VARIABILITY IN CWRS WHEAT YIELD RESPONSE TO APPLIED NITROGEN IN MANITOBA SOIL LANDSCAPES

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment for the Degree of

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ABSTRACT

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Increasing economical and environmental pressures has sparked a great deal of interest in precision agriculture. Thus, a great deal of research has been initiated in order to gain a greater understanding of how existing technologies such as global positioning systems, geographic information systems, and equipment with variable rate capabilities can be used to manage agricultural amendments at a site specific level.

In 1996 and 1997, small plot trials were established at six sites in Southern Manitoba. Four of these sites were located on glacial till landscapes of the Newdale Association and the other two were located on lacustrine landscapes of the Red River Association. A variety of soil and crop parameters were examined throughout the study. Replicated small plots with fertilizer N rates ranging from 0 to 200 kg N ha^{-1} were established in various positions in the landscape based on relative elevation, slope morphology, and slope aspect. The objective of the study was to determine if there were any significant differences in yield response to applied N in Canada Western Red Spring wheat in these landscapes.

In the glacial till landscapes, a number of the soil parameters were found to be strongly associated with landscape position. Among these parameters, electrical conductivity, depth of A horizon, solum depth, NO_3^--N, volumetric water content, and growing season N uptake tended to demonstrate the most consistent differences among landscape positions. However, yield and grain protein responses to applied nitrogen were extremely inconsistent throughout the study in these landscapes.

The soil parameters studied in the lacustrine landscapes demonstrated very different trends than those observed at the glacial till landscapes. Significant differences of the various soil properties studied were seldomly observed among landscape positions at these sites. However, the yield potential and yield response data was much more consistent and predictable.

The use of landscape position as the only variable in determining differences in yield responses to applied N proved to be ineffective in the glacial till landscapes studied. In these landscapes, more comprehensive models with various other soil parameters may need to be developed in order to make variable rate nitrogen decisions. However, the use of landscape positions to make variable rate nitrogen decisions in lacustrine landscapes may be more promising.

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LIST OF ABBREVIATIONS

(in order of appearance in text)

CWRS: Canada Western Red Spring

SCZ: Soil Climatic Zone

CWAD: Canada Western Amber Durum

NUE: Nitrogen Use Efficiency

Δplant N/ΔN fertilizer: change in plant nitrogen content/change in nitrogen fertilizer applied

UNR: Unit Nitrogen Requirement

VRF: Variable Rate Fertilization

CSSC: Canadian System of Soil Classification

GLR.BLC: Gleyed Rego Black Chernozem

O.BLC: Orthic Black Chernozem

CA.BLC: Calcareous Black Chernozem

R.BLC: Rego Black Chernozem

GL.BLC: Gleyed Black Chernozem

GLCU.HR: Gleyed Cumulic Humic Regosol

GL.HV: Gleyed Humic Vertisol

GLC.HV: Gleysolic Humic Vertisol

g ai: grams of active ingredient

vol.: volumetric

prec.: precipitation

E.C.: Electrical Conductivity

1. INTRODUCTION

Recent advances and interest in variable rate fertilizer technology has sparked a great deal of research relating to within-field variability. In a number of instances, variability in soil properties has been reported to be intimately correlated to the soil-landscape (Brubaker et al. 1993, Hanna et al. 1982, Malo et al. 1974, Moore et al. 1993, Moulin et al. 1994, Pan and Hopkins 1991, Pennock and de Jong 1987, Pennock and de Jong 1990, Verity and Anderson 1990). Many of these properties are also known to significantly influence crop yield and quality factors. As such, researchers (Franzen et al. 1997, Beckie et al. 1997) have proposed a focus on landscaped-based approaches to variable rate fertilizer applications. Unfortunately, no single approach that is consistently agronomically and economically viable has yet been found.

Although it is recognized that systematic variability within the soil-landscape exists, there has been limited work done to determine how this variability affects crop response to fertilizer amendments. In most instances, variable rate fertilizer recommendations are made on the assumption that there is variability within the soil-landscape, but responses to applied fertilizer remain constant throughout the landscape.

In 1996 and 1997, a series of small plot trials were established in both the Newdale Glacial Till Plain and the Red River Lacustrine deposits of Southern Manitoba. The crop under investigation was Canada Western Red Spring (CWRS) wheat (*Triticum aestivum*). The objectives of the study were to:

1) Measure various soil properties and determine whether they were associated with landscape position.
2) Compare differences in CWRS wheat yield and grain protein response to applied nitrogen fertilizer among landscape positions.

The premise of this study is that if systematic differences in soil properties among landscape positions exist and these differences result in predictable differences in CWRS wheat yield and protein responses, more informed variable rate N fertilization decisions can be proposed for this crop.

2. LITERATURE REVIEW

2.1 Nitrogen

Nitrogen is an essential nutrient that is frequently deficient in crop production. Nitrogen is a key component of chlorophyll and enzymes essential for plant growth processes and of amino acids and proteins which are critical components of plant tissue, cell nuclei and protoplasm. Nitrogen is also essential for carbohydrate use within plants and stimulates root growth and development which is important in uptake of water and other nutrients (Brady 1990a).

Because plant available nitrogen is often deficient in the soil system, the application of inorganic fertilizers is a common practice in Western Canada and in much of the industrialized world. Numerous researchers have studied various soil nitrogen indices and crop response models to determine optimum fertilizer N rates with the objectives of maximizing fertilizer efficiency and/or profitability. To develop an appropriate N response model, researchers require reasonable estimates of the available soil residual N, mineralizable soil N, the efficiency of fertilizer N uptake, and crop N requirements. In a Manitoba study on the nitrogen fertilizer requirements of barley, Soper et al. (1971) reported that soil NO_3^--N to a depth of 61 cm was the best indicator of residual soil N available for uptake (r^2=0.84) by barley. Using a range of ammonium nitrate fertilizer rates of 22.4 - 134.4 kg N ha^{-1}, they also reported a fertilizer recovery efficiency averaging 52%. They were then able to construct N response curves based on target yields, soil NO_3^--N to 61 cm, and a fertilizer use efficiency of 52%. In a study comparing eight different soil indices, Gelderman et al. (1988) also reported that residual NO_3^--N was most strongly correlated to N uptake in wheat (r^2=0.58); however the correlation was not as strong as the study by Soper et al. (1970). In Gelderman et al.'s (1988) study, the 0-30 cm depth had a slightly higher correlation than the 0-60 cm depth.

Due to the complexity of the nitrogen cycle and the various nitrogen transformations occurring in the soil system, it is now evident that an indicator of soil NO_3^--N concentrations alone, or any other single indicator of soil nitrogen concentrations, is often not sufficient in predicting the N supplying power of a soil. Various studies also demonstrate that it is important to first establish the yield potential of the area in question and its associated limitations to yield. Many researchers have reported that salinity (Malo and Worcester 1975), fertility (Moss et al. 1981), texture (Oberle and Keeney 1990), occurrence of pests (Moulin and Beckie 1993), temperature (Partridge and Shaykewich 1972), and particularly available soil water (Henry 1991, Selles et al. 1992) all significantly influence nitrogen uptake. Various management practices such as crop rotation (Campbell et al. 1993), tillage regime (Huggins and Pan 1993, Malhi et al. 1996), and even cultivar selection (Anderson et al. 1991) can also influence the behavior of N in the soil. This is not surprising as it is thought that over 50 different factors affect crop growth and yield (Tisdale et al. 1985), without considering the various interactions between many of these factors. These studies suggest that fertilizer N recommendations cannot be accurately assessed by simple soil NO_3^--N tests alone. More comprehensive nitrogen response models which incorporate these factors must be developed. Traditional models for fertilizer N recommendations are based on the assumption that, within a broad region, most crop productivity factors are constant. They tend to overlook localized variability in soil and microclimate properties which affect yield and response to N supplies.

One of the most important confounding factors in nitrogen uptake is the amount of available soil moisture at a given point in time. This will be discussed at greater length in the following section.

2.2 Soil Water

Soil moisture is one of the most important factors in crop production. Water plays important roles in crop production as it is involved in nutrient uptake and transport, temperature regulation, photosynthetic activities, and acts as a solvent for many chemical reactions. The availability of soil water is often considered to be the greatest limitation in crop production in Western Canadian agriculture (Selles et al. 1992). A report by the University of Saskatchewan (Henry 1990) suggests that water use is the most important factor in the determination of yield potential. In this instance, the term water use is defined as the soil moisture on May 1st in addition to the rainfall accumulated from May 1st to July 31st. de Jong and Rennie (1969) reported that wheat yields in Western Canada were linearly related to water use. From a management point of view, the effects of water on nutrient availability, particularly nitrogen availability, is of greatest importance for Western Canadian producers.

2.2.1 Water and Nitrogen Relationships

Soil moisture plays many roles in soil-crop nitrogen relations. Campbell and Paul (1978) conducted small lysimeter studies in Southwestern Saskatchewan to determine the effect of soil moisture and N fertilization on nitrogen uptake in spring wheat. They reported that increasing fertilizer N and increasing soil moisture, via irrigation, influenced nitrogen uptake in various fashions. In general, they observed that the addition of N and water increased N uptake. In dryland conditions, the authors reported that the addition of 164 kg of N ha^{-1} increased N uptake by 76%. When 17.8 cm of water was applied without the addition of N, the N uptake increased by 60%. However, when both 164 kg N ha^{-1} and 17.8 cm of water were added, N uptake increased by 210%. The distribution of the fertilizer and soil N was also found to vary significantly between the various fertilizer rate and moisture treatments. On dryland, approximately 28% of the fertilizer N was left in the soil profile at fertilizer rates below 82 kg N ha^{-1} and increased to 57% at higher N rates. Under irrigation, these values decreased to 15-21%. The authors found this to be a concern as the excess N under dryland conditions had leached to greater depths than in the irrigated trials. The increased plant growth and more thorough use of the fertilizer N under "responsible" irrigation conditions had prevented leaching when heavy precipitation events occurred. However, the authors did remark that proper timing and application rates of irrigation are essential to prevent N losses due to denitrification and leaching. As for the N that was taken up, much more was present in the grain of the irrigated vs. dryland treatments (58.3% of fertilizer N vs. 37.3%); however there were no significant differences in the amounts taken up in the straw and roots. Mineralization was also reported to be significantly greater under irrigated conditions.

In another Southwestern Saskatchewan study conducted over 63 site-years, spring wheat grain yield increase models were developed (Selles et al. 1992). The authors reported that growing season available water accounted itself for 15% of the variability in grain yield increases. Furthermore, available water had significant interactions with soil and fertilizer nitrogen and phosphorus, accounting for another 26% of the variability in grain increases. Also, soil and fertilizer nutrients significantly affected grain yield increases only when considered with available water interactions.

Reports by Henry (1990 and 1991) on the development of nitrogen fertilizer recommendation models also emphasize the importance of available water. These models are different from many traditional models that generally involve the use of nutrient response functions. Rather, these models utilize water use efficiency production functions. A different model has been developed from a collection of various N response trials for each soil climatic zone (SCZ) of the prairies. Each of these SCZs represents differences in water use efficiency, growing season precipitation, and potentially mineralizable organic N, among other properties. The first step in developing a recommendation is to calculate a target yield which is determined by the May 1st soil moisture and estimating the growing season precipitation based on long term precipitation data. Once a target yield is developed, a N fertilizer recommendation can be made based on the N requirement for the particular crop, target yield, soil test N, and expected net mineralization.

As described by Paul and Myers (1971), moisture affects nitrogen nutrition through its impact on nitrogen uptake, net mineralization, and N losses such as denitrification and volatilization. Further evidence demonstrates that N leaching losses can also be greatly affected by moisture (Campbell and Paul 1978). Furthermore, it has been reported that N fertilization can in turn increase water use efficiency (de Jong and Rennie 1969, Pierce and Rice 1988). Pierce and Rice (1988) attribute these observations to the greater biomass production of fertilized crops which allow for greater exploitation of soil moisture.

When developing models for predicting yield of cereals in Southern Manitoba, Marantz (1989) reported that nitrogen supply and water supply were the two most important dependent variables to predict grain yield of wheat and barley. Using forward stepwise regression techniques, Marantz found that although water supply was an important variable in determining yield, it was only significant when considered as an interaction with nitrogen supply.

As the intimacy of the relationship between available moisture and N supply is becoming clearer, so are its applications. Use of combined moisture and fertility functions is more commonplace in Western Canadian fertilizer recommendations (EnviroTest Laboratories, 1998). Thus, there is reason to believe that future fertilizer management practices in Western Canada will result in more responsible use of water and nitrogen resources.

2.3 Protein in Wheat Production

The high quality of Western Canadian wheat is recognized around the world and is highly valued. Protein content is an important determinant of wheat quality. With the Canadian Wheat Board's introduction of premium payments for high protein wheat, there has been a resurgence of interest in wheat protein production within the Canadian agricultural community.

The protein content of wheat is a key determinant for its end-use. High protein Canada Western Red Spring (CWRS) wheat (>13%) is generally used for pan breads, whereas low protein CWRS wheat (<13%) is used for the production of hearth breads, steamed breads, noodles, and flat breads (Lukow and Preston 1998). Increasing protein content of CWRS wheat results in greater dough strength, baking quality and bread loaf volume, desirable traits in the world market (Lukow and Preston 1998). High protein content in Canada Western Amber Durum (CWAD) wheat is also of great value. In durum wheat, higher protein contents yield good quality semolina which results in pastas that adequately swell during cooking, do not leave much residue in the cooking water, and will remain firm when kept in warm water after cooking. Generally, protein contents of at least 14-15% (dry matter basis) is desired for pasta manufacturing (Marchylo et al. 1998). There are several factors which affect the protein content of wheat. These factors can be divided into three categories; genotypic factors, environmental factors, and management factors.

2.3.1 Factors Influencing Protein Content

2.3.1.1 Genotypic influences. In a study of the environmental and genotypic factors affecting protein concentration, Fowler et al. (1990) reported that different crop types (fall rye, winter wheat, and CWRS wheat) and even crop cultivars (Norstar, Ullanovka, Redwin, and Norwin) can express significant differences in grain protein characteristics. These differences are often attributed to the strong negative relationships between grain protein content and yield. In a study comparing 16 CWRS wheat cultivars, Hucl et al. (1998) also found differences in protein contents between cultivars. However, these differences exhibited strong interactions with environmental factors, as a result, the ranking of cultivars on a protein concentration basis changed between environments and years. Furthermore, they found very weak correlations between yield and protein increases between cultivars suggesting that recent breeding efforts are capable of producing high yielding cultivars which can maintain relatively high protein concentrations.

2.3.1.2 Environmental and management influences. Because N is an essential component of protein, N availability is often of major importance in determining grain protein content. The relationship between N supply and protein content is a complex one and one that has been studied extensively. As depicted in Figure 2.1 the shape of the protein content response curve is typically a sigmoidal curve with an initial lag,

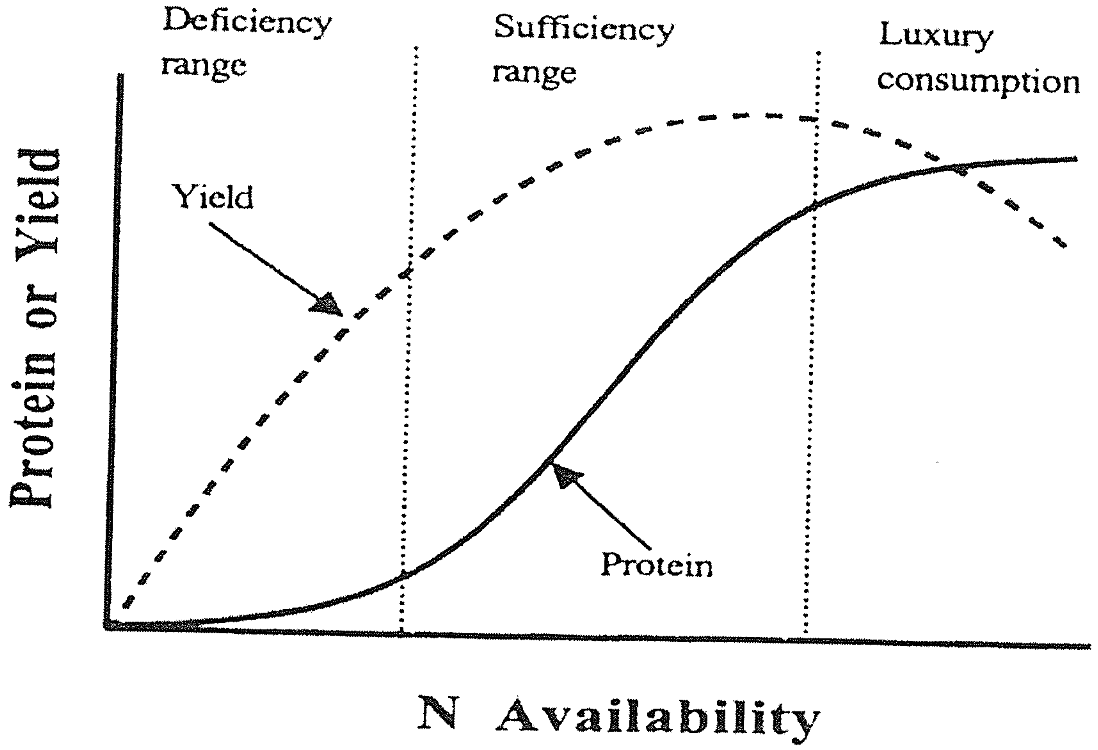

Figure 2.1 Ideal nitrogen responses for grain yield and protein (Selles et al. 1997).

followed by a steep increase phase which gradually levels off at higher nitrogen concentrations (Alkier et al. 1972; Partridge and Shaykewich 1972; Fowler et al. 1990; Holford et al. 1992; Selles et al. 1997). Anomalies to Figure 2.1 exist. A common observation occurring in the lag phase of the curve is a decrease in protein concentration with initial increases in available N. This phenomenon generally occurs in instances where N supply is very low. Under these circumstances, initial increases in N supply contribute greatly to the yield of the crop, thus diluting the N concentration in the grain (Alkier et al. 1972; Partridge and Shaykewich 1972; Fowler et al. 1990; Holford et al. 1992; Selles et al. 1997). Conversely, Holford et al. (1992) reported that when initial N supplies were relatively high and significant yield increases did not occur, the lag phase of the curve was not present and the protein response curves were linear or exponential as opposed to sigmoidal or convex to the X axis. This is similar to the explanation given by Fowler et al. (1990) who reported that the increase phase began when environmental or genotypic factors other than N supply became limiting to growth. Since less biomass is being produced under these conditions, the additional N is utilized in the production of protein. Because of the economics involved with wheat grain yield and protein content in Western Canada, the understanding of this intimate negative relationship between the two is extremely important.

Much of the factors which affect grain protein content are often indirect due to their influence on grain yields. In growth chamber studies on Neepawa wheat, Partridge and Shaykewich (1972) found that increasing temperature and decreasing light intensity resulted in increases in protein concentrations due to adverse effects on yield. In studies of protein responses to nitrogen supply in Manitoba lowlands, Alkier et al. (1972) reported that in site years where crop yields were higher, protein increases to fertilizer N only occurred at higher application rates. Alkier et al. (1972) attributed these protein responses to the fact that in the site years where high yields were observed, grain yield responses to N supply were very high at lower N supply levels. Holford et al. found that in phosphate deficient situations, additions of phosphorus fertilizers decreased protein content due to increases in wheat yield. After a review of Western Canadian protein records from 1927 to 1993, Selles et al. (1997) reported that 64% of the variability in wheat protein was accounted for by four weather variables: an index of growing season water availability, the July mean maximum temperature, the amount of rainfall during July, and the July mean minimum temperature. The authors once again attributed this to the large influence that these weather variables have on yield.

Under appropriate conditions and with proper management practices, it is still possible to produce relatively high yields while maintaining protein concentrations. To accomplish this, proper fertilizer management is critical. In a long term crop rotation study conducted at Swift Current, SK, Selles et al. (1997) reported that continuous N fertilization resulted in an increase in wheat protein content compared to wheat fertilized with P alone. Henry et al. (1986 in Roberts et al. 1998) and Roberts et al. (1998) made similar observations in their investigations of wheat protein content trends in the Western Canadian Prairies. They found that from 1927 to the mid 1970s Saskatchewan consistently produced wheat with higher protein content than Alberta and Manitoba. This was likely a reflection of the lower yields generally observed in Saskatchewan due to greater environmental stresses. However, from the mid 1970s to 1997, Manitoba has been producing higher protein wheat than the other provinces. The authors attributed this phenomenon to the differences in N fertilization between the three provinces. In 1996, Manitoba applied N fertilizers to 23% more of its cropland than Saskatchewan and 12% more than Alberta. Furthermore, the rates were 60% and 33% greater than those applied in Saskatchewan and Alberta respectively. Thus, a continuous and balanced nitrogen fertilization program can greatly enhance grain protein concentrations.

In any given year, fertilizing at rates exceeding those required for maximum yield can result in increased yields with high protein. However, many reports show that this is not a practical approach. As documented by Fowler et al. (1990), the nitrogen use efficiency (NUE) of fertilizer N declines very quickly after the first few increments of applied N. Subsequently, the N that is not utilized by the crop is subject to various losses such as leaching and denitrification which can have serious environmental consequences. Furthermore, the low NUE generally results in negative economic returns on fertilizer inputs. Proper fertilization practices can greatly decrease fertilizer N losses which has similar effects as increasing fertilizer rates (Grant and Flaten 1998). These practices include proper fertilizer placement, fertilizer source selection, and timing of application.

As described by Selles et al. (1997), in order to profit from fertilizing for protein premiums, three events must occur simultaneously:

1. Protein content must increase substantially with N applications.
2. The crop must make the grade for which a premium is paid.
3. The protein content of the crop must be within the protein range for which a premium is paid.

In most circumstances, fertilization increases profits via its impact on grain yield and profits resulting from protein increases are lesser and more uncertain (Flaten and Racz 1997, Selles et al. 1997). This is largely due to the unpredictability of weather conditions which, as reported earlier, can often be a greater yield and protein determining factor than N availability. Other elements of risk in fertilizing for protein premiums include increasing risk of lodging, disease, and delayed maturity. Also, protein premium payments vary significantly from year to year and are generally not known at the time fertilization decisions are made (Flaten and Racz 1997).

2.4 Precision Agriculture

The Precision Agriculture Center located at the University of Minnesota describes precision farming as an information intensive approach to agriculture (1995). It involves adjusting inputs and farm management practices to field characteristics, such as soil condition, landscape, and microclimate. In recent years, the concept of precision agriculture has received a great deal of attention. Much of this interest is in response to the development of technologies such as global positioning systems, geographic information systems, and variable rate application equipment.

As described by Sawyer (1994), the premise of precision agriculture is that uniform application of inputs within a field does not maximize input efficiency or field profitability. Thus, maximizing input efficiency and/or field profitability are often the major objectives of precision agriculture management practices. The concept assumes that: (i) within-field spatial variation of factors affecting yield exists; (ii) variation does influence crop yield; (iii) variation can be identified, measured, and delineated; (iv) precise crop response models are available to determine appropriate variable input rates; and (v) data processing procedures and application equipment that can effectively manage and variably apply crop production inputs are available. Unfortunately, in most instances assumptions (iii) and (iv) do not hold in this concept, suggesting that greater efforts are required to understand within-field variability and how it affects crop productivity.

2.4.1 Spatial Variability

There is significant variability in soil properties and soil processes over relatively short distances. This heterogeneity in soils is a major reason for the occurrence of within-field variability in crop productivity. Spatial variability can be divided into two components: (i) random variability and (ii) non-random or systematic variability (Pennock and de Jong 1990, Stevenson et al. 1995). The sources of the former are not traceable; however, systematic variability is a result of factors and processes that are more predictable. For this reason, systematic variability is the preferred of the two variability components to study and manage.

2.4.1.1 Systematic variability and the soil-landscape. Much of the systematic variability that occurs in the soil is a result of the soil-landscape and its associated soil-forming processes. As early as 1936, Milne described the catena concept as a topographic complex of soils formed as a result of redistribution of materials, laterally and horizontally, largely according to the hydrology of the area. Since this time, a number of authors have recognized and acknowledged the importance of the landscape in the redistribution of water and how this determines soil properties (Hugget 1975, Moore et al. 1993, McCann et al. 1997). Therefore, many studies have been conducted to determine which soil properties important to crop production vary significantly with landscape properties and how these properties influence yield and yield components.

Brubaker et al. (1993) reported significant differences among landscape positions for 13 of 19 soil chemical and physical properties measured. These properties included % sand, silt and clay, pH, $CaCO_3$, extractable Ca and Mg, exchangeable Ca and K, base saturation, organic matter, cation exchange capacity, and available K. Properties commonly reported as having a correlation with landscape properties are soil moisture, texture, organic carbon, depth of A horizon, depth to carbonates, available phosphorus, electrical conductivity, pH, erosion, and crop productivity (Hanna et al. 1982, Pennock and de Jong 1987, Miller et al. 1988, Simmons et al. 1989, Pan and Hopkins 1991, Brubaker et al. 1993, Moore et al. 1993, Moulin et al. 1994).

2.4.1.2 Landscape-based variability in soil moisture. In a study correlating wheat yield and soil properties to topography, Moulin et al. (1994) reported that relative elevation alone is often not adequate in describing the variability observed. This was largely due to the effect of slope curvature on the redistribution of water in the landscape. Therefore, the elevation by curvature interaction may be a useful tool to predict variability in soil and crop productivity properties. Other researchers have made similar observations. On a hummocky terrain, McCann et al. (1997) discussed how the surface curvature of the landscape determines the path of water flow and subsequent productivity variation within a field. They described areas as convergent, divergent, or linear. In the Western Canadian Prairies where moisture for crop production is often deficient, convergent areas tend to receive water from upslope positions often resulting in increased nutrient supplying capability and increased yields. However, convergent areas which receive excessive water can have poor productivity due to high denitrification and leaching losses, and poor root development, largely a result of a lack of oxygen. Divergent areas have a tendency to shed water and be exposed to wind and water erosion losses, resulting in thin profiles, low in organic matter and high in calcium carbonates, greatly decreasing the availability of nitrogen and phosphorus. Thus, these divergent areas generally have lower yields. The linear areas are generally considered to have intermediate moisture and intermediate to high productivity potentials.

In a study conducted in Lancaster County, Nebraska, Hanna et al. (1982) found that backslope and footslope positions had more soil available water than the summit and shoulder positions. Furthermore, they also observed differences in available water among different slope aspects. Available soil moisture on slopes with a north aspect had the greatest soil moisture, followed by the south aspect with the east aspect having the lowest available soil moisture. Therefore, slope position and/or elevation alone is often not sufficiently accurate in determining available soil stored moisture. Slope characteristics such as slope curvature, slope aspect, slope gradient, and slope length should also be considered.

2.4.1.3 Landscape-based variability in nitrogen and nitrogen indices. Because of its importance in crop production, a great deal of attention has been placed on nitrogen fertility and its spatial variability. Although it is generally believed that nitrogen concentrations are correlated with the soil landscape (Stevenson 1982), a number of studies indicate that this is not always the case.

In 1996, Hollands observed that even in landscapes with very little topographic relief, NO_3^--N concentrations were significantly correlated to elevation. The field studied was located in the Red River Valley of Minnesota and had an elevation difference of only 0.75 m between the highest and the lowest areas of the field. The NO_3^--N concentrations were reported to be lowest in the depressional areas and highest at areas of greatest elevation, ranging from 25 to 94 kg NO_3^--N ha^{-1} in the depressions versus 64 to 171 kg ha^{-1} at the elevations.

In a study comparing landscape-based sampling strategies versus various grid density sampling strategies, Franzen et al. (1997) made a number of interesting observations. The study included four sites in North Dakota, two in relatively level landscapes and two in more complex landscapes with significant relief. Each site was initially sampled in an intensive grid pattern of one sample every 30 m over a two or three year period. Nutrient maps, including NO_3^--N maps, were made according to this pattern and were considered to be quite accurate due to the high intensity of the grid. Maps of these same nutrients were made using 3 other less intensive grid patterns (60 m, 90 m, and 2 ha) and two topography based patterns (topography point and topography area based) to determine which pattern was most highly correlated to the 30 m grid. The topography based patterns were found to be the most highly correlated or similar to the most highly correlated in NO_3^--N concentrations in only 6 of the 10 site years studied. Where topography appeared to have an impact on NO_3^--N distribution, the following trends were observed. In level landscapes, NO_3^--N concentrations were lower in the depressions and higher at the elevations, much as was reported by Hollands (1996). In the more complex landscapes,

NO_3^--N concentrations tended to be greater in the depressions and lower at the higher elevations. Inconsistencies in these observations were believed to be due to interactions with crop rotations, presence of manure, and excess water. Thus, the authors concluded that using topography to map NO_3^--N concentrations was relevant, but only under certain management and environmental conditions. The reasons for landscape-based differences in NO_3^--N concentrations as observed by authors such as Hollands (1996) and Franzen et al. (1997) have been suggested by a number of authors.

In level landscapes, Pennock et al. (1992) reported that denitrification rates were significantly different between different landform elements. Denitrification rates were highest in depressional areas reaching levels as high as 20 kg N ha^{-1} d^{-1} and were most highly correlated with volumetric soil moisture and redox potential. These correlations are not surprising since volumetric soil moisture and redox potential are both reflections of the aeration status of the soil which strongly governs denitrification rates.

In rolling topography, Elliott and de Jong (1992) suggested that NO_3^--N concentrations were higher in depressional areas due to runoff from higher landform elements. They observed that significant landscape-based differences in NO_3^--N concentrations occurred on sites which were under cultivation for longer periods of time whereas recently broken land which had been exposed to minimal erosion did not exhibit these differences. Verity and Anderson (1990) also found that significant landscape-based differences in total nitrogen occurred in hummocky landscapes in Southern Saskatchewan. These differences were also attributed to erosion and length of cultivation. Other researchers have reported that other factors and processes contributing to this landscape-based distribution in NO_3^--N include higher organic carbon concentrations, higher mineralization rates, higher clay content, and better moisture conditions than in lower landscape positions (Malo and Worcester 1975, Fiez et al. 1995, Qian and Schoenau 1995, Stevenson et al. 1995).

However, soil NO_3^--N concentrations also exhibit random spatial variability. Mahler et al. (1979) found that although inorganic N concentrations were initially higher in depressional areas of a hummocky terrain, these differences quickly disappeared mainly due to increased crop uptake of nitrogen in these positions. In a study where fields were grid sampled at every 15.3 m, Wibawa et al. (1993) reported that soil NO_3^--N concentrations varied from 7 to 569 kg ha^{-1}. These concentrations did not follow any landscape patterns but rather, variations occurred over very short distances. Pennock et al. (1992) observed similar results; however these observations were in more level terrains.

Furthermore, inorganic nitrogen concentrations alone are not necessarily accurate indications of N availability. In a study conducted in Farmington and Pullman, WA, Fiez et al. (1995) compared differences in various indicators of nitrogen use efficiency at four different landscape positions: footslope, south backslope, shoulder, and north backslope. They measured N uptake efficiencies (plant N/N supply), N utilization efficiencies (grain yield/plant N), N fertilizer efficiencies (Δplant N/ΔN fertilizer), and unit nitrogen requirements (UNR, the N supply required to produce a unit of yield), and estimated the mineralized N at the four landscape positions in question. They reported significant differences among landscape positions for a number of these indices; however these differences were not always consistent between the four site years of the study. Some of the general observations made by the authors were that plant uptake was lowest in the north backslope positions and that N fertilizer uptake efficiencies were highest on the footslopes and south backslopes and lowest on the shoulder and north backslope positions. Furthermore, they discovered that UNR at optimum economic yields was highly correlated with N uptake efficiency (r = -0.80, P<0.01) and with N utilization efficiency (r = -0.62, P=0.01). The UNRs varied by up to 70% among landscape positions leading the authors to conclude that spatial variability in UNRs should be considered when making N fertilizer recommendations.

