AN ECONOMIC ANALYSIS OF VARIABLE RATE NITROGEN MANAGEMENT ON DRYLAND SPRING WHEAT IN NORTHERN MONTANA

by

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency and is ready for submission to the Division of Graduate Education.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES – CONTINUED

Table Page

LIST OF TABLES – CONTINUED

LIST OF TABLES – CONTINUED

LIST OF FIGURES

ABSTRACT

The objective of this study was to compare hard red spring wheat (*Triticum aestivum* L.) grain yield (agronomic returns) and grain value (economic returns) of variable rate and uniform nitrogen (N) management using a data set obtained from eight on-farm experiments conducted over an eleven year period (1994-2004). Field experiments were established near Simpson, Malta, Havre, and Highwood, Montana using a strip trial design where N rates were varied in replicated strips along the length of each field. A digital elevation model was created for each field site using survey quality global positioning system data. Digital elevation models were segregated into four landscape classes or management zones (Upper Slopes, Middle North Facing Slopes, Middle South Facing Slopes, and Lower Slopes) using global information system software. Geo-referenced grid soil samples were collected at each field site location to determine background soil N levels. Geo-referenced yield and protein samples were collected at all field sites using a production sized combine equipped with yield monitor. The economic analysis consisted of partial budget analysis where only the changes in costs and revenues between variable rate and uniform N management were considered as part of net returns. In addition, spatial least squares (SLS) analysis was used as the basis for establishing whether wheat yields from variable rate N management were significantly greater than those from uniform N management. The SLS analysis failed to detect a significant difference in grain yield between variable rate and uniform N management. Variable N management used more fertilizer N and was less profitable than uniform N management in seven of the eight cases. Revenues from variable N management were insufficient to offset associated costs for needed information, hardware, and software. However, if Environmental Quality Incentive Program payments of $34.57 were considered as part of net income then variable rate N management was more profitable in all cases. Little evidence existed in this study that variable rate N management improves agronomic returns and profits, or reduces N use, especially in water limited conditions found in northern Montana.

INTRODUCTION

The northern Great Plains is climatologically well suited, due to wet springs and cool, dry summers, for growing hard red spring wheat (HRSW). Northern Montana produces high quality HRSW with superior milling and baking characteristics that is consistently sought by millers and bakers (North Dakota Wheat Commission, 2009). The majority of the HRSW produced in this region is either milled for bread flour or blended with lower quality wheat to improve milling and baking characteristics. To secure a stable supply of high quality spring wheat, buyers are willing to pay a premium for grain with protein concentration between 140 g kg^{-1} (14%) and 150 g kg^{-1} (15%). Thus, producers have an economic incentive to optimize protein concentration in their grain (Long et al., 2002).

Adequate soil fertility is required to produce high quality HRSW in Montana and nitrogen (N) is the most important nutrient for optimal grain yield and grain protein concentration (Engel et al., 2001). Since N typically accounts for the largest percentage of a producer’s fertilizer input costs, it makes sense to apply N fertilizer where and when it will do the most good to improve both grain yield and grain protein. Variable rate N management involves the use of a Global Positioning System (GPS) and variable rate technology (VRT) to apply variable rates of N fertilizer in accordance with spatial patterns in soil fertility and crop productivity levels in farm fields (Larson and Robert, 1991). Placing N fertilizer only where it will do the most good avoids lost yield and quality due to under-fertilizing and wasting N fertilizer by over-fertilizing other areas. This practice has been proposed for both improving N use efficiency (Raun and Johnson, 2000), and maintaining or improving economic returns (Wang et al., 2003; Hurley et al., 2004; and Koch et al., 2004).

Crop productivity in semiarid landscapes is determined largely by plant available water (Brown and Carlson, 1990) and occurs in response to the way that soil water, soil fertility, and other crop growth determining factors are distributed in the landscape (Moore et al., 1993). In the northern Great Plains a yield gradient from low to high grain yield is frequently observed coinciding in the down slope direction (Franzen et al., 1998). In Montana, this crop spatial variability is a basis for variable rate N management, which involves dividing farm fields into smaller areas, or management zones, and fertilizing zones individually to improve consistency of grain quality and enhance economic returns (Long et al., 2000). Conversely, uniform N management refers to management of a whole field as one homogenous unit with no consideration for within-field variability.

Only a few studies have compared the profitability of uniform and variable rate N management under dryland wheat production systems (Carr et al., 1991; Wibawa et al., 1993; Fiez et al., 1994; and Long et al., 1995). These studies illustrated the need for more precise information than is available through university fertilizer recommendations, which were developed for general soil conditions within a geographical region or state. Variable rate N management produced more agronomic benefits compared to uniform N management. However, economic returns were questionable, due in large part to the cost of variable rate technology and supporting information, and the lack of knowledge concerning appropriate N recommendations.

No studies have been conducted in the northern Great Plains that investigated the profitability of variable rate N management for longer than three site-years. Therefore, the question still remains whether profit opportunities exist for variable rate N management in dryland wheat production systems. The rationale for this thesis is that crop yield varies spatially within semiarid landscapes in accordance with spatial patterns in soil water content, soil fertility, and other biophysical factors. Thus, variable rate N management that allows for this spatial variability may potentially improve agronomic and economic returns. The objective of this study was to verify this hypothesis by comparing the grain yield and grain value of variable rate and uniform N management using a data set obtained from eight on-farm experiments with dryland HRSW in northern Montana. The results will help determine the economic feasibility of this practice in Montana and other semiarid environments in the northern Great Plains.

LITERATURE REVIEW

Studies of variable rate N management in the US Midwest reported positive economic returns over uniform N management (Schnitkey et al., 1996; English et al., 1999; Thirkawala et al., 1999) whereas others reported no economic benefit (Watkins et al., 1998). A recent literature review conducted by Purdue University researchers reviewed the adoption trends and profitability of precision agriculture (Griffin et al., 2004). Twenty-eight of the 234 articles and publications reviewed dealt with variable rate N management and only half of these found positive economic results when using variable rate technology. Of this portion, only three reports (detailed below) dealt with wheat production systems in semiarid environments (Carr et al., 1991; Wibawa et al., 1993; and Fiez et al. 1994).

In Montana, one of the first studies to investigate crop productivity differences within farm fields was conducted in 1980 (Schweitzer, 1980). Wheat yields differed by 2881 kg ha^{-1} between two contrasting soil series with nearly the same use of plant available water. This work was furthered by an investigation of agronomic (yield and protein observations) and economic returns of contrasting soil units managed uniformly (Carr et al., 1991). Economic returns were calculated by subtracting the actual production costs from the price of the grain. The highest yielding, soil map units generated from \$8 to \$39 more ha^{-1} than the lowest yielding, map units. Variable rate and uniform N management were also compared, but were not significantly different in terms of agronomic and economic returns. Management zones for variable rate N application were based on soil map units of published soil surveys. Net returns were computed by subtracting the fertilizer and application costs from gross returns including protein premiums (discounts). However, greater agronomic returns were only possible when optimum N rates were used. Therefore, profitability hinged on appropriate yield goals and accurate soil test values to make accurate fertilizer recommendations for each management zone.

A third study conducted in northern Montana investigated the profitability of using large-scale aerial photographs taken prior to harvest to detect ripening differences in the crop as a management zone delineation method (Long et al., 1995). Eighteen N treatments ranging from 0 to 121 kg N ha^{-1} were randomly applied in strips down the length of a 45 ha field using production-scale equipment. Post-harvest information on the crop's response to applied N was used to identify the appropriate N rates that maximized productivity in each of five management zones. Net returns were computed by subtracting the cost of the fertilizer, soil testing, and application costs from gross returns. Variable rate N management was found to be more profitable than conventional uniform N management by \$2.50 ha^{-1}. However, the results depended upon the producer's ability to apply correct N rates. The field would have been under-fertilized had university recommendations been utilized.

In the Palouse region of Eastern Washington, (Feiz et al., 1994) investigated the potential of variable rate N applications to optimize soft white winter wheat yield and economic return by conducting a replicated small-plot N fertility trial at footslope, south backslope, shoulder, and north backslope landscape positions. Regression analysis was used to fit polynomial functions to the grain yield-N supply relationships and to predict the optimum economic yield and N supply for each landscape position. Theoretical net returns were computed by subtracting fertilizer costs from gross returns, but costs of technology and variable rate application were not considered. Net returns from variable rate N management were \$6 ha^{-1} greater than uniform N management based on university recommendations utilizing yield goals and soil NO_3-N levels.

A three year study conducted in North Dakota evaluated management zone delineation methods using grid soil sampling, soil map units, and yield goals (Wibawa et al., 1993). The researchers established up to five N management strategies to test combinations of soil grid spacing, yield goal determination, and soil map units to explain in-field soil variability. Net income was computed using a partial budget analysis where only the costs that change were subtracted from gross income to compute net income. In the first two years, uniform N application was found to be more profitable than variable rate N application whereas in the third year variable rate application based on composite soil sampling by soil map unit produced the greatest net return.

Researchers in Colorado recognized the need to find a cost-effective alternative to grid soil sampling for developing variable rate N maps in irrigated corn (Koch et al., 2004). Management zones were delineated using AgriTrac professional software (Flemming et al., 2000) utilizing three layers of information: bare-soil imagery, farmer perception of topography, and farmer crop-soil management experience. Using these layers of information, fields were divided into areas of low, intermediate, and high productivity as needed to implement variable rate N application. The researchers used an enterprise budget analysis, which considers all variable costs- not just the costs that change as in a partial budget analysis, to compare economic returns of uniform and variable rate N management. The research showed less total N was used in all three years of the trial and increased net returns ranging from \$18 to \$30 ha^{-1} when using variable rate N management.

By addressing problem areas in fields related to pest infestations or nutrient deficiencies, precision agriculture should reduce within field variability of grain yield and grain quality. Therefore, variable rate technology, which reduces variability, has been proposed as a tool for reducing economic risk (Swinton and Lowenberg-DeBoer, 1998; Lowenberg-DeBoer, 1999). For example, variable-rate fertilization of phosphorus and potassium was found to reduce the probability of low yields and returns in crop rotations of soybean, corn, and wheat (Lowenberg-DeBoer, 1999). This study, conducted in the eastern US corn-belt, used a theoretical model to show that temporal yield variability could be reduced thereby reducing economic risk. Precision agriculture is seen as a means for managing risk through the use of information, but the information only has value if it changes decisions. Economic analyses should incorporate both agronomic data and the costs of technology to arrive at the profitability of precision agriculture, which is the most important figure to stakeholders, industry, and policy makers (Swinton and Lowenberg-DeBoer, 1998; Lowenberg-DeBoer, 1999).

MATERALS AND METHODS

Study Sites

Eight field experiments were conducted within dryland production fields in northern Montana over an eleven year period (1994-2004) near Simpson, Malta, Havre, and Highwood (Fig. 1 and Table 1). Soils within each field were highly variable because of hummocky topography and glacial till parent material. Thus, differences in fertility and productivity resulting from soil forming processes and long-term cultivation could be expected. Fields near Simpson, Havre, and Malta followed a wheat-fallow production system whereby a field is cropped every other year to conserve soil water. The field near Highwood was annually cropped and alternated between winter wheat and spring wheat.

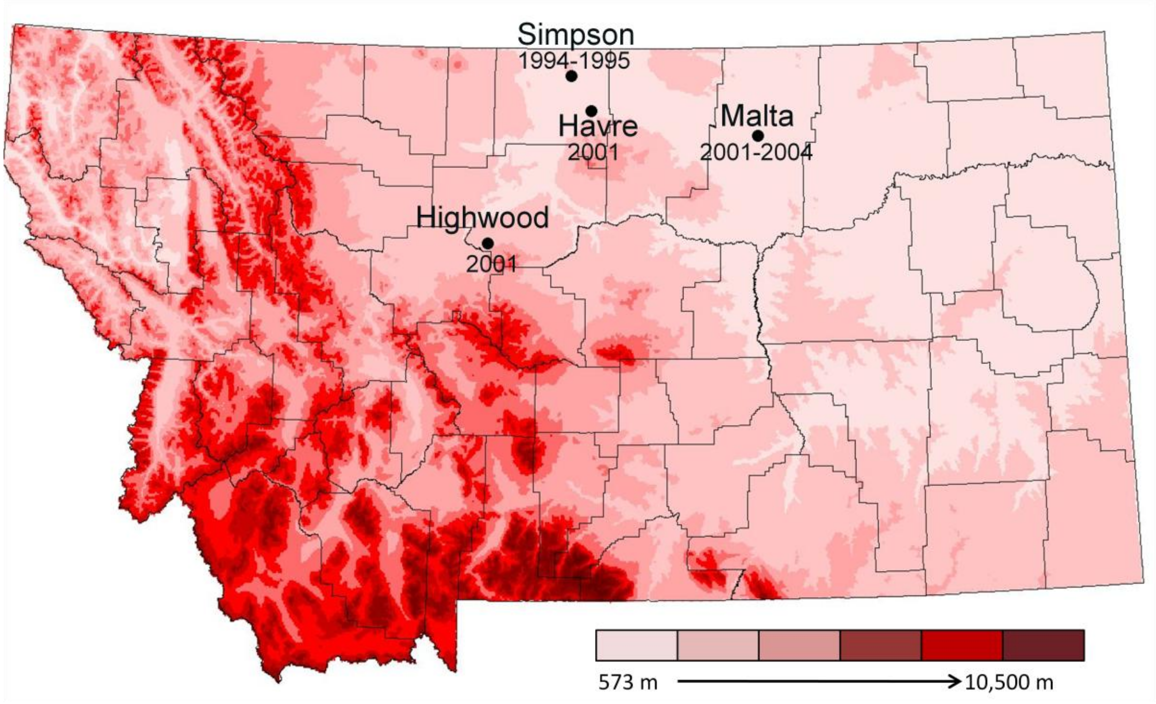


Figure 1. Study site locations and growing season.

The soils at the Simpson and Malta sites predominately consist of Telstad-Joplin loams (fine-loamy, mixed, superactive, frigid Aridic Argiustolls) with 0-4% slopes. These field sites have approximately 20-m of vertical relief with gentle rolling topography. Soils at Highwood comprise Bearpaw-Vida clay loams (fine-loamy, mixed, superactive, frigid Typic Argiustolls) with 0-4% slopes. In addition, the field was characterized by gentle rolling topography with 20-m of vertical relief. Soils at the Havre site largely consisted of Phillips-Elloam complex (Typic Eutroboralfs and Typic Natriboralfs) with 0-4% slopes. The field contained gentle rolling topography with 23-m of vertical relief.

Table 1. Latitude, longitude, vertical relief, area, and growing season (April-July) rainfall for the eight field sites in northern Montana.

Site-Year	Latitude	Longitude	Relief	Area	Rainfall†
			M	ha	cm
Simpson 1994	48.8342°	-109.9114°	22	40	15
Simpson 1995	48.8319°	-109.0811°	18	23	15
Highwood 2001	47.6950°	-110.4991°	20	34	19
Havre 2001	48.5300°	-109.9492°	23	27	17
Malta 2001	48.4144°	-107.5722°	17	22	19
Malta 2002	48.4314°	-107.5853°	13	30	19
Malta 2003	48.4344°	-107.5939°	12	15	19
Malta 2004	48.4325°	-107.5806°	17	26	19

†Long-term rainfall amount.

Grid Soil Sampling

Prior to planting, soil samples for inorganic soil N analysis were collected on the nodes of a systematic grid using a hydraulic Giddings soil core sampler (5 cm dia.) mounted in the bed of a 1-ton pickup truck. Samples were geo-referenced using a Global Positioning System (GPS) receiver (Ashtech AgNavigator, L1 code, 12-channel) with <1 m positional accuracy. To ensure samples were properly referenced, the GPS antenna was mounted to the top of the mast on the hydraulic soil sampler. The purpose of grid soil sampling was to spatially characterize soil N levels across each field as a whole as well as determine the average fertility within smaller management zones within a field.

Offset rectangular grids were established at all locations except at Simpson (1994 and 1995) where a regular grid pattern was used. Soil cores were collected to a depth of 120 cm and divided into increments of 0-15, 15-60, 60-90, and 90-120 cm at Simpson in 1994 and 1995, and Malta in 2002 prior to processing for N analysis. Soil cores were collected to a depth of 90 cm at Highwood-2001, Havre-2001, and Malta-2001. The 90 cm soil cores were divided into 0-30, 30-60, and 60-90 cm depth increments at Highwood and 0-15, 15-60 and 60-90 cm at Havre and Malta. At Malta-2003 and -2004 soil cores were collected to a 60 cm depth and divided into 0-15 and 15-60 cm depth increments.

