Net Returns from Terrain-Based Variable-Rate Nitrogen Management on Dryland Spring Wheat in Northern Montana

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ABSTRACT

Agricultural producers can use variable-rate application technology to vary N fertilizer within fields. This study was conducted to estimate changes in net returns from implementation of variable-rate N management (VNM) on hard red spring wheat (*Triticum aestivum* L.) in a summer-fallow region in northern Montana. Net return from uniform N management (UNM) traditionally used by producers was compared with that from VNM in eight dryland fields between 1994 and 2004. Field experiments consisted of a replicated series of four to six N rates applied within strips oriented with the length of each field. Management zones (MZs) were created by dividing the fields into upper slopes, south-facing middle slopes, north-facing middle slopes, and lower slopes. Nitrogen recommendations for MZs were based on soil N testing and expected yields. Grain yield data were obtained using a production-size combine equipped with a yield monitor. Mean grain protein and yield were similar between VNM and UNM. Yield differences were $<223 \text{ kg ha}^{-1}$ and averaged only 18 kg ha^{-1} . Grain yield did not differ significantly among N rates within MZs. In seven of the eight sites, net returns from VNM were up to US\$27.97 ha^{-1} less than from UNM and were not profitable if Environmental Quality Incentive Program payments of US\$6.36 ha^{-1} were considered as part of net income. Little evidence existed that VNM based on constructed MZs and predetermined N recommendations improves grain yields and profits or reduces N use in water-limited, summer-fallow systems of northern Montana.

The northern Great Plains is climatologically well suited to growing hard red spring wheat (HRSW) because of wet springs and cool dry summers. Northern Montana produces high-quality HRSW with superior milling and baking characteristics that is consistently sought by millers and bakers (North Dakota Wheat Commission, 2013). The majority of HRSW produced in this region is either milled for bread flour or blended with lower quality wheat. In many years, wheat buyers pay a premium over ordinary protein wheat to obtain spring wheat with a protein concentration (PC) between 140 g kg^{-1} (14%) and 150 g kg^{-1} (15%). Although premiums vary from year to year and are not known a priori, the highest protein premiums occur in years when the US (and world) winter wheat crop has below-average protein. Thus, producers have an economic incentive to consider the expected PC of their grain when choosing seed cultivars and fertilizer programs.

Adequate soil fertility is required to produce high-quality HRSW, and N is the most important nutrient for optimal grain

yield and PC (Engel et al., 2001). Nitrogen typically accounts for the largest percentage of a wheat producer's fertilizer inputs (National Agricultural Statistics Service, 2010). Variable-rate N management (VNM) involves the use of GPS and variable-rate application equipment to vary rates of N fertilizer according to spatial patterns in soil fertility and crop productivity in farm fields (Larson and Robert, 1991). Net returns from VNM can be greater than ordinary uniform N management (UNM) by either applying higher N rates onto areas of the field where yield will benefit from additional N or lower N rates to areas of the field that are less responsive to fertilizer N (Snyder et al., 1997, 1999).

Several VNM approaches have been developed to improve either cereal grain N use efficiency or economic returns. One approach relies on zone-based soil sampling at or near planting to determine plant-available N early in the growing season (Koch et al., 2004; Schepers et al., 2004; Franzen, 2008; Ferguson and Hergert, 2009). A second uses optical sensors to measure canopy reflectance to calculate a normalized difference vegetation index (NDVI) in a non-N-limiting strip and a parallel strip representative of the field (Raun et al., 2002). The ratios of the NDVIs are then used to calculate a fertilizer response index, and the variable N fertilizer recommendation is developed based on the yield potential of defined areas (1 m^2) across the field landscape. Optical sensing of the crop is thought to be more economically viable than soil sampling because the latter is expensive and potentially inaccurate (Biermacher et al., 2006, 2009; Boyer et al., 2011). On the

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Abbreviations: AR, autoregressive response; DEM, digital elevation model; EQIP, Environmental Quality Incentives Program; HRSW, hard red spring wheat; MZ, management zone; PC, protein concentration; UNM, uniform-rate nitrogen management; VNM, variable-rate nitrogen management.

Table 1. Location, area, N rates, and number of replications of N rates for eight site-years in northern Montana.

Site-year	Location	Area	N rates	Replications
		ha	kg ha ⁻¹	
Simpson-1994	48°50'3" N, 109°54'41" W	40	0, 22, 45, 67, 90, 112	3
Simpson-1995	48°49'55" N, 109°4'52" W	23	0, 22, 45, 67, 90	3
Highwood-2001	47°41'42" N, 110°29'57" W	34	0, 37, 75, 112	6
Havre-2001	48°31'48" N, 109°56'57" W	27	0, 22, 45, 67, 90	10
Malta-2001	48°24'52" N, 107°34'20" W	22	0, 22, 45, 67, 90	6
Malta-2002	48°25'53" N, 107°35'7" W	30	0, 22, 45, 67, 90	5
Malta-2003	48°26'4" N, 107°35'38" W	15	0, 22, 45, 67	8
Malta-2004	48°25'57" N, 107°34'50" W	26	0, 22, 45, 67	7

other hand, optical sensing may be unreliable in semiarid dryland cropping systems where the crop cover is often low (leaf area index <1.5) and crop growth and N response are controlled by the water supply (Eitel et al., 2009). Also, optical sensing approaches utilize in-season topdress application of N fertilizer to correct for potential N deficiency problems. Rainfall or irrigation is required for incorporation of fertilizer into the soil. In semiarid climates, rainfall amounts are often nominal and unpredictable, and thus topdress fertilizer N may remain at the surface for an extended period where it is unavailable for crop N uptake.

Economic studies of VNM on wheat in the semiarid western United States and Canada have been limited in number. In Montana, there was no significant economic improvement from applying fertilizer by soil type vs. by field despite the highest yielding soil types generating twice as much grain as the lowest yielding map units (Carr et al., 1991). In North Dakota, VNM based on grid soil sampling resulted in more yield of barley (*Hordeum vulgare* L.) than UNM but was less profitable because of added soil sampling and testing costs (Wibawa et al., 1993). In eastern Washington, Fiez et al. (1994) conducted a replicated N fertility trial with winter wheat at footslope, south backslope, shoulder, and north backslope positions and found net returns from variable-rate N application to be US\$6 ha⁻¹ greater than uniform N application. In Saskatchewan, Beckie et al. (1997) found that variable-rate N fertilization returned C\$10 ha⁻¹ more than uniform fertilization when fertilizer recommendations were based on soil test N levels within zones defined from upper, middle, and lower slopes in hummocky terrain.