2.4.2 Approaches to variable rate fertilization (VRF)

As an understanding of soil variability continues to develop, so do the methods to manage this variability. Applying varying rates of fertilizer which reflect the variability in soil fertility and crop production potential provides the greatest potential for benefits in a precision agriculture environment. Theoretically, the benefits can be both economical and environmental as fertilizing according to fertility requirements increases fertilizer use efficiency and fertilizer recovery. This results in greater returns on fertilizer inputs and less nutrients left in the soil system for denitrification, leaching, and other losses. However, the greatest challenge so far has been in developing methods to practically manage the inherent variability occurring in the soil-landscape. To effectively implement variable rate fertilization strategies, accurate identification and reliable interpretation of within-field variability is essential (Sawyer 1994).

2.4.2.1 Grid soil sampling procedures. One of the most popular methods of assessing within-field variability is by grid sampling. As described by Pocknee (1996) grid sampling refers to a process in which a field is divided into a number of smaller uniform cells. These cells are then individually sampled and the results combined with positional information to produce field maps depicting the parameters measured. Grid sampling patterns include square, rectangular, offset, and stratified systematic unaligned (Pocknee 1996). A particular pattern is generally selected over another in an attempt to compensate for some bias which may be present in a field. Although grid sampling techniques are reported to be practical in some instances (Cattanach et al. 1996, Franzen et al. 1997) there are a number of shortcomings to this approach.

There is very little rationale for the grid size that is used. In many instances, grid size is decided upon based on economics of sampling and analysis or simply by precedent. Cahn et al. (1994) investigated the patterns of 5 soil fertility variables (organic carbon, water content, NO_3^--N, PO_4-P, and K) in a 3.3 ha field in central Illinois. In order to obtain adequate assessments of the levels of each soil variable, the authors reported that sampling intensities required were different for different variables. Mobile nutrients such as NO_3^--N may require sampling intensities of less than a meter whereas sampling intervals for more stable variables such as PO_4-P and organic carbon may be as long as the field in question.

A second shortcoming of grid sampling is that results may be biased by localized soil irregularities. This is particularly true when a single sample is utilized to represent an entire grid cell (grid point sampling) as opposed to using a composite of samples within a cell (grid cell sampling). A potential anomaly in a small radius from which the sample is taken can result in erroneous estimates of nutrient concentrations. A fertilizer recommendation based on such an estimate would cause over- or under-fertilization of that cell.

Grid sampling is also a slave of its own uniformity (Pocknee 1996). As described by Cahn et al. (1994) soil properties do not vary uniformly across a field. Any knowledge of systematic variability cannot be accounted for when grid sampling. Hollands (1996) found this to be significant as strong landscape-based variability was overlooked when grid sampling for NO_3^--N in the Red River Valley.

Although grid sampling does have its shortcomings, many researchers still find that it still provides a relatively accurate assessment of nutrient distribution (Wibawa et al. 1993, Cahn et al. 1994, Franzen et al. 1997). However, the extensive labor involved with grid sampling and high costs associated with the analysis of so many samples generally makes grid sampling impractical and economically unfeasible (Beckie et al. 1997, Franzen et al. 1997). Wibawa et al. (1993) reported that grid sampling indicated significant variability in soil fertility over short distances. Variable rate fertilization according to this grid increased yields, but the added costs of sampling and analysis resulted in less profits per acre than conventional fertilization practices. Grid sampling is often economically feasible in fields with high variability and high responsiveness to applied nutrients (Franzen 1997) and when dealing with responsive high value crops such as sugarbeets (Cattanach et al. 1996). Although grid sampling may provide accurate information to construct nutrient maps, these maps do not necessarily provide adequate information to create accurate fertilizer recommendation maps. The parameter mapped must be a reasonable estimate of the availability of the nutrient (Cahn et al. 1994) and there must be reasonable estimates of yield response to applied nutrients (Kachanoski and Fairchild 1996) and yield potential (Beckie et al. 1997) associated with each management unit on the nutrient map.

2.4.2.2 Management units based on the soil-landscape. Because soil and yield characteristics are often intimately related to each other and to the soil-landscape, many researchers find that the soil-landscape is a useful tool in developing management units (Malo and Worcester 1975, Elliott and de Jong 1992, Moulin et al. 1994, McCann et al. 1997). In a three year study in the black soil zone of Northern Saskatchewan, Beckie et al. (1997) compared conventional fertilization techniques to three variable rate techniques.

They reported that fertilizer use efficiency was greatest for two of the variable rate application methods. These were variable rate fertilization based on topography and based on soil organic matter content. They found that variable rate fertilization based on residual NO_3^--N concentrations was the least efficient, with efficiencies being similar or less than the conventional method of one uniform application based on a field average of NO_3^--N. Variable rate application based on the NO_3^--N map became even less appealing when the additional costs of sampling and analysis of this method were considered. Solohub et al. (1996) reported that landscape-based variable rate fertilization was only profitable if an accurate assessment of yield potential and N supplying power of the management units was made. They found that weather can be a major complicating factor, particularly precipitation. In a dry year, lower slope positions would have a high yield potential relative to upper positions with the opposite being true in wet years. In their study of landscape-based variable rate fertilization, Elliott and de Jong (1992) found that the response to applied N and P was also dependent on length of cultivation. In fields that have been cultivated for several years, responses were more prominent than in recently broken fields. This generally held true for all landform elements studied. Therefore, although the soil-landscape is generally useful for delineating management units, it does not necessarily provide a complete indication of the variability occurring within a field. Thus, the soil-landscape may be used as a starting point to make variable rate decisions, but other variables should also be considered to fine tune the delineation of management units.

2.4.2.3 Other approaches to variable rate fertilization. Due to the shortcomings of the methods discussed previously, there have been many other approaches attempting to identify within-field variability and assess variable rate fertilizer requirements. Using yield maps to determine management units is one of the most popular approaches. With the increasing availability and reliability of yield monitors, yield maps are very appealing. Unfortunately, yield maps alone are not reliable to delineate management units for VRF purposes. Yield differences generally do not correspond well with nutrient maps but are often a reflection of other yield determining factors such as moisture, weeds, insects, disease, salinity, etc. (Franzen et al. 1997). However, yield maps are very useful in combination with other field information as they provide indications of yield potentials.

Various remote-sensing technologies such as color, black and white, and infrared aerial photographs and satellite images have also been utilized due to their ease and relatively low cost of implementation. Although these technologies have been reported to provide reasonable estimates of crop productivity, they are far from stand alone approaches. Various studies demonstrate that remote-sensing is only useful when the photographs can be compared to other field data such as yield, nutrient, and topography maps (Anderson and Yang 1996, Blackmer and White 1996, Schepers et al. 1996).

Soil survey maps, chlorophyll meters, on-the-go protein monitors are only a few of the other tools used in the quest to delineate management units with the objective of effectively applying fertilizer resources according to varying requirements within a field. As with all other approaches, the success of these is variable at best (Carr et al. 1991, Nolin et al. 1996, Long et al. 1997). The most popular belief among researchers today is that an approach which integrates various layers of information gathered from a combination of the techniques described may be the best approach of all (Ferguson et al. 1996). However, the success of precision agriculture may always be limited due to the unpredictability of factors such as weather patterns and the random variability associated with some soil properties.

2.4.2.4 Variability in yield responses to applied nutrients. It is generally accepted that yield responses vary on a regional scale according to differences in climate. Henry (1990 and 1991) has proposed response functions based on water use and soil climatic zones which is now utilized by local laboratories to make fertilizer nitrogen recommendations. The differences between these zones are largely due to climatic differences, particularly moisture and temperature properties. Although properties such as moisture and soil temperature are influenced by the soil landscape, virtually no research has been done to determine whether response functions differ at the landscape level.

Some researchers have eluded to the importance of considering yield responses to applied nutrients as opposed to simply considering yield potential (Kachanoski and Fairchild 1996) but little has been done to pursue this matter.

Since this type of study has not been conducted, there is little precedence for statistical procedures to measure differences in fertilizer responses. Neter et al. (1990) described a procedure to compare different regression functions that utilizes indicator variables and extra sums of squares. This procedure will be discussed in later sections.

2.5 Summary and Hypotheses

Yields of CWRS wheat are, in part, a result of many soil factors. Nutrient availability, available water, and various soil properties such as salinity, pH, depth of carbonates, organic matter, and many others are all important yield determining factors. With the growing interest in landscape-based research, it has become evident that many of these factors are closely associated with the soil-landscape. As a result, several studies in which crop yields and management units have been correlated to various landscape properties have been conducted (Moulin and Beckie 1993, Moulin et al. 1994). However, these studies generally assume that responses to various amendments are constant throughout the soil-landscape.

On a regional scale, different response models have been developed based on soil climatic zones. Unfortunately, very little research has been conducted to determine whether crop responses to fertilizer amendments vary significantly at the landscape level.

The hypotheses proposed in this study are that various soil properties that affect crop yield and quality are associated with the soil-landscape and that CWRS wheat yield and protein responses to fertilizer N differ among landscape positions as a result of this systematic soil variability at the landscape scale.

To test these hypotheses, analyses of various soil properties were conducted and compared among various slope positions of both glacial till and lacustrine landscapes. Also, small plot trials were established at these same slope positions with various rates of fertilizer N so that yield and protein responses could be determined and compared.

3. MATERIALS AND METHODS

3.1 Site Selection, Maintenance, and Handling

In 1996 and 1997, small plot trials were established at 6 locations in Southern Manitoba. Only sites with no history of manure and no recent history of legume crops were considered for the study. These locations represented both undulating glacial till landscapes of the Newdale Association and slightly undulating lacustrine landscapes of the Red River Association. Four glacial till sites were located near Minnedosa and Forrest, Manitoba and two lacustrine sites were located near Elm Creek and Dufresne, Manitoba. Brief descriptions of these sites are included in Tables 3.1 and 3.2.

CWRS wheat was sown at all sites. The cultivar selected at each site was the same as the cultivar grown by the farmer-cooperator. Various slope positions were selected and divided into small plots receiving varying rates of fertilizer N. Several soil and plant samples were collected throughout the growing season in an effort to determine relations between soil fertility factors and yield properties of CWRS wheat. Total aboveground biomass yield at anthesis and at maturity and grain yield at maturity were determined for each site. These three yield measurements will be referred to as yield indices throughout the remainder of this document. Detailed descriptions of each site and experimental procedures are provided on a site by site bases in subsequent sections.

3.1.1 Newdale Till Plain Landscapes

The Manitoba Reconnaissance Soil Survey report no. 7 (1957) describes the Newdale Association as loam to clay loam textured soils developed on medium-textured, moderately calcareous boulder till of mixed shale, limestone and granitic rock origin. The topography of these glacial tills is irregular varying from nearly level to moderately undulating.

Table 3.1 Description of landscapes studied in Newdale glacial till plain.

Site	Slope Position	Slope Morphology	Slope Aspect	Slope Gradient	Slope Length (m)	Depth of A Horizon (cm)	Depth to Carbonates (cm)	Solum Depth (cm)	CSSC Classification	Soil Series
Forrest '96	Toeslope	convergent toeslope	202-220°	8 - 10%	32	26.0	13.3	46.5	GLR.BLC/ GL.BLC	Varcoe/no series†
	Midslope	linear backslope	202-220°	8 - 10%	32	19.3	15.5	34.8	R.BLC/ O.BLC	Rufford/Newdale
	Shoulder	divergent shoulder	202-220°	8 - 10%	32	11.3	0.0	11.3	R.BLC	Rufford
Zero Tillage Farm '96	Nonsaline & Saline Toeslope	convergent toeslope	195-210°	8-9.5%	29	26.3	0.0	37.5	GLR.BLC	Varcoe
	Midslope	linear backslope	195-210°	8-9.5%	29	17.5	3.8	25.5	R.BLC/ CA.BLC	Rufford/Cordova
	Shoulder	divergent shoulder	195-210°	8-9.5%	29	12.8	3.8	28.8	R.BLC/ CA.BLC/ O.BLC	Rufford/Cordova/ Newdale
Forrest '97	Toeslope	convergent toeslope	215-230°	7-9%	33	20.0	0.0	36.7	GLR.BLC	Varcoe
	Midslope	linear backslope	215-230°	7-9%	33	14.0	8.3	21.7	CA.BLC/ O.BLC	Cordova/ Newdale
	Shoulder	divergent shoulder	215-230°	7-9%	33	9.0	0.0	13.7	CA.BLC	Cordova
Minnedosa '97	Toeslope	convergent toeslope	115-130°	9.5-11%	53	31.3	0.0	36.3	GLR.BLC/ GLCU.HR	Varcoe/no series†
	Lower Midslope	linear backslope	115-130°	9.5-11%	53	19.5	6.8	30.0	GLR.BLC/ O.BLC	Varcoe/Newdale
	Upper Midslope	linear backslope	115-130°	9.5-11%	53	14.0	21.5	25.5	CA.BLC/ O.BLC	Cordova/Newdale
	Knoll	divergent knoll	115-130°	9.5-11%	53	8.3	0.0	12.7	R.BLC/ CA.BLC/ O.BLC	Rufford/Cordova/ Newdale

† No soil series has been assigned for the Gleyed Black Chernozem or Gleyed Cumulic Humic Regosol subgroups in the Newdale Association due to their rare occurrences.

GLR.BLC = Gleyed Rego Black Chernozem
O.BLC = Orthic Black Chernozem
CA.BLC = Calcareous Black Chernozem
R.BLC = Rego Black Chernozem
GL.BLC = Gleyed Black Chernozem
GLCU.HR = Gleyed Cumulic Humic Regosol
CSSC = Canadian System of Soil Classification

Table 3.2 Description of the lacustrine landscapes studied in the Red River Association.

Site	Slope Position	Slope Morphology	Slope Gradient	Depth of A Horizon (cm)	Depth to Carbonates (cm)	Solum Depth (cm)	CSSC Classification	Soil Series
Dufresne '97	Microhigh	Divergent microelevation	0-0.5%	30.8	47.5	40.0	GL.HV/GLC.HV	Red River/ Osbourne
	Microlow	Convergent microdepression	0-0.5%	22.5	55.8	37.5	GL.HV/GLC.HV	Red River/ Osbourne
Elm Creek '97	Microhigh	Divergent microelevation	0-0.5%	14.2	19.6	28.0	GL.HV	Red River
	Microlow	Convergent microdepression	0-0.5%	19.4	59.8	27.0	GL.HV/GLC.HV	Red River/ Osbourne
	Low	Convergent microdepression	0-0.5%	18.0	26.6	29.0	GL.HV/GLC.HV	Red River/ Osbourne

GL.HV = Gleyed Humic Vertisol
GLC.HV = Gleysolic Humic Vertisol
CSSC = Canadian System of Soil Classification

All the catenas studied in these landscapes were linear slopes varying somewhat in length, gradient, and aspect. Each of the catenas was divided into different slope positions on which varying rates of nitrogen fertilizer were applied.

3.1.1.1 Forrest 1996. This site was located on the SE 36-12-19 W1 near the town of Forrest, Manitoba. Four catenas separated into toeslope, midslope, and shoulder positions were selected. The average length of the catenas was approximately 32 m. The slope aspects were in the S to SSW (202 - 220°) direction and had gradients ranging from approximately 8-10% (Figure 3.1). The toeslope positions were located next to a marsh complex and were therefore areas of relatively high water tables. Shoulder positions were located in divergent areas just below the crest of the slope with the midslope placed equidistantly between the toeslope and shoulder positions.

Immediately prior to seeding, composite soil sampling was conducted at 30 cm intervals to a depth of 120 cm at each landscape position to determine nitrate-nitrogen (NO_3^--N), exchangeable NH_4^+, PO_4-P, and soil salinity. Subsamples were also collected for gravimetric moisture determination. On May 13th, 1996 the CWRS cultivar Roblin was seeded at a rate of 101 kg ha^{-1} and a depth of 3.8 cm using a Morris™ air seeder with 20 cm row spacing. Monoammonium phosphate (11-52-0) was banded beside the seed at a rate of 60 kg ha^{-1} at the time of seeding. On May 14th, 1996 six rates of ammonium nitrate fertilizer (34-0-0), ranging from 0-200 kg N ha^{-1} (0, 40, 80, 120, 160, and 200 kg N ha^{-1}), were broadcast applied at each landscape position to determine yield response to applied fertilizer. Each treatment was applied to each landscape position in a 2 m X 6 m plot with different randomizations at each landscape position. Shortly after seeding, thermocouples were placed in the 80 kg N ha^{-1} treatments of each landscape position to monitor soil temperatures.

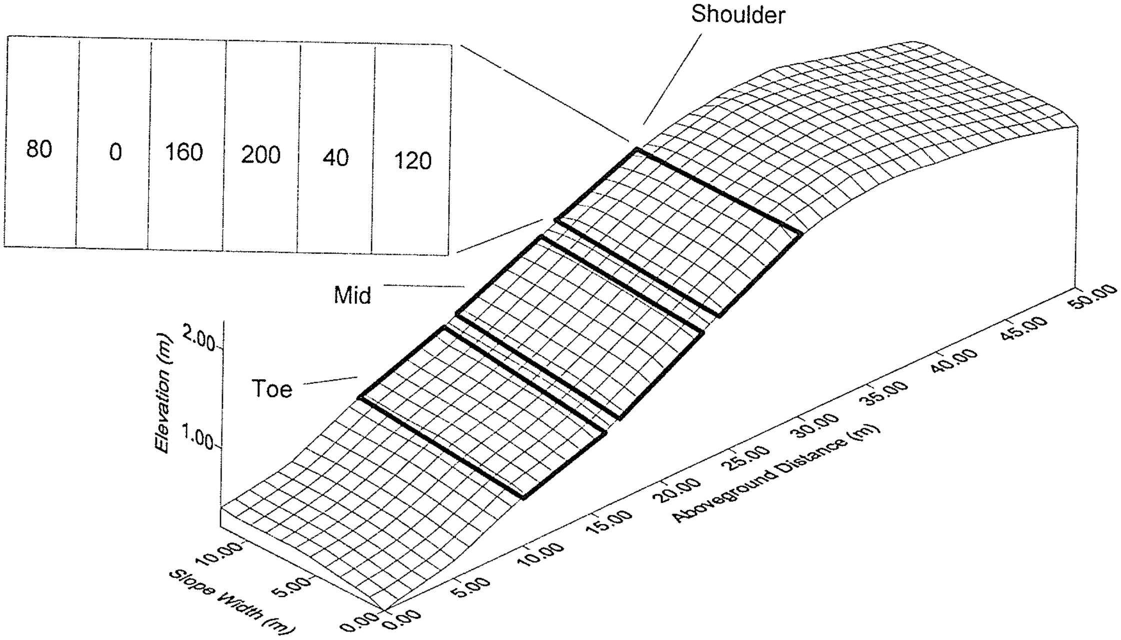

Figure 3.1 Sample catena found at Forrest 1996 site illustrating the three landscape positions studied: Toeslope, Midslope, and Shoulder, as well as a sample N fertilizer treatment randomization (kg N ha^{-1}).

On June 10th, 1996 the plots were sprayed with a tank mix of Achieve 80 DG (tralkoxydim 198 g a.i. ha^{-1}) and Estaprop (dichlorprop 526 g a.i. ha^{-1} & 2,4-D ester 495 g a.i. ha^{-1}). The major weed species included volunteer flax (*Linum usitatissimum*), wild mustard (*Brassica kaber*) , lamb's quarters (*Chenopodium album*), and wild oats (*Avena fatua*).

At anthesis (Zadok's 67-68, Zadoks et al. 1974), ½ m^2 plant samples were taken from each plot to determine aboveground biomass yield. Soil cores were also taken to a depth of 120 cm at 30 cm intervals in the 0, 80, and 200 kg N ha^{-1} treatments to determine moisture content. Unfortunately, due to miscommunications with the farmer-cooperator, the cooperator's employee harvested the plots at maturity. Therefore, no yield data was available.

After harvest, soil samples were taken to 120 cm at 30 cm intervals in the 0, 80, and 200 kg N ha^{-1} treatments to measure residual NO_3^--N and NH_4^+-N concentrations. Subsamples were once again taken to determine soil moisture status.

3.1.1.2 Zero Tillage Farm 1996. This site was located on the Manitoba Zero Tillage Research Farm (SW 31-12-18 W1) immediately adjacent to the Forrest 1996 site. Once again, four catenas separated into toeslope, midslope, and shoulder positions were selected at this site. The average length of the catenas was slightly shorter than the Forrest site, approximately 29 m. The slope aspects were in the SSW (195 - 210°) direction and had gradients ranging from approximately 8-9.5% (Figure 3.2). The landscape positions were selected in the same fashion as the Forrest site with the toeslope positions being located next to marsh complexes, shoulder positions located in divergent areas just below the crest of the slope with the midslope placed equidistantly between the toeslope and shoulder positions.

Soil sampling, seeding, and fertilizer application was done in the same fashion as the Forrest 1996 site. The site was seeded on May 23rd, 1996. Thermocouples were also placed in the same fashion as the Forrest site. Weeds were controlled chemically with a tank mix of Lontrel™ (clopyralid 178 g a.i. ha^{-1}) and 2,4-D amine (481 g a.i. ha^{-1}). Major weed species included Canada thistle (*Cirsium arvense*), wild mustard (*Brassica kaber*), volunteer canola (*Brassica napus*), and stinkweed (*Thlaspi arvense*).

Plant and soil samples were collected at anthesis (Zadoks 66-68, Zadoks et al. 1974) as at the Forrest site. At crop maturity (Zadoks 93-94, Zadoks et al. 1974), 1 m^2 samples were harvested from each plot to determine grain yield and aboveground biomass yield. The grain and straw samples were also kept to determine N content of the aboveground components. Finally, soil samples and subsamples were once again collected to determine residual inorganic N and soil moisture.

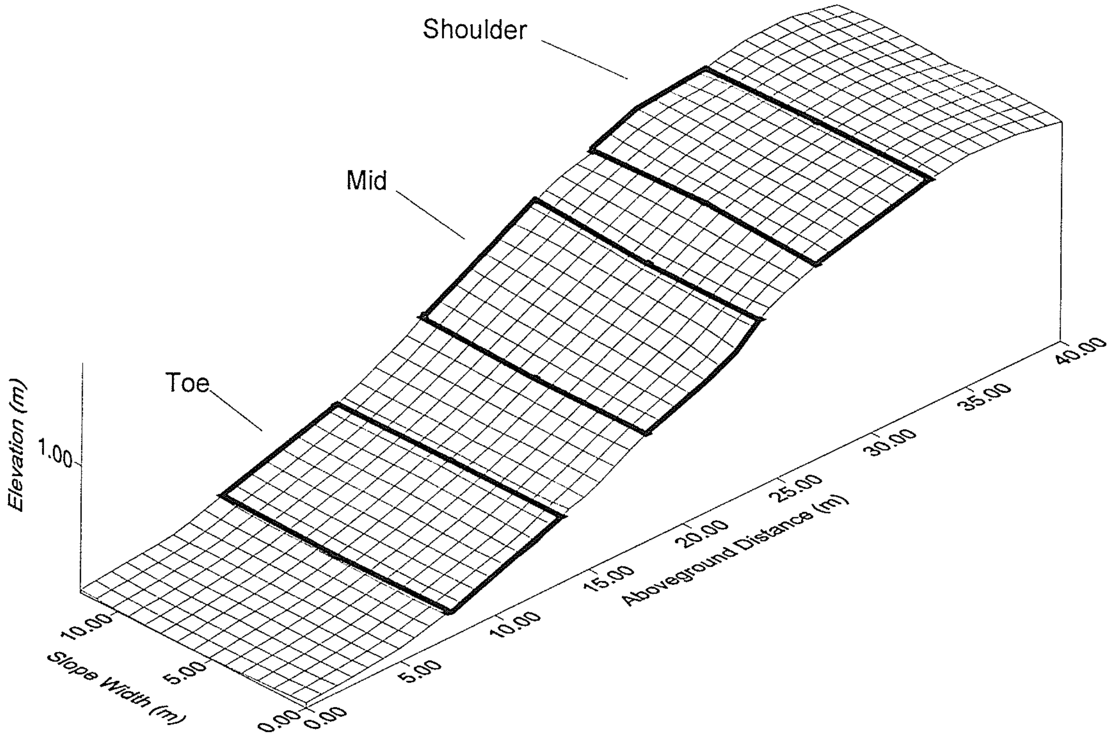

Figure 3.2 Sample catena found at Zero-Till Research Farm site illustrating the four landscape positions studied: Nonsaline and Saline Toeslopes, Midslope, and Shoulder.

3.1.1.3 Forrest 1997. This site was also located near the town of Forrest, Manitoba and was located on NW 32-12-18 W1. Four catenas separated into toeslope, midslope, and shoulder positions were selected at this site. Unfortunately, one catena was abandoned early in the season when we realized that the farmer-cooperator unintentionally applied anhydrous ammonia (82-0-0) to this replicate the previous fall. The average length of these catenas was similar to the previous sites at approximately 33 m. The slope aspects were in the SW (215 - 230°) direction and had gradients ranging from approximately 7-9% (Figure 3.3). The slope positions were selected in the same fashion as the previous sites with the toeslope positions being located next to marsh complexes, shoulder positions located in divergent areas just below the crest of the slope with the midslope placed equidistantly between the toeslope and shoulder positions.

Soil sampling was conducted in the same fashion as previously described. The CWRS cultivar Roblin was once again seeded at a rate of 101 kg ha^{-1} and 3.8 cm depth using a press drill. Monoammonium phosphate was applied with the seed at a rate of 40 kg ha^{-1}. In all 1997 sites, seven fertilizer N treatments were applied rather than the six treatments used in 1996. These rates included 0, 30, 60, 90, 120, 150, and 200 kg N ha^{-1} and were broadcast applied as ammonium nitrate. Since very few significant differences in soil temperature were observed for the sites in 1996, limited soil temperature data was obtained in 1997 using soil thermometers.

Major weed species included wild oats (*Avena fatua*), volunteer canola (*Brassica napus*), wild mustard (*Brassica kaber*), stinkweed (*Thlaspi arvense*), wild buckwheat (*Polygonum convolvulus*), and round-leaved mallow (*Malva rotundifolia*). These were controlled chemically with a Hoe-Grass 284™ (diclofop methyl 795 g ai ha^{-1}) and MCPA amine (877 g ai ha^{-1}) tank mix. This was followed by a Tilt™ (propiconazole 125g ai ha^{-1}) application for control and prevention of fungal diseases.

Crop harvesting and soil sampling at anthesis (Zadoks 68-69, Zadoks et al. 1974) and maturity (Zadoks 91-93, Zadoks et al. 1974) were conducted in the same way as described for previous sites.

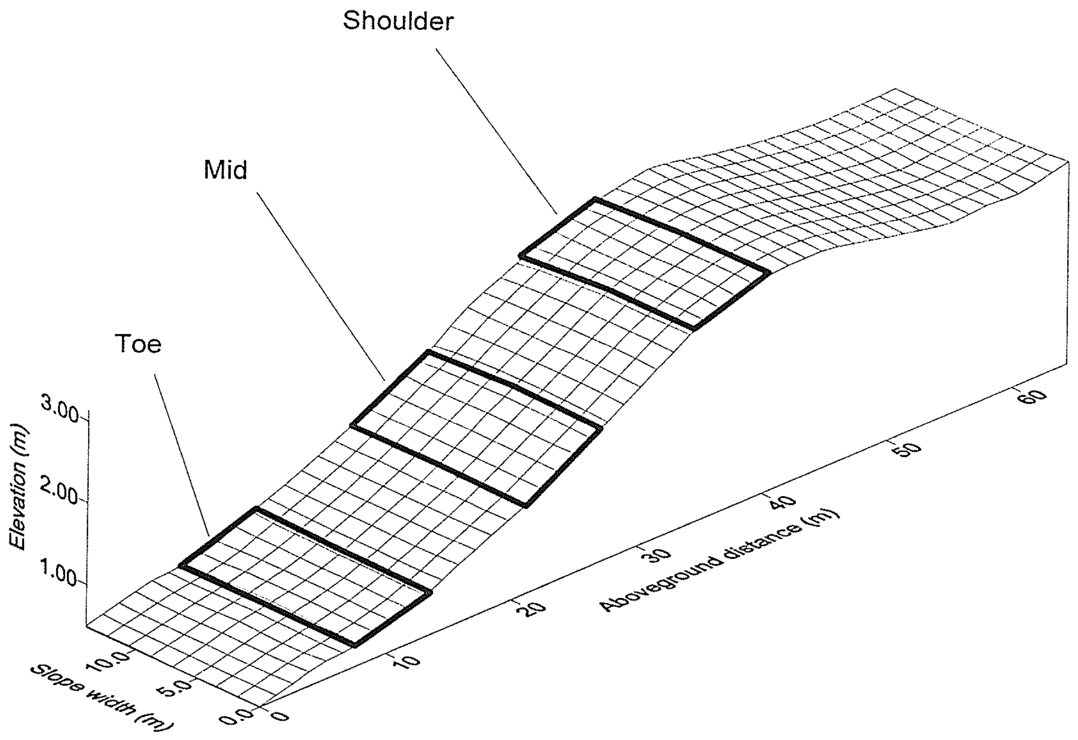

Figure 3.3 Sample catena found at Forrest 1997 site illustrating the three landscape positions studied: Toeslope, Midslope, and Shoulder.

3.1.1.4 Minnedosa. This site was located on the NW 29-14-18 W1. Four catenas were studied at this location. However, the length of these slopes was somewhat longer than the other sites at approximately 53 m. This allowed the catena to be separated into four positions rather than just three. These positions were termed toeslope, lower midslope, upper midslope, and knoll slope positions. These slopes had SE to ESE (115 - 130°) aspects and slope gradients ranging from 9.5 to 11% (Figure 3.4). The toeslope positions were located next to a marsh complex and were therefore areas of relatively high water tables. The knoll positions were located at divergent areas at the crest of the slope. The lower and upper midslope positions were then placed equidistantly between the toeslope and knoll positions. The knoll position in replicate 1 was abandoned due to poor growth associated with an ethalfluralin spill the previous spring.

Seeding, cultivar selection, spring soil sampling, fertilizer applications and anthesis (Zadoks 66-68, Zadoks et al. 1974) and maturity (Zadoks 90-93, Zadoks et al. 1974) plant and soil sampling were all conducted in the same manner as the Forrest 1997 site.

Pest control was accomplished chemically. The major weeds species occurring in this field were volunteer canola (*Brassica napus*), wild mustard (*Brassica kaber*), stinkweed (*Thlaspi arvense*), and wild buckwheat (*Polygonum convolvulus*). These were controlled with 2,4-D amine (877 g ai ha^{-1}). A sequential application of Tilt™ (propiconazole 125 g ai ha^{-1}) was also applied to control and prevent fungal diseases.