Gravimetric soil water content was estimated following oven-drying for 24-h at 50°C. Following oven drying, soil samples were ground and sieved to pass a 2 mm screen for determining the volume of coarse fragments and preparing the samples for analysis of soil NO_3-N content following KCl extraction (Mullvaney, 1996). The analysis was performed by either Western Testing (Great Falls, MT) or Harris Laboratories (Lincoln, NE).

Nitrogen Treatments

Field experiments were established using a strip trial design (Long et al., 1995) in which N rates were varied in replicated strips along the length of a field (Fig. 2). Nitrogen was applied as urea fertilizer prior to or during the planting operation. Field experiments included a series of four to six N rates that increased linearly in 22 kg ha^{-1} increments from 0 (check) to as much as 112 kg of N ha^{-1} except at Highwood where N treatments increased in 37 kg ha^{-1} increments from 0 to 112 kg ha^{-1} (Table 2). Each series of N treatments was replicated within a field at least four times.

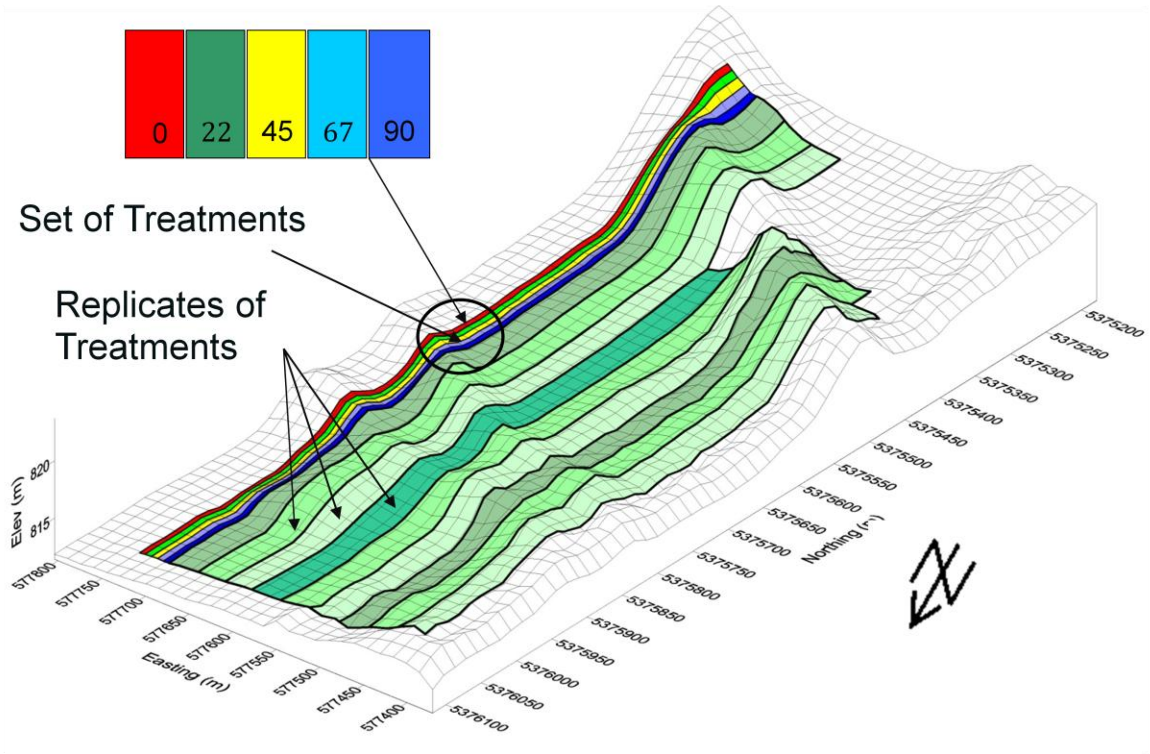


Figure 2. The nitrogen rate trial design with set of treatments organized into replicates that are oriented along the length of the field against a ridge and valley pattern.

Urea fertilizer was broadcast applied onto the soil surface prior to seeding at the Simpson and Highwood sites (Table 2) by means of a truck mounted fertilizer applicator with 18.3 m boom. Seed was then planted in 30.5 cm spaced rows with either a conventional disk drill or air-seeder with hoe-type openers. At all other sites, fertilizer was injected with an air-seeder in narrow bands below the seed (30.5 cm row spacing). In Havre, N treatments were established using two passes of a 3.1 m Concord air-seeder. All trials in Malta were established with a single pass of a 6.1 m Concord air-seeder.

Table 2. Numbers of treatment and replication, nitrogen (N) rates, and length and width of strip-plots at the eight experimental sites.

Site Year	Treatment No.	Rep No.	N Rates	Length	Width
			kg ha^{-1}	---------m--------	
Simpson 1994	6	3	0, 22, 45, 67, 90, 112	1216	18.3
Simpson 1995	5	3	0, 22, 45, 67, 90	825	18.3
Highwood 2001	4	6	0, 37, 75, 112	813	13.7
Havre 2001	5	10	0, 22, 45, 67, 90	760	6.1
Malta 2001	5	6	0, 22, 45, 67, 90	1108	6.1
Malta 2002	5	5	0, 22, 45, 67, 90	1545	6.1
Malta 2003	4	8	0, 22, 45, 67	785	6.1
Malta 2004	4	7	0, 22, 45, 67	1321	6.1

Crop Data Collection

Site-specific grain yields were obtained from production-scale combine harvesters. A Case IH 1660 combine with a 7.6 m header was used at the Simpson-1994 site. A 4.6 m header was used with this combine at the Simpson-1995, Havre-2001, Malta-2001, Malta-2002, Malta-2003, and Malta-2004 sites. At the Highwood-2001 site, a Case IH 1680 combine with a 9.1 m header was used. All combines were equipped with a GPS receiver and mass flow yield monitor (Model YF2000, AgLeader, Inc., Ames, IA). The AgLeader yield monitor utilizes a metal deflector plate attached to a load cell at the top of the clean grain elevator where all grain carried up the elevator is thrust against the plate. Yield monitors were calibrated to within ±2% of actual yield measurements using either specially designed weigh pads or a 180 kg Parker weigh cart (Model 1555, Parker Industries, Jefferson, IA). Yield measurements were collected at 1 s intervals and geo-referenced to Universal Transverse Mercator (UTM) coordinate system using a Trimble Ag-132 GPS receiver. A positional accuracy of ±1 m was achieved by means of differential GPS corrections broadcast from either the OmniSTAR wide area satellite or USCG beacon.

In each field, at least 300 samples of grain (approximately 1.0 l) were intermittently collected by hand from the combine’s bin filling auger as the grain emptied into the bulk tank. Samples were systematically collected in either 20 s or 30 s intervals as the combine traveled down the length of a strip, and were labeled with the unique Coordinated Universal Time of collection. After harvest, samples were taken to the laboratory and cleaned of foreign material by means of a Clipper Office Tester (A.T. Ferrell Company, Inc., Bluffton, IN). A near infrared whole grain analyzer (Foss Infratec Model 1226) was used to determine the protein concentration of each grain sample. Protein measurements were standardized to 120 g kg^{-1} (12%) grain moisture concentration in accordance with market standards for HRSW.

Yield and protein measurements were collected at the time the threshed grain reached the collection point at the top of the clean grain elevator. A time differential of 11 s existed between the time when the crop was cut at the header and when it reached the collection point. Therefore, the logged position of each yield and protein was corrected by subtracting the distance the combine had traveled in11 s. Histograms of yield and protein were used to identify and delete erroneous values caused by sudden stoppage of the combine, and by filling or emptying of grain as the combine entered or exited the field.

Terrain Modeling and Management Zone Delineation

Elevation measurements were collected at each study site using two survey-grade GPS receivers (Model 3151R, Novatel, Inc., Calgary, AB, Canada) along a series of parallel transects separated by 12 m in complex hummocky terrain, or 18 m in gentle rolling terrain. One “mobile” receiver was mounted to a vehicle and used to collect finely spaced elevation measurements along linear transects oriented in the lengthwise direction within each field. Parallel GPS-based guidance was used to maintain a regular spacing of 12-18 m between transects. A second receiver was used as a stationary base station with known geographic coordinates. The mobile and base station file solutions were post processed using version 6.03 of GravNav Post Processing Software (Waypoint Consulting Inc. Calgary, AB, Canada). The resultant elevation measurements had a positional accuracy of ±4 cm in both the horizontal and vertical planes.

The elevation point data from each study site were interpolated to a 5 m estimation grid using the geostatistical procedure of kriging available in ArcView ver3.2 (ESRI, Redlands, CA). The interpolated data were filtered using a combination of two 3×3 and one 5×5 low pass filters to remove linear artifacts created during the collection of elevation point data (MacMillan et al., 2000; MacMillan, 2003). Hill shade images of the data were computed before and after filtering, and visually inspected to ensure linear features were removed. The final smoothed product was a 5 m raster elevation file, or Digital Elevation Model (DEM).

The DEM was then imported into the terrain modeling software LandMapR (LandMapper Environmental Solutions, Edmonton, AB, Canada). LandMapR uses DEM values to compute 15 terrain elements, or land classes, as defined by position on landscape, slope angle, slope direction, and slope profile (Table 3 and Fig. 3). After using LandMapR to compute the land classes, the “Get Grid Value” extension in ArcView was used to extract their values directly to within 1 m of each point in a yield file.

Having extracted land class values to the yield, protein and soil maps, ArcView ver3.2 was used to group the 15 land classes into three landscape positions: termed, upper slopes, middle slopes and lower slopes (Table 3). In addition, the aspect tool in ArcView was used to compute the direction of slope for each grid point in the DEM. This information was used to split middle slopes into north and south facing slopes (Fig. 4). Therefore, four management zones (MZ) were established: upper slopes (MZ1), middle north facing slopes (MZ2), middle south facing slopes (MZ3), and lower slopes and depressions (MZ4) (Fig. 5). The rationale for these four MZ was based on the hypothesis that crop yields increase from upper to lower slopes in response to plant available soil water, which also increases down slope.

Table 3. Names and general characteristics of the 15 landform classes and three landscape positions of upper, middle, and lower slopes.

ID No.	Name	Profile	Plan	Gradient	Description	Position
1	Level Cress	Planar	Planar	Low	Near	Upper Slopes
2	Divergent Shoulder	Convex	Convex	Any	Low CTI	
3	Upper Depression	Concave	Concave	Low	High CTI	
4	Back Slope	Planar	Planar	High	Near	Middle Slopes
5	Divergent Back Slope	Planar	Convex	High	Near	
6	Convergent Back Slope	Planar	Concave	High	Near	
7	Terrace	Planar	Planar	Low	Near	
8	Saddle	Concave	Convex	Any	Near	
9	Mid Slope Depression	Concave	Concave	Low	Near	
10	Foot Slope	Concave	Concave	High	Near	Lower Slopes
11	Toe Slope	Planar	Planar	High	Near	
12	Fan	Planar	Convex	High	Near	
13	Lower Slope Mound	Convex	Convex	Any	Near	
14	Level Lower Slope	Planar	Planar	Low	Near	
15	Lower Depression	Concave	Concave	Low	Near	

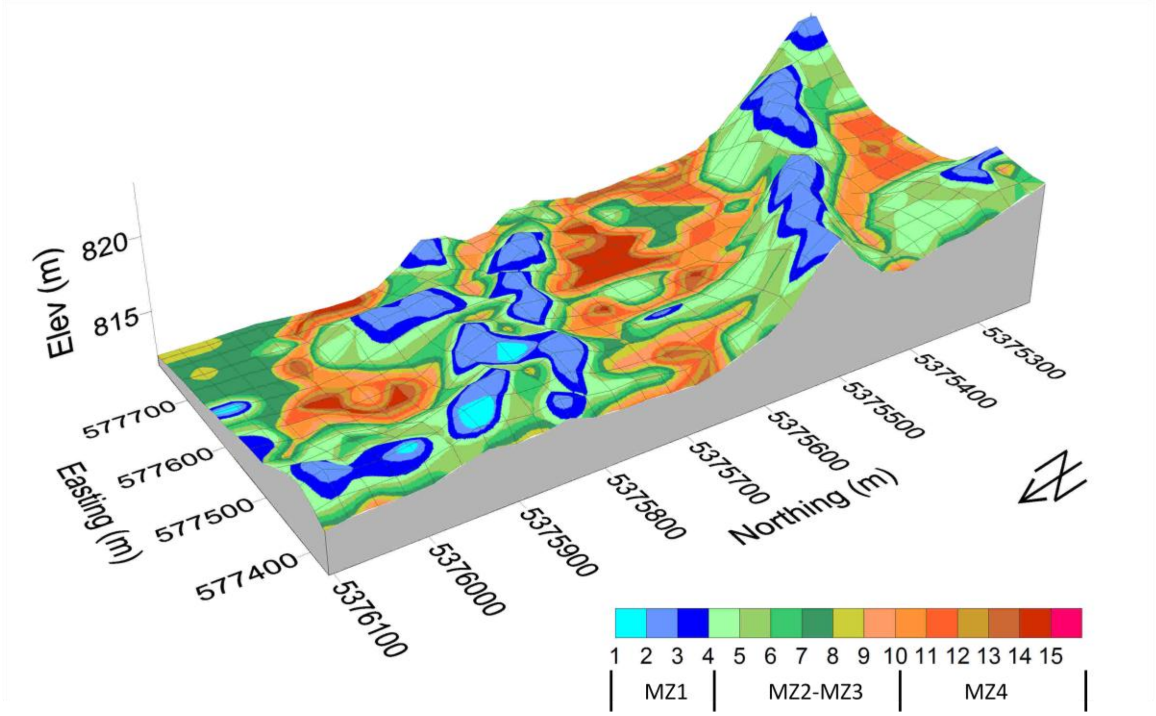


Figure 3. Digital elevation model of Havre-2001with overlay of 15 terrain elements computed by the LandMapR terrain modeling software package.

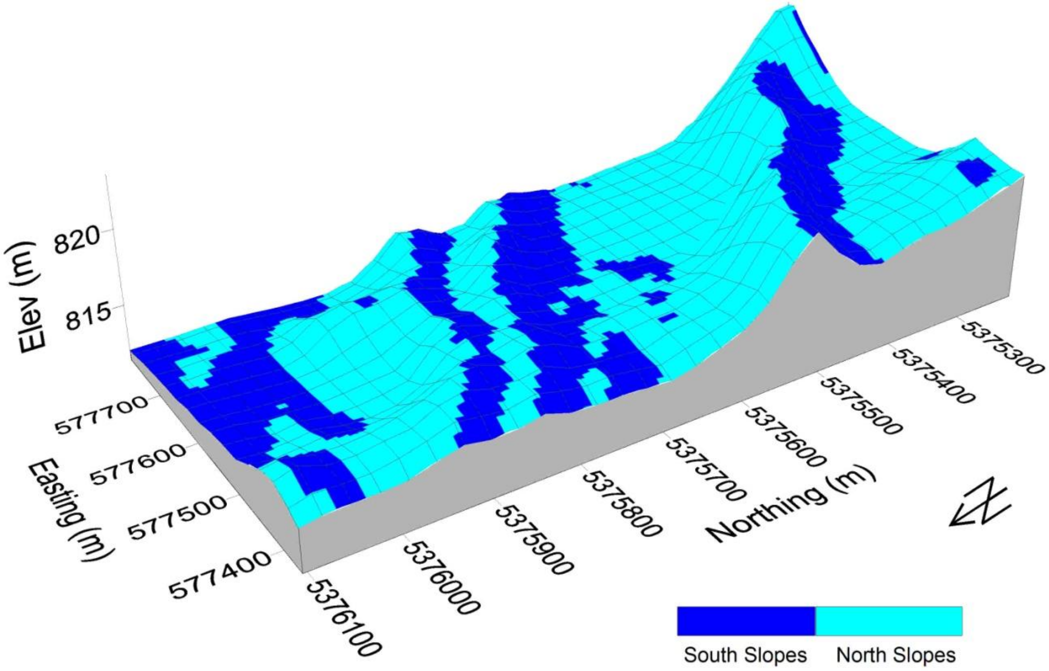


Figure 4. Digital elevation model of Havre-2001with overlay of south and north facing slopes.