Crop productivity in semiarid environments is determined largely by plant-available water (Brown and Carlson, 1990) and the manner in which soil water, soil fertility, and other crop growth determining factors are distributed across the landscape (Moore et al., 1993). Yield potential is typically lower on upper slopes because of shallow, eroded soils and greater on lower slopes because of deeper soils (Gregorich and Anderson, 1985; Moulin et al., 1994). This observation forms a basis for subdividing fields into management zones (MZs) consisting of upper, middle, and lower slopes and determining plant-available N levels in these zones (Beckie et al., 1997; Nolan et al., 1995; Pennock and Corre, 2001; Long et al., 2002).

Few studies have investigated the profitability of VNM in summer-fallow production systems in the northern Great Plains where average growing season precipitation plus stored soil water is often <350 mm. The objective of this study was to compare the grain yield and economic returns of VNM and UNM based on eight site-years and soil sampling of terrain-based MZ. The results will help establish the economic feasibility of this approach for dryland wheat production in this region.

MATERIALS AND METHODS

Field Experiments

Eight field experiments were conducted on eight production fields between 1994 and 2004 near Simpson, Havre, Malta, and Highwood in northern Montana (Table 1). Fields near Simpson, Havre, and Malta were in a wheat–fallow rotation, while the field near Highwood was annually cropped in a winter wheat–spring wheat rotation. Soils are derived from glacial till parent material and are mapped as Telstad-Joplin loams (fine-loamy, mixed, superactive, frigid Aridic Argiustolls) at the Simpson and Malta sites, Bearpaw-Vida clay loams (fine-loamy, mixed, superactive, frigid Typic Argiustolls) at Highwood, and Phillips-Elloam complex (Typic Eutroboralfs–Typic Natriboralfs) at Havre.

Elevation measurements were collected at each study site using a survey-grade GPS receiver along parallel transects separated by 12 m in complex hummocky terrain or 18 m in gentle rolling terrain. Data from a base receiver were used to correct the elevation values to within 4 cm in both the horizontal and vertical planes. Digital elevation models (DEMs, 5-m spacing) were generated using point kriging in ArcView 3.2 (ESRI). A DEM was 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). The LandMapR terrain modeling software developed by MacMillan (2003) was used to compute 15 land classes defined by slope curvature and slope gradient (Fig. 1). Using ArcView, a land class value was extracted within 1 m of each yield point. Land classes were grouped into upper slopes, middle slopes, and lower slopes. The aspect module of ArcView was then used to compute the direction of slope and split the middle slopes into north- and south-facing slopes. Four MZs were established: upper slopes, south-facing middle slopes, north-facing middle slopes, and lower slopes (Fig. 2A).

The basis for the four MZs is that crop yield potential usually increases from upper to lower slopes in response to increasing soil depth and plant-available water. Slope position effects on the soil water holding capacity in glacial till landscapes of the northern Great Plains may occur when tillage erosion has resulted in soil loss and reduced rooting depth in upper slopes vs. soil deposition and increased rooting depth in lower slopes (Moulin et al., 1994; Schumacher et al., 1999). A difference between north- and south-facing slopes is that the latter receive more direct sunlight and will lose more soil water to evaporation.

Soil cores were collected at numerous, irregularly distributed points within each field. Spacing between points varied between 30 and 50 m. Each 120-cm core was divided into increments of 0 to 15, 15 to 60, 60 to 90, and 90 to 120 cm at Simpson-1994 and -1995

Fig. 1. Block diagram of the Havre-2001 site with overlay of 15 land classes that were computed using the terrain modeling procedures of MacMillan et al. (2000). Map legend shows the name of each land class and its associated slope position.

and Malta-2002. Cores were collected to 90 cm and divided into 0 to 30, 30 to 60, and 60 to 90 cm at Highwood-2001 and 0 to 15, 15 to 60, and 60 to 90 cm at Havre-2001 and Malta-2001. At Malta-2003 and -2004, cores were collected to 60 cm and divided into 0-to-15 and 15- to 60-cm increments. Soil samples were analyzed for $\text{NO}_3\text{-N}$ following KCl extraction (Mulvaney, 1996).

Urea fertilizer (46-0-0) was applied in a series of incremental N rates to create replicated, parallel N strips across a field (Fig. 2B). Nitrogen rates ranged from 0 to 112 kg ha^{-1} in six increments at Simpson-1994 and four at Highwood-2001; 0 to 90 kg ha^{-1} in five increments at Simpson-1995, Havre-2001, Malta-2001, and Malta-2002; and from 0 to 67 kg ha^{-1} in four increments at Malta-2003 and Malta-2004 (Table 1). Strip width varied with the size of the fertilizer applicator. Urea fertilizer was broadcast at Simpson and Highwood by means of a truck-mounted applicator with a 18.3-m boom followed by seeding of wheat with either a disk- or hoe-type seeder. At the other sites, fertilizer was banded below the seed using an air seeder. At Havre, each N strip was established with two passes of a 3.1-m Concord air seeder. Strips at Malta were established with a single pass of a 6.1-m Concord air seeder.

Strips were cut using a combine harvester equipped with a GPS receiver and yield monitor (Model YM2000, AgLeader Inc.) set to read at 1-s intervals. At least 300 grain samples were collected by hand from the combine's grain bin filling auger. Samples were collected in either 20- or 30-s intervals as the combine traveled along a strip and were labeled with the Coordinated Universal Time of collection. After harvest, samples were cleaned of foreign material and analyzed for PC using a whole-grain near-infrared analyzer. Protein measurements were standardized to 120 g kg^{-1} (12%) grain moisture content in accordance with market standards for HRSW. The position of each yield and protein observation was corrected by subtracting an 11-s difference between cutting the crop at the header and collecting the grain on the top of the clean grain elevator. Histograms 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.

Creation of Data Sets

Soil test N measurements and expected yield goals were used to derive N recommendations based on fertility guidelines for HRSW (Jones and Jacobsen, 2001). Yield goals (kg ha^{-1}) were

based on farmer experience and were multiplied by $0.0467 \text{ kg N kg}^{-1}$ grain to calculate the N requirement (kg ha^{-1}). Soil $\text{NO}_3\text{-N}$ measurements were subtracted from the N requirement to produce the N recommendations. Two experimental N management scenarios were evaluated:

1. Uniform N management with an expected yield goal of 2018 kg ha^{-1} . Soil test N was determined by averaging soil $\text{NO}_3\text{-N}$ values within a field.
2. Variable N management based on MZ with variable yield goals of 1682, 2018, 2354, and 2690 kg ha^{-1} in low, moderate, moderately high, and high productivity zones. Soil test N was determined for each MZ by averaging soil $\text{NO}_3\text{-N}$ values within a MZ analogous to compositing samples into one for laboratory analysis.