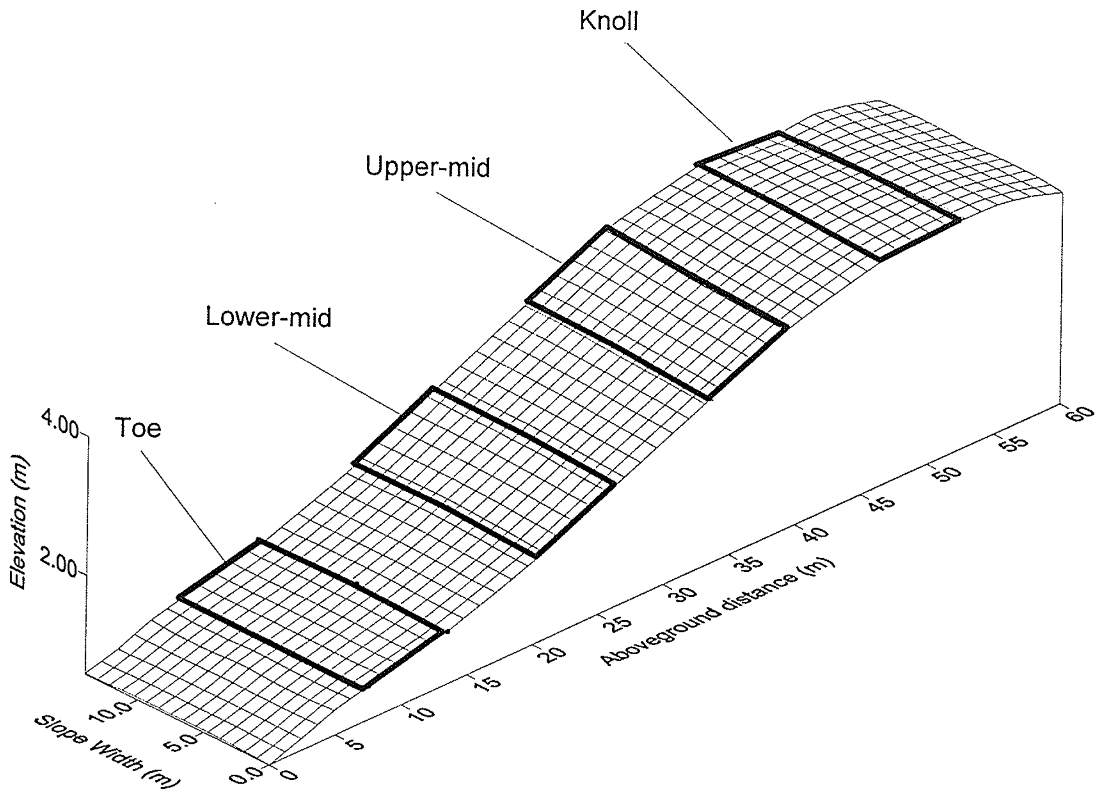

Figure 3.4 Sample catena found at Minnedosa 1997 site illustrating the four landscape positions studied: Toeslope, Lower Midslope, Upper Midslope, and Knoll.

3.1.2 Red River Lacustrine Landscapes

The Red River Association consists of soils that have developed in the central basin of glacial Lake Agassiz (Manitoba Reconnaissance Soil Survey report no. 5 1953). Some of the major characteristics of this association include very fine texture, excessive moisture at one time or another, and very little relief. Agriculture in these landscapes has been made possible by the development of elaborate surface drainage systems.

The positions studied in these landscapes were termed 'microhighs', 'microlows', or 'lows' based on their relative elevations. In these landscapes, differences in topography are quite subtle; the fields studied had a total relief of only 0.5 m to 1 m. The microlows were localized depressional areas of temporary ponding after spring snowmelt and after heavy rainfalls whereas the microhigh positions were slightly more water shedding areas occurring interspersed between the microlows. Areas designated as low were areas where ponding was more prominent and longer lasting generally due to lower relative elevation and slightly higher clay content.

3.1.2.1 Dufresne 1997. This site was located near Dufresne, Manitoba on the east half of 28-9-6 E1. In this relatively level landscape, two transects were established running nearly the length of the entire field. The first transect was approximately 860 m in length and included 2 microlow and 4 microhigh positions. The second transect was approximately 815 m in length and included 4 microlow and 2 microhigh positions thus resulting in a total of 6 replications of each of the microlow and microhigh positions. The total difference in elevation in the study area of this field was approximately 75 cm (Figure 3.5).

Sampling, seeding, and fertilizer application was conducted in the same fashion as the other 1997 sites with the exception that the CWRS cultivar AC Domain was used. The seed was treated with Vitaflo-280™ (14.9% carbatin & 13.2% thiram) fungicide and was seeded at a rate of 141 kg ha^{-1} and 4.5 cm depth due to dry conditions at seeding. Major weed species included volunteer canola (*Brassica napus*), wild buckwheat (*Polygonum convolvulus*), annual smartweed (*Polygonum lapathifolium*), and some patches of Canada thistle (*Cirsium arvense*). These were controlled chemically with a pre-seeding application of Roundup™ (glyphosate 879 g ai ha^{-1}), and Buctril M™ (bromoxynil 280.2 g ai ha^{-1} & MCPA ester 280.2 g ai ha^{-1}), Refine Extra™ (thifensulfuron methyl 2.47 g ai ha^{-1} & tribenuron methyl, 1.24 g ai ha^{-1}) and Horizon™ (clodinafop-propargyl 56.3 g ai ha^{-1}) sprayed in crop as a tank mix. Tilt™ (propiconazole, 125 g ai ha^{-1}) was applied to control and prevent fungal disease infections. Fourteen days prior to harvest, the farmer cooperator had the field sprayed one more time with Roundup™ (glyphosate 879 g ai ha^{-1}) to control some quackgrass patches. Sampling at anthesis (Zadoks 69, Zadoks et al. 1974) and harvest (Zadoks 92-94, Zadoks et al. 1974) was conducted in the same fashion as other sites.

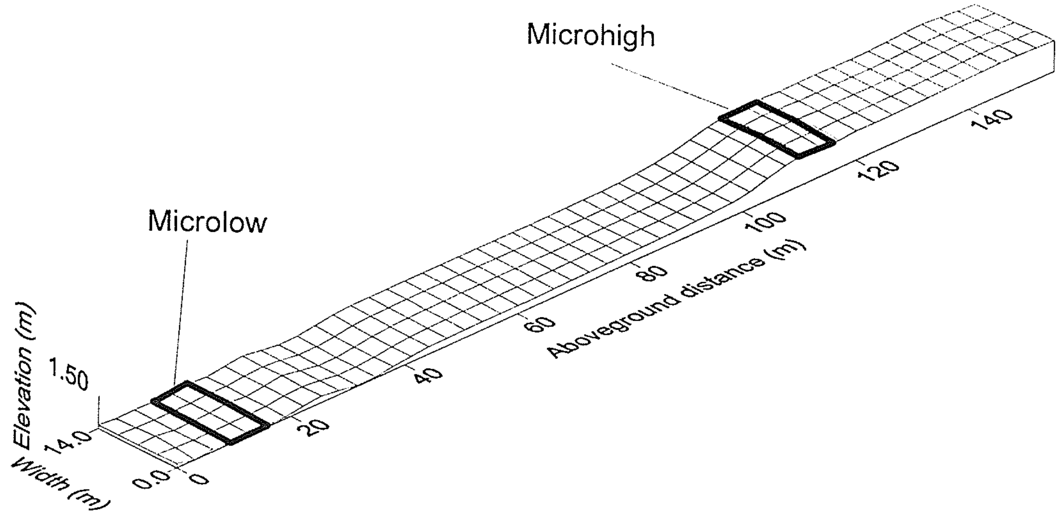

Figure 3.5 Topographic diagram of a portion of the Dufresne 1997 transects showing the two positions studied: Microhigh and Microlow.

3.1.2.2 Elm Creek 1997. This site was located on the west half of 08-09-04 W1 near the town of Elm Creek, Manitoba. Although differences in topography were slight at this site, there was an elevation gradient which ran across the field. The southwest corner is the highest area of this field with elevation gently decreasing towards the northeast corner which represents the lowest area. Like at the Dufresne 1997 site, small plots were established along two transects in this field. The first transect was located on the relatively higher western half of the field and was approximately 550 m long. Five replicates of two landscape positions were selected for study along this transect and were designated as either microhigh or microlow according to their elevation relative to each other and whether they were water shedding or water collecting areas. The second transect was located on the lower eastern half of the field and was approximately 590 m in length. In this area of the field, spring ponding was much more prominent and longer lasting. Only one position was studied in this transect and was designated as low. This slope position was also replicated five times. The total difference in elevation in these two transects was only 50 cm (Figure 3.6).

Soil sampling, seeding, and fertilizer applications were conducted in a similar fashion as the other sites with the exception that the CWRS cultivar AC Majestic was planted at a rate of 101 kg ha^{-1} and was treated with Vitaflo-280™ (14.9% carbatin & 13.2% thiram) fungicide. Forty kg ha^{-1} of monoammonium phosphate (11-52-0) was applied with the seed using a press drill. The press drill had a great deal of trouble penetrating the heavy clay soil and so seeding depth was extremely shallow. Due to difficulties in getting seed penetration to moisture, emergence was very sparse after the first two weeks. To remedy this, each position was irrigated with approximately 1.3 cm of water applied on three separate occasions, totaling 3.8 cm.

Pest control was accomplished using both cultural and chemical means. Because the wheat crop was late in emerging, weed staging was too advanced for effective chemical control so most weeds were pulled by hand. Major weed species included volunteer canola (*Brassica napus*), Canada thistle (*Cirsium arvense*), wild mustard (*Brassica kaber*), wild buckwheat (*Polygonum convolvulus*), and wild oats (*Avena fatua*). A tank mix of Puma™ (fenoxaprop-p-ethyl, 92.1 g ai ha^{-1}), Buctril M™ (bromoxynil, 280.2 g ai ha^{-1} & MCPA ester, 280.2 g ai ha^{-1}) and Refine Extra™ (thifensulfuron methyl, 2.47 g ai ha^{-1} & tribenuron methyl, 1.24 g ai ha^{-1}) was also applied later by the farmer-cooperator. Soil and plants were sampled at anthesis (Zadoks 71-72, Zadoks et al. 1974) and harvest (Zadoks 94, Zadoks et al. 1974) in the same manner as other sites.

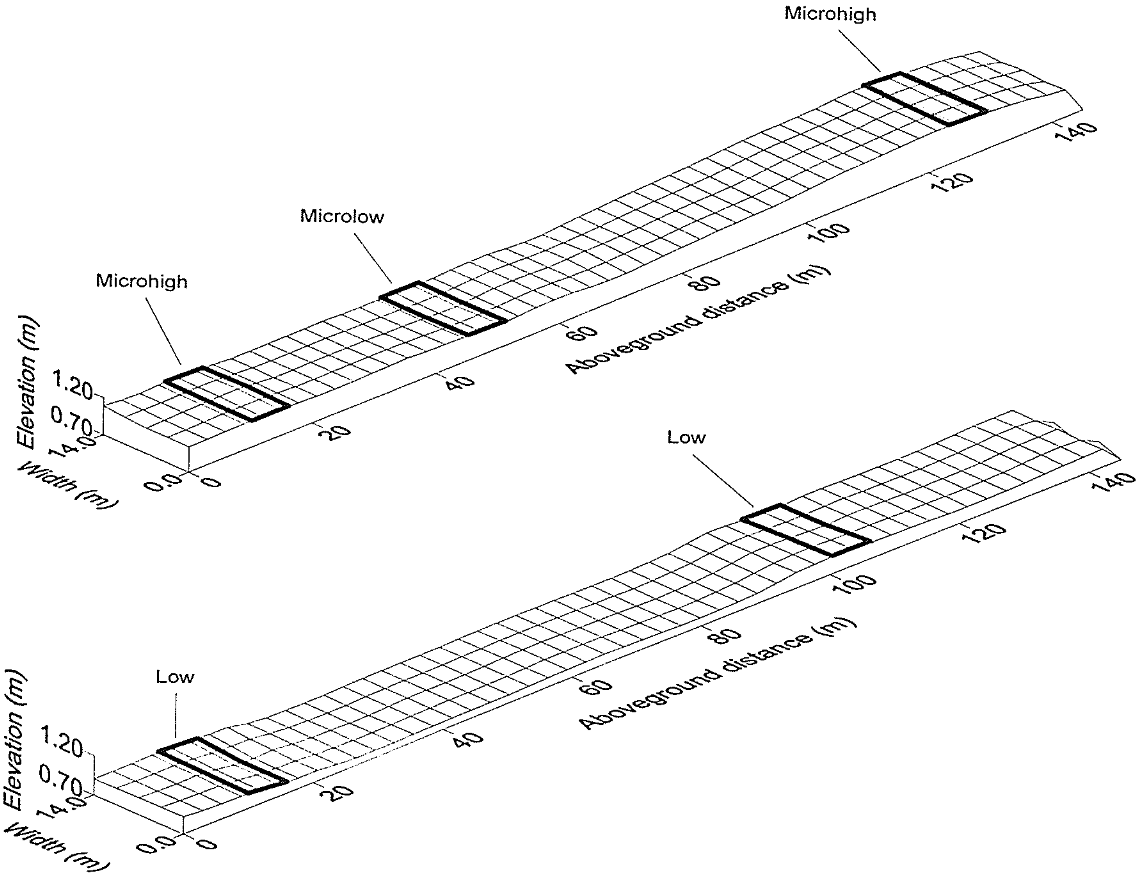

Figure 3.6 Topographic diagram of portions of the Elm Creek 1997 transects showing the three positions studied: Microhigh, Microlow, and Low.

3.2 Soil & Site Descriptions

Soil development and classification was described using the taxonomy of the Canadian System of Soil Classification (Soil Classification Working Group, 1998). Pits were dug, analyzed, and classified to the subgroup level. These soils were further classified to soil series (Manitoba Reconnaissance Soil Survey Reports nos. 5 and 7, 1953 and 1957). Slope gradient was measured using a clinometer and slope aspect using a compass. Many of these parameters are summarized in Tables 3.1 and 3.2.

Relative elevations at all sites were measured using a rod and level. This elevation data was entered into Surfer software to create digital elevation maps (Figures 3.1. to 3.6.).

3.3 Laboratory Procedures

3.3.1 Soil Analyses

Soil nitrate-nitrogen and exchangeable NH_4^+-N were determined as described by Maynard and Kalra (1993). Five grams of air-dried soil and 50 mL of 2 M KCl extraction solution were shaken together in a 100 mL Erlenmeyer flask for 30 minutes. The suspensions were then filtered through Whatman 42 filter paper. The filtrate was collected in 25 mL scintillation vials and kept frozen until analysis. Analysis of the extracts was done using a Technicon® Autoanalyzer®. Nitrate-nitrogen was determined using the cadmium reduction procedure and ammonium-nitrogen using the indophenol blue procedure. The concentrations determined were converted to kg N ha^{-1} using the following calculation:

i) extract concentration ($\mu g\ N\ g^{-1}$) x dilution factor x bulk density ($Mg\ m^{-3}$) x soil depth (m) x 10000 $m^2\ ha^{-1}$ /1000 $g\ kg^{-1}$

Moisture content was determined gravimetrically by oven drying a known weight of fresh soil at 105° C for a minimum period of 24 hours. This was converted to volumetric water content by multiplying the gravimetric moisture measurement by an estimate of the bulk density of the soil. Volumetric water content in a given depth of soil was calculated by multiplying the volumetric water content by the depth of soil. These calculations are summarized in the following equation:

ii) % gravimetric soil moisture x bulk density (g cm^{-3}) x soil depth (mm) = mm of soil water

Water use to anthesis and growing season water use were also calculated for three nitrogen fertilizer rates at each slope position (0 kg N ha^{-1}, 80 or 90 kg N ha^{-1}, 200 kg N ha^{-1}) using the following calculations:

iii) vol. H_2O at seeding + prec. to anthesis - vol. H_2O at anthesis
iv) vol. H_2O at seeding + prec. to harvest - vol. H_2O at harvest

Soil phosphate-phosphorus was determined using a 0.5 M sodium bicarbonate ($NaHCO_3$) extraction and colorimetric analysis as described by Olsen and Sommers (1982). Two and one half grams of soil, 1.0 g washed charcoal and 50 mL of 0.5 M $NaHCO_3$ were combined in a shaking flask and were shaken for 30 minutes. The suspension was filtered through Whatman 42 filter paper into 50 mL beakers. Ten mL of the samples were transferred to medicine cups, adjusted to a pH of 8.5 using 2,4-dinitrophenol as an indicator and concentrated H_2SO_4 to adjust pH. Two mL of color reagent was added to the samples which were subsequently read on a spectrophotometer at a wavelength of 885 nm. These readings were converted to $\mu g\ mL^{-1}$ PO_4-P using a standard curve containing 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 $\mu g\ mL^{-1}$ PO_4-P.

Soil conductivity was determined using the saturation extract method as described by Janzen (1993). Deionized water was added to 200 g of soil to form a saturated paste. A suction filtration procedure was conducted using Whatman 2 filter paper and Buchner funnels. The extract was collected and measured with a conductivity meter.

Potentially mineralizable N was estimated on the 0-30 cm samples of the Minnedosa and Elm Creek sites. The method used was a hot KCl NH_4^+-N extraction described by Gianello and Bremner (1986) with the exception that the NH_4^+-N extracted from a cold KCl extraction was not subtracted from the hot extraction. In a Saskatchewan study, Jalil et al. (1996) reported that potentially mineralizable N was much more closely associated with the hot KCl extraction without the subtraction of the cold KCl extraction. Three grams of soil was combined with 20 mL of 2 M KCl and heated in a digestion block at 100°C for 4 hours. After cooling to room temperature, the NH_4^+-N content was determined by steam distilling the soil-KCl mixture, in the presence of 0.2g of MgO, into 5 mL of boric acid for 6 minutes to obtain 40 mL of distillate. NH_4^+ in the distillate was back titrated with 0.0025 M H_2SO_4 using an automatic titrator. Each mL of H_2SO_4 corresponded to 0.07 mg of NH_4^+-N.

3.3.2 Plant Analyses

Total N was determined in both harvest straw and grain tissue using the combustion nitrogen analysis method as described by Williams et al. (1998). Percent grain protein was calculated by multiplying grain N by a conversion factor of 5.7 and reported at a grain moisture content of 13.5%. Aboveground N uptake was calculated using the following equation with all factors expressed on an oven-dry basis:

vi) % grain N x grain yield + % straw N x straw yield = crop aboveground N uptake

N fertilizer uptake efficiency was also calculated as described by Fiez et al. (1995) using the following equation with all factors expressed on an oven-dry basis:

vii) $(\Delta$ plant N/ΔN fertilizer$) \times 100\%$ = nitrogen fertilizer uptake efficiency

3.4 Statistical Analyses

3.4.1 Soil Property Comparisons

The Tukey-Kramer Honestly Significant Difference test in the 'Fit Y by X' command of JMPIN version 3.1.5. (SAS Institute Inc., 1996) was used to compare soil properties among different slope positions.

Because soil moisture sampling and analysis were only conducted on 3 of the 6 or 7 fertilizer treatments during anthesis and harvest sampling, estimates of soil moisture for the remaining treatments were required. Linear regression analysis for each slope position and soil depth was used to determine if there were any statistically significant trends between soil moisture content and N fertilizer treatment. Where these trends were significant ($\alpha = 0.05$), the predicted intercepts and slopes were used to estimate the missing moisture data. Otherwise, the data was pooled by soil depth and slope position and the mean was utilized.

3.4.2 Nitrogen Response Curves.

Nitrogen response curves were developed for each slope position for the midseason aboveground biomass yields, harvest aboveground biomass yields, and harvest grain yields using 2 different models. First, a quadratic plus plateau model as described by Cerrato and Blackmer (1990), was fit to describe the yield response where applicable. This was accomplished using the NLIN procedure of SAS (1985). This model is defined by the following equations:

a) $\mathrm{Y} = a + b\mathrm{X} + c\mathrm{X}^2 \qquad \text{if } \mathrm{X} < C$
b) $\mathrm{Y} = P \qquad \text{if } \mathrm{X} >= C$

where Y is the grain or aboveground biomass yield (kg ha^{-1}) and X is the rate of N application (kg ha^{-1}), *a* (intercept), *b* (linear coefficient), *c* (quadratic coefficient), *C* (fertilizer rate at the intersection of the quadratic response and the plateau lines), and *P* (plateau yield, considered to be the maximum yield) are constants obtained by fitting the model to the data.

The second model was a simple quadratic model. The parameters for this model were obtained using the 'Fit Y by X' command of JMPIN version 3.1.5. (SAS Institute Inc., 1996). This model is defined by the following equation:

a) $Y = a + bX + cX^2$

These parameters are the same as described in the quadratic plus plateau model. Analyses of Variance were also conducted on the raw data for each response curve using both models. However, for demonstration purposes, figures of the response curves were created using treatment means only.

3.4.3 Yield Response to Applied Nitrogen Comparisons

The nitrogen response curve for each slope position within a site was compared to all other response curves of that same site to determine if there was a difference in yield response to applied nitrogen among slope positions and if so, how they differed. This test was performed using extra sums of squares and indicator variables as described in Chapters 8 and 10 of Neter et al. (1990). Since the quadratic model appeared to adequately fit the yield data obtained, this model was used for the comparisons. The steps of this test are as follows:

1) Put all data from 2 slope positions in question together
2) Run a simple quadratic model through the combined data
3) Make note of the Model Sum of Squares and Error Sum of Squares

Example:

$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i1}^2 + \varepsilon_i$
Where: Y_i = Yield
X_{i1} = Nitrogen fertilizer rate

Forrest, MB 1997 site: Toeslope vs. Midslope grain yield response comparison

Table 3.3 Analysis of variance for quadratic model run through combined toeslope and midslope grain yield data of the Forrest 1997 site.
$n = 42$

ANOVA	df	SS	MS
Regression	2	2725176	1362588
Nrate (X_1)	*1*	*2275311*	
Nrate^2(X_1^2)	*1*	*449865*	
Error	39	5296474	135807
Total	41	8021650	

The analysis of variance arising from this will exhibit high error sum of squares if these curves are significantly different. However, at this stage of the analysis, there is not enough information to decide if the responses are significantly different.

4) Assign each position with an indicator or "dummy" variable
5) Run an analysis on the new model which now contains 2 independent variables; N rate and the indicator variable designating the slope position.

The model then becomes:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i1}^2 + \beta_3 X_{i2} + \beta_4 X_{i1} X_{i2} + \beta_5 X_{i1}^2 X_{i2} + \varepsilon_i$$

Where: Y_i = Yield
X_{i1} = Nitrogen fertilizer rate
X_{i2} = Indicator variable $X_{i2} = 1$ if slope position 1
$X_{i2} = 0$ if slope position 2

Example (continued) – Forrest, MB 1997:

Table 3.4 Analysis of variance for quadratic model with indicator variables run through combined toeslope and midslope grain yield data of the Forrest 1997 site.

ANOVA	df	SS	MS
Regression	5	4572890	914578
Nrate (X_1)	*1*	*2275311*	
Nrate^2(X_1^2)	*1*	*449865*	
Indicator(X_2)	*1*	*804733*	
Nrate x Indicator(X_1X_2)	*1*	*956955*	
Nrate^2 x Indicator($X_1^2X_2$)	*1*	*86026*	
Error	36	3448760	95799
Total	41	8021650	

Including an indicator variable to distinguish which slope position each yield measurement came from, the sum of squares associated with the regression has improved from 2725176 to 4572890. The next step is to determine whether or not this improvement is statistically significant. If it is, we conclude that the responses among the slope positions are significantly different.

6) Test to see if lines are the same using the following hypotheses and test statistic:
H_o: $\beta_3 = \beta_4 = \beta_5 = 0$ (i.e. there are no differences among the response curves)
H_A: not all β_k equal 0
Test Statistic:

$$F^* = \frac{SSR(X_2, X_1X_2, X_1^2X_2 \mid X_1, X_1^2)}{3} \div \frac{SSE(X_1, X_1^2, X_2, X_1X_2, X_1^2X_2)}{(n-6)}$$

if $F^* \leq F(0.95; 3, n\text{-}6)$ then we conclude H_0 (i.e. the curves are not significantly different)

This test statistic should be read as follows: "The increase in the regression sum of squares by adding the X_2 indicator variable divided by 3, divided by the mean square error of the model containing the indicator variable." Essentially, it is expected that if the two response models compared are significantly different from each other, the addition of the indicator variable should greatly increase the sum of squares associated with the regression causing the test statistic to be large.

The increase in the regression sum of squares can be calculated by subtracting the regression sum of squares in Table 3.3 from the regression sum of squares in Table 3.4 (i.e. 4572890 – 2725176). In this example, the test statistic is:

$$F^* = \frac{(4572890 - 2725176)}{3} \div \frac{3448760}{(42-6)}$$

$$F^* = 615905 \div 95799$$

$$F^* = 6.43$$

$$F(0.95, 3, 36) = 2.8663$$

Since $F^* > 2.8663$, we conclude H_A, the two nitrogen response curves are different. Since these responses were quadratic models (i.e. $Y = a + bX + cX^2$), the statistically significant test statistic indicates that either one or more of the parameter estimates (*a, b,* and/or *c*) are significantly different among the slope positions compared. At this time, it is important to discuss the practical significance of determining which parameter estimate(s) is (are) significantly different among the two landscape positions compared.

The *a* parameter estimate is an estimate of the intercept or, in this instance, the expected yield when no nitrogen is applied. If this value is found to be significantly different among the two landscape positions, it simply means that when no nitrogen is applied, it should be expected that the yield will be significantly different. However, this does not provide much insight to help determine how adding more fertilizer N would influence crop yield. To determine this, a closer investigation of the *b* and *c* parameter estimates is required.

The *b* parameter estimate indicates how strong the linear component of the model is. The greater this value, the more yield will increase with increasing N rates. If this value is deemed significantly greater at one slope position, with all else being equal, it could be said that crop yield will increase more with N application at this slope position or that response to N fertilizer is greater.

The *c* parameter estimate indicates how strong the quadratic component of the model is. As described by Cerrato and Blackmer (1990), typical quadratic yield responses to applied N exhibit a positive intercept (*a*) value, a positive linear (*b*) value, and a negative quadratic (*c*) value. In this instance, if the *c* value is a large negative value, yield will increase more rapidly at lower N application rates and decrease more rapidly at higher N rates compared to a *c* value which is closer to zero.

In this study, for practical purposes, two models that differ in the intercept (*a*) value only will not be considered to have differences in response to applied nitrogen fertilizer. Under this scenario, although the yield potential at any given nitrogen fertilizer rate will be significantly different among the two landscape positions studied, the shape of the curves will not be significantly different (Figure 3.7a). Thus, the yield increase from one nitrogen fertilizer rate to the next does not differ among the two landscape positions.

However, two models that differ in their linear (*b*) and/or quadratic (*c*) values will be considered to respond differently to applied nitrogen fertilizer. Under these circumstances, the yield increase from one nitrogen fertilizer rate to the next does differ among the two landscape positions (Figures 3.7b & 3.7c).

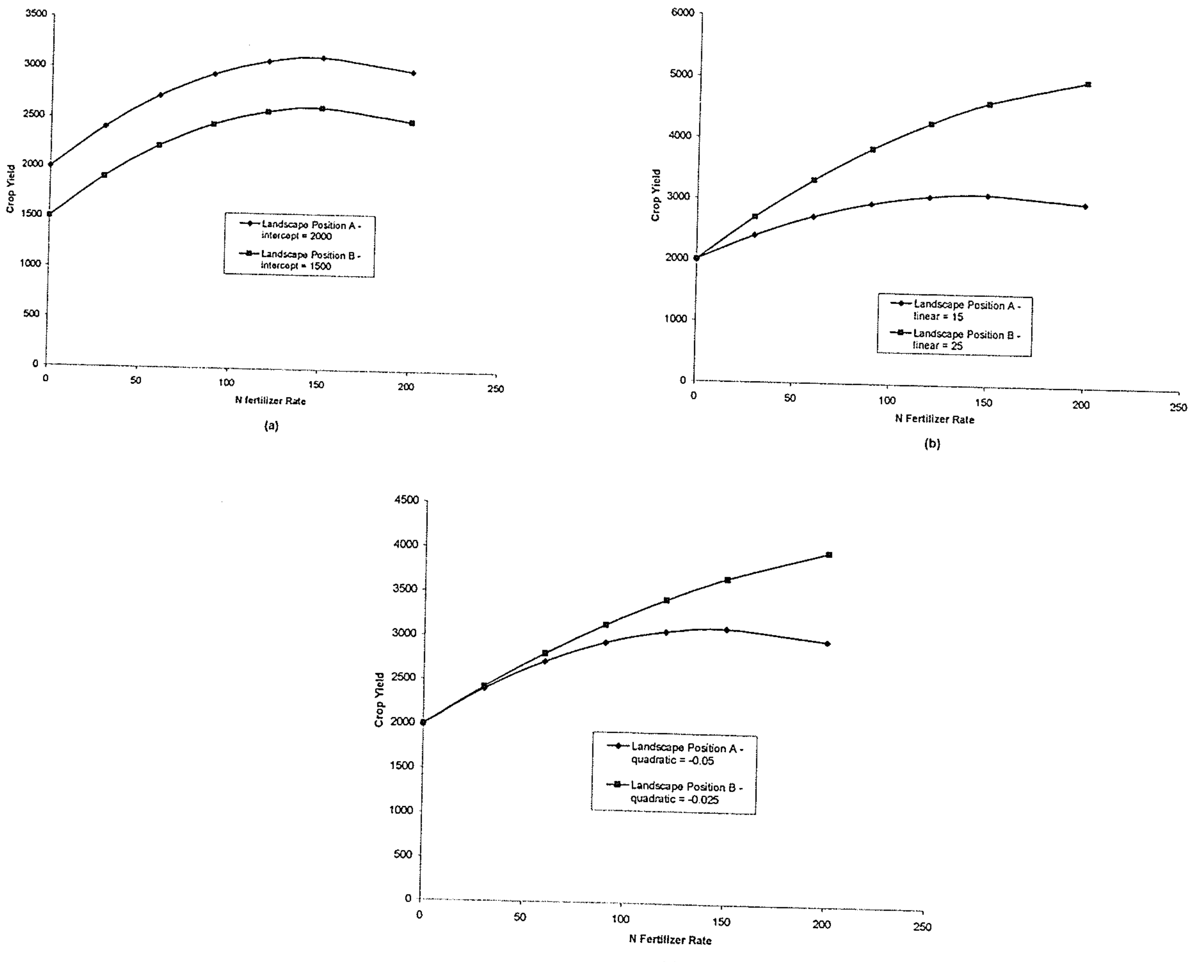

Figure 3.7 Diagrammatic representation indicating differences in quadratic response models under three different scenarios: a) models with differing intercept parameter estimates only; b) models with differing linear estimates only; and c) models with differing quadratic estimates only.

To demonstrate how to test which parameter estimates differ significantly among two models, the Forrest 1997 site example will be utilized. The next step in the analysis is to determine whether the intercept parameter estimates are significantly different. This is accomplished using the following test statistic.

7) Determine if intercepts are different: H_o: $\beta_3=0$
H_A: $\beta_3\neq0$

$$F^* = \frac{SSR\ (X_2 \mid X_1, X_1^2, X_1X_2, X_1^2X_2)}{1} \div \frac{SSE\ (X_1, X_1^2, X_2, X_1X_2, X_1^2X_2)}{(n-6)}$$

if $F^* > F(0.95, 1, 36) = 4.1213$ then the intercepts are significantly different.

Verbally, this can be stated as, "The increase in the sum of squares associated with the regression model by adding the 'X_2' or linear indicator variable, divided by the mean square error."

Similarly, to determine if the linear and quadratic components are significantly different, the following test statistics are utilized:

8) Determine if linear portions are different: H_o: $\beta_4=0$
H_A: $\beta_4\neq0$

$$F^* = \frac{SSR\ (X_1X_2 \mid X_1, X_1^2, X_2, X_1^2X_2)}{1} \div \frac{SSE\ (X_1, X_1^2, X_2, X_1X_2, X_1^2X_2)}{(n-6)}$$

9) Determine if quadratic portions are different: H_o: $\beta_5=0$
H_A: $\beta_5\neq0$

$$F^* = \frac{SSR\ (X_1^2X_2 \mid X_1, X_1^2, X1X2, X_2)}{1} \div \frac{SSE\ (X_1, X_1^2, X_2, X_1X_2, X_1^2X_2)}{(n-6)}$$

Example:

Forrest, MB 1997 site: Toeslope vs. Midslope grain yield response comparison

Test if intercepts are different:
$F^* = 804733 \div 3448760/36$
$F^* = 8.4$
$F\ (0.95, 1, 36) = 4.1213$
Therefore intercepts are statistically different

Test if linear portions are different
$F^* = 956955 \div 3448760/36$
$F^* = 9.989$
$F\ (0.95, 1, 36) = 4.1213$
Therefore linear portions are statistically different

Test if quadratic portions are different

$F^* = 86026 \div 3448760/36$

$F^* = 0.898$

$F(0.95, 1, 36) = 4.1213$

Therefore quadratic portions are not statistically different

3.4.4 Protein Response Curves and Protein Comparisons

Simple linear regression models were utilized to fit the protein content data. These models were developed using the 'Fit Y by X' function of JMPIN version 3.1.5. (SAS Institute Inc., 1996). Analyses of variance were conducted using the raw data.

