SK-17

1998

Final Report
Agricultural Development Fund
Project 95000063 Res 18BV

Agronomic and Economic Assessment of Variable Rate Fertilization

D. Pennock, F. Walley, M. Solohub

Project Number: 95000063 Res. 18BV

Project Title: Agronomic and Economic Assessment of Variable Rate Fertilization

Principal Investigators: Dr. Dan Pennock and Dr. F. L. Walley
Saskatchewan Centre for Soil Research
University of Saskatchewan
Saskatoon, Saskatchewan
S7N 5A8
Phone: (306) 966 6852
FAX: (306) 966 6881

Co-investigator: Mr. Garry Hnatowich
Research and Development
Saskatchewan Wheat Pool

Other Sponsors: Westco Fertilizers
Potash and Phosphate Institute
Russel Memory, Flexi-Coil

Final Report: June 1, 1999

(a) ABSTRACT/SUMMARY:

A collaborative field research study between the Department of Soil Science and the Saskatchewan Wheat Pool was initiated in 1996 to investigate the agronomic and economic feasibility of variable rate fertilizer application. The research sites were located on a hummocky, morainal landscape in the Black soil zone and the results of the study are most appropriate for comparable landscapes in Saskatchewan.

Results from this study indicate that management units (upper-, mid- and lower slope) developed on the basis of image analysis of black and white aerial photographs were agronomically meaningful for both wheat and canola production. Importantly, mean yields on upper slope units were consistently less than yields achieved on lower slope units, irrespective of N fertilizer treatment. We concluded that there is no yield rationale to adding more N fertilizer rates on upper slope units than lower slope units, contrary to the widely held opinion that upper slopes would benefit from higher fertilizer application rates. Thus, producers wanting to implement variable rate fertilization should

consider increasing N fertilizer inputs in the most responsive areas of the field; namely the lower slope positions. Consistent responses to P fertilizer were not detected

An economic analysis revealed that increased economic returns were associated with a variable rate scenario developed for canola as compared to a blanket application of the recommended rate of N fertilizer. The variability in the wheat yield responses to fertilizer N limited the potential for developing a "prescription" variable rate scenario for wheat.

(b) EXECUTIVE SUMMARY:

In recent years a number of technological advances including the development of Global Positioning Systems (GPS), variable rate delivery carts for fertilizer and seed, and yield monitors have resulted in a growing interest in using these technologies for precision farming in Saskatchewan. Unfortunately, however, the technological advances have proceeded more rapidly than the agronomic information required to correctly apply the technology. Clearly, the ability to vary fertilizer rates precisely is of little value if there is no sound agronomic information available to assist producers in making decisions regarding how, when, and where to vary the fertilizer rates. Finally, irrespective of whether or not any precision farming technique is agronomically meaningful, to be a viable alternative management practice precision farming techniques must be economically viable.

A collaborative field research study between the Department of Soil Science and the Saskatchewan Wheat Pool (Mr. Garry Hnatowich, Research and Development) was initiated in 1996 to investigate the agronomic and economic feasibility of variable rate fertilizer application. Our objective was to develop the agronomic information that producers need to begin making decisions regarding fertilizer application rates. As a component of this study, we further developed a mapping tool for delineating management units at a scale relevant to Saskatchewan producers. This approach to developing management unit maps is relatively inexpensive and is based on image analysis of black and white aerial photographs. Our studies confirmed that the management units developed using this technique are agronomically meaningful and are a useful tool in the implementation of a topographically based variable rate fertilization program.

The field research component of this study was conducted at two sites in the thin Black soil zone, near Hepburn, Saskatchewan. The two sites were located on commercial fields located adjacent to one another. One site was devoted to a three-year trial using canola as the test crop whereas the second site was devoted to wheat trials. In each year of the study, soils were extensively sampled and characterized in terms of their fertility and moisture status. In each year of the study, several midslope soil samples (i.e., 10 to 15) were bulked and a composite sample was sent to Enviro-Test Laboratories, using standard procedures normally employed by producers and fertility recommendations were developed. Subsequent fertility treatments used in the field trials for both canola and wheat were developed on the basis of these standard soil testing recommendations.

A series of replicated (6 replicates) fertility treatments were imposed across a complete landform cycle within the study site. Nitrogen was applied as urea (46-0-0) at 5 rates (0, 0.5, 1.0, 1.5 and 2.0 times the recommended rate) and phosphorus was applied as monoammonium phosphate (11-55-0) at 3 rates (0, 0.5 and 1.0 times the recommended rate). Fertilizer treatments were seeded using a modified Morris air seeder. Fertilizer N was side-banded whereas P was placed in the seed furrow. Treatments were harvested using a small plot harvester (10-m long sections were harvested within each of the management units).

Results from this study indicate that management units (upper, mid- and lower slope) developed on the basis of black and white aerial photographs were agronomically meaningful for both wheat and canola production. In particular, soil tests revealed that plant available soil moisture in spring was strongly related to the management units – the overall means increased from the upper slope through the mid slope to the lower slope.

The mean yields on upper slope units at both the wheat and canola siteswere consistently less than yields achieved on lower slope units regardless of the rate of N or P fertilizer addition. Application of fertilizer N did not mitigate the impact of slope position, particularly for canola grown on upper slopes, suggesting that factors other than N fertility, such as moisture availability, limited yields. In contrast, canola, in particular, continued to respond to increasing increments of fertilizer N on lower slope units. Thus, producers wanting to implement variable rate fertilization should consider increasing fertilizer inputs in the most responsive areas of the field; namely the lower slope positions.

In both 1996 and 1997, the seed yield response of canola to N application generally was curvilinear on both the upper- and mid-slope positions. In the lower slope positions, however, seed yield responses to N tended to be linear, indicating that yield maximums were not achieved, even at the 2 × the recommended rate of N application. In 1998, canola was relatively unresponsive to N application, irrespective of landscape position. Lack of response to fertilizer application during the 1998 field season was a reflection of the very dry soil moisture conditions experienced at the time of seeding and early in the growing season at this site.

At the wheat site, yield responses to fertilizer N differed between years. In 1998, wheat was unresponsive to fertilizer N additions, irrespective of landscape position. The unpredictable nature of the wheat N response curves at Hepburn limited the potential for developing a successful variable rate N fertilizer strategy for this location. Clearly, the success of variable rate fertilizer application depends on our ability to predict crop response to inputs.

Although responses to N fertilizer were not consistent, some similarities in wheat yield responses to landscape existed. For example, wheat grain yields were consistently lower on the upper slope units as compared to lower slope units.

On the basis of the N fertilizer response curves for canola, the economically optimum rate of fertilizer N was identified for the upper-, mid- and lower-slope positions and a variable N rate scenario or "prescription" was developed. In years where a distinct downslope increase in spring available soil moisture exists (i.e., 1996 and 1997) a variable rate scenario of 1.0 × recommended N rate on the upper slopes and midslopes, and 2.0 × the recommended rate in the lower slope units was compared to a single blanket application of fertilizer N applied according to soil test recommendation for each year. In all three years, the variable rate scenario provided better returns than the blanket application of the recommended N rate. However, it is important to note that the variable rate scenario resulted in more fertilizer N being applied to the entire field as compared to the recommended N rate in 1996 and 1997. In a year where dry spring soil moisture conditions occur in all three management units (i.e., 1998) a lower input scenario of 0.5X the recommended rate in upper slope positions and 1X the recommended rate in midslope and lower slope positions was developed. This reduced input scenario resulted in a slight increase in net return in 1998 as compared to the blanket 1.0 × N recommendation.

Over the three years of the study, implementation of the variable rate scenario for canola production resulted in an increase in the returns of approximately \$20 ha^{-1} as compared to the recommended rate of fertilizer N. These results are encouraging as they suggest that an economic potential exists for the application of variable rate technology for canola production. The correction selection of a VRF scenario by producers in a given year will require further development of soil and site diagnostic tools based on properties measured in spring.

The development of a variable rate scenario for the production of wheat at Hepburn was hampered by the variation in the response of wheat to N fertilizer application from year to year. Indeed, the best combination of rates varied between years and was largely unpredictable. This, it was not possible to develop a prescription variable rate scenario for wheat production.

An economic analysis revealed that increased economic returns were associated with a variable rate scenario developed for canola as compared to a blanket application of the recommended rate of N fertilizer. The variability in the wheat yield responses to fertilizer N limited the potential for developing a "prescription" variable rate scenario for wheat.

(c) TECHNICAL REPORT

Background:

A three-year study was initiated in 1996 in collaboration with the Saskatchewan Wheat Pool (Mr. Garry Hnatowich, Research and Development) to investigate the agronomic and economic potential for the implementation of variable rate N and P fertilization in wheat (var. AC Barrie) and canola (var. Maverick). Field operations including seeding, chemical weed control and harvesting were conducted by the

Saskatchewan Wheat Pool. In each year of the study, two research experiments (i.e., wheat and canola) were conducted. The experiments were conducted on separate but adjacent fields.

Materials and Methods

Climate

Climatic conditions during the growing season for all three years were assessed using a Campbell CR-10 located at the canola site. The climate station was located on a level landscape position, and the minimum temperatures recorded in periods of frost are probably an underestimate of the actual minimum temperatures achieved in the lower slope positions of the research sites. The rainfall values were recorded as millimeters of precipitation, and the temperature values were used to calculate Growing Degree Days where:

Growing Degree Days =((Daily Maximum Temperature + Daily Minimum Temperature)/2)-5

In addition, the occurrence of significant events such as the occurrence of frost and rainfall events greater than 20 mm (i.e., those that produced significant runoff events) were tabulated separately.

Field Operations and Sampling

Fall, 1995

The major focus of the 1995 work was on site selection and sampling. Two 12.5 acre sites were selected in the Black soil zone near Hepburn, Saskatchewan. The site chosen for canola production was the NE quarter of section 7, Tp 40, R5, W3. The wheat site was located on the SE quarter of the same section. Both sites are mapped as Oxbow association soils whose parent materials are medium to moderately fine textured, moderately to strongly calcareous, unsorted glacial till. The map unit is Oxbow 8, which is dominated (> 40%) by Orthic Black soils with significant inclusions (15 to 40 %) of Rego Black, Calcareous Black, and Gleysolic soils. The dominant texture of the mapped unit is loam although a considerable range in textures is common in these landscapes. The surface form is a ridged morainal surface, although these ridges are more evident at the canola site than the wheat site. The mapped slope class was class 4 which has average slopes between 6-9%. This type of land surface is the most common (in terms of area) in the agricultural zone of Saskatchewan.

The canola site is owned by Mr. Jake Fehr and the wheat site by Mr. John Goetz. Both producers were extremely cooperative throughout the study despite the inconvenience the work caused for them and we are very grateful for their cooperation.

In the fall of 1995 a topographical survey of each site was completed and Digital Elevation Models were developed from the surveys. As well, ground control points were taken from each site and its surroundings using a Garmin Survey II GPS unit. These ground control points were used to geo-rectify the aerial photographs used in the delineation of the management units. The topographical survey was used to classify each of the cells of the DEM into one of four landform element complexes: shoulders, backslopes, footslopes and level depressional complexes. These topographically defined classes were used to assess the validity of the delineation of management units based on the digital number classification (Pennock et al., 1994).

At both sites a 99 point sampling grid was established. Each site had a 9 by 11 grid laid out with a spacing of 25 m between sample points. The soils at each point were described and sampled in four 15-cm increments.

Existing aerial photographs for each site were scanned into the computer and imported into the VGA-Erdas image analysis system. The scanned images were then geo-rectified using the ground control points taken in the GPS survey. The images for each quarter-section were stored as gray tone images. The pixel size used initially was 3m by 3m, and each pixel also contained the appropriate digital number indicating the specific gray tone the pixel fell into. Digital numbers range from 1 (black) to 255 (white).

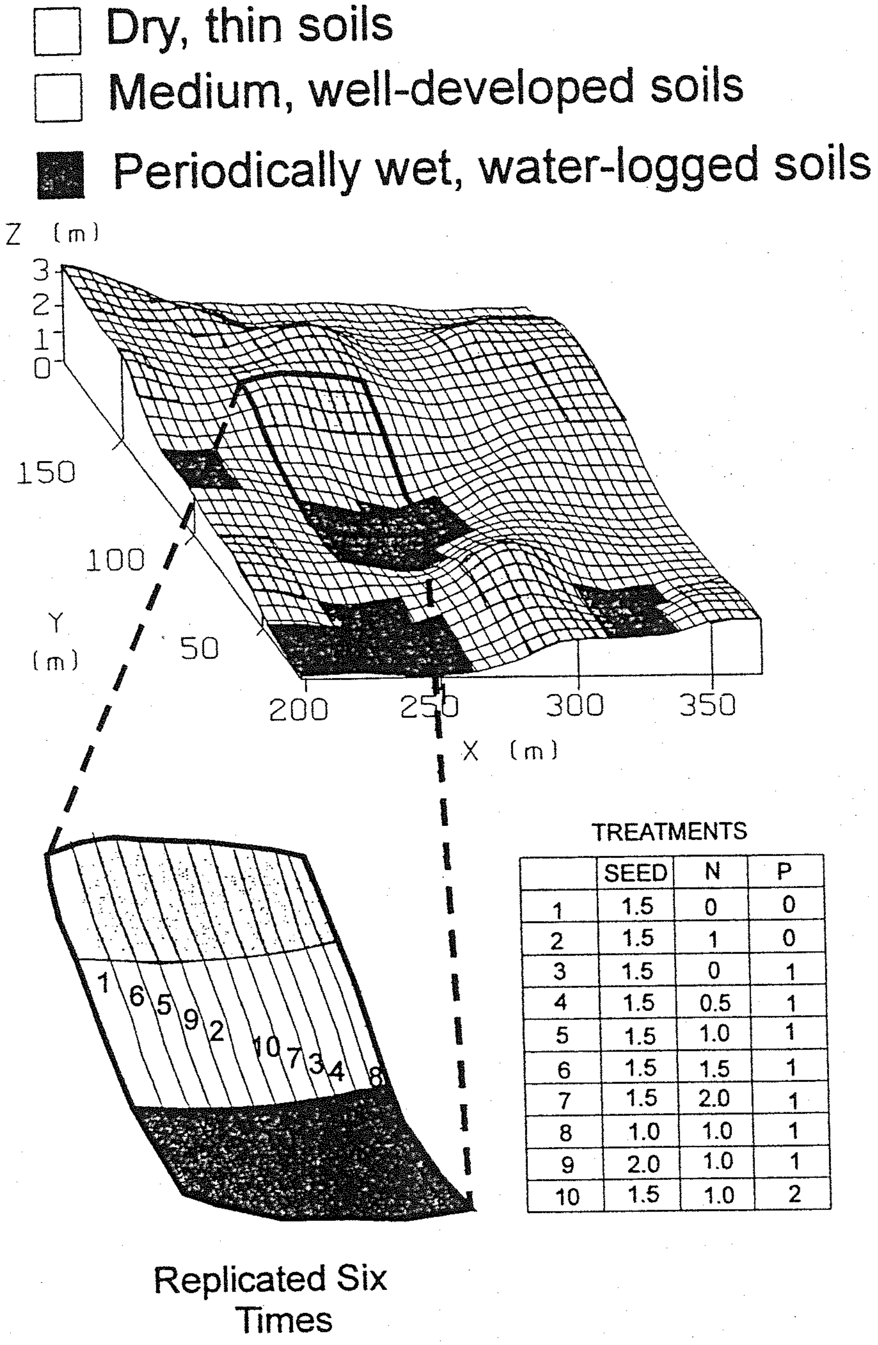
The digital number range for each site initially was split into four classes: upper slopes, midslopes, lower slopes, and depressions. These classes form the main management units at the sites, and are hereafter referred to as management units. The specific digital numbers for the cells sampled in the grid soil sampling were extracted, and the organic and inorganic carbon values for these cells were compared to the digital numbers. Generally the upper slope units had light gray digital numbers and low levels of organic carbon but the distinctions between the remaining units in terms of soil organic carbon levels of the surface soil were limited. The management units were also compared with the topographically defined units and here a more clear association occurred. The management units defined from the aerial photographs were used to select the units for sampling in the three years of the study. In some cases the midslopes units were not well expressed on the management unit maps and in these cases the midslopes were arbitrarily placed between the upper and lower slope units.