Collecting 10 to 15 randomly distributed surface cores and six to eight subsoil cores is considered acceptable for representing the average nutrient status in 16.2-ha areas (Ferguson and Hergert, 2009). In this study, the sample number ranged from five in 2.9 ha (Simpson-1995) to 50 in 19 ha (Highwood-2001) (Table 2). Therefore, the zone sampling approach of this study was deemed appropriate.

Figure 2C shows the method of simulating uniform-rate or variable-rate treatments across a field. Fertilizer rates for UNM consisted of the N strips that corresponded with the N recommendation for the entire field. The VNM program consisted of the N strips that corresponded with the N recommendations for all MZs within the field. If uniform- and variable-rate treatments shared the same N strip within a MZ, then the yield measurements within the N strip were randomly allocated to one group for UNM or one for VNM (Fig. 2C, see inset). At Simpson-1994 and Simpson-1995, each strip was wide enough to cut into two parallel, non-overlapping swaths, and so the observations in one swath could be allocated to one group and those of the second swath to the other. In all other trials, the strips were wide enough to accommodate only one combine swath. In that case, yield and protein observations in a data series were randomly assigned to either a variable group or a uniform group if both shared the same N rate within the same MZ.

Each data set was also analyzed using expected crop responses to applied N, the costs of N, and the expectations of harvest prices based on available information at planting. The N rate that

optimized net dollar returns for UNM was predicted from a plot of net return vs. applied N. For VNM, the N rates that optimized net returns were predicted from plots of mean grain yield vs. applied N using the data within each MZ. Thus, only the yield observations of the N rates that were predicted to optimize grain net returns, either for the whole field or for each MZ, were selected for analysis.

Each yield and protein record of a data series was classified by treatment strip number, replication, N fertilizer rate, and MZ. The Proc Univariate of SAS (SAS Institute) was used to compute the mean, standard deviation, and minimum and maximum values for yield and gross return with respect to N rate, N rate within a MZ, and variable and uniform N management. The average PC within an N strip of a MZ was used to establish the wheat price to be associated with the grain yield received from variable or uniform N management. Gross returns were computed on a US dollars per kilogram basis by multiplying the grain yield times the average Portland market price for Dark Northern Spring Wheat during the 11 yr (1994–2004). Prices paid to producers were obtained from the Montana Wheat and Barley Committee. Portland prices are reported in US dollars

per bushel to the whole percentage of PC (Pacific Northwest Grain Market News, <http://www.ams.usda.gov/mnreports/lswpnwgrain.pdf>) but county elevators pay premiums to the nearest 0.25% PC, with premiums applied between 14 (140 g kg⁻¹) and 16% and discounts between 12 and 14%. Protein premiums and discounts are rounded down to the nearest 0.25% (i.e., 142.4 g kg⁻¹ protein is priced at the 140 g kg⁻¹ price), as is common in this market. Thus, protein values were rounded down to the nearest 0.25% to establish the price for this wheat.

Statistical Analyses

The irregularly spaced yield data were extracted to the cells of a regular square grid using the Geoprocessing Wizard extension to ArcView 3.2 as needed for lagged autoregressive response (AR) modeling (Upton and Fingleton, 1985). The SAS code of Griffith (1993) was used to estimate an AR model having the form

$$Y = \rho CY + \beta_0 + \varepsilon \quad [1]$$

where Y is grain yield, ρ is the spatial autocorrelation parameter, C is a spatial weights matrix, β is a coefficient to be

Fig. 2. Block diagrams of the Havre-2001 site with overlays of (A) four management zones that were computed using terrain modeling procedures, (B) N trial design with sets of N rate organized into replicates that are oriented along the length of the field against a ridge and valley pattern, and (C) N management treatments created for comparison of variable-rate (0 and 22 kg N ha⁻¹, green colored strips in lower slope positions and red colored strips in remaining management zones) and uniform-rate (0 kg N ha⁻¹, red colored strips across field) fertilizer application. Black dots within the green-colored strip in the lower slopes are yield data points allocated to a data set for variable N management (inset). White dots within the red-colored strip in the lower slopes are yield points that are allocated to a data set for uniform management. Elsewhere, black and white dots appearing together within the same red-colored N strip shared the same N rate and thus are randomly allocated within the strip to either a data set for variable management or one for uniform management.

estimated, and ε are randomly distributed errors. This method transforms a variable containing spatial autocorrelation into one free of autocorrelation by partitioning the variance of the original georeferenced variable (Y) into variance that is attributable to autocorrelation and variance that is attributable to nonspatial effects (Griffith and Peres-Neto, 2006). The nonspatial variate that is adjusted for autocorrelation (Y_{adj}) is calculated by subtracting the variate containing the autocorrelation (ρCY) from the original variate (Y):

$$Y_{\text{adj}} = Y - (\rho CY - \rho\beta_0) \quad [2]$$

Ordinary statistical methods can then be used to test for associations between dependent and independent variables.

After this transformation, analysis of variance (ANOVA) was conducted using Proc GLM (SAS Institute) to determine if the effect of N on yield differed within the MZs of each field. The ANOVA model was

Table 2. Yield goal, soil sample number (n), soil test $\text{NO}_3\text{-N}$, N recommendation, and N applied in each field by site-year and its management zones.

Management zone	Yield Goal	n	Soil $\text{NO}_3\text{-N}$	N recommendation	N applied
	kg ha^{-1}			kg ha^{-1}	
Simpson-1994					
Whole field	2018	60	70	24	22
Upper slopes	1682	11	61	18	22
Middle north	2018	13	65	29	22
Middle south	2354	26	70	40	45
Lower slopes	2690	10	68	58	67
Simpson-1995					
Whole field	2018	39	52	42	45
Upper slopes	1682	8	49	30	22
Middle north	2018	5	65	29	22
Middle south	2354	16	49	61	67
Lower slopes	2690	10	53	73	67
Highwood-2001					
Whole field	2018	90	17	79	75
Upper slopes	1682	19	16	77	75
Middle north	2018	50	17	77	75
Middle south	2354	5	16	93	112
Lower slopes	2690	16	18	108	112
Havre-2001					
Whole field	2018	76	99	0	0
Upper slopes	1682	15	90	0	0
Middle north	2018	11	91	3	0
Middle south	2354	30	100	10	0
Lower slopes	2690	20	100	26	22
Malta-2001					
Whole field	2018	68	75	19	22
Upper slopes	1682	19	73	6	0
Middle north	2018	25	84	10	0
Middle south	2354	15	62	48	45
Lower slopes	2690	9	84	42	45
Malta-2002					
Whole field	2018	141	76	18	22
Upper slopes	1682	28	61	18	22
Middle north	2018	38	74	20	22
Middle south	2354	42	70	40	45
Lower slopes	2690	33	103	23	22
Malta-2003					
Whole field	2018	38	72	22	22
Upper slopes	1682	7	45	34	45
Middle north	2018	10	65	29	22
Middle south	2354	15	66	44	45
Lower slopes	2690	6	126	0	0
Malta-2004					
Whole field	2018	77	66	28	22
Upper slopes	1682	21	47	32	22
Middle north	2018	21	59	35	45
Middle south	2354	24	71	39	45
Lower slopes	2690	114	91	35	45

Table 3. Cost of materials and supplies used for uniform-rate and variable-rate N management.

