertilizer recommendation.

With grouping number, *K*, decided, then for each group a "centroid" of the group is chosen (a centroid in one-dimensional data is the mean). An observation is a member of the group with the nearest centroid. The methods to classify observations (objects) are called nearest centroid sorting methods (Massart and Kaufman). One straightforward method is by minimizing the sum of the squares (when the distance is Euclidean) of the distances to the centroid:

$$E = \sum_{k=1}^{K} \sum_{i \in C_k} | \mathbf{x}_{i.} - \bar{x}_k |^2$$

where $\bar{x}_k$ is the pattern of the centroid of cluster C_k with m_k members, i.e.,

$$\bar{x}_k = \frac{1}{m_k} \sum_{i \in C_k} \mathbf{x}_{i.} \text{ and } m = \sum m_k$$

The procedure to carry out the actual cluster analysis described can be found in Massart and Kaufman, p. 105-107.

To develop functional zones within a field, first, the field is divided into 30x30 square meters grids which represent the smallest practical management unit for the farmer. Yield maps are developed for the whole field at the scale of these grids from data recorded by a yield monitor with GPS system installed. The yield of each grid equals the average of yield monitor observations within the grid. Then the SAS PROC FASTCLUS is used to carry out the functional clustering analysis which classifies these 30x30 grids into several distinct groups (i.e. the functional zones). Then for each functional zone, a distinct N application rate is generated based on the value of the centroid of the group. The N application rate generated by functional zone information for each 30x30 square meters grid is regarded as the most accurate for the grid site-specific situation. For the purpose of this study, the numbers of functional zones for wheat and corn are eight and fifteen, respectively.

Results and Discussion

Observed within-field variability

The observed within-field variability of yields for each field is reported in Table 4 based on the results of clustering analysis. There are several points worth noting: First, within field variability of yield is obviously much larger than indicated by soil type distribution. For example, for field E3&4, only 0.4% of the area is of soil type Argent silt loam which has low yield potentials (30 bushels for wheat and 65 bushels for corn). However, the actual area with low yield levels (around and below 30 and 65 bushels for wheat and corn) is more than 9% and 13%, respectively, for wheat and corn.

Second, observed corn yield levels are much higher than yield potentials suggested by VALUES for some parts of the fields. For example, if N is applied at yield potential of 160 bushels for Pamunkey soil, then for field E3&4, more than 10% of the field is heavily overapplied while more than 40% of the field is underapplied. Uniform N applications according to soil yield potential for corn are inadequate for maximizing profit, as later discussion makes clear. However, wheat yields are much closer to the suggested yield potentials as compared to the situation of corn, indicating that wheat yield is less restrained by factors other than soil properties (Simpson et al.).

Third, the seemingly most homogeneous field in terms of soil type distribution (see Tables 1 and 2), i.e. E3&4, has the lowest weighted C.V. for wheat but the highest C.V. for corn. As for wheat, the more homogeneous the field is in term of yield potential related to soil type, the smaller the weighted C.V. indicating that soil type can be used to explain partially wheat yield variability within a field. For corn, homogeneity in terms of soil type does not indicate the extent of yield variability.

Fourth, as Table 5 indicates, the rotational order for fields E3&4 and F1B is wheat in 1995 and corn in 1996, while that for fields F10 and F8B is corn in 1995 and wheat in 1996. As the weighted C.V.s indicate, weather condition is very likely related with observed within-field yield variability. For example, the weighted C.V.s for wheat in 1995 (fields E3&4 and 1B) are clearly lower than those in 1996 (fields F10 and F8B), as are the C.V.s for corn.

N applied, yield penalty and excess N for each strategy

Table 5 reports the field-level N application rate, total N application, yield penalty, and excess N for each strategy on each field. For wheat, the N application rates (thus total N applied) for the conventional strategy are always the highest, soil zone strategies in the middle, and N rates for functional zone strategies are the lowest. For corn, in two cases (fields E3&4 and F8B), N applied for functional zone strategies (the best information level) is the highest, indicating SSM does increase N input in some cases.