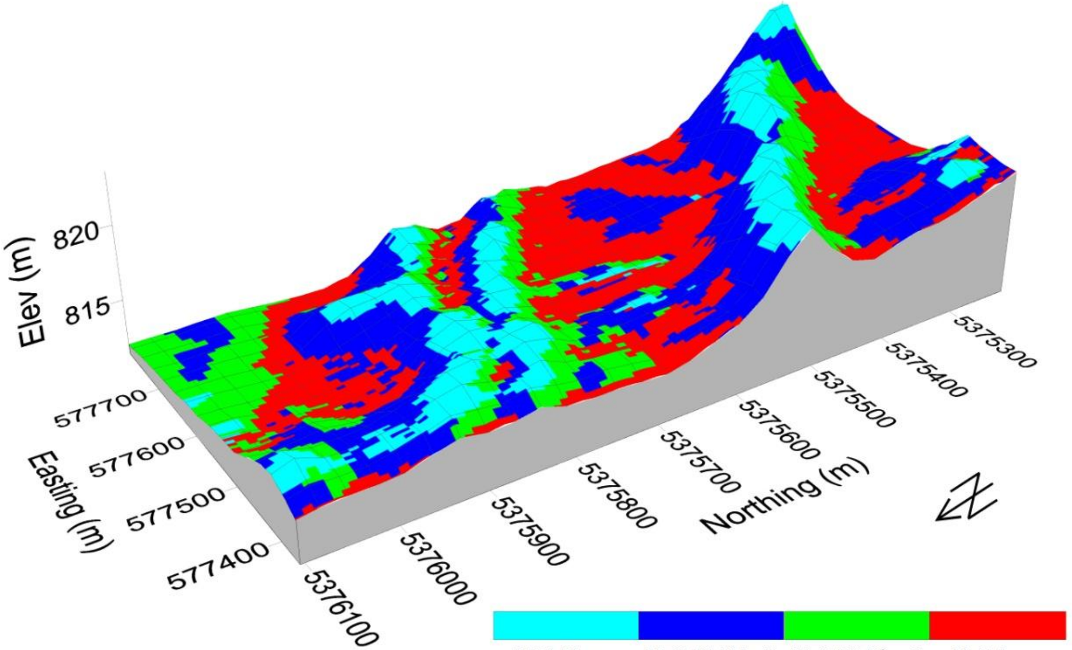


Figure 5. Digital elevation model of Havre-2001with overlay of four management zones.

Data Preparation and Encoding

In the Simpson-1994 and Simpson-1995 trials, each 18.3 m treatment strip had been cut into two parallel, non-overlapping swaths using the combine harvester with 7.6 m header. Grain yield measurements of each swath were randomly allocated to one of two independent groups of data: one resulting from variable rate N application and the second resulting from uniform N application. In all other trials, the treatment strips were wide enough to accommodate only one combine swath. In that case, each pair of yield observations was systematically assigned to the variable rate group or the uniform N rate groups. Therefore, two independent data sets could be created for statistical analysis. The eight field studies were analyzed separately because climate, soils, N rates, and yield potential differed among the study locations.

Gross returns were computed on a dollar per kg basis by multiplying the grain yield and the Portland market quotes for Dark Northern Spring Wheat average price over the 11 years (Table 4). Price premiums for this grain are received for each quarter of a percent above a protein concentration of 140 g kg^{-1} (14%) and discounted for each quarter below 140 g kg^{-1}. Protein premiums and discounts are rounded down to the nearest quarter percent (i.e., 142.4 g kg^{-1} protein is priced at the 140 g kg^{-1} price) as is the common practice in this market. Thus, protein concentration values were rounded down to the nearest quarter percent as needed to establish the price for the spring wheat.

Table 4. Average Portland market quotes for dark northern spring wheat over 11 years (1994-2004).

Protein	Quote
%	\$ kg^{-1}
<12.24	0.1562
12.25-12.49	0.1583
12.5-12.74	0.1606
12.75-12.9	0.1626
13.0-13.24	0.1647
13.25-13.49	0.1673
13.5-13.74	0.1699
13.75-13.9	0.1725
14.0-14.24	0.1750
14.25-14.49	0.1765
14.5-14.74	0.1781
14.75-14.9	0.1796
>15.0	0.1811

Each yield and protein record of a data series was classified by treatment strip number, replication, N fertilizer rate, and MZ. The statistical software package SAS (SAS Inst., Cary, NC) and Proc Univariate were used to compute the summary statistics (mean, standard deviation, minimum value, and maximum value) for yield and gross return with respect to N treatment, N treatment within a management zone, and variable rate and uniform N management. The average grain protein within a treatment strip of a management zone was used to establish the wheat price to be associated with the grain yield received from variable rate and uniform N management.

Each data set was analyzed according to either an *a priori* or *a posteriori* approach to identifying N rates for uniform and variable rate N management. The *a priori* approach used soil test N (kg ha^{-1}) measurements and expected yield goals to derive N recommendations based on university fertility guidelines (Jones and Jacobsen 2001). Yield goals for uniform and variable rate N treatments were based on farmer experience. Therefore, yield goals were multiplied by the unit N requirement of 0.0467 kg, which represents the amount of N needed to produce 1 kg of wheat. Residual soil N measurements were subtracted from the N requirement to produce N recommendations. In contrast, the *a posteriori* approach used knowledge of the crop’s response to applied N to identify the N rate that optimized net dollar returns. In practice, the *a posteriori* approach cannot be implemented because it is impossible to know final grain yield and thus, actual crop N requirements at the start of the growing season. In this study, the *a posteriori* approach results were included for their comparison with the *a priori* results as needed to gage the performance of variable rate N management based on limited information at planting.

In the *a posteriori* approach, the N rate that optimized net dollar returns for uniform management was identified from a scatter plot of net return versus applied N. For variable rate management, the N rates that optimized net returns were identified from scatter plots of mean grain yield versus applied N using the data within each management zone. Thus, only the yield observations of the treatment N rates that optimized grain net returns, either for the whole field or each management zone, were selected for analysis.

The method of comparing the grain yield from uniform or variable fertilization is illustrated in Figure 6. The fertilizer rates for uniform fertilization involved the yield observations from a series of continuous swaths equal to the number of replications within an entire field. The fertilizer rates representing variable fertilization involved the yield observations from the swaths of a treatment that fell within a management zone.

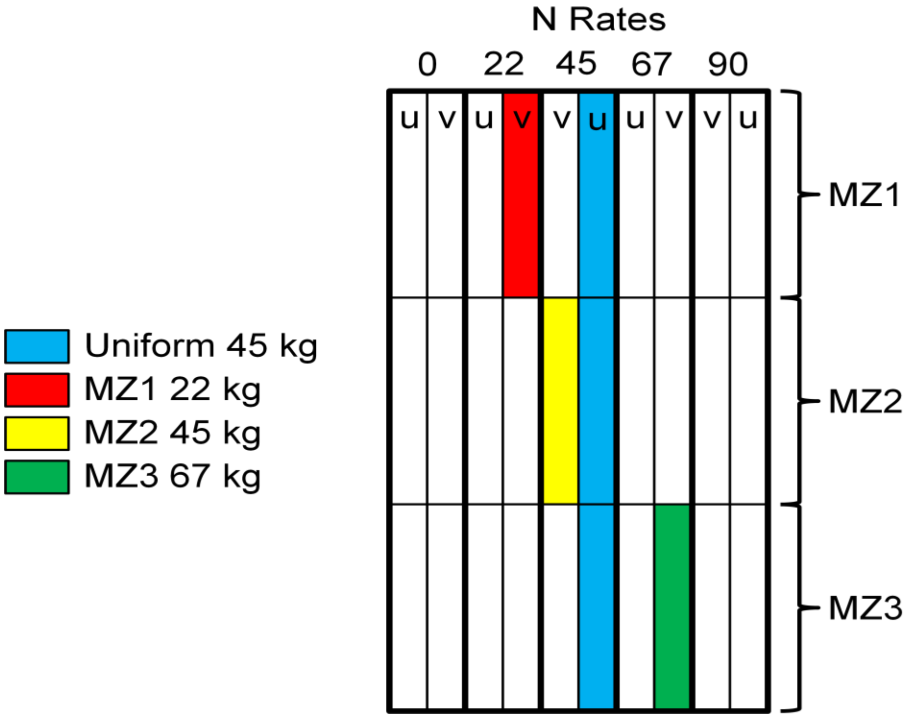


Figure 6. Illustration of procedure used to create uniform and variable rate nitrogen (N) treatments from available N rates within a field and its management zones.

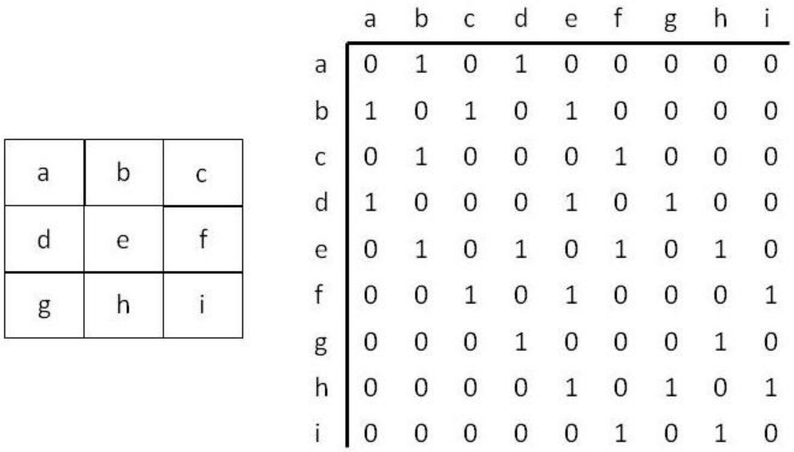
Autoregressive Response Modeling

Applying ordinary least squares (OLS) methods into statistical analysis of site-specific yield monitor data can lead to inflated levels of significance and explained variance because of the deleterious effects of spatial autocorrelation (Long, 1998). Spatial autoregressive models can be used to diminish the negative impact of spatial autocorrelation and provide for valid inferences concerning the dependence of Y on X variables (Griffith, 1990, 1993; Anselin, 1991). In this study, the autoregressive response (AR) model (Upton and Fingleton, 1985) was implemented because of its simplicity and relative ease of use. The results from this “spatial least squares” (SLS) analysis were then used as the basis for establishing whether wheat yields from variable rate N management were significantly greater than those from uniform N management.

The AR model is specified in accordance with the following equation:

$$Y = \rho CY + \beta 0 + \varepsilon \qquad \text{Eq. [1]}$$

where rho (ρ) is the spatial autocorrelation parameter, C is a spatial weights matrix, and ε are randomly distributed errors. An AR model utilizes a regular square lattice of grain yield values in which the geographic location of each value in the lattice is defined by unique row and column values (Fig. 7). Matrix CY specifies the spatial connectivity solely between adjacent observations of grain yield in this lattice. A value of unity in this binary matrix designates pairs of observation that possess a common boundary and are potentially autocorrelated. In contrast, the zero elements of this matrix reflect observations that are not contiguous and thus are uncorrelated.



a	b	c
d	e	f
g	h	i

	a	b	c	d	e	f	g	h	i
a	0	1	0	1	0	0	0	0	0
b	1	0	1	0	1	0	0	0	0
c	0	1	0	0	0	1	0	0	0
d	1	0	0	0	1	0	1	0	0
e	0	1	0	1	0	1	0	1	0
f	0	0	1	0	1	0	0	0	1
g	0	0	0	1	0	0	0	1	0
h	0	0	0	0	1	0	1	0	1
i	0	0	0	0	0	1	0	1	0

Figure 7. Relationship between geographic arrangement of example 3 × 3 square lattice, and corresponding 9 × 9 binary spatial weights matrix specifying the configuration of cells in the lattice.

Yield monitor data were made to conform to a regular square grid by their extraction to the cells of a regular square grid (illustrated in Fig. 8). A regular 8 m grid of X and Y coordinates was created using Surfer ver. 8.09 (Golden Software, Inc., Golden, CO) mapping software. The regular spacing of treatment strips meant that the "skewed" easting UTM coordinate of the yield file could be made to conform to the "square" easting coordinate of the grid. A grid size of 8 m was arbitrarily chosen, which approximates the standard width of a combine's header. The Geoprocessing Wizard, an extension to ArcView ver3.2, was then used to intersect the yield and grid data files. Specifically, the nearest yield value was extracted to each node of the regular grid. Nodes outside of the experimental area and greater than 5 m from a yield value were coded with a missing value.

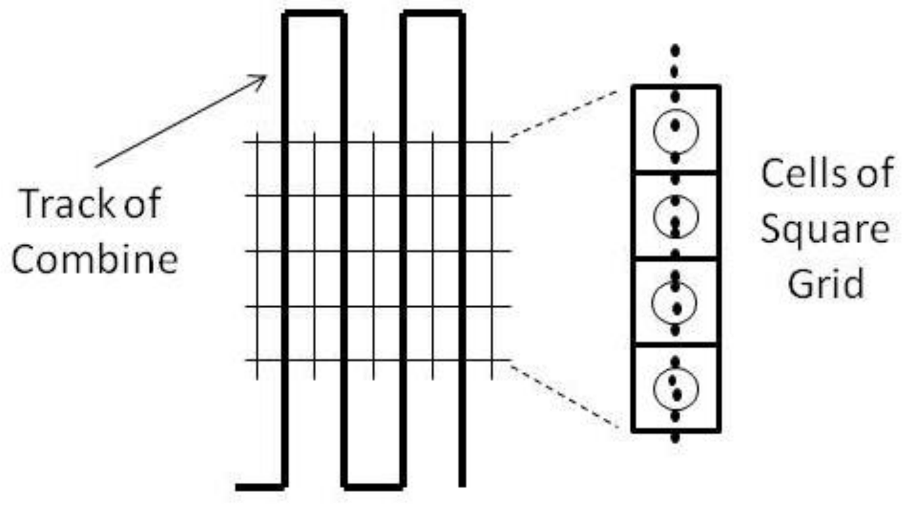


Figure 8. Process by which yield data are selected to obtain values for each cell of a square lattice that has been imposed upon a set of irregularly spaced yield observations.

The sheer volume of grain yield observations (<30,000) was reduced to a tractable number (<6,000) by selecting the yield measurements within small cells equal to the size of the combine's header. For example, the cell size was 8×8 m within a strip if the combine's header width had been 8 m. The SAS statistical software package and Proc Univariate (SAS Inst., Cary, NC) were used to compute the variance of the yield data before and after gridding. Though the number of observations was drastically reduced, this selection process changed the yield variance by only 2% [Table 5 (as for Simpson-1994)]. Consequently, there was little negative impact on the original information content in grain yield.

Table 5. Number of observations (N), mean, standard deviation (s), minimum (min), maximum (max), and range in values of wheat yield under varying cell size.

Cell Size	N	Mean	s	Min	Max	Range
M		------------------------------kg ha^{-1}--------------------------				
1.5×8	25,817	2448.2	347.2	1022.4	3981.8	2959.4
8 × 8	5,184	2440.1	355.3	1103.1	3914.5	2811.4

After the data were fit to the 8 m lattice, the SAS code of (Griffith, 1993) and Proc NLIN of SAS were used to estimate an AR model. Initially, the AR model was applied to estimating the mean of the data series with zero intercept term as specified by Equation 1. This operation not only provided an estimate of parameter ρ, but also effectively removed spatial autocorrelation from the yield data so that only the variance would remain that was attributable to experimental treatment effects. Performance of the AR model was evaluated by comparing semivariograms depicting the relationship between the semivariance and relative distance between pairs of residuals from OLS regression and residuals from SLS regression (Fig. 9 depicts results for Simpson-1994). The semivariogram for OLS regression shows semivariance increasing from about 20,000 to 80,000 through a distance of separation of about 100 m. In contrast, the semivariogram of residuals from SLS regression does not behave in this manner, i.e., semivariance remains invariant throughout its range of separation distance. Therefore, the AR method is more effective than the OLS method in accommodating autocorrelation in site-specific grain yield and is deemed warranted.

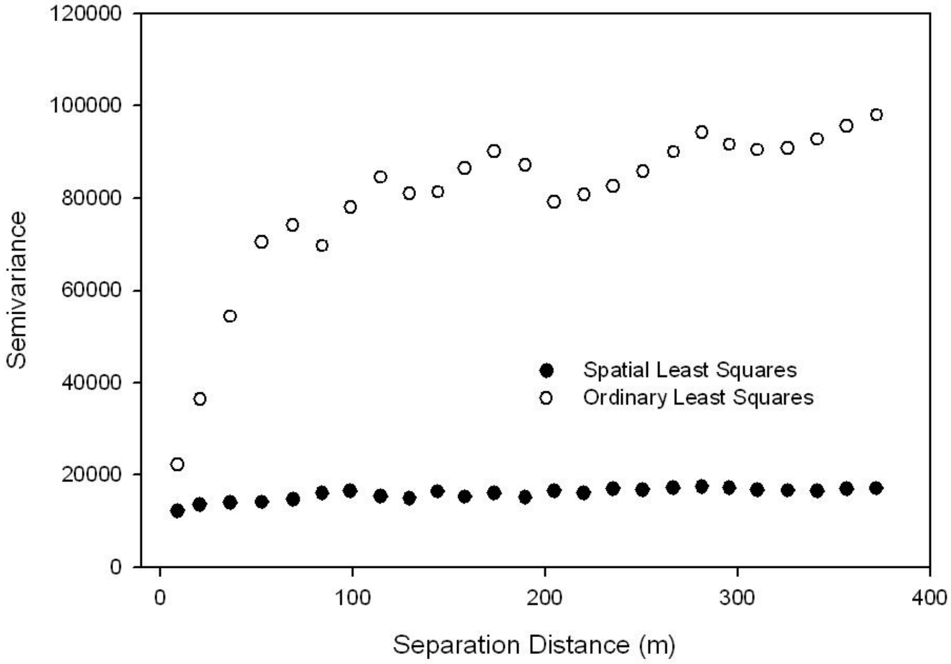


Figure 9. Semivariograms of residuals from regression by ordinary least squares and spatial least squares.