Operation	Material or service	Unit	Price per unit	Units	Cost
			US\$	no. ha ⁻¹	US\$ ha ⁻¹
Soil sampling	custom service	field	165	—	4.15–11.00
Management zone delineation	custom service	ha	1.76	1.00	1.76
Fertilization	N	kg	0.87	0–112	0–97.4
Variable-rate N application	rate controller	—	14,000	—	4.45
Harvest	yield monitor	—	5,295	—	1.69
Harvest	GPS receiver	—	895	—	0.28
Harvest	mapping software	—	750	—	0.35

Table 4. Example partial budget by change in grain yield, grain value, and costs between uniform-rate and variable-rate N management (VNM) for the Simpson-1994 site by management zone (MZ).

Parameter	Rate	Cost	
	kg ha ⁻¹	US\$ kg ⁻¹	US\$ ha ⁻¹
Upper slopes (MZ 1), 22 kg N ha ⁻¹			
Change in grain yield†	0	0.1562	0.00
Change in value of grain‡	2218	0.00	0.00
Total avg. gross returns			0.00
Added VNM costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			4.15
Total avg. costs			12.68
Net return			–12.68
North-facing middle slopes (MZ 2), 22 kg N ha ⁻¹			
Change in grain yield	0	0.1765	0.00
Change in value of grain	2398	0.0	0.00
Total avg. gross returns			0.00
Added VNM costs			8.53
Change in N costs	0	0.8747	0.00
Change in soil sampling costs			4.15
Total avg. costs			12.68
Net return			–12.68
South-facing middle slopes (MZ 3), 45 kg N ha ⁻¹			
Change in grain yield	169	0.1765	29.82
Change in value of grain	2512	0.0203	50.99
Total avg. gross returns			80.81
Added VNM costs			8.53
Change in N costs	23	0.8747	20.12
Change in soil sampling costs			4.15
Total avg. costs			32.80
Net return			48.01
Lower slopes (MZ 4), 67 kg N ha ⁻¹			
Change in grain yield	–38	0.1811	–6.88
Change in value of grain	2700	0.0185	49.95
Total avg. gross returns			43.07
Added VNM costs			8.53
Change in N costs	45	0.8747	39.36
Change in soil sampling costs			4.15
Total avg. costs			52.04
Net return			–8.97
Net return to variable-rate N management (–US\$12.68 × 0.19) + (–US\$12.68 × 0.21) + (US\$48.01 × 0.43) + (–US\$8.97 × 0.17)			14.05
Added EQIP payment§			4.77
Added yield observation payment§			1.59
Total EQIP payments			6.36
Net return including EQIP payments			20.41

† 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.

§ Environmental Quality Incentives Program (EQIP) payment applied to 202 ha or about 18.4% of typical 1100-ha northern Montana farm.

$$Y_{\text{adj}} = \beta_0 + \beta_1 \text{AN} + \beta_2 R + \beta_3 \text{MZ} + \beta_4 (\text{AN} \times \text{MZ}) + \beta_5 (\text{AN} \times R \times \text{MZ}) + \epsilon \quad [3]$$

where Y_{adj} is spatially adjusted grain yield, AN is applied N, R is the replicate, MZ is the management zone, β are parameters, and ϵ is an error term. Regression terms were evaluated for significance using a partial F test (Type III sums of squares) with $\text{AN} \times R \times \text{MZ}$ used as the error term. Average wheat yields and net returns from VNM and UNM could not be statistically compared because the same N strip within certain MZs had been used twice to compute these returns.

Partial Budget Analysis

Economic benefits from VNM were determined using partial budget analysis, which focuses on only those cost and revenue items that change because of the adoption of a new practice. Changes in revenue from adopting VNM resulted from changes in the yield and value of grain. Changes in costs resulted from changes associated with soil sampling, MZ delineation, fertilizer, variable-rate control equipment, and yield mapping equipment and software (Table 3). Partial budgets were constructed for all eight sites by MZ. Total mean net return for a field was the sum of the net returns from each MZ weighted by the area of each MZ. Table 4 illustrates an example of a partial budget by cost and revenue item for the Simpson-1994 site.

Variable costs associated with VNM included soil sampling, zone delineation, fertilizer, hardware, and software. Although combines can be purchased with yield monitors and air seeders with variable-rate hardware installed, it was assumed that a producer does not own pre-installed equipment. Fixed ownership costs associated with other machinery were ignored because they do not change with N management strategy. All variable costs are based on an average size farm (about 1100 ha) in the north-central region of Montana (National Agricultural Statistics Service, 2009). Equipment costs were for acquiring a yield monitor, GPS receiver, and hardware and software for adapting an air seeder for variable-rate application.

Environmental Quality Incentives Program (EQIP) payments from the USDA–NRCS offset the costs of adopting new technologies for VNM. To participate, producers must delineate at least three MZs based on soil electrical conductivity maps, sequential yield maps, aerial imagery, grid soil sampling, or some other suitable method and apply fertilizer to the zones using a variable-rate applicator. In Montana, EQIP pays US\$25.93 ha⁻¹ with a maximum benefit of US\$5250 or enough money to use VNM on 202 ha. A yield mapping payment of US\$18.52 ha⁻¹ is included for the first year and US\$3.70 ha⁻¹ for the remaining 2 yr of a 3-yr contract. This benefit was averaged across the 3 yr (US\$8.64 ha⁻¹). A total EQIP payment of US\$34.57 ha⁻¹ for 202 ha was spread across a total of 1100 ha, which brought it to US\$6.35 ha⁻¹.

An initial investment in technology, information, and software is required to participate in VNM. Therefore, a 10% opportunity cost was considered for each item of the investment. Opportunity costs represent the next best alternative use for a producer's investment (Lowenberg-DeBoer, 2000). For instance, if a farmer could have reduced interest expenses by reducing debt rather than purchasing equipment, then the interest rate on the debt becomes the opportunity cost for investing in VNM. Information, technology, and software costs were treated as durable goods because they are capital

assets. These costs were spread across an assumed 4 yr of useful life. After the average annual cost of capital assets was established, the cost was divided by the number of productive hectares on a farm during a given year to calculate the cost in US dollars per hectare.