As expected, soil zone strategies reduce field-level N input as compared to conventional strategy, but in all cases soil zone strategies incur larger or equal yield penalty as compared with the conventional strategies. The increased yield penalty for corn is much larger than that for wheat. For example, for field F1B, the yield penalty for wheat increases 228 bushels to 318 bushels when strategy changes from conventional to soil zone uniform and variable strategies, respectively, while the corresponding increases of yield penalty for corn are 681 bushels and 591 bushels, respectively. This result indicates two points, the first is that soil zone information alone is not adequate to direct SSM practices for N. The second point is that comparatively, soil zone information is more useful for wheat than for corn.

The yield penalty for functional zone-uniform strategy is lower in corn but higher in wheat as compared to soil zone strategies. In all cases except for corn on field F8B, the functional zone-uniform strategy has a larger yield penalty as compared with the conventional strategy. Since functional zone information is assumed to be accurate about yield potential, the functional zone-variable strategy does not incur any yield penalty.

In wheat production, excess N from the conventional strategy is the largest for all fields and in all cases it is larger than excess N from the soil zone strategies. Variable rate application does not necessarily reduce excess N for soil zone strategies, indicating again soil type information alone does not convey enough information about variation in yield potential to guide N applications. At the functional zone information level, uniform application strategy does reduce excess N for wheat in all cases as compared with all other non-functional zone strategies.

For corn, the functional zone-uniform strategy does not have lower excess N in all cases as compared with the conventional strategy and actually increases excess N as compared with soil zone strategies. In all cases, the functional zone-variable strategy has the lowest excess N, which is not surprising since it is assumed that functional zone information is most accurate about N needs for each grid within the field. Maximum reductions of excess N in a field are obtained with accurate information about N needs for each unit of the field and the ability to carry out variable rate application.

Values of information and variable rate application, and excess N reduction

The values of information and variable rate applications and the excess N reductions from all strategies are reported in Table 6. Excess N reduction is positive but information values in most of the cases (five out of eight) are negative, indicating that basing uniform applications on within-field variability alone may not improve the farmer's net return but can reduce excess N. In wheat, information values are lower for functional zone strategies than for soil zone strategies while in corn, it is the opposite, indicating that corn is more suitable for generating better site-specific information. The only case where information value is positive for soil zone strategies involves field F8B for wheat, which is the most variable field in terms of soil type (Table 1). In all cases except soil zone uniform strategy on field F8B wheat, soil zone strategies are less profitable than the conventional strategy. In corn, the values of information for functional zone strategies are higher than for soil zone strategies. In wheat, functional zone-variable outperforms soil zone variable but soil zone uniform outperforms the functional zone uniform strategy.

Variable rate application values for the soil zone strategies are all negative, indicating the fact that soil zone information alone is not adequate to direct variable rate application. But variable rate application values are all positive for functional zone-variable rate applications, indicating variable rate application is profitable to use once the true yield variability patterns are revealed. Fields with higher C.V.'s (for each crop) generally have higher per acre values for variable rate application (the only exception is F8B for corn which has slightly higher per acre value for variable rate application than F10 even though these two fields have almost the same C.V.'s).

Functional zone-variable strategy is profitable in all cases. Generally, fields with higher yield C.V.'s have higher net returns per acre from the functional zone-variable strategy. This relationship holds for all wheat fields. For corn, the exception is field F8B which has the second highest net return per acre even though its C.V. is among the smallest.

For wheat, functional zone strategies achieve higher excess N reduction than soil zone strategies. Variable rate application with soil zone information actually decreases excess N reduction in three out of four cases with wheat. The functional zone-uniform strategy outperforms soil zone strategies in reducing excess N.