The protein response curve for each slope position within a site was compared to all other protein response curves of that same site to determine if there was a difference in protein response to applied nitrogen among slope positions and if so, how they differed. Much like the comparisons of yield response, this test was performed using extra sums of squares and indicator variables as described in Chapters 8 and 10 of Neter, Wasserman, and Kutner (1990). However, in this instance, the comparisons were among linear models rather than quadratic models as was the case for the yield data. Since a description of this statistical analysis was described in the previous section, only a brief description with example will be presented here. The description of this test is as follows:

1) Put all data from 2 slope positions in question together
2) Assign each position with an indicator or "dummy" variable
3) Run one regression function for all the data together. Since we are considering a linear function, the regression model becomes:

$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1} X_{i2} + \varepsilon_i$

Where: Y_i = Protein content

X_{i1} = Nitrogen fertilizer rate

X_{i2} = Indicator variable $X_{i2} = 1$ if slope position 1

$X_{i2} = 0$ if slope position 2

4) Test to see if lines are the same using the following hypotheses and test statistic:

H_o: $\beta_2 = \beta_3 = 0$ (i.e. there are no differences among the response curves)

H_A: not all β_k equal 0

Test Statistic:

$$F^* = \frac{SSR(X_2, X_1X_2 \mid X_1)}{2} \div \frac{SSE(X_1, X_2, X_1X_2)}{(n-4)}$$

if $F^* \leq F(0.95; 2, n-4)$ then we conclude H_0 (i.e. the curves are not significantly different)

5) If lines are different, use the following tests to determine how they differ:

i) Determine if intercepts are different: H_o: $\beta_2=0$

H_A: $\beta_2\neq0$

$$F^* = \frac{SSR\,(X_2 \mid X_1X_2)}{1} \div \frac{SSE\,(X_1, X_2, X_1X_2)}{(n-4)}$$

ii) Determine if slopes are different: H_o: $\beta_3=0$

H_A: $\beta_3\neq0$

$$F^* = \frac{SSR\,(X_1X_2 \mid X_1, X_2)}{1} \div \frac{SSE\,(X_1, X_2, X_1X_2)}{(n-4)}$$

Example:

Table 3.5 Analysis of variance for linear model with indicator variables run through combined toeslope and midslope protein content data of the Forrest 1997 site.

n=42

ANOVA	df	SS	MS
Regression	3	74.1801	24.73
Nrate (X_1)	*1*	*50.2772*	
Indicator(X_2)	*1*	*22.3701*	
Nrate x Indicator(X_1X_2)	*1*	*1.5328*	
Error	38	42.1338	1.11
Total	41	116.3139	

$$F^* = \frac{SSR\,(X_2, X_1X_2 \mid X_1)}{2} \div \frac{SSE\,(X_1, X_2, X_1X_2)}{n-4}$$

$F^* = (22.3701 + 1.53281)/2 \div 42.1338/38$

$F^* = 10.78$

$F(0.95, 2, 38) = 3.2448$

Since $F^* > 3.2448$ we conclude H_A, the two grain protein response curves are different

Test if intercepts are different:

$F^* = 22.3701 \div 42.1338/38$

$F^* = 20.18$

$F(0.95, 1, 38) = 4.1393$

Therefore intercepts are statistically different

Test if slopes are different

$F^* = 1.5328 \div 42.1338/38$

$F^* = 1.38$

$F(0.95, 1, 38) = 4.1393$

Therefore slopes are not statistically different

4. RESULTS AND DISCUSSION

Soil properties at different slope positions of both glacial till and lacustrine landscapes were analyzed in order to test the hypothesis that soil properties are associated with the soil landscape. Properties such as NO_3^--N, PO_4-P, electrical conductivity, and particularly soil moisture properties have all been reported to be strongly associated with crop yield and quality properties (Selles et al. 1992, Pan and Hopkins 1991, Malo and Worchester 1975, Partridge and Shaykewich 1972, Henry 1990). In many of these studies, these parameters and others such as depth of A horizon and depth of carbonates (Pennock and de Jong, 1990) have also been reported to be strongly associated with the soil-landscape.

The hypotheses proposed in this study are that soil properties vary systematically according to landscape position and that this variability results in systematic differences in yield and grain protein responses at the soil-landscape scale. Since the aforementioned soil properties have been associated with yield, quality, and the soil-landscape, indices of these properties were analyzed along with grain yield and protein responses to applied nitrogen fertilizer.

4.1 Newdale Till Plain Landscapes

4.1.1 Forrest 1996

4.1.1.1 Catena descriptions. Three slope positions, termed toeslope, midslope, and shoulder, were studied. Each of these positions was located on each of the four catenas studied. These catenas were relatively short and steep with an average length of approximately 32 m and gradients ranging from 8-10% (Table 3.1).

The toeslope positions were adjacent to marsh complexes and thus relatively close to groundwater. According to the Canadian System of Soil Classification (Soil

Classification Working Group 1998), these positions were classified as either Gleyed Rego Black Chernozems or Gleyed Black Chernozems. The 'gleyed' description suggests the presence of faint to distinct mottles within the top 50 cm of these soils. These mottles are the result of fluctuating oxidizing and reducing conditions in soil caused by periods of fluctuating water tables and saturated soil conditions. The occurrence of a near-surface water table likely contributed to relatively higher salt contents in these slope positions (Table 4.1).

The midslope positions were classified as either Rego Black Chernozem or Orthic Black Chernozem profiles. Rego Black Chernozems have very thin B horizons (< 5 cm) or lack a B horizon altogether. In this instance, the lack of well developed B horizons is likely due to the lack of downward migration of water at these locations. Because of the shortness and steepness of these catenas, water will tend to flow over these soils rather than penetrating through the profile. The Orthic Black Chernozems have more prominent B horizons suggesting that water has had more opportunity to penetrate the soil and contribute to profile development.

The shoulder positions were classified as Rego Black Chernozems. Again this suggests that these are areas where water will have a greater tendency to runoff due to the divergent contour and steepness of the slope.

4.1.1.2 Comparisons of soil properties. Differences in spring soil NO_3^--N concentrations among landscape positions were usually not statistically significant (Table 4.1). Only the 0-60 cm depth exhibited differences among the toeslope and shoulder positions with the toeslope having higher nitrate concentrations. Nitrate-nitrogen concentrations have often been found to be higher in lower slope positions in more complex landscapes such as these glacial tills (Franzen et al. 1997). These observations

Table 4.1 Soil property comparisons among slope positions of the Forrest 1996 catenas.

	Spring NO_3-N 0-30 cm (kg ha^{-1})	Spring NO_3-N 0-60 cm (kg ha^{-1})	Spring NO_3-N 0-90 cm (kg ha^{-1})	Spring NO_3-N 0-120 cm (kg ha^{-1})	PO_4-P (mg kg^{-1})	A horizon depth (cm)	Depth to carbonates (cm)	Solum depth (cm)	E.C. 0-30 cm (mS cm^{-1})	E.C. 30-60 cm (mS cm^{-1})	E.C. 60-90 cm (mS cm^{-1})	E.C. 90-120 cm (mS cm^{-1})
Toeslope	52.3a*	104.9a	153.5a	197.7a	9.6a	26.0a	13.3a	46.5a	3.1a	7.0a	8.4a	8.9a
Midslope	52.8a	89.2ab	131.3a	163.7a	6.8a	19.3b	15.5a	34.8b	0.8b	1.4b	3.1b	3.2b
Shoulder	39.7a	64.0b	82.2a	108.9a	4.0a	11.3c	0.0a	11.3c	0.6b	0.6b	0.7c	0.9b

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

have been attributed to erosion from areas higher in the landscape (Elliot and de Jong 1992) and higher mineralization rates at lower positions (Fiez et al, 1995). Spring phosphate concentrations did not differ significantly among slope positions.

Depth of A horizon and solum depth both varied significantly with slope position (Table 4.1) reflecting differences in soil profile development and possibly erosion/deposition processes of A horizon material. A horizon thickness was greatest at lower slope positions and decreased upslope. This was consistent with observations by Pennock and de Jong (1990) who reported that depth of A horizons were highest in lower landscape positions with concave slope curvatures. Moulin et al. (1994) also found similar trends and attributed the greater depths of A horizon to accumulations of organic matter from erosion processes. The importance of this property lies in its association with soil organic matter. Malo et al. (1974) measured % organic matter in the A horizon at different areas in the landscape. They reported that % organic matter content was negatively related to slope positions which experienced high erosion. As such, shoulder slope positions exhibited the lowest organic matter contents with lower slope positions experiencing higher organic matter contents. Due to its importance in many processes such as water retention and nutrient supply through mineralization/immobilization, the organic matter content of a soil is important when considering yield potentials and yield responses at particular positions in the landscape. Depth to carbonates was very shallow at all slope positions (Table 4.1). This is contrary to observations by other researchers (Pennock and de Jong 1990, Brubaker et al. 1993) who reported that carbonate concentrations are generally higher at upper divergent slope positions. However, the slopes in these other studies generally had lower gradients than the ones at the Forrest 1996 site. As described in Section 4.1.1.1, none of these slope positions exhibited profiles that would suggest that leaching is an important process. Significant leaching would be required to redistribute slightly soluble carbonates further down into the soil profile. The shoulder positions were areas where water would have a greater tendency to runoff rather than infiltrate through the soil profile due to the divergent contours. Because the slopes in this study were of relatively high gradient and short in length (Table 3.1), the midslope positions tended to continue this water shedding nature. The toeslope positions were located adjacent to marsh complexes. Downward water flow through the profile would be minimal at these locations and may even be upwards in some instances due to shallow water tables and capillary movement of water. This upward movement of water would be particularly prominent in spring when water tables are generally at their highest levels.

Electrical conductivity (E.C.) measurements were highest at the toeslope positions at all depths (Table 4.1). There were no significant differences in E.C. among the midslope and shoulder positions with the exception of the 60-90 cm depth where the midslope had higher salt concentrations. Similar results by Malo and Worcester (1975) were attributed to higher water tables which brought salts near the soil surface at lower slope positions. Since these toeslopes were adjacent to marsh complexes, it is likely that this is the same process occurring at this site.

Slope position did not have a consistent effect on soil temperature at the Forrest 1996 site (Table 4.2). Only a few soil depths and dates demonstrated statistically significant differences in soil temperature among landscape positions. There were no obvious trends in soil temperature.

Table 4.2 Comparisons of soil temperature in the 80 kg N ha^{-1} treatment among slope positions of the Forrest 1996 catenas.

Date	Depth (cm)	Toeslope	Midslope	Shoulder
May 14	5	8.0a*	8.3a	8.4a
	10	6.7a	6.3a	6.1a
June 11	0	21.8a	22.4a	23.1a
	10	19.7a	19.1a	19.1a
	20	18.9a	18.0b	18.1ab
	30	17.3a	16.4a	16.3a
	60	12.4a	10.9b	10.4b
	90	9.4a	7.2b	6.4b
June 22	0	21.0a	21.7a	21.2a
	10	17.6a	17.9a	17.8a
	20	16.8a	17.2a	17.1a
	30	16.7a	17.0a	16.8a
	60	14.8a	15.2a	15.1a
	90	12.8a	13.2a	13.4a
July 4	0	25.1a	28.3a	27.1a
	10	19.4a	19.6a	19.7a
	20	18.1a	18.0a	18.3a
	30	17.2a	16.9a	17.2a
	60	14.5a	13.5a	13.4a
	90	12.3a	11.1b	11.0b
July 11	0	20.2a	23.2b	22.8b
	10	17.4a	18.0a	17.6a
	20	17.5a	18.1a	17.3a
	30	17.4a	18.0a	17.4a
	60	15.4a	16.0a	15.3a
	90	14.2a	14.2a	13.7a
July 22	0	20.7a	21.7a	21.5a
	10	17.7a	17.9a	17.8a
	20	17.1a	17.2a	17.0a
	30	16.9a	17.0a	16.8a
	60	15.2a	15.2a	14.7a
	90	13.5a	13.2a	12.7a
Aug. 12	0	20.2a	23.2b	22.8ab
	10	17.4a	18.0a	17.6a
	20	17.5a	18.1a	17.3a
	30	17.4a	18.0a	17.4a
	60	15.4a	16.0a	15.3a
	90	14.2a	14.2a	13.7a

* Means within a row followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.1.1.3 Soil water. Slope position had a significant effect on volumetric water content throughout the growing season (Table 4.3). Toeslope positions tended to have higher moisture contents than the midslope or shoulder positions which generally did not differ from each other. Higher soil moisture at lower positions was likely the result of upward capillary flow of groundwater at the toeslope positions and perhaps some accumulation of runoff water from upper slope positions (Malo and Worcester 1975, Elliot and de Jong 1992). As indicated in Table 4.4, despite the higher moisture contents at the toeslopes, water use at anthesis was lowest at these positions and did not differ from the midslope and shoulder positions at harvest. These results may be misleading as they are likely affected by water movement within the soil profile beyond the 120 cm soil depth studied. Because these toeslope positions are located closer to the water table compared to the other positions in the study, capillary rise of ground water may accumulate in these profiles. The calculations in equations iii) and iv) of the Materials and Methods section do not account for capillary water. Therefore, any residual water that originated from capillary forces was subtracted in these equations giving the perception that these areas in the slope with higher accumulations of capillary water were areas of lower water use when in fact this may not have been the case. However, as discussed by Henry (1991) there is a strong positive relationship between water use and yield of wheat. Thus, given the results in Tables 4.5 and 4.6 which demonstrates overall greater yields at the toeslope positions, water use would be expected to be greatest at the toeslopes and least at the shoulder positions.

4.1.1.4 Wheat yield. Although aboveground biomass and grain yields at maturity are unavailable for this site, total aboveground biomass yields at anthesis were taken. Both quadratic and quadratic plus plateau models were fit to this data to determine yield

Table 4.3 Comparisons of volumetric water contents in the 0 kg N ha^{-1} treatment among slope positions of the Forrest 1996 catenas.

	Volumetric Water at Seeding (mm)				Volumetric Water at Anthesis (mm)				Volumetric Water at Harvest (mm)			
Soil Depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Toeslope	127a*	255a	390a	505a	99a	207a	312a	404a	105 a	217a	335a	443a
Midslope	101b	223a	333ab	430ab	49b	112b	196b	279b	75b	144b	240b	329b
Shoulder	95b	197a	295b	393b	53b	118b	198b	274b	71b	147b	227b	310b

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.4 Comparisons of water use in the 0 kg N ha^{-1} treatment among slope positions of the Forrest 1996 catenas.

	Water use to Anthesis (mm)†				Water use to Harvest (mm)‡			
Soil Depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Toeslope	127b*	147b	177b	200a	223a	238a	255a	263a
Midslope	150a	210a	236a	319a	227a	279a	294a	301a
Shoulder	141ab	178ab	198ab	218a	225a	252a	268a	284a

† Precipitation to anthesis was 99 mm
‡ Growing season precipitation was 201 mm
* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

response to applied N. The parameter estimates and p-values from the analyses of variance are summarized in Tables 4.5 and 4.6. The comparisons among these yield response models are listed in Tables 4.7 to 4.9.

According to the 'Whole model' tests, the yield response functions at each slope position differed from all others at this site. Individual tests of the intercept, linear, and quadratic parameters revealed that in all three instances the only differences among the functions of the different slope positions were in the intercept parameter (all differences significant at the p = 0.01 level). As described in the Materials and Methods section, this suggests that the response to incremental applications of N is not different among the different slope positions. To express this in other terms, an additional unit of N fertilizer resulted in a similar increase in yield for all three slope positions in this study. Figure 4.1 demonstrates this visually as very little difference in the shapes of the response curves can be observed. The toeslope had the highest yield potential, followed by the midslope, with the shoulder position expressing the lowest yield potential.

Table 4.5 Parameter estimates and p-values from the analyses of variance for the quadratic model of the midseason biomass yield nitrogen response curves.

Slope Position	Intercept	Linear	Quadratic	Prob. > F
Toeslope	4143.8	16.58	-0.056	0.051
Midslope	3599.4	13.47	-0.047	0.114
Shoulder	3218.7	8.98	-0.031	0.146

Table 4.6 Parameter estimates and p-values from the analyses of variance for the quadratic plus plateau model of the midseason biomass yield nitrogen response curves.

Slope Position	Intercept	Linear	Quadratic	Plateau N rate (kg ha^{-1})	Plateau Yield (kg ha^{-1})	Prob. > F
Toeslope	4004.8	25.20	-0.128	98.6	5246.6	0.043
Midslope	3401.8	26.61	-0.169	78.8	4450.0	0.079
Shoulder	2931.3	40.09	-0.479	41.9	3770.0	0.091

Table 4.7 Comparison among midseason biomass yields of the toeslope and the midslope at Forrest '96 site.

	Test Statistic (F*) value	Prob. > F
Whole model	4.57	0.007
Intercept	13.51	<0.001
Linear component	0.17	0.684
Quadratic component	0.032	0.858

Table 4.8 Comparison among midseason biomass yields of the toeslope and the shoulder position at Forrest '96 site.

	Test Statistic (F*) value	Prob. > F
Whole model	19.71	<0.001
Intercept	58.03	<0.001
Linear component	0.79	0.380
Quadratic component	0.32	0.573

Table 4.9 Comparison among midseason biomass yields of the midslope and the shoulder position at Forrest '96 site.

	Test Statistic (F*) value	Prob. > F
Whole model	2.83	0.008
Intercept	13.14	<0.001
Linear component	0.20	0.658
Quadratic component	0.15	0.704

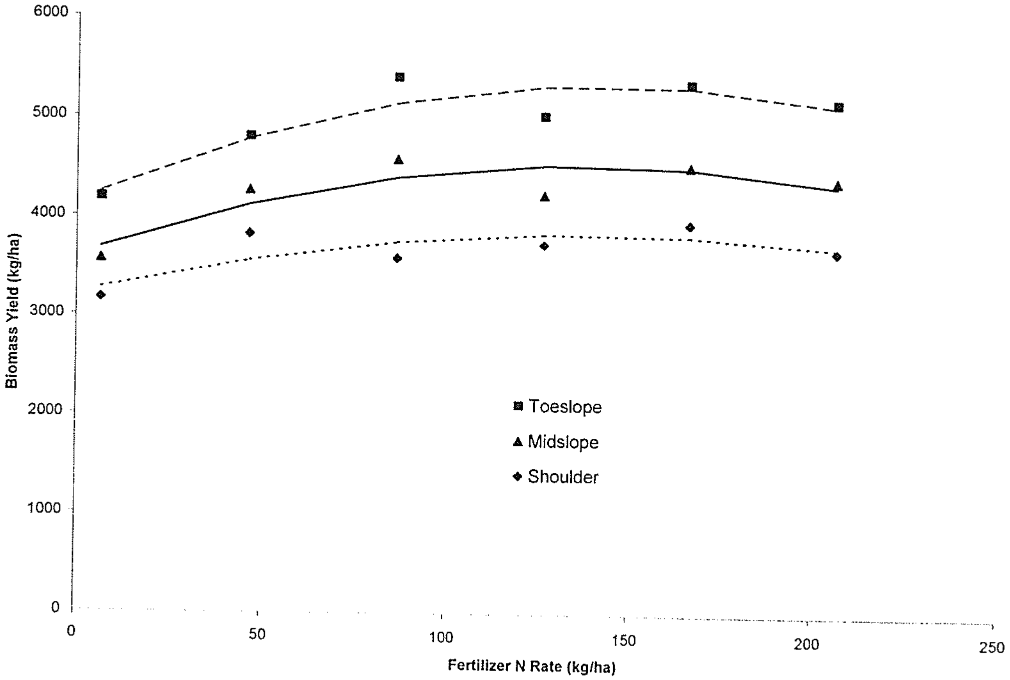

Figure 4.1 Quadratic model indicating total aboveground biomass yield at anthesis – Forrest 1996 site.

4.1.2 Zero Tillage Farm 1996

4.1.2.1 Catena descriptions. This site was set up similar to the Forrest 1996 site. Three slope positions were studied; toeslope, midslope, and shoulder positions. The four catenas at this site averaged 29 m in length and had slope gradients ranging from 8-9.5%.

Once again the toeslope positions studied were adjacent to marsh complexes. The toeslope positions at this site were overall quite saline. However, two of the four replications of these toeslopes were particularly high in salts and visual reductions in crop performance were observed. As such, the toeslope positions were separated into either nonsaline toeslopes or saline toeslopes (two replications of each) based on this visual difference in performance. Therefore, the positions studied at this site became nonsaline toeslopes, saline toeslopes, midslopes, and shoulders. Both the nonsaline and saline toeslopes were classified as Gleyed Rego Black Chernozems; thus, minimal leaching occurs at these sites. Rather, upward movement of water through the profile would be more prominent.

The midslope positions were classified as Rego Black Chernozems or Calcareous Black Chernozems. This suggests once again that leaching would be minimal at these slope positions and that water would tend to runoff instead.

Three different classifications were associated with the shoulder positions. These included Orthic Black Chernozem, Calcareous Black Chernozem, and Rego Black Chernozem subgroups. Given the divergent contours observed at these positions, it was surprising to find that there was enough leaching at one replication to form an orthic profile. However, the overall general tendencies of these positions would be to experience water runoff.

4.1.2.2 Comparisons of soil properties. There were no statistically significant differences between nitrate-nitrogen concentrations for the various slope positions at any depth (Table 4.10). This differs from the Forrest 1996 site where significant differences between slope positions were observed, albeit only at the 0-60 cm depth. Inconsistencies in landscape-based variability in nitrate-nitrogen concentrations are common in agricultural research. Some researchers have found significant differences in this soil property between landscape positions and have attributed it to erosion (Elliot and de Jong 1992) and differences in mineralization rates and organic matter content (Fiez et al. 1995, Malo and Worcester 1975). Brubaker et al. (1993) attributed lack of differences of residual soil nitrates to the application of fertilizer N on a regular basis which leads to uniformity across landscape positions. Franzen et al. (1997) noted variations in correlations between landscape and NO_3^--N to differences in crop rotations and other aspects of field history. There were no statistically significant differences between phosphate concentrations among the slope positions in the present study.

Depth of A horizon was greatest in the saline toeslope followed by the nonsaline toeslope and midslope positions, with the shoulder positions having the shallowest A horizon. Considering that soil A horizons arise from the addition of organic matter to mineral soil, and that organic matter concentrations are often reported to be higher at lower slope positions (Brubaker et al. 1993, Malo et al. 1974), these results are not surprising. These same trends observed by Malo et al. (1974) were described as being due to erosion of organic matter from upper slope positions and higher moisture regimes of the lower positions. Better moisture conditions at these lower slope positions often results in better growing conditions which causes a buildup of organic matter in these areas in the landscape.

Table 4.10 Soil property comparisons among slope positions of the Zero Tillage Farm 1996 catenas.

	Spring NO_3-N 0-30 cm (kg ha^{-1})	Spring NO_3-N 0-60 cm (kg ha^{-1})	Spring NO_3-N 0-90 cm (kg ha^{-1})	Spring NO_3-N 0-120 cm (kg ha^{-1})	PO_4-P (mg kg^{-1})	A horizon depth (cm)	Depth to carbonates (cm)	Solum depth (cm)	E.C. 0-30 cm (mS cm^{-1})	E.C. 30-60 cm (mS cm^{-1})	E.C. 60-90 cm (mS cm^{-1})	E.C. 90-120 cm (mS cm^{-1})
Nonsaline Toeslope	47.0 a*	89.0a	147.7a	193.3a	7.1a	20.0a	0.0a	30.0a	3.3b	7.1ab	7.8a	5.5a
Saline Toeslope	68.6a	138.4a	194.2a	240.9a	9.5a	32.5b	0.0a	45.0a	6.2a	8.4a	8.8a	5.5a
Midslope	45.8a	109.9a	175.3a	257.3a	5.9a	17.5ac	3.8a	25.5a	1.6c	3.7bc	6.0ab	5.7a
Shoulder	37.6a	64.7a	132.6a	176.9a	6.3a	12.8c	3.8a	28.8a	1.3c	1.4c	2.7b	2.4a

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Because leaching is not likely to be a prominent process in any of these slope positions, the depth to carbonates was shallow throughout these catenas and did not differ between the slope positions studied. For similar reasons, the solum depth did not differ between the slope positions either.

Electrical conductivity values differed significantly between the slope positions studied. At the 0-30 cm depth, the saline toeslope had the highest salt content followed by the nonsaline toeslope with the midslope and shoulder positions showing relatively low salt concentrations. Again, this is probably due to the higher water tables associated with the toeslope positions as they occurred adjacent to marsh complexes. These higher water tables facilitate upward migration of salt via capillary rise into the soil profile. Differences in E.C. values between slope positions gradually disappeared with greater soil depth.

As demonstrated in Table 4.11, there were no significant differences in soil temperature between slope positions at any time during the growing season.

4.1.2.3 Soil water. At seeding time, volumetric water content did not differ between slope positions for the 0-30 cm soil depth (Table 4.12). However, differences occurred with increasing soil depth. These differences were as expected as generally the saline toeslope had the greatest volumetric water, followed by the nonsaline toeslope, and decreasing at the higher slope positions. These soil moisture trends may be the result of a combination of strong rise of capillary water at these toeslope positions as evidenced by the high E.C. estimates and perhaps some runoff from upper slope positions.

No differences in volumetric moisture content between landscape positions were observed at anthesis. Hanna et al. (1982) observed interactions between slope position and time of growing season. They described that these interactions were due to higher

Table 4.11 Comparisons of soil temperature in the 80 kg N ha^{-1} treatment among slope positions of the Zero Tillage Farm 1996 catenas.

Date	Depth (cm)	Nonsaline Toeslope	Saline Toeslope	Midslope	Shoulder
May 14	5	14.1a*	13.2a	14.3a	14.2a
	10	10.2a	9.2a	10.4a	10.8a
June 11	0	31.3a	29.7a	31.5a	32.9a
	10	22.4a	21.4a	22.8a	23.3a
	20	18.1a	17.5a	18.6a	19.0a
	30	15.8a	15.6a	16.3a	16.6a
	60	11.6a	11.5a	11.7a	11.8a
	90	8.5a	8.6a	8.6a	8.3a
June 22	0	24.0a	22.3a	21.8a	21.7a
	10	19.4a	19.1a	18.6a	18.6a
	20	17.9a	17.8a	17.6a	17.7a
	30	17.4a	17.8a	17.3a	17.4a
	60	15.5a	16.2a	15.6a	15.8a
	90	13.5a	14.1a	13.8a	13.8a
July 4	0	26.0a	32.0a	28.3a	31.1a
	10	20.0a	19.9a	20.9a	22.3a
	20	18.2a	18.5a	18.6a	19.1a
	30	17.1a	17.6a	17.4a	18.2a
	60	14.4a	14.1a	14.4a	14.5a
	90	11.7a	12.2a	12.2a	11.9a
July 22	0	20.6a	22.8a	21.8a	22.7a
	10	18.3a	19.0a	18.6a	19.2a
	20	17.5a	17.9a	17.6a	17.8a
	30	17.2a	17.7a	17.3a	17.6a
	60	15.7a	16.0a	15.6a	15.9a
	90	13.9a	13.8a	13.8a	13.8a
Aug. 12	0	17.6a	17.7a	17.4a	17.8a
	10	16.7a	17.4a	16.8a	16.6a
	20	17.1a	17.9a	17.2a	16.9a
	30	17.0a	17.7a	17.1a	17.0a
	60	15.5a	15.8a	15.3a	15.3a
	90	14.3a	14.2a	13.9a	13.7a
Sept. 3	0	21.8a	21.8a	22.7a	23.2a
	10	17.3a	17.8a	17.7a	17.7a
	20	16.8a	17.4a	16.6a	16.8a
	30	16.8a	17.4a	17.0a	16.8a
	60	16.0a	16.3a	16.0a	15.8a
	90	14.6a	14.8a	14.6a	14.2a

* Means within a row followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

evapotranspiration and drainage during the summer months resulting in a net loss of water. However, in their study, the trends reported were opposite to the observations in this study. Hanna et al.'s (1982) data suggested that the spread between available water between the lower slope positions and the upper positions widened rather than narrowed. It is possible that higher evapotranspiration rates at lower slope positions may have caused somewhat of an 'evening out' effect on soil moisture which would explain these observations. However, there is no direct evidence to prove this. At harvest, trends similar to those observed at seeding time were observed once again.

There were very few differences in water use between slope positions at both anthesis and harvest (Table 4.13). Only the water use at the 0-30 cm soil depth at harvest exhibited significant differences between slope positions. In this instance, the water use at the shoulder position was higher than the water use at the saline toeslope. The fact that the saline toeslope appears to have utilized the least amount of water may be a reflection of the poor crop growth at this position throughout the year (Henry 1990). However, it should once again be noted that water arising from capillary forces at the toeslope positions may confound these results.

4.1.2.4 Nitrogen uptake. Growing season nitrogen uptake by the aboveground portions of the crop in the 0, 80, and 200 kg N ha^{-1} treatments is summarized in Table 4.14. Crops on the saline toeslope generally used the least amount of nitrogen season regardless of the amount of N applied. This was a reflection of the poor growth caused by the high salt concentrations at these positions.

There were no significant differences in N fertilizer uptake efficiency at the Zero Tillage 1996 site (Table 4.15). These results are contrary to the general trends observed by Fiez et al. (1995) who reported uptake efficiencies were generally highest at footslope

Table 4.12 Comparisons of volumetric water contents in the 0 kg N ha^{-1} treatment among slope positions of the Zero Tillage Farm 1996 catenas.

	Volumetric Water at Seeding (mm)				Volumetric Water at Anthesis (mm)				Volumetric Water at Harvest (mm)			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Nonsaline Toeslope	112a*	233ab	353ab	477ab	110a	218 a	341a	452a	94ab	161 ab	242ab	327ab
Saline Toeslope	123a	251a	378a	504a	123a	213a	345a	461a	119a	210a	305a	400a
Midslope	107a	201ab	321bc	425bc	96a	189a	294a	399a	73bc	150ab	223ab	327ab
Shoulder	96a	191b	290c	390c	93a	170a	255a	351a	58c	114b	174b	237b

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.13 Comparisons of water use in the 0 kg N ha^{-1} treatment among slope positions of the Zero Tillage Farm 1996 catenas.

	Water use to Anthesis (mm)†				Water use to Harvest (mm)‡			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Nonsaline Toeslope	101a*	114a	111a	125a	219ab	273a	312a	352a
Saline Toeslope	89a	107a	111a	104a	205a	241a	274a	305a
Midslope	111a	113a	132a	136a	236ab	254a	305a	317a
Shoulder	102a	120a	134a	138a	239b	278a	317a	354a

† Precipitation to anthesis was 99 mm

‡ Growing season precipitation was 201 mm

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.14 Growing season nitrogen uptake by the crop in the 0, 80, and 200 kg N ha^{-1} treatments at the Zero Tillage Farm 1996 site.

Slope Position	Nuptake in 0 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 80 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 200 kg N ha^{-1} treatment (kg N ha^{-1})
Nonsaline Toeslope	72.0ab*	122.2a	130.2a
Saline Toeslope	23.3b	59.7b	65.7b
Midslope	115.9a	137.8a	153.3a
Shoulder	100.5a	130.3a	129.0a

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.15 Influence of slope position on increase in N uptake and N fertilizer uptake efficiency at the Zero Tillage Farm 1996 site.