1996 Field Season:

In early spring 1996, one composite sample (from 10 to 15 subsamples) was taken from midslope positions at each of the two sites and sent to the Enviro-Test laboratory for a standard soil test recommendation. The results of the soil test recommendation were used to determine the rates of fertilizer inputs required at the site. This procedure was followed in all three years of the study.

In 1996 the soil test recommended N rate at the canola site was 75 lbs. acre^{-1} and the P rate was 22.5 lbs. P_2O_5 acre^{-1}. At the wheat site the N rate was 55 lbs. acre^{-1} and the P rate was again 22.5 lbs. P_2O_5 acre^{-1}. The recommended soil test levels were used to develop fractional rates of the recommended values for N and P at the sites. In 1996 two groups of treatments were used. The main N treatments (0. 0.5, 1, 1.5 and 2X the soil test rate) and P treatments (0, 0.5, and 1X the soil test rate) were replicated six times. Because of the novel nature of the research program (i.e., placing the fertilizer treatments on non-level plots, rather than the standard level plots) it was decided to also use 0.25X increments for the N treatments. Four blocks (replicates) of treatments also included 0.25, 0.75, 1.25, and 1.75X the soil test N rate. The results from the 0.25 increments were used to assess the statistical validity of the research design over the following winter but were not used in the development of the yield functions for the sites.

The treatments were randomized in each block (or replicate) and each block of treatments spanned the management units at each site. The layout of the main treatments is shown schematically in Figure 1.



TREATMENTS

	SEED	N	P
1	1.5	0	0
2	1.5	1	0
3	1.5	0	1
4	1.5	0.5	1
5	1.5	1.0	1
6	1.5	1.5	1
7	1.5	2.0	1
8	1.0	1.0	1
9	2.0	1.0	1
10	1.5	1.0	2

Figure 1: Schematic diagram of the research design used at the wheat and canola site at Hepburn, Saskatchewan.

Seeding in 1996 was delayed by wet soil conditions and several rainfalls in April. Seeding at the wheat site was completed on June 3 and at the canola site on June 4. Seeding was accomplished using a modified Morris air seeder (2.13m width with 30 cm row spacing). Fertilizer N, supplied as urea (46-0-0), was side-banded whereas P, supplied as monoammonium phosphate (11-55-0), was placed in the seed furrow. Rates of urea were adjusted to reflect the N applied as 11-55-0. Chemical weed control was carried out over the summer in accordance with typical practices used in the production area.

Prior to seeding, soil cores were taken from each management units in selected treatments and were assessed for mineral N to a depth of 30 cm and for spring available moisture to a depth of 60 cm. Bulk densities also were calculated for each increment to convert the concentration measurements to mass per area (or volumetric) units. Selected samples were used to measure the water remaining after 15 atmospheres of suction was applied to the sample using a pressure plate apparatus. The 15-atm threshold is typically referred to as the permanent wilting point (PWP). The PWP were re-expressed on a volumetric basis and were used to determine plant available water in spring.

Due to the late seeding date, harvest operations were carried out later than usual for this region. The wheat site was harvested on September 30, and the canola site on October 2. In each of the treatment strips a 10 m long, 1.52-m wide harvest sample was taken using a small plot combine from each of the three management units. In addition, a 1-m^2 sample was hand harvested from within each treatment plot for the determination of harvest index. Sample weights, moisture contents and, for the wheat crop, grain protein were assessed by staff of the Saskatchewan Wheat Pool under the supervision of Mr. G. Hnatowich.

1997 Field Season:

The same basic approach was followed in the 1997 field season. In 1997 only the main N treatments (0, 0.5, 1, 1.5, and 2X the soil test rate) were used at both sites. The recommended soil tests rates based on the spring midslope sampling were for 80 lbs. acre^{-1} of N and 27.5 lbs. P_2O_5 acre^{-1} at the canola site and 55 lbs. acre^{-1} of N and 27.5 lbs. acre^{-1} of P_2O_5 at the wheat site.

Pre-seeding soil samples were taken from each management unit in all the blocks for the 0N1P, 1N1P, and 2N1P treatments. These treatments were sampled for spring moisture and mineral N as in 1996. Soil descriptions were also carried out at each site.

Seeding occurred on May 15 and 16. Chemical weed control was carried out over the growing season, as required. Again, 10-m long, 1-m wide harvest strips were taken on August 23 and 24, in addition to a 1-m^2 hand harvested sample (for the determination of harvest index) and the same measurements were made on these samples as in 1996.

1998 Field Season:

The same treatment structure was used as in the previous two years except for the addition of a 1N2P treatment to ensure that a P benefit at higher P rates was not being overlooked. The soil test rate for the canola site was 80 lbs. $acre^{-1}$ of N and 30 lbs. $acre^{-1}$ of P_2O_5 and for the wheat site 62.5 lbs. $acre^{-1}$ of N and 27.5 lbs. $acre^{-1}$ of P_2O_5 were added.

The two sites were seeded on May 15 and 16. As will be discussed below, soil conditions at the time of seeding were very dry and no significant moisture was received for 30 days after seeding. The dry conditions caused very uneven germination and emergence of the crops at both sites. Prior to seeding the same treatments as in previous years were sampled for spring moisture and N levels. The crops were harvested on August 23 and 24.

Soil Analysis

Soil samples taken in the course of field sampling were used to measure mineral N, soil organic carbon (SOC), gravimetric soil moisture, and bulk density. Field moist soil samples (approximately 20 g) were shaken for 1 h in 200 ml 2 M KCl and the solution was subsequently filtered through a Whatman No. 40 filter paper. Mineral N in the soil extract was measured colorimetrically using an Technicon AutoAnalyzer (Technicon Industrial Systems, 1978). Mineral N is the sum of the nitrate and ammonium extracted by the solution. Soil organic carbon was determined using dry combustion at 840°C using a LECO CR-12 Carbon Determinator (LECO Corp., St. Joseph, MO).

Soil samples from Treatment 3 (1N1P) in 1997 were also analyzed for plant available phosphorus, copper and zinc. The anion exchange membrane procedure developed by Schoneau and Huang (1991) was used for plant available P measurements. One anion exchange membrane strip (2 cm by 6 cm) in bicarbonate form was added to a 16 dram vial containing 5 grams of ground (< 2mm) soil. Fifty ml of distilled water was added and the vials were shaken for one hour. The membrane was then removed with forceps, washed free of soil with distilled water, placed in a clean 16 dram vial and shaken with 30 ml of 0.5 M HCl for one hour to remove the adsorbed P. The membrane was then removed and washed three times with 0.5 M $NaHCO_3$ to convert it back to the bicarbonate form. Resin-extractable P in the HCl extract was measured on an autoanalyzer.

DTPA-extractable copper and zinc were determined following the procedure outlined by Liang and Karamanos (1993). Ten grams of soil were shaken with 20 ml DTPA solution for 2 hours and filtered with Whatman No. 42 filter paper. Copper and zinc were then measured by atomic absorption using a Perkin-Elmer spectrophotometer.

The Permanent Wilting Point (PWP) was determined by applying 15-atmospheres of suction to samples in a pressure plate apparatus. The PWP values were corrected to a volumetric basis using the bulk density of the sample and then was subtracted from the volumetric soil moisture of the sample to give available moisture in the sample. These values were converted to cm water/ cm soil using the depth of the sample.

Statistical and Yield Function Analysis:

The development of landscape-scale fertility trials is in its infancy and few literature sources are available to guide the statistical analysis of the results. In our design, the management units are defined by their inherent nature – for example, an upper slope is designated as an upper slope unit by virtue of its slope morphological characteristics and its position in the landscape. The management units cannot be randomized in the classic sense of being randomly assigned to their position in the trial. Instead they are characteristic treatments, where the material defines its status in the treatment structure by its inherent characteristics.

In our design, an area of land which contains all three management units and which is of sufficient width to accommodate all of the treatments is designated as a block. The nine main fertility treatments were then randomly assigned to each block. Hence, while a constraint exists on the randomization of the management units, the fertility treatments were randomly assigned in each block.

Given the constraint on randomization of the management units, we believe that the design can best be analyzed using a split-plot Analysis of Variance (ANOVA) approach. The split-plot designs were developed to accommodate research situations where a constraint on the randomization of one of the treatments exists. The split-plot analysis were run using the MANOVA option in the statistical package SPSS.

Separate fertilizer response curves were developed specific to each of the three management units for each growing season. The average yield of six replicates for each fertilizer treatment was plotted against fertilizer rate. A quadratic function was subsequently fitted to each yield vs. fertilizer rate plot. Quadratic fertilizer response equations are found to be a satisfactory representation of a crop's response to a given nutrient (Cooke, 1972, p118). In general increased fertilizer application rates result in increased crop yield. However, increasing fertilizer rates results in diminishing increments in yield to some maximum yield, any additional fertilizer results in decreased crop yield. (Figure 2).

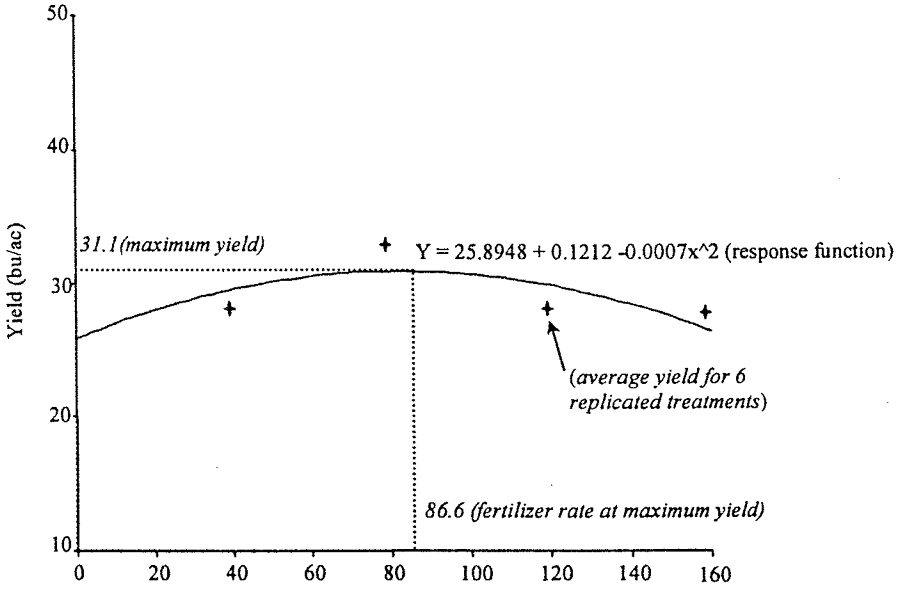


Figure 2: Hypothetical fertilizer response curve.

In some instances where fertilizer rates were not sufficient to result in maximum yields the fertilizer response curves were approximated as being linear.

The economically optimum N-fertilizer rate, or economic optima, was derived at the end of each growing season for each management unit. The economic maximum was determined applying simple differential calculus to each of the acquired response functions. The fertilizer rate resulting in the maximum yield for each management unit was determined by setting the first derivative of the yield function equal to zero. Maximum yield differs from the economic optima due to the relationship between input costs and the value of the crop, for this reason the economic optima is determined by considering the price ratio between the unit cost of inputs, namely nitrogen, and the unit value of yield. The price ratio is defined as the cost of the input divided by the value of the crop (Heady and Dillon, 1961, p 497). The economic optimum is thus determined by setting the first derivative of the response function equal to the price ratio. Since the price ratio is a positive value, the economic optimum is always to the left of the yield maximum on the fertilizer response curve. The fertilizer rate coinciding with maximum yield converges with the fertilizer rate coinciding with the economic optima as the price ratio approaches zero, that is as either commodity prices rise or the price of nitrogen falls.

RESULTS

Growing Season Conditions at the Hepburn sites

The thermal regime varied little over the three years of the study – the total Growing Degree Days over the growing season varied from a minimum of 1234 in 1998 to 1278 in 1996 (Tables 1 to 3). The distribution of the GDD was also relatively even and nonlimiting to plant growth throughout the growth periods in all three years.

During the 1996 growing season, the two sites (i.e., canola and wheat) received the highest amounts of precipitation recorded over the three years of the study. In 1996, a major precipitation event on July 4 (64.2 mm of rainfall) caused extensive flooding of the depressional sites in both landscapes and a loss of existing crop in those areas. In the subsequent two years of the study, no attempt was made to seed the depressional areas which were known to be prone to flooding.

The total growing season precipitation was less in 1997 (158.3 mm compared to 243.8 mm in 1996) but precipitation events were evenly distributed throughout the growing season (Table 2). Indeed, only one significant precipitation event (i.e., greater than 20 mm) occurred during the 1997 growing season and no flooding was noted in the 1997 season. Two frost events were recorded, two days after seeding on May 14 and also on May 23. There was no visual evidence to suggest that the latter event had a significantly detrimental impact on crop growth.

Although the amount of total growing season precipitation in 1998 was comparable to 1997 (169.4 mm in 1998 vs. 158.3 mm in 1997), the major feature of the precipitation regime in 1998 was the very dry conditions that occurred during the first 25 days after seeding (Table 3). Only 12.1 mm were received in this period in 1998, compared to 47 mm in 1997 and 63.2 mm in 1996. The two rainfall events in June 16 and June 19 caused temporary flooding of some of the lower slope treatments at both sites. In addition, a frost event occurred on May 31 and again on June 3, approximately two weeks after seeding. Visual examination of the canola plot suggested that the latter event may have caused some crop damage at the canola site. Similarly, visual examination of the wheat following the June 3 frost indicated that some frost damage may have occurred, particularly in the lower slope position. However, crop stress symptoms may have been related to moisture stress and we were unable to clearly define the extent of the frost damage.

