Relationships Among Soil Properties, Crop Yield, Protein, and Response to Nitrogen Fertilizer Application in an Undulating Landscape in South Central Saskatchewan

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By

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Abstract

A field experiment initiated in spring 2012 was established to assess the relationships between grain yield, grain protein and soil properties including elevation, electrical conductivity, pH, and organic carbon in an undulating landscape. Grain protein can reflect the balance of nitrogen (N) relative to other yield limiting factors. The objective of this study was to 1) assess relationships between soil properties, crop yield and protein content in an undulating landscape in south-central Saskatchewan, and 2) determine feasibility of using protein content along with yield and soil data in identifying variable rate N application zones. In 2012, wheat, canola and peas were seeded. Soil samples and harvest measurements were taken from two transects in each field area. Wheat, canola and pea yields ranged from 882 to 2554, 1143 to 2342, and 839 to 3122 kg ha^{-1} respectively, while protein content for wheat, canola and peas ranged from 10.5 to 14.4, 14.2 to 20.6 and 14.5 to 17.7 percent respectively. Protein in wheat was positively correlated with pH in the 30-60 cm depth and negatively correlated with electrical conductivity in the 30-60 cm depth. Protein in canola was positively correlated with organic carbon in the 0-30 cm depth. Wheat yield was positively correlated with organic carbon in the 0-30 cm depth. Pea yield was negatively correlated with electrical conductivity in the 0-30 and 30-60 cm depths. In spring 2013, wheat was seeded on canola and pea stubble and canola seeded on wheat stubble with varied N rates on one side of each transect with a constant N rate on the other. Greater mean yields were observed from the varied N rate versus the control in the canola-wheat (3163 vs 2256 kg ha^{-1}) and wheat-pea (4716 vs 4155 kg ha^{-1}) rotations. A negative yield from the varied N rate versus the control was observed in the wheat-canola (2216 vs 3012 kg ha^{-1}) rotation. However, these yield differences were not significant at $p < 0.05$.

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I especially want to acknowledge and thank my mom, Marlene Hildebrand, for encouraging my educational pursuits and always being there for me.

And most of all, I want to thank my wife, Nancy, for the joy that she has brought into my life. I love her dearly!

DEDICATION

This thesis is dedicated to the memory of my dad, John Richard Hildebrand (1945-2004), and my brother Matthew Kurt Hildebrand (1987-2014).

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1 INTRODUCTION

Fertilizer application decisions for crops grown on the prairies are traditionally based on measuring the nutrient status of the soil. Typically, this involves analyzing a soil sample taken prior to sowing the next crop. Variable rate application seeks to improve the efficiency of applied fertilizers by identifying areas in a given field with different yield potentials based on topography, texture and moisture. This data is uploaded to a seeding drill capable of applying fertilizer at varied rates based on GPS location. However, there is a cost in money and time to identify and sample separate management zones, and predicting the crop response to added fertilizers requires the identification of limitations on yield in each of the zones. Thus, the challenge is to identify efficient and reliable information that can form the basis of the variable rate prescription map. Both yield and protein harvest data may be useful along with soil data to delineate management zones. Controlling factors on yield and protein content of crops in the landscape need to be identified and relationships determined.

If a variable rate fertilizer prescription map can be developed using yield and protein data, ideally obtained from a combine monitor map, it could contribute to enhanced economic returns and environmental quality by reducing over and under-application of nitrogen fertilizers (Long et al., 2000). The protein content of a crop such as wheat reflects the balance between available N and other limitations on plant growth. For example, a protein content greater than 15% would indicate high N availability relative to other limitations such as water and salinity, while a protein content less than 13% would indicate that not enough N was applied to maximize yield (Engel et al., 1999).

The objective of this study is to examine the relationship of soil properties to crop yield and protein concentration to identify controlling factors, and along with yield and soil properties to determine if protein is a useful additional parameter in creating a variable rate N prescription for a subsequent crop. Soil and crop properties measured and relationships evaluated through correlation analysis include: elevation, grain and straw yield, N and phosphorus (P) concentration, soil available N, P, potassium (K), pH, electrical conductivity (EC). and organic carbon (OC).

2 LITERATURE REVIEW

2.1 Information Requirements for Precision Agriculture

Precision agriculture seeks to account for the inherent variation in a field by identifying and dividing the field into sub-field homogenous zones to which different managements (e.g. fertilizer rates) are applied (Moral et al., 2009). Variable rate fertilization is one component of this system with potential to increase efficiency of applied fertilizer, leading to increased profitability and decreased losses to the environment. Landscape scale variation has been identified as important in agricultural studies for examining and predicting relationships in farm fields (Stevenson et al., 2001). Water, nutrient and sediment transfer occur in landscapes of variable topography, and the referencing of specific landscape positions provides a means to explain these conditions (Pennock and Corre, 2001). Technology exists to manage variable field zones, such as GPS, yield monitors, and variable rate equipped air drills. However, there is a need to obtain information such as elevation, soil texture, organic matter (OM), available moisture and nutrients, salinity, pH and crop history (yield and quality) to develop these zones and examine relationships among these properties to enable a basis for predicting response to added fertilizer, and subsequently select the appropriate rate of application. Variable rate fertilization will only be practical if there exists enough variation in field properties (Beckie et al., 1997).

2.2 Relationships Among Soil Properties and Crop Yield

Many studies have been conducted that examine the relationships among soil properties, and between soil properties and yield (Stewart et al., 2002; Fowler, 2003; Nyiraneza et al, 2012). For example, nitrate N increases with depth, and available N generally increases with available moisture and organic matter content. Soil texture influences available moisture and N. For example a clay soil will hold more moisture than a sandy soil. In turn, this may contribute to greater crop growth and return more organic matter, which increases potential N availability. There are often strong relationships that are reported between crop yield and mineral N, with increased elevation associated with decreased yields due to less mineral N and less available moisture (Baxter et al., 2003).

Electrical conductivity (EC) as measured using an EM-38 can be an efficient means of delineating zones of variation in a field, or even if enough variation exists to make variable rate application practical. There has been reported in many areas a rather consistent relationship between clay content and high yield zones and high sand content and low yield zones. This coincides with higher EC values for high clay and yield zones and lower EC values for low yield zones. Clay content will directly affect EC readings, while sand content will affect EC through site hydrology (King et al., 2005). However, EC readings are applicable only if enough moisture is present. Brevik et al. (2006) found that half of the variation in EC readings could simply be explained by changes in soil moisture. Local knowledge of the field is also needed to give interpretive value to EC measurements. Aerial images are also useful to delineate management zones (Fleming et al., 2000), as are soil survey maps (Hartsock et al., 2005).

Variable rate N application involves two steps: 1) accurately predicting soil N supply as it varies across a field, and then 2) applying N fertilizer at rates that reflect variable crop N requirements across a field (Walley et al., 2002). Walley et al. (2002) looked at the relationships between soil properties and yield of wheat, but found few significant correlations at the landscape level which limited the accuracy of predicting crop N requirements. Relative elevation did not improve these relationships when added to the analysis, which was opposite to findings by Bao-Liang et al. (2009) who reported that in dry years that the upslope length was a good predictor of crop yield, due to moisture redistribution to lower landscape positions. However, in wet years, upslope length was unable to accurately predict crop yield variability.

2.3 Rationale for Using Protein to Delineate Management Zones

Increasing N rates result in "c-shaped" curves in relationships depicting crop yield versus protein, with an initial decrease in protein associated with increasing yield until a plateau is reached where yield no longer increases, but protein continues to increase which is known as the "Steenbjerg effect" (Steenbjerg, 1951). Cereal yields are nearly maximized when protein concentration is 13.4% [Fig. 2.1 from Engel et al. (1999)] known as the critical protein concentration (CPC). This is significant because it is this CPC that has the potential to make protein sensing valuable (Engel et al., 1999). Other studies have reported other slightly different CPCs for wheat, but in general, they are very close to 13%.

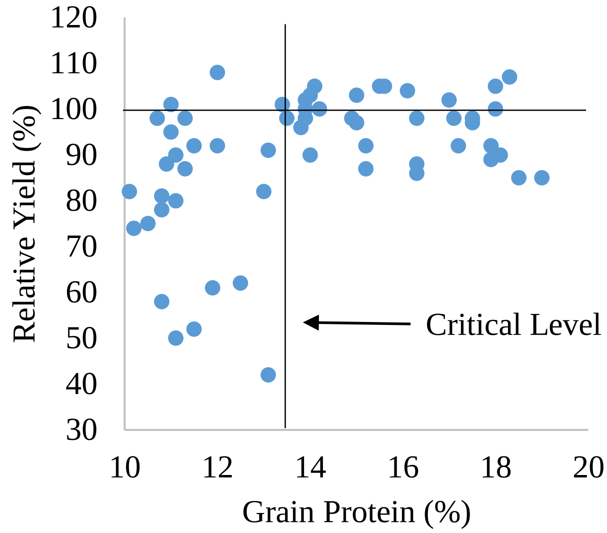

Fig. 2.1. Typical grain and protein curve in wheat (adapted from Engel et al., 1999).

Where protein concentrations are below ≈13.5% protein a N building approach may be used, whereas protein concentrations above 13.5% indicate a N maintenance approach or reduction would be appropriate. Engel et al. (1999) found 13.2% protein to be the critical protein concentration. However, this number is not entirely capable of predicting the loss of yield due to inadequate fertility. Their analysis showed 12-18 kg N ha^{-1} are required to increase protein content by one percentage point (i.e., from 12% to 13%).

In another study, Long et al. (2000) followed up on the research of Engel et al. (1999) on a hilly 101 ha field in Montana. They targeted 15% protein because at time of the study, protein premiums at US point of grain delivery were maximized at 15%. The influence of soil moisture was considered in their study. To maintain 15% protein as soil moisture moved from a low moisture (18.5 cm total growing season available moisture) to moderate moisture (29.2 cm total growing season available moisture) regime required a calculated increase in applied N of 50 kg N ha^{-1}. They concluded that moisture must play a role in any variable rate N application model. Five management zones were delineated. A randomized strip trial design was chosen (15.5 x 2000 m) with 17 variable strips and 17 uniform rate strips. Zone 1 was based on low yield, high protein and high soil N (i.e., slopes and summits). Zones 2 and 3 included moderate yield, protein and soil N (i.e., toe and mid slopes). Zones 4 and 5 were based on high yields, low soil N and low protein (i.e., toe slopes). Results were encouraging: zones 4 and 5 experienced increased protein levels, although the total N applied in both systems was equal. Protein ranged from 12-17% under the uniform rate, but was more uniform under the variable rate (15.6-16.5%) on a whole field basis. Thus, the authors were confident that protein concentrations could play a part in variable rate N management and that future work should include a detailed examination of the underlying soil factors, and to include pulses and oilseeds.

The study described in this thesis includes field peas and canola. However, the literature is scarce on the relationship between yield and protein of these crops compared to wheat. Still, this is very important as different crops are commonly grown in rotation on the Canadian prairies such as a canola-wheat-pea rotation rather than continuous wheat or wheat fallow rotations that may be more common in northern U.S. states like Montana (Lenssen et al., 2007). In canola, an inverse relationship has been found between protein and oil concentration (Mason and Brennan, 1998). Interestingly, the total concentration of protein and oil in canola remains relatively consistent at about 62% and it was found that a 1% increase in protein decreased oil content by 0.93% (Brennan et al., 2000).

The relationship between protein and starch in peas is similar to the relationship between protein and starch in wheat, and protein and oil in canola in that as protein increases, starch decreases. Fore example, Holl and Vose (1980) found protein levels varied from 14.2 to 27.1% in a single small plot study of field pea (*Pisum sativum* var. Trapper) at Hagen, SK, Canada, combined with a survey of nine commercial fields (locations not reported). Protein is produced first in a developing seeds, and decreases as starch synthesis increases during maturation. Holl and Vose (1980) reported that symbiotic N fixation was unable to maintain high, stable protein levels and the authors conclude that to ensure high protein peas, N fertilizer should be applied. Protein concentrations in pea do appear to be highly dependent on available N in the soil (Mclean et al., 1974; Sosulski et al., 1974). Field pea yield was found to be inversely related to protein ($r^2 = -0.44$) by Tar'an et al. (2004), and days to maturity ($r^2 = -0.37$). However, pea protein concentration was directly related to days to maturity ($r^2 = 0.53$). Inoculants can have an effect on pea yield and protein as observed by Clayton et al. (2003) in which pea yield increased by 17-56% and protein by 12-15% when a soil applied inoculant (granular) was used versus a seed applied the and uninoculated check. Nitrogen fertilizer application consistently increased pea protein at increasing rates ($p < 0.0001$), however, inoculant had no effect in a study by Igbasan et al. (1996) on two sites near Morden, MB, Canada. The type of inoculant used was not stated.

2.4 Landscape Controls on Yield

A similar study to the current study described in this thesis was conducted at Hepburn and Alvena, Saskatchewan in 2009. Bao-Liang et al. (2009) investigated the effects of water flow, slope and relative elevation in a rolling topography to determine if any of these factors could be useful in delineating field management zones. While soil moisture was the limiting factor for wheat yield, it was the length of upslopes that was the best factor determining how this yield varied in the landscape. This was a consequence of the situation that as the slope length increases, more rainfall can redistribute to lower slope positions. Relative elevation was a useful parameter as well, but ranked second to upslope length. However, it was also found that in wet years the effectiveness of these landscape indices to indicate yield variability was reduced.

2.5 Real-time Protein Sensing Technology

Technology has become available that could allow protein monitoring as the combine is harvesting a crop. Several studies have been conducted studying the value of on-the-go protein sensing as a tool for creating management zones (e.g. Engel et al., 1997; Engel et al., 1999; Long and Rosenthal, 2005; Long et al., 2008), however, often underlying soil properties have not been included in the analysis.

Protein concentrations have proven useful in determining an appropriate N rate for a subsequent crop. Engel et al. (1997) performed a table-top test of an on-the-go protein sensor for spring wheat in Montana. The sensor was accurate to within 0.5% protein points based on 240 samples compared to laboratory wet digestion. Norng et al. (2005) found a significant relationship between protein and yield of sorghum and conclude in their paper that adoption of on-combine protein monitors to make such maps could be useful, and two different on-combine protein sensors were tested. Long et al. (2005) used a continuous flow sensor, but the sensor was not sufficiently accurate in measuring protein. Long and Rosenthal (2005) used a Zeltex Accuharvest Analyzer. It slightly underestimated protein when concentrations were below 16%, but with more samples the calibration could be improved. Standard error reported was good at 0.49%, as Zeltex claimed 0.5%. They concluded that the Zeltex Accuharvest® would be sensitive enough to be useful for protein mapping.

In this study, protein concentrations of grain from each crop were derived from laboratory measurements of N content of the grain. However, a Zeltex Accuharvest® protein sensor was used concurrently in this study to evaluate its effectiveness relative to hand harvested values. Technical difficulties were encountered with the Zeltex assessment, which limited the utility of this analysis. Please see Appendix A for more details.

3 MATERIALS AND METHODS

3.1 Experimental Location Description

This study was located at legal location SW31-20-03-W3 (50.733° N; 106.416° W) near Central Butte, SK, Canada (Fig. 3.1). The soil is classified as a Brown Solodized Solonetz of the Kettlehut Association which exists in a complex with Ardill Association Orthic Brown soil (Ayres et al., 1985). Loam is the dominant texture. Terrain is characterized by gently undulating knolls and depressions, and is moderately stony. The Kettlehut Association describes Brown Solonetzic soils that have developed from moderately saline glacial till parent material and that are also moderately calcareous due to the presence of Cretaceous clay-shales. Gleysolic soils develop in depressions of an otherwise generally well drained topography. The Ardill Association is characterized by Brown Chernozemic soils developed from the same glacial till parent material as the Kettlehut Association, but occupy the upper slopes, whereas the Kettlehut soils occur mainly in mid to low slope positions (Ayres et al., 1985). The site layout on this farm field is depicted in Fig. 3.2 indicating the field areas and location of transect points. A description of each transect point that was made as the transects were laid out in spring of 2012 for each field area is found in Table 3.1. This was used to identify individual transect locations through the two crop seasons and the crop rotation used in this study: 2012 and 2013. The protein:yield combinations at each point from the 2012 crop year are reported in this table as they were used as the basis for the development of management basis for the 2013 field season described in section 3.2.

Fig. 3.1. Experimental location at legal land description SW 31 20 W3 near Central Butte, SK.

Fig. 3.2. Aerial photo of site location indicating field areas and transect point locations and numbering.

Table 3.1. Transect point descriptions and protein: yield relationship for each field area.

Field Area		Crop in 2012	Crop in 2013	Landscape Description	2012 Protein:Yield
1	Point	Wheat	Canola		
Transect 1	1	W1[†]	CW 1[‡]	Gleysol	HP HY[§]
	2	W2	CW 2	Toe-Slope	MP HY
	3	W3	CW 3	Lower-Mid	HP MY
	4	W4	CW 4	Mid-Slope	HP MY
	5	W5	CW 5	Rego-Knoll	HP LY
	6	W6	CW 6	Rego-Knoll	HP LY
	7	W7	CW 7	Mid-Slope	HP MY
	8	W8	CW 8	Saline Toe-Slope Slough	LP LY
Transect 2	9	W9	CW 9	Level	MP MY
	10	W10	CW 10	Toe-Slope	HP MY
	11	W11	CW 11	Toe-Slope	MP MY
	12	W12	CW 12	Shoulder	MP MY
	13	W13	CW 13	Mid-Slope	HP MY
	14	W14	CW 14	Foot-Slope	MP MY
	15	W15	CW 15	Up-Level	MP MY
	16	W16	CW 16	Toe-Slope Slough	MP LY
2	Plot	Canola	Wheat		
Transect 1	1	C1	WC 1	Toe-Slope	HP MY
	2	C2	WC 2	Fertile Depression	LP HY
	3	C3	WC 3	Mid-Slope Gravel	MP LY
	4	C4	WC 4	Eroded Knoll	LP LY
	5	C5	WC 5	Sandy Eroded Knoll	LP MY
	6	C6	WC 6	Mid-Slope	MP MY
	7	C7	WC 7	Saline Depression	HP LY
	8	C8	WC 8	Depression	MP MY
Transect 2	9	C9	WC 9	Saline Solonetz BNT Depression	HP LY
	10	C10	WC 10	Lower level	LP MY
	11	C11	WC 11	Upper level	LP LY
	12	C12	WC 12	Mid-Level	LP MY
	13	C13	WC 13	Foot-Slope	MP HY
	14	C14	WC 14	Depression	MP HY
	15	C15	WC 15	Mid-Slope	MP HY
	16	C16	WC 16	Knoll	LP LY
3	Plot	Peas	Wheat		
Transect 1	1	P1	WP 1	Shoulder	HP HY
	2	P2	WP 2	Mid-Slope	MP HY
	3	P3	WP 3	Toe-Slope	LP HY
	4	P4	WP 4	Saline Depression	MP LY
	5	P5	WP 5	Level	HP LY
	6	P6	WP 6	Wet	HP LY
	7	P7	WP 7	Mid-Slope	MP MY
	8	P8	WP 8	Upper Level	LP MY
Transect 2	9	P9	WP 9	Level	MP MY
	10	P10	WP 10	Upper-Level	HP MY
	11	P11	WP 11	Mid	LP HY
	12	P12	WP 12	Toe-Slope Depression	MP LY
	13	P13	WP 13	Saline Depression	MP LY
	14	P14	WP 14	Lower	HP MY
	15	P15	WP 15	Reclaimed RR Line	HP MY
	16	P16	WP 16	Upper-Slope	MP MY

† "W" denotes spring wheat; "C" denotes canola; "P" denotes peas

‡ "CW" denotes canola grown on wheat stubble; "WC" denotes wheat grown on canola stubble; "WP" denotes wheat grown on pea stubble

§ "HP", "MP", and "LP" denote high, medium, and low protein respectively; "HY", "MY", and "LY" denote high, medium, and low yield respectively from the 2012 season. The derivation of these designations may be found in section 3.2.

3.1.1 Field Operations in 2012

Approximately 11 ha each of hard red spring wheat (*Triticum aestivum*, var. Waskeda), argentine canola (*Brassica napus*, var. Liberty Link 5770) and yellow peas (*Pisum sativum*, var. Meadow) were seeded on May 9, May 2, and April 27 respectively in the spring of 2012 on the three areas of the field as shown in Figure 3.3.

Pre-seed glyphosate was applied as a weed burn off to the wheat and canola, but not to the peas. Seeding rates were 70, 4.5, and 160 kg ha^{-1} respectively for wheat, canola and peas. Fertilizer application was 50 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1} for wheat and 60 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1} for canola. Peas were inoculated with Tag-Team® rhizobial and *P. bilaii* inoculant, but received no fertilizer. Herbicide application included fenoxaprop-p-ethyl (Puma®) and fluroxypyr and 2,4-D (Attain XC®) for wheat, gluphosinate ammonium (Liberty®) for canola and ethalfluralin (Edge®) and imazamox (Solo®) for peas.

Two transects were laid out east to west in each field in June of 2012. Each transect included eight geo-referenced points for a total of sixteen sampling points per crop. These were also marked by burying a magnetic ball at approximately 30 cm depth, making them easily found later in the season with a metal detector, and allowing unhindered field operations.

Precipitation in 2012 was 318 mm from April to October which is considerably greater than the 190mm received in the 2011 growing season, but is similar to the fifteen year average (Table 3.2). May and June of 2012 were much wetter than normal.

Fig. 3.3. Plot layout at SW 31-20-03 W3 showing location of wheat, canola and peas in 2012.

Table 3.2. 2012 growing season rainfall (Environment Canada, Elbow SK).

Month	Year		
	2012	2011	15 year mean
	---------- precipitation (mm) -----------		
April	26	3	17
May	116	38	51
June	109	11	79
July	37	52	53
August	26	53	45
September	4	6	34
October	0	27	15
Total	318	190	294

3.1.1.1 Field Measurements

Measurements taken in fall of 2012 included crop grain and straw yield and N and P content. The N content of the grain was used to calculate protein data by multiplying grain percent N by a factor of 5.7 (Tkachuk, 1969). Soil samples were analyzed in two depth increments: 0-30 and 30-60 cm for available N, P, K, pH, organic carbon (OC), and electrical conductivity (EC) as described below. The coefficient of variation for replicate analyses of soil and plant samples was ≤ 5%. To ensure accuracy, all routine analyses included a standard reference soil or plant material of known established concentration every 40 samples.

3.1.1.2 Fall Soil Sampling

Soil samples were taken in fall of 2012 using a hydraulic punch truck with a 5 cm diameter coring tube in 0-30 and 30-60 cm increments after harvest from each transect point for wheat, canola and peas. These were analyzed for nitrate-nitrogen (Keeney and Nelson, 1982), modified Kelowna extractable P and K (Qian et al., 1994), pH, and EC (Rhoades, 1982). Anion resin membrane strips were also used to analyze for the supply rate of nitrate (NO_3^- -N) and phosphate (PO_4^--P) (Qian and Schoenau, 2008). Organic carbon was determined by dry combustion with a LECO carbon analyzer according to Wang and Anderson (2008).

3.1.1.3 Plant Samples and Protein

Two one meter square plant harvests were performed at crop maturity at each transect point for wheat, canola and pea harvest in the last week of August, 2012. The values of the two harvest measurements were averaged for each transect point. Total biomass, grain biomass, grain N and P, straw N and P were measured and expressed on a kg per ha basis. Grain protein was calculated by multiplying the grain N percentage by a factor of 5.7 (Tkachuk 1966; Sosulski and Holt, 1980; Sosulski and Imafidon, 1990). The 5.7 factor is considered acceptable for general use in converting grain N to protein in many crops (Sosulski and Imafidon, 1990). However, while a conversion factor of 5.6 is often reported as more accurate for wheat (Tkachuk, 1969; Sosulski and Holt, 1980; Mariotti et al., 2008), Fujihara (2008) reported a wheat conversion factor of 5.8. Therefore, for this study, the 5.7 factor was chosen for all crops. Another common grain N to protein conversion factor of 6.25, known as Jones' factor, has been widely studied and recently concluded to be less relevant than 5.7 (Mariotti et al., 2008).