After AR modeling was used to remove autocorrelation, statistical analysis of grain yield or gross return was then undertaken with the General Linear Model (GLM) under a valid assumption of independent, randomly distributed errors. The GLM was implemented by means of Proc GLM in SAS for one-way analysis of variance (ANOVA) to compare the overall mean yields and gross returns of spatially variable and conventional uniform N application. The ANOVA model was:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 (X_1 \times X_2) + \varepsilon \qquad \text{Eq. [2]}$$

where Y is grain yield or gross return; X_1 contains classificatory values of N management strategy (spatially variable or uniform); X_2 contains classificatory values of replication; $X_1 \times X_2$ is an interaction term; β_0 is the intercept parameter; and β_1 , β_2, and β_3 are slope parameters; and ε is an error term. Terms in an ANOVA model were evaluated for significance using a partial F-test (Type III sums of squares) with the interaction of X_1 and X_2 used as the error term.

Due to improved fertilizer distribution, it was hypothesized that average wheat yields from variable rate N management are the same or better than those from conventional N management. On the other hand, grain yield response to applied N is limited because of water limiting conditions found in semiarid environments. Therefore, grain yields from variable rate management may not differ from uniform N management. An hypothesis test consistent with the above expectations was used to determine if variable rate yields are equal to reference uniform values. Using a significance level of 5%, a hypothesis test was structured so that rejection of the null hypothesis (Ho) results in acceptance of an alternative hypothesis (Ha), which is consistent with prior expectations. The following pair of hypotheses may be expressed as follows:

$$Ho: \bar{x} \leq \mu$$

$$Ha: \bar{x} \geq \mu$$

where $\bar{x}$ is the variable rate mean of the selected parameter, and μ is the corresponding uniform value.

Partial Budget Analysis

Economic benefits from variable rate N management were determined using the original yield monitor data and the partial budget approach described by (Lowenberg-DeBoer, 2000). Partial budgeting on a per hectare or per field basis focuses on only those cost and revenue items that change when using a new practice. It subtracts changes in cost from changes in revenue to estimate the change in net revenue that results from adopting a new practice:

Net Revenue Change = Revenue Change – Cost Change.

Revenue changes resulted from changes in the amount and value of grain. Payments available under the USDA-NRCS Environmental Quality Incentives Program (EQIP) (NRCS, 2004) were also considered apart from the actual partial budget.

Grain growers practicing variable rate nutrient management may qualify for payments under EQIP. This program offers producers the opportunity to try new technology for variably managing fields (NRCS, 2004). To participate, producers must delineate at least three management zones based on soil electrical conductivity (EC) maps, sequential yield maps, aerial imagery, grid soil sampling, or other acceptable method. Fertilizer must be applied to the zones using a variable rate applicator. Producers are paid to produce a yield map for verification of variable rate N management and to adjust management zones. In Montana, EQIP pays \$25.93 ha^{-1} to a maximum benefit of \$5250, or enough money to treat 203 ha. A yield mapping payment of \$18.52 ha^{-1} is included for the first year and \$3.70 ha^{-1} for the remaining two years of a three year contract. This benefit was averaged over the three years (\$8.64 ha^{-1}).

Variable costs associated with variable rate N application included soil sampling, zone delineation, fertilizer, hardware, and software (Table 6). Though combine harvesters can be purchased from the factory with yield monitors and air-seeders are equipped for variable rate application, it is assumed that the producer does not own pre-installed equipment. Fixed costs were ignored, as they do not change with N management strategy. All variable costs are based on an 1100 ha farm size typical of northern Montana (USDA 2008). Equipment costs were for acquiring a yield monitor, GPS receiver, and hardware and software for adapting an air-seeder for variable-rate application.

A significant initial investment in technology, information, and software is required to participate in variable rate management. Therefore, a 10% opportunity cost was considered for each item of the investment. Opportunity costs represent the next best alternative use for a farmer’s money (Lowenberg-DeBoer, 2000). For instance, if the farmer had paid down debt instead of purchasing equipment, then the interest rate of 10% on the debt becomes the opportunity cost for investing in variable rate N management. Information, technology, and software costs were treated as durable goods because they are useful for more than one year. These costs were spread over four years of the items useful life. Once the average yearly cost of the expense was established, the expense was divided by the number of productive hectares on the farm during a given year to arrive at the cost in dollars per hectare.

Nitrogen was applied as urea fertilizer (46-0-0) and was the only nutrient subject to variable rate application. Fertilizer costs were calculated by multiplying the unit cost of N in urea fertilizer by the rate of application. Fertilizer costs were based on the average 2009 spring fertilizer price of \$365 ton^{-1}, or \$0.87 kg^{-1} (personal communication with a local dealer). Currently, soil fertility information is gathered using a directed sampling approach whereby the soil samples are taken at a limited number of locations and bulked to form one composite sample per management zone (Franzen, 2008). Since, local fertilizer dealers offer soil sampling and analysis as a service to their clients, soil sampling is charged on a per field basis where one composite sample is collected and analyzed at a cost of \$55. Added cost for soil sampling under variable rate management would entail one composite soil sample per MZ instead of one for the entire field. Four MZ were involved in this study and so the total cost difference was \$165 per field ($3 \times 55 = 165$). Therefore, the cost difference per hectare for each field was \$165 divided by the total hectares of the field.

Typically, producers work through a consulting service to build variable rate control maps for their farms. Information costs were quoted by LandMapper Environmental Solutions, Inc. (Edmonton, Alberta, Canada) at \$1300 per section of land (640 ac = 259 ha) for acquiring a 30 m digital elevation model (DEM) from USGS and using the LandMapR software to divide the DEM into upper, middle, and lower slopes. This information was treated as a durable asset with a four year useful life and subject to a 10% opportunity cost. The opportunity cost equaled 10% of \$1300, or \$130, and the annual cost was \$1300/4, or \$325. This brought the total annual cost to \$455 (130+325=455). The cost per hectare was \$455 divided by 259 ha, or \$1.76 ha^{-1}.

Based on a quotation from a local dealer, the cost of a yield monitor is \$5295 and a suitable GPS receiver used with this monitor is \$895. A producer will need to purchase the variable rate control system for their air till drill. A local vendor estimated this cost at ≤\$14,000. This technology was treated as a four year durable asset with a 10% opportunity cost spread over 1100 ha of the farm, which meant that the annual cost of the variable rate control system was \$4900 (\$1400 + \$3500 = 4900), or \$4.45 ha^{-1} (\$4900/1100 ha = \$4.45 ha^{-1}). Equipment costs of the yield monitor and GPS receiver were computed in the same way. In addition, mapping software is needed to satisfy EQIP program requirements of producing as-applied N maps and yield maps. The SMS software package, priced at \$750 from AgLeader Technology, Inc., Ames, IA, satisfies this requirement. A maintenance fee of \$120 is charged for each year the producer uses the software. Therefore, total annual cost of the software over the four years of its useful life is \$385, or \$0.35 ha^{-1}.

Table 6. Cost of materials, equipment, and services for variable rate nitrogen management.

Operation	Material or service	Unit	$ unit^{-1}	Units	$ ha^{-1}
Soil sampling	Custom service	Field	220	165	4.15-11.00
Management zone	Custom service	Ha	1.76	1.00	1.76
Fertilization	Urea (46-0-0)	Kg	0.87	0-112	0-97.97
Variable rate N	Rate control system	1	14,000		4.45
Harvest	Yield monitor	1	5295		1.69
Harvest	GPS receiver	1	895		0.28
Harvest	Mapping software	1	750		0.35

RESULTS AND DISCUSSION

Nitrogen Treatments

At Simpson 1994, soil NO_3-N (0-60 cm) averaged 70 kg ha^{-1} in the whole field (Table 7). Therefore, the uniform fertilizer N recommendation was 24 kg ha^{-1} based on a yield goal of 2018 kg ha^{-1}. The closest actual N rate was 22 kg ha^{-1} for uniform management. Soil NO_3-N levels were nearly the same in each MZ ranging between 61 kg ha^{-1} and 70 kg ha^{-1}. Based on yield goals of 1682, 2018, 2354, and 2690 kg ha^{-1} in order of MZ1, MZ2, MZ3, and MZ4, the variable rate fertilizer N recommendations were 18, 29, 40, and 58 kg ha^{-1}. The actual N rates selected were 22, 22, 45, and 67 kg ha^{-1} for MZ1, MZ2, MZ3, and MZ4, respectively and closely matched the recommended rates for these management zones.

At Simpson 1995, soil NO_3-N (0-60 cm) averaged 52 kg ha^{-1} on a whole field basis and thus, the uniform N recommendation was 42 kg ha^{-1} to reach a yield goal of 2018 kg ha^{-1}. The actual N rate most closely matching this N recommendation was 45 kg ha^{-1}. For variable rate N management, soil NO_3-N levels (0-60 cm) were 49 kg ha^{-1} in MZ1, 65kg ha^{-1} in MZ2, 49 kg ha^{-1} in MZ3, and 53 kg ha^{-1} in MZ4. The variable rate N recommendations associated with these test N levels were 30, 29, 61, and 73kg ha^{-1} to reach yield goals of 1682, 2018, 2354, and 2690 kg ha^{-1} in order of MZ1, MZ2, MZ3, and MZ4. The actual N rates closely matching these recommendations were 22, 22, 67, and 67 kg ha^{-1} for MZ1 through MZ4.

At Highwood 2001, soil NO_3-N (0-60 cm) averaged 17 kg ha^{-1} for the whole field and the uniform N recommendation was 79 kg ha^{-1} to reach a yield goal of 2018 kg ha^{-1}. The actual N rate closely matching this N recommendation was 75 kg ha^{-1}. Soil NO_3-N (0-60 cm) ranged between 16 and 18 kg ha^{-1} and indicated a requirement of 77, 77, 93, and 108 kg ha^{-1} to reach yield goals of 1682 kg ha^{-1} in MZ1, 2018 kg ha^{-1} in MZ2, 2354 kg ha^{-1} in MZ3, and 2690 kg ha^{-1} in MZ4. Nitrogen recommendations closely matched actual N rates of 75 kg ha^{-1} in MZ1, 75 kg ha^{-1} for MZ2, 112 kg ha^{-1} for MZ3, and 112 kg ha^{-1} for MZ4.

At Havre 2001, soil NO_3-N ha^{-1} (0-60cm) averaged 99 kg ha^{-1} and thus no fertilizer N was needed under the uniform N program to meet the yield goal of 2018 kg ha^{-1}. For variable rate N management, soil NO_3-N levels exceeded 90 kg ha^{-1} and resulted in N recommendations of 0, 3, 10, and 26 kg ha^{-1} to reach yield goals of 1682 kg ha^{-1} in MZ1, 2018 kg ha^{-1} in MZ2, 2354 kg ha^{-1} in MZ3, and 2690 kg ha^{-1} in MZ4. Actual nitrogen rates closely matching theses N recommendations were 0, 0, 0, and 22 kg ha^{-1} in order of MZ1 through MZ4.

At Malta 2001, soil NO_3-N (0-60 cm) averaged 75 kg ha^{-1} and the recommendation for the uniform N rate was 19 kg ha^{-1} to reach a yield goal of 2018 kg ha^{-1}. Thus, the actual N rate most closely matching this N recommendation was 22 kg ha^{-1}. For variable rate management, the soil NO_3-N (0-60 cm) varied slightly between 62 and 84 kg ha^{-1} across all MZ. They indicated N needs of 6, 10, 48, and 42 kg ha^{-1} to reach yield goals of 1682, 2018, 2354 and 2690 kg ha^{-1} in order of MZ1, MZ2, MZ3, and

MZ4. Actual nitrogen rates closely matching these N recommendations were 0, 0, 45, and 45 kg ha^{-1} respectively for MZ1 through MZ4.

At Malta 2002, soil test NO3-N (0-60 cm) averaged 76 kg ha^{-1} in the field and thus, 18 kg ha^{-1} were recommended to reach a yield goal of 2018 kg ha^{-1}. The actual uniform N rate, therefore, was 22 kg ha^{-1}. Meanwhile, soil NO3-N averaged 61 kg ha^{-1} in MZ1, 74 kg ha^{-1} in MZ2, 70 kg ha^{-1} in MZ3, and 103 kg ha^{-1} in MZ4. Therefore, for variable rate management, the actual N rates were 22, 22, 45, and 22 kg ha^{-1} for yield goals of 1682 kg ha^{-1} in MZ1, 2018 kg ha^{-1} in MZ2, 2354 kg ha^{-1} in MZ3, and 2690 kg ha^{-1} in MZ4.

At Malta 2003, soil NO_3-N (0-60 cm) averaged 72 kg ha^{-1} on a whole field basis and thus 22 kg of N ha^{-1} was required for a yield goal of 2018-kg ha^{-1}. This recommended rate matched the actual rate of 22 kg of N ha^{-1} exactly. For variable rate management, soil tests revealed 45, 65, 66, and 126 kg of NO3-N ha^{-1} in MZ1 through MZ4. The corresponding N recommendations were 34, 29, 44, and 0 kg ha^{-1} and therefore, the actual N rates were determined to be 45, 22, 45, and 0 kg ha^{-1} to reach yield goals of 1681 kg ha^{-1} in MZ1, 2018 kg ha^{-1} in MZ2, 2354 kg ha^{-1} in MZ3, and 2690-kg ha^{-1} in MZ4.

At Malta 2004, soil NO3-N (0-60 cm) averaged 66 kg ha^{-1} on a whole field basis and thus, the uniform N recommendation was 28 kg ha^{-1} to reach an initial yield goal of 2018 kg ha^{-1}. The actual N rate most closely matching the N recommendation was 22 kg ha^{-1}. For variable rate N management, soil NO_3-N (0-60 cm) levels were 47 kg ha^{-1} in MZ1, 59 kg ha^{-1} in MZ2, 71 kg ha^{-1} in MZ3, and 91 kg ha^{-1} in MZ4. The variable rate N recommendations associated with these soil NO_3-N levels were 32, 35, 39, and 35 kg ha^{-1} to reach yield goals of 1682, 2018, 2354, and 2690 kg ha^{-1} in order of MZ1, MZ2, MZ3, and MZ4. Actual N rates closely matching these recommended N rates were 22, 45, 45, and 45 kg ha^{-1} for MZ1 through MZ4.

Table 7. Yield goals, soil test N levels, N recommendations, and maximum N rates derived for each field site and its management zones (MZ).

	Whole Field	Upper	Middle North	Middle South	Lower
		MZ1	MZ2	MZ3	MZ4
	Simpson 1994				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	70	61	65	70	68
N recommendation (kg ha^{-1})	24	18	29	40	58
Actual N rate applied (kg ha^{-1})	22	22	22	45	67
	Simpson 1995				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	52	49	65	49	53
N recommendation (kg ha^{-1})	42	30	29	61	73
Actual N rate applied (kg ha^{-1})	45	22	22	67	67
	Highwood 2001				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	17	16	17	16	18
N recommendation (kg ha^{-1})	79	77	77	93	108
Actual N rate applied (kg ha^{-1})	75	75	75	112	112
	Havre 2001				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	99	90	91	100	100
N recommendation (kg ha^{-1})	0	0	3	10	26
Actual N rate applied (kg ha^{-1})	0	0	0	0	22
	Malta 2001				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	75	73	84	62	84
N recommendation (kg ha^{-1})	19	6	10	48	42
Actual N rate applied (kg ha^{-1})	22	0	0	45	45

Table 7. Continued.

	Whole Field	Upper	Middle North	Middle South	Lower
		MZ1	MZ2	MZ3	MZ4
	Malta 2002				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	76	61	74	70	103
N recommendation (kg ha^{-1})	18	18	20	40	23
Actual N rate applied (kg ha^{-1})	22	22	22	45	22
	Malta 2003				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	72	45	65	66	126
N recommendation (kg ha^{-1})	22	34	29	44	0
Actual N rate applied (kg ha^{-1})	22	45	22	45	0
	Malta 2004				
Yield Goal (kg ha^{-1})	2018	1682	2018	2354	2690
N Requirement (kg ha^{-1})	94	79	94	110	126
Soil NO3-N (kg ha^{-1})	66	47	59	71	91
N recommendation (kg ha^{-1})	28	32	35	39	35
Actual N rate applied (kg ha^{-1})	22	22	45	45	45

Nitrogen Application and Crop Response by Field

The fertilizer N applied for both management strategies ranged from 0 to 112 kg ha^{-1} across site years (Table 8). The weighted amount for variable rate N application fell between 13 and 84 kg ha^{-1}. The amount of N applied was least under uniform N management in six of the eight field sites. Compared to uniform management, N applied from variable rate management was less than or equal in Malta 2001, but had greater N applications in Simpson 1994 (82%), Simpson 1995 (16%), Highwood 2001 (12%), Malta 2002 (32%), Malta 2003 (41%), and Malta 2004 (89%). Therefore, variable rate N application, which attempts to reduce the N application in areas of low yield potential where crop N uptake is also less, does not always reduce total fertilizer usage.