Table 1: Climate conditions at the Hepburn research sites in 1996

Growth period	Dates	Precipitation (mm)	Growing Degree Days
Seeding to 25 Days DAP	June 3 to June 28	63.2	297
26DAP to 50 DAP	June 29 to July 23	107.4	319
51 DAP to 75 DAP	July 24 to August 17	16.3	317
76 DAP to Harvest	August 18 to September 30	56.9	345
Harvest+1 to Late Fall	October 1 to November 18	7.5	
Total growing Season		243.8	1278

Significant Events

Date	Frost	Precipitation Greater than 20 mm
June 17		26.4
July 4		64.2
July 17		20.7

Table 2: Climate conditions at the Hepburn research sites in 1997

Growth period	Dates	Precipitation (mm)	Growing Degree Days
Seeding to 25 Days DAP	May 12 to June 12	47	279
26DAP to 50 DAP	June 13 to July 7	55.8	266
51 DAP to 75 DAP	July 8 to July 31	20.3	327
76 DAP to Harvest	August 1 to August 28	35.2	367
Harvest+1 to Late Fall	August 29 to September 22	55.3	
Total growing Season		158.3	1238

Significant Events

Date	Frost (Minimum Temperature. °C)	Precipitation Greater than 20 mm
May 14	-1.45	
May 23	-0.11	
June 8		21.7

Table 3: Climate conditions at the Hepburn research sites in 1998

Growth period	Dates	Precipitation (mm)	Growing Degree Days
Seeding to 25 Days DAP	May 15 to June 10	12.1	231
26DAP to 50 DAP	June 11 to July 6	85.8	302
51 DAP to 75 DAP	July 7 to July 29	29.3	314
76 DAP to Harvest	July 30 to August 24	42.2	387
Harvest+1 to Late Fall	October 1 to November 18	1.3	
Total growing Season		169.4	1234

Significant Events

Date	Frost (Minimum Temperature. °C)	Precipitation Greater than 20 mm
May 31	-0.12	
June 3	-0.07	
June 16		29.2
June 19		36.6

Soil Conditions and Crop Yields at the Canola Site

Soil Distribution

The site is mapped into the Oxbow association. This association occurs on glacial till surfaces in the Black soil zone. The surface form of the site is hummocky, indicating that a complex series of knolls and depressions occurs on the surface. At the site the knoll features show some preferred orientation associated with crevasse fills on the glacial ice surface. Soil texture at the site ranges from sandy clay loam to clay loam, typical of these glacial till landscapes.

The distribution of soils at the site is also very typical of glacial till surfaces throughout the agricultural zone of Saskatchewan. There is a clear association between the soil subgroups at the site and the management units defined from the scanned aerial photograph of the site (Table 4). The upper slope units are dominated by thin Orthic Regosolic soils (which lack a significant B horizon and have a thin A horizon) as well as thinner variants of the Chernozemic order. The lower slope units have a distinct assemblage of soils, primarily those associated with periodic water saturation in the solum (i.e., the gleyed subgroups of the Chernozemic order and the Gleysolic soils).

The midslope units lack a clear relationship with the soil subgroups. The midslopes contain soils from the dry, Rego Chernozemic subgroup through to the wettest of the soils at the site, the Gleysolic soils. The results for soil distribution indicate that at this site the midslopes do not represent a functionally distinct pedogenic region (as do the other two groups); instead they are a relatively arbitrary grouping of transitional middle slope segments into a distinct class.

Soil Characteristics

The lack of a distinct identity for the midslope units is reinforced by the results for several of the soil properties are summarized in Table 5. The upper slope units have distinctly lower levels of soil organic carbon than the midslope and lower slope units. Others similarly have observed increasing levels of soil organic carbon in Saskatchewan landscapes (Gregorich and Anderson, 1985; Verity and Anderson, 1990; McConkey et al., 1997), and have related crop productivity gradients to soil organic carbon gradients (McConkey et al., 1997)

The pH and E.C. values for the midslope and lower slope units are very alike. None of the tabulated values for E.C. or pH indicate a possible growth limitation due to soil chemical conditions.

The calculated values for anion exchange membrane extractable P (P_{AEM}) (determined in the fall of 1997) should be multiplied by a factor of 4 to obtain values roughly equivalent to standard Olsen P in lbs./ac (Schoenau and Huang, 1991). The calculated P values range from approximately 12 lbs./ac in the upper slope units to 16 lbs./ac in the lower slope units. According to the 1990 Nutrient Requirement Guidelines from the Saskatchewan Soil Testing Laboratory, this would indicate a recommended P addition of 20-to 25-lbs/acre of P_2O_5 for canola production. The marginal soil test level for zinc is 0.26 to 0.5 $\mu g\ g^{-1}$ and for copper is 0.6 to 1 $\mu g\ g^{-1}$ for a 0-15 cm sample. The zinc levels measured for the site soils (Table 5) are well in excess of the marginal rates. The copper are in the high end of the marginal level for the surface increment, but show a increase with depth to above marginal level.

Table 4: Distribution of Soil subgroups in the Management Units at the canola site. The subgroups are arrayed in approximate order from driest to wettest. These results are tabulated from a 9 x 11 survey grid (sampled in fall, 1995) that covered the entire extent of the canola site.

Orders and Soil Subgroup	Upper Slope	Midslope	Lower Slope
Regosolic Order			
Orthic	5		
Chernozemic Black			
Rego	5	3	
Calcareous	2	1	
Orthic	12	15	2
Eluviated	1	13	6
Gleyed Calcareous		4	4
Gleyed Rego		6	
Gleyed Eluviated			3
Gleysolic Order			
Humic Luvic		3	9
Other Gleysols		1	3

Table 5: Selected soil properties of the management units at the Hepburn Canola site. Values shown are mean and standard error of the mean (in italics). Soils sampled in fall, 1995.

Unit	Soil Organic Carbon Mg ha^{-1}		pH		Electrical Conductivity dS m^{-2}		Permanent Wilting Point (%, volumetric)	
	0-15 cm	0-60 cm	0-15 cm	45-60 cm	0-15 cm	45-60 cm	0-30 cm	30-60 cm
Upper	33.9	61.1	7.8	8.4	.31	.89	19.34	22.63
	2.3	*7.0*	*.1*	*.1*	*.01*	*.13*	*1.41*	*3.64*
Midslope	51.8	96.7	7.7	8.01	.49	1.46	19.35	22.29
	1.9	*4.2*	*.1*	*.1*	*.06*	*.17*	*1.47*	*7.91*
Lower	56.3	97.5	7.6	7.9	.53	1.31	20.2	18.6
	2.3	*6.2*	*.1*	*.1*	*.08*	*.24*	*1.13*	*3.47*

Table X: Phosphorus and micronutrient status of the management units at the Hepburn Canola site. Values shown are mean and standard deviation (in italics). Soil sampled in fall, 1997.

Unit	Anion exchange membrane-P µg g^{-1}			Available Zinc µg g^{-1}		Available Copper µg g^{-1}	
	0-15 cm	15-30	30-60	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Upper	2.01	0.85	0.55	1.21	0.67	0.90	1.35
	.60	*.62*	*.07*	*.36*	*.31*	*.29*	*.44*
Midslope	2.01	0.39	0.41	1.41	0.49	0.84	1.17
	.91	*.09*	*.10*	*.70*	*.08*	*.34*	*.57*
Lower	2.94	0.40	0.31	2.62	0.64	0.70	0.88
	.87	*.16*	*.10*	*.78*	*.12*	*.11*	*0.18*

Spring Available Water and Nitrogen Levels at the Canola Site

A significant landscape effect for spring moisture existed for all three years of the study (Table 6). In each year, spring available water was highest in the lower slope units, decreased through the midslopes, and was lowest in the upper slope units. Hence despite the overlap in some soil properties between the units, the differences between the management units were clearly expressed in terms of spring moisture conditions. Sinai et al. (1981) similarly observed a strong correlation between soil moisture content and the curvature of the soil surface. They observed that both the soil moisture contents and crop yields were highest at concave parts of the landscape and lowest at convex parts of the landscape and suggested that lateral flow of water within unsaturated soils zones contributed to these observed differences. McConkey et al. (1997) similarly hypothesized that such unsaturated flow may contribute to increased soil water in lower slope positions in southwestern Saskatchewan. Surprisingly, however, they observed the opposite pattern of soil water content distribution, measured to a depth of 120 cm, in a fallow-wheat rotation. They concluded that high soil bulk densities (1.7 Mg m^{-3}) below 60 cm at upper slope positions limited root penetration and thereby limited root extraction of water at depth at these positions. As a consequence, the soil water content at upper slope positions increased relative to lower slope positions, where root growth (and root extraction of water) was unrestricted.

The spring available water levels show a progressive decline over the three years of the study (Table 6). Spring soil moisture levels were highest overall in 1996 for all three units. The upper slope units decreased in 1997 and were stable at levels around the permanent wilting point for 1997 and 1998, whereas the midslope and lower slope units continue to show a decline through to 1998. The difference between 1997 and 1998 lies in the climatic conditions discussed earlier – in 1997 the site received 47.0 mm of precipitation in the first 25 days after seeding, whereas in 1998 only 12.1 mm were received in the same period. Moreover, in 1997, crop water uptake served to deplete the soil of available water (i.e., from precipitation events during the growing season) and significant moisture recharge during the winter months apparently did not occur. Hence, soils were relatively dry at seeding in 1998 and these dry soil conditions were not alleviated by "timely" rainfalls in the first 25 days of the growing season.

Although a consistent landscape pattern for available water levels occurred in all three years of the study at both sites, consistent patterns of spring mineral N levels were not detected (Table 7). In 1996 the upper slope units have less mineral N than the midslope and lower slope units; in 1997 no significant difference occurs among the units; and in 1998 the upper slope and midslopes have significantly less available N than the lower slope units. Overall the lowest levels of mineral N across all three units occurred in 1996 and the highest levels in 1997. Others similarly have reported variability in soil nitrates with no significant effect of slope position. For example, McConkey et al. (1997) reported that soil nitrate levels, determined in the fall, were variable and there was no significant effect of slope position in a Brown Chernozem in Saskatchewan in any of the three study years. Pennock et al. (1992) observed a random pattern of mineral N in a Brown Chernozemic soil in southern Saskatchewan.

Table 6: Available Water (cm water /60 cm of soil) at the time of spring sampling, Canola site. Values shown are the mean and the standard error of the mean (in italics). Results are shown for a mean comparison based on the Least Significant Difference test ($\alpha=0.05$) among management units in a given year.

Management Unit	1996	1997	1998
Upper slope	3.82^{a}	-0.07^{a}	-0.04^{a}
	0.34	*0.19*	*0.32*
Midslope	7.05^{b}	1.28^{b}	0.65^{b}
	0.56	*0.33*	*0.36*
Lower slope	10.62^{c}	5.64^{c}	2.69^{c}
	0.62	*0.23*	*0.63*

Table 7: Mineral nitrogen (kg ha^{-1}, 0-30 cm) at the time of spring sampling, Canola site. Values shown are the mean and the standard error of the mean (in italics). Results are shown for a mean comparison based on the Least Significant Difference test ($\alpha=0.05$) among management units in a given year.

Management Unit	1996	1997	1998
Upper slope	18.3^{a}	39.2^{a}	22.4^{a}
	1.9	*4.0*	*1.6*
Midslope	28.1^{b}	35.5^{a}	23.4^{a}
	2.0	*3.0*	*1.8*
Lower slope	32.2^{b}	42.1^{a}	40.0^{b}
	4.2	*5.0*	*3.2*

Results for the Nitrogen Treatments at the Canola Site

The major purpose of the N treatments was to facilitate the development of yield response functions for each year of the study. These yield functions can then be used to derive the principal measures used in the economic analysis, such as the economic optimum yield for each year.

Prior to the development of the yield response function, however, it is necessary to view the results overall in an ANOVA framework to determine if the design was suitable for determining the differences in yield between the management units. Unless distinct yield responses are associated with the three management units used in the analysis there is no rationale for examining management-unit-specific yield functions.

The results of the ANOVA analysis indicate that the differences between the N treatments themselves are highly significant in 1996 and 1997, and are different in 1998 at an α of 0.06 (Table 8-10). Although the results in 1998 are slightly above the arbitrary α threshold of 0.05, the functions will be developed as for the previous two years. It has been argued in several recent research articles that the use of an arbitrary limit in landscape-scale studies is of limited relevance, given the high inherent variability in these designs (e.g., Walley et al., 1996).

Others similarly have reported significant canola yield responses to N fertilizer application on soil containing a wide range of available N (Johnston et al., 1997; Grant et al., 1999).

The overall differences among the management units are highly significant in all three years (Tables 8 to 10). In all three years, the mean yields for both the 0N1P treatment (i.e., the treatment that reflects the inherent productivity of the units) and for the N treatments averaged across the five N treatments increase from the upper slope units through the midslopes and are highest in the lower slope units. Spratt and McIver (1972) examined wheat yields at 15 sites in southeastern Saskatchewan and observed that with or without fertilizer additions, wheat grain yields were least on the upper slope positions (i.e., crown of the knoll) and increased progressively downslope. Typically, grain yields were 50% greater in the depressions than on the upper knolls. Interestingly, fertilizer application on the upper knolls did not increase the yield potential to the level achieved in the lower slopes and it was concluded that basic pedological and microclimatological factors of the soil catena (i.e., aridity of the upper slopes) had a greater influence on yield than did soil fertility. McConkey et al. (1997) similarly reported that wheat yields decreased significantly with distance downslope on a Brown Chernozem in southern Saskatchewan. However, these authors suggested that because the productivity gradient could not be related to the crop water use or availability, the crop productivity gradient was related to the gradient in the historical net erosion of productive topsoil and, presumably, inherent nutrient availability. These authors also reported, however, that high bulk densities in upper slope positions limited the extent to which root development and water extraction occurred. This observation may, in part, explain the lack of correlation between apparent available soil water to 120 cm and crop productivity.

There is a striking degree of consistency when the ratio of yield in the midslope and lower slope units is compared to those for the upper slope units. For the 0N1P treatments, the yields in the midslopes range from 1.6× those of the upper slopes in 1998 to 2.3× in 1997. For the lower slopes, the yields range from 4× the upper slopes in 1996 to 2.7× in 1998. The results are even more consistent when the ratios are taken on the yields averaged across the N treatments for each management unit (i.e., the row total in Tables 8-10). For the midslopes, the yield ratios (i.e., midslope:upper slope yields) range from 1.77× the upper slope yields in 1996 to 1.86x in 1997; for the lower slopes, the ratios range from 2.56× the upper slope yields in 1996 to 2.8× in 1997. Hence the proportional differences in yields among the management units show a great consistency across years, although the absolute yields differ greatly in response to seasonal conditions.