3.2 2013 Field Season

3.2.1 Selecting Nitrogen Rates

Yield and protein values from the 2012 harvest were evaluated, and each transect point was assigned to a protein:yield category (see Table 3.1). These categories are described in this section and were used as the basis for choosing an N rate for each transect point for the subsequent crop in rotation to be grown in 2013. Wheat was seeded on both the canola and pea stubble crops, while canola was seeded on the wheat stubble. Yield and protein values were arranged into high, medium and low categories, and the resulting combinations were assessed. For wheat, high protein was set as any value 13.5% or greater, medium protein between 12.3% to 13.4% and low protein to be 12.2% or lower. Wheat yield was set to be high if 2300 kg ha^{-1} or higher, medium if between 1600- 2299 kg ha^{-1} and low if 1599 kg ha^{-1} or less. These high, medium and low values were set arbitrarily according to general average yield and crop protein data for the field and crop district (Crop District 4, Saskatchewan Crop Insurance Corporation).

Canola protein was set to be high if 18.1% or higher, medium if between 17.1 and 18.0% and low if less than 17.1%. Canola yield was said to be high if 2200 kg ha^{-1} or higher, medium 1700- 2199 kg ha^{-1} and low if 1699 kg ha^{-1} or lower.

Pea protein was said to be high if 17% or higher, medium if 16.1 to 16.9% and low if 16.0% or lower. Pea yield was said to be high if 2800 kg ha^{-1} or higher, medium if 2000-1799 kg ha^{-1} and low if 1699 kg ha^{-1} or less.

3.2.1.1 Protein:Yield Combinations

The protein: yield combinations of canola, wheat and peas were interpreted to create four N management zones which is consistent with Taylor et al. (2007) where it was reported that it is rare to have more than two to four management zones, even in fields greater than 100 ha. The N rates chosen either increase or decrease 20% and 40% from the constant N rate, similar to the procedure used by Welsh et al., (2003).

The strategy employed to help delineate management zone N application rates from the yield: protein combinations is described in Tables. 3.3 and 3.4. In these Figures, the N rate strategy describes an N rate that would likely be beneficial if the same crop were to be seeded on those transect points the following year. However, the purpose of this study was to determine if protein could help delineate N management zones for a following rotational crop. Therefore, protein: yield combinations such as high, medium and low protein (HP, MP, LP) and high, medium and low yield (HY, MY, LY) were assigned to create a system that would uniquely identify a transect point with a specific protein: yield response.

Wheat protein: yield combinations from 2012 using the rationale in Table 3.3 were matched with the canola protein: yield combinations as shown in Fig. 3.4 and the pea protein: yield combinations as shown in Fig. 3.7 and the N rates were assigned for wheat to each transect point accordingly. Likewise, canola protein: yield combinations using rationale in Table 3.4 were matched with the wheat protein: yield combinations as shown in Fig. 3.8 and the N rate assigned accordingly. For example, MP: MY in wheat in 2012 in Field Area 1 in 2012 was assigned a rate of 60 kg N ha^{-1}. This rate was then assigned to each transect point in Field Area 2 in 2013 where canola exhibited a MP: MY relationship. This method worked well for most transect points, however, differences in protein: yield combinations between crops meant that not every transect point was a perfect match. In these cases (WC2, WC5, WC10, WC12 in Field Area 2; WP3, WP8, WP11 in Field Area 3), the N rate was prescribed using best judgment.

Table 3.3. Variable rate N strategies for wheat grown in 2013 on canola (Fig. 3.4; Field Area 2) and pea stubble (Fig. 3.7; Field Area 3).

Protein: Yield Combination		N Rate Rationale for Each Protein: Yield Combination
HP HP HP	HY MY LY	High protein indicates N not limiting; therefore will reduce N rate to 40 kg ha^{-1}
MP MP	HY MY	Medium protein indicates more N required; therefore will increase N rate to 60 kg ha^{-1}
MP	LY	Medium protein and low yield indicates more N required; therefore raise N to super rate of 70 kg ha^{-1}
LP	LY	Low protein and low yield indicates some other factor limiting yield, therefore reduce N rate to 0 kg ha^{-1}

Table 3.4. Variable rate N rate strategies for canola grown in 2013 on wheat stubble (Fig. 3.8; Field Area 1).

Protein: Yield Combination		N Rate Rationale for Each Protein: Yield Combination
HP	MY	High protein indicates N not limiting yield, therefore reduce N rate to 48 kg ha^{-1}
HP	LY	High protein indicates N not limiting yield, therefore reduce N rate to 42 kg ha^{-1}
MP MP	HY MY	Medium protein indicates more N required, therefore increase N to 72 kg ha^{-1}
MP	LY	Medium protein and low yield & gravel soil indicates soil property limiting yield: reduce N rate to 48 kg ha^{-1}
LP LP LP	HY MY LY	Low protein and medium to high yields indicates more yield could be achieved, increase N rate to 84 kg ha^{-1}

3.2.1.2 Wheat on Canola Stubble

For wheat, high protein with high, medium or low yield indicates that N is not the yield limiting factor, therefore, in these transect points, N was reduced to a low rate of 40 kg ha^{-1}, which is 20% less than the control constant rate of 50 kg N ha^{-1}. These occur in four instances and are areas of lower elevation. Combinations of medium protein and high and medium yield indicates that more N was required, and therefore, in these transect points N was increased to 60 kg N ha^{-1}, which is a 20% increase over the control rate. There are five instances of this rate and these are either mid slopes or depressions. Medium protein and low yield without identified soil limitations suggests that even more N was required, therefore, N was increased to the highest rate of 70 kg ha^{-1}, which is 40% greater than the control. The last combination of low protein and low yield was associated with high salinity identified as a factor that is strongly limiting yield, therefore, in these transect points N was reduced to 0 kg ha^{-1}. This occurs in three instances, including eroded knolls (Fig. 3.4).

Fig. 3.4. N fertilizer zone map for **w**heat grown in 2013 on canola stubble N; Field Area 2.

3.2.1.3 Wheat on Pea Stubble

The same N rates for each protein: yield combination which were applied with wheat on the canola stubble were applied to wheat on pea stubble. However, since peas did not show any low protein and low yield combination, the 0 kg N ha^{-1} rate was not used (Fig. 3.5). The value of using pea protein and yield to make N recommendations for wheat may be questioned due to the additional factor of N fixation which can supply N to pea and promote yield while a cereal or oilseed must rely entirely on soil N supply from residual mineral N, mineralization and fertilizer.

Fig. 3.5. N fertilizer zone map for **w**heat grown in 2013 on pea stubble; Field Area 3.

3.2.1.4 Canola on Wheat Stubble

High protein and medium yield of wheat suggests that N is not a major limitation to yield (at least for wheat) and therefore, for canola grown at these transect points, the N rate was reduced to 48 kg ha^{-1}, which is a 20% decrease from the control rate of 60 kg N ha^{-1}. There are seven instances of this rate which typically occupy lower slope positions with greater inherent fertility. High protein and low yield indicates that N is even less limiting, with some other factor like inherently low moisture as an overriding factor, and the N was reduced to 42 kg ha^{-1}, a 30% reduction. There are two instances of this rate both of which are rego-knolls. Medium protein and high and medium yield suggests more N was required, therefore, the N rate was increased to 72 kg ha^{-1}, which is a 20% increase over the control rate. There are six instances of this rate which occupy upper slope positions. Medium protein and low yield indicates a soil property is limiting yield along with N (in this case was a gravelly soil) and the N rate was reduced to 48 kg ha^{-1}. Low protein with high, medium and low yields without any identified soil limitations indicates that more yield could be achieved by increasing N to highest rate of 84 kg N ha^{-1}, representing a 40% increase over the control. There is one instance of this rate at position eight beside the slough. This is a region with low inherent N status (Fig. 3.6).

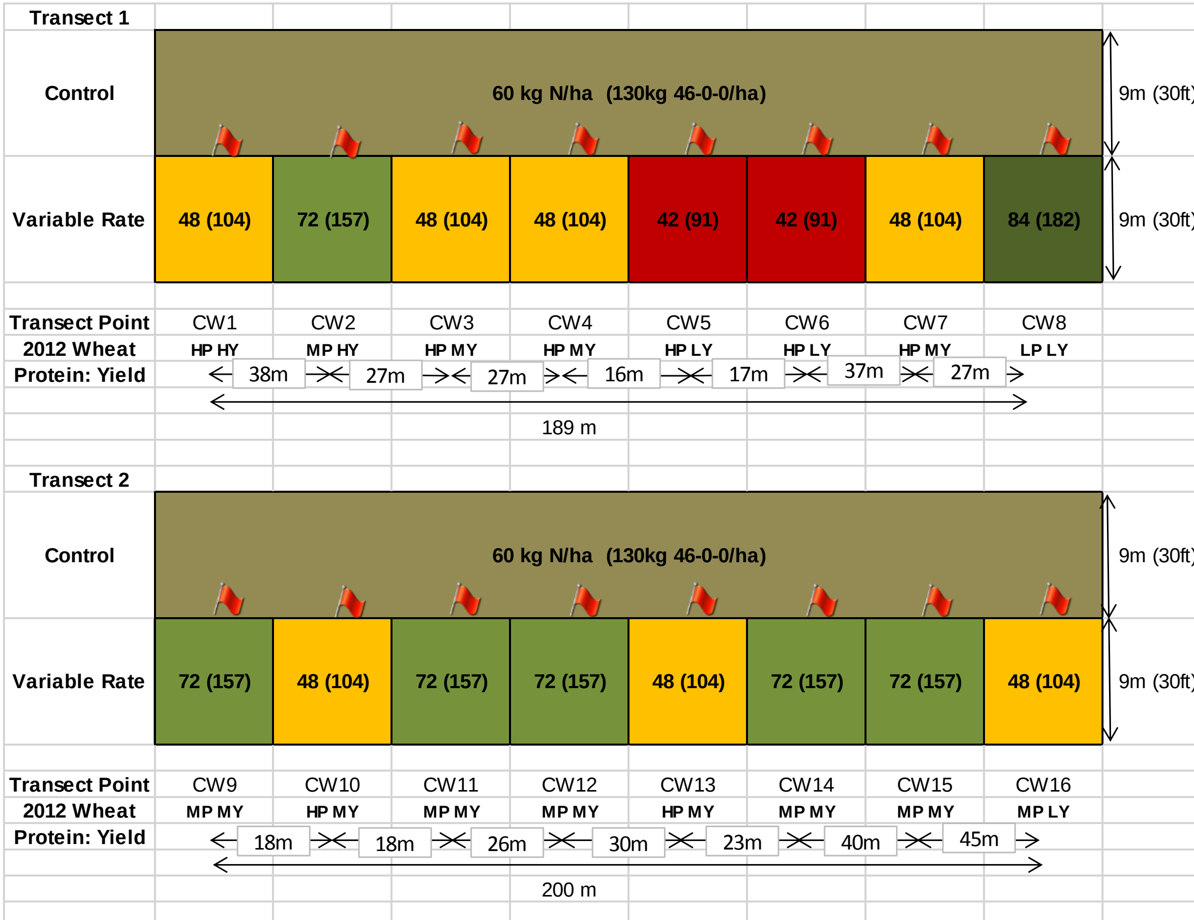

Fig. 3.6. N fertilizer zone map for **c**anola grown in 2013 on wheat stubble; Field Area 1.

3.2.2 Field Operations in 2013

3.2.2.1 Spring Soil Sampling

Soil samples were taken before seeding on May 7, 2013 to two depths (0-30 and 30-60 cm). These were analyzed for the same properties as in fall 2012 to account for changes in nutrient supply, such as denitrification, that may have occurred over winter.

3.2.2.2 Spring Seeding

In spring of 2013, seeding commenced on the field areas that were sampled in 2012 (Fig. 3.7). As evident by comparing Figs. 3.3 and 3.7, canola was grown on wheat stubble, while wheat was grown on canola stubble and pea stubble. Seeding was performed with a Case IH 800 precision hoe drill and 3450 variable rate air cart (Fig. 3.8). InVigor L150® canola was seeded on the wheat stubble on May 21 at 5 kg ha^{-1} at 10 mm depth, with a constant rate of 56 kg ha^{-1} of 11-52-0 fertilizer. This supplies 29 kg ha^{-1} P_2O_5 phosphate equivalent, representing the maximum seed row applied safe rate (Saskatchewan Ministry of Agriculture, 2012). Urea nitrogen fertilizer (46-0-0) was applied at 133 kg ha^{-1} on the control strip supplying 61 kg ha^{-1} of actual N. There were four variable rates of nitrogen applied across the transect on the other side of the control (constant N rate) strip: 44, 51, 76 and 89 kg actual N ha^{-1} respectively. Initially, the intent was for variable rates of 42, 48, 72, and 84 kg ha^{-1} respectively. However, calibration calculation errors in the field resulted in these slightly higher rates being applied.

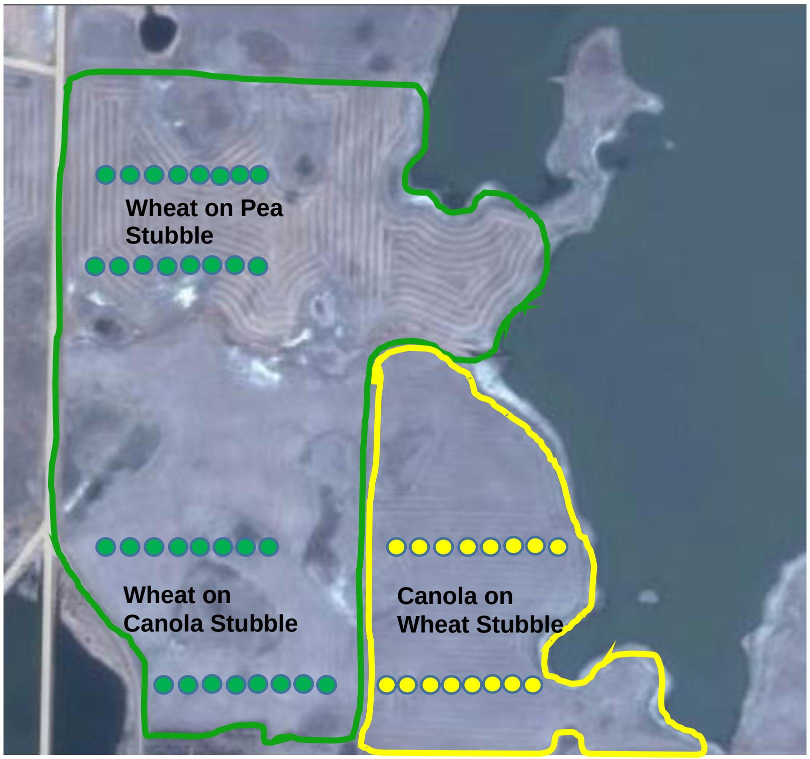

Fig. 3.7. Layout at SW 31-20-03 W3 showing location of wheat and canola with transect points in 2013

Fig. 3.8. Transect seeding with Case IH 800 precision hoe drill and 3450 air cart.

Waskeda hard red spring wheat was seeded on both canola and pea stubble at 83 kg ha^{-1} at 10 mm depth on May 23 and 24. Phosphorus fertilizer was also applied to the wheat at 56 kg ha^{-1} of 11-52-0 fertilizer product. The nitrogen control rate was 109 kg ha^{-1} of 46-0-0 supplying 50 kg ha^{-1} of actual N. The variable rates of actual N applied to the wheat transects were 0, 40, 60 and 70 kg actual N ha^{-1} as planned. Only wheat and canola was seeded this season, as N is typically not applied with peas.

3.2.2.3 Crop Protection

Wheat and canola emergence was uniform. On June 7, a tank mix of Deploy® (tribenuron), and Banvel® (dicamba) herbicides were applied to the wheat on canola stubble at labelled rates. Five days later on June 12, the wheat received a tank mix of herbicides fluroxypyr and 2,4-D (OcTTain®) and clodinafop (Signal®) were applied. This same day the canola on wheat stubble was sprayed with glufosinate ammonium (Liberty®) tank mixed with clethodim (Select®).

3.2.2.4 Hand Harvest

Crop harvest at maturity was performed by hand at the transect points established in spring of 2012 on August 23, 2013. Two 1 m row length crop samples were taken, and bulked together, from each side of each transect point representing the varied and constant (control) N rates. In the canola, these samples were taken approximately 2 m from each side of the transect point to avoid an effect of possible seeding and fertilizer overlap. In the wheat, samples were taken approximately 1 m from each side of the transect point in order to avoid an edge effect even though there was no seeding overlap. Flags were placed where the samples were harvested in order to facilitate fall soil sampling from exactly the same location. Transect point #7 of the wheat on canola had no harvestable material within a reasonable distance due to weeds.

3.2.2.5 Combine Harvest

The crops were swathed after the hand harvesting operation. They were combined on September 6, 2013. A Case IH 9120 combine was fitted with a Zeltex Accuharvest® batch protein sampler. For more information on this operation, please see Appendix A.

3.2.2.6 Fall Soil Sampling

Fall soil sampling occurred on September 17, 2013. Samples were taken from 0-30cm and 30-60cm depths with a 5cm diameter probe mounted on a hydraulic punch truck. Samples were taken from each side of each transect point as indicated by the flags placed at harvest in order to compared the varied N rate treatment to the control.

3.2.2.7 Rainfall

Precipitation was 273 mm from April to October which is 45 mm less than the amount of rainfall received in 2012, however, this is only 21 mm less than the 15 year mean. Growing season precipitation in 2013 was closer to the long term average than in 2012.

Table 3.5. 2013 growing season rainfall (Environment Canada, Elbow, SK)

Month	Year			
	2013	2012	2011	15 year mean
	---------------------- precipitation (mm) ---------------------			
April	6	26	3	17
May	29	116	38	51
June	82	109	11	79
July	54	37	52	53
August	60	26	53	45
September	42	4	6	34
October	0	0	27	15
Total	273	318	190	294

3.3 Laboratory Methods

3.3.1 Soil Analysis

Soil samples were placed in a freezer upon return from the field. These samples were laid out to dry and finely ground at a later date when all field operations were complete. Soil nitrate (NO_3^- -N) was determined by following the procedure of Keeney and Nelson (1982). In brief, 10 g of air dried soil was weighed out into plastic containers to which 50 mL of 2 M KCl was added. This was shaken for 1 h and then filtered (Whatman #4 filter paper). The resulting sample was placed in a refrigerator until being analyzed colorimetrically with a Technicon AutoAnalyzer II (Tarrytown, NY).

Phosphorus and potassium were determined colorimetrically by the modified Kelowna extraction method (Qian et al., 1994). Briefly, 28 mL of acetic acid, 38.5 mL ammonium acetate, and 1.11 g ammonium flouride were prepared as an extracting solution. 30 ml of this solution was added to 3 g of soil, shaken for 5 min and filtered. Samples were refrigerated until analysis on the Technicon AutoAnalyzer II (for P) and the Varian SpectraAA 220 flame atomic absorption spectrometer (Varian Australia, 2000) (for K). Nitrogen availability was also measured by anion exchange resin following the method of Qian and Schoenau (2008). This was done in the lab by making a "sandwich". Two snap cap vial lids were filled with air-dried and ground soil, wetted to field capacity with distilled water, and pressed together with a 4 cm^2 resin strip between them and sealed with parafin wax. After 24 hours, the "sandwiches" were taken apart, and the resins were eluted with 2 M KCl and analyzed colorimetrically, again, on the Technicon AutoAnalyzer II (Tarrytown, NY).

Electrical conductivity and pH were determined in a 1: 2 v/v soil:deionized water extraction following the method of Rhoades (1982). 40ml deionized water was added to 20 g of soil, shaken for 20 min at 142 rpm and left for 1 h to settle. The resulting filtrate was analyzed for pH with a Beckman pH meter, and for EC with a Accument AP85 conductivity meter.

Soil OC was determined by dry combustion using a Leco® carbon analyzer. following the procedure of Wang and Anderson (2008). Clay boats containing 0.25g of soil were placed in the combustion chamber at 837° C for approximately 3 min and the results were recorded.

3.3.2 Plant Analysis

Harvested crop material was air dried and threshed with a mechanical thresher. The seed was then further cleaned with a small gravity table separator. Straw and seed were both then finely ground and stored in snap cap vials to await digestion by the sulphuric acid-peroxide diegest method (Thomas et al., 1967) to determine straw and grain N and P. 100 ml test tubes were were used to mix 0.25 g of plant material and 5ml of sulfuric acid which were shaken on a mechanical vortex table and then heated in a block digester for 20 min at 360^{o} C. After heating, the tubes were cooled for half an hour and hydrogen peroxided was added (0.5 ml; 30% $^{v}/_{v}$). This process was repeated five more times. The tubes were filled to exactly 75 ml with deionized water after the final heating and cooling and a subsample of approximately 50 ml was transferred to a snap cap vial to await further analysis using the Technicon AutoAnalyzer II.

3.3.3 Grain Nitrogen and Protein

Grain N uptake was calculated by multiplying the grain N concentration by the yield. Grain protein was calculated by multiplying the grain N concentration by a factor of 5.7 (Tkachuk, 1969).

3.4 Statistical Analysis

Statistical relationships were assessed with SAS 9.3 (SAS Cary NC). Correlations among crop yield, protein, and soil properties were performed with PROC CORR. Paired t-tests were performed with PROC TTEST to compare yields among the varied N rate and constant N rate transects. Significance level was set at $p < 0.05$.

4 RESULTS AND DISCUSSION

4.1 2012 Field Season

Results from the 2012 field season, including soil and landscape properties, soil and plant nutrient status, and protein for wheat, canola and peas are shown in Tables 4.1, 4.2, and 4.3 respectively.

Table 4.1. Descriptive soil and landscape properties for the 16 transect points located in wheat, canola, and pea fields sampled in fall of 2012.

	Soil and Landscape Property						
n= 16	Elevation	----------- OC (%) ----------		------------ pH -----------		------ EC (dS m^{-1}) ------	
	(m)	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Wheat							
Mean†	608 ± 1.6	1.28 ± 0.4	0.69 ± 0.2	7.93 ± 0.3	7.99 ± 0.4	1.14 ± 2.2	2.00 ± 2.2
Median	608.2	1.29	0.65	8.02	7.98	0.38	0.62
Min	605.0	0.50	0.38	7.27	7.18	0.08	0.08
Max	610.2	2.10	1.34	8.21	8.48	8.19	6.12
Interquartile Range	2.60	0.40	0.35	0.38	0.45	0.24	3.60
Canola							
Mean	610 ± 2.0	1.35 ± 0.4	0.63 ± 0.3	7.97 ± 0.3	8.08 ± 0.3	3.19 ± 3.5	2.94 ± 2.6
Median	610.5	1.27	0.59	7.99	8.11	0.80	2.43
Min	606.3	0.77	0.36	7.33	7.76	0.18	0.15
Max	613.0	2.26	1.65	8.32	8.58	9.15	7.19
Interquartile Range	1.60	0.47	0.22	0.37	0.43	5.31	4.76
Pea							
Mean	608 ± 1.8	1.56 ± 0.4	0.91 ± 0.6	7.93 ± 0.2	7.93 ± 0.4	2.43 ± 3.4	4.16 ± 3.5
Median	608.4	1.51	0.73	7.89	7.94	0.68	4.08
Min	606.6	0.88	0.43	7.61	6.58	0.16	0.08
Max	613.0	2.59	2.78	8.27	8.24	11.12	11.88
Interquartile Range	2.21	0.30	0.35	0.31	0.28	2.48	5.09

† mean ± SD

Table 4.2. Soil nutrient status in fall 2012 for wheat, canola, and pea fields.

Soil Nutrient Status						
	---------------- NO_3^- N -------------		P	K	AEM‡ NO_3^- N	AEM P
n= 16	---------------------------------- kg ha^{-1}--------------------------------------				ug-24 hrs^{-1}	
	0-30cm	30-60cm	0-30cm	0-30cm	0-30cm	0-30cm
Wheat						
Mean†	6.8 ± 2.9	5.2 ± 4.7	28.4 ± 12.6	1278 ± 586	5.6 ± 2.0	0.2 ± 0.2
Median	6.7	3.7	25.7	1298	5.9	0.2
Min	3.0	1.0	15.8	403	2.1	0.1
Max	14.9	18.7	54.5	2851	9.5	0.6
Interquartile Range	3.1	3.0	16.5	551	2.4	0.2
Canola						
Mean	22.4 ± 47.1	11.4 ± 24.6	39.2 ± 27.6	1296 ± 634	9.3 ± 11.9	0.2 ± 0.2
Median	9.5	3.70	30.3	1249	7.0	0.15
Min	5.9	2.2	13.9	586	3.9	0.1
Max	198.0	102.4	112.8	2733	53.2	0.6
Interquartile Range	5.2	2.9	22.4	802	2.9	0.1
Pea						
Mean	11.4 ± 5.6	7.5 ± 6.3	36.7 ± 26.3	1329 ± 440	7.5 ± 3.7	0.3 ± 0.3
Median	12.2	6.0	25.1	1282	9.1	0.2
Min	3.0	1.1	13.7	750	1.3	0.1
Max	21.5	22.6	108.3	2452	12.9	1.0
Interquartile Range	7.9	6.6	37.6	434	6.1	0.3

† Mean ± SD

‡ AEM= anion exchange membrane sorbed NO_3^- -N and PO_4^--P.