Fertilizer costs were calculated by multiplying the unit cost of N in urea by the application rate. Fertilizer costs were based on the average 2009 spring fertilizer price of US\$365 ton⁻¹ of urea, or US\$0.87 kg⁻¹ of N. Typically, 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 MZ (Franzen, 2008). Local fertilizer dealers charged US\$55 per field for soil sampling and laboratory analysis of a single composite sample. Added costs for soil sampling under VNM would entail one composite soil sample per MZ instead of one for the entire field. Four MZs were involved in this study and so the total cost difference was US\$165 per field ($3 \times 55 = 165$). Therefore, the cost difference per hectare for each field was US\$165 divided by the total hectares of the field.

Producers often use the services of companies to build variable-rate control maps for their farms. Information costs were quoted by LandMapper Environmental Solutions, Inc., at US\$1300 per section (640 acres = 259 ha) for acquiring a 30-m DEM from the 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 4-yr useful life and subject to a 10% opportunity cost. The opportunity cost equaled 10% of US\$1300, or US\$130, and the annual cost was US\$1300/4, or US\$325, which brought the total annual cost to US\$455 ($130 + 325 = 455$). The cost per hectare was US\$455 divided by 259 ha or US\$1.76 ha⁻¹.

Based on quotations from a local dealer, the cost of a yield monitor was US\$5295, and a suitable GPS receiver used with this monitor was US\$895. A producer must also purchase the variable-rate control system for their seed drill. A local vendor estimated this cost at ≤US\$14,000. This technology was treated as a 4-yr durable asset with a 10% opportunity cost spread across 1100 ha of the farm, which meant that the annual cost of the system was US\$4900 ($1400 + 3500 = 4900$) or US\$4.45 ha⁻¹ ($4900/1100 = 4.45$). Equipment costs of the yield monitor and GPS receiver were computed in the same way. In addition, mapping software is needed to satisfy EQIP requirements of producing as-applied N maps and yield maps. The SMS software package, priced at US\$750 from AgLeader Technology, Inc., satisfies this requirement. A maintenance fee of US\$120 is charged for each year the producer uses the software. Therefore, the total annual cost of the software across its 4-yr useful life is US\$385 or US\$0.35 ha⁻¹.

RESULTS AND DISCUSSION

Growing conditions were unusually dry in 2001 at Highwood and Havre, with above-normal July temperatures during grain filling (Table 5). In contrast, growing season rainfall was above the long-term average at Simpson-1995 in June and July so wheat experienced little drought stress. Precipitation was somewhat below average (87–89%) at Malta in 2001, 2002, and 2004, but July rainfall was above average during grain filling in 2001 and 2004. Seasonal rainfall was near normal at the Simpson-1995 and Malta-2003 sites, but July was dry with above-average temperatures during grain filling.

Table 5. Monthly precipitation (Precip.), average temperature (Temp.), and the fraction of long-term precipitation recorded at the nearest weather stations for eight sites in northern Montana.

Site-year†	Variable	April	May	June	July	Fraction of long-term
						%
Simpson-1994	Precip., mm	24.4 (19.6)‡	33.5 (41.4)	74.9 (60.2)	11.9 (33.8)	93
	Temp., °C	7.4 (6.0)	13.9 (12.1)	16.9 (16.3)	20.7 (20.3)	—
Simpson-1995	Precip., mm	22.4 (19.6)	37.8 (41.4)	148.6 (60.2)	58.7 (33.8)	173
	Temp., °C	4.8 (6.0)	11.6 (12.1)	16.6 (16.3)	18.6 (20.3)	—
Highwood-2001	Precip., mm	22.1 (35.6)	9.9 (75.4)	84.1 (90.2)	72.6 (38.6)	79
	Temp., °C	—	—	—	—	—
Havre-2001	Precip., mm	24.9 (25.9)	10.9 (45.7)	35.6 (65.3)	50.8 (36.6)	70
	Temp., °C	5.8 (6.6)	14.6 (12.6)	17.2 (16.9)	22.4 (21.1)	—
Malta-2001	Precip., mm	18.5 (24.9)	21.6 (58.7)	73.4 (66.0)	52.8 (41.9)	87
	Temp., °C	6.2 (7.3)	14.1 (13.1)	16.6 (17.9)	22.2 (21.3)	—
Malta-2002	Precip., mm	7.9 (24.9)	18.8 (58.7)	108.7 (66.0)	35.3 (41.9)	89
	Temp., °C	4.0 (7.3)	10.7 (13.1)	18.6 (17.9)	22.7 (21.3)	—
Malta-2003	Precip., mm	43.4 (24.9)	69.9 (58.7)	54.6 (66.0)	29.7 (41.9)	103
	Temp., °C	8.7 (7.3)	12.1 (13.1)	16.6 (17.9)	22.8 (21.3)	—
Malta-2004	Precip., mm	10.2 (24.9)	86.1 (58.7)	25.1 (66.0)	46.0 (41.9)	87
	Temp., °C	8.8 (7.3)	10.3 (13.1)	14.8 (17.9)	20.4 (21.3)	—

† Site and nearest NOAA cooperative weather station (with period of record in parentheses): Simpson, Simpson 6N (1931–2013); Malta, Malta 7E (1972–2013); Havre, Fort Assiniboine (1917–2013); Highwood, Highwood 7 NE (1948–2013). Temperature and precipitation data summaries for NOAA cooperative stations available online at <http://www.wrcc.dri.edu/climatedata/climsum/>.

‡ Long-term averages in parentheses.

Weighted Mean Nitrogen Rates, Grain Yields, and Grain Protein

The N applied for both management strategies ranged from 0 to 112 kg N ha⁻¹ across the eight sites (Table 1). The areal weighted rate of N fell between 7 and 84 kg ha⁻¹ for VNM and 0 and 75 kg N ha⁻¹ for UNM (Table 6). The average rate of N applied was lower under UNM at seven of the eight field sites. Compared with UNM, the N applied from VNM was 50% less at Malta-2001 but was up to 82% more on the remaining sites. Therefore, VNM based on zone sampling and university N recommendations did not reduce total fertilizer usage.

Weighted mean grain yield across all sites ranged from 838 to 3422 kg ha⁻¹ (Table 6), probably in response to differences in plant-available water. In general, field-average grain yields increased with growing season rainfall (April–July) in the 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%). The 2003 Malta yield departed from the trend because of heat stress during grain filling. Mean grain PC varied inversely to yield, from 178 to 104 g kg⁻¹. There was little practical difference in weighted mean grain yield and PC between the two N management strategies.