Table 8: Results for the Nitrogen treatments at the Canola site, 1996. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Unit	Grain Yield in the N Treatments (kg ha^{-1})					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	334.0	568.7	655.9	829.6	693.0	616.2
Midslope	684.0	1012.4	1119.3	1289.2	1351.8	1091.4
Lower Slope	1313.5	1281.0	1657.1	1658.8	1977.5	1577.6
Column Mean	777.3	954.0	1144.1	1259.2	1340.8	

ANOVA Results	Significance of F
Replicate	.000
Management Units	.000
N treatments	.000
Management Unit X N treatment Interaction	.008

Table 9: Results for the Nitrogen treatments at the Canola site, 1997. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Unit	Grain Yield in the N Treatments (kg ha^{-1})					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	368.7	547.9	604.7	617.8	598.2	547.5
Midslope	850.7	964.1	1033.9	1098.5	1151.2	1019.2
Lower Slope	1089.3	1403.2	1547.3	1749.3	1949.5	1547.7
Column Mean	769.6	971.8	1063.6	1155.2	1232.9	

ANOVA Results	Significance of F
Replicate	.000
Management Units	.000
N treatments	.001
Management Unit X N treatment Interaction	.367

Table 10: Results for the Nitrogen treatments at the Canola site, 1998. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Unit	Grain Yield in the N Treatments (kg ha^{-1})					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	356.5	383.8	430.4	473.6	473.2	423.5
Midslope	564.6	788.5	892.3	828.4	845.2	783.8
Lower Slope	964.3	1187.0	1187.4	1206.4	1145.3	1138.1
Column Mean	628.4	786.5	836.7	836.1	821.2	

ANOVA Results	Significance of F
Replicate	.000
Management Units	.000
N treatments	.062
Management Unit X N treatment Interaction	.819

Development of Yield Response Curves for the Nitrogen Treatments at the Canola Site

A major objective of the research program was to develop yield response curves for the response of canola to the five nitrogen treatments. These yield functions can then be used to develop optimum fertilization scenarios for each year of the study. The common elements between the curves across years can also be used to develop an optimum set of scenarios for the different growth conditions encountered in the study.

The initial stage in the analysis is the development of the yield response functions themselves (Figure 3, 4, and 5). The curves for 1996 and 1997 are very similar. The curves show major separation between the functions for the three management units at both the origin (i.e., where no fertilizer is added) and throughout the full extent of the N treatments. This confirms the clear differences between the management units discussed above. The curves for 1998 are less steep than those for the previous two years (indicating less responsiveness of the crop to added fertilizer inputs) but again show a clear separation between the management units over most of their extent. Thus, the management units, developed on the basis of aerial photographs, clearly are agronomically meaningful in that they differ in terms of productivity potential and responsiveness to fertilizer application.

The curves for the three units do not intersect in any of the three years. This indicates that (regardless of economic considerations) there is no point on the response curves at which a larger yield is achieved by adding more fertilizer to the upper slope units than to the midslope and lower slope units. In fact, in all three years of the study, the maximum yield achieved in the upper slope units is well below the yield from the unfertilized (i.e., 0N1P) treatment for the lower slope unit. Hence the data unambiguously indicates that there is no yield rationale to adding higher rates of fertilizer to the upper slope units than to the lower slope units, contrary to the widely held opinion that the upper slope units would benefit from higher fertilizer rates.

In an early study using wheat as the test crop, McIver and Spratt (1972) similarly concluded that basic pedological and microclimatological factors associated with a soil catena affected wheat yields more than did soil fertility or fertilizer application. They concluded that fertilizer application could not mitigate or eliminate the large yield

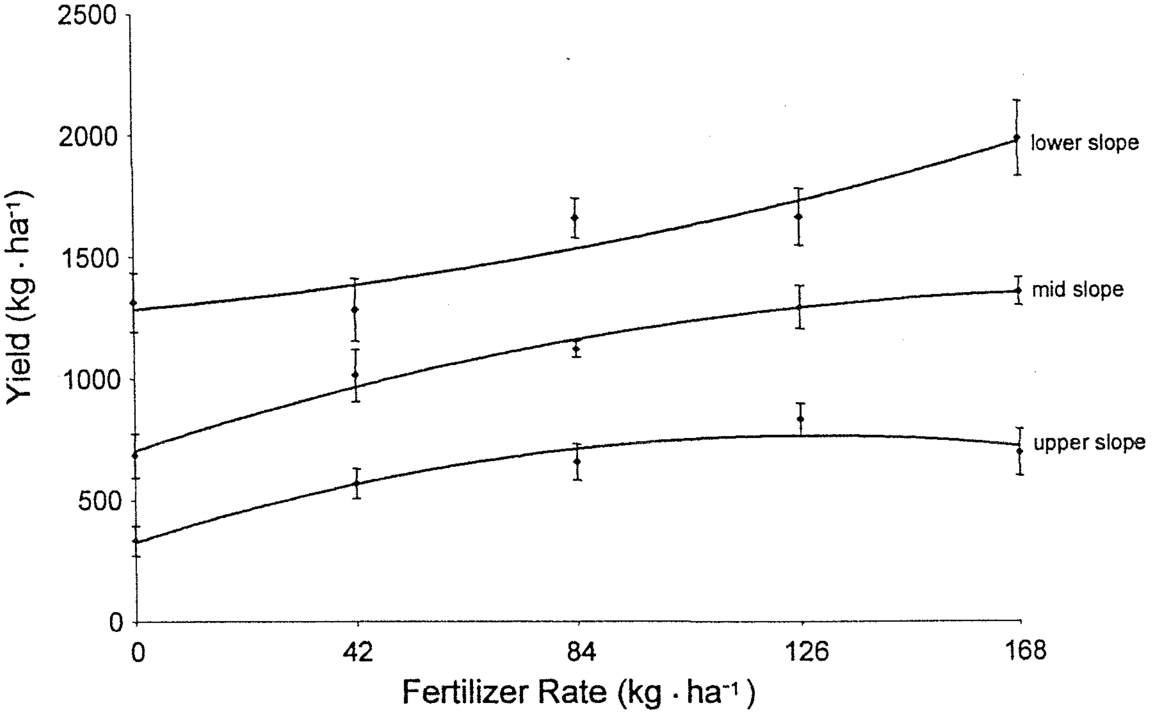


Figure 3: Fertilizer response curves, Hepburn Canola 1996

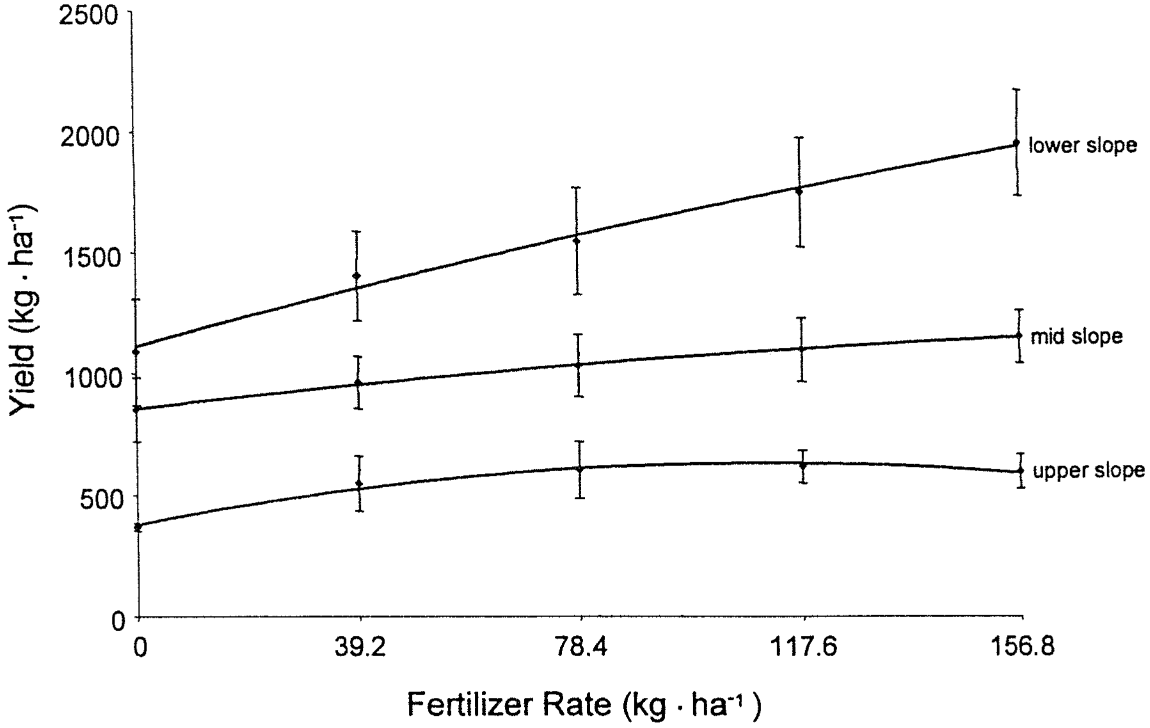


Figure 4: Fertilizer response curves, Hepburn Canola 1997

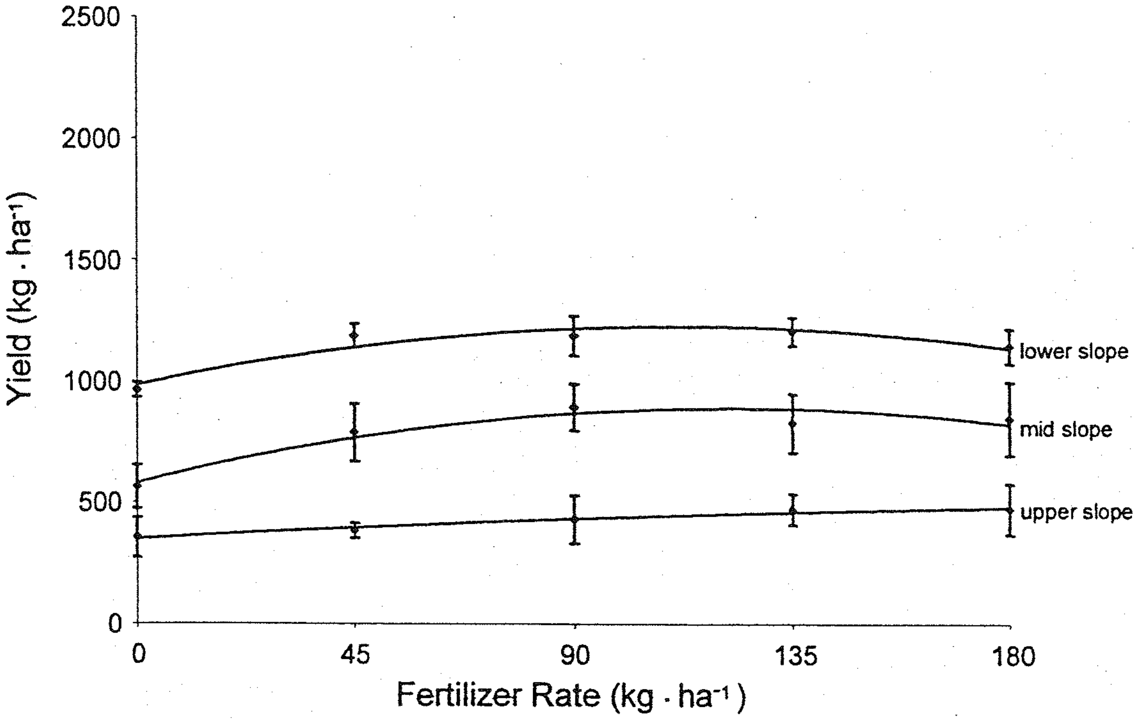


Figure 5: Fertilizer response curves, Hepburn Canola 1998

variations associated with topographical features of a landscape and related limited yield potential and fertilizer response on the upper slopes to limitations imposed by relatively arid conditions.

By fitting the appropriate linear or quadratic equation to the individual yield functions a quantitative measure of the function in a given year can be obtained. These curves can then be used to calculate the economic optimum N rate and associated yield for each curve following the procedures outlined in the Materials and Methods section of this report.

The analysis of the equations again indicates the similarity between the 1996 and 1997 seasons (Table 11). The intercepts (i.e., the yield where no fertilizer is added) are similar in 1996 and 1997, whereas the second term of the equations indicates a steeper slope in 1996 (and hence a greater responsiveness to added fertilizer in that year).

The economic optimum rate for the upper slope units in both 1996 and 1997 is very close to or at the recommended soil test rate. As discussed previously, this N application rate was based on a composite sample of soils from midslope positions at the site. Interestingly, the recommended N rate in 1996 under-fertilizes the midslope units themselves (the average economic optimum rate for 1996 is very close to 1.5X the recommended rate) but was very close to the economic optimum in 1997.

The analysis of the equations for the lower slope units places the economic optimum yield beyond the 2X treatments in the first two years of the study. In a fixed effect design, such as the one we utilized (i.e., where set fertilizer rates are applied), the results cannot be extended beyond the minimum and maximum N treatments and hence the economic optimum yields are set at the 2X treatment. This clearly indicates an under-fertilization of these lower slope units in 1996 and 1997 if a constant soil test rate is used for the field as a whole.

The cost of the under-fertilization in both years can be calculated by comparing the net return (i.e., value of yield – cost of N fertilizer) for the economic optimum rate to the return for a constant 1X recommended rate (Table 11). For both years, the under-fertilization of the lower slope units cost the producer \$70 to \$90 ha^{-1}. The net return for the higher fertilizer rate in the midslope units in 1996 is much lower. The economic optimum rate for the upper slope units is very close to the soil test recommended rate, and hence no differential in return exists.

To facilitate comparisons between fields in each of the three years, we assume that each management unit occupies an equal proportion of the field. We chose this approach for comparing returns between years because it was clear that the greatest returns could be achieved in the lower slope positions. Moreover, the proportion of the landscape occupied by lower slope positions varied from year to year (depending on the location of the experiment) and an economic analysis based on this variability would favour years in which lower slope positions dominated the experimental site. If we multiply the net return at the economic optimum by 0.3333 and sum for the three units, the whole-field return of the economic optimum scenario can be calculated (Table 11). The whole-field increase in net return due to the application of the economically optimum rate is averages out at approximately \$29 ha^{-1} for 1996 and \$ 33 ha^{-1} in 1997. The increase is almost entirely due to the much higher returns in the lower slope units.

The curves for 1998 represent a very clear departure from the previous two years of the study (Table 11). The curve for the upper slope units is linear with a slope of only 0.7180. This indicates that the yield return for each kg of N fertilizer added is less than the cost of the fertilizer, and hence the economic optimum N rate is 0 kg ha^{-1}. The economic optimum rates for the midslope and lower slope units are slightly below the 1X recommended rate for the field as a whole. The increase in net return for the economic optimum scenario compared to the 1X rate lies largely in a reduction in fertilizer inputs in the upper slope position, and is limited to approximately \$12 ha^{-1} on a whole field basis.

Calculations based on the economic optimum for a given year are based on hindcasting – once the form of the curve is known for a given year, the producer can determine what they should have done in terms of developing a fertilizer management plan. Clearly, this is of limited relevance for producers who make their fertilizer decisions on the basis of the information available to them prior to seeding. Hence, for the successful application of VRF, it is necessary to develop a management scenario that is based on the information available to the producer at or before seeding.