Table 4.3. Harvest 2012 wheat, canola, and pea yield, grain and straw N and P concentration and protein.

	Grain Biomass	Grain N	Grain P	Straw N	Straw P	Protein
n = 16	-- kg ha^{-1}				---------------------------------------	---- % ----
Wheat						
Mean†	1851 ± 469	43.2 ± 12.4	7.1 ± 1.9	9.3 ± 3.7	2.7 ± 0.8	13.2 ± 1.1
Median	1998	46.5	7.5	9.4	2.7	13.4
Min	882	16.2	3.0	4.2	1.4	10.5
Max	2554	64.7	9.8	18.7	5.0	14.4
Interquartile Range	571	16.3	2.6	4.6	0.7	1.4
Canola						
Mean	1847 ± 405	54.6 ± 13.0	10.1 ± 2.1	16.9 ± 8.0	2.9 ± 0.8	16.8 ± 1.8
Median	2001	56.1	10.5	14.3	2.8	17.1
Min	1143	30.3	6.1	5.6	1.7	14.2
Max	2342	73.6	13.3	35.4	4.6	20.6
Interquartile Range	649	21.0	3.4	12.0	0.95	2.6
Pea						
Mean	2198 ± 672	63.1 18.5	6.9 ± 2.2	20.0 ± 6.4	1.6 ± 0.6	16.5 ± 0.8
Median	2221	64.5	6.9	18.6	1.5	16.5
Min	839	25.1	2.6	13.0	1.0	14.5
Max	3122	85.5	10.4	32.7	2.9	17.7
Interquartile Range	981	27.8	3.4	8.9	0.7	0.8

† Mean ± SD

The 2012 wheat, canola and pea yields across the transects ranged from 882-2554, 1143-2342, and 839-3122 kg ha^{-1} respectively. Protein content for wheat, canola and peas ranged from 10.5-14.4, 14.2-20.6 and 14.5-17.7 percent respectively (Table 4.3).

Correlations between crop protein, yield and basic soil properties measured in the fall of 2012 are shown in Table 4.4. Protein in wheat was positively correlated with pH in the 30-60 cm depth (r = 0.51, $p < 0.05$) and negatively correlated with electrical conductivity in the 30-60 cm depth (r = -0.56, $p < 0.02$). Protein in the 2012 canola crop was positively correlated with organic carbon (r = 0.65, $p < 0.01$). Yield in wheat was positively correlated with organic carbon in the 0-30 cm depth (r = 0.74, $p < 0.001$), and negatively correlated with electrical conductivity in the 0-30 cm depth (r = -0.5, $p < 0.03$). Canola yield was not significantly correlated with any measured soil properties. Pea yield was negatively correlated with electrical conductivity in both the 0-30 and 30-60 cm depths (r = -0.68, $p < 0.004$; and r = -0.51, $p < 0.04$ respectively) (Table 4.4). The positive correlations between wheat yield and pH in the 30-60 cm depth is difficult to explain as a direct cause-effect relationship, but may reflect the effect of another soil property that is related to both yield and pH at this depth. The observed negative correlation between yield and electrical conductivity (soil salinity) is expected. Higher protein in canola that was associated with higher soil organic carbon may be explained by soil organic carbon acting as proxy for organic nitrogen mineralization potential.

Positive correlations between yield and soil organic carbon that were observed in this study wheat have been observed in other research. A long term study by Sandhu et al. (1996) at Punjab, India, observed that increasing soil organic carbon resulted in greater mean wheat yield. For example, wheat grain yield grown with 80 kg N ha^{-1}, 50 cm of water, and 0.2% soil OC was 3.8 t ha^{-1}. However, yield was increased by 0.8 t ha^{-1} when soil OC was increased to 0.4%. Similarly in another long term study, Mikanova et al. (2012) observed winter wheat yield to increase by approximately 4 t ha^{-1} when the soil OC increased from 1.6% to 2.2% at Prague, Czech Republic.

Table 4.4. Correlations between 2012 crop parameters and soil properties for each field area.

Soil Property		Wheat		Canola		Peas	
		Yield	Protein	Yield	Protein	Yield	Protein
OC† 0-30 cm (%)	r p-value	**0.74** **0.001****	n/s	n/s	**0.65** **0.007****	n/s	n/s
OC 30-60 cm (%)	r p-value	n/s	**-0.53** **0.04***	n/s	n/s	n/s	n/s
pH 0-30 cm	r p-value	n/s	n/s	n/s	n/s	n/s	n/s
pH 30-60 cm	r p-value	n/s	**0.51** **0.05***	n/s	n/s	n/s	n/s
EC‡ 0-30 cm ($\mu S\ cm^{-1}$)	r p-value	**-0.5** **0.03***	**-0.56** **0.02***	n/s	n/s	**-0.68** **0.004****	n/s
EC 30-60 cm ($\mu S\ cm^{-1}$)	r p-value	n/s	n/s	n/s	n/s	**-0.51** **0.04***	n/s

†OC denotes organic carbon,
‡ EC denotes electrical conductivity
* Significant correlation at $p < 0.05$
** Significant correlation at $p < 0.01$

The relationship between crop yield and N uptake was assessed to establish a benchmark for this site. Yield and crop N uptake, measured as a sum of the N in the grain and straw, was regressed linearly. In wheat, there was a strong relationship between total N uptake and yield ($r^2 = 0.92$) (Fig. 4.1). Canola and pea yields exhibited a weaker relationship ($r^2 = 0.64$ and 0.88 respectively) (Figs. 4.2 and 4.3).

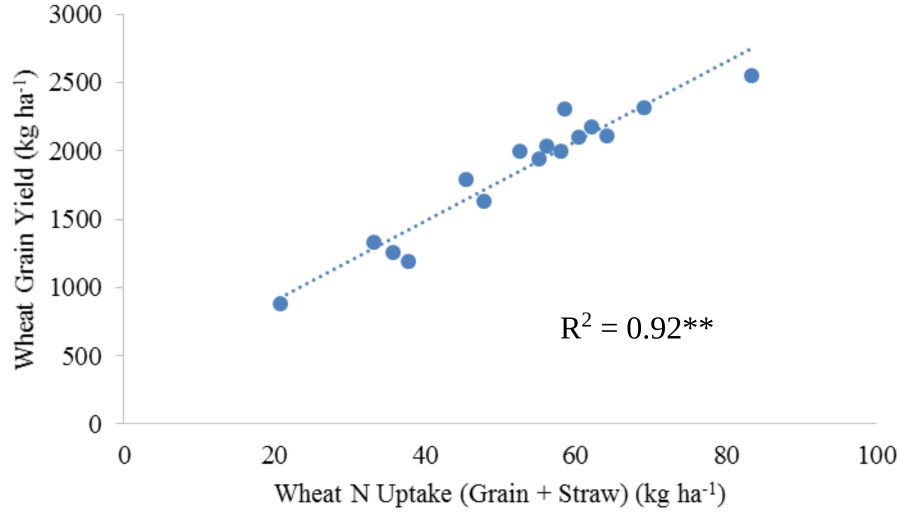

Fig. 4.1. Regression relationship between wheat grain yield (kg ha^{-1}) and total crop N uptake (straw and grain kg N ha^{-1}) in 2012. ** indicates significant at *p* < 0.01.

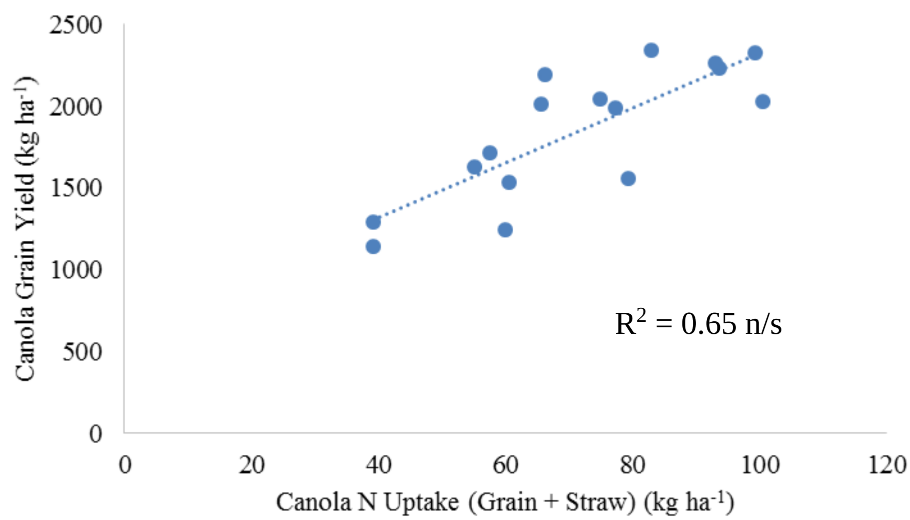

Fig. 4.2 Regression relationship between canola grain yield (kg ha^{-1}) and total crop N uptake (straw and grain kg N ha^{-1}) in 2012. n/s indicates not significant at *p* < 0.05

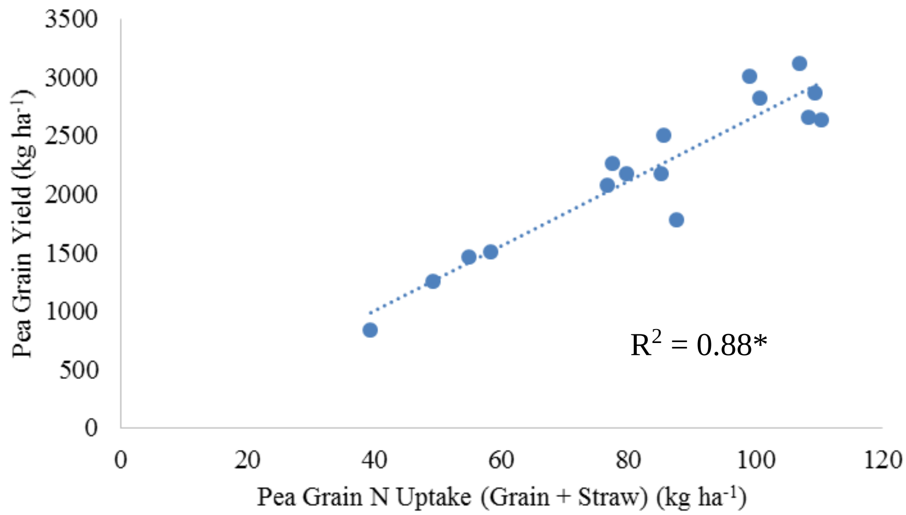

Fig. 4.3. Regression relationship between pea grain yield (kg ha^{-1}) and total crop N uptake (straw and grain kg N ha^{-1}) in 2012. * indicates significant at $p < 0.05$.

The relationship between protein, yield and elevation for wheat in 2012 is depicted in Fig. 4.4. Elevation affects the distribution of moisture in the landscape. Specifically, water runs off into areas of lower elevation with associated effects on increasing available water, organic matter, and mineralization. This would contribute to greater yields on the mid and low slope positions (Verity and Anderson, 1990). However, this is not the case for protein. As expected, the rego-knoll positions have a high protein, as the yield is low due to moisture stress. However, as transect position W1 shows, it is possible to have a high yield and high protein at low elevation due to the ability of the soil to supply a greater amount of N throughout the growing season via mineralization which contributes to protein production. Wheat yield and protein were found to be maximized at approximately 13.5% (Fig. 4.5) consistent with other studies (Flaten and Racz, 1997; Engel et al., 1999).

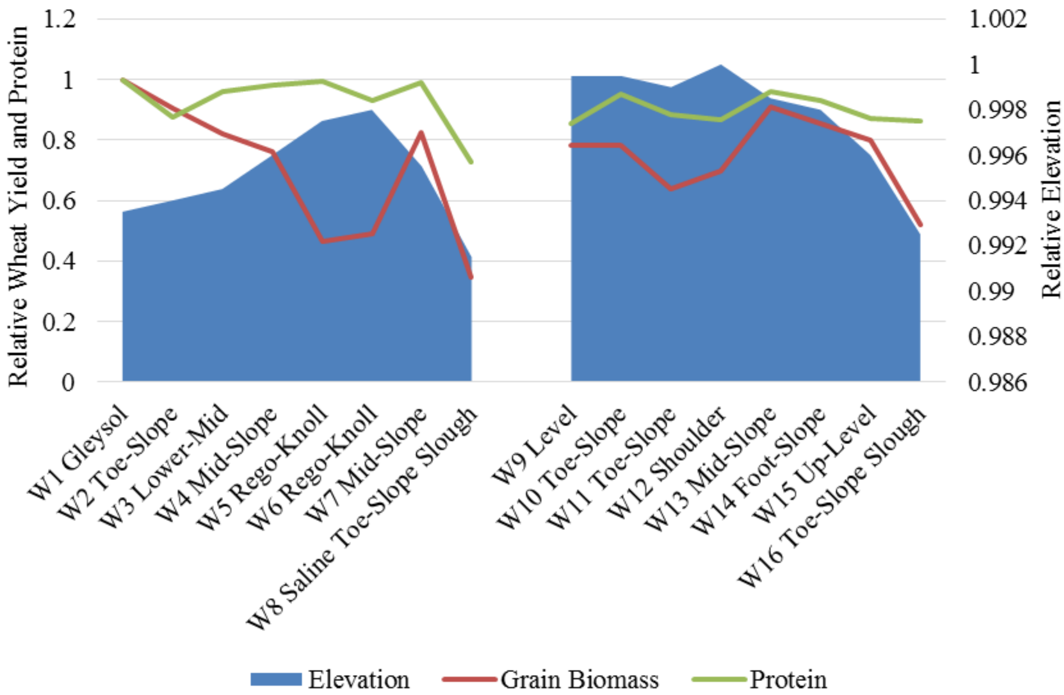

Figure 4.4. Wheat grain yield and protein across the landscape transect points in fall 2012. Yield, protein, and elevation are each expressed relatively as a percentage of the greatest value for each data set.

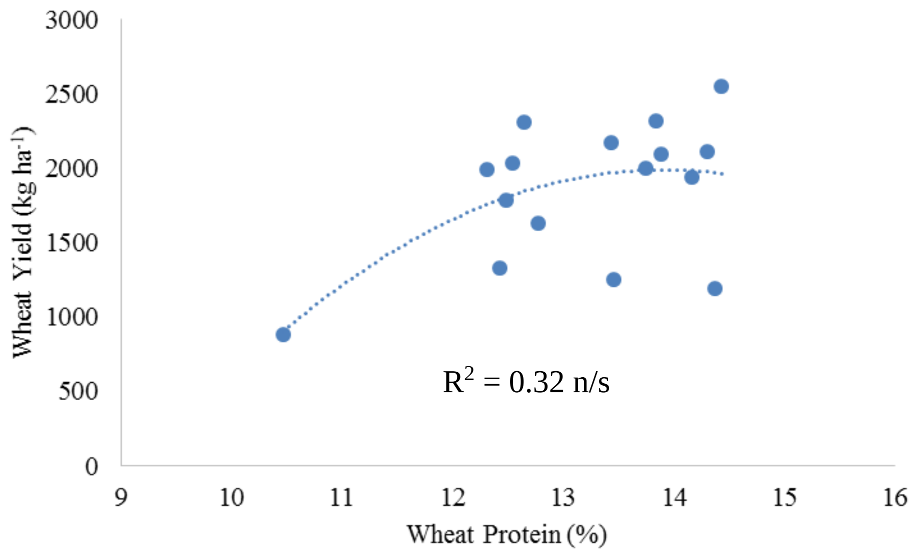

Figure 4.5. Relationship between **w**heat yield and protein in fall 2012. n/s indicates not significant at $p < 0.05$.

Canola yield and protein in 2012 showed no significant ($p < 0.05$) relationships with the landscape (Fig. 4.6). In canola, the range in protein values was large, which is consistent with the results of Malhi et al. (2007), who reported a range in canola protein between 23%-31% over a three year study near Star City, SK, Canada. A large variation in canola protein (18.6%-28.0%) over three years and with four N treatments was also reported by Kutcher et al. (2005) near Prince Albert, SK, Canada. When the protein and yield values were plotted, a parabolic curve best describes the relationship (Fig. 4.7), with the greatest yields generally found when protein is in the 17% range. However, because there was no high protein and high yield combination found in the canola at the rate of N applied in this field in 2012 (50 kg N ha^{-1}), one cannot rule out the possibility that higher rates of N could produce both high protein and high yield. A literature search revealed, that unlike for wheat, studies of the relationship between canola yield and protein were lacking to enable determination of a critical grain protein concentration for this crop. Malhi and Gill (2007) and Hamzei (2011) did report that canola protein increases linearly in response to increasing rates of added N but no plateau was reported.

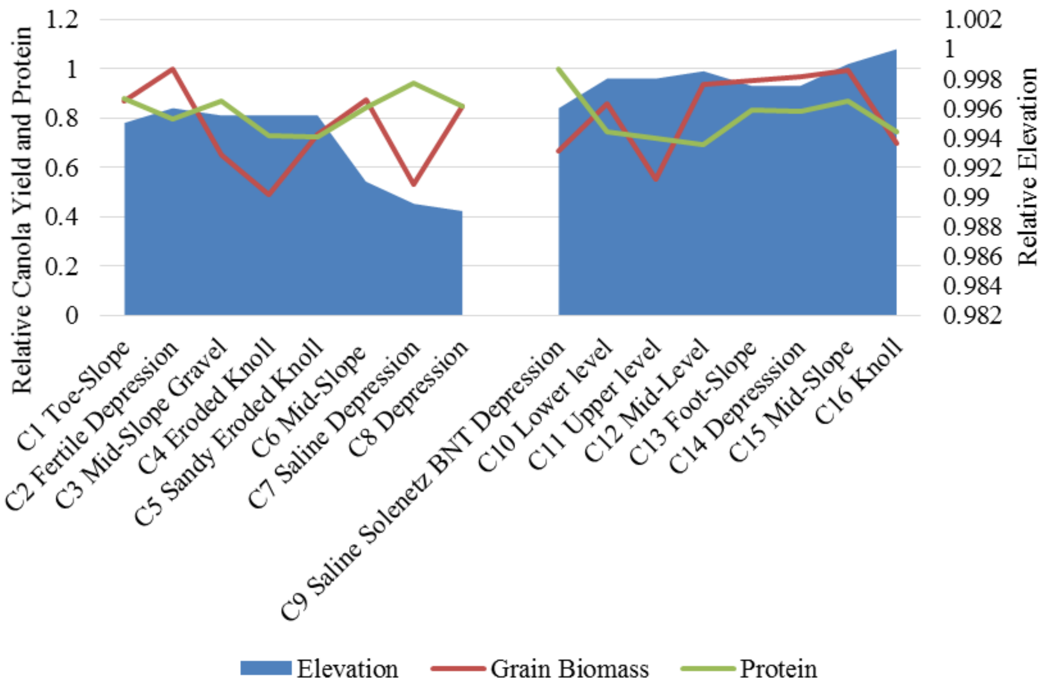

Fig. 4.6 Canola yield and protein across the landscape transect points in fall 2012. Yield, protein, and elevation are each expressed relatively as a percentage of the greatest value for each data set.

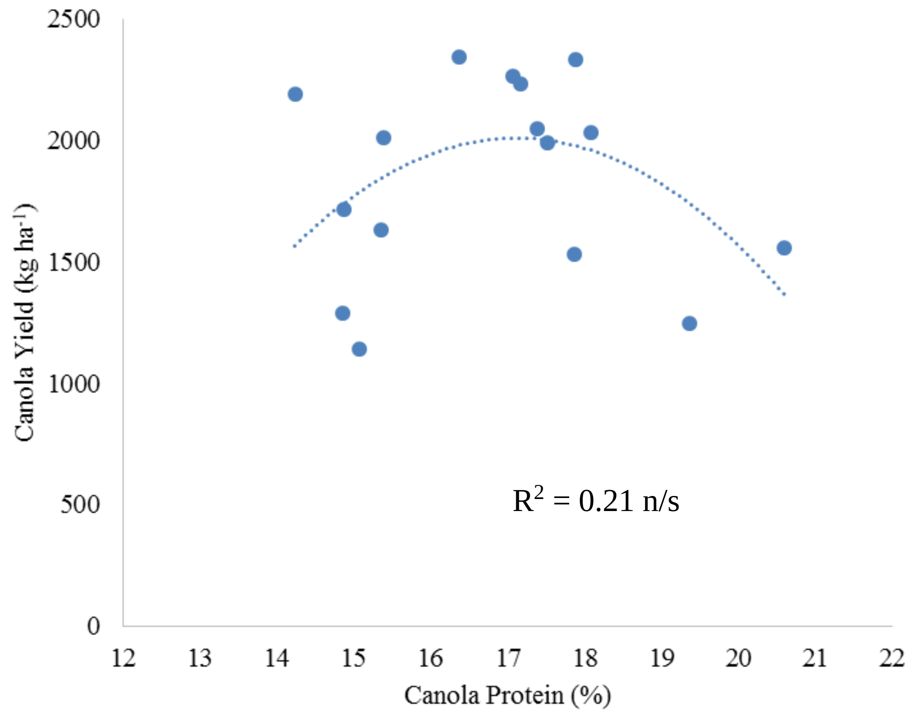

Fig. 4.7 Relationship between canola grain yield and protein content in fall 2012. n/s indicates not significant at $p < 0.05$.

The wet growing season of 2012 contributed to heavy disease pressure in peas. This explains the low yields at the lower elevations (Fig. 4.8). Low slope regions in the landscape in 2012 were saturated in the spring, creating conditions conducive to foot rot and leaf diseases in the peas. Pea yield is also inversely related to EC (Table 4.4), reflecting the high sensitivity of peas to salinity (Steppuhn et al., 2001). However, protein in peas is more stable than wheat or canola, as for example there was no occurrence of both low protein and low yield in peas. When pea yield is plotted against protein, an inverse parabola shape emerges, suggesting that stressed yields may be associated with lower protein content (Fig. 4.9). This might be explained by soil and environmental stresses reducing both N fixation and photosynthetic carbon fixation by the peas, such that both the yield and protein move in the same direction. However, there are few reported studies on the relationship between pea protein and yield. McLean et al. (1974) reported that there was only a very low correlation between pea protein and yield. This is a pattern distinctly different from wheat, but similar to canola in that both peas and canola exhibit a trend where yield does not plateau while protein continues to increase. The pea grain protein contents reported in the field in this study (14.5-17.7) are lower than reported by Wang and Daun (2004) who conducted a survey of pea samples from western Canada from 1997-2002. In these five years, the mean pea grain protein was reported to be between 23.2% and 26.2%, while individual samples from producers was reported to be between 17.7% and 31.1%. It is unclear why the pea protein in the current study is low compared with these results, but may reflect low soil N availability or low fixation. However, however, Miller et al. (2006) reported pea grain protein values that were similar to those of the current study, with pea protein ranging from 12.6% to 18.4%, and 12.4% to 14.8% respectively at two sites in Montana, USA.