Crop Response to Applied Nitrogen within Management Zones

Grain yield was similar for UNM and VNM programs within the four MZs at each of the eight field locations. Yield differences never exceeded 223 kg ha⁻¹ and averaged only 18 kg ha⁻¹, indicating that the agronomic performance of the two management strategies was similar (Table 6). Despite having the greatest long-term precipitation, yields at Highwood were least due to abnormally dry conditions that were further compounded by continuous cropping. In contrast, summer fallow at the other sites probably improved the availability of water and N, and increased the yield

potential and nutrient requirement. In 2001, which was a dry year, UNM resulted in more N in south-facing middle slopes and lower slopes than UNM at Highwood, and more N in lower slopes than UNM at Havre. Overfertilizing with N reduces grain yield by stimulating increased vegetative growth that in turn depletes soil moisture before flowering and grain filling (Campbell et al., 1977). Therefore, the amount of N applied coupled with drought probably reduced yield and increased protein in these MZs.

Under above-average precipitation, such as at Simpson-1995, mean grain yield was greatest and PC was least. In water-limited environments, an inverse yield–protein relationship is attributed to dilution of a fixed amount of grain N by a much larger biomass with increases in plant-available water (Terman et al., 1969). At this location, upper and south-facing middle slopes under VNM received 50% less N than those under UNM and had decreased PC and yield, which would be expected if N was insufficient. In contrast, VNM, which applied 33% more N on lower slopes, increased yield and PC in this MZ. An exception occurred for north-facing middle slopes, where the yield change was negative, possibly due to overfertilization.

Long-term growing season precipitation was near normal at the Simpson and Malta sites during 1994, 2001, 2002, 2003, and 2004. Grain yield and PC was increased in south-facing middle slopes at Simpson-1994, Malta-2001, Malta-2002, and Malta-2003 and lower slopes at Malta-2001 and Malta-2004, where the variable N rate exceeded that of the uniform N rate. In contrast, grain yield and protein tended to decrease on upper and north-facing middle slopes at Malta-2001, where the N applied in the variable treatment was less than that in the uniform treatment, which suggests that N recommendations for VNM at this site were inaccurate.

For VNM, wheat yields increased from upper to lower slopes at Simpson-1994, Simpson-1995, and Malta-2003 (Table 7), where precipitation was near to above normal. In contrast, in 2001,

Table 6. Uniform N rate, variable N rate, change (Δ) in grain yield, change in grain protein, and area percentage by management zone, along with weighted mean N rate, weighted mean grain yield, and weighted grain protein at eight sites in northern Montana.

Parameter	Simpson		Highwood	Havre	Malta			
	1994	1995	2001	2001	2001	2002	2003	2004
<u>Upper slopes</u>								
Uniform N rate, kg ha ⁻¹	22	45	75	0	22	22	22	22
Variable N rate, kg ha ⁻¹	22	22	75	0	0	22	45	22
Δ Yield, kg ha ⁻¹ †	0	-223	0	0	-126	0	-91	0
Δ Protein, g kg ⁻¹	0	-2	0	0	-7	0	9	0
Area, %	19	20	21	18	27	21	18	27
<u>South-facing middle slopes</u>								
Uniform N rate, kg ha ⁻¹	22	45	75	0	22	22	22	22
Variable N rate, kg ha ⁻¹	45	22	112	0	45	45	45	45
Δ Yield, kg ha ⁻¹	169	-124	-68	0	12	46	52	-13
Δ Protein, g kg ⁻¹	25	-9	5	0	5	15	6	7
Area, %	21	14	55	32	36	26	26	26
<u>North-facing middle slopes</u>								
Uniform N rate, kg ha ⁻¹	22	45	75	0	22	22	22	22
Variable N rate, kg ha ⁻¹	22	67	75	0	0	22	22	45
Δ Yield, kg ha ⁻¹	0	-93	0	0	-58	0	0	125
Δ Protein, g kg ⁻¹	0	7	0	0	-6	0	0	4
Area, %	43	40	7	16	22	29	39	31
<u>Lower slopes</u>								
Uniform N rate, kg ha ⁻¹	22	45	75	0	22	22	22	22
Variable N rate, kg ha ⁻¹	67	67	112	22	45	22	0	45
Δ Yield, kg ha ⁻¹	-38	199	-5	-12	168	0	113	84
Δ Protein, g kg ⁻¹	23	17	4	6	4	0	-6	6
Area, %	17	26	17	34	15	24	17	16
<u>Weighted mean N rate‡, kg ha⁻¹</u>								
Uniform	22	45	75	0	22	22	22	22
Variable	40	52	84	7	11	29	31	39
<u>Weighted mean grain yield, kg ha⁻¹</u>								
Uniform	2354	3383	848	1061	2473	2057	1512	2718
Variable	2327	3422	838	1035	2402	2050	1561	2757
<u>Weighted mean grain protein, g kg⁻¹</u>								
Uniform	145	104	164	169	141	149	176	152
Variable	142	112	165	166	142	154	178	152

† Change in grain yield or grain protein when changing from uniform to variable N management.

‡ Mean net return weighted by percentage of management zone area.

which was the driest year, yields in upper slope positions at Havre and Malta were highest. Based on our experience, in dry years, upper slopes may yield best because coarser textured soils in these positions have more infiltration and release of the water that fell from short-duration, high-intensity thunderstorms than finer textured soils on lower slopes. At other locations, little difference in yield was observed between MZs, probably due to extreme dryness. The lack of a consistent relationship between slope position and grain yield indicates how weather can influence yield response to N application and makes it difficult to establish yield goals and use slope position to accurately construct MZs.

The autocorrelation parameter (ρ) accounted for a large proportion of variance in grain yield and was highly significant ($P > 0.05$) in each site-year (Table 7). Accordingly, grain yield significantly differed among MZs in most fields by ordinary ANOVA but only in a few fields by AR-based ANOVA. Maximum grain yield with N level ranged from 692 to 3938 kg ha⁻¹ across all site-years. Grain yield was increased by N fertilization in four out of eight site-years that received normal to above-normal precipitation. However, the

effect of the N $\times$ MZ interaction was insignificant, indicating that the response of grain yield to N did not vary significantly by MZ. One would not expect VNM to perform better than UNM if changing the N rate (increasing N on lower slopes or decreasing N on upper slopes) produced little yield response. An exception is Havre-2001, where the AR-based ANOVA showed a significant N $\times$ MZ interaction.