For corn, the potential to reduce excess N is smaller for the functional zone-uniform strategy than for the soil zone strategies because N is generally under applied in the soil zone strategies for corn (see Table 5). Variable rate application increases the excess N reduction with soil zone information on three of four fields as compared to uniform application. The functional zone variable strategy achieves the largest reductions in excess N.

Above discussion shows that the four case fields display great yield variability and N pollution reduction potential. However, the most crucial factors to justify advanced SSM practices are the ability to identify the within-field yield variability and the ability to carry out variable rate application. Furthermore, variable rate application increases net returns to larger degrees where the within-field yield C.V.'s are higher for the same crop. No subsidies are needed to encourage the adoption of SSM on these four fields.

Conclusion and implications

The management of N is important both to the economic well being of crop producers and to the environmental well being of society. The objective of this study is to develop and evaluate several site-specific nitrogen application strategies for the Virginia Coastal Plains situation in terms of profitability and nitrogen pollution potential. Four fields are selected from a case farm in the Virginia Coastal Plains area which produces corn and wheat (double-cropped with soybean). Five N application strategies, the conventional (baseline), soil zone-uniform, soil zone-variable, functional zone-uniform, and functional zone-variable strategies are developed for the case farm.

The information strategies are able to reduce excess N for all wheat fields and in almost all cases for corn as compared to the baseline. The functional zone-variable strategy is profitable in all cases. Due to the cost of information, other strategies are often not profitable compared with the conventional strategy. The functional zone-variable strategy achieves the largest excess N reduction on all crops and fields.

The study demonstrates that a seemingly homogeneous field in terms of soil types may actually have large within field variability both in yield potential and N pollution potential. It is crucial to identify the true pattern of yield variability within a field in order to employ variable rate application. Soil maps alone are limited in providing information to direct site-specific N management, especially for corn. Variable rate application is important to achieving potential gain in excess N reduction and profitability.

A resource manager may target certain fields with greater spatial variability in yield potential and N pollution potential in order to reduce a region's N pollution potential in a cost effective manner. Further study is needed to identify the site-specific characteristics (in addition to soil map information) that make a field desirable candidate for site-specific N application. These factors could include variations in elevation, drainage, and location relative to field boundaries.

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Table 1. Soil type distribution for each study field on the case farm

Field name	Soil #	Soil code	Soil name	Soil acres	Field total (ac)
F10	148	3	Argent silt loam	7.7	
	151	6	Bolling Silt Loam	4.3	
	171, 172	22A, 22B	Pamunkey Loam	28.8	40.7
F1B	148	3	Argent silt loam	5.6	
	151	6	Bolling Silt Loam	9.0	
	168	19	Muckalee loam[a]	0.2	
	171, 172	22A, 22B	Pamunkey Loam	37.8	52.6
F8B	148	3	Argent silt loam	2.0	
	151	6	Bolling Silt Loam	22.7	
	171, 172	22A, 22B	Pamunkey Loam	24.1	48.8
E3&4	148	3	Argent silt loam	0.5	
	160	12F	Emporia soils	3.4	
	161	13D	Emporia&Slagle soil	3.6	
	171, 172	22A, 22B	Pamunkey Loam	107.0	114.5
Total					256.5

a. Muckalee loam is identical to Aegent silt loam for the purpose of this study because their yield potentials are equal.

Table 2. Total acreage, corn and wheat yield potentials, and N application rate for each soil type on the farm

Soil name	Soil # (VirGIS)	Soil code	Farm total acres (ac)	Wheat[b]		Corn[b]	
				Yield (bu/ac)	N rate (lb/ac)	Yield (bu/ac)	N rate (lb/ac)
Argent silt loam	148	3	13.8	30	38	65	45
Bolling Silt Loam	151	6	36.0	80	100	130	110
Emporia soils	160	12F	3.4	70	88	120	100
Emporia & Slagle soil[a]	161	13D	3.6	75	94	125	105
Pamunkey Loam	171, 172	22A, 22B	188.7	90	113	160	140

a. Average of Emporia and Slagle soil.
b. Yield potentials and N applications are based on VALUES (Simpson et al.).