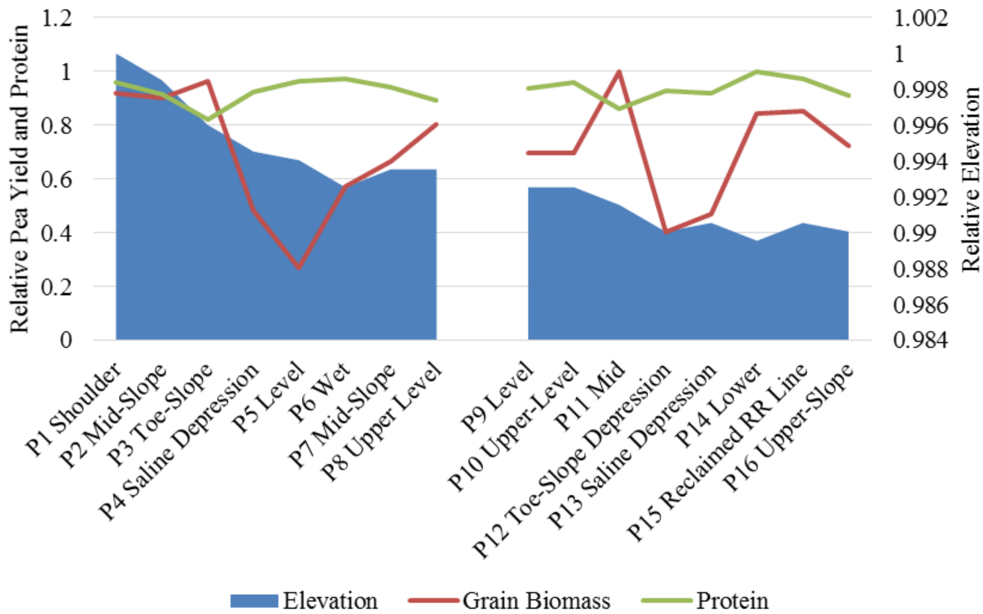

Fig. 4.8. Pea yield and protein across the landscape transect points in fall 2012. Yield, protein, and elevation are each expressed relatively as a percentage of the greatest value for each data set.

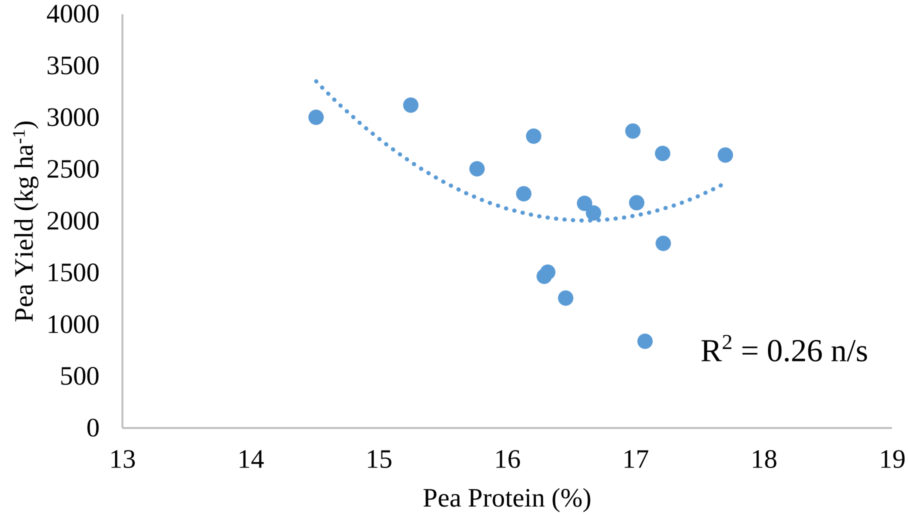

Fig. 4.9. Relationship between pea grain yield and protein content in fall 2012. n/s indicates not significant at $p < 0.05$.

2013 Field Season

4.1.1 Canola Yield Grown on Wheat Stubble

Canola grown in 2013 on wheat stubble had a small and non-significant ($p < 0.05$) grain yield benefit of 127 kg ha^{-1} from the varied N rates. Comparing the average (n = 16) yield of canola in the variable rate to constant rate, there was no significant yield difference ($p < 0.05$) (Fig. 4.10).

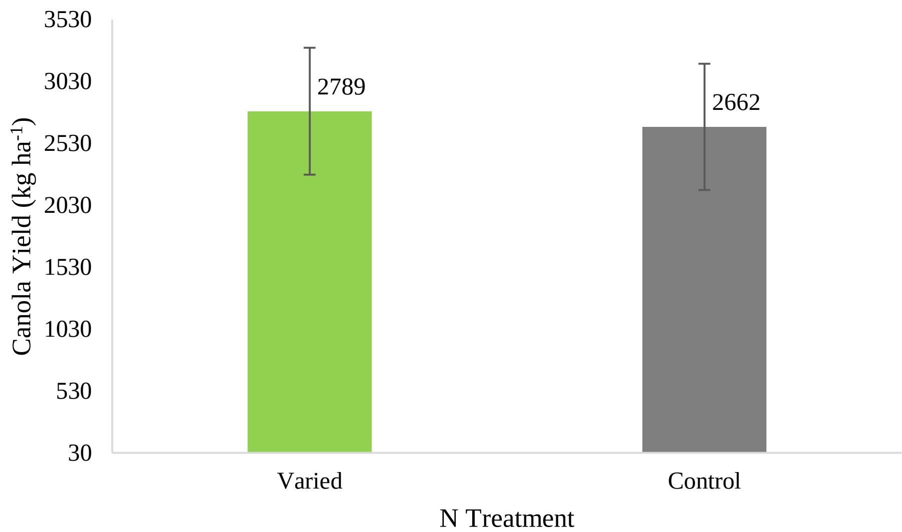

Fig. 4.10. Mean canola yield grown in 2013 on wheat stubble (kg ha^{-1}) on Field Area 1. Bars indicate standard deviation of the mean (n=16).

To aid in interpretation of these results, canola yield at each transect point in the variable versus constant N rate is shown in Fig. 4.11. The lowest N rate (44 kg N ha^{-1}) was applied to two plots and yielded 2501 kg ha^{-1} versus 2245 kg ha^{-1} for the control rate of 60 kg N ha^{-1} (Fig. 4.12). These two plots (CW5 and CW6) were adjacent to each other on top of a rego-knoll (Fig. 4.11). In 2012 the wheat had a high protein and a low yield. Therefore, the rationale was to reduce N rates as low moisture was considered to be an inherent yield limiting factor on the Rego-knolls. Thus, it would seem that this was a successful strategy as the yield of the lower, varied rate was not significantly different from the higher constant rate. However, as Fig. 4.12 shows, there was more variability in yield in the constant rate treatment. In fact, the constant rate (60 kg N ha^{-1}) on CW5 yielded nearly twice the constant rate (60 kg N ha^{-1}) on CW6: 2948 vs 1541 kg ha^{-1} respectively (Fig. 4.11), suggesting another yield limiting factor besides N is coming into play, as soil N levels were almost identical (Table B.2).

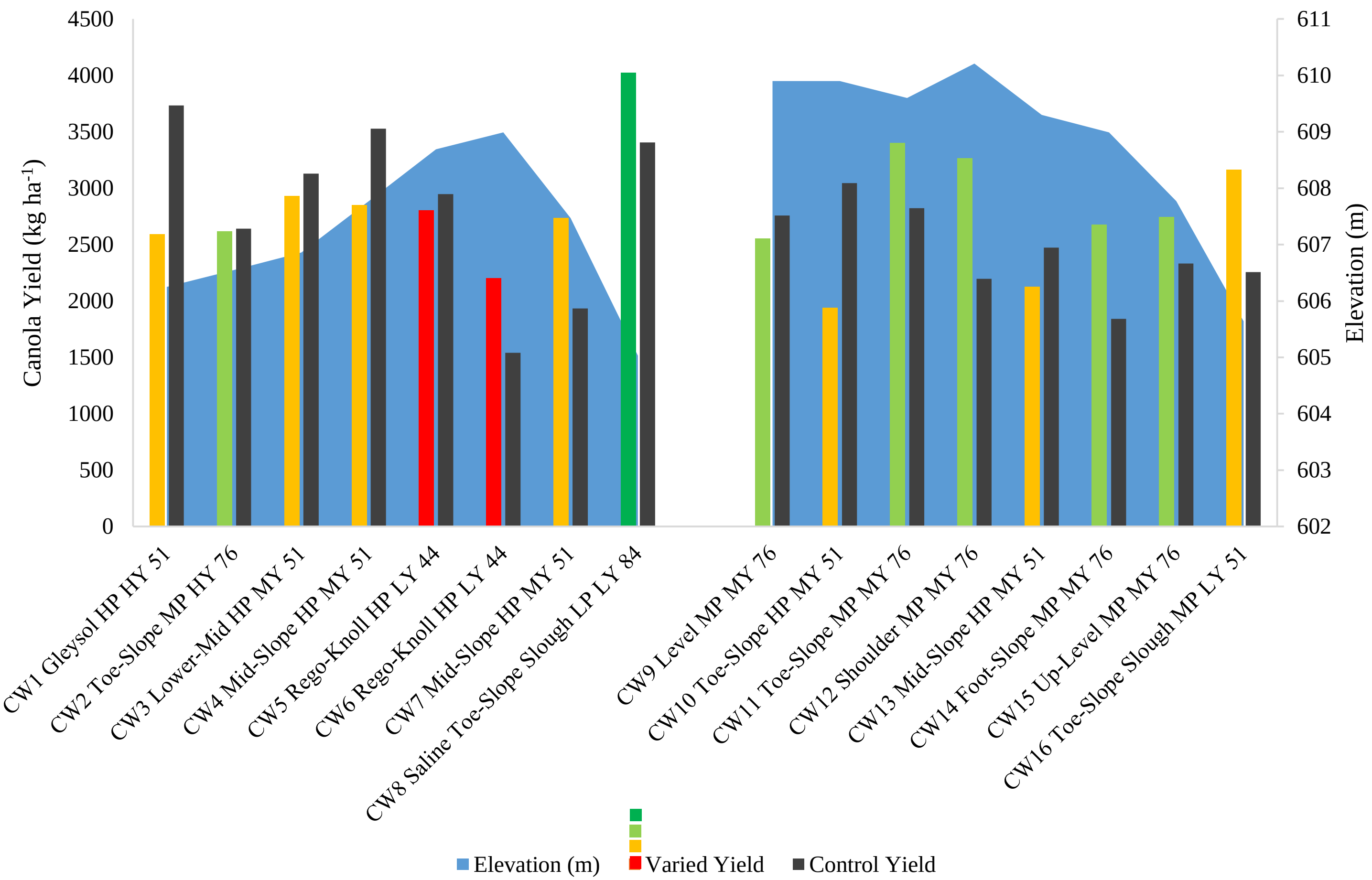

Fig. 4.11. Relationships between the transect point in the landscape and yield for canola grown on wheat stubble in 2013 for varied N rates (44, 51, 76, and 84 N kg ha^{-1} represented by red, yellow, light green and dark green bars respectively) versus a constant N rate (60 kg N ha^{-1} represented by black bars). The horizontal axis includes the transect point, landscape description, yield (HY, MY, LY) and protein (HP, MP, LP) description of the wheat grown on that point in 2012, and the rate of N applied in spring 2013.

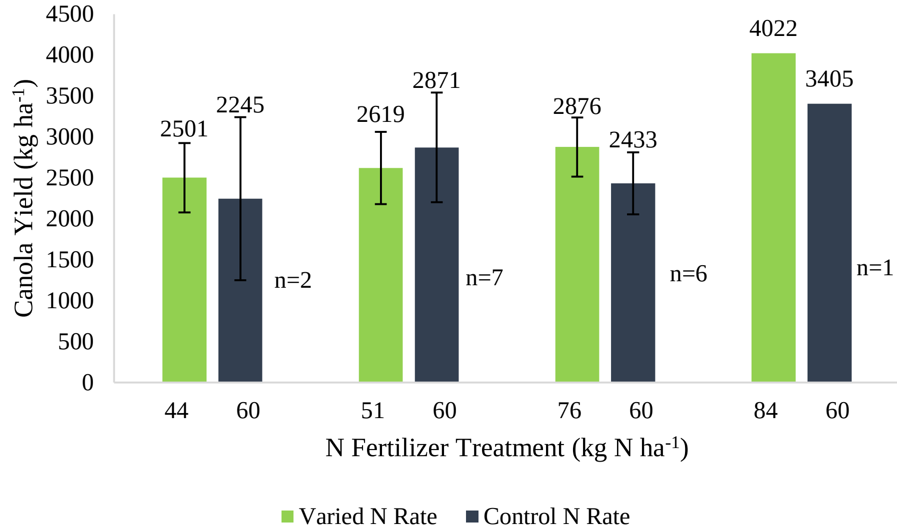

Fig. 4.12. 2013 canola yield (kg ha^{-1}) by N on wheat stubble in Field Area 1. Bars indicate standard deviation of the mean.

The second lowest rate of 51 kg N ha^{-1} yielded less than the control, but the difference was not significant (Fig. 4.12). There were seven plots of this rate. The soil N amounts and supply rates were very similar for these plots (Table B.2), and N is likely the limiting factor for yield. In 2012, the wheat grown had a high protein and medium yield for five of these plots (Fig. 4.11). Thus the N rate was reduced for canola in 2013 because, based on Fig. 2.1, N was not quite as limiting in these plots for wheat. However, CW1 was a high protein and high yielding transect point, and CW16 had a medium protein and low yield. These points were included in this reduced rate because CW1 is a lower elevation gleysol where N and moisture are not limiting and CW16 occupies a toe slope position adjacent to a saline slough (Fig. 4.11). Therefore the rationale to include these in the 51 kg N ha^{-1} rate was to rely on soil N supply in CW1 and not to waste N in the CW16 position. Of these seven points, five had lower yield vs the control. Points CW7 and CW16 ended up having higher yield with a lower N rate, thus masking the overall yield penalty from reducing

N for this treatment. As can be seen from the variability observed in response from point to point, many factors appear to come into play in affecting the response to N fertilizer at specific points in the landscape.

The increased rate of 76 kg N ha^{-1} yielded more than the 60 kg N ha^{-1} constant rate but was not significantly ($p < 0.05$) higher (Fig. 4.12). There were six points that received this treatment. The wheat on these plots in 2012 had a medium protein and a high yield, thus indicating N limitation (Fig. 19). Overall, this N strategy either increased (four plots) or yielded the same (two plots) as the control. Therefore, this strategy may be considered somewhat successful, in that there was a good canola response to greater N application rate.

The points receiving the highest rate, 84 kg N ha^{-1}, had the greatest mean yield at 4022 kg ha^{-1} vs the control of 3405 kg ha^{-1} (Fig. 4.12). There was only one point that received this rate, CW8, so a statistical comparison was not possible. In 2012, wheat had a low protein and a low yield at this point, likely because of the salinity present (Fig. 4.11). There was low N fertility as well. A high rate, 84 kg N ha^{-1} was chosen for this point to see if these limitations could be overcome. It would seem that there was some success with this strategy. However, there was only one transect point that received this rate. Overall, canola in this field exhibited a strong response to added fertilizer N.

4.1.2 Canola Protein Content on Wheat Stubble

When all sixteen transect points were considered and averaged, mean protein content of the varied N rate strip (16.0%) and the constant N rate strip (16.1%) were not significantly different (n = 16, $p < 0.05$) (Fig. 4.13). However, canola protein was quite variable across the landscape (Fig. 4.14).

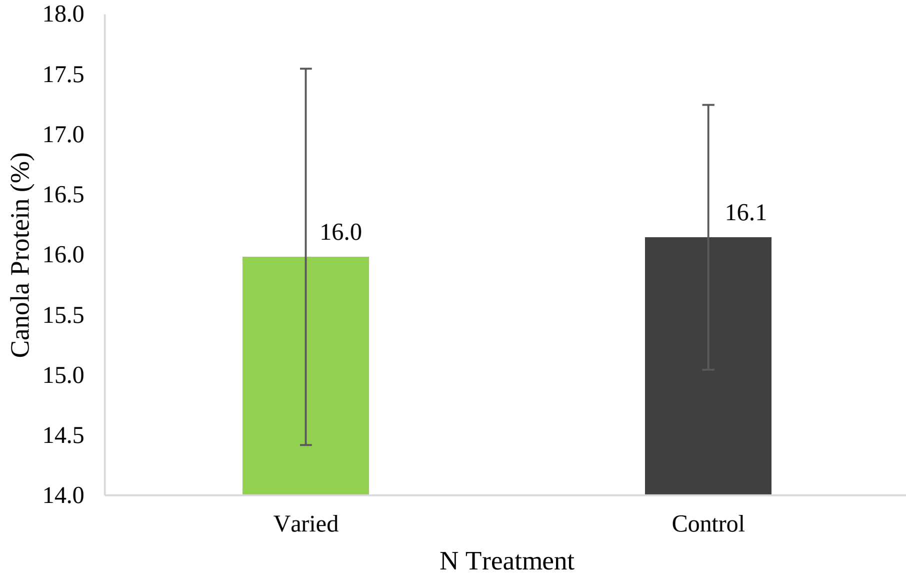

Fig. 4.13. 2013 canola protein (%) by N treatment on wheat stubble on Field Area 1. Bars indicate standard deviation of the mean (n=16).

Canola protein responded positively to increased N fertilization versus a constant rate as shown across the landscape (Fig. 4.14). With the exception of transect points CW9 and CW10, canola protein decreased with decreased N rates, and increased with increased N rates versus the constant N rate. It should also be noted that while canola did indeed exhibit a wide range of protein content of six percentage points (14.1-20.1%), the majority of the transect points had protein clustered much more closely within a range of three percentage points (14-17%). Transect points CW7, CW8, and CW10 with protein values of 18% or greater were the exception (Fig. 4.14).

There were two transect points which received the low 44 kg N ha^{-1} rate. Decreasing the N rate on the rego knoll (points CW5 and CW6) may have been an unsuccessful strategy for protein because it decreased mean protein for this N rate by nearly 2% (14.5% varied rate vs 16.3% constant rate) (Fig. 4.15). In 2012, the wheat at these two points was high protein and low yield. Based on this, it was hypothesized that moisture was more limiting than N, and so the N rate was reduced for the canola in 2013. However, it would appear that on these hilltop rego-knolls that canola protein is limited by N.

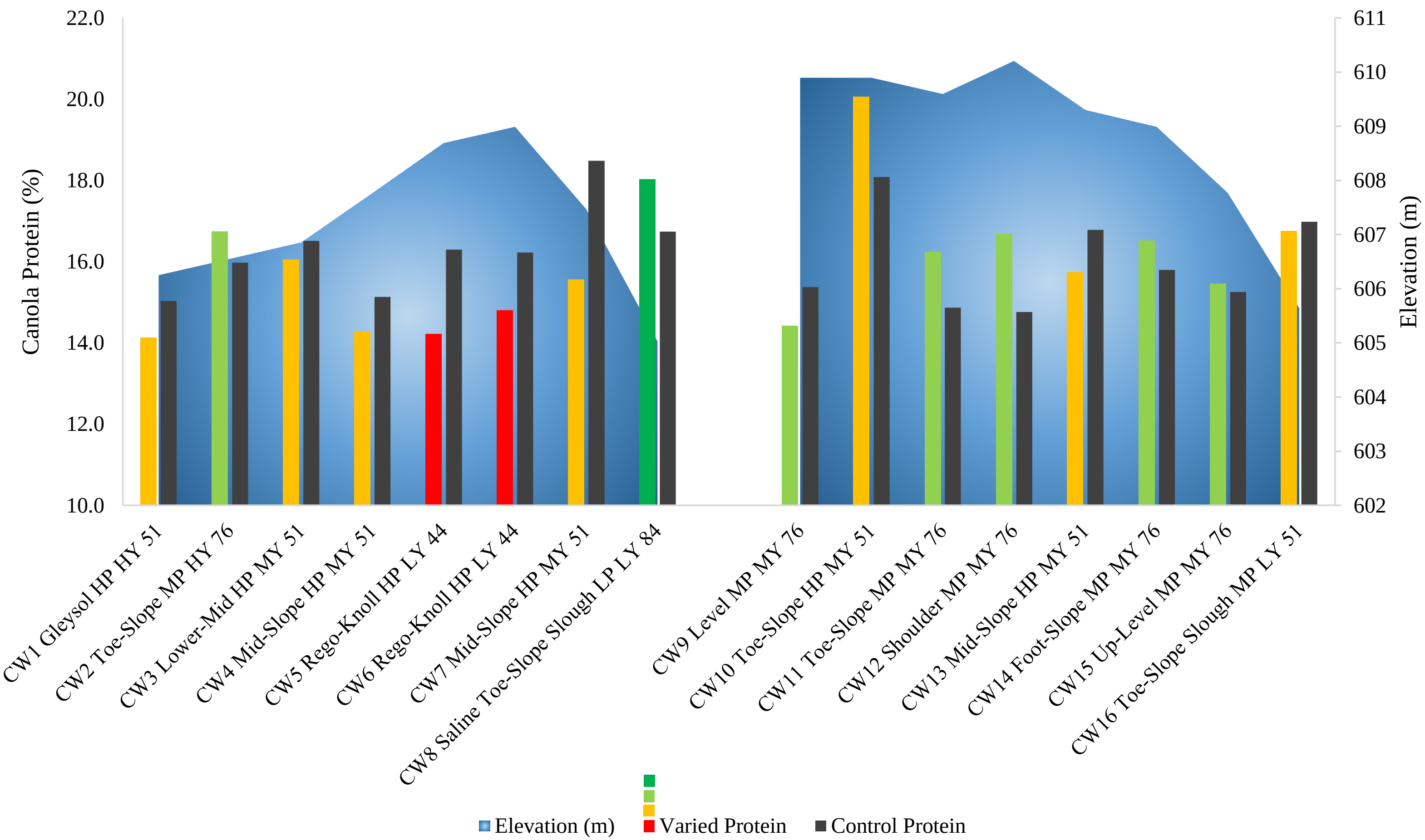

Fig. 4.14. Relationships between transect positions in the landscape and protein content of canola grown on wheat stubble in 2013 for varied N rates (44, 51, 76, and 84 kg N ha^{-1} represented by red, yellow, light green and dark green bars respectively) vs a constant N rate (60 kg N ha^{-1} represented by black bars). The horizontal axis includes the transect point, brief landscape description, yield and protein description of the wheat grown on that point in 2012, and the rate of N applied in spring 2013.

There were seven treatments of the 51 kg N ha^{-1} rate (Fig. 4.15) which were applied for the 2013 canola to mid and toe slopes at points where wheat was generally high protein and medium yield in 2012 (Fig. 4.14). The basis for this rate was that high protein wheat with medium yield meant that N was not limiting, therefore, the N rate for canola could be reduced, though not as much as the 44 kg ha^{-1} rate because the medium yield would have taken more N out of the soil.

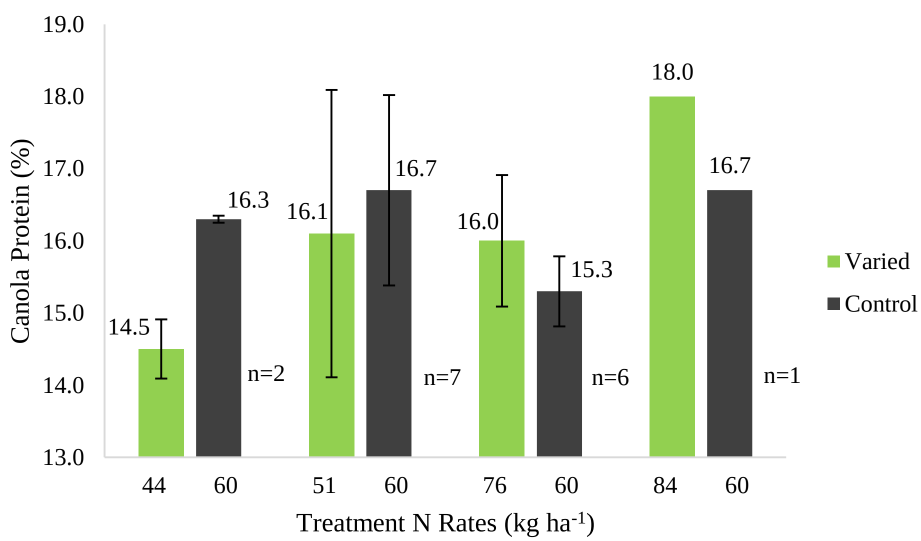

Fig. 4.15. Canola protein by N treatment grown in 2013 on wheat stubble on Field Area 1. Bars indicate standard deviation of the mean.

Six transect points received the 76 kg N ha^{-1} rate (Fig. 4.15). The wheat on these points in 2012 was medium protein and medium yield (Fig. 4.14). Therefore, the hypothesis was to increase N rates above the 60 kg N ha^{-1} constant rate because medium protein indicated N was limiting yield. Mean protein content for canola under the varied N transect was slightly greater than the constant N strip (16.0 vs 15.3%) though this was not significantly different. There were no obvious relationships with the landscape at this N rate (Fig. 4.14).