Both the available water and mineral N in spring can be assessed by producers – albeit at greatly different costs. When the levels of these two properties are correlated to the yields at the economic optimum, spring available water emerges as the best parameter in terms of correlation to yields. The Pearson correlation of spring available water to the economic optimum yield has a correlation coefficient of 0.81 (at a two-tailed significance of 0.09) whereas the correlation for spring mineral N is 0.54 (with a two-tailed significance of 0.14). Hence at the simplest level the economic optimum yield is more clearly related to spring available water than to mineral N.

The analysis presented above suggests that two basic scenarios exist. In years where a well-defined landscape pattern in soil moisture occurs such as 1996 and 1997, a VRF program with higher N rates added to lower slope units, as compared to the upper and midslope units, is warranted. Based on the economic optimum rates calculated above, a program that added 1X the soil test recommended rate (based on a composite sample obtained from the midslope position) on upper slope units and midslope units, and 2X the recommended rate on lower slopes could be suggested. In a year with a dry spring, such as 1998, a more conservative VRF program that added 0.5X the soil test rate on upper slope units, and 1X the soil test rate on both midslope and lower slope units would be appropriate. The net return of this VRF scenario compared to a constant 1X application indicates very comparable returns to the economic optimum scenario presented above (Table 12).

Table 11: Yield functions and economic optimum N rates and net return. Calculations assume N@\$0.587 and canola@0.320 for a price ratio of 1.8344.

Unit	Yield Function	N Rate at Economic Optimum	Yield at Economic Optimum	Net Return at Economic Optimum	Minus Net Return at 1X Rate
		kg ha^{-1}		\$	
		Hepburn Canola 1996			
Upper	$Y=330.408+6.0026x-0.0266x^2$	84.3 (1.0X)[1]	637.0	158.20	0.00
Mid	$Y=678.771+7.4859x-0.0218x^2$	130.9 (1.62X)	1284.0	334.57	14.45
Lower	$Y=1206.18+4.521x$	168.0 (2.0X)	1966.4	530.50	72.14
Whole Field[2]					28.86
		Hepburn Canola 1997			
Upper	$Y=378.690+4.5654x-0.0205x^2$	67.0 (0.85X)	593.	150.43	0.93
Mid	$Y=854.481+2.8082x-0.0059x^2$	83.0 (1.05X)	1047.	286.32	0.18
Lower	$Y=1110.25+6.5059x-0.0079x^2$	156.8 (2.0X)	2018.	637.48	97.55
Whole Field					32.89
		Hepburn Canola 1998			
Upper	$Y=358.876+0.7180x$	0.0 (0.0X)	359.	114.88	32.35
Mid	$Y=580.420+5.0308x-0.0205x^2$	78.0 (0.87X)	848.	225.57	0.96
Lower	$Y=983.345+4.3344x-0.0194x^2$	64.0 (0.71X)	1181.	340.35	3.74
Whole Field					12.35

1: N rate at economic optimum as a fraction of whole-field recommended rate

2: Whole field return calculated assuming equal proportions of the three units in the field.

Table 12: Yields and net return based on VRF scenario discussed in text. Calculations assume N@$0.587 and canola@0.320 for a price ratio of 1.8344.

Unit	Yield Function	VRF N rate	Yield at VRF N Rate	Net Return at VRF N rate	Minus Net Return at 1X Rate
		kg ha^{-1}		$	
	Hepburn Canola 1996				
Upper	$Y=330.408+6.0026x-0.0266x^2$	84.3 (1.0X)[1]	647.4	185.99	0.00
Mid	$Y=678.771+7.4859x-0.0218x^2$	84.3 (1.0X)	1155.0	320.12	0.00
Lower	$Y=1206.18+4.521x$	168.0 (2.0X)	1966.4	530.50	72.14
Whole Field[2]					24.15
	Hepburn Canola 1997				
Upper	$Y=378.690+4.5654x-0.0205x^2$	78.4 (1.0X)	622.5	180.78	0.00
Mid	$Y=854.481+2.8082x-0.0059x^2$	78.4 (1.0X)	1038.0	286.14	0.00
Lower	$Y=1110.25+6.5059x-0.0079x^2$	156.8 (2.0X)	2018.5	553.88	96.86
Whole Field					32.29
	Hepburn Canola 1998				
Upper	$Y=358.876+0.7180x$	45.0 (0.5X)	391.2	98.77	16.24
Mid	$Y=580.420+5.0308x-0.0205x^2$	90.0 (1.0X)	867.8	224.61	0.00
Lower	$Y=983.345+4.3344x-0.0194x^2$	90.0 (1.0X)	1216.3	336.61	0.00
Whole Field					5.41

1: N rate for scenario as a fraction of whole-field recommended rate

2: Whole field return calculated assuming equal proportions of the three units in the field.

Phosphorus Treatments at the Canola Site

No treatment effect was observed for the P treatments in any of the three years of the study at the canola site (Table 13 to 15) although soil test recommendations indicated requirements of 22.5, 27.5 and 30.0 lbs./acre P_2O_5 in 1996, 1997 and 1998, respectively. Nuttall et al. (1992) examined the response of canola to P fertilizers in relation to soil tests over a 16-year period and concluded that soil tests for P gave a good estimation of canola grain yield responses to P_2O_5 fertilization. Their data, however, indicate that within a relatively narrow range of sodium bicarbonate soluble P levels (i.e. 9 to 15 mg kg-1) canola grain yield response ranged from as much as 40 to 460 kg ha^{-1}.

The range in yields for the P treatment summed across the management units was very small. In 1996, the difference between the highest yielding P treatment (1N1P) and the lowest (1N0P) was 73.8 kg ha^{-1}; in 1997, the difference was 344.5 kg ha^{-1} (between 1391.8 kg ha^{-1} for the 1N0.5P and 1047.3 kg ha^{-1} for the 1N0P); and for 1998 the difference was only 177.7 (between 889.9 kg ha^{-1} for the 1N2P and 712.2 kg ha^{-1} for the 1N0P). The relatively narrow range of yields summed across the management units serves to reinforce the observation that application of P at the recommended soil test rate had little influence on canola yields at the sites examined in this study.

In all three years, there was a strong management unit effect, irrespective of P fertilizer rate, and yields increased from lowest yields in the upper slopes to highest yields in the lower slope units. Generally the yields in the lower slope units were 2- to 3-X as high as in the upper slope units.

Table 13: Results for the Phosphorus treatments at the Canola site, 1996. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Units	Grain Yield in the Phosphorus Treatments (kg ha^{-1})			
	1N0P	1N0.5P	1N1P	Row Mean
Upper Slope	517.5	651.5	655.9	627.4
Midslope	1102.9	1119.2	1119.3	1116.0
Lower Slope	1590.4	1510.9	1657.1	1614.5
Column Mean	1070.3	1093.9	1144.1	

ANOVA Results	Significance of F
Replicate	.196
Management Units	.000
P treatments	.562
Management Unit X P treatment Interaction	.977

Table 14: Results for the Phosphorus treatments at the Canola site, 1997. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Units	Grain Yield in the Phosphorus Treatments (kg ha^{-1})			
	1N0P	1N0.5P	1N1P	Row Mean
Upper Slope	539.8	567.5	604.7	579.2
Midslope	902.7	1376.0	1033.0	1091.4
Lower Slope	1699.3	2231.8	1547.3	1756.4
Column Mean	1047.3	1391.8	1063.6	

ANOVA Results	Significance of F
Replicate	.120
Management Units	.000
P treatments	.565
Management Unit X P treatment Interaction	.137

Table 15: Results for the Phosphorus treatments at the Canola site, 1998. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Units	Grain Yield in the Phosphorus Treatments (kg ha^{-1})				
	1N0P	1N0.5P	1N1P	1N2P	Row Mean
Upper Slope	240.0	429.2	430.4	590.8	422.6
Midslope	845.8	790.7	892.3	885.4	853.9
Lower Slope	1073.2	1118.6	1187.4	1193.5	1143.2
Column Mean	712.2	779.5	836.7	889.9	

ANOVA Results	Significance of F
Replicate	.002
Management Units	.000
P treatments	.615
Management Unit X P treatment Interaction	.425

Soil Conditions and Crop Yields at the Wheat Site

Soil Distribution

The wheat site is also site is mapped into the Oxbow association. Soil texture at the site ranges from sandy clay loam to clay loam, typical of these glacial till landscapes.

The distribution of soils at the wheat site overall indicates a higher quality soil than at the adjacent canola site (Table 16). The upper slope units at this site have no members of the Regosolic order, which, in cultivated landscapes, normally result from loss of topsoil through the combined action of water, wind, and tillage erosion. The lower slope units are again dominated by a distinct assemblage of soils, primarily those associated with periodic water saturation in the solum (i.e., the gleyed subgroups of the Chernozemic order and the Gleysolic soils). At this site, however, the Gleysolic soils in the lower slope positions lack a layer of deposited soil, and are classified into the Orthic Luvic Gleysol subgroup rather than the Humic Luvic subgroups such as at the canola site.

The midslope units have a clearer relationship with the soil subgroups. The midslopes at this site are dominated by Orthic Chernozemic and more deeply leached Eluviated subgroups, with fewer representatives of the water-saturated Gleysolic soils.

Soil Characteristics

The higher overall soil quality at the wheat site is confirmed by the soil organic carbon (SOC) results (Table 17). The upper slope soils at this site have 11 Mg ha^{-1} more SOC in the surface increment than the canola site, indicating that less of the SOC has been lost through either mineralization or soil erosion. It also is interesting to note that the total solum SOC in the lower slope soils is lower at the wheat site than at the canola site. Again this may indicate less deposition of organic-rich topsoil from the upper slope positions into the lower slope positions. The SOC values at this site should indicate a higher total soil N content, which in turn may mean a higher potential for N mineralization from the soil organic fraction. Both the pH and E.C. of the wheat site soils are low slightly lower than at the canola site, which may indicate a slightly more leached soil condition than at the canola site. The PWP moisture contents are very similar at this site in all three management units.

According to the anion exchange membrane extractable P (P_{AEM}) (multiplied by a factor of 4 to obtain values roughly equivalent to standard Olsen P in lbs./acre (Schoenau and Huang 1991)), the calculated P values range from approximately 12 lbs./ac in the upper slope units to 28 lbs./ac in the lower slope units. According to the 1990 Nutrient Requirement Guidelines from the Saskatchewan Soil testing Laboratory, this would indicate a recommended P addition of 20 to 25 lbs. acre^{-1} of P_2O_5 for wheat production in the upper and midslope units, and a need for additions of approximately 15 lbs. acre^{-1} in the lower slope position. The higher P levels in the lower slope positions was unique to the wheat site and was not observed at the canola site.

The marginal soil test level for zinc is 0.26 to 0.5 μg g^{-1} and for copper is 0.6 to 1 μg g^{-1} for a 0-15 cm sample. The zinc levels measured for the site soils (Table 17) are well in excess of the marginal rates. The copper levels are in the high end of the marginal level for the surface increment, but showed an increase with depth to above marginal levels. The levels for both micronutrients are very similar to the range observed at the canola site, which may reflect the common parent materials at the two sites.

Table 16: Distribution of soil subgroups in the management units at the wheat site. The subgroups are arrayed in approximate order from driest to wettest. These results are tabulated from a 9 x 11 survey grid (sampled in fall, 1995) that covered the entire extent of the wheat site.

Orders and Soil Subgroup	Upper Slope	Midslope	Lower Slope
	Regosolic Order		
Orthic	0		
	Chernozemic Black		
Rego	7	2	
Calcareous	4	11	
Orthic	3	18	7
Eluviated	1	7	7
Gleyed Calcareous		6	1
Gleyed Rego	1	2	3
Gleyed Eluviated		1	4
	Gleysolic Order		
Luvic		1	11
Other Gleysols			2

Table 17: Selected soil properties of the management units at the Hepburn wheat site. Values shown are mean and standard error of the mean (in italics). Soils sampled in fall, 1995.

Unit	Soil Organic Carbon Mg ha^{-1}		pH		Electrical Conductivity dS m^{-2}		Permanent Wilting Point (%, volumetric)	
	0-15 cm	0-60 cm	0-15 cm	45-60 cm	0-15 cm	45-60 cm	0-30 cm	30-60 cm
Upper	44.2	71.7	7.9	8.4	.38	.94	26.2	25.3
	2.8	*7.0*	*.1*	*.1*	*.00*	*.15*	*.82*	*.93*
Midslope	52.6	95.6	7.5	8.2	.39	1.22	19.7	20.87
	1.4	*4.1*	*.1*	*.1*	*.01*	*.13*	*.86*	*.38*
Lower	55.0	86.0	7.1	7.6	.34	0.71	20.1	19.1
	1.7	*3.7*	*.1*	*.2*	*.02*	*.16*	*.93*	*.72*

Table X: Phosphorus and micronutrient status of the management units at the Hepburn wheat site. Values shown are mean and standard deviation (in italics). Soil sampled in fall, 1997.

Unit	Anion exchange membrane-P µg g^{-1}			Available Zinc µg g^{-1}		Available Copper µg g^{-1}	
	0-15 cm	15-30	30-60	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Upper	2.20	0.36	0.33	1.21	0.58	0.95	1.36
	1.71	*.15*	*.06*	*.53*	*.13*	*.27*	*.41*
Midslope	1.54	0.39	0.43	1.20	0.81	0.82	1.31
	.54	*.10*	*.10*	*.19*	*.34*	*.14*	*.30*
Lower	6.52	1.48	0.91	2.68	0.69	0.77	1.25
	3.80	*1.41*	*.62*	*1.18*	*.10*	*.13*	*0.42*

Spring Available Water and Nitrogen Levels

As was observed at the canola site, a significant landscape effect for spring moisture existed for all three years of the study (Table 18). In each year, spring available water was lowest in the upper slope units, increased through the midslopes, and was highest in the lower slope units. Hence despite the apparent overlap in some soil properties between the units, the differences between the units were clearly expressed in terms of spring moisture conditions.

The spring available water levels at the wheat site also show a progressive decline over the three years of the study (Table 18). Spring soil moisture levels are highest overall in 1996 for all three units. Interestingly, the upper slope units decreased in 1997 to levels below the PWP, measured prior to seeding, and showed a further decrease in 1998 to levels well below the PWP. The midslope units in 1998 also showed levels well below the PWP in spring, and, as discussed above, no significant rainfall amounts were received in the first 25 days after seeding. Available soil water levels at or below the PWP undoubtedly influenced germination and early seedling development. The lower slope units at this site also showed significantly lower levels of spring available moisture in 1998 as compared to the canola site (0.99 cm water per 60 cm of soil compared to 2.69 cm of water at the canola site). Hence soil moisture conditions at the wheat site in 1998 were even drier than that experienced at the canola site.