Slope Position	0 to 80 kg N ha^{-1} treatment		0 to 200 kg N ha^{-1} treatment	
	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency
Nonsaline Toeslope	50a*	63%a†	58a	29%a
Saline Toeslope	25a	31%a	42a	21%a
Midslope	22a	27%a	37a	19%a
Shoulder	30a	37%a	29a	14%a

† N fertilizer efficiency calculated as (Δ plant N/ΔN fertilizer) x100%

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

and south backslope positions and lowest at shoulder and north backslope positions. The lack of significant differences observed suggests that the efficiency of fertilizer nitrogen uptake for the various slope positions did not differ.

4.1.2.5 Wheat yield. The parameter estimates for the midseason aboveground biomass, harvest aboveground biomass, and grain yields using the quadratic and quadratic plus plateau models respectively are summarized in Tables 14.16 and 14.17. Overall, both models fit the data reasonably well with the exception of the grain yield at the saline toeslope position. Most of the curves follow the law of diminishing returns where a second order polynomial model exhibits a positive value for the linear parameter estimate and a negative parameter estimate for the quadratic term. In this instance the statistical software generated a function that followed more of a 'U-shaped' yield response with the negative linear estimate and positive quadratic estimate (Figure 4.4). Given our understanding of nitrogen yield responses we would not expect to see yields respond in this fashion with increasing N levels (Cerrato and Blackmer, 1990). Thus, it would not be practical to assume that these results reflect what is actually occurring in nature. As such, there were no comparisons made between the grain yield responses of the saline toeslopes and other slope positions.

Both the midseason and harvest aboveground biomass yield responses to fertilizer N differed between the nonsaline toeslopes and the saline toeslopes (Table 4.18). Further analysis revealed that these differences were mainly due to differences in the intercept value of the models (differences significant at the $p = 0.01$ level). However, differences in the quadratic component of the harvest aboveground biomass were also observed to be significant at the $\propto = 0.20$ level (p-value = 0.195). Figure 4.3 demonstrates this well with the nonsaline toeslope having a much stronger curvilinear appearance compared to the

Table 4.16 Parameter estimates and p-values from the analyses of variance for the quadratic model of the Zero Tillage Farm 1996 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Prob. > F
Nonsaline Toeslope	Midseason biomass	4691.7	22.63	-0.083	0.156
Saline Toeslope	Midseason biomass	2225.2	22.66	-0.084	0.207
Midslope	Midseason biomass	5545.3	8.20	-0.013	0.104
Shoulder	Midseason biomass	4400.3	27.04	-0.116	<0.001
Nonsaline Toeslope	Harvest biomass	4808.9	60.47	-0.241	0.131
Saline Toeslope	Harvest biomass	2200.4	7.25	-0.016	0.825
Midslope	Harvest biomass	7999.4	7.17	-0.009	0.205
Shoulder	Harvest biomass	6837.3	29.49	-0.113	0.064
Nonsaline Toeslope	Grain Yield	2334.3	7.26	-0.030	0.763
Saline Toeslope	Grain Yield	846.2	-1.78	0.025	0.434
Midslope	Grain Yield	2780.5	1.51	-0.0001	0.483
Shoulder	Grain Yield	2491.9	6.07	-0.022	0.415

Table 4.17 Parameter estimates and p-values from analyses of variance for the quadratic plus plateau model of the Zero Tillage Farm 1996 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Plateau N rate (kg ha^{-1})	Plateau Yield (kg ha^{-1})	Prob. > F
Nonsaline Toeslope	Midseason biomass	4729.8	21.49	-0.085	126.4	6087.6	0.196
Saline Toeslope	Midseason biomass	2109.2	28.46	-0.136	104.6	3598.3	0.189
Midslope	Midseason biomass	5545.3	8.20	-0.013	319.6	6856.4	0.230
Shoulder	Midseason biomass	4526.0	21.07	-0.094	112.4	5709.9	0.023
Nonsaline Toeslope	Harvest biomass	2488.2	244.46	-2.676	45.7	8070.0	0.010
Saline Toeslope	Harvest biomass	2200.4	7.25	-0.016	233.6	3046.6	0.825
Midslope	Harvest biomass	7999.4	7.17	-0.009	379.9	9360.6	0.205
Shoulder	Harvest biomass	6475.2	64.44	-0.527	61.1	8443.1	0.067
Nonsaline Toeslope	Grain Yield	1760.1	45.05	-0.515	43.7	2745.4	0.310
Saline Toeslope	Grain Yield	1052.3	-9.28	6.173	0.75	1048.8	1.000
Midslope	Grain Yield	2780.5	1.51	-0.0002	4079.9	5854.3	0.483
Shoulder	Grain Yield	2294.5	26.24	-0.308	42.5	2852.4	0.305

relatively flat saline toeslope response curve. As discussed earlier, this suggests that the marginal yield increases per unit of N added differ significantly.

Comparisons between the nonsaline toeslope and midslope positions revealed that these functions only differed when considering the harvest aboveground biomass yield index (Table 4.19). Once again, this was due to differences in the intercept value (at the $p = 0.01$ level) and the quadratic component (at the $p = 0.05$ level) suggesting that differences in actual yield response to applied N were observed.

There were no significant differences in responses between any of the yield indices of the nonsaline toeslopes and shoulders (Table 4.20). Malo and Worcester (1975) made similar observations. They reasoned that the poor yield responses at the lower slope positions were due to the high moisture contents which caused high salinity and poor root development. The shoulder positions on the other hand experienced poor yield responses due to erosion and minimal water infiltration. Given the soil profile and soil characteristics observed at this site, the same processes may have affected the non-saline toeslope and shoulder positions in this study. Also, the relatively high spring nitrate concentrations at this site may have contributed to small responses to applied N.

Significant differences in midseason and harvest aboveground biomass yield responses to applied N were observed between the saline toeslope and midslope positions, and between the saline toeslope and shoulder positions (Tables 4.21 and 4.22). In all these instances the differences were only due to differences in the intercept values (at $p = 0.01$ level). Higher salt concentrations at these saline toeslopes negatively affected the yields relative to other slope positions. However, once again other factors such as higher spring

Table 4.18 Comparison among the yield indices of the Nonsaline toeslopes and the Saline toeslopes at the Zero Tillage Farm 1996 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	19.21	<0.001
	Intercept	57.62	<0.001
	Linear component	0.006	0.980
	Quadratic component	<0.001	0.994
Harvest Aboveground Biomass	Whole model	16.87	<0.001
	Intercept	48.53	<0.001
	Linear component	0.27	0.608
	Quadratic component	1.81	0.195
Grain Yield	Whole model	*na	na
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na

*na: Not available. These comparisons were not made due to the irregularities in the saline toeslope grain yield response.

Table 4.19 Comparison among yield indices of the Nonsaline toeslopes and the Midslopes at the Zero Tillage Farm 1996 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	1.14	0.349
	Intercept	*na	na
	Linear component	na	na
	Quadratic component	na	na
Harvest Aboveground Biomass	Whole model	4.21	0.013
	Intercept	7.79	0.009
	Linear component	0.37	0.548
	Quadratic component	4.46	0.043
Grain Yield	Whole model	1.32	0.285
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

Table 4.20 Comparison among yield indices of the Nonsaline toeslopes and the Shoulders at the Zero Tillage Farm 1996 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	1.12	0.358
	Intercept	*na	na
	Linear component	na	na
	Quadratic component	na	na
Harvest Aboveground Biomass	Whole model	1.36	0.275
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na
Grain Yield	Whole model	0.28	0.843
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

Table 4.21 Comparison among yield indices of the Saline toeslopes and the Midslopes at the Zero Tillage Farm 1996 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	33.68	<0.001
	Intercept	100.08	<0.001
	Linear component	0.026	0.874
	Quadratic component	0.94	0.339
Harvest Aboveground Biomass	Whole model	70.46	<0.001
	Intercept	211.35	<0.001
	Linear component	0.042	0.839
	Quadratic component	0.003	0.953
Grain Yield	Whole model	*na	na
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na

*na: Not available. These comparisons were not made due to the irregularities in the saline toeslope grain yield response.

Table 4.22 Comparison among yield indices of the Saline toeslopes and the Shoulders at the Zero Tillage Farm 1996 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	30.05	<0.001
	Intercept	89.36	<0.001
	Linear component	0.49	0.492
	Quadratic component	0.31	0.582
Harvest Aboveground Biomass	Whole model	49.71	<0.001
	Intercept	148.33	<0.001
	Linear component	0.045	0.834
	Quadratic component	0.76	0.389
Grain Yield	Whole model	*na	na
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na

*na: Not available. These comparisons were not made due to the irregularities in the saline toeslope grain yield response.

nitrate concentrations or moisture availability may have limited crop response to applied N at the midslope and shoulder positions causing the responses to be similar.

Finally, comparisons between the midslope and shoulder slope positions revealed that there were response differences for the midseason aboveground biomass index only (Table 4.23). These differences were due to differences in both the intercept values (p = 0.01 level) and the quadratic component (p = 0.10 level) of the models. Thus, at this time of season, yield response to applied N was different for these two slope positions. The midslope tended to have yields that were higher than the shoulder at very low and very high N rates with the difference being the least at middle N rates (Figure 4.2). This is typical of relatively higher quadratic values as observed at the shoulder position.

Table 4.23 Comparison among yield indices of the Midslopes and the Shoulders at the Zero Tillage Farm 1996 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	6.41	0.0012
	Intercept	14.33	<0.001
	Linear component	0.86	0.359
	Quadratic component	4.04	0.051
Harvest Aboveground Biomass	Whole model	1.38	0.260
	Intercept	*na	na
	Linear component	na	na
	Quadratic component	na	na
Grain Yield	Whole model	0.65	0.585
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

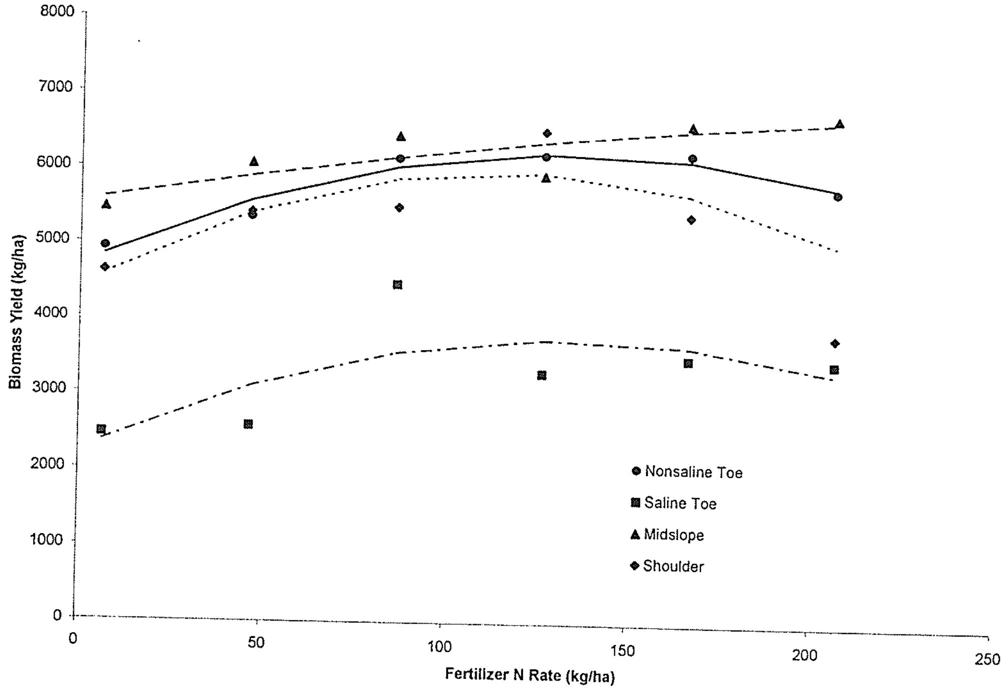

Figure 4.2 Quadratic model indicating total aboveground biomass yield at anthesis – Zero Tillage Farm 1996 site.

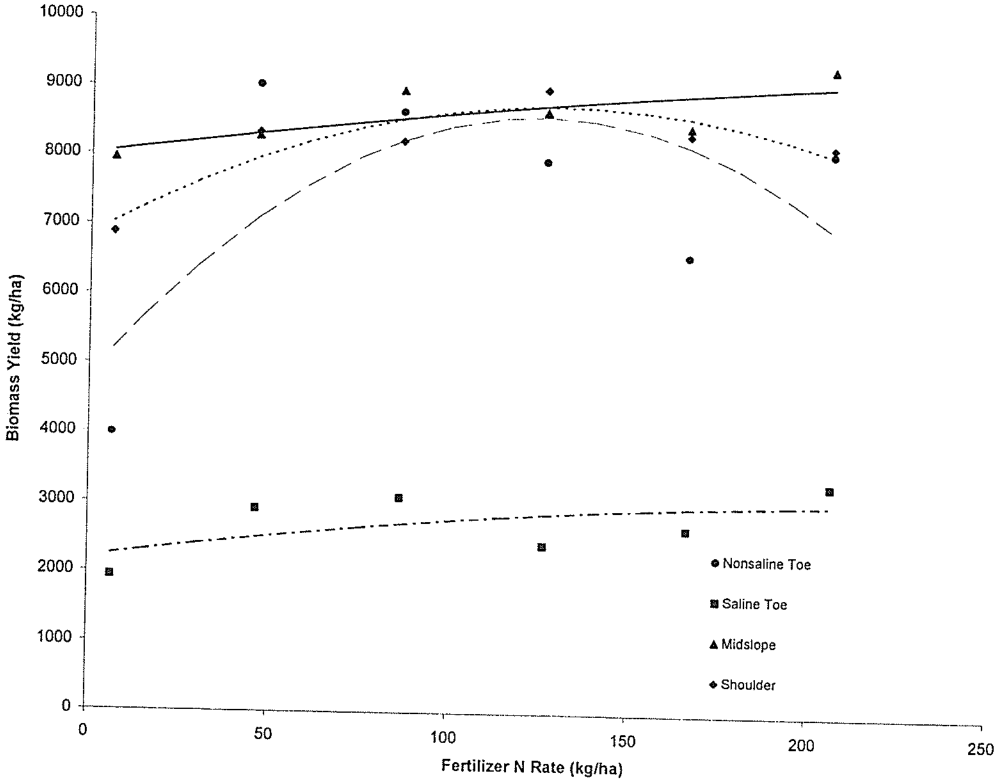

Figure 4.3 Quadratic model indicating total aboveground biomass yield at maturity – Zero Tillage Farm 1996 site.

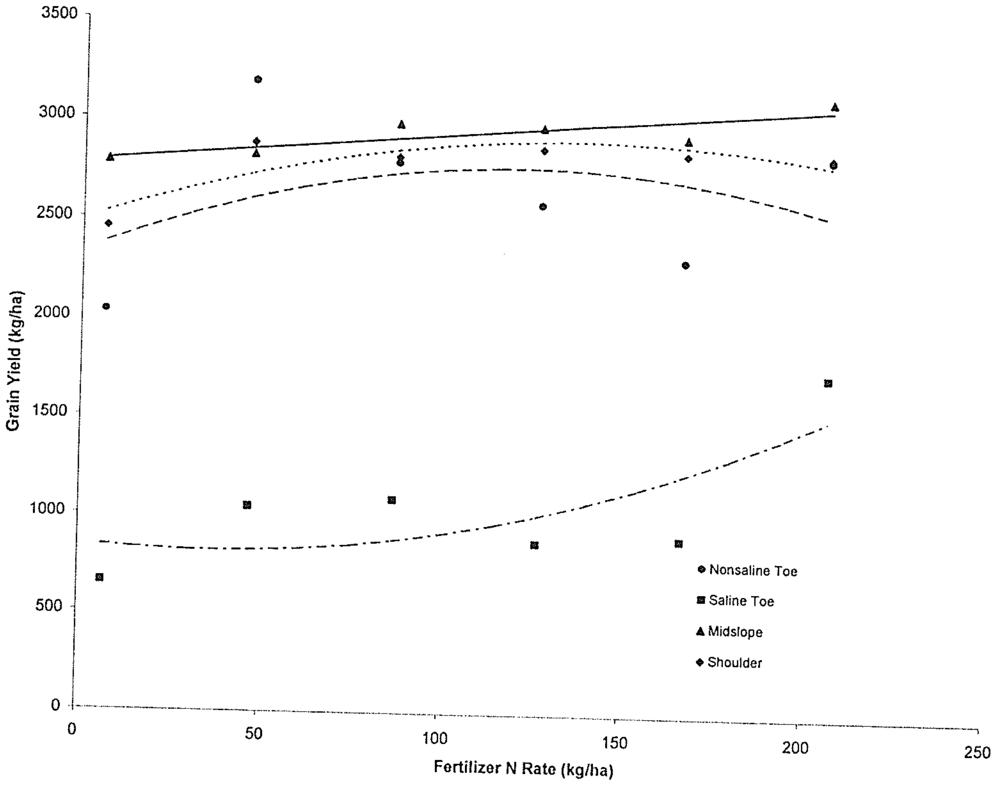

Figure 4.4 Quadratic model indicating grain yield at maturity – Zero Tillage Farm 1996 site.

4.1.2.6 Grain protein. Simple linear regression models were performed on the grain protein data for this site (Table 4.24). Comparisons between these responses revealed significant differences between the following slope positions: nonsaline vs. saline toeslopes, saline toeslopes vs. midslopes, saline toeslopes vs. shoulders, and midslopes vs. shoulders (Table 4.25). In all these cases, the differences occurred in the intercept value (all significant at the $p = 0.01$ level except saline toeslope vs. shoulder was significant at the $p = 0.05$ level) but no differences were observed between the slopes of the curves. Thus, no differences between protein responses were observed at the Zero Tillage Farm 1996 site. This is important in making nitrogen fertilizer rate decisions. With premiums being paid for high protein content in CWRS wheat, even in cases where yield response to added nitrogen is low, it may be economically feasible to add nitrogen if there are significant protein responses.

Table 4.24 Parameter estimates and p-values from the analyses of variance for the protein response curves at the Zero Tillage Farm 1996 site.

Slope Position	Intercept	Slope	Prob. > F
Nonsaline Toeslope	16.3%	0.005	0.050
Saline Toeslope	14.8%	0.009	0.046
Midslope	16.7%	0.004	0.051
Shoulder	15.9%	0.006	0.003

Table 4.25 Comparison among grain protein responses at the Zero Tillage Farm 1996 site.

Slope positions compared		Test Statistic (F*) value	Prob. > F
Nonsaline toeslope vs. Saline toeslope	Whole model	6.28	0.010
	Intercept	11.28	0.004
	Slope	1.29	0.274
Nonsaline toeslope vs. Midslope	Whole model	1.56	0.226
	Intercept	*na	na
	Slope	na	na
Nonsaline toeslope vs. Shoulder	Whole model	0.97	0.390
	Intercept	na	na
	Slope	na	na
Saline toeslope vs. Midslope	Whole model	10.56	<0.001
	Intercept	19.60	<0.001
	Slope	1.52	0.228
Saline toeslope vs. Shoulder	Whole model	3.65	0.040
	Intercept	6.38	0.018
	Slope	0.91	0.349
Midslope vs. Shoulder	Whole model	6.76	0.003
	Intercept	13.16	<0.001
	Slope	0.36	0.552

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

4.1.3 Forrest 1997

4.1.3.1 Catena descriptions. Three slope positions were studied at this site; toeslopes, midslopes, and shoulders. The three catenas at this site were similar to the Forrest 1996 and Zero Tillage Farm 1996 sites in both length (average 32 m) and slope gradient (7-9%).

The toeslopes were next to marsh complexes. With the high water contents associated with these positions, Gleyed Rego Black Chernozem soil profiles prevailed. A horizon depths and solum depths were relatively deep with carbonates found at the soil surface (Table 4.26).

The midslope positions were placed equidistantly between the toeslope and shoulder positions on the catenas. The soil profiles were classified as either Calcareous Black Chernozems or Orthic Black Chernozems suggesting that these profiles experienced slight to moderate leaching.

The shoulder positions were placed just below the crest of the catenas. These positions had a divergent contour which is not generally conducive to leaching. These profiles were classified as Calcareous Black Chernozem profiles. A horizon, carbonates, and solum depths were all relatively shallow due to the lack of moisture at these slope positions (Table 4.26).

4.1.3.2 Comparisons of soil properties. The comparisons between the soil properties measured at the Forrest 1997 site are summarized in Table 4.26. Spring nitrate-nitrogen concentrations were generally high at all landscape positions studied, particularly the midslope position. Nitrate-nitrogen concentrations varied significantly at the 0-60 and 0-90 cm depths only. At the 0-60 cm depth, soil nitrate concentrations were highest at the midslope position. At the 0-90 cm depth, nitrate concentrations were still highest at the

Table 4.26 Soil property comparisons among slope positions of the Forrest 1997 catenas.

	Spring NO_3-N 0-30 cm (kg ha^{-1})	Spring NO_3-N 0-60 cm (kg ha^{-1})	Spring NO_3-N 0-90 cm (kg ha^{-1})	Spring NO_3-N 0-120 cm (kg ha^{-1})	PO_4-P (mg kg^{-1})	A horizon depth (cm)	Depth to carbonates (cm)	Solum depth (cm)	E.C. 0-30 cm (mS cm^{-1})	E.C. 30-60 cm (mS cm^{-1})	E.C. 60-90 cm (mS cm^{-1})	E.C. 90-120 cm (mS cm^{-1})
Toeslope	26.9a	40.9b	65.4ab	90.8a	8.0a	20.0a	0.0a	36.7a	5.0a	8.4a	9.9a	9.7a
Midslope	25.4a	70.9a	144.8a	187.0a	2.5a	14.0ab	8.3a	21.7ab	1.4b	1.7b	4.6b	3.8b
Shoulder	19.5a	31.3b	49.9b	77.0a	4.8a	9.0b	0.0a	13.7b	0.9b	0.8c	1.2c	1.4c

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

midslope position with the toeslope not differing from either the midslope or the shoulder positions. The relatively lower nitrate-nitrogen concentrations observed at the shoulder positions may be due to less contributions from mineralization processes and some erosion losses. The occurrence of intermediate nitrate concentrations in the toeslope position is different from the other glacial till sites in this study which exhibited either higher nitrate concentrations at the toeslope positions or no differences at all between positions. This may be the result of opposing processes with regard to nitrate accumulation. High mineralization rates may be a major factor contributing to nitrate accumulation in the toeslope positions. However, higher crop removal rates and higher potential for denitrification due to higher moisture contents at these toeslopes may result in nitrate losses which offset some of these initial accumulations. None of these processes may be particularly prominent at the midslope positions. In this study, the midslopes tended to outyield the other slope positions but this may not be the case every year. If the toeslope positions significantly outyielded the midslope positions the previous year, then residual nitrate-nitrogen concentrations would be expectedly lower. Leaching or denitrification would not be great concerns at these midslopes. Because the gradients associated with the midslopes of this study are quite steep, there is less opportunity for water to remain standing at these positions. Soil phosphate concentrations were not significantly different between slope positions.

The toeslope positions exhibited greater depths of the A horizon than shoulder positions. The A horizon depth of the midslope positions did not differ from either the toeslope or the shoulder. The thicker A horizons at these toeslope positions are probably largely a result of organic matter buildup from larger crop production and accumulation of eroded materials from upslope positions. There were no significant differences in depth to carbonates between any of the slope positions. This is not unexpected as none of these slope positions would tend to experience strong leaching. The upper slope positions would tend to experience runoff whereas the lower positions would experience capillary rise from a relatively shallow water table. Similar to the A horizon depth, the toeslope had a greater depth of solum than the shoulder positions but the midslope did not differ from either. In this instance, the A horizons of the toeslopes would be quite thick due to the organic matter accumulation as discussed. Although the midslopes had a thinner A horizon, they had B horizon development due to the slight leaching that occurs at these positions, thus adding to the solum depth. The shoulder positions likely experience very little leaching with very thin and poorly developed B horizons.

Electrical conductivity trends can once again be best explained by considering water movement throughout the catenas. With the groundwater table closest to the surface at toeslope positions and furthest from the surface at the shoulder positions, salts are much more prominent at lower positions in the landscape. This is likely the reason why the trends of the E.C. values were highest for the toeslope positions, lowest for the shoulder positions, and intermediate for the midslope positions.

Because of the relatively high costs associated with making thermocouples together with the lack of significant differences in soil temperatures between slope positions in studies conducted the previous year, the acquisition of soil temperature data was less extensive in 1997. Soil temperatures were taken with soil thermometers exclusively. Again, there were few significant differences in soil temperature (Table 4.27). The only statistically significant temperature differences observed were minor (1.2°C or less) and were confined to greater soil depths.

4.1.3.3 Soil water As demonstrated in Table 4.28, volumetric water content was highest at the toeslope positions at seeding. This was probably a result of a combination of runoff from upper slope positions and rise of capillary water at the toeslope positions.

At anthesis, there were no significant differences in volumetric water content between slope positions. As discussed previously, this may be due to high evapotranspiration rates at this time of year which may cause an evening out effect on soil water contents. At harvest, the trends shifted towards higher volumetric water values in the toeslope position with no significant differences between the midslope and shoulder positions. These volumetric water trends at harvest may be caused by lower soil moisture conditions in the shoulder positions due to runoff, lower soil moisture at the midslopes due to a combination of runoff and high crop usage, and water accumulation at the toeslope positions from runoff and capillary rise through the profile and the relatively lower crop yields observed at these positions.

There were no significant differences in water use among slope position neither at anthesis nor at harvest (Table 4.29). As explained previously, the higher yields generally observed at the midslope and toeslope positions would lead one to believe that water use would be highest at these two slope positions (Henry 1990). However, differences in rates of water redistribution among slope positions via processes such as runoff and capillary rise may confound water use data.

4.1.3.4 Nitrogen uptake. Nitrogen uptake by wheat at a particular rate of N was not significantly affected by slope position (Table 4.30). Few differences in yield were observed between slope positions and N uptake is a direct function of yield, thus the lack of significant differences in N uptake were not unexpected. The efficiency of fertilizer uptake did not differ between slope positions (Table 4.31).

Table 4.27 Comparisons of soil temperature in the 90 kg N ha^{-1} treatment among slope positions of the Forrest 1997 catenas.

Date	Depth (cm)	Toeslope	Midslope	Shoulder
May 20	5	9.7a*	8.5a	9.5a
	10	7.0a	6.2a	6.3a
	15	6.2a	5.0b	5.0b
June 6	5	20.3a	19.8a	19.3a
	10	17.5a	17.7a	16.5a
	15	16.8a	16.5ab	15.8b
July 15	5	26.5a	26.2a	27.5a
	10	24.3a	23.5a	25.5a
	20	19.8a	20.2a	21.3a
	30	17.0b	17.5ab	18.2a

* Means within a row followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.28 Comparisons of volumetric water contents in the 0 kg N ha^{-1} treatment among slope positions of the Forrest 1997 catenas.

	Volumetric Water at Seeding (mm)				Volumetric Water at Anthesis (mm)				Volumetric Water at Harvest (mm)			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Toeslope	105a*	216a	325a	436a	92a	192a	301a	409 a	98a	201a	306a	412a
Midslope	92b	188b	298ab	403a	82a	178a	244a	334a	66b	138b	224b	307b
Shoulder	88b	178b	272b	357b	75a	153a	243a	326a	71b	139b	216b	295b

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.29 Comparisons of water use in the 0 kg N ha^{-1} treatment among slope positions of the Forrest 1997 catenas.

	Water use to Anthesis (mm)†				Water use to Harvest (mm)‡			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Toeslope	187a*	197a	197a	200a	236a	243a	247a	253a
Midslope	183a	184a	215a	221a	255a	279a	302a	325a
Shoulder	186a	198a	245a	246a	274a	309a	326a	332a

† Precipitation to anthesis was 173 mm

‡ Growing season precipitation was 228 mm

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.30 Growing season nitrogen uptake by the crop in the 0, 90, and 200 kg N ha^{-1} treatments of the Forrest 1997 site.

Slope Position	Nuptake in 0 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 90 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 200 kg N ha^{-1} treatment (kg N ha^{-1})
Toeslope	49.2a*	106.3a	133.1a
Midslope	84.2a	113.5a	133.6a
Shoulder	65.7a	96.7a	114.0a

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.31 Influence of slope position on increase in N uptake and N fertilizer uptake efficiency at Forrest 1997 site.

Slope Position	0 to 90 kg N ha^{-1} treatment		0 to 200 kg N ha^{-1} treatment	
	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency
Toeslope	57a*	63%a†	84a	42%a
Midslope	29a	32%a	48a	24%a
Shoulder	31a	34%a	49a	24%a

† N fertilizer efficiency calculated as (Δ plant N/ΔN fertilizer) x100%

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.1.3.5 Wheat yield. The parameter estimates for the yield responses to applied N using the quadratic and quadratic plus plateau models respectively are summarized in Tables 4.32 and 4.33. Overall, both models appear to fit the data well.

The comparisons between the models of the toeslope and midslope positions are summarized in Table 4.34. At midseason, there were no significant differences between the two yield responses to applied N. However, at harvest, differences in both the aboveground biomass and grain yield were statistically significant. The harvest aboveground biomass differences observed were largely due to differences in the intercept values (at $p = 0.01$ level) but the linear component was also significant but only at the $\propto = 0.20$ level (p-value 0.196). Grain yield responses to fertilizer N were also significantly different between the toeslope and midslope positions. These response differences were the result of significant differences in both the intercept and linear parameter estimates (at $p = 0.01$ level). These results suggest that although the midslope positions tend to be higher yielding, particularly at lower N application rates, the toeslope positions were more responsive to applied N. As illustrated in Figures 4.6 and 4.7 the difference in yield at low N concentrations is quite wide initially, but narrows significantly with increasing concentrations of N to a point where there is even a crossover in grain yield at high application rates. In a study using various soil parameters to model CWRS wheat, Selles et al. (1992) reported that indices of soil water and soil test

Table 4.32 Parameter estimates and p-values from the analyses of variance for the quadratic model of the Forrest 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Prob. > F
Toeslope	Midseason biomass	3476.1	18.42	-0.046	<0.001
Midslope	Midseason biomass	4061.5	16.53	-0.050	0.139
Shoulder	Midseason biomass	2894.8	21.29	-0.069	0.006
Toeslope	Harvest biomass	4113.6	34.11	-0.083	<0.001
Midslope	Harvest biomass	5719.6	25.57	-0.074	0.030
Shoulder	Harvest biomass	4442.8	41.05	-0.131	<0.001
Toeslope	Grain Yield	1529.6	13.75	-0.038	<0.001
Midslope	Grain Yield	2410.2	4.323	-0.015	0.191
Shoulder	Grain Yield	1762.7	10.05	-0.032	0.018

Table 4.33 Parameter estimates and p-values from the analyses of variance for the quadratic plus plateau model of the Forrest 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Plateau N rate (kg ha^{-1})	Plateau Yield (kg ha^{-1})	Prob. > F
Toeslope	Midseason biomass	3474.3	18.50	-0.0470	197.0	5296.8	<0.001
Midslope	Midseason biomass	3758.4	35.53	-0.236	79.5	5250.3	0.128
Shoulder	Midseason biomass	2811.1	26.03	-0.104	124.8	4435.3	0.006
Toeslope	Harvest biomass	4109.9	34.26	-0.084	202.9	7585.9	<0.001
Midslope	Harvest biomass	5693.1	26.97	-0.084	160.4	7855.5	0.038
Shoulder	Harvest biomass	4433.0	42.07	-0.142	148.1	7548.1	<0.001
Toeslope	Grain Yield	1385.8	21.51	-0.091	118.2	2657.0	<0.001
Midslope	Grain Yield	2204.0	29.64	-0.462	32.1	2679.9	0.070
Shoulder	Grain Yield	1768.8	9.88	-0.032	154.0	2529.9	0.019

nitrates significantly affected yield responses. Where available water was greater and soil-test nitrates were lower, responses to fertilizer N tended to be greater. As summarized in Tables 4.26 and 4.28, this is the case for the toeslope position vs. the midslope at this site.