There was one application of the 84 kg N ha^{-1} rate at transect point CW8 (Fig. 4.14). This location is a saline toe-slope next to a slough with ample water from a high water table. In 2012, the wheat at this point was low protein and low yield. This combination indicated that perhaps not enough N was present to support wheat growth, unlike a combination, for example, of high protein and low yield. Therefore, in this instance it was hypothesized that a high rate of N may be effective. It appears that this was a successful strategy as shown in Fig. 4.15 in that canola protein from the varied rate was nearly 2% greater than the constant N rate (18.0% vs 16.3%), but statistical verification is not possible. This does follow the same pattern as the 76 kg ha^{-1} rate, in that increased rates of N fertilizer above the constant rate, increase protein content of canola.

4.1.3 Wheat Yield on Canola Stubble

Yield of wheat grown on canola stubble showed no significant differences ($p<0.05$) between N fertilizer rate treatments when the 16 points were averaged and compared (Fig. 4.16).

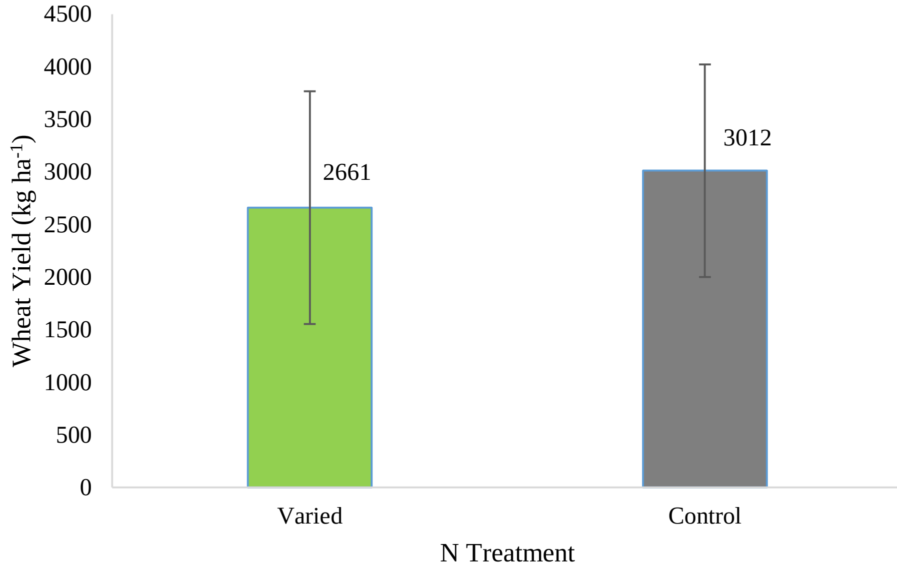

Fig. 4.16. Mean wheat yield grown in 2013 on canola stubble (kg ha^{-1}) on Field Area 2. Bars indicate standard deviation of the mean (n=16).

The 2013 wheat yield at each transect point is shown in Fig. 4.17. There were three points of the lowest N rate (0 kg N ha^{-1}). These were upper levels and eroded knolls where in 2012 the canola had a low protein and a low yield. Therefore, fertilizer N rates were reduced in these plots, perhaps to an extreme degree, to 0 kg N ha^{-1}, to test the hypothesis that something other than N was limiting yield, and therefore it may not be economical to apply N fertilizer at these points. As Fig. 4.18 suggests, this approach was successful, as the control rate of 50 kg N ha^{-1} yielded only 400 kg ha^{-1} more than the rate of 0 kg N ha^{-1}, but this effect is masked somewhat by the large standard deviation of the 0 N rate. Transect points WC4 and WC16 yielded two and three times less than the paired control (639 vs 1340 and 751 vs 2206 kg ha^{-1} respectively). However, WC11 yielded 3034 kg ha^{-1} versus 2086 kg ha^{-1} in the control (Fig. 4.17). Such variations demonstrate how many complex factors may be interacting to control N fertilizer response at specific points in the landscape, and that protein and yield alone may not be sufficient to predict response to added fertilizer N.

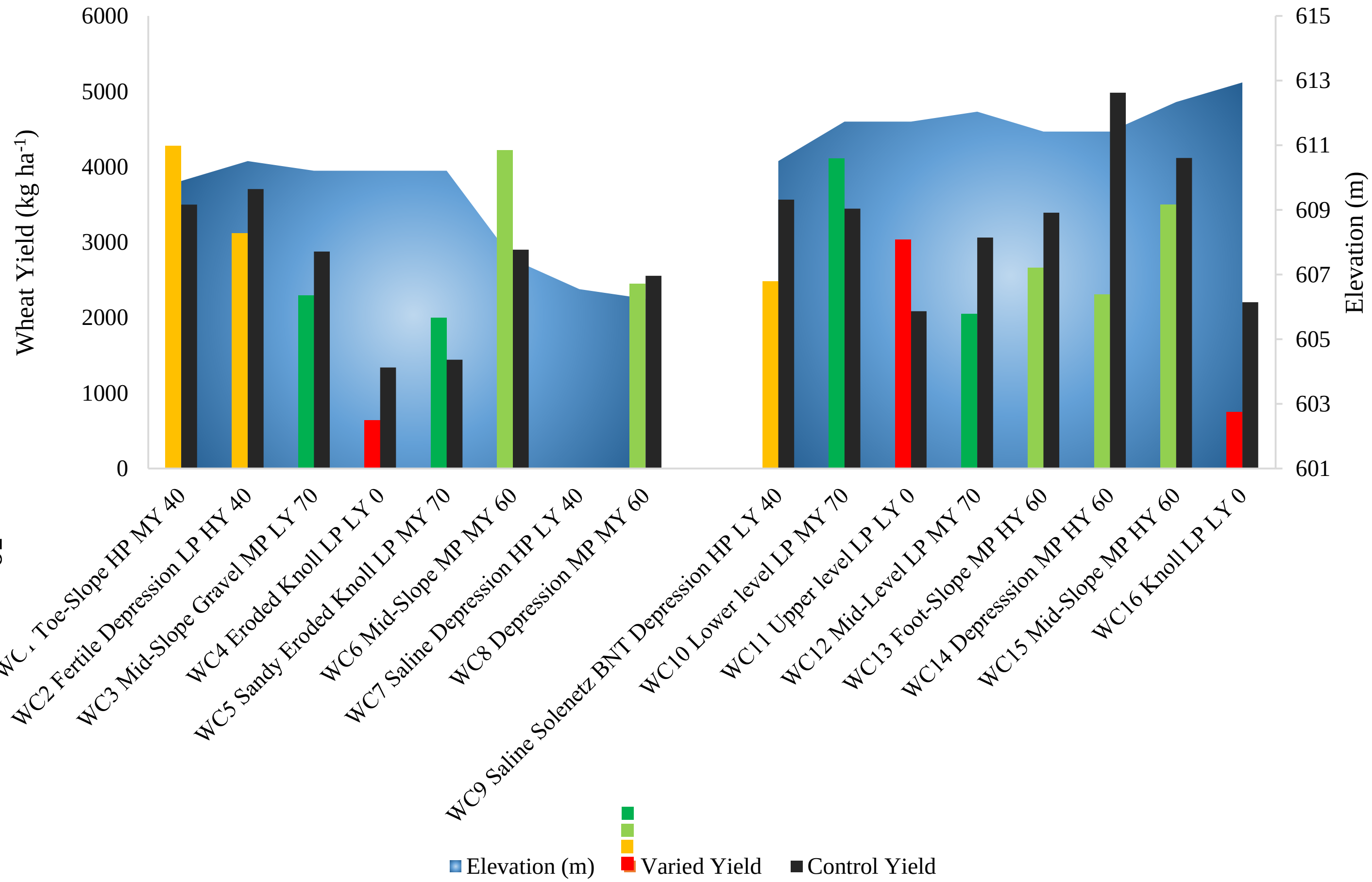

Fig. 4.17 Relationships between the transect position in the landscape and yield for wheat grown on canola stubble in 2013 for varied N rates (0, 40, 60, and 70 kg N ha^{-1} represented by red, yellow, light green and dark green bars respectively) vs a constant N rate (50 kg N ha^{-1} represented by black bars). The horizontal axis includes the transect point, landscape description, yield and protein description of the canola grown on that point in 2012, and the rate of N applied in spring 2013. No data was collected for transect point WC7 because of weed growth that completely crowded out the crop.

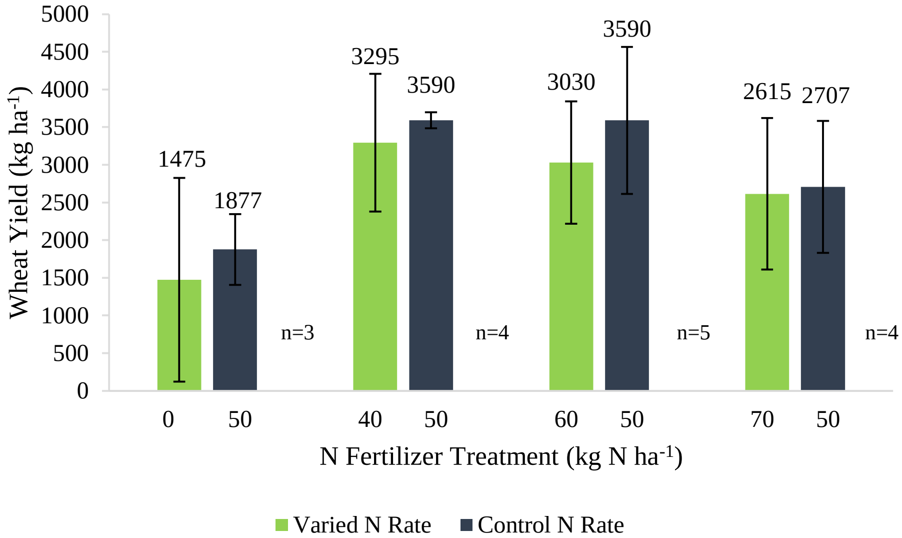

Fig. 4.18. 2013 wheat yield (kg ha^{-1}) by N treatment grown in 2013 on canola stubble in Field Area 2. Bars indicate standard deviation of the mean.

There were four variable rate transect points that received the 40 kg N ha^{-1} rate. These were toe slopes and depressions where in 2012 the canola had high protein and medium yield (WC1), low protein and high yield (WC2) and high protein and low yield (WC9) (Fig. 4.17). Point WC7 is a depression and no yield was recorded in this point due to excess moisture and weed pressure, and the 40 kg N ha^{-1} rate was applied in 2013. Point WC2 had a low protein and high yield in 2012, and choosing this rate was a test to see how reducing the N rate under this condition would affect yield. Point WC1 yielded 4284 kg ha^{-1} vs the control of 3501 kg ha^{-1}, suggesting that reducing the N rate in this toe slope position was successful. However, in the adjacent point WC2, the varied N rate point yielded 3121 kg ha^{-1} versus the control of 3707 kg ha^{-1} suggesting that the low protein and high yield combination should have received the same or a higher rate of N. Point WC9 is a saline solonetzic depression with a very high amount of nitrate in the soil (greater than 200 kg N ha^{-}

^{1} in the 0-60cm depth). This explains the high protein and low yield in 2012. However, the reduced rate of N (40 kg ha^{-1}) yielded less than the control (2840 vs 3564 kg ha^{-1} respectively), suggesting that it is possible to still increase yield with a greater rate of N application. Despite high soil nitrate measured the previous fall, some nitrate may be lost in the overwinter period. The control rate of 50 kg N ha^{-1} in these points produced similar yields as shown by the small standard deviation versus the rate of 40 kg N ha^{-1} (Fig. 4.18). This suggests that overall in the 40 kg N ha^{-1} points, that N was limiting yield, and that 10 kg N kg ha^{-1} extra application was enough to maximize yield.

There were five points of the 60 kg N ha^{-1} rate (Fig. 4.18). In 2012, the canola had a medium protein and either a medium yield (WC6 midslope, WC8 depression) or high yield (WC13 foot slope, WC14 depression, WC15 mid-slope) (Fig. 4.17). In only one point, WC6, did the wheat in the varied treatment respond to higher N application (4225 vs 2900 kg ha^{-1}). In the other four plots, despite greater N availability from a higher rate of N added, the varied rate yielded less than the control rate of 50 kg N ha^{-1}. This suggests that despite more N available, perhaps another yield limiting factor such as disease caused no response or a reduction in yield from the extra N added.

There were four plots that received the highest N rate of 70 kg N ha^{-1} (Fig. 4.18). In 2012 the canola on these plots had a medium protein and low yield (WC3) or a low protein and medium yield (WC5, WC10, WC12) (Fig. 4.17). These combinations suggested that N was limiting to canola yield. WC3 is a gravelly mid slope which yielded 2298 kg ha^{-1} versus 2876 kg ha^{-1} for the control, suggesting that increasing the N rate at this position was not successful because of the gravelly nature with low moisture holding capacity and low availability of other nutrients. However, WC5 is a sandy eroded knoll, where the varied rate yielded 1998 kg ha^{-1} versus 1444 kg ha^{-1}. WC10 is a lower level landscape position where there was a good response to N, as the varied rate point yielded 4111 kg ha^{-1} versus 3445 kg ha^{-1} for the control. WC12 is a mid-level landscape position, and the varied rate yielded substantially less than the control: 2052 vs 3061 kg ha^{-1}. Thus, there was some success with increasing yields with the high rate of 70 kg N ha^{-1}. However, these were offset by yield reductions at two points, so overall, on average, this treatment did not differ significantly than the control.

4.1.4 Wheat Protein Content on Canola Stubble

Mean protein content of wheat that was grown on canola stubble, was the same for both the varied and constant N rate treatments (Fig. 4.19).

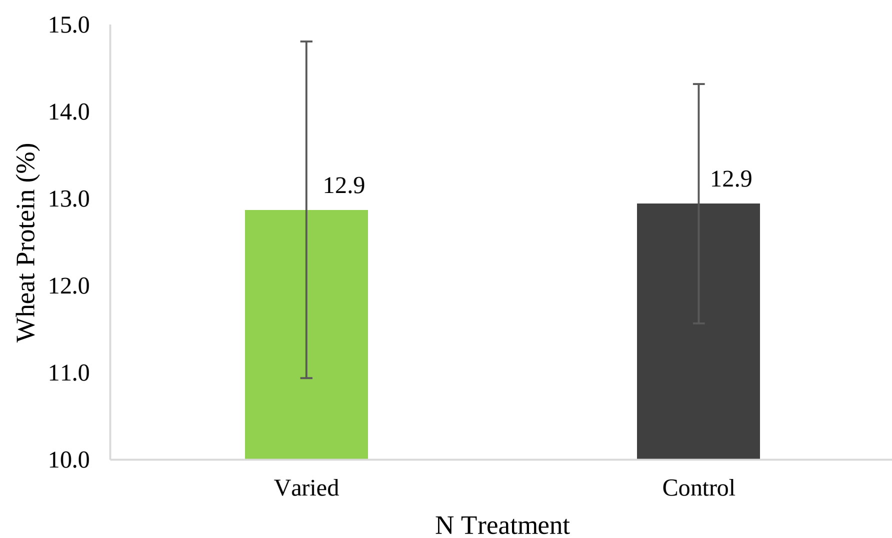

Fig. 4.19. Mean protein content of wheat grown in 2013 on canola stubble on Field Area 2. Bars indicate standard deviation of the mean (n=16).

There were few clear relationships between wheat protein and the landscape and varying N rates. However, with the exception of transect point WC9, it appears that lower slope and depressional areas of the landscape tend to have decreased protein values versus mid to high slope positions, possibly due to less available moisture stress in the upper slope positions. High protein values were obtained with little to no N applied, as well as from high N application rates (Fig. 4.20). Other researchers have observed similar trends. Walley et al. (2001) reported that there were no consistent differences between wheat protein and landform positions, but that protein generally increased with increased N fertilizer application.

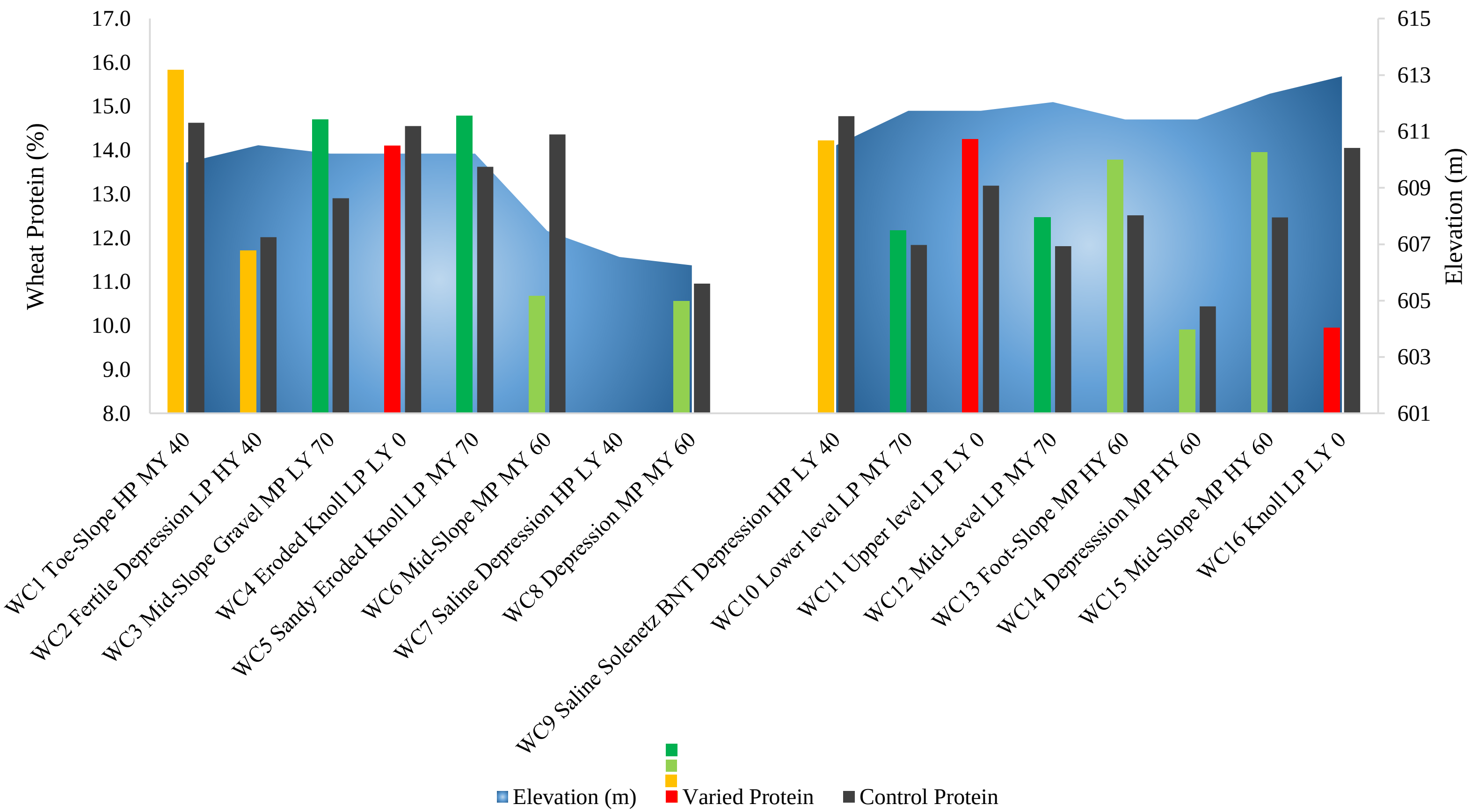

Fig. 4.20. Relationships between the transect point in the landscape and protein for wheat grown on canola stubble in 2013 for varied N rates (0, 40, 60, and 70 kg N ha^{-1} represented by red, yellow, light green and dark green bars respectively) vs a constant N rate (50 kg N ha^{-1} represented by black bars). The horizontal axis includes the transect point, landscape description, yield and protein description of the canola grown on that point in 2012, and the rate of N applied in spring 2013. No data was collected for transect point WC7 because of weed growth that had completely crowded out the crop.

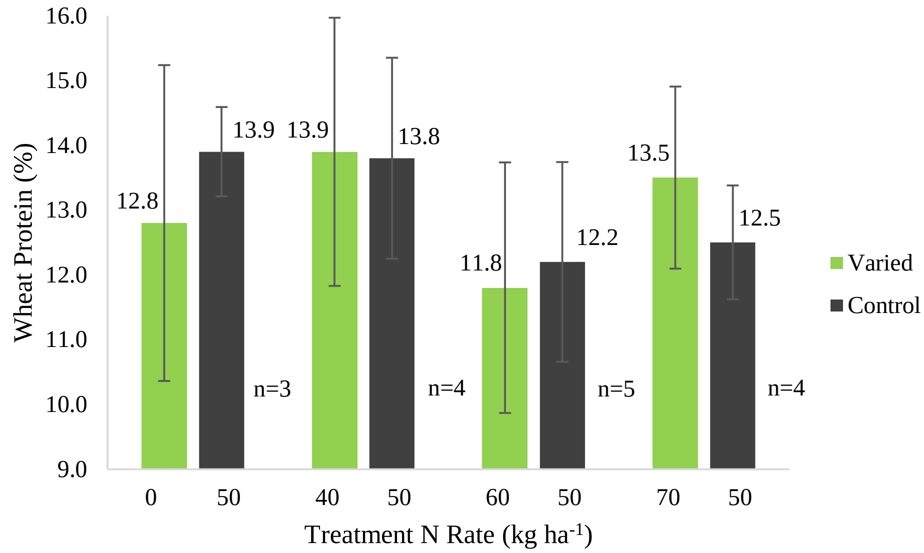

Fig. 4.21. Wheat protein by N rate on canola stubble in Field Area 2 in 2013. Bars indicate standard deviation of the mean.

Three transect points in the 2013 wheat grown on canola stubble in Field Area 2 received 0 kg N ha^{-1}. These were WC4, WC11, and WC16, which are upper slope eroded knolls where in 2012, the canola had low protein and low yield, possibly because applied fertilizer N is very inefficient at these slope positions because of volatilization or runoff. The fertilizer strategy for these plots then was a reduction in applied N because both low protein and low yield suggested potential limitations beyond N and that no penalty would be incurred. It is apparent that this strategy resulted in reduced protein versus the constant N rate (12.8% vs 13.9%) though these differences were not significant at $p < 0.05$ (Fig. 4.21). As with yield in Fig. 4.18, there could be a protein penalty with decreasing N rates to zero. Therefore, a variable rate N plan for wheat following canola, where canola is described by low protein and low yield, it may be better to simply assign a constant or lower rate to that zone, rather than eliminating the fertilizer N completely.

There were four transect points that received the 40 kg N ha^{-1} rate. With the exception of WC2, these points had high protein and medium to low yield. The reduced rate of 40 kg N ha^{-1} strategy was used because the high protein meant that there had been sufficient N available to the crop, and that because these were depressional areas, perhaps the soil would be able to supply enough N to the crop through mineralization (Fig. 4.20). This strategy was successful because the protein values from the varied N strips was nearly identical to the control strip (13.9% vs 13.8%) (Fig. 4.21).

Five of the transect points received the 60 kg N ha^{-1} rate. These transect points were mid slopes and depressional areas where canola was characterized as medium protein and medium to high yield in 2012, and identified as regions of high productivity in the landscape. Based on the medium protein of the canola in 2012, the fertilizer strategy was to increase N by 10 kg N ha^{-1} vs the control. This had no significant ($p < 0.05$) detectable effect on protein (Fig. 4.21).

There were four transect points that received the highest N rate treatment of 70 kg N ha^{-1}. These included mid-levels, a lower level and a sandy eroded knoll where in 2012, canola was generally characterized by low protein and medium yield, however WC3 was a medium protein low yield (Fig. 4.20). This high rate was chosen because the low protein and medium yield suggested considerable potential for more yield. The effect on protein was positive whereby the varied N strip resulted in a 1% protein increase over the control (13.5% vs 12.5%) (Fig. 4.21). A paired t-test of these four points revealed that this was a significant increase at $p<0.05$. Therefore, while yield of this treatment was similar between the varied and control strips (Fig. 4.19), it is evident that higher N rates may increase the quality, and therefore value, of the crop. It is interesting to note however, that WC4, an eroded knoll, that received 0 kg N ha^{-1} had 14.1% protein vs 14.8% for an application of 70 kg N ha^{-1}, and the protein concentration for the control rate on these points were 14.6% and 13.5% respectively. Therefore the lack of protein response confirms that reducing the N rate on the knolls is a more successful strategy. A similar finding was reported by Walley et al. (2001) where it was observed that fertilizer N application increased wheat yield in upper landform positions. However, the full potential of this N was utilized by the wheat due to moisture deficit.