Table 3. Corn production cost specifically related to N application strategy

Strategy	Fertilizer application ($)[a]	Information cost ($)[b]	Variable rate application ($)[c]	Production interest ($)[d]	Total ($/acre)
Corn					
Conventional	13.00	0	0	0.59	13.59
Soil zone-uniform	13.00	0	0	0.59	13.59
Func. zone-uniform	13.00	3.50	0	0.74	17.24
Soil zone-variable	13.00	0	1.00	0.63	14.63
Func. zone-variable	13.00	3.50	3.00	0.88	20.38
Wheat					
Conventional	19.50	0	0	0.88	20.38
Soil zone-uniform	19.50	0	0	0.88	20.38
Func. zone-uniform	19.50	3.50	0	1.04	24.04
Soil zone-variable	19.50	0	1.00	0.92	21.42
Func. zone-variable	19.50	3.50	3.00	1.17	27.17

a. N is applied twice to corn and three times to wheat with all strategies.
b. Information cost is incurred for yield maps and generating functional zones.
c. This application cost is the cost in addition to the uniform application cost. Soil zone-variable application cost is assumed to be less than that for functional zone-variable because the zones where application rates are varied are fewer and larger and requires less sophisticated application equipment..
d. Calculated as 0.09*(sum of all the costs to the left in the table)/2 where 0.09 is the annual interest rate.

Table 4. Observed within-field yield variability for the study fields

Crop	Field E3&4		Field F1B		Field F10		Field F8B	
	Area (%)[a]	Mean (bu/ac)[b]	Area (%)	Mean (bu/ac)	Area (%)	Mean (bu/ac)	Area (%)	Mean (bu/ac)
		1995 yields		1995 yields		1996 yields		1996 yields
Wheat	9	13	9	12	17	8	15	9
	2	45	7	38	11	29	12	44
	5	61	7	55	13	44	11	57
	6	76	9	71	9	49	17	66
	13	85	23	80	12	56	25	73
	24	94	25	88	17	62	14	80
	29	102	21	99	17	69	5	86
	12	109	0	192	4	77	2	97
Mean		86		74		47		59
Weighted std.		100		96		81		92
Weighted C.V.[c]		117		129		173		154
		1996 yields		1996 yields		1995 yields		1995 yields
Corn	6	22	7	33	7	28	6	31
	7	49	4	56	3	73	2	53
	3	68	4	79	1	92	1	77
	3	95	2	93	4	111	1	111
	1	114	3	108	3	121	0	125
	1	125	2	121	6	129	1	131
	1	134	5	130	6	139	2	141
	1	141	2	138	1	143	5	154
	3	150	6	149	8	148	6	162
	5	162	8	161	17	154	5	172
	9	176	7	171	14	161	5	179
	13	190	11	182	12	170	3	184
	21	205	17	192	10	180	17	195
	19	222	14	203	6	191	27	207
	10	243	9	218	2	198	19	222
Mean		172		157		145		181
Weighted std.		175		143		109		133
Weighted C.V.[c]		101		91		75		74

a. The percentage of the area of the functional zone in the whole fields;
b. The mean yield for a functional zone.
c. C.V. is coefficient of variation which is the standard deviation divided by the mean expressed in percentage. The weight used here is the percentage of the area of the functional zones.