Comparing the yield responses of the toeslopes and the shoulders (Table 4.35) revealed that significant differences between the responses to applied N at these slope positions occurred only on the midseason aboveground biomass yield. The significant difference between these slope positions was due to differences in the intercept value (at p = 0.01 level), suggesting that at this period of the growing season, the yield potential was higher for the toeslope position but that biomass yield response to the N fertilizer was not significantly different. Because there were no significant differences observed at harvest, one nitrogen response model would likely be sufficient for both of these positions.

The response models of the midslope and shoulder positions for the midseason aboveground biomass and grain yield data were significantly different (Table 4.36). In the case of the midseason biomass results, the differences observed were largely due to the differences in the intercept values (at $p = 0.01$ level). However, for the grain yield index, the intercepts were significant (at $p = 0.01$ level) but the linear components were also significant at the $\propto = 0.20$ level (p-value 0.153). The nearly significant results suggest that although the midslope tended to exhibit higher yields, the shoulder slope was perhaps more responsive to applied N. It is difficult to understand the reason behind this phenomenon. This may be partially due to higher spring soil NO_3^--N concentrations at the midslope positions (Table 4.26).

Table 4.34 Comparison among the yield indices of the Toeslopes and the Midslopes at the Forrest 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	0.91	0.446
	Intercept	*na	na
	Linear component	na	na
	Quadratic component	na	na
Harvest Aboveground Biomass	Whole model	3.16	0.036
	Intercept	7.73	<0.001
	Linear component	1.74	0.196
	Quadratic component	0.013	0.911
Grain Yield	Whole model	2.87	<0.001
	Intercept	8.40	0.006
	Linear component	9.99	0.003
	Quadratic component	0.90	0.350

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

Table 4.35 Comparison among yield indices of the Toeslopes and the Shoulders at the Forrest 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	4.04	0.014
	Intercept	11.48	0.002
	Linear component	0.39	0.538
	Quadratic component	0.24	0.627
Harvest Aboveground Biomass	Whole model	0.76	0.524
	Intercept	*na	na
	Linear component	na	na
	Quadratic component	na	na
Grain Yield	Whole model	0.75	0.530
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

Table 4.36 Comparison among yield indices of the Midslopes and the Shoulders at the Forrest 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	4.74	0.007
	Intercept	14.07	<0.001
	Linear component	0.059	0.809
	Quadratic component	0.081	0.778
Harvest Aboveground Biomass	Whole model	1.30	0.290
	Intercept	*na	na
	Linear component	na	na
	Quadratic component	na	na
Grain Yield	Whole model	4.67	0.007
	Intercept	11.39	0.001
	Linear component	2.14	0.153
	Quadratic component	0.49	0.487

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

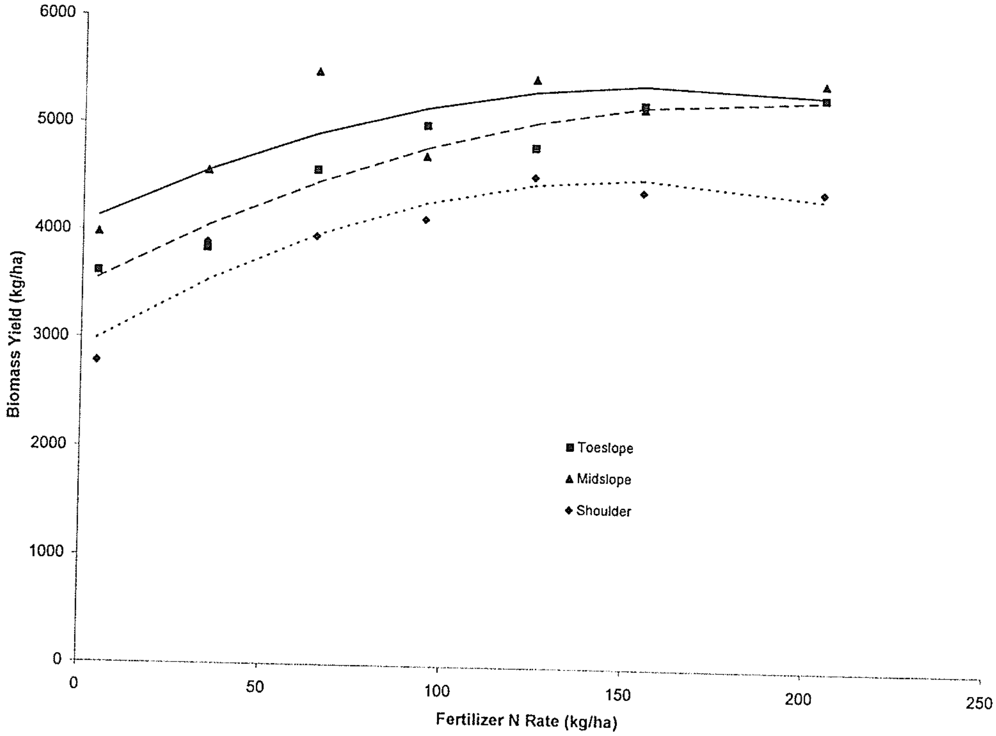

Figure 4.5 Quadratic model indicating total aboveground biomass yield at anthesis – Forrest 1997 site.

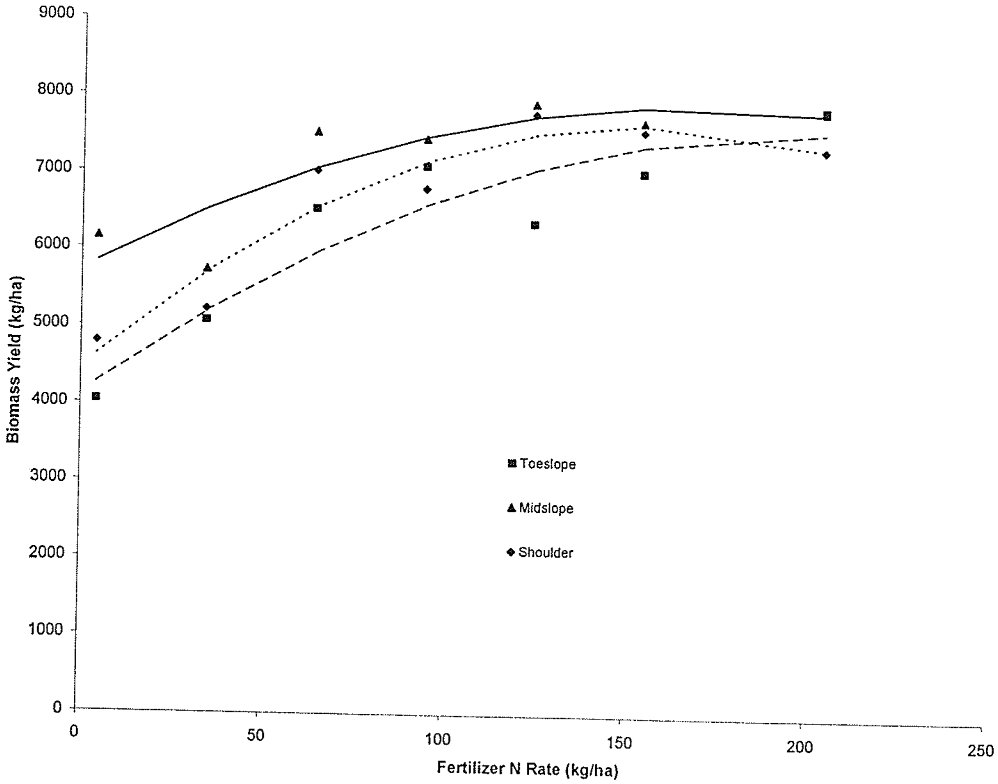

Figure 4.6 Quadratic model indicating total aboveground biomass yield at maturity – Forrest 1997 site.

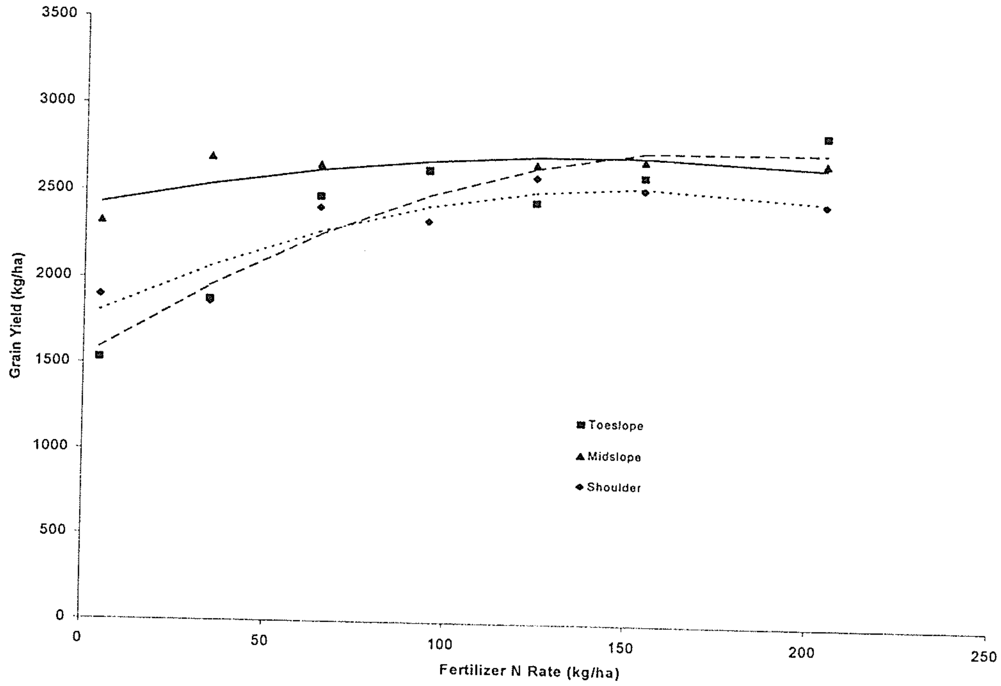

Figure 4.7 Quadratic model indicating grain yield at maturity – Forrest 1997 site.

4.1.3.6 Grain protein. The parameter estimates for the linear regressions performed on the grain protein data are displayed in Table 4.37. The protein content linear regressions appeared to fit the data well. Differences in grain protein responses to applied N were significant between toeslope and midslope and between the midslope and shoulder positions (Table 4.38). There were no statistically significant differences between the toeslope and shoulder positions.

In the toeslope vs. midslope comparison, the differences in response lie in the intercept only (at p = 0.01 level). The midslope experienced higher protein concentrations throughout. This observation is consistent with what was expected, given the smaller grain yield response in the midslope positions. In this instance, it would appear that the additional nitrogen not used for yield went into protein production, a well understood phenomenon (Selles et al. 1997).

The lack of significant differences in the protein content responses to applied N between the toeslope and shoulder positions were not surprising. Although the soil at these slope positions are different and have different forces acting upon them, there were a number of similarities at this site which would account for similar protein contents and protein responses to applied N. These include similar spring nitrate-nitrogen concentrations and the strong similarities in yield responses. Because the yields and the available nitrogen were so similar, the protein concentrations and protein responses to added N turned out similar.

The differences observed between protein responses of the midslope and shoulder positions were largely due to differences in the intercept value (at $p = 0.01$ level) but the differences in slope were also significant at the $\propto = 0.20$ level (p-value 0.154). This suggests that although the protein contents were overall higher at the midslope positions at lower nitrogen rates, protein content increases per unit of nitrogen applied were greater at the shoulder positions than at the midslope positions.

Table 4.37 Parameter estimates and p-values from the analyses of variance for the protein response curves at the Forrest 1997 site.

Slope Position	Intercept	Slope	Prob. > F
Toeslope	12.6%	0.020	<0.001
Midslope	14.6%	0.014	<0.001
Shoulder	12.9%	0.022	<0.001

Table 4.38 Comparisons among grain protein responses at the Forrest 1997 site.

Slope positions compared		Test Statistic (F*) value	Prob. > F
Toeslope vs. Midslope	Whole model	10.78	<0.001
	Intercept	20.18	<0.001
	Slope	1.38	0.247
Toeslope vs. Shoulder	Whole model	0.97	0.338
	Intercept	*na	na
	Slope	na	na
Midslope vs. Shoulder	Whole model	4.93	0.012
	Intercept	7.74	0.008
	Slope	2.12	0.154

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

4.1.4 Minnedosa 1997

4.1.4.1 Catena descriptions. The catenas at the Minnedosa 1997 site were different than the catenas studied in the other three glacial till sites in this (Table 3.1). The Minnedosa 1997 catenas were longer, averaging approximately 53 m in length, and had a different slope aspect, SE to ESE (115-130°). The gradients were comparable to other sites ranging from 9.5% to 11%. Because of the longer slope lengths, these catenas were separated into four slope positions named the toeslope, lower midslope, upper midslope, and knoll positions, respectively. The toeslope positions were located adjacent to a marsh complex. The knolls were on the crest of the catena. The lower midslope and upper midslope positions were placed in between these two in such a fashion that each position would be at an equal distance to the adjacent position(s) on that same catena.

The toeslope positions were classified as either Gleyed Rego Black Chernozems or Gleyed Cumulic Humic Regosols which suggests that these positions have been exposed to periods of saturation and that B horizons are either very poorly developed or absent. Because these toeslopes were adjacent to marsh complexes, these periods of saturation are likely due to near-surface water tables, particularly in the spring.

The lower midslope positions were classified as either Gleyed Rego Black Chernozem or Orthic Black Chernozem profiles. This suggests that gleization at these positions is not as dominant as at the toeslope positions. At the lower midslopes, the mottling suggests that reducing conditions occur periodically, but the presence of B horizons and greater depths to carbonates indicate that there is also some net downward movement of water contributing to profile development.

The upper midslope positions were classified as either Orthic Black Chernozem or Calcareous Black Chernozem profiles. These positions are far enough up the catena that groundwater does not appear to have significantly influenced soil development. The orthic to calcareous designation indicates that there are B horizons present in all of these replications. The leaching potential is slightly greater than the lower midslopes as indicated by the depth to carbonates observed. The calcareous designation in some of these replications suggests that leaching conditions are still not particularly dominant but that some runoff may also be occurring.

The knoll positions were classified as either Rego Black Chernozems, Calcareous Black Chernozems, or Orthic Black Chernozems. The trend towards a less defined B horizon at these crests without any gleying indicates that water runoff is likely a dominant process at these positions. The fact that the carbonates are still found at the soil surface and that solum depths are shallow also support this.

4.1.4.2 Comparisons of soil properties. The comparisons between the soil properties of the slope positions of the Minnedosa 1997 site are summarized in Table 4.39. The toeslope positions had higher concentrations of nitrate-nitrogen than the upper midslope

Table 4.39 Soil property comparisons among slope positions of the Minnedosa 1997 catenas.

	Spring NO_3-N 0-30 cm (kg ha^{-1})	Spring NO_3-N 0-60 cm (kg ha^{-1})	Spring NO_3-N 0-90 cm (kg ha^{-1})	Spring NO_3-N 0-120 cm (kg ha^{-1})	PO_4-P (mg kg^{-1})	Potentially mineralizable N (kg ha^{-1})	A horizon depth (cm)	Depth to carbonates (cm)	Solum depth (cm)	E.C. 0-30 cm (mS cm^{-1})	E.C. 30-60 cm (mS cm^{-1})	E.C. 60-90 cm (mS cm^{-1})	E.C. 90-120 cm (mS cm^{-1})
Toeslope	47.1a*	76.0a	88.8a	98.0a	9.1a	620.1a	31.3a	0.0b	36.3a	4.5a	6.0a	5.5a	4.7a
Lower Midslope	39.9ab	48.5ab	53.5ab	59.5ab	5.1ab	619.1a	19.5b	6.8ab	30.0a	1.4b	1.1b	2.7b	2.8ab
Upper Midslope	21.4b	28.2b	31.5b	34.2b	3.3b	424.8ab	14.0b	21.5a	25.5ab	0.8b	0.6b	0.8b	0.8b
Knoll	20.1ab	24.1b	26.0b	26.7b	2.5b	299.6b	8.3b	0.0b	12.7b	0.8b	0.6b	0.7b	0.8b

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

positions at all depths studied and higher concentrations than the knoll positions at all depths except the 0-30 cm depth where there were no significant differences. The reason why significant differences were not found between the toeslope and the knoll positions at this depth is likely due to insufficient degrees of freedom in the analysis. One of the replications of the knoll positions was abandoned early in the growing season after it was realized that there were high concentrations of ethalfluralin from a chemical spill the previous year at this position. This resulted in poor crop growth and greatly skewed some of the soil analyses.

There were no statistically significant differences in spring nitrate-nitrogen concentrations between any of the other slope positions. Higher organic matter accumulation at lower slope positions may have created greater potential for mineralization which may partially explain the higher NO_3^--N concentrations observed. This is supported by the potentially mineralizable N analyses obtained for this site (Table 4.39). Also, accumulation of nitrates by erosion from upper slope positions and via capillary rise of groundwater may also have contributed to the higher concentrations of NO_3^--N at these toeslopes.

Similarly, phosphate-phosphorus concentrations were higher at the toeslope positions than they were at the upper midslope or knoll positions. This was unlike the other sites in the Newdale Glacial Till plain where no differences were observed. However, several researchers (Verity and Anderson 1990, Franzen et al. 1997, Malo and Worcester 1975, Pan and Hopkins 1991) have reported similar results. This has been correlated to higher organic matter concentrations at lower slope positions (Malo and Worcester 1975) and to higher erosion rates at higher slope positions (Verity and Anderson 1990). There were no other significant differences between phosphate concentrations observed at this site.

Potentially mineralizable nitrogen was also estimated at this site at the 0-30 cm soil depth. This chemical analysis provides an estimate of the amount of nitrogen a particular soil can release from its organic nitrogen pool. Even though every slope position studied appeared to have a high potential to mineralize organic nitrogen, the toeslope and lower midslope positions had significantly higher potentials than the knoll positions. Organic matter concentrations have frequently been reported to be higher at lower positions in the landscape (Verity and Anderson 1990, Malo et al. 1974, Chang 1995). Organic matter has also been reported to be positively associated with A horizon depth (Malo et al. 1974). Given the greater depths of A horizon observed at these lower slope positions of this site (Table 4.39), it is expected that organic concentrations would also be higher at these positions. This would explain the higher potentially mineralizable N values associated with these slope positions.

The depth of A horizon tended to decrease from lower to higher slope positions. The A horizon thickness was the greatest at the toeslope position but there were no other statistically significant differences between other slope positions. Relatively high plant production and accumulation of organic materials via erosion will result in high organic matter accumulation in lower slope positions which would explain these observations. Depth of carbonates was greatest at upper midslope positions, followed by the lower midslope with the toeslope and knoll positions exhibiting the presence of carbonates right to the soil surface. As described in the previous section, greater leaching in the two midslope positions would move these slightly soluble carbonates downward into the profile. Solum depth followed a similar trend to the A horizon depth, decreasing moving upwards on the catenas. The knoll positions had significantly shallower solum depths than the toeslope and lower midslope positions. Relatively lower organic matter accumulations due to poorer plant growth and tendencies for runoff rather than leaching resulted in poorly developed profiles on the knolls in this study.

Electrical conductivity measurements also strongly reflect the water movement in the landscape. The highest levels were observed at the toeslope positions where upward percolation of water through the soil profile has resulted in higher salt concentrations at the soil surface. Although the lower midslope positions exhibited higher salt concentrations than the upper midslope and knoll positions, these differences were not statistically significant.

Soil temperatures observed at this site demonstrated a much stronger pattern than the other sites studied in the Newdale till plain (Table 4.40). There was a general trend of higher soil temperatures at higher slope positions. This is probably due to the high specific heat of water which is more abundant in the lower slope positions.

Table 4.40 Comparisons of soil temperature in the 90 kg N ha^{-1} treatment among slope positions of the Minnedosa 1997 catenas.

Date	Depth (cm)	Toeslope	Lower Midslope	Upper Midslope	Knoll
May 14	5 cm	5.3b*	5.5b	6.3a	5.8ab
	10 cm	4.5b	4.9ab	5.5a	5.3ab
	15 cm	3.6b	4.3ab	4.8a	4.2ab
June 6	5 cm	24.4a	25.5a	24.4a	26.0a
	10 cm	19.8a	21.5a	20.5a	22.0a
	15 cm	16.5b	18.1a	17.5ab	18.7a
July 14	5 cm	23.6a	25.3a	25.5a	27.0a
	10 cm	21.1b	22.9ab	23.1ab	24.5a
	20 cm	17.8c	19.4b	20.1ab	20.8a
	30 cm	16.1c	17.6b	18.4bc	19.0a
August 13	5 cm	19.8a	19.3a	20.6a	21.7a
	10 cm	15.8a	16.8a	18.0a	18.8a
	20 cm	14.6b	14.6b	16.0a	15.5ab
	30 cm	14.6b	14.8ab	15.8a	15.3ab

* Means within a row followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.1.4.3 Soil water Volumetric water contents were expectedly highest at the toeslope positions throughout the growing season (Table 4.41). At seeding time, volumetric water content at the toeslope positions was significantly greater than all other slope positions other than the lower midslope position at the 0-30 cm and 0-120 cm depths. None of the other positions differed significantly from each other at this time. At anthesis, the toeslope was once again significantly higher in volumetric water content than all other positions at all depths with the exception of the 0-60 cm depth of the knoll position. The lack of significant differences observed between these two slope positions may be partly due to insufficient degrees of freedom at the knoll position as discussed earlier. Also, an examination of the yield data demonstrates that all of the yield indices measured were lower at this slope position so water use may be slightly lower. At harvest, volumetric water contents of the toeslopes were significantly higher than the upper midslope positions and the 0-30 cm and 0-60 cm depths of the knoll positions. As at seeding and anthesis, there were no significant differences between the lower midslope, upper midslope, and knoll positions in volumetric moisture content at harvest at any soil depth. The infrequent significant differences observed at harvest time may once again be due to the higher moisture use of the toeslope positions relative to other toeslope positions which is observed in the water use data (Table 4.42) and expected from the higher yields generally observed at the toeslopes (Tables 4.45 & 4.46 and Figures 4.8 to 4.10). Water use was not significantly different between any slope position at anthesis. However, at harvest, particularly at the 0-30 and 0-60 cm depths, significant differences became evident. After a full season of growth, it appeared that water use was greater at the toeslope positions than the upper midslope and knoll positions.

Table 4.41 Comparisons of volumetric water contents in the 0 kg N ha^{-1} treatment among slope positions of the Minnedosa 1997 catenas.

	Volumetric Water at Seeding (mm)				Volumetric Water at Anthesis (mm)				Volumetric Water at Harvest (mm)			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Toeslope	117a*	221a	329a	436a	87a	169a	256a	353a	69a	141a	218a	299a
Lower Midslope	91ab	176b	262b	364ab	69b	119b	199b	278b	59ab	122ab	205ab	289ab
Upper Midslope	78b	153b	231b	306b	61b	121b	184b	249b	54b	104b	167b	236b
Knoll	76b	158b	234b	313b	61b	125ab	192b	257b	53b	109b	173ab	2428ab

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.42 Comparisons of water use in the 0 kg N ha^{-1} treatment among slope positions of the Minnedosa 1997 catenas.

	Water use to Anthesis (mm)†				Water use to Harvest (mm)‡			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Toeslope	185a*	207a	228a	238a	293a	327a	357a	383a
Lower Midslope	178a	188a	195a	218a	278ab	300ab	304b	321a
Upper Midslope	173a	187a	203a	212a	270b	296b	311ab	316a
Knoll	171a	188a	197a	211a	269b	295b	307ab	318a

† Precipitation to anthesis was 155 mm
‡ Growing season precipitation was 246 mm
* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly significant Difference (HSD) Test.

4.1.4.4 Nitrogen uptake. At all nitrogen rates studied, there was a trend of decreasing N uptake from the toeslopes to the upper slope positions in the catena (Table 4.43). This is consistent with the general yield patterns observed where yields were highest at lower slope positions and decreased with increasing elevation.

As demonstrated in Table 4.44, the increase in N uptake for the 90 kg N ha^{-1} treatment at the toeslope position was lower than the upper midslope and knoll positions exhibiting a low N fertilizer uptake efficiency (10%). This may have been due to high mineralization rates through the growing season and/or high spring nitrate concentrations. These differences tended to disappear at the 200 kg N ha^{-1} treatment.

Table 4.43 Growing season nitrogen uptake by the crop in the 0, 90, and 200 kg N ha^{-1} treatments of the Minnedosa 1997 site.

Slope Position	Nuptake in 0 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 90 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 200 kg N ha^{-1} treatment (kg N ha^{-1})
Toeslope	132.1a*	141.0a	175.5a
Lower Midslope	94.6b	119.9ab	168.3a
Upper Midslope	77.3bc	113.3ab	126.9b
Knoll	56.2c	104.4b	112.0b

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.44 Influence of slope position on increase in N uptake and N fertilizer uptake efficiency at Minnedosa 1997 site.

Slope Position	0 to 90 kg N ha^{-1} treatment		0 to 200 kg N ha^{-1} treatment	
	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency
Toeslope	9b*	10%b†	43a	22%a
Lower Midslope	25ab	28%ab	74a	37%a
Upper Midslope	39a	44%a	50a	25%a
Knoll	48a	53%a	48a	24%a

† N fertilizer efficiency calculated as (Δ plant N/ΔN fertilizer) x100%

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.1.4.5 Wheat yield. Results of the yield responses to applied N fertilizer are summarized in Tables 4.45 and 4.46. Overall, none of the slope positions appeared to be responsive to nitrogen fertilizer. Several of the yield responses at this site followed unusual patterns, similar to the saline toeslope of the Zero Tillage Farm 1996 site. The unusual responses to N occurred in the harvest biomass yield index of the toeslope positions and all three yield indices of the lower midslope position using the quadratic model. Using the quadratic plus plateau model, the harvest aboveground biomass and grain yield indices were found to contain unusual responses. Also, the PROC NLIN procedure of SAS was unable to generate parameter estimates for the toeslope harvest aboveground biomass data using the quadratic plus plateau model. As described at the Zero Tillage site for the saline toeslope position, these types of responses to applied

Table 4.45 Parameter estimates and p-values from the analyses of variance for the quadratic model of the Minnedosa 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Prob. > F
Toeslope	Midseason biomass	3952.7	9.84	-0.049	0.821
Lower Midslope	Midseason biomass	3861.9	-2.46	0.027	0.655
Upper Midslope	Midseason biomass	2148.7	13.81	-0.051	0.039
Knoll	Midseason biomass	1610.8	18.80	-0.075	0.006
Toeslope	Harvest biomass	9630.0	-14.41	0.087	0.564
Lower Midslope	Harvest biomass	7130.3	0.30	0.055	<0.001
Upper Midslope	Harvest biomass	5446.7	22.54	-0.065	0.003
Knoll	Harvest biomass	4484.7	24.58	-0.076	0.007
Toeslope	Grain Yield	2666.5	5.61	-0.014	0.155
Lower Midslope	Grain Yield	2561.5	-0.61	0.020	<0.001
Upper Midslope	Grain Yield	2200.3	2.61	-0.001	0.065
Knoll	Grain Yield	1663.8	7.83	-0.027	0.019

Table 4.46 Parameter estimates and p-values from the analyses of variance for the quadratic plus plateau model of the Minnedosa 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Plateau N rate (kg ha^{-1})	Plateau Yield (kg ha^{-1})	Prob. > F
Toeslope	Midseason biomass	3967.3	7.76	-0.044	89.1	4312.7	0.821
Lower Midslope	Midseason biomass	3583.1	16.99	-0.150	56.6	4064.0	0.655
Upper Midslope	Midseason biomass	1742.4	53.17	-0.584	45.5	2952.0	0.009
Knoll	Midseason biomass	1542.0	25.28	-0.147	86.0	2629.4	0.014
Toeslope	Harvest biomass	PROC NLIN FAILED TO CONVERGE					
Lower Midslope	Harvest biomass	7912.9	0.30	109.245	0.0	7912.9	1.000
Upper Midslope	Harvest biomass	5389.6	25.39	-0.083	152.4	7323.7	0.003
Knoll	Harvest biomass	4059.7	52.56	-0.318	82.7	6233.3	0.003
Toeslope	Grain Yield	2515.7	6.86	-0.016	218.1	3263.6	0.233
Lower Midslope	Grain Yield	2776.0	-1.96	14.117	0.1	2775.9	1.000
Upper Midslope	Grain Yield	2200.3	2.61	-0.002	825.5	3278.4	0.065
Knoll	Grain Yield	1530.7	17.22	-0.116	74.5	2172.50	0.008

nitrogen are not natural. Therefore, slope positions expressing these peculiar yield responses were not compared to other positions.

The reason for these anomalous fertilizer response results may have been due to one or both of the following factors. The high potentially mineralizable N results observed at this site (Table 4.39) suggest that the organic fraction of the soil may have contributed significant amounts of nitrogen for the crop in the year of this study. Using labeled

$^{15}NH_4NO_3$ Paul and Myers (1971) observed that mineralized nitrogen can account for up to 55% of the nitrogen taken up by a crop. Under these circumstances, nitrogen derived from fertilizer is much less efficient. Also, the high spring nitrate concentrations measured at the Minnedosa 1997 site could explain the low responses to applied fertilizer N.

The midseason aboveground biomass and grain yield responses for the toeslopes and upper midslopes were significantly different (Table 4.47). In both instances, these differences were mostly due to differences in the intercept values (at the $p = 0.01$ level). This suggests that nitrogen amendments on both of these positions will increase yields in a similar fashion but that the overall yield potential would be greatest for the toeslope positions.

Comparisons in midseason aboveground biomass and grain yield responses of the toeslope vs. knoll positions followed a similar trend as the toeslope vs. upper midslope comparisons (Table 4.48). Significant differences in response to applied N were observed for both yield indices but again these differences are mainly due to different intercept values (at $p = 0.01$ level). It is not difficult to understand why these toeslopes would have higher yield potentials than the two upper slope positions. As seen in much of the data presented, the toeslopes generally demonstrated better fertility levels and better moisture contents. However, these attributes of the toeslope positions should also result in greater responses to applied nitrogen. However, if the toeslope positions have the ability to provide large amounts of nitrogen via existing spring soil nitrates and through mineralization, responses to fertilizer N will be limited. As a result, any fertilizer nitrogen added would not greatly increase crop yield.

There were also significant differences in yield responses between the upper midslopes and knolls when considering all yield indices (Table 4.49). In these instances again, yield differences were mainly a reflection of differences in the intercept values only (at p = 0.01 level). The differences observed between these two positions can once again be attributed to better fertility and moisture contents at the upper midslope positions compared to the knoll positions.

Table 4.47 Comparison among the yield indices of the Toeslopes and the Upper midslopes at the Minnedosa 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	19.52	<0.001
	Intercept	57.12	<0.001
	Linear component	1.44	0.237
	Quadratic component	0.002	0.967
Harvest Aboveground Biomass	Whole model	*na	na
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na
Grain Yield	Whole model	9.64	<0.001
	Intercept	28.66	<0.001
	Linear component	0.08	0.780
	Quadratic component	0.19	0.666

*na: Not available. These comparisons were not made due to the irregularities in the toeslope harvest aboveground biomass response.

Table 4.48 Comparison among yield indices of the Toeslopes and the Knolls at the Minnedosa 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	29.42	<0.001
	Intercept	86.55	<0.001
	Linear component	1.43	0.240
	Quadratic component	0.27	0.607
Harvest Aboveground Biomass	Whole model	*na	na
	Intercept	na	na
	Linear component	na	na
	Quadratic component	na	na
Grain Yield	Whole model	21.78	<0.001
	Intercept	65.11	<0.001
	Linear component	0.05	0.817
	Quadratic component	0.18	0.674

*na: Not available. These comparisons were not made due to the irregularities in the toeslope harvest aboveground biomass response.