Mean grain yield across all N management strategies and site-years ranged from 824 kg ha^{-1} to 3475 kg ha^{-1}. Notable differences in mean grain yield likely resulted from differences in plant available water as determined by rainfall. In general, grain yields increased with growing season rainfall (April-July) in order of Highwood (73% of long-term), Havre (71%), Malta 2003 (105%), Malta 2001 (89%), Malta 2002 (89%), Simpson 1994 (100%), Malta 2004 (89%) and Simpson 1995 (180%). Departure in 2003 resulted from heat stress during grain fill. At the same time, mean protein concentration of grain varied inversely from 178 to 104 g kg^{-1} (Table 3). In semiarid environments, the inverse relationship is attributed to dilution of a fixed amount of grain N by a much larger biomass with increases in plant available water (Terman, 1969).

When examining each site year; however, statistical differences in mean grain yields and proteins between uniform and variable rate N placement were not found within any of the eight field sites. The one-way ANOVA that was undertaken, with allowance for spatial autocorrelation, failed to detect significant differences between conventional uniform and variable rate N management in terms of grain yield. In addition, significant differences were not found using an ANOVA based on conventional, ordinary least squares. Therefore, variable rate N fertilizer application apparently may not improve overall agronomic returns under the water limited conditions found in northern Montana.

Table 8. Range in nitrogen (N) rates, weighted N rate, mean yield by spatial least squares (SLS) and ordinary least squares (OLS), and grain protein for uniform and variable rate N management in the eight field sites.

Site Year	Management	N Range	Weighted N	Yield-SLS†	Yield-OLS†	Protein	Rainfall
		kg ha^{-1}				g kg^{-1}	cm (%)‡
Simpson 1994	Uniform	22	22	2354 a	2468 a	145	15 (100)
	Variable	22-67	40	2327 a	2400 a	142	
Simpson 1995	Uniform	45	45	3383 a	3454 a	104	27 (180)
	Variable	45-67	52	3422 a	3364 a	112	
Highwood 2001	Uniform	75	75	848 a	853 a	164	14 (73)
	Variable	75-112	84	838 a	843 a	165	
Havre 2001	Uniform	0	0	1061 a	1066 a	169	12 (71)
	Variable	0-22	7	1035 a	1015 a	166	
Malta 2001	Uniform	22	22	2473 a	2466 a	141	17 (89)
	Variable	0-45	11	2402 a	2364 a	142	
Malta 2002	Uniform	22	22	2057 a	2054 a	149	17 (89)
	Variable	22-45	29	2050 a	2045 a	154	
Malta 2003	Uniform	22	22	1512 a	1512 a	176	20 (105)
	Variable	0-45	31	1561 a	1565 a	178	
Malta 2004	Uniform	22	22	2718 a	2710 a	152	17 (89)
	Variable	22-45	39	2757 a	2752 a	152	

†Values followed by same letters are not significantly different at $P < 0.05$. ‡Value in parenthesis is percent of long term rainfall at each location.

Crop Response by Management Zone

The 40 ha Simpson 1994 field had little history of N fertilization and soil NO_3-N varied widely across the field with some locations containing as little as 13 kg ha^{-1} of residual NO_3-N, while others contained as much as 235 kg ha^{-1} of residual NO_3-N in the upper 60 cm of the soil profile (data not shown). The field had been fallowed in the previous year and thus the water content of the soil profile was likely full at the start of the 1994 growing season. There was little apparent difference in soil water content among the MZ (Table 9). As expected, average grain yield increased from 2306 kg ha^{-1}, 2369 kg ha^{-1}, 2445 kg ha^{-1}, and 2717 kg ha^{-1} in order of upper, middle north, middle south, and lower slopes. Grain protein concentration was less affected by landscape position than grain yield as indicated by small differences among the MZs.

The Simpson 1995 field had a relatively uniform distribution of soil NO_3-N (46 kg ha^{-1}). As expected, grain yield increased in the down slope direction 3120 kg ha^{-1}, 3233 kg ha^{-1}, 3467 kg ha^{-1}, and 3531 kg ha^{-1} in order of upper, middle north, middle south and lower slopes with a field average of 3419 kg ha^{-1}. Initial profile soil water content also increased in down slope from 111 g kg^{-1} in upper slopes to 120 g kg^{-1} in lower slopes. In general, grain proteins increased down slope from 101 g kg^{-1} in upper slopes to 111 g kg^{-1} in lower slope positions.

At Highwood 2001, abnormally dry growing season conditions combined with prolonged drought led to depressed yields of 833 kg ha^{-1} and elevated grain proteins of 159 g kg^{-1}. The dry growing conditions were compounded by a continuous cropping rotation following an average winter wheat crop in 2000 resulting in relatively low field average NO_3-N levels of 15 kg ha^{-1}. Little difference in grain yield or protein was observed with respect to landscape position due to the extremely dry conditions. Soil water content among management zones was nearly equal except for MZ3 (south facing middle slopes) which was at least 6 g kg^{-1} drier than other landscape positions.

At Havre 2001, extreme dry conditions combined with prolonged drought led to depressed yields of 1053 kg ha^{-1} and elevated proteins of 172 g kg^{-1}. At 99 kg ha^{-1}, the level of soil NO3-N was elevated likely because of drought in previous years, which reduced crop yields and N uptake. High profile NO_3-N levels can occur in arid environments where farmers fertilize based on average yield goals and receive half of the expected yield leaving addition NO_3-N in the soil for the next crop. Grain yield decreased down slope from 1178, 1029, 1042 and 1014 kg ha^{-1} in order of management zone. Grain protein increased down slope: 168, 170, 175, and 174 g kg^{-1} respectively for MZ1, MZ2, MZ3, and MZ4. The combination of reduced yield and elevated protein in the down slope direction is indicative of hot dry growing season conditions. Improved yield potential and biomass in lower landscape positions is compromised by the lack of precipitation and heat during the grain fill period in late July. Soil water content as expected followed the catena and increased from 122, 128, 132, and 134 g kg^{-1} in order of upper, middle north, middle south and lower slopes.

At Malta 2001, average growing season precipitation led to average yields of 2462 kg ha^{-1} and above average grain quality of 147 g kg^{-1}. Initial soil N levels ranged from 36 kg ha^{-1} to 126 kg ha^{-1} with a field average of 75 kg ha^{-1}. Little difference was noted in yield, which increased only slightly from 2472 kg ha^{-1} in upper landscape positions to 2503 kg ha^{-1} in lower positions. Grain protein increased from 145 g kg^{-1} to 151g kg^{-1} in the down slope direction. The combination of low yield response and elevated protein with slope position was indicative of late season heat stress on the crop even though sufficient growing season precipitation had occurred. Soil water content for all MZs were nearly equal with MZ3 (south facing middle slopes) suffering greatest loss of soil water content 8 g kg^{-1} less than the other MZs.

At Malta 2002, near normal growing season precipitation of 17 cm was observed leading to average yields of 1989 kg ha^{-1} and above average grain protein of 161 g kg^{-1}. As expected, soil water content increased from 124 g kg^{-1} in upper positions to 151 g kg^{-1} in lower positions. Soil NO_3-N also followed this general trend and increased from 61 kg^{-1} in upper slopes to 103 kg ha^{-1} in lower slopes. Yield decreased from 2252 kg ha^{-1} in upper slope positions to 1771 kg ha^{-1} in lower slope positions. Grain protein increased from 155 g kg^{-1} in upper slopes to 167 g kg^{-1} in lower slopes. Similar to Malta 2001, near normal June precipitation combined with excessive heat during the grain fill period resulted in high yield potential in lower positions that was later compromised by July heat.

At Malta 2003, late planting and heat stress during the grain fill period resulted in depressed average yields of 1476 kg ha^{-1} and elevated protein concentration of 177 g kg^{-1}. Yields increased down slope with average yields of 1398 kg ha^{-1} in the upper positions and 1817 kg ha^{-1} in the lower positions. Average protein was relatively flat across all MZs varying little from the field average of 177 g kg^{-1}. A notable difference was found between soil NO_3-N levels and landscape position where average NO_3-N levels increased from 45 kg ha^{-1} in upper slope positions to 126 kg ha^{-1} in lower positions. Though growing season precipitation was above normal (105%), a combination of late planting and July heat suppressed yields.

At Malta 2004, average precipitation of 17 cm combined with cool growing season conditions resulted in above average yields of 2768 kg ha^{-1} and average protein content of 152 g kg^{-1}. Soil NO_3-N levels increased down slope: 42, 53, 64, and 82 kg ha^{-1} in order of MZ1, MZ2, MZ3, and MZ4. Grain yield was nearly equal between management zones except for MZ3 where yield was on average 200 kg ha^{-1} less than upper, middle north, and lower slope positions. Soil water also followed this trend and was at least 5 g kg^{-1} less in MZ3 than the other management zones possibly accounting for yield losses observed in MZ3. Average grain protein measurements were elevated in all four management zones indicating that optimum N rates had been reached.

Table 9. Mean and standard deviation for soil nitrate-nitrogen (NO_3-N) (0-60 cm), soil water content, and grain yield and protein concentration for all field sites and their management zones.

Management Zone	NO_3-N	Soil Water	Grain Yield	Grain Protein
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}
		Simpson-1994		
Whole Field	70 ± 47.1	131 ± 18.9	2449 ± 350	142 ± 21.2
Upper Slopes	61 ± 23.5	134 ± 24.8	2306 ± 353	142 ± 21.3
Middle Slopes-N	65 ± 41.5	137 ± 14.6	2369 ± 288	148 ± 20.2
Middle Slopes-S	70 ± 56.1	135 ± 19.8	2445 ± 295	139 ± 20.7
Lower Slopes	68 ± 32.5	134 ± 16.2	2717 ± 369	141 ± 22.7
		Simpson-1995		
Whole Field	46 ± 19.1	113 ± 20.5	3419 ± 632	106 ± 15.0
Upper Slopes	44 ± 12.3	111 ± 17.4	3120 ± 568	101 ± 14.0
Middle Slopes-N	58 ± 32.5	104 ± 22.7	3233 ± 556	106 ± 16.0
Middle Slopes-S	44 ± 13.5	111 ± 24.2	3467 ± 482	104 ± 14.0
Lower Slopes	47 ± 28.0	120 ± 17.0	3531 ± 480	111 ± 15.0
		Highwood 2001		
Whole Field	15 ± 7.9	123 ± 20.9	828 ± 312	159 ± 12.0
Upper Slopes	14 ± 10.1	122 ± 20.9	782 ± 268	160 ± 12.0
Middle Slopes-N	15 ± 7.9	124 ± 22.2	849 ± 327	159 ± 12.0
Middle Slopes-S	14 ± 6.7	115 ± 15.7	779 ± 260	154 ± 15.0
Lower Slopes	16 ± 7.9	121 ± 17.8	815 ± 282	158 ± 11.0
		Havre 2001		
Whole Field	99 ± 37.0	129 ± 21.8	1053 ± 365	172 ± 10.0
Upper Slopes	90 ± 31.4	122 ± 15.4	1178 ± 280	168 ± 6.0
Middle Slopes-N	91 ± 33.6	128 ± 19.4	1029 ± 365	170 ± 8.0
Middle Slopes-S	100 ± 54.9	132 ± 30.5	1042 ± 337	175 ± 13.0
Lower Slopes	100 ± 32.5	134 ± 21.3	1014 ± 375	174 ± 9.0

Table 9. Continued.

Management Zone	Soil NO3-N	Soil Water	Grain Yield	Grain Protein
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	g kg^{-1}
		Malta 2001		
Whole Field	75 ± 28.0	156 ± 20.1	2463 ± 543	147 ± 9.0
Upper Slopes	73 ± 41.5	159 ± 19.4	2477 ± 473	145 ± 10.0
Middle Slopes-N	84 ± 25.8	148 ± 17.1	2437 ± 536	146 ± 10.0
Middle Slopes-S	62 ± 13.5	161 ± 20.1	2459 ± 577	148 ± 8.0
Lower Slopes	84 ± 21.3	162 ± 23.8	2503 ± 702	151 ± 8.0
		Malta 2002		
Whole Field	76 ± 28.0	132 ± 29.7	1989 ± 427	161 ± 19.0
Upper Slopes	61 ± 21.3	124 ± 15.7	2235 ± 452	155 ± 19.0
Middle Slopes-N	74 ± 29.2	132 ± 27.1	2091 ± 469	158 ± 19.0
Middle Slopes-S	70 ± 19.1	122 ± 18.5	1919 ± 468	161 ± 20.0
Lower Slopes	103 ± 24.7	151 ± 44.4	1745 ± 492	168 ± 17.0
		Malta 2003		
Whole Field	72 ± 49.3	163 ± 16.7	1476 ± 611	177 ± 10.0
Upper Slopes	45 ± 14.6	164 ± 13.7	1401 ± 422	175 ± 10.0
Middle Slopes-N	65 ± 28.0	164 ± 11.8	1464 ± 439	176 ± 10.0
Middle Slopes-S	66 ± 29.2	158 ± 22.6	1362 ± 442	179 ± 10.0
Lower Slopes	126 ± 84.1	167 ± 11.0	1829 ± 894	178 ± 10.0
		Malta 2004		
Whole Field	59 ±30.3	137 ± 18.7	2768 ± 561	152 ± 11.4
Upper Slopes	42 ±16.8	138 ± 22.3	2814 ± 559	150 ± 12.1
Middle Slopes-N	53 ± 22.4	140 ± 15.4	2845 ± 599	150 ± 11.3
Middle Slopes-S	64 ± 30.3	133 ± 20.2	2628 ± 527	155 ± 10.8
Lower Slopes	82 ± 35.9	138 ± 16.9	2841 ± 668	154 ± 10.2

Crop Response by Nitrogen Treatment within Management Zones

Tables 10-17 show the average grain yields, proteins, and gross returns associated with each increment of applied N within the whole field and each management zone. Values for grain yield are derived from irregularly positioned yield monitor measurements. In general, increases in applied N produced modest increases in grain yield (<600 kg ha^{-1}) before tapering off, but they produced relatively large increases in grain protein (<50 g kg^{-1}) that increased linearly. The largest changes occurred at Simpson 1994 and Simpson 1995 where rainfall exceeded long-term averages. Though the unit price increases with protein concentration, the gross return is still largely a function of grain yield. As an aside, the relatively high yields at Simpson 1995 were accompanied by protein concentrations below 120 g kg^{-1}. This inverse yield-protein relationship is caused by dilution of grain N by a much greater biomass accumulation (Terman et al., 1969).

These relationships between applied N, and grain yield or gross return were used to estimate the average value of the change in either yield or protein, and ultimately establish the economic benefit derived from variable rate N management. For this study, partial budget analysis was used to evaluate these changes together with changes in costs. Each site-year was treated as a separate enterprise. The following section entitled "Partial Budget Analysis" compares the estimated net returns from uniform and variable rate N management as needed to identify the most profitable N management strategy.