Table 5: Field-level N application rate, total N application, yield penalty, and excess N for each strategy

Field and rotation order	N application strategy	Wheat					Corn				
		N rate (lb/ac)	Total N (lb)	Excess N (lb)	Yield loss (bu)	Yield (bu/ac)	N rate (lb/ac)	Total N (lb)	Excess N (lb)	Yield loss (bu)	Yield (bu/ac)
E3&4	conventional	113	12916	1918	728	80	140	16002	4306	3935	139
1995: wheat	soil zone-uniform	111	12729	1853	825	79	137	15698	4234	4166	137
1996: corn	soil zone-variable	Variable[a]	12729	1794	778	79	Variable[a]	15698	4172	4104	137
	functional zone-uniform	107	12228	1677	1086	77	153	17520	4729	2840	148
	functional zone-variable	Variable[a]	12228	320	0	86	Variable[a]	17520	1889	0	173
F1B	conventional	113	6153	1330	125	73	140	7623	2006	1084	138
1995: wheat	soil zone-uniform	100	5462	924	353	69	122	6626	1690	1765	126
1996: corn	soil zone-variable	Variable[a]	5462	1037	443	67	Variable[a]	6626	1601	1675	127
	functional zone-uniform	94	5132	816	531	65	138	7518	1970	1153	137
	functional zone-variable	Variable[a]	5132	152	0	75	Variable[a]	7518	817	0	158
F10	conventional	113	4602	2342	0	47	140	5702	1392	254	140
1995: corn	soil zone-uniform	98	3973	1712	0	47	119	4847	1054	772	127
1996: wheat	soil zone-variable	Variable[a]	3973	1808	76	45	Variable[a]	4847	1074	792	127
	functional zone-uniform	58	2374	571	366	38	126	5125	1136	575	132
	functional zone-variable	Variable[a]	2374	114	0	47	Variable[a]	5125	561	0	146
F8B	conventional	113	5492	2053	6	59	140	6804	1439	1616	148
1995: corn	soil zone-uniform	104	5045	1623	20	59	122	5930	1307	2359	132
1996: wheat	soil zone-variable	Variable[a]	5045	1629	24	58	Variable[a]	5930	1266	2317	133
	functional zone-uniform	74	3583	724	470	49	161	7822	1699	858	163
	functional zone-variable	Variable[a]	3583	136	0	59	Variable[a]	7822	841	0	181

a. Current study uses weighted average approach in deciding uniform N application rate for soil zone and functional zone strategies. As such, the average N application rate for variable application strategies are the same as the uniform application at given information levels. Research on determining economically optimal uniform N rates for soil and functional strategies is underway.

Table 6. Information values, values of variable rate application, and excess reduction opportunity for each strategy for given fields and crops.

Field		Strategy	Wheat				Corn			
			Valuation ($)			Excess N reduction	Valuation ($)			Excess N reduction
Name	Acreage	name	Information	VRA[a]	Net gain ($)		Information	VRA[a]	Net gain ($)	
E3&4	114.5	Soil zone-uniform	-217	0	-217	65	-376	0	-376	72
		Soil zone-variable	-217	-291	-508	124	-376	-297	-673	134
		Functional zone-uniform	-919	0	-919	241	1636	0	1636	-423
		Functional zone-variable	-919	2294	1375	1598	1636	4880	6516	2417
F1B	52.6	Soil zone-uniform	-447	0	-447	406	-1079	0	-1079	316
		Soil zone-variable	-447	-438	-885	293	-1079	-17	-1096	405
		Functional zone-uniform	-903	0	-903	514	-163	0	-163	36
		Functional zone-variable	-903	1141	238	1178	-163	1946	1783	1189
F10	40.7	Soil zone-uniform	-496	0	-496	630	-795	0	-795	338
		Soil zone-variable	-496	-397	-893	534	-795	-188	-983	318
		Functional zone-uniform	-595	0	-595	1771	-524	0	-524	256
		Functional zone-variable	-595	1235	640	2228	-524	888	364	831
F8B	48.8	Soil zone-uniform	73	0	73	430	-1230	0	-1230	132
		Soil zone-variable	73	-190	-117	424	-1230	-97	-1327	173
		Functional zone-uniform	-836	0	-836	1329	1173	0	1173	-260
		Functional zone-variable	-836	998	162	1917	1173	1392	2565	598

a. VRA stands for variable rate application.