4.1.5 Wheat Yield Grown on Pea Stubble

Wheat grown in 2013 on pea stubble had a higher mean yield (230 kg ha^{-1} higher) from the transects with varied N rates (Fig. 4.23). As for wheat on canola stubble, this difference between varied and constant N rate treatments was not significant at $p<0.05$.

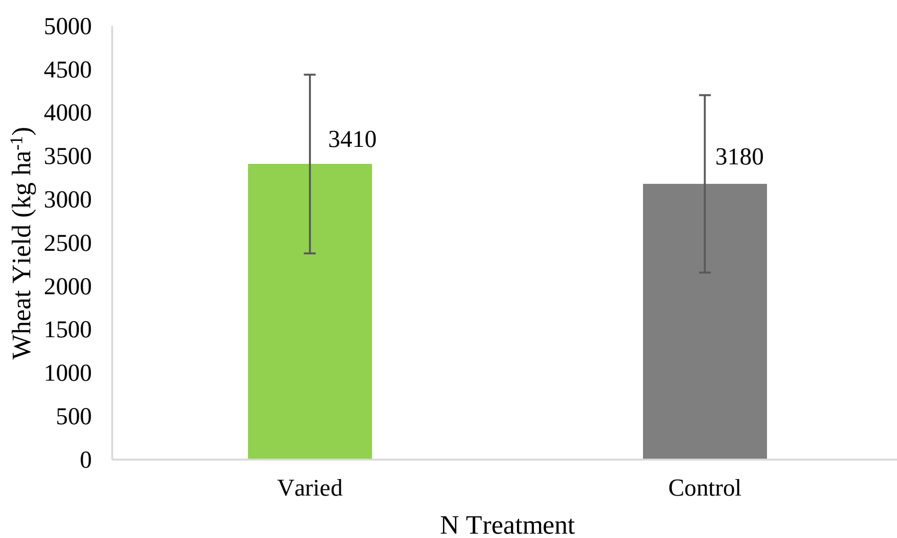

Fig. 4.22. Mean wheat yield grown in 2013 on pea stubble (kg ha^{-1}) on Field Area 3. Bars indicate standard deviation of the mean (n=16).

Wheat yields grown on pea stubble at each transect point are shown in Fig. 4.24 There is an apparent trend toward increasing yield with increasing N rates. There were seven plots where the low rate of 40 kg N ha^{-1} was applied. These ranged from upper levels to lower wet landscape positions. In 2012, peas had high protein and high yield, high protein and medium yield and high protein and low yield (Fig. 4.24). In all these cases, decreasing the N rate was chosen because the high protein suggested that N was not limiting. Variability in responses among points were observed, resulting in no significant differences in yield. In particular, the constant rate point at WP6 yielded 5120 kg ha^{-1} vs the varied rate yield of 2395 kg ha^{-1}. This point suffered in yield from reducing N rate and it is unclear why this point should yield so much more, as soil extractable nitrate-N status was only 10 kg ha^{-1} higher. However, it is apparent that while in some cases reducing the N rate can be successful in having no yield penalty, it would seem that this approach needs some refining as it may be false economy to try and reduce N rates in too many instances.

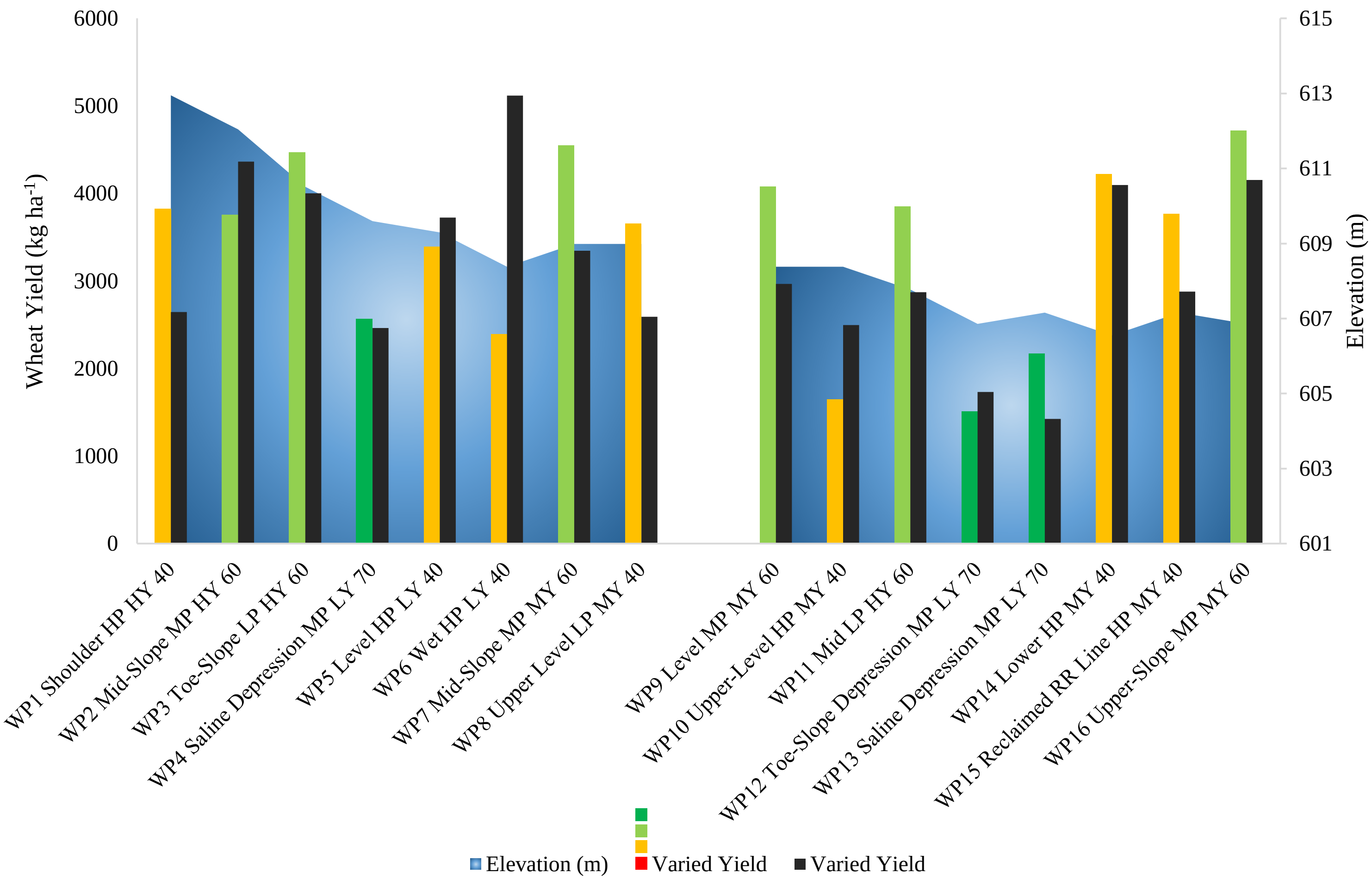

Fig. 4.23. Relationships between the transect point in the landscape and yield for wheat grown on pea stubble in 2013 for varied N rates (40, 60, and 70 kg N ha^{-1} represented by yellow, light green and dark green bars respectively) vs a constant N rate (50 kg N ha^{-1} represented by black bars). The horizontal axis includes the transect point, landscape description, yield and protein description of the peas grown on that point in 2012, and the rate of N applied in spring 2013.

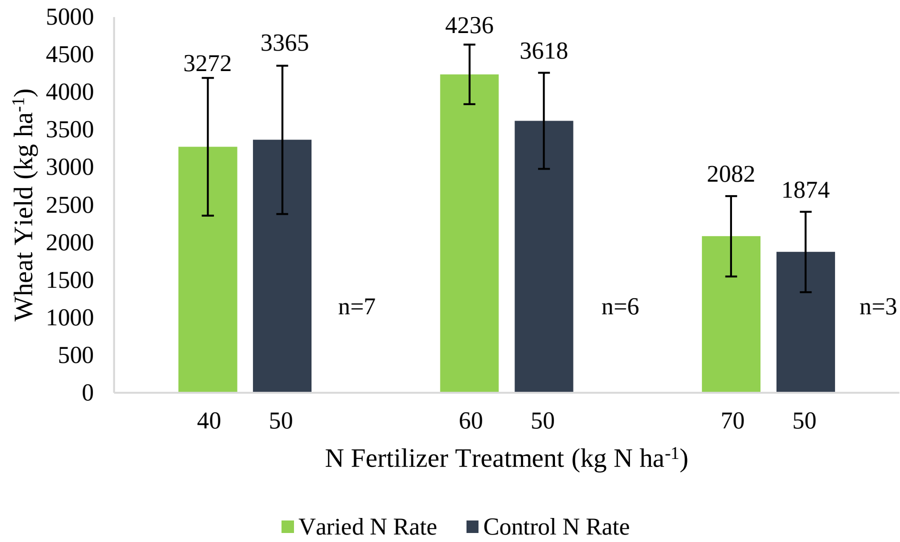

Fig. 4.24. 2013 wheat yield (kg ha^{-1}) by N treatment on pea stubble. Bars indicate standard deviation of the mean.

There were six points that in the variable rate transect that received the medium rate of 60 kg N ha^{-1}. The variable rate appears to have been more consistent in its effect on yield due to a standard deviation of about half the value of the control (Fig. 4.25). The peas on these points were either medium protein and high yield or medium protein and medium yield in 2012, suggesting that more N could be required. Indeed, this was successful in three of four points, which had higher yields under the increased N rate regime (Fig. 4.24).

Three points in the wheat grown on pea stubble received the high N rate treatment of 70 kg N ha^{-1}. These were saline and toe-slope depressions where peas had medium protein and low yield in 2012 (Fig. 4.25). The strategy was to increase N in an attempt to see if this could increase both yield and protein. The average yields in the 70 kg N ha^{-1} treatment were significantly lower than either the 40 or 60 kg N ha^{-1} rates, suggesting strongly that N was not limiting in these positions. Thus, the salinity at these positions likely is the limiting factor to yield. It should be noted as well that there was significant disease pressure in these low elevation points in 2012 as well, which would have reduced yield and affected the protein: yield relationships. Also the N-fixing ability of peas likely has an effect on the protein: yield relationship in that it would mask to a large degree the soil supply to the crop. Previously, there has been noted to be little correlation between pea protein and yield (McLean et al., 1974). Nonetheless, as Fig. 4.25 shows, it may be worthwhile to continue looking at pea protein: yield relationships because, in contrast to the wheat grown on canola stubble, there was a trend to yield gain from the varied rate.

4.1.6 Wheat Protein Content Grown on Pea Stubble

Mean wheat protein for the wheat-pea rotation was generally greater than in the wheat-canola rotation. Slowly mineralizing labile soil organic N derived from the pea crop would explain a high mean protein content of wheat grown on pea stubble (14.5% protein) compared to the wheat grown on canola stubble (12.9% protein) (Fig. 4.19). These findings agree with Lafond et al. (2011) who reported 1% greater wheat protein in wheat grown on field pea stubble compared to wheat on wheat stubble at Indian Head, SK, Canada. However, this effect may not occur every year, and may be difficult to accurately predict depending on environmental conditions (Walley et al., 2007).

Averaged across the landscape, the protein content for varied rate and constant rate were similar at 14.6% for the varied N vs 14.5% for the constant N rate (Fig. 4.25).

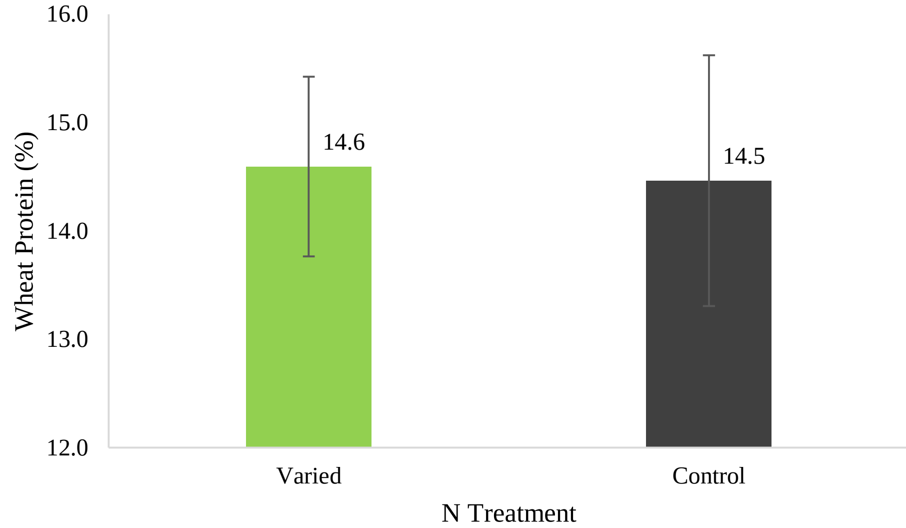

Fig. 4.25. Mean wheat protein grown in 2013 on canola stubble on Field Area 3. Bars indicate standard deviation of the mean.

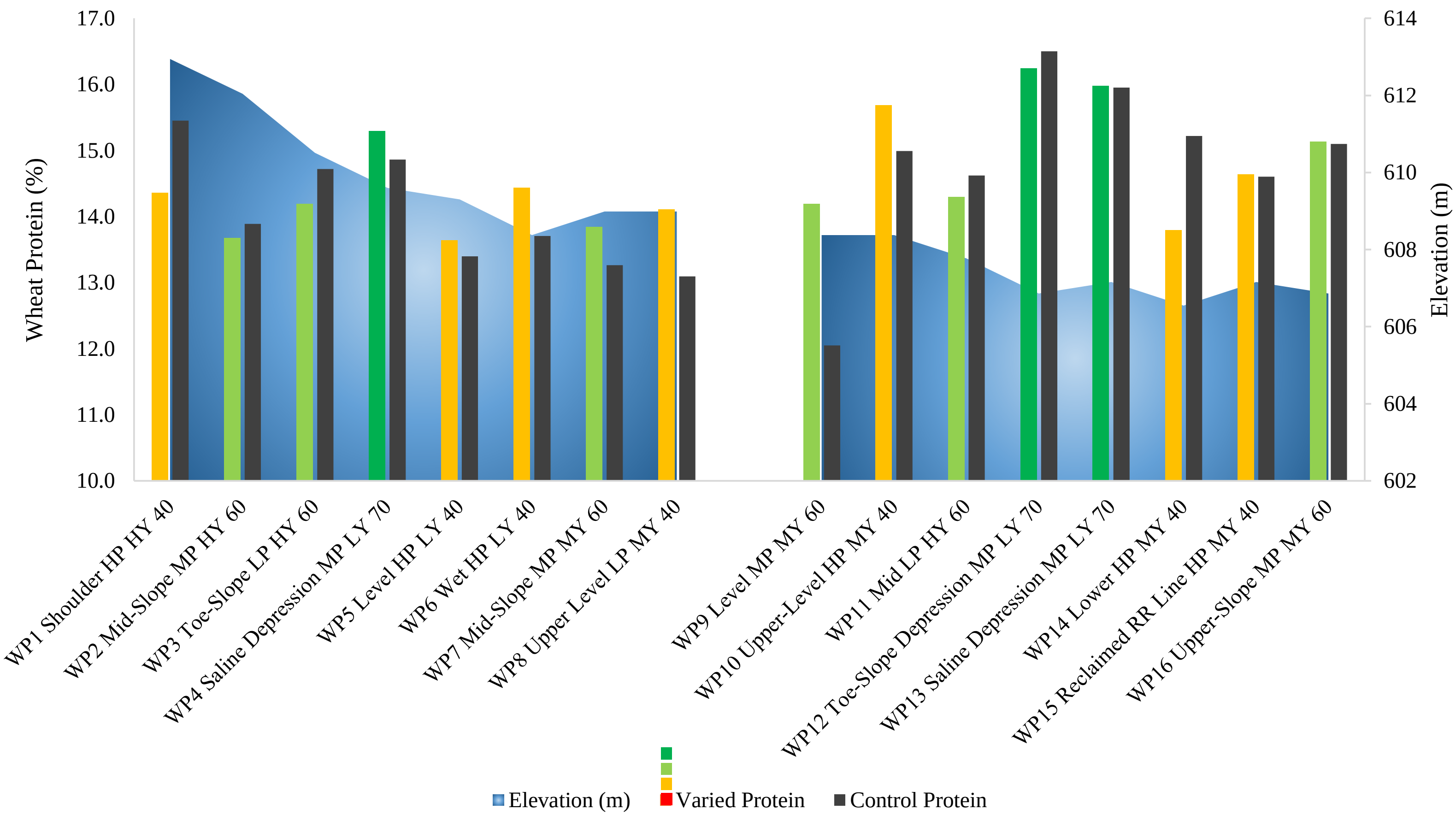

Fig. 4.26. Relationships between the transect points in the landscape and protein for wheat grown on pea stubble in 2013 for varied N rates (40, 60, and 70 kg N ha^{-1} represented by yellow, light green and dark green bars respectively) vs a constant N rate (50 kg N ha^{-1} represented by black bars). The horizontal axis includes the transect point, landscape description, yield and protein description of the peas grown on that point in 2012, and the rate of N applied in spring 2013.

It is clear that there are protein differences across the landscape (Fig. 4.27). There were seven transect points that received the 40 kg N ha^{-1} rate. In 2012, peas were characterized by high protein and low to high yield, with the exception of WP8 which had low protein. A reduced N rate was applied on these points because the high protein meant that the peas had adequate N, and perhaps it was possible to rely on the N supplying ability of the soil to maintain yield in the 2013 wheat crop. Mean protein from the varied N strip was 14.3% vs 14.2% in the control strip, and the varied N rates had a slightly less variation (Fig. 4.28). There was no significant difference between these protein levels. Yield on these points (Fig. 4.25) also did not differ significantly, therefore, in this landscape, a reduction of N from 50 to 40 kg N ha^{-1} based on the high protein of peas in 2012, did not cause a significant yield or protein penalty.

Six transect points received the 60 kg N ha^{-1} rate where peas in 2012 were characterized by medium to low protein and medium to high yield (Fig. 4.27). This meant that while pea yield was generally satisfactory, the low and medium protein indicated that more N could have been beneficial to yield. These points also occurred over the entire landscape from toe-slopes to upper slopes. The result was a trend to increasing protein over the control (14.4% versus 13.8%). Yield from these transect points (Fig. 4.25) also showed the same pattern, though while not significantly different, the trend was increasing N application rates based on low and medium protein has potential to be a successful strategy. However, it is clear that in this landscape, a 10 kg ha^{-1} increase in N application rates is not enough to create significant differences.

There were three transect points that received the highest N application rate of 70 kg N ha^{-1}. The points were WP4, WP12, and WP13, and the peas in these areas in 2012 had medium protein, but low yield (Fig. 4.27). This combination of protein and yield was thought to mean that a high rate of N would be required to produce wheat with both high protein and high yield. However, the result was a mean protein of the same value for both the varied and constant N strips (15.8% vs 15.8%) (Fig. 4.28). These are high protein values for wheat, and when yield is considered (Fig. 4.25) it is apparent that this strategy was only successful at increasing wheat protein, but not yield. In fact, this N rate had the lowest yield in this rotation. Therefore, there must be a soil property that is more limiting to crop production than N. As these are saline depressions, it is likely that this factor is excess salinity. Had canola been seeded in these points, this may have been a worthwhile strategy as canola is slightly more tolerant to a saline environment (Steppuhn et al., 2001). Therefore, when selecting N rates, crop tolerance to such factors as salinity must be considered. It also must be remembered that pea protein may not be as reliable an indicator of the relationship between crop productivity and the N supplying ability of the soil because peas are able to fix their own N.

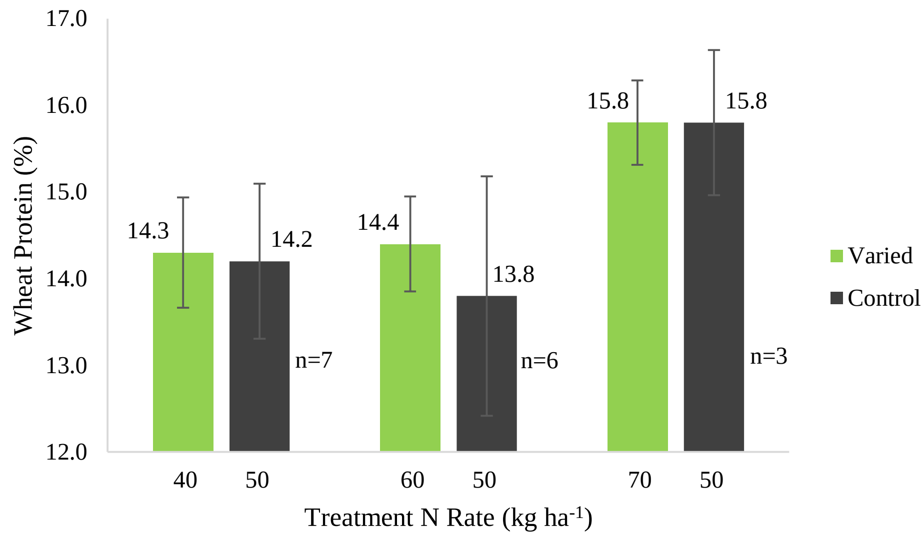

Fig. 4.27. 2013 wheat protein by N treatment on pea stubble in Field Area 3. Bars indicate standard deviation of the mean.

4.2 Yield and Protein Relationships with Soil Properties

The information collected from sampling and analyzing soil properties in fall 2012 had a limited benefit for predicting yield in 2013 (Table 4.5) where only two correlations were significant. Available N as predicted by anion resin probes had a moderate ability to predict yield for the constant N rate treatment of wheat on pea stubble (r = 0.55, p = 0.03). Extractable potassium in the 0-30 cm depth had a positive, significant relationship (r = 0.52, p = 0.04) with wheat yield in the constant N rate transects for wheat on pea stubble. Potassium fertilizer was not used in this study, though greatly varying soil potassium levels (Table B.8) in this field area raise the possibility that some transect points may benefit from potassium application. This raises the scenario that more than one nutrient besides N may be required to be varied across the landscape, which should be investigated in a future study.

Table 4.5. Correlations between soil nutrients in fall 2012 and crop yield in 2013.

Soil Property	Wheat on Canola		Wheat on Peas		Canola on Wheat	
	Varied	Control	Varied	Control	Varied	Control
Extractable NO_3^- (0-30 cm)	n/s	n/s	n/s	n/s	n/s	n/s
Extractable NO_3^- (30-60 cm)	n/s	n/s	n/s	n/s	n/s	n/s
Extractable PO_4^- (0-30 cm)	n/s	n/s	n/s	n/s	n/s	n/s
Extractable K (0-30 cm)	n/s	n/s	n/s	**0.52* (0.04)‡**	n/s	n/s
AEM† NO_3^- (0-30 cm)	n/s	n/s	n/s	**0.55 (0.03)**	n/s	n/s
AEM PO_4^- (0-30 cm)	n/s	n/s	n/s	n/s	n/s	n/s

† AEM= anion exchange membrane
‡ Value in brackets indicates *p* - value
* Significant correlation at $p < 0.05$.

There were few significant correlations between canola yield and protein and soil properties (Table 4.6). However, organic carbon in the top 30 cm of soil did have a significant effect on canola protein in 2012 (r = 0.65, $p < 0.007$) and on canola yield in the constant N rate transect in 2013 (r = 0.57, $p < 0.02$). This is of particular interest because canola was grown on different field areas in the two years. Canola yield from the varied N rate strip in 2013 was positively correlated with EC in the 0-30 cm depth (r = 0.51, $p < 0.04$). This is explained by Table 4.8 that shows that in this landscape EC and NO_3^- N are positively related. Canola protein in the control N rate transect was negatively related to spring soil moisture in the 30-60 cm depth (r= -0.50, p < 0.05) which may be explained by greater subsoil soil moisture contributing to increased yield, therefore diluting the protein. There was no effect of pH on canola yield or protein in either year, consistent with the pH in this landscape ranging from neutral to slightly alkaline (Table B.1) which is ideal for canola growth (Canola Council of Canada, 2014).

Table 4.6. Correlations between soil properties and canola yield and protein in the 2012 base year and 2013 varied and constant N rates.