Table 10. Grain yield, protein, grain price and gross return as affected by nitrogen (N) rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Simpson 1994. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate kg ha^{-1}	Grain yield kg ha^{-1}	Grain Protein g kg^{-1}	Price \$ kg^{-1}	Gross Return† \$ ha^{-1}
Upper Slopes MZ 1				
0	2027	120	0.1562	316.71
22	2218	120	0.1562	346.50
45	2390	146	0.1781	425.62
67	2448	154	0.1811	443.33
90	2325	152	0.1811	421.04
112	2424	160	0.1811	439.04
North Facing Middle Slopes MZ 2				
0	2367	122	0.1562	369.76
22	2398	143	0.1765	423.32
45	2445	150	0.1811	442.75
67	2382	157	0.1811	431.43
90	2278	161	0.1811	412.58
112	2337	162	0.1811	423.16
South Facing Middle Slopes MZ 3				
0	2257	114	0.1562	352.48
22	2343	118	0.1562	365.95
45	2512	143	0.1765	443.28
67	2526	144	0.1765	445.82
90	2498	152	0.1811	452.32
112	2501	156	0.1811	452.89
Lower Slopes MZ 4				
0	2718	118	0.1562	424.60
22	2738	129	0.1626	445.23
45	2906	140	0.1750	508.60
67	2700	152	0.1811	489.02
90	2600	150	0.1811	470.79
112	2564	166	0.1811	464.29
Uniform Treatment				
0	2322	118	0.1562	362.63
22	2405	126	0.1606	386.18
45	2475	145	0.1781	440.85
67	2547	151	0.1811	461.24
90	2460	154	0.1811	445.51
112	2485	159	0.1811	449.98

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Table 11. Grain yield, protein, grain price and gross return as affected by applied N rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Simpson 1995. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate kg ha^{-1}	Grain yield kg ha^{-1}	Grain Protein g kg^{-1}	Price \$ kg^{-1}	Gross Return† \$ ha^{-1}
Upper Slopes MZ 1				
0	2933	90	0.1562	458.20
22	2825	97	0.1562	441.30
45	3048	98	0.1562	476.16
67	3563	119	0.1562	556.56
90	3389	114	0.1562	529.30
North Facing Middle Slopes MZ 2				
0	3114	98	0.1562	486.44
22	2954	92	0.1562	461.40
45	3621	108	0.1562	565.63
67	3528	115	0.1562	551.06
90	3377	114	0.1562	527.46
South Facing Middle Slopes MZ 3				
0	3151	97	0.1562	492.15
22	3264	97	0.1562	509.90
45	3388	106	0.1562	529.25
67	3686	118	0.1562	575.71
90	3477	110	0.1562	543.06
Lower Slopes MZ 4				
0	3423	99	0.1562	534.67
22	3611	98	0.1562	564.04
45	3739	106	0.1562	584.08
67	3938	123	0.1583	623.34
90	3819	115	0.1562	596.57
Uniform Treatment				
0	3103	96	0.1562	484.64
22	3299	96	0.1562	515.29
45	3470	104	0.1562	542.06
67	3697	120	0.1562	577.53
90	3522	112	0.1562	550.12

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Table 12. Grain yield, protein, grain price and gross return as affected by applied N rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Highwood 2001. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate $kg\ ha^{-1}$	Grain yield $kg\ ha^{-1}$	Grain Protein $g\ kg^{-1}$	Price $\$\ kg^{-1}$	Gross Return† $\$\ ha^{-1}$
		Upper Slopes MZ 1		
0	862	147	0.1781	153.57
37	725	159	0.1811	131.34
75	782	167	0.1811	141.70
112	750	171	0.1811	135.87
		North Facing Middle Slopes MZ 2		
0	885	144	0.1765	156.25
37	871	158	0.1811	157.76
75	871	164	0.1811	157.77
112	775	169	0.1811	140.30
		South Facing Middle Slopes MZ 3		
0	852	143	0.1726	150.32
37	703	145	0.1781	125.13
75	760	164	0.1811	137.68
112	692	169	0.1811	125.27
		Lower Slopes MZ 4		
0	838	147	0.1781	149.22
37	824	153	0.1811	149.30
75	797	165	0.1811	144.29
112	792	169	0.1811	143.44
		Uniform Treatment		
0	867	145	0.1781	154.37
37	832	157	0.1811	150.61
75	837	164	0.1811	151.65
112	773	169	0.1811	140.06

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Table 13. Grain yield, protein, grain price and gross return as affected by applied N rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Havre 2001. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate kg ha^{-1}	Grain yield kg ha^{-1}	Grain Protein g kg^{-1}	Price \$ kg^{-1}	Gross Return† \$ ha^{-1}
		Upper Slopes MZ 1		
0	1189	160	0.1811	215.38
22	1221	165	0.1811	221.07
45	1171	169	0.1811	212.15
67	1159	172	0.1811	209.89
90	1151	173	0.1811	208.46
		North Facing Middle Slopes MZ 2		
0	1003	162	0.1811	181.68
22	1064	168	0.1811	192.65
45	1053	171	0.1811	190.76
67	1023	176	0.1811	185.25
90	1027	177	0.1811	186.04
		South Facing Middle Slopes MZ 3		
0	1010	169	0.1811	182.98
22	1073	172	0.1811	194.28
45	1066	175	0.1811	193.07
67	1038	178	0.1811	188.01
90	1019	182	0.1811	184.45
		Lower Slopes MZ 4		
0	1027	164	0.1811	185.98
22	1015	170	0.1811	183.82
45	1079	175	0.1811	195.34
67	942	180	0.1811	170.60
90	1018	178	0.1811	184.28
		Uniform Treatment		
0	1043	163	0.1811	188.93
22	1077	169	0.1811	194.97
45	1082	173	0.1811	196.00
67	1015	177	0.1811	183.33
90	1038	177	0.1811	188.00

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Table 14. Grain yield, protein, grain price and gross return as affected by applied N rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Malta 2001. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate kg ha^{-1}	Grain yield kg ha^{-1}	Grain Protein g kg^{-1}	Price \$ kg^{-1}	Gross Return† \$ ha^{-1}
Upper Slopes MZ 1				
0	2394	131	0.1647	394.36
22	2520	138	0.1725	434.75
45	2519	146	0.1781	448.71
67	2492	152	0.1811	451.35
90	2445	155	0.1811	442.73
North Facing Middle Slopes MZ 2				
0	2397	134	0.1673	401.08
22	2455	140	0.1750	429.62
45	2468	147	0.1781	439.50
67	2420	154	0.1811	438.34
90	2456	155	0.1811	444.77
South Facing Middle Slopes MZ 3				
0	2347	137	0.1699	398.68
22	2483	143	0.1765	438.25
45	2495	148	0.1796	448.04
67	2601	153	0.1811	471.02
90	2403	157	0.1811	435.18
Lower Slopes MZ 4				
0	2389	144	0.1765	421.72
22	2394	147	0.1781	426.31
45	2562	151	0.1811	464.02
67	2593	156	0.1811	469.55
90	2576	158	0.1811	466.57
Uniform Treatment				
0	2369	136	0.1699	402.52
22	2473	141	0.1750	432.73
45	2501	148	0.1796	449.21
67	2505	154	0.1811	453.68
90	2465	156	0.1811	446.36

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Table 15. Grain yield, protein, grain price and gross return as affected by applied N rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Malta 2002. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate kg ha^{-1}	Grain yield kg ha^{-1}	Grain Protein g kg^{-1}	Price \$ kg^{-1}	Gross Return† \$ ha^{-1}
Upper Slopes MZ 1				
0	2134	130	0.1647	351.48
22	2247	144	0.1765	396.56
45	2301	158	0.1811	416.78
67	2374	168	0.1811	429.96
90	2203	176	0.1811	398.94
North Facing Middle Slopes MZ 2				
0	1915	137	0.1699	325.43
22	2186	144	0.1765	385.84
45	2207	160	0.1811	399.61
67	2203	171	0.1811	362.68
90		175	0.1811	394.77
South Facing Middle Slopes MZ 3				
0	1963	135	0.1699	333.53
22	1925	151	0.1811	348.67
45	1971	166	0.1811	356.87
67	2067	173	0.1811	374.28
90	1932	181	0.1811	349.85
Lower Slopes MZ 4				
0	1691	149	0.1796	303.76
22	1808	161	0.1811	327.45
45	1872	165	0.1811	338.94
67	1799	176	0.1811	325.83
90	1679	182	0.1811	304.10
Uniform Treatment				
0	1930	137	0.1699	327.88
22	2047	149	0.1796	367.68
45	2096	162	0.1811	379.67
67	2070	172	0.1811	374.96
90	2006	179	0.1811	363.26

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Table 16. Grain yield, protein, grain price and gross return as affected by applied N rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Malta 2003. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate kg ha^{-1}	Grain yield kg ha^{-1}	Grain Protein g kg^{-1}	Price \$ kg^{-1}	Gross Return† \$ ha^{-1}
Upper Slopes MZ 1				
0	1312	163	0.1811	237.61
22	1477	172	0.1811	267.46
45	1386	181	0.1811	251.00
67	1427	184	0.1811	258.49
North Facing Middle Slopes MZ 2				
0	1442	167	0.1811	261.12
22	1554	174	0.1811	281.41
45	1446	181	0.1811	261.93
67	1420	184	0.1811	257.17
South Facing Middle Slopes MZ 3				
0	1327	169	0.1811	240.30
22	1346	177	0.1811	243.68
45	1398	183	0.1811	253.19
67	1381	186	0.1811	250.10
Lower Slopes MZ 4				
0	1933	170	0.1811	350.03
22	1820	176	0.1811	329.56
45	1686	182	0.1811	305.31
67	1813	184	0.1811	328.33
Uniform Treatment				
0	1471	167	0.1811	266.45
22	1508	176	0.1811	273.05
45	1450	182	0.1811	262.57
67	1482	185	0.1811	268.30

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Table 17. Grain yield, protein, grain price and gross return as affected by applied N rate for four management zones (MZ1, MZ2, MZ3, and MZ4) at Malta 2004. Applied N rate that corresponds to fertilizer N recommendations is denoted by light shading.

N Rate kg ha^{-1}	Grain yield kg ha^{-1}	Grain Protein g kg^{-1}	Price \$ kg^{-1}	Gross Return† \$ ha^{-1}
Upper Slopes MZ 1				
0	2750	137	0.1699	467.23
22	2764	147	0.1781	492.22
45	2881	156	0.1811	521.75
67	2869	159	0.1811	519.52
North Facing Middle Slopes MZ 2				
0	2806	142	0.1750	491.06
22	2769	148	0.1796	497.24
45	2894	152	0.1811	524.07
67	2895	158	0.1811	524.27
South Facing Middle Slopes MZ 3				
0	2611	147	0.1796	464.98
22	2607	152	0.1811	472.07
45	2594	159	0.1811	469.80
67	2711	162	0.1811	490.97
Lower Slopes MZ 4				
0	2788	148	0.1796	500.66
22	2749	151	0.1811	497.89
45	2861	156	0.1811	518.04
67	2963	159	0.1811	536.60
Uniform Treatment				
0	2726	143	0.1765	481.20
22	2710	150	0.1811	490.80
45	2794	156	0.1811	506.02
67	2840	160	0.1811	514.41

†Gross return is the product of average grain yield in each N treatment and price determined by average protein in each N treatment.

Partial Budget Analysis

Simpson 1994

Variable rate N management yielded 169 kg more grain ha^{-1} and an extra \$30 ha^{-1} in gross return primarily in MZ3 (south facing, middle slopes) due to an additional 23 kg of N ha^{-1} that was applied (Table 18). Despite a slight loss in grain yield (-38 kg ha^{-1}) in

MZ4 (lower slopes), the value of the grain was increased up to \$50 ha^{-1} due to improved grain protein, which captured a greater premium. However, this increased revenue was not enough to offset additional fertilizer, VRT, and soil sampling costs resulting in a loss of about \$9 ha^{-1}. There was no change in grain yields or proteins in MZ1 and MZ2 likely because of the 22 kg ha^{-1} N rate that equaled uniform management. With no source of income in MZ1 and MZ2 a cost of \$12.68 kg^{-1} was the only item considered in the partial budget. The overall total average net return to precision N management was \$14.05 ha^{-1} after the average net returns are weighted by the percentage of area comprised by the management zones [\$14.05 ha^{-1} = (-\$12.68×0.19) + (-\$12.68×0.21) + (\$48.01×0.43) + (-\$8.97×0.17)]. Additional revenue was obtained from EQIP payments, which amounted to about \$35 ha^{-1} for a total net return of \$48.62. Without EQIP payments, net returns from variable rate N management would have been only \$14 ha^{-1} (\$48.61 - \$34.57 = \$14.04).

Table 18. Partial budget for spatially variable N management in Simpson-1994.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 22 kg of N ha^{-1}			
Change in grain yield†	0	0.1562	0.00
Change in value of grain‡	2218	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			4.15
Total average costs			12.68
Net return			-12.68
North Facing Middle Slopes (MZ 2) 22 kg of N ha^{-1}			
Change in grain yield†	0	0.1765	0.00
Change in value of grain‡	2398	0.0	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			4.15
Total average costs			12.68
Net return			-12.68
South Facing Middle Slopes (MZ 3) 45 kg of N ha^{-1}			
Change in grain yield†	169	0.1765	29.82
Change in value of grain‡	2512	0.0203	50.99
Total average gross returns			80.81
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			4.15
Total average costs			32.80
Net return			48.01
Lower Slopes (MZ 4) 67 kg of N ha^{-1}			
Change in grain yield†	-38	0.1811	-6.88
Change in value of grain‡	2700	0.0185	49.95
Total average gross returns			43.07
Added VRT costs			8.53
Change in N costs	45	0.8747	39.36
Change in soil sampling costs			4.15
Total average costs			52.04
Net return			-8.97
Total net return to variable rate N management= (-\$12.68×0.19) + (-\$12.68×0.21) + (\$48.01×0.43) + (-\$8.97×0.17)			14.05
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			48.62

†The change in grain yield in each management zone over the actual uniform N rate.

‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

Simpson 1995

Yield was increased by 298 kg ha^{-1} in MZ3 and by 199 kg ha^{-1} in MZ4 in response to additional N (Table 19). In MZ4, there was a slight improvement in grain protein as well. The increase in grain yield and quality totaled more than \$39 ha^{-1}, more than covering the costs for fertilizer, equipment, and information in these zones. In contrast, yield reductions of 223 kg ha^{-1} and 667 kg ha^{-1} were observed in MZ1 and MZ2, and likely resulted from 23 kg ha^{-1} under application of N. Consequently, gross income was reduced by almost \$35 ha^{-1} and \$104 ha^{-1}. The savings in N fertilizer from under applying did not adequately compensate for the loss in yield in these zones. The overall total average net return to variable rate N management was -\$14.14 ha^{-1} after the average net returns are weighted by the percentage of area comprised by the management zones [-\$14.14 ha^{-1} = (-\$30.41×0.20) + (-\$99.77×0.14) + (\$11.61×0.40) + (\$4.83×0.26). Additional EQIP payments of approximately \$35 ha^{-1} sufficiently compensated for the losses and associated costs incurred in MZ1 and MZ2 resulting in a positive net return of about \$20 ha^{-1}. In this case study, variable rate N fertilization gave greater returns than uniform N fertilization only because of added EQIP payments. Without these payments, variable rate N management would not have been more profitable than uniform N management.

Table 19. Partial budget for spatially variable N management in Simpson-1995.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 22 kg of N ha^{-1}			
Change in grain yield†	-223	0.1562	-34.83
Change in value of grain‡	2825	0.00	0.00
Total average gross returns			-34.83
Added VRT costs			8.53
Change in N costs	-23	0.8747	-20.12
Change in soil sampling costs			7.17
Total average costs			-4.42
Net return			-30.41
North Facing Middle Slopes (MZ 2) 22 kg of N ha^{-1}			
Change in grain yield†	-667	0.1562	-104.19
Change in value of grain‡	2954	0.00	0.00
Total average gross returns			-104.19
Added VRT costs			8.53
Change in N costs	-23	0.8747	-20.12
Change in soil sampling costs			7.17
Total average costs			-4.42
Net return			-99.77
South Facing Middle Slopes (MZ 3) 67 kg of N ha^{-1}			
Change in grain yield†	298	0.1562	46.55
Change in value of grain‡	3686	0.00	0.00
Total average gross returns			46.55
Added VRT costs			8.53
Change in N costs	22	0.8747	19.24
Change in soil sampling costs			7.17
Total average costs			34.94
Net return			11.61
Lower Slopes (MZ 4) 67 kg of N ha^{-1}			
Change in grain yield†	199	0.1583	31.50
Change in value of grain‡	3938	0.0021	8.27
Total average gross returns			39.77
Added VRT costs			8.53
Change in N costs	22	0.8747	19.24
Change in soil sampling costs			7.17
Total average costs			34.94
Net return			4.83
Total net return to variable rate N management= (-\$30.41×0.20) + (-\$99.77×0.14) + (\$11.61×0.40) + (\$4.83×0.26)			-14.14
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			20.43

†The change in grain yield in each management zone over the actual uniform N rate.
‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

Highwood 2001

Variable rate N management, based on N recommendations derived from yield goals and soil tests, did not improve overall yield or save fertilizer within MZ1 or MZ2 likely because the N application equaled that of uniform N management (Table 20). Additionally, slight grain yield decreases in MZ3 and MZ4 apparently resulted from over fertilization of 37 kg of N ha^{-1}. The negative impact of over fertilizing under drought conditions is not only loss in grain yield, but also increased fertilizer costs resulting in a loss of about \$58 and \$47 respectively for MZ3 and MZ4. The overall total average net return to variable rate N management was -\$22.16 ha^{-1} after the average net returns are weighted by the percentage of area comprised by the management zones. An EQIP payment of \$34.57 ha^{-1}would compensate for the losses in revenue in MZ3 and MZ4 such that gross return is \$12.41 ha^{-1}. Without EQIP payments; however, variable rate N management would not have been more profitable than uniform N management.