Mineral N levels at spring seeding are generally more stable over the three years of the study than was the case at the canola site (Table 19). A striking difference between the two sites is the generally low levels of mineral N in the lower slope positions at the wheat site. In all three years at the wheat site, mineral N levels at the lower slope positions are not significantly different than the upper slope positions, whereas at the canola site the lower slope positions were consistently the highest in mineral N. This may be due to the lack of deposition of organic-rich topsoil in the lower slope units at the wheat site as discussed above. For a very similar landscape at Lanigan, Saskatchewan, Pennock et al. (1994) argues that the deposition of topsoil in these lower slope position actually improves the quality of the soil – a "benefit" of higher rates of soil erosion from the upper slope position.

Table 18: Available Water (cm water /60 cm of soil) at the time of spring sampling, Wheat site. Values shown are the mean and the standard error of the mean (in italics). Results are shown for a mean comparison based on the Least Significant Difference test ($\alpha=0.05$) among management units in a given year.

Management Unit	1996	1997	1998
Upper slope	2.36a	-1.16a	-2.30a
	.25	*.70*	*.54*
Midslope	7.80b	2.16	-1.46b
	.39	*.44*	*.39*
Lower slope	10.24c	2.76c	0.99c
	.30	*.41*	*1.0*

Table 19: Mineral nitrogen (kg ha^{-1}, 0-30 cm) at the time of spring sampling, Wheat site. Values shown are the mean and the standard error of the mean (in italics). Results are shown for a mean comparison based on the Least Significant Difference test ($\alpha=0.05$) among management units in a given year.

Management Unit	1996	1997	1998
Upper slope	32.8ab	21.4a	25.7a
	1.9	*1.7*	*2.6*
Midslope	37.1b	39.7b	37.9b
	2.0	*4.4*	*3.2*
Lower slope	27.0a	24.9a	30.1a
	2.9	*2.3*	*2.1*

Results for the Nitrogen Treatments at the Wheat Site

As was the case for the canola experiment, the major purpose of the N treatments was to allow the development of yield response functions for each year of the study. The results for the wheat site also include data for the protein content of the wheat, which often is closely related to the N inputs. These yield functions can then be used to derive the principal measures used in the economic analysis, such as the economic optimum yield for each year.

The results of the ANOVA analysis show much less consistent results than those for the canola site (Table 20 to 22). Again the overall differences among management units are highly significant in all three years. The differences between N treatments are only significant in 1996 and 1997 but are lost in 1998.

The results for the 0N1P treatment show a consistent difference among management units in the three years, with yields increasing downslope. Others similarly have reported an increase in wheat grain yield with distance downslope (de Jong and Rennie, 1969; Spratt and McIver, 1972, Verity and Anderson, 1990, McConkey et al., 1997). Verity and Anderson (1990) examined the productivity of Dark Brown soils in the Weyburn association and similarly observed that yields were least on shoulder positions where runoff and erosion was greatest, and highest on depositional, footslope positions that had gained both soil and water. They suggested that the productivity gradient was best described by a third-order polynomial, with the yields in the lower slope positions often more than double those achieved on upper slopes.

Grain yields also show a very pronounced decline over the three years. The yields (in kg ha^{-1}) for the upper slope units show a decline from 1934 to 1436 to 1192 for the three consecutive years of the study. Similarly, grain yields in the midslopes decrease from 3076 to 2824 to 1332 for the three years whereas grain yields in the lower slope positions show an even more pronounced decline from 3732 to 2701 to 1819 over the same period. Given the fact that the spring N levels changed little over the three years, this severe decrease in yields presumably reflects the marked decrease in spring available water over the period. The strong moisture control is also reflected in the very low yields that occurred in the driest year, 1998. Others have reported that stored moisture at seeding has an important influence on grain yield (Warder et al., 1963). De Jong and Rennie (1969) reported that stored moisture at seeding in lower slope positions was correlated to grain yield although a similar relationship was not detected in other landscape positions.

The increases in yields due to N fertilizer additions are also much less consistent for the wheat site than for the canola site. In 1996 the difference in yield between the highest yielding treatment and the 0N1P treatment was greatest in the midslope position – an increase of 829 kg ha^{-1} for the 1X treatment. The highest yielding treatment in the lower slope units was the 0N1P treatment itself – the lowest yields overall in this position occurred for the 2XN treatment. Hence a complete lack of positive response for the lower slope positions to added fertilizer also occurred in the year where the yields of grain for the 0XN treatment was at a maximum for this position.

The greatest increases due to fertilization for the upper and lower slope positions occurred in 1997 (Table 21). The difference between the 0N1P treatment and the highest yielding treatment was 1245 kg ha^{-1} (1.5X treatment) for the upper slopes and 1446 kg ha^{-1} (2X) for the lower slope units. The maximum yields for the 2XN treatment were the highest observed for the three years at 4147 kg ha^{-1}. Spratt and McIver (1972) reported that although wheat grain yields (averaged over 15 locations in southeastern Saskatchewan) increased from 1152 kg ha^{-1} on upper knoll positions to 1932 kg ha^{-1} in lower slope depressional areas, the average response to fertilizer N (33.6 kg ha^{-1}) was a mere 74 kg ha^{-1}. Moreover, the average response to fertilizer N was no greater on the upper knoll than in the depressions, irrespective of the levels of available soil N.

The response to the added N fertilizer in 1998 was essentially non-existent (Table 22). The highest differential for any of the three units was only 273 kg ha^{-1} (in the lower slope units). Averaged over all three units, the greatest response to any N treatment occurred for the 0.5N treatment, but the mean increase was only 141 kg ha^{-1} over the 0N1P treatment. Hence the very dry soil conditions at seeding and lack of rainfall in the first 25 days after seeding combined to greatly limit yields.

It is known that the maximum yield potential for wheat is established early in the growing season (Baier and Robertson, 1967; Entz and Fowler, 1988; Johnston and Fowler, 1992). Frank and Bauer (1984) reported that two parameters that strongly contribute to grain yield, namely spikes per plant and spikelets per spike, are determined by the apex terminal spikelet stage which, in their study, occurred between 26 and 30 days. These authors further observed that number of spikes per plant and consequent grain yield were strongly affected by soil water levels and N fertilizer applied. Typically, increasing increments of both water and N fertilizer during early developmental stages (i.e., prior to the apex terminal spikelet stage) increased the number of spikes per plant and grain yields. Baier and Robertson (1967) reported that the number of kernels per spike of wheat was most severely reduced by water stress during the 15 d prior to anthesis. In 1997 and 1998, soil moisture levels at or below PWP in the upper and midslope positions likely imposed a physiological limitation on the maximum yield potential.

It is interesting to note that the same limitations do not necessarily apply to canola. Indeed, research suggests that canola yields are positively correlated to growing season precipitation (Nuttell et al., 1992). Moreover, studies with oilseed rape have shown that increased water availability following flowering was critical for high yields (Stoker and Carter, 1984). Thus, although moisture availability (as controlled by landscape position) plays an important role in determining yields of both wheat and canola, the mechanisms by which water availability affects yields, and the critical drought stress periods, may differ between canola and wheat. It follows that VRF management strategies for wheat and canola must take into consideration these basic differences in responses to varying levels of soil water availability within a landscape.

Table 20: Results for the Nitrogen treatments at the Wheat site, 1996. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Unit	Grain Yield in the N Treatments (kg ha^{-1})					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	1934.8	2392.6	2452.6	2222.4	1902.5	2190.6
Midslope	3076.9	3763.1	3905.1	3389.5	3451.4	3532.4
Lower Slope	3732.3	3636.5	3551.7	3633.8	3357.0	3582.3
Column Mean	2905.1	3264.1	3303.1	3081.9	2962.5	

ANOVA Results	Significance of F
Replicate	.000
Management Units	.000
N treatments	.035
Management Unit X N treatment Interaction	.393

Table 21: Results for the Nitrogen treatments at the Wheat site, 1997. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Unit	Grain Yield in the N Treatments (kg ha^{-1})					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	1436.3	2114.0	2559.0	2681.9	2358.0	2229.9
Midslope	2824.3	3195.7	3301.6	3145.5	3373.0	3168.0
Lower Slope	2701.8	3514.1	3923.8	3923.8	4147.3	3636.9
Column Mean	2320.8	2941.3	3261.4	3241.7	3292.8	

ANOVA Results	Significance of F
Replicate	.000
Management Units	.000
N treatments	.000
Management Unit X N treatment Interaction	.638

Table 22: Results for the Nitrogen treatments at the Wheat site, 1998. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Unit	Grain Yield in the N Treatments (kg ha^{-1})					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	1192.4	1204.8	1177.3	1128.9	1222.1	1185.1
Midslope	1332.8	1457.6	1393.2	1422.7	1404.1	1402.1
Lower Slope	1819.3	2039.9	1941.9	2092.9	1935.8	1971.0
Column Mean	1426.3	1567.5	1504.1	1548.2	1520.7	

ANOVA Results	Significance of F
Replicate	.035
Management Units	.000
N treatments	.587
Management Unit X N treatment Interaction	.978

Protein-Yield Relationships for the N Treatments

Nitrogen is an essential component of grain protein and the addition of N fertilizer can influence both yield and grain protein content (Grant et al., 1991). Because grain protein reflects the ratio between N and C accumulation within the plant, factors that influence the accumulation of either N or C can influence the grain protein content (Fowler et al., 1989). Thus protein response can not be viewed in isolation from the yield response.

The ANOVA results for the wheat site indicate that highly significant effects on grain protein exist for both the management units and the N treatments in all three years of the study (Tables 23 to 25). Overall, grain protein increases from 1996 to 1998 – an inverse relationship to the grain yields across the three years. Several studies have demonstrated that grain yield and grain protein content are negatively correlated (review by Selles and Zenter, 1998).

In all three years, the highest overall grain protein levels (i.e., the mean for each unit across the N treatment levels) is associated with the lower slope (1996) or the midslope units (1997, 1998). For the N treatments, the highest protein levels occur in the higher N treatments – the 2N1P treatment in 1996 and 1997, and the 1.5N1P treatment in 1998. The ON1P treatment consistently has the lowest protein levels in all three years. Hence even when no significant yield response to the N treatments occurred (e.g. for the lower slope units in 1996 and all three units in 1998), an increase in protein with added N was observed.

The interaction between yield and protein can be better understood using yield-protein graphs (Figure 6 to 8). It is clear from the discussion above that differences in yield are associated with the management units and hence for this presentation the results are grouped by management units for the three years.

For all three years the graphs show a shift to the left (i.e., towards higher protein levels) and downwards (i.e., towards lower yields) as we move from 1996 to 1998. In the upper slope units, large increases in protein at the higher N rates occur in 1996 and 1997 and (with the exception of the 1.5N1P treatment in 1997) the increases in protein with a 0.5 increase in N fertilizer rate is relatively constant. In 1998, however, the increases in yield are negligible, as are the increases in protein.

The form of the curves for the midslope units is very similar in 1996 and 1997, although the curve for 1997 is clearly offset towards higher protein levels (Figure 7). The protein levels for the 0.5N and 1XN treatments are the same in both years. Again the 1998 curve shows a very minor increase in both yield and protein, irrespective of N rate.

The curves for the lower slope units show little consistency over the three years of the study. In 1996, very limited increases in either yield or protein occurred. In 1996, precipitation events following seeding resulting in flooded conditions in the lower slope units and it is possible that excess moisture limited response to fertilizer N. Alternatively, the relatively high levels of soil water availability in these positions may have led to enhance N mineralization which subsequently masked potential responses to fertilizer n application. In 1997, the greatest increases in both yield and protein occurred, with a major increase in both parameters occurring between the 0N1P and the 0.5N1P treatments. The increases in protein were lower for the higher N rates, although continued increases in yield occurred. In 1998, a substantial increase in protein again occurred between the 0N1P and the 0.5N1P treatments, but negligible increases occurred beyond this.

Table 23: Protein results for the Nitrogen treatments at the Wheat site, 1996. Values shown are the mean values of six replicates for protein in %.

Management Unit	Protein of grain in the N Treatments (%)					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	9.7	10.6	11.3	12.0	12.9	11.3
Midslope	10.7	12.2	12.2	12.5	13.3	12.2
Lower Slope	11.8	12.1	12.4	12.8	13.0	12.4
Column Mean	10.7	11.6	11.7	12.4	13.0	

ANOVA Results	Significance of F
Replicate	.160
Management Units	.000
N treatments	.000
Management Unit X N treatment Interaction	.012

Table 24: Protein results for the Nitrogen treatments at the Wheat site, 1997. Values shown are the mean values of six replicates for protein in %.

Management Unit	Grain protein in the N Treatments (%)					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	11.7	12.5	13.4	13.3	14.3	13.0
Midslope	12.6	12.9	12.9	14.2	14.4	13.6
Lower Slope	11.2	13.1	13.3	13.7	14.0	13.1
Column Mean	11.8	12.8	13.5	13.7	14.2	

ANOVA Results	Significance of F
Replicate	.331
Management Units	.013
N treatments	.000
Management Unit X N treatment Interaction	.332

Table 25: Protein results for the Nitrogen treatments at the Wheat site, 1998. Values shown are the mean values of six replicates for protein in %.

Management Unit	Grain protein in the N Treatments ($kg\ ha^{-1}$)					
	0N1P	0.5N1P	1N1P	1.5N1P	2N1P	Row Mean
Upper Slope	13.8	14.1	14.3	14.4	14.6	14.2
Midslope	13.7	14.2	14.7	14.7	14.4	14.4
Lower Slope	13.0	14.1	14.2	14.5	14.3	14.0
Column Mean	13.5	14.1	14.4	14.5	14.4	

ANOVA Results	Significance of F
Replicate	.031
Management Units	.006
N treatments	.000
Management Unit X N treatment Interaction	.208

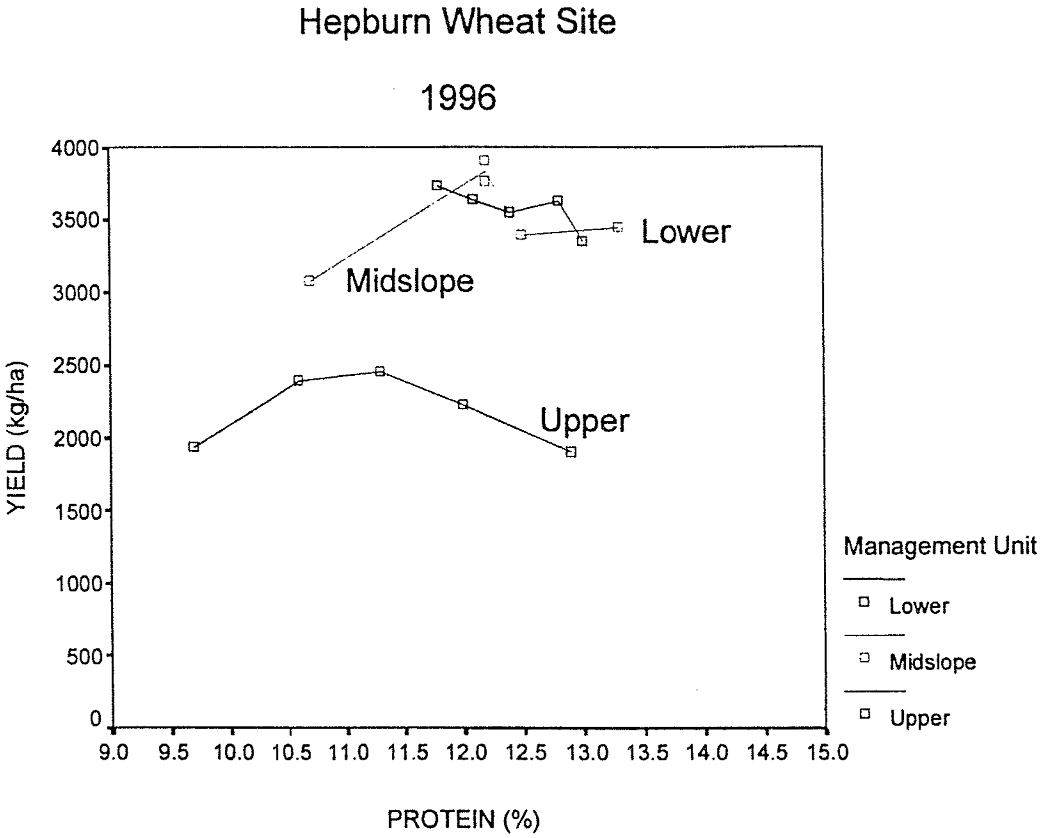


Figure 6: Yield-protein curves for the Hepburn Wheat site in 1996.