	2012		2013		2013	
	Base Year		Varied Rate		Control Rate	
	Yield	Protein	Yield	Protein	Yield	Protein
OC† 0-30 cm (%)	n/s	**0.65*** **(0.007)§**	n/s	n/s	**0.57** **(0.02)**	n/s
OC 30-60 cm (%)	n/s	n/s	n/s	n/s	n/s	n/s
pH 0-30 cm	n/s	n/s	n/s	n/s	n/s	n/s
pH 30-60 cm	n/s	n/s	n/s	n/s	n/s	n/s
EC‡ 0-30 cm (dS m^{-1})	n/s	n/s	**0.51** **(0.04)**	n/s	n/s	n/s
EC 30-60 cm (dS m^{-1})	n/s	n/s	n/s	n/s	n/s	n/s
2013 Soil Moisture Spring 30-60 cm	n/s	n/s	n/s	n/s	n/s	**-0.50** **(0.05)**

† OC denotes organic carbon
‡ EC denotes electrical conductivity
§ Value in brackets indicates *p* -value
* Significant correlation at $p < 0.05$.

For both canola (Table 4.6) and wheat (Table 4.7), OC and EC are major soil properties affecting yield and protein, though EC seems to have a greater effect on wheat than canola (Table 4.7). There was no effect of pH on wheat yield in either year. Organic carbon in the top 30 cm of soil had a positive correlation with wheat yield in 2012 (r = 0.71, $p < 0.001$), and with the variable N strip in the wheat on canola stubble in 2013 (r = 0.51, $p < 0.05$). However, wheat protein in 2012 was negatively correlated with organic carbon in 30-60cm depth (r = -0.53, $p < 0.04$) which may indicate a spurious correlation because the opposite relationship to what others have reported (Sandhu et al., 1996; Mikanova et al., 2012). The relationship between wheat yield and EC is generally negative. Since this relationship, in this landscape, is relatively consistent over two years and in different parts of the field, it may be concluded that this property should be considered when making variable rate N application decisions in fields with salinity. The relationship of EC and protein is less clear though, because it is both positive (r = 0.51, $p < 0.05$ 0-30 cm depth, 2012; r = 0.57, $p < 0.02$ 30-60 cm depth 2013, constant rate strip, wheat on pea rotation) and negative (r = -0.56, $p < 0.02$, 30-60 cm depth 2012). Spring soil moisture in the 30-60 cm depth had a negative correlation with wheat protein in the wheat canola rotation (r= -0.60, p<0.02), consistent with greater moisture leading to higher yields and grain protein dilution.

Table 4.7. Correlations between soil properties and wheat yield and protein in the 2012 base year and the varied and control N rates in for wheat grown in 2013 on canola and pea stubble.

	2012		2013		2013		2013		2013	
	Base Year		Wheat on Canola				Wheat on Peas			
			Varied		Control		Varied		Control	
	Yield	Protein	Yield	Protein	Yield	Protein	Yield	Protein	Yield	Protein
OC† 0-30 cm (%)	**0.74* (0.001)§**	n/s	**0.51 (0.05)**	n/s	n/s	n/s	n/s	n/s	n/s	n/s
OC 30-60 cm (%)	n/s	**-0.53 (0.04)**	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s
pH 0-30 cm	n/s		n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s
pH 30-60 cm	n/s	**0.51 (0.05)**	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s
EC‡ 0-30 cm (μS cm^{-1})	n/s	**0.51 (0.05)**	n/s	n/s	n/s	n/s	**-0.52 (0.04)**	n/s	**-0.51 (0.05)**	n/s
EC 30-60 cm (μS cm^{-1})	**-0.53 (0.03)**	**-0.56 (0.02)**	n/s	n/s	n/s	n/s	n/s	n/s	**-0.59 (0.02)**	**0.57 (0.02)**
2013 Soil Moisture Spring 30-60 cm	n/s	n/s	n/s	n/s	n/s	**-0.60 (0.02)**	n/s	n/s	n/s	n/s

† OC denotes organic carbon
‡ EC denotes electrical conductivity
§ Value in brackets indicates *p* -value
* Significant correlation at $p < 0.05$.

The relationship of EC to available N is of particular interest in this landscape because as shown in Tables 4.6 and 4.7, the soil property most affecting yield and protein is EC. The importance of this relationship in planning future variable rate N prescriptions is that in the field areas including canola on wheat stubble, and wheat on canola stubble, there is a positive relationship between the EC and soil N. However, in the field area that included wheat on pea stubble, this relationship is negative (Table 4.8). This is likely due to greater salinity levels that may mask soil N, since even with high rates of applied N, the greater salinity in area of the field had a negative impact on wheat yield.

Table 4.8: Correlations between electrical conductivity (EC) and soil N for each field area in fall 2012 and spring 2013.

	Extractable NO_3^- - N				AEM† NO_3^- - N	
	Depth (cm)					
	0-30	30-60	0-30	30-60	0-30	30-60
	---Spring 2013---		---Fall 2012---			
Canola on Wheat Field Area 1						
EC 0-30cm (µS cm^{-1})	**0.55* (0.02)‡**	n/s	n/s	n/s	n/s	n/s
EC 30-60cm (µS cm^{-1})	**0.68 (0.004)**	n/s	n/s	n/s	n/s	n/s
Wheat on Canola Field Area 2						
EC 0-30cm (µS cm^{-1})	**0.52 (0.05)**	**0.57 (0.02)**	**0.52 (0.04)**	n/s	n/s	n/s
EC 30-60cm (µS cm^{-1})	n/s	**0.53 (0.04)**	n/s	n/s	n/s	n/s
Wheat on Peas Field Area 3						
EC 0-30cm (µS cm^{-1})	n/s	**-0.51 (0.05)**	**-0.69 (0.003)**	**-0.51 (0.04)**	**-0.71 (0.002)**	n/s
EC 30-60cm (µS cm^{-1})	n/s	n/s	n/s	n/s	n/s	n/s

† AEM= anion exchange membrane
‡ Value in brackets indicates *p* -value
* Significant correlation at $p < 0.05$.

5 Summary and Conclusions

The 2012 growing season was the baseline year of this study. Its purpose was to set up transects that would receive uniform crop management that would provide data upon which to analyze the relationships between crop yield, protein, and soil properties. This in turn was used to develop a variable rate N application prescription for 2013 that was evaluated in side by side comparisons of variable rate management zones versus constant N rate strips set up along the transects. Thus, the value in the 2013 data comes from being able to compare yield and protein values between the varied and constant N rate treatments, and to compare them to 2012 results. Statistical comparison of yield and protein among variable and constant N rate treatments across the transects is difficult and must be interpreted carefully, since each landscape point is unique, differing from others because of elevation, soil properties, and environment. This results in inherently large variability in soil and plant parameters, and the need for a treatment to produce a very large impact to result in a significant result.

Precision farming is a broad term encompassing many different practices. It was defined by Sylvester-Bradley et al. (1999, pp. 1) as “the process of adjusting husbandry practices within a field according to measured spatial variability.” Site specific crop management of nutrients is predicated on the ability to exploit identifiable spatial variability in a field to enable better management practices (Shaner et al., 2008). However, an inherent weakness of any variable rate crop nutrition (e.g., N), program is complicated by uncontrolled factors that can overwhelm the otherwise predictable site characteristics (Pennock et al., 2001). The complex contribution of many different soil and environmental factors to create a variable yield and often unpredictable response to applied fertilizer N at each transect point was also evident in the current study. A key component of a site specific nutrient management program is the method by which separate zones are delineated. Several methods are often combined in order to increase the confidence that separate zones are truly different and will respond positively to different rates of a given nutrient. These include electrical conductivity (EC) maps, soil survey maps, and combine harvester generated yield maps. However, special advisers are often needed to aid farmers in interpreting these maps and developing fertilizer plans. A lack of knowledgeable consultants and the cost of describing and interpreting zones are significant impediments to widespread adoption of site specific nutrient management. This is compounded by poor or inadequate communication between scientists, agronomic consultants, technology developers, sales people and the farmer. Site specific nutrient management must be the product of multi-disciplinary communication and development, without which it will not meet expectations (Betteridge et al., 2008). In this study, technology was used that was capable of applying variable rates of N fertilizer. This technology has a steep learning curve. Appendix A provides additional details.

The relationship between wheat yield and protein has been studied for a long time (Terman et al., 1969) because protein is a primary quality parameter, and the significance of landscape has also long been identified (Rennie and Clayton, 1960; Spratt and McIver, 1972). However, besides being a quality parameter, the value of protein measurements, when combined with yield measurements, lies in the fact that it is the juncture where it is possible to assess the adequacy of N fertility. In hard red spring wheat, the protein content of 13.5% is used as the critical plateau point indicating that enough N was available to maximize yield, as this is the point where further additions of N fertilizer go mainly to increasing protein rather than yield. In canola there is an inverse relationship between protein and oil content, and likewise in peas there is an inverse relationship between protein and starch content. However, no studies have been found to date that extend this research in these crops to ascertain the protein content that indicates yield maximized. In the current study, for canola this protein content appears to be around 17%, compared to hard red spring wheat which was determined to be around 13.5%.

There has been interest in protein concentration, particularly in wheat, because of its potential to aid in precision agriculture applications (Long et al., 2000; Reyns et al., 2000; Manning et al., 2001; Selles and Zentner, 2001; Walley et al., 2001; Morari et al., 2013). This is because new technology has made it possible to measure protein content potentially on-the-go during the harvesting operation (Long et al., 2008; Long and Rosenthal, 2005). In this way a map may be generated, along with yield, and protein and yield variability may be seen at a glance over the field. Areas of low protein may indicate that N fertility was inadequate, whereas areas of high protein indicate that either N fertility was adequate or there was another yield limitation. Therefore, it would seem possible to gain insight into the effectiveness of a particular fertility regime without needing to perform intensive and expensive soil testing.

Variable rate technology is becoming increasingly common for two reasons: 1) potential gains in economic efficiencies of applied fertilizer and 2) potential improvement in environmental safety by reducing over-application of N fertilizers. However, in the literature most studies document no significant yield or environmental gains from variable rate N application when applied over a landscape (Long et al., 2000; Boyer et al., 2001).

In the current study, apparent yield gains and/or improved N efficiencies (same yield with reduced N) at some transect points from the variable N rates were observed, but were equally offset by yield losses and reduced efficiency (same or lower yield with higher N) so that overall, the net benefit of the variable rate N prescription was negligible. However, these results may be beneficial to future research in that it may help to improve methodology to make an N prescription map based on protein of the previous crop.

Adequate soil moisture in both growing seasons of this study was fortunate as this was an ideal opportunity to study the effects of N fertilization and soil properties without the typical moisture limitation observed in the Brown soil zone. This is because lack of moisture is typically the first limiting factor to crop yield in the semiarid prairies, and when this occurs grain protein concentration may not provide a reliable N-sufficiency index for the crop (Selles and Zentner, 2001). However, these authors also found that when moisture is non-limiting, low and medium grain protein concentrations mean that N supply was inadequate, which is what we found in this study. What these authors also found, which was similar to results of the current study, is that high grain protein concentrations (above the critical level) are not so easily interpreted because while it may indicate adequate N fertility, there may have been localized moisture stress, or another unidentified stress limiting photosynthetic production.

There is a broad body of literature on variable rate N application with which the results of this study agree, which is that no significant benefits between varied and constant N rates are generally noted (Walley et al., 2001; James and Godwin, 2003; Welsh et al., 2003). Though theoretically yield gains should be possible through a variable rate N application program, actual yield improvements on the farm have been difficult to document (Ferguson et al., 1999). This is a reflection of knowledge gaps of temporal and spatial variation in soil and environmental controls and how this affects response to applied N (Cassman et al., 2002). Walley et al. (2001) in a study at Hepburn SK, Canada, reported that a variable rate N prescription based on slope position and historic yield was not feasible because of difficulty predicting grain yield response to applied N. Spring available moisture was identified as a controlling factor in the landscape on yield and protein, however wheat protein did not exhibit consistent differences with slope position. Similarly, James and Godwin (2003) reported that variable rate N application based on three years of historic yield data in barley at Cambridgeshire, UK, were unable to yield significantly and economically greater than constant N rates. Year to year weather variability was identified as limiting the ability to confidently predict yield response to variable rate N application. Welsh et al. (2003) also reported that previous yield maps were insufficient to prepare accurate variable rate N prescriptions. In a split N application study on wheat over three years at Bedforshire, UK, aerial photography was used to generate a crop density map via normalized difference vegetation index (NDVI). The authors reported that the yield from the variable rate prescription based on the NDVI map was 460 kg ha^{-1} greater than the constant N rate. This demonstrated the potential utility in being able to assess crop variability and N deficiency during the growing season and being able to address this through variable N applications made post-emergent in crop. This is a major limitation of placing all the N fertilizer at time of seeding as was done in the research described in this thesis.

This study has identified soil OC and EC as having a significant impact on yield and protein and therefore of value in potential predicting crop response to applied N. Soil assessment of available N was significant only for anion exchange membranes (AEM) and only for one crop. Yield alone from previous crops does not provide enough information to differentiate potential and actual yield response for different zones, but it is also important to simplify as much as possible the data sources being used to create zones, otherwise it is difficult to manage different zones with any confidence (Taylor et al., 2007).

Given all the limitation described previously, protein combined with yield provided some enhanced resolution. It allowed for the identification of areas, such as low and medium protein combined with medium and high yields that fairly consistently responded positively to increased rates of added N above the typical constant rate. High protein combined with medium and low yield also was sometimes useful in identifying areas in which N rate could be reduced without major yield and/or protein penalty.

5.1 Future Research Considerations

This experiment was initiated as a proof of concept study that included unique consideration of landscape soil properties on yield and protein content, management zone delineation, and rotation between different crops rather than a single crop. Only one study was found in the literature that included a crop rotation (Delin, 2004), while most other studies involved monoculture wheat grown on wheat (Long et al., 2000) or canola grown on canola (Pennock et al., 2001). Several future research considerations may be drawn from this study regarding variable rate project design and rate selection. The study design described in this thesis included a benchmark season that was subsequently split in equal strips to incorporate the variable and constant N rates. For the purposes of this study, this was a sufficient means to assess, side-by-side, the effect of the varied N rates versus the constant rate. However, for a long term study this may not be the ideal design. This is because in the second growing season after the benchmark year, the varied N rates are being applied over top of varied N rates from the previous season. The constant rate may also need to be adjusted in the next growing season depending on environmental conditions such as moisture. The constant N rate may also need to be adjusted based on the variable N rates that are derived for the next growing season. This is because if the variable N rates on average are greater than the control, it is difficult to compare to the original constant rate. For variable rate N fertilization to be cost effective, its value must be determined to be greater than simply applying greater blanket N rates. Thus, a future study could be based on Long et al. (2000) and include five N strategy strips: 1) original constant N rate to enable comparison to when the study started- this strip would receive this rate every year; 2) a constant N rate of the lowest variable N rate to represent the low end of N application rate; 3) would receive variable N rates based on the yield and protein of the previous crop; 4) a constant N rate based on the average of the current variable N rates; 5) a constant N rate of the greatest variable N rate: this represents the scenario where the farmer does not invest in variable rate technology, and simply increases N rates to compensate. Ideally, this set of strips would be replicated across a field, and the underlying landscape properties would be identified.

The results of this thesis work suggest ways to improve the selection of variable N rates based on protein and yield. There were no significant differences between the mean yields of the varied N rate and constant N rate for each field area, but ability to detect significant differences is limited by inherently high variation in productivity from one transet point to the next. While the results showed some trends to greater yields and protein in plots with increased N application, these were offset by reduction in yield and protein in plots that received decreased N application (Table 5.1).

Table 5.1. Mean impact of VR N strategy on yield and protein vs constant N rate.

VR Strategy		Canola on Wheat	Wheat on Canola	Wheat on Peas
Decrease N Rate	Yield (kg ha^{-1})	-99	-336	-67
	Protein (%)	-1.2	-0.5	0.1
Increase N Rate	Yield (kg ha^{-1})	395	-336	471
	Protein (%)	1.0	0.3	0.3

Overall, there was no net large, consistently positive benefit to variable rate N application with approximately the same amount of N added across the landscape as a typical constant rate for the area in this study. However, these results may guide future research work relating to variable N fertilization. Instead of attempting to reduce N rates, it may be more beneficial to keep N rates constant and look for field areas that may benefit from additional N. The results from this study indicate that field areas of low and medium protein from the previous crop, wheat and canola, were most consistent as identifiers that the subsequent crop will benefit from additional N. Soil OC, EC, AEM NO_3^--N and extractable K were occasionally significantly related to yield and protein. Areas of high protein were thought have sufficient soil N and that N rates could be reduced. However, this was not the case. Therefore, areas of high protein may best receive the constant N rate as insurance (Fig 5.1).

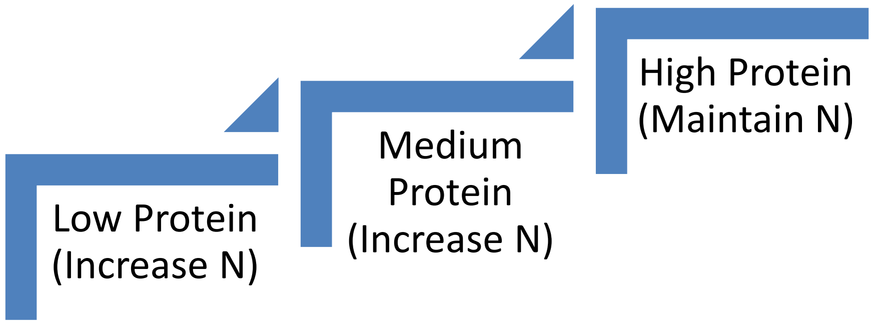

Fig. 5.1. N strategy for subsequent crop based on protein content of current crop.

A potential problem with using protein content to delineate management zones, is that the magnitude of N increase is difficult to ascertain. Therefore, in future research, it would be beneficial to study the possibility of using protein and yield maps to identify management zones, and to use those zones to direct soil sampling. This would enable a greater degree of precision in selecting variable N rates.

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7 APPENDICES

7.1 Appendix A: Remote sensing field operations

This study was made possible by the use of modern farming technology for seeding crops and applying N in varying rates along each transect. From personal experience with this technology it is easy to understand why its adoption by farmers may be limited as it has a significant learning curve. The basis for the variable rate fertilizer prescriptions was the yield and protein obtained from hand sampling the transect points, along with the yield map obtained from the combine (Case IH 8120) in the fall of 2012. This map was then uploaded into a software program called SMS Advanced v13.0 from AgLeader (2013). Then the georeferenced transect points were located on the yield map, drawing the prescription zones, and setting the rates for each zone. Once this was accomplished, each prescription map was exported to a memory stick and uploaded to the monitor (Case IH Pro 700) in the cab of the tractor (Case IH 600) which controlled the variable rate drive on the air cart (Case IH 3450). Once all systems and steps were familiar, the variable rate application worked well, and watching the N rates changing as seeding progressed was impressive.

Another technology used concurrently in this study was an on-the-go protein sensor manufactured by Zeltex. This has been used in several other studies as well. Technical problems encountered in fall 2012 prevented a useable protein map of the field from being produced. Technical difficulties were again encountered in fall 2013, but not until a portion of the wheat crop on canola had been harvested, so a partial map of protein content of the wheat could be created for the field (Fig. A.1). Recent research in Australia (Taylor et al., 2013; Taylor et al., 2007) has described yield and protein mapping on the combine and several ways to interpret the data. The methods these authors used are similar to the ones used in this study in that two to four management zones, and that two to three classes of protein are likely the most practical to be used in the prescription development.

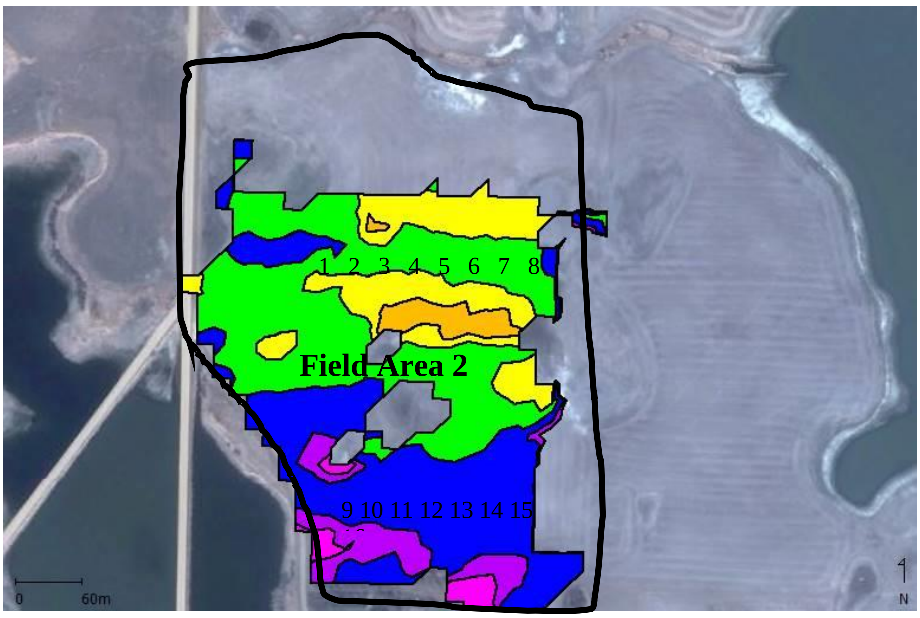

Figure A.7.1. Protein map of wheat grown in 2013 on canola stubble. Purple and blue represent areas of high protein (>13.5%) and green and yellow areas represent areas of low protein (<13.5%). Transect points 1 through 16 are indicated numerically.

7.2 Appendix B: Landscape Position Properties

Table B.7.1. Spring wheat soil and landscape properties including organic carbon, pH, and electrical conductivity. Fall 2012

Transect Position Description	Elevation† (m)	OC‡ 0-30cm (%)	OC 30-60cm (%)	pH 0-30cm	pH 30-60cm	EC§ 0-30cm ($dS\ m^{-1}$)	EC 30-60cm ($dS\ m^{-1}$)
W1 Gleysol	606.3	2.1	0.9	7.8	8.1	0.4	0.4
W2 Toe-Slope	606.6	1.7	0.7	7.3	7.6	0.7	6.0
W3 Lower-Mid	606.9	1.6	0.7	8.1	8.5	0.3	0.4
W4 Mid-Slope	607.8	1.3	0.6	7.8	8.2	0.1	0.2
W5 Rego-Knoll	608.7	0.7	0.4	8.2	8.4	0.2	0.2
W6 Rego-Knoll	609.0	0.7	0.5	8.2	8.4	0.2	0.3
W7 Mid-Slope	607.5	1.1	0.6	8.1	8.3	0.3	0.5
W8 Saline Toe-Slope Slough	605.0	0.5	1.3	8.1	7.8	5.1	2.4
W9 Level	609.9	1.3	1.1	7.7	7.6	0.1	0.8
W10 Toe-Slope	609.9	1.1	0.8	8.0	7.9	0.4	0.4
W11 Toe-Slope	609.6	1.7	0.7	7.8	7.2	0.3	0.1
W12 Shoulder	610.2	1.5	0.5	8.1	7.9	0.4	4.4
W13 Mid-Slope	609.3	1.3	0.8	7.6	7.8	0.4	4.0
W14 Foot-Slope	609.0	1.3	0.4	8.2	8.0	0.5	2.2
W15 Up-Level	607.8	1.2	0.6	8.1	8.0	0.7	3.9
W16 Toe-Slope Slough	605.6	1.3	0.5	8.0	8.2	8.2	6.1

† Elevation measured from GPS
‡ Organic carbon measured by dry combustion (LECO)
§ Electrical conductivity

Table B.7.2. Spring wheat soil nutrient status: nitrate-N, modified Kelowna P and K, and PRS available N and P. Fall 2012.