Table 4.49 Comparison among yield indices of the Upper midslopes and the Knolls at the Minnedosa site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	2.20	0.102
	Intercept	6.21	0.017
	Linear component	0.001	0.975
	Quadratic component	0.38	0.539
Harvest Aboveground Biomass	Whole model	4.70	0.006
	Intercept	14.05	<0.001
	Linear component	0.01	0.924
	Quadratic component	0.04	0.853
Grain Yield	Whole model	6.68	<0.001
	Intercept	18.70	<0.001
	Linear component	0.001	0.969
	Quadratic component	1.33	0.256

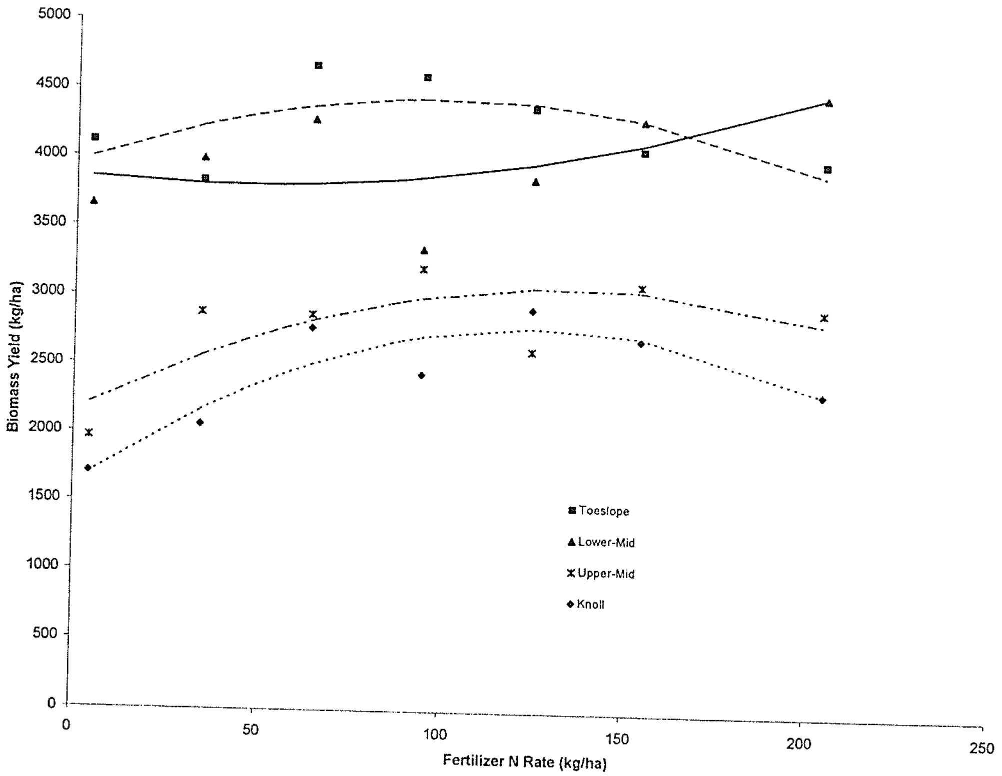

Figure 4.8 Quadratic model indicating total aboveground biomass yield at anthesis – Minnedosa 1997 site.

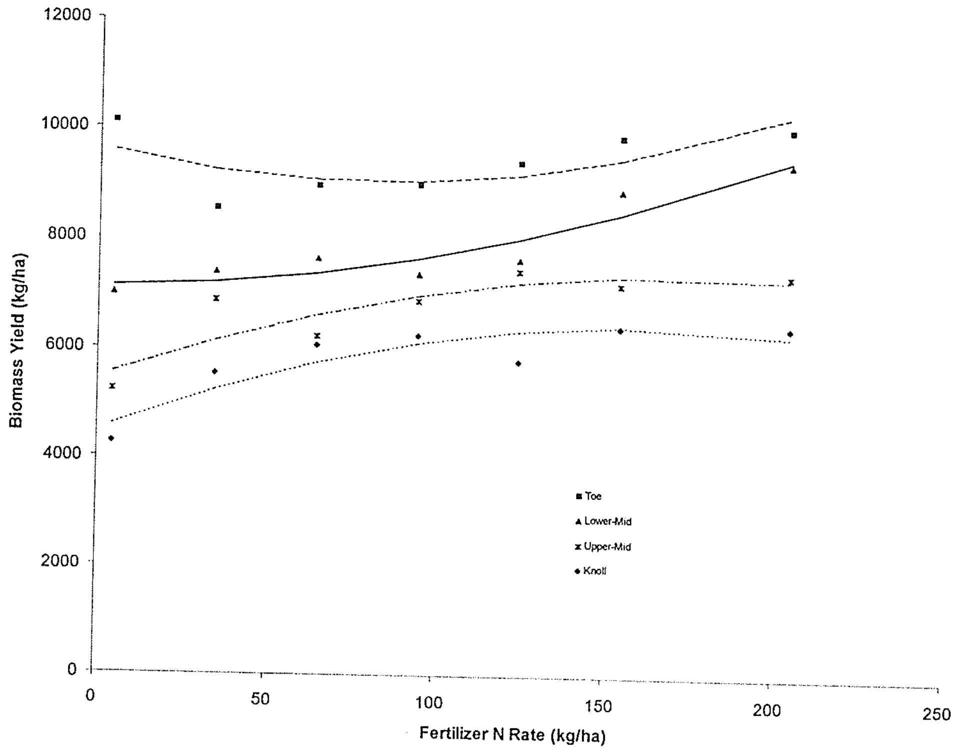

Figure 4.9 Quadratic model indicating total aboveground biomass yield at maturity – Minnedosa 1997 site.

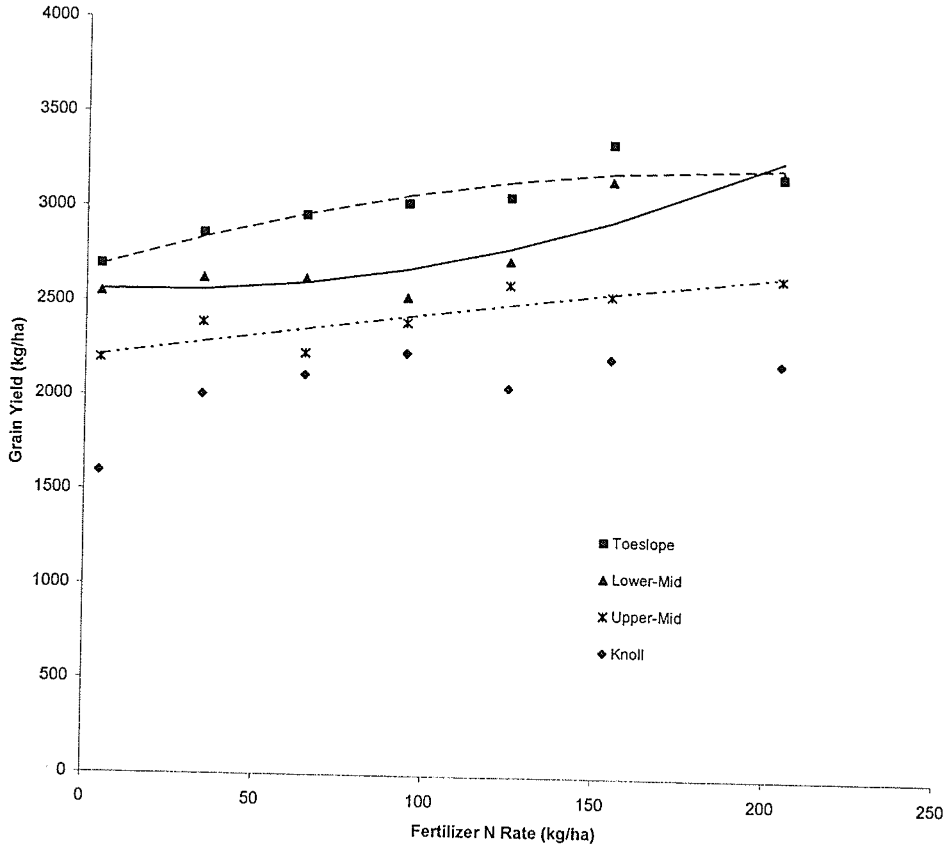

Figure 4.10 Quadratic model indicating grain yield at maturity –Minnedosa 1997 site.

4.1.4.6 Grain protein. The parameter estimates for the protein responses are listed in Table 4.50. Comparisons of the protein response curves (Table 4.51) revealed that the toeslope response differed significantly from the responses of all other slope positions in the study. These differences were significant at the p = 0.05 level for all of the intercept and slope values for each of these comparisons although the comparison with the upper midslope only yielded significant differences in slope at the ∝ = 0.20 level (p-value = 0.129). This suggests that the toeslope positions have higher protein contents overall, particularly at lower nitrogen rates. However, with increasing nitrogen rates, these higher protein contents will become more negligible as the other slope positions are more responsive to applied nitrogen from a protein increase standpoint. Since the grain yield potential was generally more limiting at these upper slope positions, it is not surprising that the protein response to applied N would be greater at these positions (Fowler et al. 1990). There were no significant differences observed between the grain protein responses of the other slope positions at this site.

Table 4.50 Parameter estimates and p-values from the analyses if variance for the protein response curves at the Minnedosa 1997 site.

Slope Position	Intercept	Slope	Prob. > F
Toeslope	16.7%	0.009	0.003
Lower Midslope	15.4%	0.018	<0.001
Upper Midslope	15.4%	0.016	<0.001
Knoll	14.8%	0.021	<0.001

Table 4.51 Comparison among grain protein responses at the Minnedosa 1997 site.

Slope positions compared		Test Statistic (F*) value	Prob. > F
Toeslope vs. Lower Midslope	Whole model	4.31	0.019
	Intercept	3.44	0.069
	Slope	5.19	0.027
Toeslope vs. Upper Midslope	Whole model	4.36	0.018
	Intercept	6.34	0.015
	Slope	2.38	0.129
Toeslope vs. Knoll	Whole model	6.96	0.002
	Intercept	7.80	0.008
	Slope	6.12	0.017
Lower Midslope vs. Upper Midslope	Whole model	0.48	0.622
	Intercept	*na	na
	Slope	na	na
Lower Midslope vs. Knoll	Whole model	0.79	0.461
	Intercept	na	na
	Slope	na	na
Upper Midslope vs. Knoll	Whole model	0.51	0.604
	Intercept	na	na
	Slope	na	na

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

4.2 Lacustrine Landscapes of the Red River Valley

4.2.1 Dufresne 1997

4.2.1.1 Description of landscapes studied. The field where this study was conducted can be characterized as relatively level. It was estimated that there was a maximum of 75 cm of relief throughout the field. The soils had a heavy clay texture. There were two groups of slope positions studied at this site: microhighs and microlows.

As described in Table 3.2, the slope morphology of the microhigh positions can best be described as divergent microelevations. Although they have a slight tendency to shed water, because of the gentle slope gradients (0-0.5%) and the heavy clay soil texture, excess water can still be a concern at these positions. This was evidenced by the Gleyed Humic Vertisol (2 of the 6 replications) and Gleysolic Humic Vertisol (4 of the 6 replications) profiles that were observed at these slope positions. Unlike the excess water observed in the toeslope positions of the Newdale Glacial Till Plain landscapes, this water is mainly due to surface ponding rather than upward percolation from groundwater which is evidenced by the much greater depths to carbonate concentrations.

The microlow positions were depressional areas where water tended to converge. In spring after snowmelt and after heavy showers, these areas experienced water ponding conditions. The classification of these areas were Gleysolic Humic Vertisol (5 of the 6 replications) and one replication was a Gleyed Humic Vertisol although even this replication was very close to a Gleysolic Humic Vertisol. Therefore, it would be expected that these areas experience wetter conditions than the microhighs and at times during the study it was observed that excess moisture negatively affected crop performance.

4.2.1.2 Comparisons of soil properties.

Nitrate-nitrogen concentrations were low at both slope positions (Table 4.52). It is not known why these values were lower than observed at the glacial till sites but it may be due to a number of factors such as low fertilizer application rates by the producer, high crop production and N uptake, and high denitrification rates. The NO_3^--N concentrations of the two slope positions did not differ significantly. Once again, there were no differences in soil phosphate concentrations.

Depth of A horizon, depth to carbonates, and solum depth for the microhighs and microlows did not differ significantly. Based on the similarities observed in soil profiles and the relatively level landscape, we would expect that many of the soil forming processes have been similar between these positions.

Electrical conductivity estimates differed only at the 0-30 cm depth where the microlow positions appeared to be slightly more saline. Given the great depths to carbonates observed at these positions, it is difficult to explain why there would be salts near the soil surface.

Table 4.52 Soil property comparisons among slope positions of the Dufresne 1997 site.

	Spring NO_3-N 0-30 cm (kg ha^{-1})	Spring NO_3-N 0-60 cm (kg ha^{-1})	Spring NO_3-N 0-90 cm (kg ha^{-1})	Spring NO_3-N 0-120 cm (kg ha^{-1})	PO_4-P (mg kg^{-1})	A horizon depth (cm)	Depth to carbonates (cm)	Solum depth (cm)	E.C. 0-30 cm (mS cm^{-1})	E.C. 30-60 cm (mS cm^{-1})	E.C. 60-90 cm (mS cm^{-1})	E.C. 90-120 cm (mS cm^{-1})
Microhigh	14.2a*	25.2a	33.2a	44.3a	6.2a	30.8a	47.5a	40.0a	0.8a	0.7a	0.6a	1.4a
Microlow	14.2a	23.5a	29.2a	35.0a	5.7a	22.5a	55.8a	37.5a	2.4b	0.6a	0.7a	0.7a

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

The only significant differences in soil temperature between landscape positions occurred on the July 25th date (Table 4.53). On this date, temperatures at the microlow positions were higher than the microhigh positions but these slight differences would not likely be agronomically important.

4.2.1.3 Soil water Overall, volumetric water contents in both slope positions were higher than for the glacial till landscapes. The relatively low relief of the lacustrine landscapes and the heavy clay content are important factors contributing to this. At seeding time, there were no significant differences in volumetric water content observed (Table 4.54). At anthesis, significant differences at the 0-30 cm depth were observed with the microlow positions having greater amounts of volumetric water. This is likely due to rainwater starting to converge at these slightly lower areas and not being able to drain through the heavy clay soil profile very quickly. At harvest, these differences were also evidenced at greater depths (0-60, 0-90, and 0-120 cm). Because yields were greater at the microhigh positions, it would be expected that the crop would have taken up more water at these positions (Henry 1990). These positions would also shed some of the excess rainwater to the microlow positions further increasing differences between the observed depth of water.

Water use at anthesis was greater at the microhigh position for the 0-30 cm depth only (Table 4.55). However, by harvest time these differences were observed at all soil depths. The greater crop production at these microhigh positions would be the major reason for the higher water use. Possible redistribution of some water towards the microlow positions would also tend to cause a widening of these values.

Table 4.53 Comparisons of soil temperature in the 90 kg N ha^{-1} treatment among slope positions of the Dufresne 1997 site.

Date	Depth (cm)	Microhigh	Microlow
June 13	5 cm	19.4a*	18.7a
	10 cm	15.8a	15.8a
	15 cm	15.3a	15.6a
July 25	5 cm	23.9a	24.9a
	10 cm	20.4b	21.8a
	20 cm	18.9b	19.7a
	30 cm	18.1b	18.7a

* Means within a row followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.54 Comparisons of volumetric water contents in the 0 kg N ha^{-1} treatment among slope positions of the Dufresne 1997 site.

	Volumetric Water at Seeding (mm)				Volumetric Water at Anthesis (mm)				Volumetric Water at Harvest (mm)			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Microhigh	143a*	301a	459a	613a	134b	285a	446a	601a	140a	265b	407b	553b
Microlow	140a	301a	470a	631a	142a	294a	449a	610a	149a	298a	460a	629a

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.55 Comparisons of water use in the 0 kg N ha^{-1} treatment among slope positions of the Dufresne 1997 site.

	Water use to Anthesis (mm)†				Water use to Harvest (mm)‡			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Microhigh	150a*	156a	153a	152a	199a	232a	248a	256a
Microlow	138b	147a	162a	161a	188b	198b	207b	198b

† Precipitation to anthesis was 140 mm

‡ Growing season precipitation was 196 mm

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.2.1.4 Nitrogen uptake. Nitrogen uptake was significantly greater at the microhigh positions compared to the microlows (Table 4.56). Again, this is largely a reflection of the greater crop production associated with the microhighs.

The data presented in Table 4.57 suggests that the efficiencies associated with the fertilizer use at this site did not differ significantly between the slope positions studied.

Table 4.56 Growing season nitrogen uptake by the crop in the 0, 90, and 200 kg N ha^{-1} treatments of the Dufresne 1997 site.

Slope Position	Nuptake in 0 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 90 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 200 kg N ha^{-1} treatment (kg N ha^{-1})
Microhigh	94.2a*	123.1a	152.8a
Microlow	47.9b	82.9b	100.5b

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.57 Influence of slope position on increase in N uptake and N fertilizer uptake efficiency at Dufresne 1997.

Slope Position	0 to 90 kg N ha^{-1} treatment		0 to 200 kg N ha^{-1} treatment	
	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency
Microhigh	29a*	36%a†	59a	29%a
Microlow	37a	46%a	54a	27%a

† N fertilizer efficiency calculated as (Δ plant N/ΔN fertilizer) x100%

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.2.1.5 Wheat yield. The parameter estimates of the yield responses for the quadratic and quadratic plus plateau models are summarized in Tables 4.58 and 4.59 respectively. Despite the initially low spring soil nitrate-nitrogen concentrations, yield responses to applied N were minimal and crop yields were quite high even when no nitrogen was applied, particularly at the microhigh positions. According to the "General Recommendations for Fertilization in Saskatchewan" (1988), wheat yields comparable to those observed at the zero kg N ha^{-1} treatments should utilize over 100 kg of N ha^{-1}. The zero treatments of the microhigh positions did not have this much nitrogen supplied to them. Mineralization rates were probably high at this site to provide enough nitrogen to support the yields observed.

The comparisons between the responses to applied nitrogen for all three yield indices were significantly different (Table 4.60). However, for all three yield indices, these differences in response functions were due to differences in intercept only (at p = 0.01 level). This suggests that the marginal responses to applied N were similar and that the yield potential is higher at the microhigh positions. The lower yields observed at the microlow positions were largely due to excess water after rainfall events. At times, standing water was observed at some of these positions.

Table 4.58 Parameter estimates and p-values from the analyses of variance for the quadratic model of the Dufresne 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Prob. > F
Microhigh	Midseason biomass	3845.2	1.353	-0.00053	0.766
Microlow	Midseason biomass	2178.4	14.26	-0.042	0.012
Microhigh	Harvest biomass	7087.2	18.36	-0.057	0.016
Microlow	Harvest biomass	3815.9	31.93	-0.100	0.032
Microhigh	Grain Yield	2927.6	6.02	-0.018	0.067
Microlow	Grain Yield	1327.7	13.86	-0.045	0.039

Table 4.59 Parameter estimates and p-values from the analyses of variance for the quadratic plus plateau model of the Dufresne 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Plateau N rate (kg ha^{-1})	Plateau Yield (kg ha^{-1})	Prob. > F
Microhigh	Midseason biomass	3845.2	1.35	-0.00053	1280.2	4711.1	0.669
Microlow	Midseason biomass	2192.3	13.72	-0.040	173.6	3383.5	0.012
Microhigh	Harvest biomass	7067.3	19.47	-0.066	147.3	8501.3	0.032
Microlow	Harvest biomass	3818.1	32.19	-0.106	152.4	6271.4	0.017
Microhigh	Grain Yield	2959.3	3.76	-0.013	149.1	3239.7	0.259
Microlow	Grain Yield	1330.8	13.92	-0.047	146.8	2352.5	0.041

Table 4.60 Comparison among the yield indices of the Microhigh and the Microlow positions at the Dufresne 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	3.71	0.017
	Intercept	8.81	0.004
	Linear component	0.11	0.746
	Quadratic component	2.21	0.143
Harvest Aboveground Biomass	Whole model	19.73	<0.001
	Intercept	58.12	<0.001
	Linear component	0.80	0.372
	Quadratic component	0.26	0.611
Grain Yield	Whole model	2.80	<0.001
	Intercept	70.19	<0.001
	Linear component	1.10	0.297
	Quadratic component	0.53	0.466

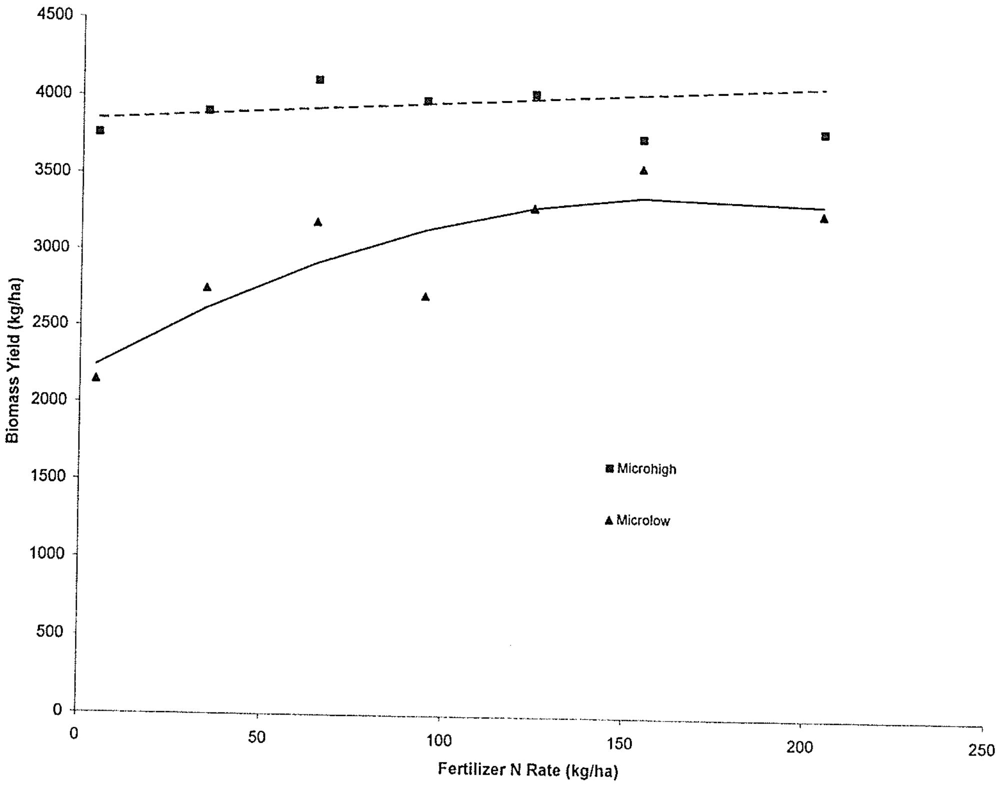

Figure 4.11 Quadratic model indicating total aboveground biomass yield at anthesis – Dufresne 1997 site.

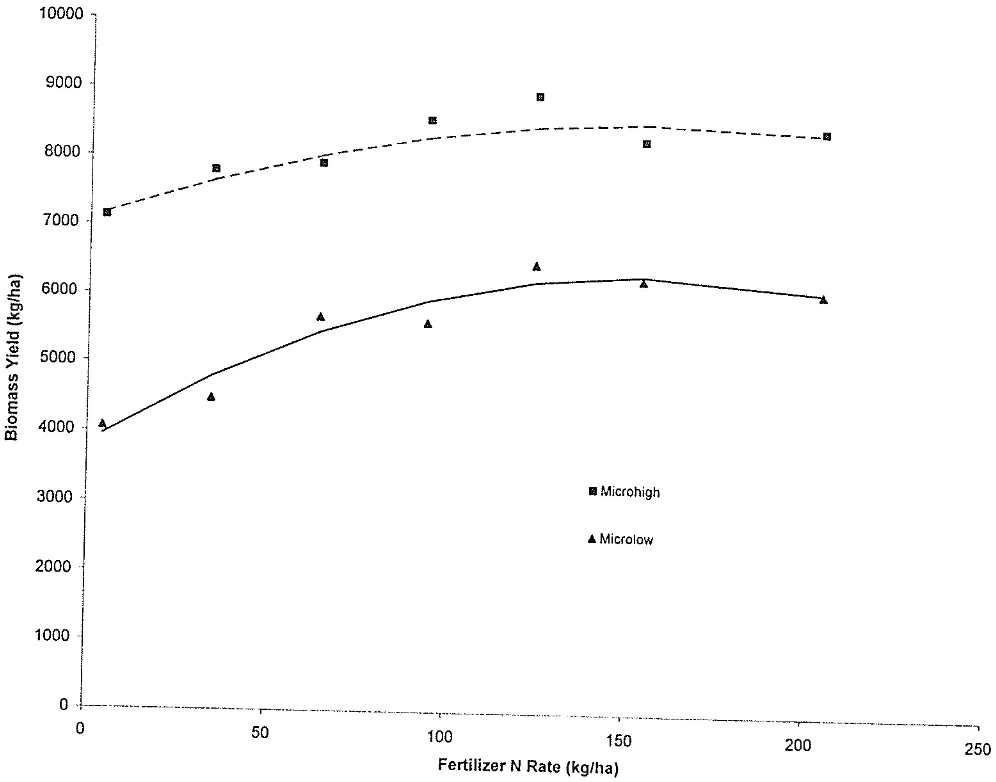

Figure 4.12 Quadratic model indicating total aboveground biomass yield at maturity –Dufresne 1997 site.

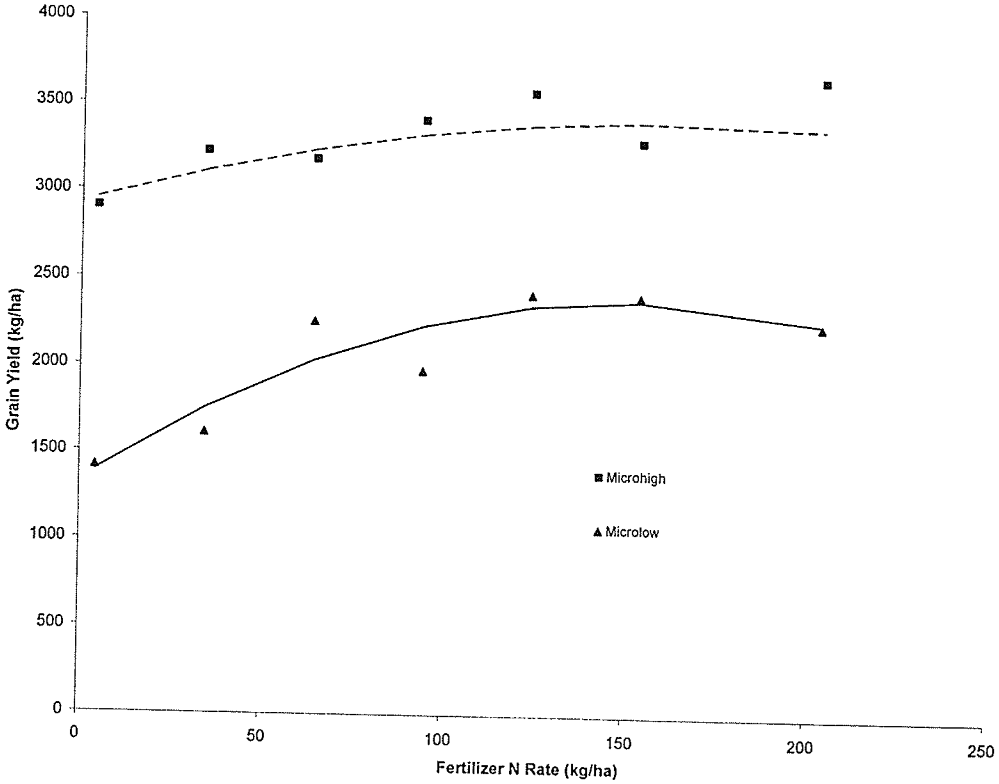

Figure 4.13 Quadratic model indicating grain yield at maturity – Dufresne 1997 site.

4.2.1.6 Grain protein. The parameter estimates for the grain protein content responses to applied nitrogen using a linear model are summarized in Table 4.61. These models were significantly different (Table 4.62). This difference is largely due to differences in the slope of the curves (at p = 0.10) however the intercept was also significant at the ∝ = 0.20 level (p-value = 0.179). This suggests that the microlow positions exhibited higher protein contents, particularly at lower nitrogen rates. However, as nitrogen rates increase, these differences in protein content disappear. At higher nitrogen rates, yields increase at decreasing rates thus the extra nitrogen is used for protein. Once again this is not unexpected given the yield responses observed. Where yields are generally lower protein contents are higher, hence the greater intercept values at the microlow positions. However, because overall yield response trends were generally greater for the microlow positions, in these cases the extra N would be used for yield production whereas the lesser yield responding microhighs would utilize the extra N for protein production (Fowler et al. 1990).

Table 4.61 Parameter estimates and p-values from the analyses of variance for the protein response curves at the Dufresne 1997 site.

Slope Position	Intercept	Slope	Prob. > F
Microhigh	12.5%	0.019	<0.001
Microlow	13.2%	0.014	<0.001

Table 4.62 Comparison among grain protein responses at the Dufresne 1997 site.

Slope positions compared		Test Statistic (F*) value	Prob. > F
Microhigh vs. Microlow	Whole model	2.77	0.069
	Intercept	1.84	0.179
	Slope	3.70	0.058

4.2.2 Elm Creek 1997

4.2.2.1 Description of landscapes studied. This site was also located on a relatively level field with a heavy clay soil texture. The total difference in elevation of the slope positions studied was only 50 cm. Three slope positions were studied and were termed microhigh, microlow, and low and were each replicated five times.

The microhigh positions were slightly elevated with a divergent contour. These microhighs were all classified as Gleyed Humic Vertisols (Table 3.2). The gleying observed in these positions suggests that these positions experienced periods of water saturation. However, these microhighs tend to be a little better drained internally than those observed at the Dufresne site where both Gleyed Humic Vertisol and Gleysolic Humic Vertisol profiles prevailed.

The microlow positions were depressional areas where water tended to pond. The microlow positions were classified as either Gleyed Humic Vertisols (4 of 5 replications), or Gleysolic Humic Vertisol (1 replication). Once again, the gleying observed at these positions reflects periods of water saturation. The periods of saturation at these positions would be more extensive and/or frequent than in the microhigh positions as is indicated by the shift towards Gleysolic Humic Vertisol profile.

The low positions were much like the microlow positions as these were depressional areas where water tended to pond. The difference between the two was that the lows occurred at lower elevations than the microlow microdepressions. As such, ponding at the low positions was more extensive in size and longer lasting. This was evidenced by the profiles observed with only one replicate exhibiting a Gleyed Humic Vertisol profile and the other four having Gleysolic Humic Vertisol profiles.

4.2.2.2 Comparisons of soil properties. Soil property comparisons are summarized in Table 4.63. Significant differences in nitrate concentrations between the microhigh and low positions were observed at all soil depths studied but the microlow positions did not differ significantly from either of the other positions. A possible reason for the higher nitrate concentrations at the microhigh positions may be due to lower denitrification losses than at the low positions where extended anaerobic conditions were more likely to occur (Pennock et al. 1992). Phosphate concentrations between slope positions once again did not exhibit significant differences.

Potentially mineralizable N analyses at the 0-30 cm soil depth were conducted at this site. No significant differences were observed between slope positions for this soil property (Table 4.63). The similarities in the soil profiles, particularly the depth of A horizon, suggests that these different positions likely do not differ greatly in their respective organic matter concentrations. As such, little differences were expected in their abilities to release organic nitrogen into an inorganic form.

There were no significant differences in A horizon depth or in the solum depths for any of the slope positions (Table 4.63). The depth of carbonates was significantly greater for the microlow position compared to the microhigh position with the low position not differing from either of the others. This would suggest that these microlows may have a greater leaching potential than the other positions.