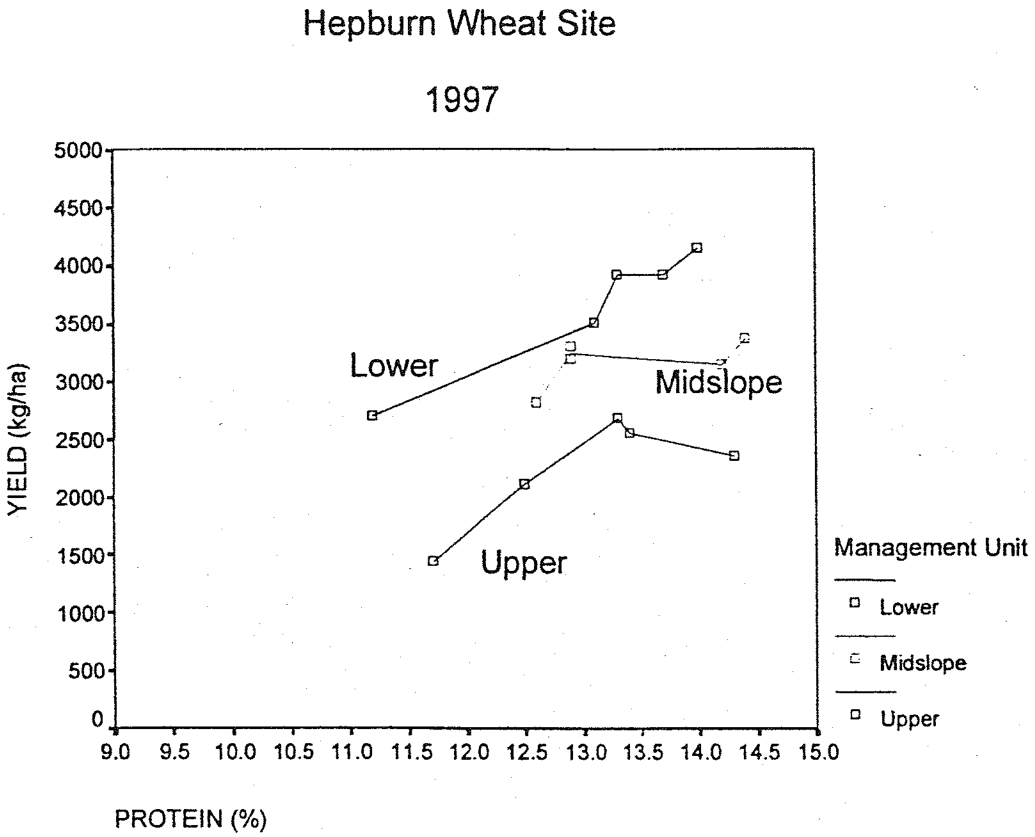


Figure 7: Yield-protein curves for the Hepburn wheat site, 1997.

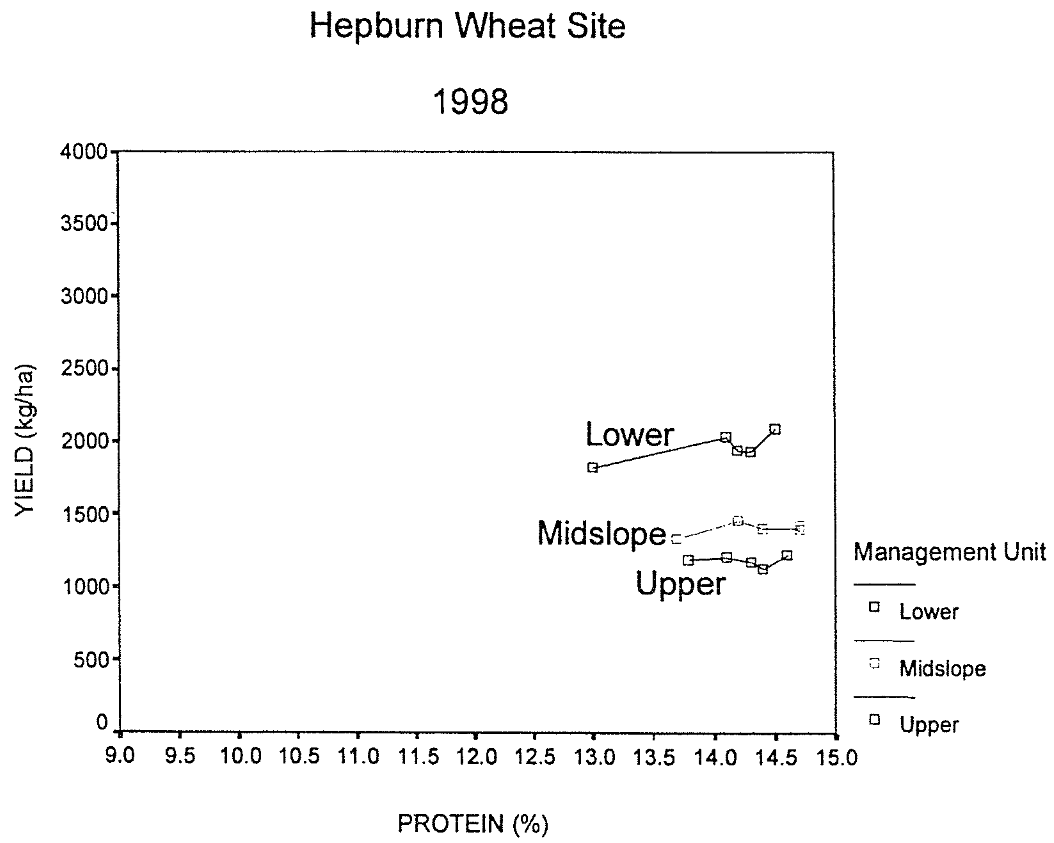


Figure 8: Yield-protein curves for the Hepburn wheat site in 1998.

Development of Yield Response Curves for the Nitrogen Treatments at the Wheat Site

As would be anticipated from the discussion above, the yield functions for the N treatments at the wheat site have little consistency over the three years of the study (Figure 9 to 11).

In 1996, both the curves for the upper slope and midslope units show the "expected" quadratic (i.e., curved) form. The yield relationship for the lower slope units is, however, best described by a linear equation with a slight negative slope (Table 26), which indicates a decrease in yield for every unit of fertilizer added.

The curves for the 1997 season again show a range in response. The upper and lower slope curves show a considerable inflexion and a similar overall form, although the curves for the lower slope units are, of course, offset towards higher yields. The midslope equation is best described by a linear form but with a positive slope of 2.6202 rather than a negative slope (Table 26). The slope is, however, quite slight.

In 1998, all three equations are best described by linear equations with very small slopes (ranging from 0.0469 for the upper slopes to 0.7226 for the lower slopes). Overlap occurs in the curves for the upper and midslopes. The line for the lower slopes is somewhat higher, but this is due entirely to the higher Y intercept (i.e., higher inherent yields at the 0N1P treatment) rather than to any fertilizer response.

The great within- and between-year variation is also reflected in the calculations of the economic optimum rates for N additions (Table 26). For the lower slope units in 1996, the midslopes in 1997, and all three units in 1998, the economically optimum rate of N addition is 0 kg ha^{-1}. Although it could be argued that the dry conditions in 1998 indicated the need for reduced fertilizer inputs, it would have been very difficult to predict the lack of response for the units in 1996 and 1997. Moreover the economic optimum rates in 1996 for the upper and midslope units were below the soil test recommended rate and the optimum rates for the upper and lower slope units in 1997 were above the recommended rates. Given this variation it is impossible to develop a consistent suggested VRF scenario as was possible for the canola site.

The lack of consistency in the yield functions both within and between years greatly limits our ability to suggest an optimum VRF scenario for wheat production based on the results from the wheat site. These sites have been supplemented by the research funded by the Agri-Food Innovation Fund at four other sites in the Province of Saskatchewan. The combination of all the data may suggest a clear VRF approach for wheat production, but no clear approach can be developed for the three years from the Hepburn site alone.