Net Returns

A decision to practice VNM would be based on the added revenue associated with an advantage in grain quality and/or yield minus the added cost of new equipment and soil sampling and net increases or decreases in N use. Table 8 shows partial budget analyses based on the grain quality and yield data at the eight sites and market prices at Portland, OR. Greater annual fixed costs for implementing variable-rate N application were associated with the purchase of a yield monitor, GPS receiver, and variable-rate control system for a grain drill. Greater variable costs include additional soil testing costs based on four MZs and the size of a field.

Table 7. Effect of N rate and management zone (MZ) on spring wheat yield for eight site-years in northern Montana.

Management zone	N rate	Simpson-1994	Simpson-1995	Havre-2001	Highwood-2001	Malta-2001	Malta-2002	Malta-2003	Malta-2004
	kg ha ⁻¹	kg ha ⁻¹							
Upper slopes	0	2027	2933	1189	862	2394	2134	1312	2750
	22	2218	2825	1221	—	2520	2247	1477	2764
	37	—	—	—	725	—	—	—	—
	45	2390	3048	1171	—	2529	2301	1386	2881
	67	2448	3563	1159	—	2492	2374	1427	2869
	75	—	—	—	782	—	—	—	—
	90	2325	3389	1151	—	2445	2203	—	—
	112	2424	—	—	750	—	—	—	—
North-facing middle slopes	0	2367	3114	1003	885	2397	1915	1442	2806
	22	2398	2954	1064	—	2455	2186	1554	2769
	37	—	—	—	871	—	—	—	—
	45	2445	3621	1053	—	2468	2207	1446	2894
	67	2382	3528	1023	—	2420	2203	1420	2895
	75	—	—	—	871	—	—	—	—
	90	2278	3377	1027	—	2456	2167	—	—
	112	2337	—	—	775	—	—	—	—
South facing middle slopes	0	2257	3151	1010	852	2347	1963	1327	2611
	22	2343	3264	1073	—	2483	1925	1346	2607
	37	—	—	—	703	—	—	—	—
	45	2512	3388	1066	—	2495	1971	1398	2594
	67	2526	3686	1038	—	2601	2067	1381	2711
	75	—	—	—	760	—	—	—	—
	90	2498	3477	1019	—	2403	1932	—	—
	112	2501	—	—	692	—	—	—	—
Lower slopes	0	2718	3423	1027	838	2389	1691	1933	2788
	22	2738	3611	1015	—	2394	1808	1508	2749
	37	—	—	—	824	—	—	—	—
	45	2906	3739	1079	—	2562	1872	1686	2861
	67	2700	3938	942	—	2593	1799	1813	2963
	75	—	—	—	797	—	—	—	—
	90	2600	3819	1018	—	2576	1679	—	—
	112	2564	—	—	792	—	—	—	—
Ordinary ANOVA									
N rate		0.017	0.002	0.308	0.063	0.117	0.014	0.699	0.031
MZ		0.000	0.000	0.000	0.025	0.012	0.000	0.000	0.000
N rate × MZ		0.139	0.998	0.105	0.786	0.906	0.125	0.850	0.749
Autoregressive response based ANOVA									
ρ		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N rate		0.007	0.021	0.178	0.065	0.149	0.020	0.308	0.014
MZ		0.278	0.131	0.012	0.196	0.479	0.000	0.009	0.013
N rate × MZ		0.447	0.999	0.025	0.773	0.693	0.130	0.399	0.802

Applying N using the variable-rate strategy consistently decreased farm profitability by up to US\$56 ha⁻¹ for upper and north-facing middle slopes at all eight sites. In most instances, the reduction in profit with VNM was a result of lower yields relative to uniform N and higher costs. Net returns from variable-rate placement were mostly negative for south-facing middle and lower slope positions. The additional N that was applied by VNM mostly increased grain quality and yield but not enough to offset the added fixed and variable costs of this practice. An increase in the cost of fertilizer N would be expected to decrease benefits from VNM further.

Overall, net returns from VNM vs. UNM were negative and unfavorable (> -US\$28 ha⁻¹) at all sites except Simpson-1994, where the net return was US\$14 ha⁻¹. At

Simpson-1994, differences in net return between UNM and VNM in south-facing middle slopes were sufficient to offset the costs and revenue losses in the remaining three MZs. When EQIP payments were included, variable-rate N fertilization based on zone sampling and university N recommendations was only profitable at Simpson-1994. However, EQIP payments are sufficient to cover only 202 ha per farm. Unless these acreage limits are expanded, only about one-fifth as much per hectare is available for a typical 1100-ha farm. Overall, these results are in contrast to those of Beckie et al. (1997), who found enhanced fertilizer use efficiency and improved economic returns when varying fertilizer N rates according to topography in hummocky, glaciated terrain of northern Saskatchewan, where more fertilizer N is required.

Table 8. Partial budget results for variable-rate N management (VNM) on eight site-years of dark northern spring wheat in northern Montana.

Item	Simpson-1994	Simpson-1995	Highwood-2001	Havre-2001	Malta-2001	Malta-2002	Malta-2003	Malta-2004
US\$ ha ⁻¹								
<u>Upper slopes</u>								
ΔYield	0.00	-34.83	0.00	0.00	-20.75	0.00	-16.48	0.00
ΔGrain value	0.00	0.00	0.00	0.00	-18.67	0.00	0.00	0.00
VNM costs	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
N costs	0.00	-20.12	0.00	0.00	-19.24	0.00	20.12	0.00
Sampling costs	4.15	7.17	4.85	6.11	7.50	5.50	11.00	6.35
Net return	-12.68	-30.41	-13.38	-14.64	-36.21	-14.03	-56.13	-14.88
<u>North-facing middle slopes</u>								
ΔYield	0.00	-14.53	0.00	0.00	-9.70	0.00	0.00	22.64
ΔGrain value	0.00	0.00	0.00	0.00	-18.46	0.00	0.00	4.34
VNM costs	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
N costs	0.00	-20.12	0.00	0.00	-19.24	0.00	0.00	20.12
Sampling costs	4.15	7.17	4.85	6.11	7.50	5.50	11.00	6.35
Net return	-12.68	-10.11	-13.38	-14.64	-24.95	14.03	-19.53	-8.02
<u>South-facing middle slopes</u>								
ΔYield	29.82	-19.37	-12.31	0.00	2.16	8.33	9.42	-2.35
ΔGrain value	50.99	0.00	0.00	0.00	7.73	0.00	0.00	0.00
VNM costs	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
N costs	20.12	19.24	32.36	0.00	20.12	20.12	20.12	20.12
Sampling costs	4.15	7.17	4.85	6.11	7.50	5.50	11.00	6.35
Net return	48.01	-54.31	-58.05	-14.64	-26.26	-25.82	-30.23	-37.35
<u>Lower slopes</u>								
ΔYield	-6.88	31.50	-0.91	-2.17	30.42	0.00	20.46	20.28
ΔGrain value	49.95	8.27	0.00	0.00	7.69	0.00	0.00	0.00
VNM costs	8.53	8.53	8.53	8.53	8.53	8.53	8.53	8.53
N costs	39.36	19.24	32.36	19.24	20.12	0.00	-19.24	20.12
Sampling costs	4.15	7.17	4.85	6.11	7.5	5.50	11.00	6.35
Net return	-8.97	4.83	-46.74	-36.05	1.96	-14.03	20.17	-14.72
<u>Weighted mean net return</u>								
Total†	14.05	-27.97	-22.16	-21.92	-24.25	-17.46	-23.54	-20.13
Total-EQIP‡	20.41	-21.61	-15.80	-15.56	-17.89	-11.10	-17.18	-13.77

† Mean net return weighted by percentage of management zone area.