Transect Position Description	NO_3^--N† 0-30cm (kg ha^{-1})	NO_3^--N 30-60cm (kg ha^{-1})	P‡ 0-30cm (kg ha^{-1})	K‡ 0-30cm (kg ha^{-1})	AEM§ NO_3^--N 0-30cm	AEM P 0-30cm
W1 Gleysol	7.7	5.2	43.8	2851	7.1	0.5
W2 Toe-Slope	14.9	18.7	18.2	1429	9.5	0.1
W3 Lower-Mid	7.7	6.6	17.0	1202	6.5	0.2
W4 Mid-Slope	7.5	3.7	16.8	665	6.2	0.2
W5 Rego-Knoll	5.5	4.4	15.8	403	4.0	0.1
W6 Rego-Knoll	3.0	3.0	19.7	569	2.4	0.1
W7 Mid-Slope	7.2	13.0	16.2	1222	6.0	0.2
W8 Saline Toe-Slope Slough	5.1	8.2	19.6	612	2.1	0.1
W9 Level	3.8	2.2	27.8	1059	4.4	0.3
W10 Toe-Slope	4.1	1.6	50.4	1751	3.8	0.6
W11 Toe-Slope	4.9	1.0	28.2	1583	5.8	0.3
W12 Shoulder	6.2	2.6	38.7	1646	6.3	0.3
W13 Mid-Slope	8.7	3.4	33.0	1320	7.3	0.4
W14 Foot-Slope	4.1	1.9	31.6	1489	5.8	0.2
W15 Up-Level	8.2	4.1	23.6	1368	7.9	0.1
W16 Toe-Slope Slough	9.9	3.7	54.5	1276	4.3	0.1

† Nitrate-N measured by 2M KCl extraction

‡ P and K measured by modified Kelowna method

§ N and P supply rate measured by anion exchange membranes

Table B.7.3. Spring wheat yield, protein and plant nutrient status. Fall 2012.

	Total Biomass	Grain Biomass	Grain N	Grain P	Straw N	Straw P	Grain Protein
Transect Position Description	kg ha^{-1}						Protein (%)
W1 Gleysol	6850	2554	64.7	9.8	18.7	5.0	14.4
W2 Toe-Slope	5880	2307	51.0	8.3	7.4	2.4	12.6
W3 Lower-Mid	5490	2099	51.1	8.5	9.2	3.1	13.9
W4 Mid-Slope	4785	1942	48.2	7.4	6.8	2.4	14.2
W5 Rego-Knoll	3325	1190	30.0	5.0	7.8	1.9	14.4
W6 Rego-Knoll	3180	1254	29.4	5.0	6.3	1.8	13.5
W7 Mid-Slope	5915	2110	53.0	8.6	11.2	3.3	14.3
W8 Saline Toe-Slope Slough	2100	882	16.2	3.0	4.6	1.4	10.5
W9 Level	5525	1994	43.1	7.6	9.6	2.9	12.3
W10 Toe-Slope	5115	2002	48.3	8.8	9.6	2.8	13.7
W11 Toe-Slope	5190	1631	36.5	6.2	11.3	3.2	12.8
W12 Shoulder	4650	1787	39.4	7.4	6.1	2.3	12.5
W13 Mid-Slope	5810	2318	56.0	8.3	13.2	3.0	13.8
W14 Foot-Slope	5700	2177	51.2	8.5	10.9	2.6	13.4
W15 Up-Level	5900	2038	44.5	6.8	11.6	3.2	12.5
W16 Toe-Slope Slough	2870	1328	28.9	4.6	4.2	2.4	12.4

Table B.7.4. Canola soil and landscape properties including organic carbon, pH, and electrical conductivity. Fall 2012.

Transect Position Description	Elevation† (m)	OC‡ 0-30cm (%)	OC 30-60cm (%)	pH 0-30cm	pH 30-60cm	EC§ 0-30cm (dS m^{-1})	EC 30-60cm (dS m^{-1})
C1 Toe-Slope	609.9	2.3	0.8	8.0	8.0	0.2	0.9
C2 Fertile Depression	610.5	1.4	0.6	8.0	7.9	1.1	4.2
C3 Mid-Slope Gravel	610.2	1.8	1.6	8.3	8.3	0.3	0.1
C4 Eroded Knoll	610.2	1.1	0.4	8.3	8.2	0.3	0.4
C5 Sandy Eroded Knoll	610.2	1.0	0.6	8.3	8.6	0.3	0.4
C6 Mid-Slope	607.5	1.5	0.8	7.8	8.2	0.3	1.4
C7 Saline Depression	606.6	1.3	0.7	7.6	7.8	8.8	5.9
C8 Depression	606.3	1.3	0.7	7.6	7.8	8.3	5.4
C9 Saline Solenetz BNT Depression	610.5	1.6	0.5	7.9	7.8	9.2	7.2
C10 Lower level	611.7	1.1	0.4	7.9	8.0	5.8	6.3
C11 Upper level	611.7	1.3	0.4	8.3	7.8	0.5	4.5
C12 Mid-Level	612.0	0.8	0.4	8.0	8.2	5.6	3.5
C13 Foot-Slope	611.4	1.5	0.5	8.0	8.2	5.6	0.4
C14 Depresssion	611.4	1.1	0.6	7.3	7.8	0.3	1.0
C15 Mid-Slope	612.3	1.5	0.7	8.0	8.4	4.2	5.1
C16 Knoll	613.0	0.9	0.6	8.2	8.4	0.4	0.3

† Elevation measured from GPS

‡ Organic carbon measured by dry combustion (LECO)

§ Electrical conductivity

Table B.7.5. Canola soil nutrient status: nitrate-N, modified Kelowna P and K, and PRS available N and P. Fall 2012.

Transect Position Description	NO_3^--N† 0-30cm (kg ha^{-1})	NO_3^--N 30-60cm (kg ha^{-1})	P‡ 0-30cm (kg ha^{-1})	K‡ 0-30cm (kg ha^{-1})	AEM§ NO_3^--N 0-30cm	AEM P 0-30cm
C1 Toe-Slope	9.7	3.6	39.9	1613	7.3	0.2
C2 Fertile Depression	12.3	5.5	17.8	931	7.4	0.1
C3 Mid-Slope Gravel	8.3	3.2	21.0	586	5.3	0.3
C4 Eroded Knoll	5.9	2.6	20.4	605	4.7	0.2
C5 Sandy Eroded Knoll	8.5	4.9	13.9	715	6.8	0.2
C6 Mid-Slope	16.2	5.5	29.3	1383	11.2	0.4
C7 Saline Depression	7.9	2.7	112.8	2733	4.4	0.1
C8 Depression	17.8	7.2	57.5	2515	7.7	0.1
C9 Saline Solenetz BNT Depression	198.0	102.4	91.0	1568	53.2	0.1
C10 Lower level	8.2	3.8	30.5	1041	3.9	0.1
C11 Upper level	9.9	3.2	29.3	1217	7.9	0.2
C12 Mid-Level	6.1	2.2	32.1	798	4.1	0.1
C13 Foot-Slope	11.5	10.1	33.9	1354	5.8	0.1
C14 Depresssion	9.2	3.1	53.2	1698	7.3	0.6
C15 Mid-Slope	21.7	19.1	30.0	1280	7.4	0.1
C16 Knoll	6.5	3.1	15.2	703	4.1	0.2

† Nitrate-N measured by 2M KCl extraction
‡ P and K measured by modified Kelowna method
§ N and P supply rate measured by anion exchange membranes

Table B.7.6. Canola yield, protein and plant nutrient status. Fall 2012.

	Total Biomass	Grain Biomass	Grain N	Grain P	Straw N	Straw P	Grain Protein
Transect Position Description	kg ha^{-1}						(%)
C1 Toe-Slope	7150	2032	65.0	10.5	35.4	3.8	18.1
C2 Fertile Depression	7200	2342	67.1	12.7	15.8	2.8	16.4
C3 Mid-Slope Gravel	4705	1532	48.7	8.1	11.9	1.7	17.9
C4 Eroded Knoll	3990	1143	30.3	6.1	8.8	1.8	15.1
C5 Sandy Eroded Knoll	6205	1715	44.7	10.1	12.9	3.4	14.9
C6 Mid-Slope	6990	2047	62.2	11.3	12.6	2.5	17.4
C7 Saline Depression	3780	1246	41.0	7.5	19.0	2.8	19.4
C8 Depression	5605	1993	61.3	11.4	15.9	2.6	17.5
C9 Saline Solenetz BNT Depression	4540	1559	56.4	8.4	23.0	2.4	20.6
C10 Lower level	6180	2010	54.0	10.5	11.5	2.4	15.4
C11 Upper level	4720	1289	33.6	7.1	5.6	2.7	14.9
C12 Mid-Level	6985	2190	55.9	11.9	10.4	2.9	14.2
C13 Foot-Slope	7665	2234	67.4	11.8	26.1	3.7	17.2
C14 Depresssion	7995	2263	68.2	13.3	24.8	4.6	17.1
C15 Mid-Slope	7540	2331	73.6	11.7	25.7	3.7	17.9
C16 Knoll	5780	1630	44.0	9.1	11.1	2.6	15.4

Table B.7.7. Pea soil and landscape properties including organic carbon, pH, and electrical conductivity. Fall 2012.

Transect Position Description	Elevation† (m)	OC‡ 0-30cm (%)	OC 30-60cm (%)	pH 0-30cm	pH 30-60cm	EC§ 0-30cm (dS m^{-1})	EC 30-60cm (dS m^{-1})
P1 Shoulder	613.0	2.6	1.3	7.9	6.6	0.3	0.1
P2 Mid-Slope	612.0	1.9	1.3	7.9	8.1	0.4	0.4
P3 Toe-Slope	610.5	1.6	0.7	7.6	7.7	0.5	6.8
P4 Saline Depression	609.6	0.9	0.5	7.8	7.9	9.0	7.0
P5 Level	609.3	1.5	0.8	7.8	7.9	6.1	5.0
P6 Wet	608.4	2.3	0.7	7.7	8.1	0.8	0.9
P7 Mid-Slope	609.0	1.3	0.7	8.1	8.0	2.8	3.5
P8 Upper Level	609.0	1.1	0.6	8.2	8.2	0.4	2.1
P9 Level	608.4	1.5	0.4	8.0	7.9	0.3	4.5
P10 Upper-Level	608.4	1.4	0.5	8.3	8.1	1.4	5.5
P11 Mid	607.8	1.2	0.7	8.2	8.2	1.7	3.7
P12 Toe-Slope Depression	606.9	1.5	0.6	7.8	7.9	3.0	9.4
P13 Saline Depression	607.2	1.4	0.8	7.8	7.7	11.1	11.9
P14 Lower	606.6	1.8	2.8	7.8	8.0	0.4	5.2
P15 Reclaimed RR Line	607.2	1.6	1.6	8.2	8.2	0.3	0.4
P16 Upper-Slope	606.9	1.4	0.7	8.0	8.2	0.2	0.3

† Elevation measured from GPS
‡ Organic carbon measured by dry combustion (LECO)
§ Electrical conductivity

Table B.7.8. Pea soil nutrient status: nitrate-N, modified Kelowna P and K, and PRS available N and P. Fall 2012.

Transect Position Description	NO_3^--N† 0-30cm (kg ha^{-1})	NO_3^--N 30-60cm (kg ha^{-1})	P‡ 0-30cm (kg ha^{-1})	K‡ 0-30cm (kg ha^{-1})	AEM§ NO_3^--N 0-30cm	AEM P 0-30cm
P1 Shoulder	6.3	1.8	60.0	1505	7.3	0.8
P2 Mid-Slope	12.7	9.4	13.7	1247	9.9	0.3
P3 Toe-Slope	10.8	9.0	33.6	750	9.3	0.5
P4 Saline Depression	3.0	1.6	27.1	1066	1.3	0.1
P5 Level	5.0	4.1	17.3	1295	3.4	0.1
P6 Wet	11.8	3.2	63.4	2452	10.1	0.4
P7 Mid-Slope	12.7	3.4	19.3	1448	9.5	0.1
P8 Upper Level	12.6	9.5	15.1	971	2.4	0.2
P9 Level	21.5	9.4	37.9	1404	12.9	0.5
P10 Upper-Level	13.7	11.8	18.2	1039	9.0	0.1
P11 Mid	10.7	5.7	18.8	946	6.2	0.1
P12 Toe-Slope Depression	5.0	1.6	61.9	960	4.0	0.1
P13 Saline Depression	4.6	1.1	108.3	1301	2.7	0.1
P14 Lower	17.7	22.6	54.1	2136	11.7	1.0
P15 Reclaimed RR Line	20.3	19.7	23.1	1482	11.8	0.3
P16 Upper-Slope	14.4	6.2	15.2	1269	9.3	0.2

† Nitrate-N measured by 2M KCl extraction
‡ P and K measured by modified Kelowna method
§ N and P supply rate measured by anion exchange membranes

Table B.7.9. Pea yield, protein and plant nutrient status. Fall 2012.

Transect Position Description	Total Biomass	Grain Biomass	Grain N	Grain P	Straw N	Straw P	Grain Protein
	kg ha^{-1}						(%)
P1 Shoulder	5255	2871	85.5	10.4	24.0	1.9	17.0
P2 Mid-Slope	5140	2820	79.6	8.2	21.2	1.5	16.2
P3 Toe-Slope	5510	3004	75.8	8.6	23.4	1.7	14.5
P4 Saline Depression	3000	1507	43.1	4.8	15.0	1.1	16.3
P5 Level	2175	839	25.1	2.6	14.2	1.0	17.1
P6 Wet	4825	1784	54.9	7.0	32.7	2.6	17.2
P7 Mid-Slope	4265	2079	60.8	4.9	15.9	1.2	16.7
P8 Upper Level	4805	2506	69.5	6.9	16.0	1.4	15.8
P9 Level	4255	2173	62.9	7.7	22.4	1.7	16.6
P10 Upper-Level	3860	2178	65.0	6.4	14.7	1.2	17.0
P11 Mid	6080	3122	84.0	8.2	23.0	1.9	15.2
P12 Toe-Slope Depression	2615	1256	36.1	4.3	13.2	1.2	16.5
P13 Saline Depression	2785	1465	41.8	4.7	13.0	1.1	16.3
P14 Lower	5665	2640	81.6	10.3	28.9	2.9	17.7
P15 Reclaimed RR Line	6005	2654	80.2	8.6	28.3	2.3	17.2
P16 Upper-Slope	4045	2264	63.9	6.6	13.5	1.1	16.1

7.3 Appendix C: Protein and Yield Relationships in 2013

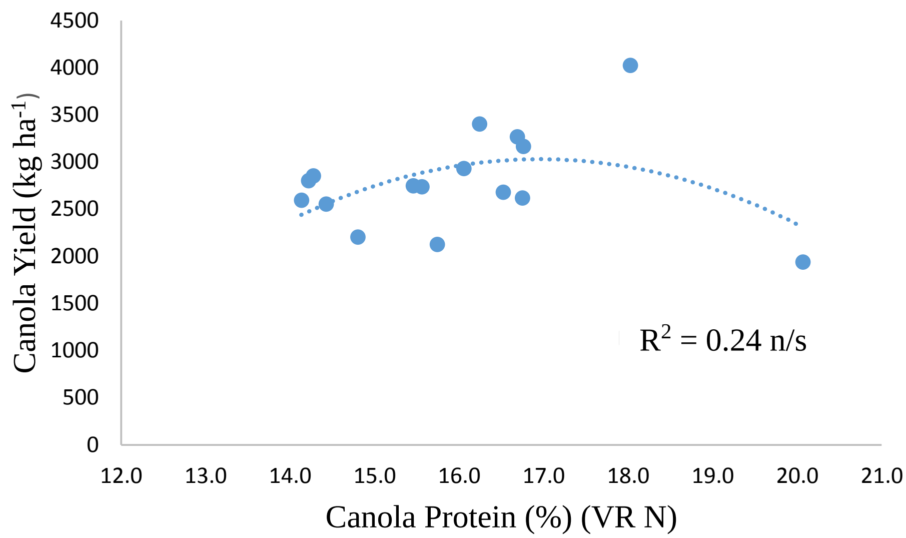

Figure C.7.2. Relationship between canola yield and protein grown on wheat stubble in the VR N rate transects in fall 2013. n/s indicates no significance at $p < 0.05$.

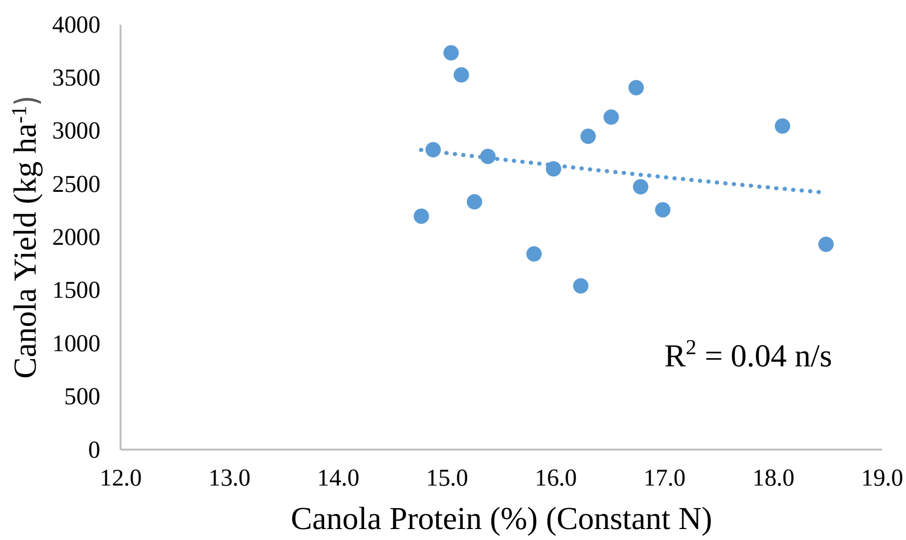

Figure C.7.3. Relationship between canola yield and protein grown on wheat stubble in the constant N rate transects in fall 2013. n/s indicates no significance at $p < 0.05$.

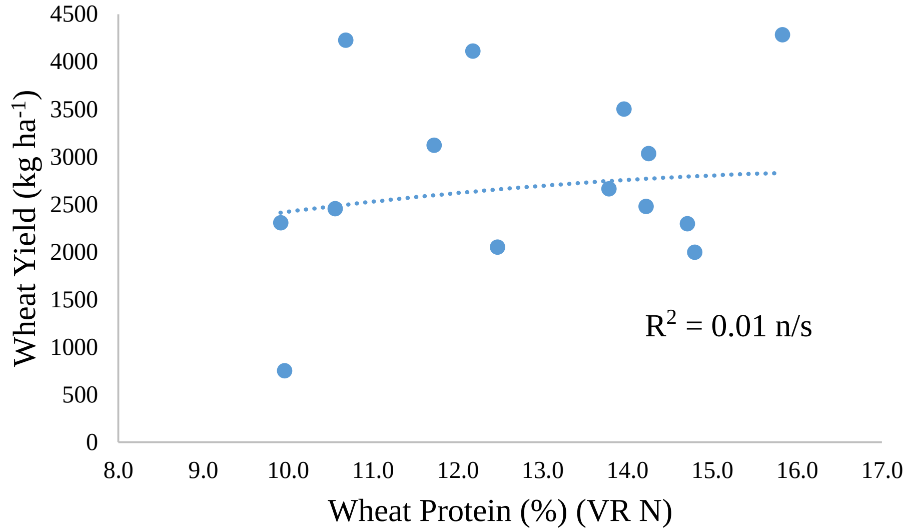

Figure C.7.4. Relationship between wheat yield and protein grown on canola stubble in the VR N transects in fall 2013. n/s indicates no significance at $p < 0.05$.

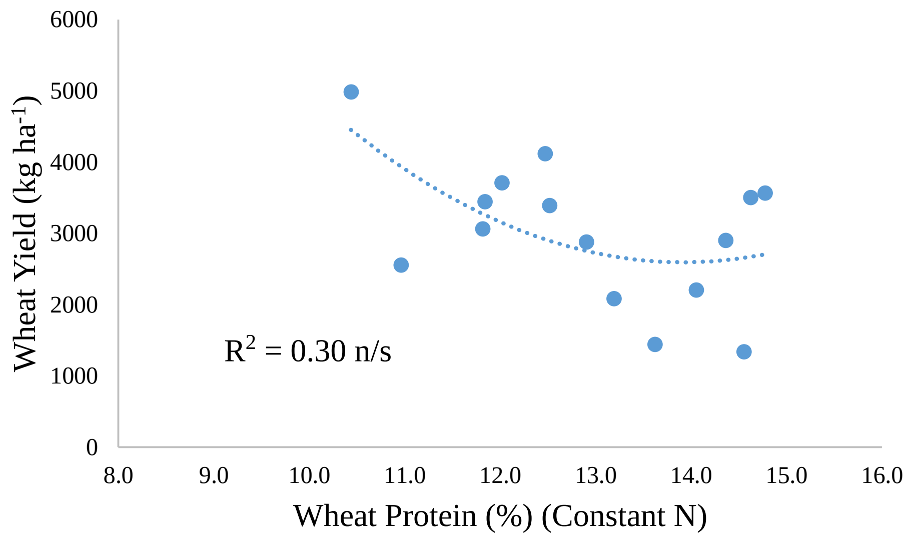

Figure C.7.5. Relationship between wheat yield and protein grown on canola stubble in the constant N transects in fall 2013. n/s indicates no significance at $p < 0.05$.

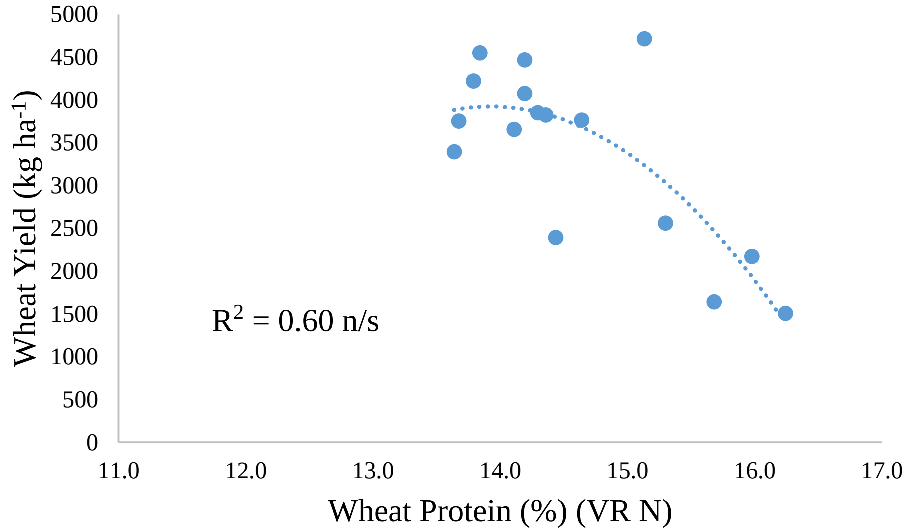

Figure C.7.6. Relationship between wheat yield and protein grown on pea stubble in the VR N transects in fall 2013. n/s indicates no significant at $p < 0.05$.

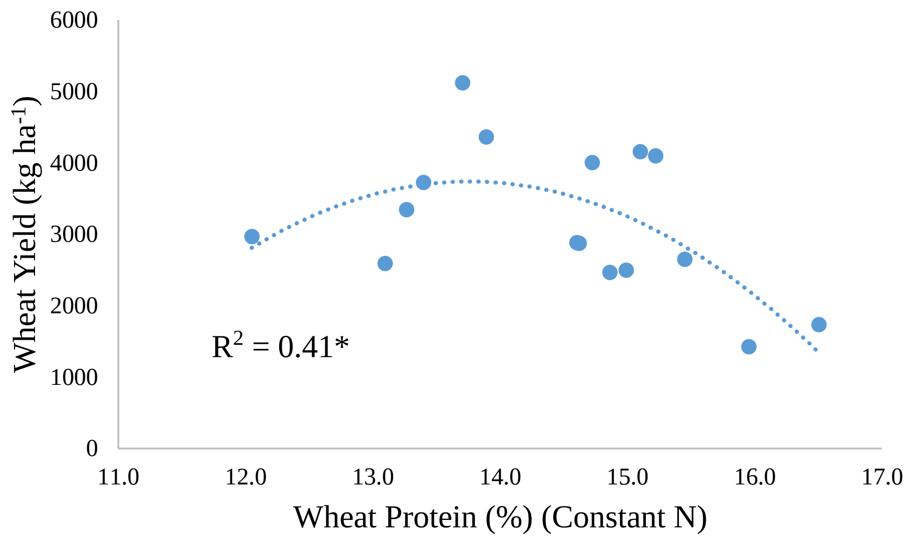

Figure C.7.7. Relationship between wheat yield and protein grown on pea stubble in the constant N transects in fall 2013. * indicates significant at $p < 0.05$.