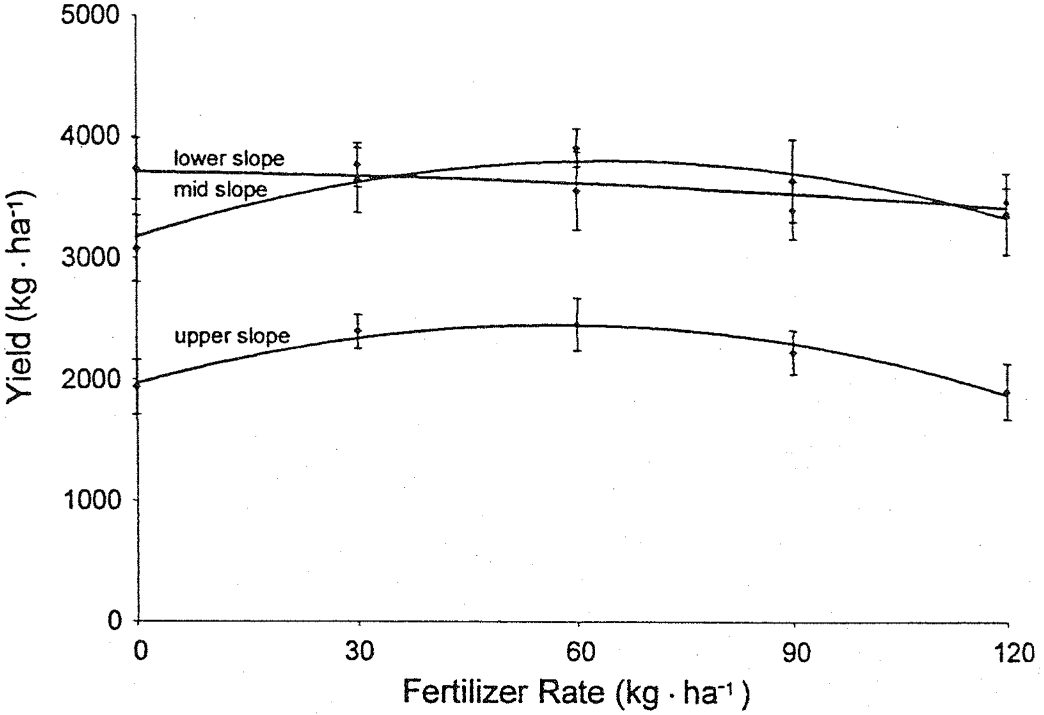


Figure 9: Fertilizer response curves, Hepburn Wheat 1996

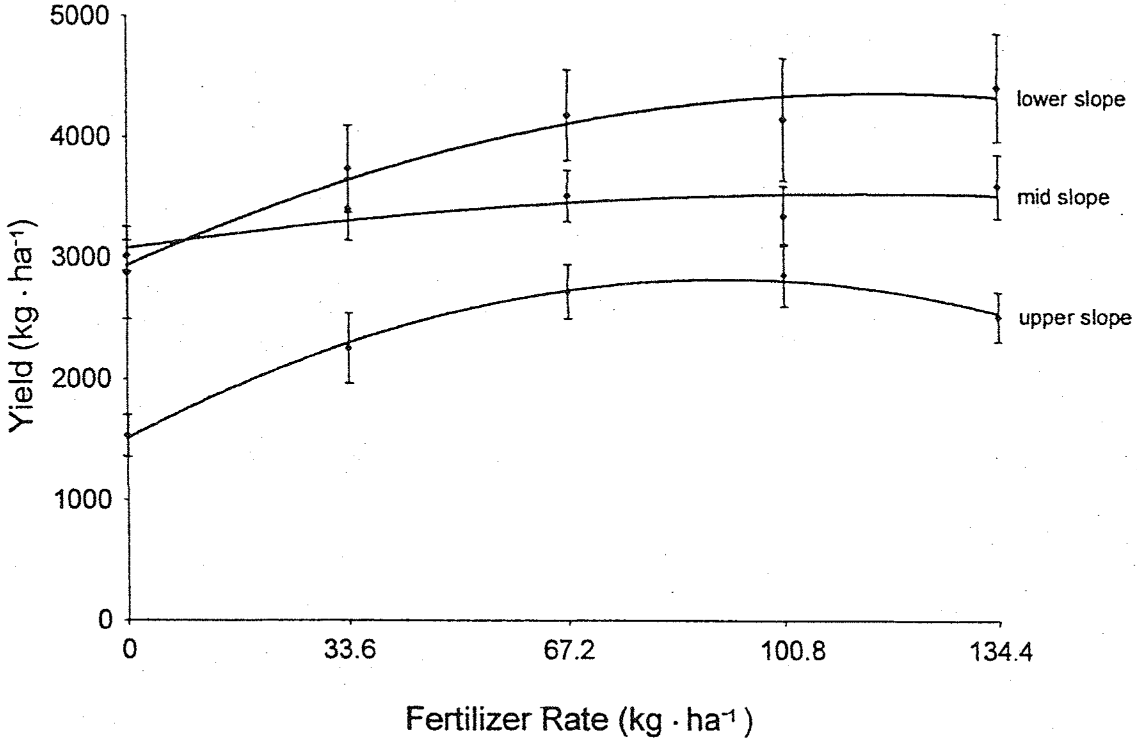


Figure 10: Fertilizer response curves, Hepburn Wheat 1997

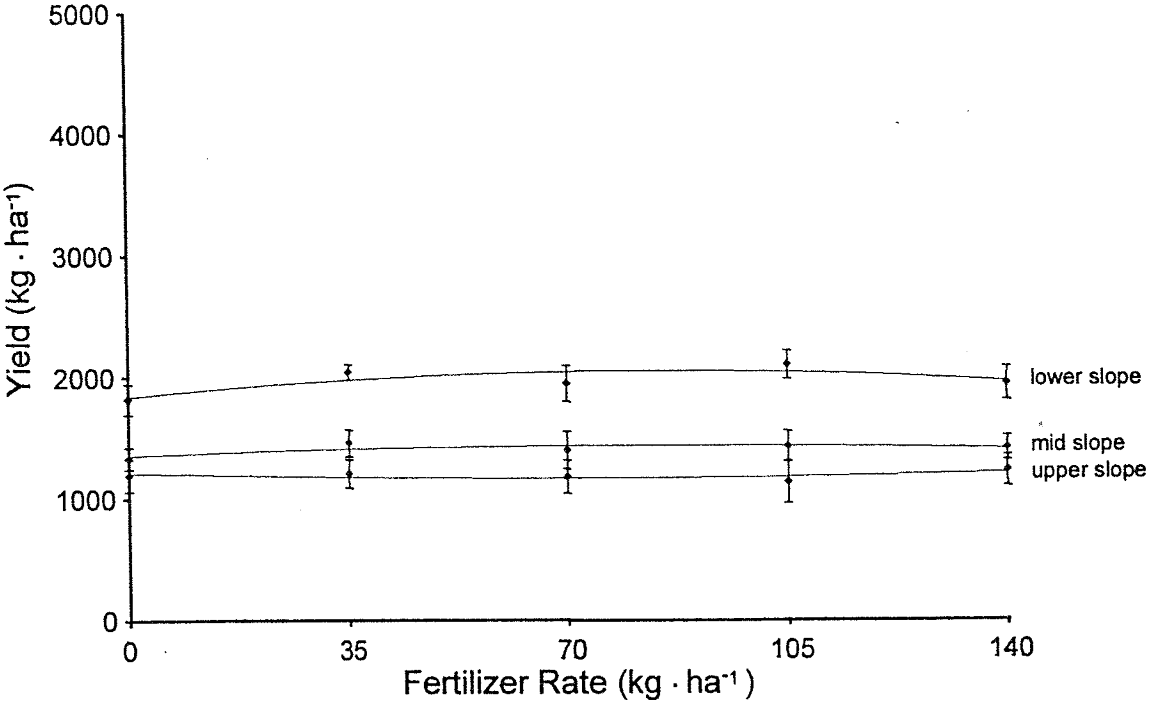


Figure 11: Fertilizer response curves, Hepburn Wheat 1998

Table 26: Yield functions and economic optimum N rates and net return. The calculations assume a value of wheat of $0.11043/kg and nitrogen of $0.587/kg for a price ratio of 5.3156.

Unit	Yield Function	N Rate at Economic Optimum	Yield at Economic Optimum	Net Return at Economic Optimum	Minus Net Return at 1X Rate
		kg ha^{-1}		$	
		Hepburn Wheat 1996			
Upper	$Y=1963.93+16.8656x-0. 1474x^2$	39.0 (0.65X)[1]	2397.0	241.69	7.09
Mid	$Y=3195.00+18.6701x-0.1467x^2$	46.0 (0.77X)	3743.0	386.20	3.40
Lower	$Y=3742.75-2.6202x$	0.0 (0.0X)	3586.0	413.34	52.74
		Hepburn Wheat 1997			
Upper	$Y=1507.77+28.7586x-0.1569x^2$	75.0 (1.12X)	2782.0	262.97	0.92
Mid	$Y=3157.88+3.2866x$	0.0 (0.0X)	3158.0	348.74	15.25
Lower	$Y=2935.45+24.7227-0.1067x^2$	91.0 (1.35X)	4302.0	421.38	6.61
		Hepburn Wheat 1998			
Upper	$Y=1188.38+0. 0469x$	0.0 (0.0X)	1188.0	131.19	40.86
Mid	$Y=1380.54+0.3076x$	0.0 (0.0X)	1381.0	152.50	38.98
Lower	$Y=1918.71+0.7226x$	0.0 (0.0X)	1919.0	211.92	35.78

1: N rate at economic optimum as a fraction of whole-field recommended rate

2: Whole field return calculated assuming equal proportions of the three units in the field.

Phosphorus Treatments at the Wheat Site

No treatment effect was observed for the P treatments in 1996 and 1998 at the wheat site (Table 27 to 29), nor was there a consistent pattern of increases in yield at higher P rates for these two years. In 1996, yields decreased slightly from the 0.5P to the 1P treatment. In 1998, we added a 2XPO treatment to ensure that we were not missing a P response at higher input levels; the yield at the 2XP level was less than the response at the 0XP rate.

In 1997, a P treatment effect was observed. The increases in overall yield with the P treatments (i.e., summarized across the three management units) showed an increase of 447 kg ha^{-1} from the 0XP to the 0.5P treatment, but only a 29 kg ha^{-1} increase at the 1XP rate. Hence the results clearly do not indicate any rationale for a variable rate phosphorus program at the wheat site.

Table 27: Results for the Phosphorus treatments at the Wheat site, 1996. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Units	Grain Yield in the Phosphorus Treatments (kg ha^{-1})			
	1N0P	1N0.5P	1N1P	Row Mean
Upper Slope	2310.8	2012.1	1951.5	2091.5
Midslope	2795.6	3378.2	2933.9	3035.9
Lower Slope	2795.6	3519.7	3497.4	3467.8
Column Mean	2830.9	2970.0	2794.2	

ANOVA Results	Significance of F
Replicate	.997
Management Units	.001
P treatments	.739
Management Unit X P treatment Interaction	.970

Table 28: Results for the Phosphorus treatments at the Wheat site, 1997. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Units	Grain Yield in the Phosphorus Treatments (kg ha^{-1})			
	1N0P	1N0.5P	1N1P	Row Mean
Upper Slope	2048.7	2559.0	2198.2	2268.6
Midslope	2739.8	3301.5	3531.0	3190.8
Lower Slope	3655.1	3923.8	4142.0	3906.9
Column Mean	2814.6	3261.4	3290.4	

ANOVA Results	Significance of F
Replicate	.001
Management Units	.000
P treatments	.024
Management Unit X P treatment Interaction	.318

Table 29: Results for the Phosphorus treatments at the Wheat site, 1998. Values shown are the mean values of six replicates for yield (kg ha^{-1}).

Management Units	Grain Yield in the Phosphorus Treatments (kg ha^{-1})				
	1N0P	1N0.5P	1N1P	1N2P	Row Mean
Upper Slope	1112.3	1335.1	1177.3	1155.8	1195.1
Midslope	1299.9	1343.3	1393.2	1307.4	1335.9
Lower Slope	1888.8	1785.9	1941.9	1830.5	1861.8
Column Mean	1433.6	1488.1	1504.1	1431.2	

ANOVA Results	Significance of F
Replicate	.146
Management Units	.000
P treatments	.637
Management Unit X P treatment Interaction	.939

References

Baier, W. and G. W. Robertson. 1967. Estimating yield components of wheat from calculated soil moisture. Can. J. Plant Sci. 47:617-630.

De Jong, E. and D.A. Rennie. 1969. Effect of soil profile type and fertilizer on moisture use by wheat grown on fallow or stubble land. Can. J. Soil Sci. 49:189-197.

Entz, M.H. and D.B. Fowler. 1988. Critical stress periods affecting productivity of no-till winter wheat in western Canada. Agron. J. 80:987-992.

Technicon Industrial Systems, 1978. Ammonium in water and seawater. Industrial Method 154-71 W / B. Technicon Industrial Systems, Tarrytown, NY.

Frank, A.B. and A. Bauer. 1984. Cultivar, nitrogen, and soil water effects on apex development in spring wheat. Agron. J. 76:656-660.

Fowler, D.B., J. Brydon, J., and R.J. Baker. 1989. Nitrogen fertilization of no-till winter wheat and rye. II. Influence on grain protein. Agron. J. 81:72-77.

Grant, C.A., L. E. Gauer., D.T. Gehl., and L.D. Bailey. 1991. Protein and nitrogen utilization by barley cultivars in response to nitrogen fertilizer under varying moisture conditions. Can. J. Plant Sci. 71:997-1009.

Grant, C.A., D.A. Derkson, L.D. Bailey, A.M. Johnston, G. Clayton, G.P. Lafond. 1999. Considerations for side-banded nitrogen fertilization. Proceedings of the Soils and Crops Workshop, University of Saskatchewan, Saskatoon, Saskatchewan.

Gregorich, E.G., and D.W. Anderson. 1985. Effects of cultivation and erosion on soil of four toposequences in the Canadian Prairies. Geoderma 36: 343-354.

Johnston, A., G. Lafond, G. Hultgren and G. Hnatowich. 1997. Fertilizing No-till cereals and canola. Proceedings of the Soils and Crops Workshop, University of Saskatchewan, Saskatoon, Saskatchewan.

Johnston, A.M. and D.B. Fowler. 1992. Response of no-till winter wheat to nitrogen fertilization and drought stress. Can. J. Plant Sci. 72:1075-1089.

McConkey, B.G., D.J. Ulrich and F. B. Dyck. 1997. Slope position and subsoiling effects on soil water and spring wheat yield. Can J. Soil Sci. 77: 83-90.

Nuttall, W.F., A.P. Moulin and L.J. Townley-Smith. 1992. Yield response of canola to nitrogen, phosphorus, precipitation and temperature. Agron. J. 84:765-768.

Popoff, R.W. and D.W. Anderson. 1990. Relationships among landform elements, soil properties, and crop yields on Blaine Lake – Hamlin soils. Proceedings of the Soils and Crops Workshop, University of Saskatchewan, Saskatoon, Saskatchewan.

Pennock, D.J., C. van Kessel, R.E. Farrell and R.A. Sutherland. 1992. Landscape-scale variation in denitrification. Soil Sci. Soc. Am. J. 56: 770-776.

Pennock, D.J., Anderson, D.W., and E. de Jong. 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. Geoderma 64: 297-315.

Schoenau, J.J. and W.Z. Huang. 1991. Anion-exchange membrane, water, and sodium bicarbonate extractions as soil tests for phosphorus. Comm. In Soil Sci. Plant Anal.:, 22: 465-492.

Selles, F. and R.P. Zentner. 1998. Environmental factors affecting wheat protein. In Wheat Protein , Production and Marketing. D.B. Fowler, W.E. Geddes, A.M. Johnston and K.R. Preston (eds.), Proceedings of the Wheat Protein Symposium, March 9 and 10, 1998, Saskatoon, Saskatchewan, Canada.

Verity, G.E. and D.W. Anderson. 1990. Soil erosion effects on soil quality and yield. Can. J. Soil Sci. 70: 471-484.

Walley, F.L., C. van Kessel and D.J. Pennock, 1996. Landscape-scale variability of N mineralization in forest soils. Soil Biology & Biochemistry: 28, 383-391.

Warder, F.G., J.J. Lehane., W.C. Hinman. and W.J. Staple. 1963. The effect of fertilizer on growth, nutrient uptake and moisture use of wheat on two soils in southwestern Saskatchewan. Can. J. Soil Sci. 43:107-116.

(d) Personnel

Project Managers

Blair McCann (100%, September, 1995- May, 1997)

M. P. Solohub (40% of fulltime, May 1997 to May 1999)

Note: Solohub has been jointly paid by the AFIF Precision Farming Grant. Over the time period listed his time and salary from the ADF grant has averaged at a 40% commitment.

Technical Staff:

R. F. Anderson (40% of fulltime, February 1997 to May 1999)

Summer Staff and Laboratory Technicians

S. Vavanthan (100% for 4 months, 1995)
C. Braithwaite (100% for one month, 1996)
T.T. Yates (100% for four months, 1997)
Myles Dyck (100% for 1.5 months, 1998)

(e) Equipment Purchased

None

(f) Project Developed Materials

Discussed under (h) below

(g) Project Photos

Field operations were recorded on film and the slides from these have been extensively used in our extension work.

(h) Acknowledgements and Extension Activities

The following is a list of the major extension activities and materials prepared during the duration of the project. The presentations made after the fall of 1997 often included results from both the ADF and the AFIF sponsored research but the contribution of the ADF funding was clearly acknowledged in every case.

Oral Presentations

1995-1996

Third Annual International Conference on Precision Agriculture, Minneapolis, Minnesota
Saskatchewan Soil Conservation Association Direct Seeding Workshop in Regina.
Northeast Agricultural Research Foundation in Melfort
Saskatchewan Agriculture and Food Soil Fertility Seminar in Saskatoon.

1997
Saskatchewan Agriculture Soil Fertility Seminar in Weyburn, Outlook, Saskatoon.
Saskatchewan Agriculture and Food Soil Fertility Seminar in Outlook
One presentation at Soils and Crops Workshop '97, Saskatoon
Western Canada Agronomy Workshop
Presentation to Staff of SAF and SSCA

1998
College Seminar Series, College of Agriculture, University of Saskatchewan
Saskatchewan Soil Conservation Association Direct Seeding Workshop in Regina
Two presentations at Soils and Crops Workshop '98
Agronomy Training Workshop, Saskatoon
Fourth International Conference on Precision Agriculture, St. Paul, Minnesota
Third Annual Manitoba Precision Farming Conference, Brandon, Manitoba

1999
Canola Development Council Annual Meeting, Saskatoon

Written Research Reports

McCann, B., D. Pennock, and C. van Kessel. 1996. The development of management units for site specific farming. Proceedings of Soils and Crops Workshop '96. Saskatoon, Saskatchewan. Pp. 365-374.

McCann, B., D. Pennock, C. van Kessel, and F. Walley. 1996. The development of management units for site specific farming. Proceedings of the Third International Conference on Precision Agriculture, Minneapolis, Minnesota. Pp. 295-302.

McCann, B., D. Pennock, F. Walley, and G. Hnatowich. 1997. Yield responses to variable rate fertilizer applications across a hummocky till landscape in the black soil zone. Proceedings of Soils and Crops Workshop '97. Saskatoon, Saskatchewan. Pp. 106-118.

Pennock, D., F. Walley, M. Solohub, B. McConkey, A. Johnston, T. Hogg, and G. Hnatowich. 1998. Developing Precision Farming Strategies. Proceedings of Soils and Crops Workshop '98. Saskatoon, Saskatchewan. Pp. 216-224.

Walley, F. D. Pennock, G. Hnatowich, M. Solohub, and B. McCann. 1998. Variable Rate Fertilizer Application in a Thin Black Soil. Proceedings of Soils and Crops Workshop '98. Saskatoon, Saskatchewan. Pp. 225-229.

Solohub, M., D. Pennock, and F. Walley. 1998. Grain Yield Response to N Fertilizer Across Landscape Positions. Proceedings of Soils and Crops Workshop '98. Saskatoon, Saskatchewan. Pp. 230-238

Pennock, D.J., F.L. Walley, M. Solohub, and G. Hnatowich. 1998. Yield response of wheat and canola to a topographically based variable rate fertilization program in Saskatchewan. Proceedings of the Fourth International Conference on Precision Farming, St. Paul, Minnesota (in press).