Table 20. Partial budget for spatially variable N management in Highwood-2001.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 75 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	782	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			4.85
Total average costs			13.38
Net return			-13.38
North Facing Middle Slopes (MZ 2) 75 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	871	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			4.85
Total average costs			13.38
Net return			-13.38
South Facing Middle Slopes (MZ 3) 112 kg of N ha^{-1}			
Change in grain yield†	-68	0.1811	-12.31
Change in value of grain‡	692	0.00	0.00
Total average gross returns			-12.31
Added VRT costs			8.53
Change in N costs	37	0.8747	32.36
Change in soil sampling costs			4.85
Total average costs			45.74
Net return			-58.05
Lower Slopes (MZ 4) 112 kg of N ha^{-1}			
Change in grain yield†	-5	0.1811	-0.91
Change in value of grain‡	792	0.00	0.00
Total average gross returns			-0.91
Added VRT costs			8.53
Change in N costs	37	0.8747	32.36
Change in soil sampling costs			4.85
Total average costs			45.74
Net return			-46.65
Total net return to variable rate N management= (-\$13.38×0.21) + (-\$13.38×0.55) + (-\$58.05×0.07) + (-\$46.65×0.17)			-22.16
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			12.41

†The change in grain yield in each management zone over the actual uniform N rate.
‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

Havre 2001

In 2001, which was a year of drought at the Havre site, did not produce conditions favorable to a grain yield response to N fertilizer application. Consequently, uniform and variable rate N management systems were similar in terms of levels of grain yield and grain protein. Since the N treatment rate in MZ1, MZ2 and MZ3 was the same as uniform treatment, a loss in net return of -\$14.64 ha^{-1} was noted resulting from increased VRT and soil sampling costs (Table 21). In MZ4 a slight loss in yield of 12 kg ha^{-1} combined with additional fertilizer costs of about \$22 ha^{-1} resulted in an overall loss in net returns of \$36.05 ha^{-1}. The overall total average net return to variable rate N management was about -\$22 ha^{-1} after the average net returns are weighted by the percentage of area comprised by the management zones. A positive difference in revenue was derived from EQIP payments, which favored variable rate N management by >\$12 ha^{-1}. These EQIP payments would offset the added costs of soil sampling, variable rate equipment, and needed information. Without EQIP payments; however, variable rate N management would not have been more profitable than uniform N management.

Table 21. Partial budget for spatially variable N management in Havre-2001.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 0 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	1189	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			6.11
Total average costs			14.64
Net return			-14.64
North Facing Middle Slopes (MZ 2) 0 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	1003	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			6.11
Total average costs			14.64
Net return			-14.64
South Facing Middle Slopes (MZ 3) 0 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	1010	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			6.11
Total average costs			14.64
Net return			-14.64
Lower Slopes (MZ 4) 22 kg of N ha^{-1}			
Change in grain yield†	-12	0.1811	-2.17
Change in value of grain‡	1015	0.00	0.00
Total average gross returns			-2.17
Added VRT costs			8.53
Change in N costs	22	0.8747	19.24
Change in soil sampling costs			6.11
Total average costs			33.88
Net return			-36.05
Total net return to variable rate N management= (-\$14.64×0.18) + (-\$14.64×0.32) + (-\$14.64×0.16) + (-\$36.05×0.34)			-21.92
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			12.65

†The change in grain yield in each management zone over the actual uniform N rate.

‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

Malta 2001

Variable rate N management, which applied 22 kg ha^{-1} more N than uniform management, led to more grain of greater quality in MZ3 (12 kg ha^{-1}) and MZ4 (168 kg ha^{-1}) (Table 22). However, these increases were enough to offset additional fertilizer, VRT and soil sampling costs in MZ4, but not MZ3. Consequently, average net returns was about -\$26 ha^{-1} in MZ3 and \$2 ha^{-1} in MZ4. In contrast, changes in yield were negative in MZ1 and MZ2 possibly because no N was applied versus uniform management, which applied 22 kg ha^{-1}. Fertilizer savings in MZ1, and MZ2 were not enough to offset losses in both yield and quality. In fact, losses of about \$36 and \$25 ha^{-1} were observed for MZ1 and MZ2. With the inclusion of EQIP payments of about \$35, the overall total average net return to variable rate N management was \$10.32 ha^{-1} after the average net returns are weighted by the percentage of area comprised by the management zones. Without EQIP payments; however, variable rate N management would not have been more profitable than uniform N management.

Table 22. Partial budget for spatially variable N management in Malta-2001.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 0 kg of N ha^{-1}			
Change in grain yield†	-126	0.1647	-20.75
Change in value of grain‡	2394	-0.0078	-18.67
Total average gross returns			-39.42
Added VRT costs			8.53
Change in N costs	-22	0.8747	-19.24
Change in soil sampling costs			7.50
Total average costs			-3.21
Net return			-36.21
North Facing Middle Slopes (MZ 2) 0 kg of N ha^{-1}			
Change in grain yield†	-58	0.1673	-9.70
Change in value of grain‡	2397	-0.0077	-18.46
Total average gross returns			-28.16
Added VRT costs			8.53
Change in N costs	-22	0.8747	-19.24
Change in soil sampling costs			7.50
Total average costs			-3.21
Net return			-24.95
South Facing Middle Slopes (MZ 3) 45 kg of N ha^{-1}			
Change in grain yield†	12	0.1796	2.16
Change in value of grain‡	2495	0.0031	7.73
Total average gross returns			9.89
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			7.50
Total average costs			36.15
Net return			-26.26
Lower Slopes (MZ 4) 45 kg of N ha^{-1}			
Change in grain yield†	168	0.1811	30.42
Change in value of grain‡	2562	0.0030	7.69
Total average gross returns			38.11
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			7.50
Total average costs			36.15
Net return			1.96
Total net return to variable rate N management= (-\$36.21×0.27) + (-\$24.95×0.36) + (-\$26.26×0.22) + (\$1.96×0.15)			-24.25
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			10.32

†The change in grain yield in each management zone over the actual uniform N rate.
‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

Malta 2002

Variable rate N management differed from uniform N management only in MZ3 where 22 kg more N ha^{-1} was applied (Table 23). Here, the change in yield was 46 kg ha^{-1} and change in gross return was about \$8 ha^{-1} favoring variable rate N management. However, the additional revenue generated was not enough to cover the additional VRT costs. The overall total average net return to variable rate N management was -\$17.11 ha^{-1} after the average net returns are weighted by the percentage of area comprised by the management zones. EQIP payments were more than sufficient to overcome costs of soil sampling, equipment, and information needed to implement variable rate management. Without EQIP payments; however, variable rate N management would not have been more profitable than uniform N management.

Table 23. Partial budget for spatially variable N management in Malta-2002.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 22 kg of N ha^{-1}			
Change in grain yield†	0	0.1765	0.00
Change in value of grain‡	2247	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			5.50
Total average costs			14.03
Net return			-14.03
North Facing Middle Slopes (MZ 2) 22 kg of N ha^{-1}			
Change in grain yield†	0	0.1765	0.00
Change in value of grain‡	2186	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			5.50
Total average costs			14.03
Net return			14.03
South Facing Middle Slopes (MZ 3) 45 kg of N ha^{-1}			
Change in grain yield†	46	0.1811	8.33
Change in value of grain‡	1971	0.00	0.00
Total average gross returns			8.33
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			5.50
Total average costs			34.15
Net return			-25.82
Lower Slopes (MZ 4) 22 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	1808	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			5.50
Total average costs			14.03
Net return			-14.03
Total net return to variable rate N management= (-\$14.03×0.21) + (-\$14.03×0.26) + (-\$25.82×0.29) + (-\$14.03×0.24)			-17.46
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			17.11

†The change in grain yield in each management zone over the actual uniform N rate.
‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

Malta 2003

Grain yield was increased by 113 kg ha^{-1} in MZ4 and 52 kg ha^{-1} in MZ3 resulting from variable rate N management (Table 24). Consequently, gross returns were increased by about \$20 ha^{-1} in MZ4 and \$9 ha-1 in these zones. Positive net returns of about \$20 ha^{-1} were observed in MZ4 while MZ3 had negative net returns of about -\$30 ha^{-1} resulting primarily from increased fertilizer costs. As excessive N fertilization during vegetative growth coupled with drought stress may reduce yield and grain weight (Brown and Petrie, 2006), the increase in yield in MZ4 might be due to the zero N rate in this zone.

Though growing season rainfall was 105% of long-term, the excessively hot temperatures that occurred at this site after flowering would have increased water deficits, and shortened the grain filling period, especially in upper slopes. Including EQIP payments the overall total average net return to variable rate N management was \$11.03 ha^{-1} after the average net returns are weighted by the percentage of area comprised by the management zones. Without EQIP payments, the variable rate N management would not have been more profitable than uniform N management.

Table 24. Partial budget for spatially variable N management in Malta-2003.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 45 kg of N ha^{-1}			
Change in grain yield†	-91	0.1811	-16.48
Change in value of grain‡	1386	0.00	0.00
Total average gross returns			-16.48
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			11.00
Total average costs			39.65
Net return			-56.13
North Facing Middle Slopes (MZ 2) 22 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	1554	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			11.00
Total average costs			19.53
Net return			-19.53
South Facing Middle Slopes (MZ 3) 45 kg of N ha^{-1}			
Change in grain yield†	52	0.1811	9.42
Change in value of grain‡	1398	0.00	0.00
Total average gross returns			9.42
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			11.00
Total average costs			39.65
Net return			-30.23
Lower Slopes (MZ 4) 0 kg of N ha^{-1}			
Change in grain yield†	113	0.1811	20.46
Change in value of grain‡	1933	0.00	0.00
Total average gross returns			20.46
Added VRT costs			8.53
Change in N costs	-22	0.8747	-19.24
Change in soil sampling costs			11.00
Total average costs			0.29
Net return			20.17
Total net return to variable rate N management= (-\$56.13×0.18) + (-\$19.53×0.26) + (-\$30.23×0.39) + (\$20.17×0.17)			-23.54
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			11.03

†The change in grain yield in each management zone over the actual uniform N rate.
‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

Malta 2004

In MZ1, the same N rate was used for uniform and variable rate N management, and thus no change in grain yield and grain protein was noted (Table 25). However, a loss in net return of -\$14.88 ha^{-1} resulted from the increased VRT and soil sampling costs. Spatially variable N management applied 22 kg ha^{-1} more N in MZ2, MZ3, and MZ4, which resulted in 125 kg more grain ha^{-1} in MZ2 and 112 kg more grain ha^{-1} in MZ4. It is not known why the change in yield is negative in MZ3. Though average gross returns derived from increased yield were positive in MZ2 and MZ4, they were not enough to offset the change in cost of N fertilization from adopting variable rate technologies. Consequently, the total net return resulting from a change to precision N management was -\$20.13 ha^{-1} after the net returns are weighted by the percentage of area comprised by the management zones. Total net return would have been \$14.52 ha^{-1} when the partial budget analysis allows for the EQIP payment of \$34.57 ha^{-1}. Clearly, without EQIP, spatially variable N management would not have been more profitable than uniform N management.

Table 25. Partial budget for spatially variable N management in Malta-2004.

Item	**kg ha^{-1}**	**\$ kg^{-1}**	**\$ ha^{-1}**
Upper Slopes (MZ 1) 22 kg of N ha^{-1}			
Change in grain yield†	0	0.1811	0.00
Change in value of grain‡	2764	0.00	0.00
Total average gross returns			0.00
Added VRT costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			6.35
Total average costs			14.88
Net return			-14.88
North Facing Middle Slopes (MZ 2) 45 kg of N ha^{-1}			
Change in grain yield†	125	0.1811	22.64
Change in value of grain‡	2894	0.0015	4.34
Total average gross returns			26.98
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			6.35
Total average costs			35.00
Net return			-8.02
South Facing Middle Slopes (MZ 3) 45 kg of N ha^{-1}			
Change in grain yield†	-13	0.1811	-2.35
Change in value of grain‡	2594	0.00	0.00
Total average gross returns			-2.35
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			6.35
Total average costs			35.00
Net return			-37.35
Lower Slopes (MZ 4) 45 kg of N ha^{-1}			
Change in grain yield†	112	0.1811	20.28
Change in value of grain‡	2861	0.00	0.00
Total average gross returns			20.28
Added VRT costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			6.35
Total average costs			35.00
Net return			-14.72
Total net return to variable rate N management= (-\$14.88×0.27) + (-\$8.02×0.26) + (-\$37.35×0.31) + (-\$14.72×0.16)			-20.13
Added EQIP payment			25.93
Added yield observation payment			8.64
Total EQIP Payments			34.57
Total net return including EQIP payments			14.52

†The change in grain yield in each management zone over the actual uniform N rate.
‡Change in value of grain is the difference in price determined by protein measurements between each management zone and the actual uniform N rate.

A Posteriori Analysis

The post-harvest N response curves within each field and its management zones were used to identify the N treatment rates that would have optimized grain yields and dollar returns (Tables 26-33). These ideal, economically optimal N rates were used to gage the economic performance of *a priori* variable rate N management that had been based on yield potentials and limited soil test information at planting. Economically optimal net returns were computed by subtracting all variable costs from total gross returns with and without EQIP payments. The results, summarized in Table 34, compare the economically optimal net returns resulting from uniform N management and its variable rate counterpart.

If variable rate N management improves agronomic returns by increasing N within areas needing more N for yield and reducing fertilizer costs by reducing N within areas needing less N, then one would expect net returns from variable rate management to be greater than that from uniform management. Despite applying less fertilizer in Simpson 1994 and Simpson 1995 and increasing crop N response in the other fields, variable rate management returned from \$2 ha^{-1} to \$20 ha^{-1} less than uniform management (Table 34). Apparently, variable rate N management was less profitable than uniform N management because of greater operating costs. On the other hand, dollar returns from variable rate N management were >\$20 more per hectare than uniform management only when EQIP payments were available to offset the added costs. These *a posterori* results confirm the previous *a priori* results in which variable rate N application was mainly profitable in the presence of EQIP payments.

Table 26. Simpson-1994 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP \$ ha^{-1}	Gross Returns With EQIP \$ ha^{-1}	Variable† Costs \$ ha^{-1}	Net Returns‡ Without EQIP \$ ha^{-1}	Net Returns With EQIP \$ ha^{-1}
Upper Slopes MZ 1					
0	316.71	351.28	12.68	304.03	338.60
22	346.50	381.07	31.92	314.58	349.15
45	425.62	460.19	52.04	373.58	408.15
67	443.33	477.90	71.28	372.05	406.62
90	421.04	455.61	91.40	329.64	364.21
112	439.04	473.61	110.65	328.39	362.96
North Facing Middle Slopes MZ 2					
0	369.76	404.33	12.68	357.08	391.65
22	423.32	457.89	31.92	391.39	425.96
45	442.75	477.32	52.04	390.71	425.28
67	431.43	466.00	71.28	360.15	394.72
90	412.58	447.15	91.40	321.18	355.75
112	423.16	457.73	110.65	312.51	347.08
South Facing Middle Slopes MZ 3					
0	352.48	387.05	12.68	339.80	374.37
22	365.95	400.52	31.92	334.02	368.59
45	443.28	477.85	52.04	391.24	425.81
67	445.82	480.39	71.28	374.54	409.11
90	452.32	486.89	91.40	360.91	395.48
112	452.89	487.46	110.65	342.25	376.82
Lower Slopes MZ 4					
0	424.60	459.17	12.68	411.92	446.49
22	445.23	479.80	31.92	413.31	447.88
45	508.60	543.17	52.04	456.56	491.13
67	489.02	523.59	71.28	417.74	452.31
90	470.79	505.36	91.40	379.38	413.95
112	464.29	498.86	110.65	353.64	388.21
Uniform Treatment*					
0	362.63		0.00	362.63	
22	386.18		19.24	366.94	
45	440.85		39.36	401.49	
67	461.24		58.60	402.64	
90	445.51		78.72	366.78	
112	449.98		97.97	352.01	

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 27. Simpson-1995 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP \$ ha^{-1}	Gross Returns With EQIP \$ ha^{-1}	Variable† Costs \$ ha^{-1}	Net Returns‡ Without EQIP \$ ha^{-1}	Net Returns With EQIP \$ ha^{-1}
Upper Slopes MZ 1					
0	458.20	493.17	15.70	442.50	478.07
22	441.30	476.87	34.94	406.35	441.92
45	476.16	511.73	55.06	421.10	456.67
67	556.56	592.13	74.30	482.25	517.82
90	529.30	564.87	94.42	434.88	470.45
North Facing Middle Slopes MZ 2					
0	486.44	522.01	15.70	470.74	506.31
22	461.40	496.97	34.94	426.46	462.03
45	565.63	601.20	55.06	510.57	546.14
67	551.06	586.63	74.30	476.75	512.32
90	527.46	563.03	94.42	433.03	468.60
South Facing Middle Slopes MZ 3					
0	492.15	527.72	15.70	476.45	512.02
22	509.90	545.47	34.94	474.96	510.53
45	529.25	564.82	55.06	474.19	509.76
67	575.71	611.28	74.30	501.40	536.97
90	543.06	578.63	94.42	448.64	484.21
Lower Slopes MZ 4					
0	534.67	570.24	15.70	518.97	554.54
22	564.04	599.61	34.94	529.09	564.66
45	584.08	619.65	55.06	529.02	564.59
67	623.34	658.91	74.30	549.03	584.60
90	596.57	632.14	94.42	502.15	537.72
Uniform Treatment*					
0	484.64		0.00	484.64	
22	515.29		19.24	496.04	
45	542.06		39.36	502.70	
67	577.53		58.60	518.93	
90	550.12		78.72	471.40	