‡ Weighted mean net return with USDA–NRCS Environmental Quality Incentive Payment.

Economically Optimum Nitrogen Rates and Sensitivity Analysis

The N rates that would have optimized net returns were identified based on the N responses of a site and its MZs (Table 7) and the last increment of N that gave the largest net return. These economically optimal N rates can be used to gauge the economic performance of variable-rate N management based on yield potentials and limited soil test information before planting. The results indicated VNM returning between US\$4 and US\$20 ha⁻¹ less than UNM (data not shown). Apparently, VNM was less profitable because of no yield benefit or N cost reduction. Except for Simpson-1994, returns from VNM were between US\$1 and US\$14 ha⁻¹ less than that of UNM when EQIP payments were available to help offset the added costs.

Variable rate N management must accurately match N requirements to crop N demands for this practice to be profitable. Unfortunately, most of the N recommendations did not agree with the optimal rates of N fertilizer, probably because of the aforementioned difficulty with predicting the influence of weather on crop N response. Of the 16 N management scenarios, comprising both N management systems across eight fields, four had N recommendations that were optimal, four were less than optimal,

and eight were greater than optimal (Fig. 3). Net returns were negative due to underfertilization and lower yields when the recommended N rate was less than the optimal N rate. In addition, net returns were negative when the recommended N rate exceeded the optimal N rate because of the additional N fertilizer costs without an accompanying yield improvement.

Recently, Whelan et al. (2012) used a randomized, replicated “small strip” experimental design to obtain site-specific information about optimum N response within management zones of dry-land fields. Multiple experiments were conducted for six seasons in three regions of the Australian Wheat Belt. Management zones were derived from maps of apparent electrical conductivity and historical yield maps. The optimal N rate for each zone was used to compute the potential gross margin from VNM for comparison with that achieved from UNM. Results on crop yield response to N showed that the difference in net return always favored VNM even when the N response functions were relatively flat and returns were expected to be poor in years of below-average rainfall. Their results suggested that economic benefits can be derived from VNM through the optimization of fertilizer application rates.

A sensitivity analysis was conducted to show the effect of various HRSW prices and changes in grain yield on net return in the

Table 9. Sensitivity of net return to changes (Δ) in grain yield, wheat price from US\$0.1248 to US\$0.4112, and protein premium for variable-rate N management for the Simpson-1994 site-year.

Δ Yield kg ha ⁻¹	Net return					
	US\$0.1248	US\$0.1821	US\$0.2393	US\$0.2966	US\$0.3539	US\$0.4112
	US\$ ha ⁻¹					
	No protein premium					
50	-21.78	-18.92	-16.05	-13.19	-10.33	-7.46
100	-15.54	-9.81	-4.09	1.64	7.37	13.10
150	-9.30	0.71	7.88	16.47	25.06	33.65
200	-3.06	8.39	19.85	31.30	42.76	54.21
250	3.18	17.50	31.82	46.13	60.45	74.77
300	9.42	26.60	43.78	60.96	78.15	95.33
350	15.56	35.70	55.75	75.79	95.84	115.89
400	21.90	44.81	67.72	90.62	113.54	136.44
	Protein premium of US\$0.05 kg ⁻¹					
50	-9.46	-6.60	-3.73	-0.87	1.99	4.86
100	-3.22	2.51	8.23	13.96	19.69	25.42
150	3.02	11.61	20.20	28.79	37.38	45.97
200	9.26	20.71	32.17	43.62	55.08	66.53
250	15.50	29.82	44.14	58.45	72.77	87.09
300	21.74	38.92	56.10	73.28	90.47	107.65
350	27.98	48.02	68.07	88.11	108.16	128.21
400	34.22	57.13	80.04	102.94	125.86	148.76

Fig. 3. Difference between actual and economically optimal rates of applied N vs. the difference in net return between actual and optimal rates of applied N.

most profitable site-year (Simpson-1994; Table 9). Grain prices ranged from US\$0.125 kg⁻¹ (US\$3.40 bu⁻¹) to US\$0.411 kg⁻¹ (US\$11.18 bu⁻¹) to capture extremes in market variability since 1999. Likewise, the change in grain yield ranged up to 400 kg ha⁻¹ to indicate potential year-to-year variability. Positive net returns are generated when the yield change is ≥ 250 kg ha⁻¹ at the relatively low grain price of US\$0.125 kg⁻¹ but are also possible from changes in yield as small as ≥ 50 kg ha⁻¹ if grain prices are sufficiently large. Returns are also shown to be positive for prices $\geq$ US\$0.125 kg⁻¹ and yield changes ≥ 50 kg ha⁻¹.

SUMMARY AND CONCLUSIONS

A partial budget analysis of field-size strip trials with dryland HRSW at eight locations in northern Montana found that VNM utilizing conventional soil tests, fertilizer N recommendations, and terrain-based MZs was not more profitable than UNM. The reasons can be traced to modest yield gains and N savings, nominal response to fertilizer N, and the inability to define MZs and

optimal N rates. Gross returns were largely a function of grain yield. If EQIP payments were included as a part of gross returns, VNM was still not more profitable than UNM at seven of the eight sites. Based on sensitivity analysis, VRN would generate greater net returns than UNM only with higher grain prices, in fields and growing seasons with larger yield potentials than found in this study, or both.

Varying N rates according to MZ based strictly on terrain analysis and soil available N levels may not be useful for land managers in semiarid landscapes who would like to conduct VNM based on an association between landscape position and soil water availability. Integrating terrain data with agronomic information (e.g., sequential yield maps, remotely sensed imagery, and farmer knowledge) might have better delineated MZs and contributed to greater crop N response than was found in this experiment. Clearly, a precise VNM method is needed to overcome the difficulties associated with drought and modest grain yields in the summer-fallow system of the semiarid northern Great Plains.

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