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 28. Highwood-2001 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP \$ ha^{-1}	Gross Returns With EQIP \$ ha^{-1}	Variable† Costs \$ ha^{-1}	Net Returns‡ Without EQIP \$ ha^{-1}	Net Returns With EQIP \$ ha^{-1}
			Upper Slopes MZ 1		
0	153.57	189.14	13.38	140.19	175.76
37	131.34	166.91	45.74	85.60	121.17
75	141.70	177.27	78.98	62.72	98.29
112	135.87	171.44	111.35	24.53	60.10
			North Facing Middle Slopes MZ 2		
0	156.25	191.82	13.38	142.87	178.44
37	157.76	193.33	45.74	112.01	147.58
75	157.77	193.34	78.98	78.79	114.36
112	140.30	175.87	111.35	28.95	64.52
			South Facing Middle Slopes MZ 3		
0	150.32	185.89	13.38	136.94	172.51
37	125.13	160.70	45.74	79.39	114.96
75	137.68	173.25	78.98	58.70	94.27
112	125.27	160.84	111.35	13.93	49.50
			Lower Slopes MZ 4		
0	149.22	184.79	13.38	135.84	171.41
37	149.30	184.87	45.74	103.56	139.13
75	144.29	179.86	78.98	65.31	100.88
112	143.44	179.01	111.35	32.09	67.66
			Uniform Treatment*		
0	154.37		0	154.37	
37	150.61		32.36	118.25	
75	151.65		65.60	86.05	
112	140.06		97.97	42.09	

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 29. Havre-2001 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP \$ ha^{-1}	Gross Returns With EQIP \$ ha^{-1}	Variable† Costs \$ ha^{-1}	Net Returns‡ Without EQIP \$ ha^{-1}	Net Returns With EQIP \$ ha^{-1}
			Upper Slopes MZ 1		
0	215.38	250.95	14.64	200.74	236.31
22	221.07	256.64	33.88	187.19	222.76
45	212.15	247.72	54.00	158.14	193.71
67	209.89	245.46	73.24	136.65	172.22
90	208.46	244.03	93.36	115.10	150.67
			North Facing Middle Slopes MZ 2		
0	181.68	217.25	14.64	167.04	202.61
22	192.65	228.22	33.88	158.77	194.34
45	190.76	226.33	54.00	136.76	172.33
67	185.25	220.82	73.24	112.01	147.58
90	186.04	221.61	93.36	92.68	128.25
			South Facing Middle Slopes MZ 3		
0	182.98	218.55	14.64	168.34	203.91
22	194.28	229.85	33.88	160.40	195.97
45	193.07	228.64	54.00	139.07	174.64
67	188.01	223.58	73.24	114.77	150.34
90	184.45	220.02	93.36	91.09	126.66
			Lower Slopes MZ 4		
0	185.98	221.55	14.64	171.34	206.91
22	183.82	219.39	33.88	149.93	185.50
45	195.34	230.91	54.00	141.34	176.91
67	170.60	206.17	73.24	97.36	132.93
90	184.28	219.85	93.36	90.92	126.49
			Uniform Treatment*		
0	188.93		0.00	188.93	
22	194.97		19.24	175.73	
45	196.00		39.36	156.64	
67	183.88		58.60	125.28	
90	188.00		78.72	109.28	

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 30. Malta-2001 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP \$ ha^{-1}	Gross Returns With EQIP \$ ha^{-1}	Variable† Costs \$ ha^{-1}	Net Returns‡ Without EQIP \$ ha^{-1}	Net Returns With EQIP \$ ha^{-1}
Upper Slopes MZ 1					
0	394.36	429.93	13.38	380.98	416.55
22	434.75	470.32	32.62	402.13	437.70
45	448.71	484.28	52.74	395.97	431.54
67	451.35	486.92	71.98	379.36	414.93
90	442.73	478.30	92.10	350.62	386.19
North Facing Middle Slopes MZ 2					
0	401.08	436.65	13.38	387.70	423.27
22	429.62	465.19	32.62	396.99	432.56
45	439.50	475.07	52.74	386.76	422.33
67	438.34	473.91	71.98	366.35	401.92
90	444.77	480.34	92.10	352.67	388.24
South Facing Middle Slopes MZ 3					
0	398.68	434.25	13.38	385.30	420.87
22	438.25	473.82	32.62	405.63	441.20
45	448.04	483.61	52.74	395.29	430.86
67	471.02	506.59	71.98	399.03	434.60
90	435.18	470.75	92.10	343.07	378.64
Lower Slopes MZ 4					
0	421.72	457.29	13.38	408.34	443.91
22	426.31	461.88	32.62	393.69	429.26
45	464.02	499.59	52.74	411.28	446.85
67	469.55	505.12	71.98	397.57	433.14
90	466.57	502.14	92.10	374.47	410.04
Uniform Treatment*					
0	402.52		0.00	402.52	
22	432.73		19.24	413.49	
45	449.21		39.36	409.85	
67	453.68		58.60	395.08	
90	446.36		78.72	367.64	

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 31. Malta-2002 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP \$ ha^{-1}	Gross Returns With EQIP \$ ha^{-1}	Variable† Costs \$ ha^{-1}	Net Returns‡ Without EQIP \$ ha^{-1}	Net Returns With EQIP \$ ha^{-1}
Upper Slopes MZ 1					
0	351.48	387.05	14.03	337.45	373.02
22	396.56	432.13	33.64	362.92	398.49
45	416.78	452.35	53.25	363.53	399.10
67	429.96	465.53	72.86	357.10	392.67
90	398.94	434.51	92.47	306.46	342.03
North Facing Middle Slopes MZ 2					
0	325.43	361.00	14.03	311.40	346.97
22	385.84	421.41	33.64	352.20	387.77
45	399.61	435.18	53.25	346.36	381.93
67	362.68	398.25	72.86	289.81	325.38
90	394.77	430.34	92.47	302.30	337.87
South Facing Middle Slopes MZ 3					
0	333.53	369.10	14.03	319.50	355.07
22	348.67	384.24	33.64	315.03	350.60
45	356.87	392.44	53.25	303.62	339.19
67	374.28	409.85	72.86	301.42	336.99
90	349.85	385.42	92.47	257.37	292.94
Lower Slopes MZ 4					
0	303.76	339.33	14.03	289.73	325.30
22	327.45	363.02	33.64	293.80	329.37
45	338.94	374.51	53.25	285.68	321.25
67	325.83	361.40	72.86	252.97	288.54
90	304.10	339.67	92.47	211.63	247.20
Uniform Treatment*					
0	327.88		0.00	327.88	
22	367.68		19.61	348.06	
45	379.67		39.22	340.45	
67	374.96		58.83	316.13	
90	363.26		78.44	284.81	

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 32. Malta-2003 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP \$ ha^{-1}	Gross Returns With EQIP \$ ha^{-1}	Variable† Costs \$ ha^{-1}	Net Returns‡ Without EQIP \$ ha^{-1}	Net Returns With EQIP \$ ha^{-1}
Upper Slopes MZ 1					
0	237.61	273.18	19.53	218.08	253.65
22	267.46	303.03	38.77	228.69	264.26
45	251.00	286.57	58.89	192.11	227.68
67	258.49	294.06	78.13	180.36	215.93
North Facing Middle Slopes MZ 2					
0	261.12	296.69	19.53	241.59	277.16
22	281.41	316.98	38.77	242.63	278.20
45	261.93	297.50	58.89	203.04	238.61
67	257.17	292.74	78.13	179.03	214.60
South Facing Middle Slopes MZ 3					
0	240.30	257.87	19.53	220.77	256.34
22	243.68	279.25	38.77	204.90	240.47
45	253.19	288.76	58.89	194.30	229.87
67	250.10	285.67	78.13	171.97	207.54
Lower Slopes MZ 4					
0	350.03	385.60	19.53	330.50	366.07
22	329.56	365.13	38.77	290.79	326.36
45	305.31	340.88	58.89	246.42	281.99
67	328.33	363.90	78.13	250.20	285.77
Uniform Treatment*					
0	266.45		0.00	266.45	
22	273.05		19.24	253.81	
45	262.57		39.36	223.20	
67	268.30		58.60	209.69	

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 33. Malta-2004 gross returns by N rate for determination of economic optimal N rate. Economic optimal nitrogen recommendations denoted by light shading.

N Rate kg ha^{-1}	Gross Returns Without EQIP $ ha^{-1}	Gross Returns With EQIP $ ha^{-1}	Variable† Costs $ ha^{-1}	Net Returns‡ Without EQIP $ ha^{-1}	Net Returns With EQIP $ ha^{-1}
Upper Slopes MZ 1					
0	467.23	502.80	14.88	452.35	487.92
22	492.22	527.79	34.49	457.73	493.30
45	521.75	557.32	54.10	467.65	503.22
67	519.52	555.09	73.71	445.81	481.38
North Facing Middle Slopes MZ 2					
0	491.06	526.63	14.88	476.18	511.75
22	497.24	532.81	34.49	462.75	498.32
45	524.07	559.64	54.10	469.97	505.54
67	524.27	559.84	73.71	450.56	486.13
South Facing Middle Slopes MZ 3					
0	464.98	500.55	14.88	450.10	485.67
22	472.07	507.64	34.49	437.58	473.15
45	469.80	505.37	54.10	415.69	451.26
67	490.97	526.54	73.71	417.26	452.83
Lower Slopes MZ 4					
0	500.66	536.23	14.88	485.78	521.35
22	497.89	533.46	34.49	463.40	498.97
45	518.04	553.61	54.10	463.94	499.51
67	536.60	572.17	73.71	462.89	498.46
Uniform Treatment*					
0	481.20		0.00	481.20	
22	490.80		19.61	471.18	
45	506.02		39.22	466.79	
67	514.41		58.83	455.58	

†Total variable costs in the amount of $8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Table 34. Economically optimal average returns for variable and uniform rate nitrogen (N) management with and without EQIP payments.

Treatment	Applied N kg ha^{-1}	Average Net Returns† Without EQIP \$ ha^{-1}	Average Net Returns‡ With EQIP payments \$ ha^{-1}
Simpson 1994			
Variable Rate	40	399.02	433.59
Uniform Rate*	67	402.64	402.64
Simpson 1995			
Variable Rate	64	511.24	546.81
Uniform Rate	67	518.93	518.93
Highwood 2001			
Variable Rate	0	140.70	176.27
Uniform Rate	0	154.37	154.37
Havre 2001			
Variable Rate	0	174.78	210.35
Uniform Rate	0	188.93	188.93
Malta 2001			
Variable Rate	25	402.42	437.99
Uniform Rate	22	413.49	413.99
Malta 2002			
Variable Rate	20	331.08	366.65
Uniform Rate	22	348.06	348.06
Malta 2003			
Variable Rate	10	246.53	282.10
Uniform Rate	0	266.45	266.45
Malta 2004			
Variable Rate	12	467.33	502.90
Uniform Rate	0	481.20	481.20

†Total variable costs in the amount of \$8.53 variable costs plus fertilizer and soil sampling costs.

‡Net returns without EQIP payments consider all costs without EQIP payment benefits.

*The uniform treatment considers only costs associated with fertilizer application.

Lastly, variable rate N management must accurately match N requirements to crop N demands for this practice to be profitable. Unfortunately, most of the actual, *a priori* N recommendations did not agree with the economically optimal, *a posteriori* N recommendations. Of the 16 N management scenarios, comprising both N management systems across eight fields, four had actual N recommendations that were optimal, four had actual N recommendations that were less than optimal, and eight were greater than optimal (Fig. 10). Net returns were negative, due to under fertilization and loss in yield, when the actual N rate was less than the optimal N rate. In addition, net returns were negative when the actual N rate exceeded the optimal N rate because of the high cost associated with over fertilization and lack of yield response. Clearly, the conventional N recommendation methods largely failed to predict crop N demands and negatively affected profitability by either increasing N costs or reducing grain yields.

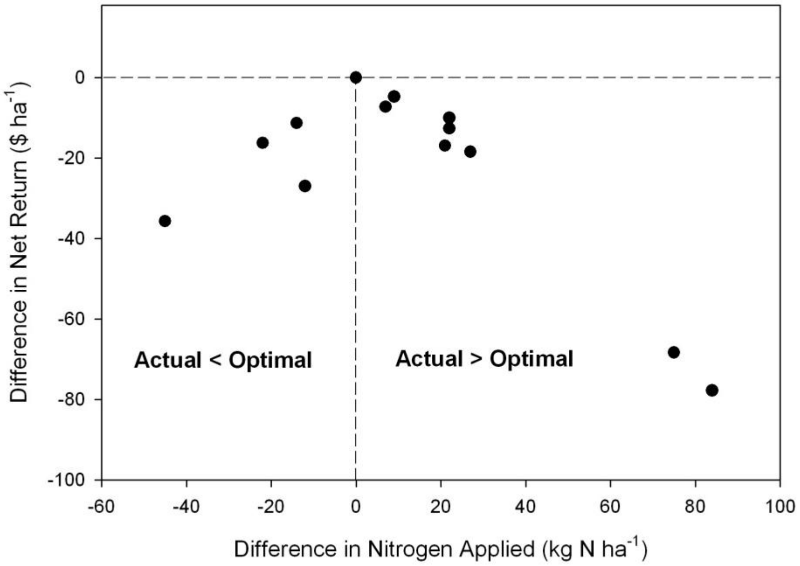


Figure 10. Average difference in nitrogen (N) applied between actual N rate and economically optimal N rate versus average difference in net return between actual N rate and economically optimal N rate.

SUMMARY AND CONCLUSIONS

Crop yields vary spatially within semiarid landscapes in accordance with spatial patterns in soil water content, soil fertility, and other biophysical factors. We tested the hypothesis that variable N rate programs applied to four management zones (upper slopes, north facing middle slopes, south facing middle slopes, and lower slopes) would improve agronomic and economic returns from hard red spring wheat. To examine this hypothesis, a partial budget analysis was applied to a series of eight strip trials conducted at diverse locations in northern Montana over an 11 year period. A one-way ANOVA, with allowance for spatial autocorrelation, failed to detect significant grain yield differences between uniform and variable rate N management. The experimental design that was used in this study, with its reliance upon field-size strips and production-scale equipment, limited the number of replicates that could be fit within a field and may have contributed to experimental error. Nevertheless, little evidence was found in this study that variable rate N management improved overall economic returns under the water limited conditions found in northern Montana. Increased dollar returns resulting from variable rate N management were evident at the eight sites only when EQIP payments were included as a part of gross returns. Without EQIP payments, variable rate N management was found to be less profitable than uniform N management. Similar results were obtained when post-harvest N response curves were used to identify the N treatment rates that would have optimized grain yields and dollar returns (*a posteriori*).

The impact of plant available water on spring wheat response to N was important in this study. Partial budget analysis showed that profitability of variable rate N management hinged largely on the magnitude of yield response to N fertilizer and was not greatly affected by improvements in grain protein. Because of Montana’s semiarid climate, spring wheat yield response to N was frequently insufficient to provide enough additional returns to cover the added cost associated with variable rate N management, including soil sampling, variable rate technology, and information costs. It is possible that the choice of spring wheat as a test crop may have impacted the conclusions of this study. For example, some agronomists believe winter wheat is more responsive to fertilizer N in Montana’s semiarid climate because of its early maturity and heat stress avoidance. Hence, the results of this study may not be applicable to winter wheat systems in Montana. Montana wheat growers have been much more reluctant to adopt variable N rate technologies, in contrast to growers from more humid regions. The results of this study indicate this reluctance may be valid.

Crop yields vary spatially within semiarid landscapes in accordance with spatial patterns in soil water content, soil fertility, and other biophysical factors. By accommodating this spatial variability, variable rate N management promises to improve agronomic and economic returns. To examine the above hypothesis, a partial budget analysis was applied to a series of eight strip trials with hard red spring wheat. These field-scale trials were conducted at diverse locations in northern Montana over an 11 year period and thus, demonstrated the agronomic and economic potential of precision N management for dryland wheat production in this region.

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