The electrical conductivity measurements suggest that salts do not appear to be a concern at this site. Although all slope positions and depths measured had low E.C. values, significantly higher salt concentrations were observed in the subsoils of the microhigh positions compared to the microlow positions. This is consistent with the carbonate observations where it was speculated that leaching potential may be higher at

Table 4.63 Soil property comparisons among slope positions of the Elm Creek 1997 site.

	Spring NO_3-N 0-30 cm (kg ha^{-1})	Spring NO_3-N 0-60 cm (kg ha^{-1})	Spring NO_3-N 0-90 cm (kg ha^{-1})	Spring NO_3-N 0-120 cm (kg ha^{-1})	PO_4-P (mg kg^{-1})	Potentially Mineralizable N (kg ha^{-1})	A horizon depth (cm)	Depth to carbonates (cm)	Solum depth (cm)	E.C. 0-30 cm (mS cm^{-1})	E.C. 30-60 cm (mS cm^{-1})	E.C. 60-90 cm (mS cm^{-1})	E.C. 90-120 cm (mS cm^{-1})
Microhigh	27.1a*	41.5a	50.7a	56.8a	3.8a	358.2a	14.2a	19.6b	28.0a	0.7a	0.6a	1.1a	2.3a
Microlow	22.1ab	31.4ab	44.6ab	50.3ab	4.4a	312.3a	19.4a	59.8a	27.0a	0.6a	0.5a	1.0a	1.4b
Low	16.1b	24.7b	30.8b	34.3b	3.9a	358.4a	18.0a	26.6ab	29.0a	0.6a	0.6a	1.1a	1.8ab

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

the microlow positions. However, these relatively slight differences are probably of little agronomic significance.

There were no significant differences in soil temperature at the time of seeding (May 29th) for any of the slope positions (Table 4.64). On June 24th, the soil temperatures at the microhigh positions were lower than at the microlow positions at the 5 cm depth and lower than at the low positions at both the 5 and 10 cm depths. However, at the 15 cm depth, these trends changed somewhat with the microlow positions having significantly higher temperatures than the low positions and the microhighs not differing significantly from either of the other positions. Although these temperatures are significantly different from a statistical perspective, there is not a great difference in the temperatures from an agronomic perspective.

4.2.2.3 Soil water As seen in Table 4.65, there were few differences in amounts of volumetric moisture between the different slope positions at the three sampling stages. The only difference was between the low and microhigh positions at anthesis at the 0-120 cm depth. Although there did not appear to be any drought stress throughout the growing season, precipitation was relatively low at this site in the year of this study (137 mm throughout the growing season). As a result, there was less opportunity to observe differences in moisture content due to redistribution to lower slope positions and ponding, compared to other site years of this project.

Water use did not differ between any slope positions at any soil depth considered at either the anthesis or harvest timings (Table 4.66). These results were not expected. There were significant differences in yields for all positions studied (Tables 4.71 to 4.73) and water redistribution in the landscape would likely be negligible due to lower than normal rainfall. Therefore, the higher yielding areas would be expected to utilize more water the lower yielding areas. The fact that nitrogen uptake also differed significantly (Table 4.63) according crop yields also tends to make one believe that there was higher water use in the microhigh positions. It is difficult to say why no differences were observed. Evapotranspiration rates may have been higher at the microlow and low positions; however, there is no objective evidence to support this.

Table 4.64 Comparisons of soil temperature in the 90 kg N ha^{-1} treatment among slope positions of the Elm Creek 1997 site.

Date	Depth (cm)	Microhigh	Microlow	Low
May 29	5	20.7a*	21.5a	21.0a
	10	17.3a	18.9a	18.3a
	15	14.3a	15.6a	14.5a
June 24	5	20.0b	21.3a	21.9a
	10	18.0b	18.5ab	18.7a
	15	18.0ab	18.2b	17.9a

* Means within a row followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.65 Comparisons of volumetric water contents in the 0 kg N ha^{-1} treatment among slope positions of the Elm Creek 1997 site.

	Volumetric Water at Seeding (mm)				Volumetric Water at Anthesis (mm)				Volumetric Water at Harvest (mm)			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Microhigh	112a*	236a	379a	510a	100a	212a	340a	472b	110a	221a	349a	478a
Microlow	114a	253a	396a	531a	99a	212a	346a	478ab	109a	227a	361a	497a
Low	120a	252a	403a	538a	103a	227a	373a	508a	117a	241a	372a	497a

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.66 Comparisons of water use in the 0 kg N ha^{-1} treatment among slope positions of the Elm Creek 1997 site.

	Water use to Anthesis (mm)†				Water use to Harvest (mm)‡			
Soil depth (cm)	0-30	0-60	0-90	0-120	0-30	0-60	0-90	0-120
Microhigh	131a*	143a	158a	157a	139a	152a	167a	170a
Microlow	134a	160a	170a	173a	143a	164a	173a	172a
Low	136a	145a	150a	149a	140a	149a	168a	179a

† Precipitation to anthesis was 119 mm

‡ Growing season precipitation was 137 mm

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.2.2.4 Nitrogen uptake. There were significant differences in nitrogen uptake between some of the slope positions (Table 4.67). Where no fertilizer N was applied, the microhigh positions had greater uptake than the low positions. At the 90 kg N ha^{-1} fertilization rate, both the microhigh and microlow positions had greater N uptake values than the low position. However, at the 200 kg N ha^{-1} rates, no significant differences were observed although the general trends in the values of N uptake continued. These trends can likely be most easily explained by the higher crop productivity in the microhigh positions, followed by the microlows, with the low positions having the lowest yields.

The increase in nitrogen used from the 0 to 90 kg N ha^{-1} and from the 0 to 200 kg N ha^{-1} treatments is summarized in Table 4.68. As with most sites, there was no difference between increase in N uptake or N fertilizer use efficiency between slope positions. However, this site showed greater increases in N uptake than in any of the other sites.

Table 4.67 Growing season nitrogen uptake by the crop in the 0, 90, and 200 kg N ha^{-1} treatments of the Elm Creek 1997 site.

Slope Position	Nuptake in 0 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 90 kg N ha^{-1} treatment (kg N ha^{-1})	Nuptake in 200 kg N ha^{-1} treatment (kg N ha^{-1})
Microhigh	67.2a*	132.6a	153.3a
Microlow	41.7ab	110.9a	132.3a
Low	35.1b	88.3b	117.8a

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

Table 4.68 Influence of slope position on increase in N uptake and N fertilizer uptake efficiency of the Elm Creek 1997 site.

Slope Position	0 to 90 kg N ha^{-1} treatment		0 to 200 kg N ha^{-1} treatment	
	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency	Increase in N uptake (kg N ha^{-1})	N fertilizer uptake efficiency
Microhigh	59a*	74%a†	86a	43%a
Microlow	69a	87%a	91a	45%a
Low	53a	66%a	83a	41%a

† N fertilizer efficiency calculated as (Δ plant N/ΔN fertilizer) x100%

* Means within a column followed by the same letter do not differ significantly at the 10% level of probability according to the Tukey-Kramer Honestly Significant Difference (HSD) Test.

4.2.2.5 Wheat yield. The parameter estimates for the yield responses to applied nitrogen using the quadratic and quadratic plus plateau models are summarized in Tables 4.69 and 4.70 respectively. Both models appeared to fit the data well.

Comparisons of the responses between the microhigh and microlow positions revealed significant differences for all three yield indices (Table 4.71). For the midseason aboveground biomass data, these differences were due largely to differences in the intercept values (at p = 0.01 level). Thus, at this time of year, the differences were more a function of yield potential as opposed to yield response. However, at harvest, the significant differences were noted in both the intercept values (at p = 0.01) and the linear components for both the aboveground biomass (at p = 0.20 level) and grain yield (at p = 0.05 level) indices. Even though the microhigh positions produced higher grain yields throughout the range of N rates applied, the microlow positions tended to show greater yield increases per unit of N applied (i.e. greater yield responses). Therefore, in this instance, nitrogen input dollars may be best spent in these microlow positions, in spite of their lower overall yield potential.

Similar results were observed in the comparisons between the microhigh and low positions (Table 4.72). In this instance the differences observed on the midseason and harvest aboveground biomass indices were largely due to a difference in the intercept values (at p = 0.01 level). But at harvest, significant differences were noticed for the linear component of grain yield data at $\propto = 0.20$ level (p-value 0.119). Thus, once again nitrogen inputs may be better spent in areas of higher yield response, but lower yield potential.

Response differences between the microlow and low positions were not evident for the midseason aboveground biomass yields (Table 4.73). However, there were significant differences for both the harvest aboveground biomass (at p = 0.05 level) and grain yields (at p = 0.01 level) but these were mainly due to the intercept. Therefore, it could be said that for these two positions the differences lie mainly in yield potential and not in response to applied N.

Table 4.69 Parameter estimates and p-values from the analyses of variance for the quadratic model of the Elm Creek 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Prob. > F
Microhigh	Midseason biomass	3147.6	59.72	-0.198	<0.001
Microlow	Midseason biomass	2309.8	45.92	-0.123	<0.001
Low	Midseason biomass	1645.2	45.21	-0.114	<0.001
Microhigh	Harvest biomass	4536.9	50.62	-0.153	<0.001
Microlow	Harvest biomass	2191.0	62.79	-0.175	<0.001
Low	Harvest biomass	1929.2	50.33	-0.120	<0.001
Microhigh	Grain Yield	1669.6	18.84	-0.060	<0.001
Microlow	Grain Yield	661.0	25.43	-0.074	<0.001
Low	Grain Yield	594.9	18.22	-0.043	<0.001

Table 4.70 Parameter estimates and p-values from the analyses of variance for the quadratic plus plateau model of the Elm Creek 1997 nitrogen response curves.

Slope Position	Yield Index	Intercept	Linear	Quadratic	Plateau N rate (kg ha^{-1})	Plateau Yield (kg ha^{-1})	Prob. > F
Microhigh	Midseason biomass	3077.6	64.13	-0.237	135.6	7424.1	<0.001
Microlow	Midseason biomass	2175.0	52.24	-0.162	162.0	6398.2	<0.001
Low	Midseason biomass	1648.3	45.09	-0.113	199.6	6148.4	<0.001
Microhigh	Harvest biomass	4471.1	54.21	-0.180	151.0	8563.5	<0.001
Microlow	Harvest biomass	2228.7	61.37	-0.169	181.7	7802.8	<0.001
Low	Harvest biomass	1929.2	50.33	-0.121	208.8	7185.0	<0.001
Microhigh	Grain Yield	1612.4	21.96	-0.084	131.5	3056.1	<0.001
Microlow	Grain Yield	683.0	24.60	-0.071	174.3	2826.8	<0.001
Low	Grain Yield	594.9	18.22	-0.043	212.7	2533.2	<0.001

Table 4.71 Comparison among the yield indices of the Microhigh and the Microlow positions at the Elm Creek 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	5.67	0.002
	Intercept	15.88	<0.001
	Linear component	0.12	0.733
	Quadratic component	1.00	0.322
Harvest Aboveground Biomass	Whole model	8.17	<0.001
	Intercept	21.96	<0.001
	Linear component	2.48	0.120
	Quadratic component	0.08	0.780
Grain Yield	Whole model	9.34	<0.001
	Intercept	23.43	<0.001
	Linear component	4.35	0.041
	Quadratic component	0.23	0.637

Table 4.72 Comparison among yield indices of the Microhigh and the Low positions at the Elm Creek 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	13.14	<0.001
	Intercept	37.69	<0.001
	Linear component	0.41	0.526
	Quadratic component	1.317	0.255
Harvest Aboveground Biomass	Whole model	15.14	<0.001
	Intercept	43.67	<0.001
	Linear component	1.60	0.211
	Quadratic component	0.15	0.698
Grain Yield	Whole model	18.86	<0.001
	Intercept	53.77	<0.001
	Linear component	2.50	0.119
	Quadratic component	0.32	0.575

Table 4.73 Comparison among yield indices of the Microlow and the Low positions at the Elm Creek 1997 site.

Yield Index		Test Statistic (F*) value	Prob. > F
Midseason Aboveground Biomass	Whole model	1.61	0.196
	Intercept	*na	na
	Linear component	na	na
	Quadratic component	na	na
Harvest Aboveground Biomass	Whole model	1.85	0.147
	Intercept	5.06	0.028
	Linear component	0.05	0.824
	Quadratic component	0.45	0.505
Grain Yield	Whole model	3.08	0.034
	Intercept	8.02	0.006
	Linear component	0.15	0.697
	Quadratic component	1.06	0.307

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

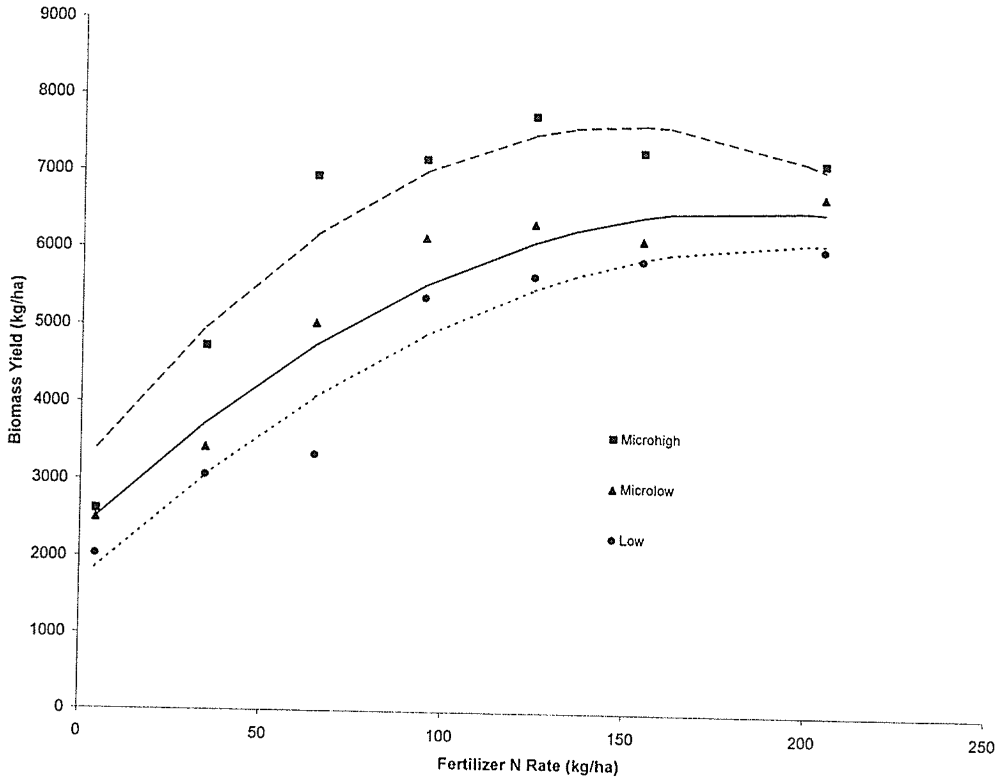

Figure 4.14 Quadratic model indicating total aboveground biomass yield at anthesis – Elm Creek 1997 site.

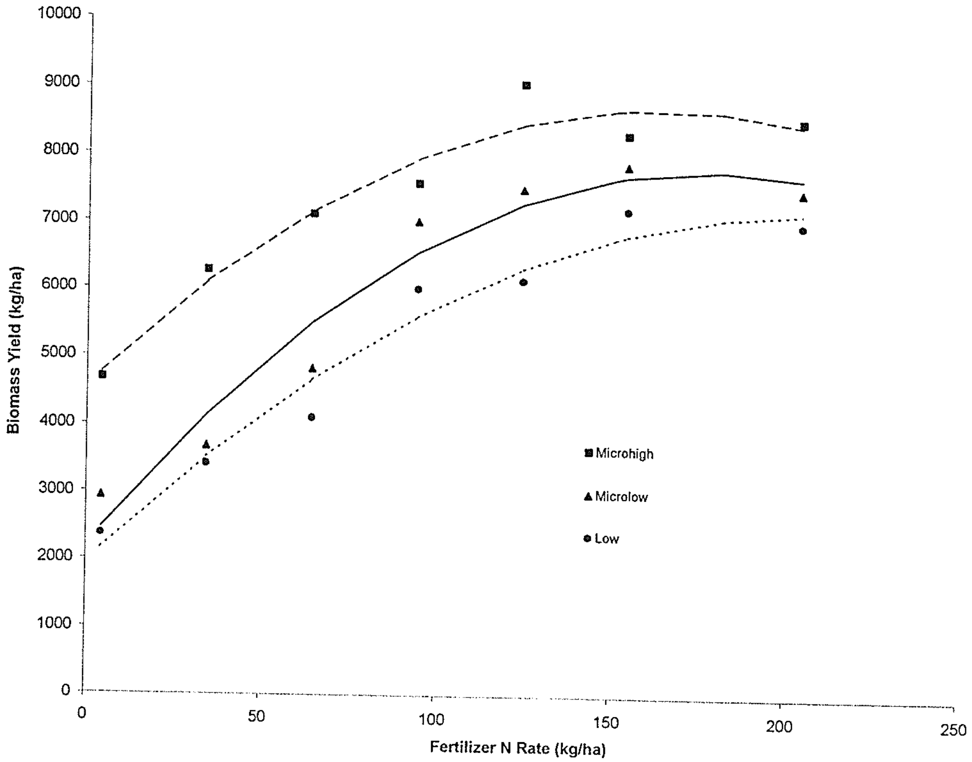

Figure 4.15 Quadratic model indicating total aboveground biomass yield at maturity – Elm Creek 1997 site.

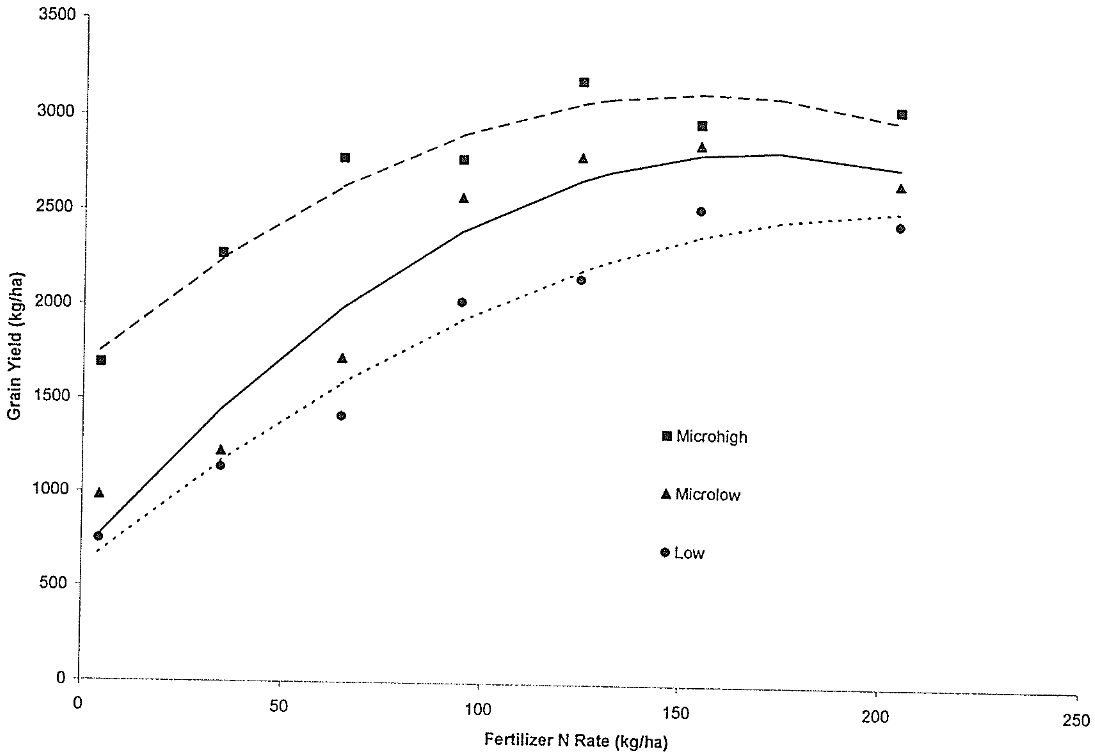

Figure 4.16 Quadratic model indicating grain yield at maturity – Elm Creek 1997 site.

4.2.2.6 Grain protein. Grain protein content response results are listed in Table 4.74. Significant differences in protein content response to applied N were observed between the microhigh and microlow positions and between the microhigh and low positions. However, no significant differences were observed between the microlow and low positions. In both comparisons, the differences observed were a result of significant differences in the intercept and the slope values. The intercept values were lower for the microhigh positions, a typical observation for higher yielding areas (Partridge and Shaykewich 1972). However, the slope of the curve was greater at the microhigh positions. This is consistent with most of the data observed at the other sites in this project. The positions with the lower intercept values or protein contents at low N rates tend to respond more to applied N.

Table 4.74 Parameter estimates and p-values from the analyses of variance for the protein response curves at the Elm Creek 1997 site.

Slope Position	Intercept	Slope	Prob. > F
Microhigh	14.1%	0.010	<0.001
Microlow	15.0%	0.004	0.045
Low	15.2%	0.003	0.072

Table 4.75 Comparison among grain protein responses at the Elm Creek 1997 site.

Slope positions compared		Test Statistic (F*) value	Prob. > F
Microhigh vs. Microlow	Whole model	5.35	0.002
	Intercept	3.50	0.066
	Slope	7.19	0.009
Microhigh vs. Low	Whole model	8.26	<0.001
	Intercept	9.09	0.004
	Slope	7.44	0.008
Microlow vs. Low	Whole model	0.65	0.588
	Intercept	*na	na
	Slope	na	na

*na: Data not available. Because there were no significant differences among the two slope positions (Whole model test) it is irrelevant to test individual components.

5. SUMMARY AND CONCLUSIONS

5.1 Newdale Till Plain Landscapes

As reported in many studies of sites with hummocky terrains (Brubaker et al. 1993, Moulin et al. 1994, Miller et al. 1988, Malo et al. 1974), the comparisons made between the soil properties at different landscape positions showed some significant trends from site to site. At all four glacial till sites, A horizon depth and electrical conductivity were found to be significantly higher at lower slope positions with values decreasing at higher slope positions. At three of the four sites, solum depth was also significantly greater at the lower slope positions gradually decreasing moving upslope. There were also significant differences in NO_3^--N in three of the four sites. However these trends were not clearly defined. In two of these three sites, nitrate concentrations tended to decrease moving upslope but at the Forrest 1997 site, significantly higher levels were found at the midslope positions. Concentration of soil PO_4-P and depth to carbonates were not significantly different among slope positions except at the Minnedosa site. Potentially mineralizable N was measured only at the Minnedosa site where there was a trend towards higher levels at lower slope positions with these levels decreasing at higher slope positions. Significant differences in soil temperature among slope positions were not commonly observed. The trends observed were generally higher temperatures at higher slope positions. However, these differences tended to be minor (often less than 1° C) and only at greater depths (15 cm or more).

Significant differences in volumetric water content were observed at all sites and all timings with the exception of the anthesis timings of the Zero Tillage Farm 1996 and the Forrest 1997 sites. The overall tendency was that lower slope positions had higher moisture contents than upslope positions. Water use data also differed significantly between landscape positions. However, there were no consistent trends with regards to which landscape positions were highest in water use and which were lowest. In these landscapes, water accumulations and losses may occur via processes such as runoff and capillary rise. Furthermore, these processes will occur at different rates depending on weather conditions and the landscape position in question. Therefore, commonly used water use calculations that do not take into account water redistribution within the landscape or even within the soil profile are not particularly useful in landscape studies.

Significant differences in nitrogen uptake were observed in two of the three sites with N uptake data. At both of these sites, there were significant differences at all of the rates of N applied. The landscape position ranking in N uptake varied from site to site. This is consistent with reports from Fiez et al. (1995) who found that differences in nitrogen uptake was dependent on both site and year of study.

Despite the significant differences in N uptake, slope position did not have a consistent effect on the efficiency of N fertilizer uptake. Only the Minnedosa site had significant differences between slope positions with the toeslope having a lower efficiency of N fertilizer uptake than the upper midslope and knoll positions. Fiez et al. (1995) also reported inconsistencies in the efficiency of N fertilizer uptake between sites in their study.

Although some studies have reported that the soil-landscape holds some potential to delineate management units in a precision agriculture environment, this study casts doubts. Beckie et al. (1997) reported that variable rate N fertilization based on topography, along with variable rate N fertilization based on soil organic matter, provided the highest fertilizer use efficiency as well as the greatest net returns in crop revenues. However, a major distinguishing feature between the study by Beckie et al. (1997) and the study presented herein, was that only one nitrogen fertilizer rate was applied in the Beckie et al. (1997) study and this rate was based upon residual soil NO_3^--N at different topographical locations. Thus, the authors made uniform applications within the topographical elements without considering that these elements may respond differently to available nitrogen. On the other hand, the study presented herein focuses on differences in nitrogen response with little consideration of residual soil NO_3^--N. In a number of instances in this study, yield responses to applied nitrogen were very modest. These instances were often, but not always, associated with landscape positions exhibiting high spring NO_3^--N concentrations. A study which would incorporate some of the concepts of both this study and the study by Beckie et al. (1997) could possibly bridge some of the information gaps that plague the success of variable rate fertilization.

Suffice it to say that the yields and yield responses of anthesis and harvest aboveground biomass as well as grain yield to applied nitrogen fertilizer were inconsistent throughout these sites. For example, toeslope positions were found to have the highest yields, medium yields, and lowest yields depending on the site in question. Of the 34 yield response comparisons made between different landscape positions, 23 were significantly different. When further analysis was conducted on the data to determine how these responses differed, all 23 differed in their intercept values. However, only 3 differed in both the intercept and the linear values (although two of the linear differences were only significant at the $\propto = 0.20$ level) and only 3 differed in both the intercept and quadratic values (one at the $\propto = 0.05$ level, one at the $\propto = 0.10$ level, one at the $\propto = 0.20$ level). These results suggest that there were significant differences in marginal yield response in only 6 of 34 instances at these sites. Therefore, when considering unit yield increases per unit N additions, only 6 of the 34 showed significant differences. In the other 17 comparisons where only the intercept was significantly different, these unit yield increases did not differ between landscape positions, but overall yield potentials did.

Grain protein content responses to applied N did not show any consistent trends with landscape position. The positions with the highest protein contents or highest responses to applied N varied from site to site. Of the 15 protein response comparisons between landscape positions, 9 were significantly different. Of these 9, five differed in intercept only and four differed in both intercept and slope values (two at p-values of 0.05 or less and two at p-values of 0.20 or less). Therefore, when considering unit increases in protein per unit of N applied, it would only be justifiable to apply different N application rates between landscape positions in only 4 of the 15 instances.

In the soil-landscapes studied, utilizing slope position as the sole criterion to delineate management units for variable rate nitrogen applications proved to be insufficient. Both yield and grain protein content responses to applied nitrogen fertilizer were too inconsistent from site to site to make this a feasible option. However, many other soil factors did appear to more strongly influence yield responses. These include properties such as spring NO_3^--N, soil electrical conductivity, potentially mineralizable N, and a variety of soil development parameters. Although many of these soil properties were associated with slope position, these associations were not strong enough to make landscape position alone a useful parameter to make nitrogen fertilizer rate determinations. More sophisticated models incorporating a number of these soil properties, and probably other properties not measured in this study, would be required to make better informed variable rate nitrogen decisions.

5.2 Lacustrine Landscapes of the Red River Valley

Few landscape based studies have been conducted in level terrains such as is found in the Red River Valley. Therefore, there was little opportunity for comparisons with previous studies. Hollands (1996) reported trends in both spring NO_3^--N concentrations and soil moisture in his studies of lacustrine landscapes in the Red River Valley. In the study herein, significant differences between the soil properties of the different landscape positions were less common and more subtle in the lacustrine landscapes compared to the glacial till landscapes. This suggests that there is less variability in soil properties in these lacustrine landscapes. The significant differences between properties observed were not consistent from site to site. At the Elm Creek site, there were some significant differences observed in NO_3^--N, depth to carbonates, electrical conductivity (at the 90-120 cm depth only), and soil temperature. At the Dufresne site, significant differences were observed in only the electrical conductivity (0-30 cm only) and soil temperature soil properties. In all, the statistically significant differences observed were often small and, therefore, agronomically unimportant.

Both sites had significant differences in volumetric water content. At both sites, the trend was that greater volumetric water content occurred at lower slope positions and decreased with higher slope positions. There were no significant differences in water use at the Elm Creek site for either the anthesis or harvest timings. However, at the Dufresne sites, significant differences occurred at both timings with the microhigh positions having greater water use estimates than the microlow positions.

Nitrogen uptake estimates were significantly different at both sites and all nitrogen rates studied with the exception of the 200 kg N ha^{-1} rate at Elm Creek. In all cases, N uptake was greatest at the microhigh positions and decreased with decreasing relative elevation.

Although there were only two sites under study in these landscapes, the yield patterns observed appeared to be more consistent than those in the glacial till landscapes. At both sites, overall higher yields were observed at higher relative elevations and these yields decreased with decreasing elevation. Comparisons between the yield curves revealed significant differences in 11 of the 12 comparisons made. Of these 11 significantly different curves, 7 differed in the intercept value only, whereas 4 differed in both the intercept and linear or quadratic values (one at a p-value of 0.05 or less and three at p-values of 0.20 or less). It appears that in these landscapes, the microlow positions generally were more responsive to applied N fertilizer than both the microhigh and low positions regardless of the site.

Three of the four grain protein content response comparisons were significantly different (two at p-values of 0.05 or less and one at a p-value of 0.10 or less). In all three instances, the curves differed significantly in both the intercept and slope values. At both sites, initial protein content values were higher at positions with lower elevations. However, the slopes of the protein response curves were highest at the microhigh positions suggesting that the grain protein content at these areas was more responsive to additions of nitrogen than at the lower slope positions.

The use of slope position as a tool to delineate management units for variable rate nitrogen fertilization decisions in these lacustrine landscapes has excellent potential. This study exhibited consistent results in yield potentials, yield response, and grain protein content responses to applied N from site to site. Due to the few differences in many of the soil properties observed, including these to help decide on nitrogen rates in these landscapes may not improve recommendations a great deal.

5.3 Newdale Glacial Till Plain versus Red River Lacustrine Landscapes

The differences observed between the two greatly different types of soil landscapes in this study were interesting. The glacial till landscapes exhibited many significant differences in soil properties according to landscape position. Although these properties appeared to have a degree of consistency from site to site, yield potentials, yield responses to applied N, and grain protein content responses to applied N were inconsistent and, as such, unpredictable. At the other extreme, few differences in soil properties between landscape positions were observed in the lacustrine landscapes. However, trends in yield indices and grain protein content responses were consistent. It seems odd that where soil properties were more strongly associated with landscape properties, crop yield potential, yield response, and grain protein content would be less strongly associated with landscape properties. However, this was the case in this study.

Although it would seem that site specific practices such as variable rate nitrogen application would be more suited towards more variable terrains such as glacial till landscapes, this study suggests that more work is required before this can be done effectively and affordably. For the time being, adoption of variable rate nitrogen practices may be more appropriate in less complex landscapes such as those found in the lacustrine deposits of the Red River Valley.

6. CONTRIBUTIONS TO KNOWLEDGE

The most significant concept that this study has contributed to knowledge is that it is important to consider not only variability in soil properties within the landscape, but that variability (or similarities) in crop response to nitrogen fertilizer should also be considered. The most interesting finding of this study is that where soil variability appeared to be the greatest (i.e. Newdale Glacial Till landscapes), variability in crop response was the least consistent.

This study also revealed that crop grain yield and protein potential in glacial till landscapes are not easily predicted utilizing a single soil-property or landscape parameter. For instance, it cannot be said that toeslope positions hold the potential for highest yields as some of them may be affected by high salt concentrations or a combination of factors which restrict crop potential in most years. However, in lacustrine landscapes there appears to be more predictability of yield and protein characteristics which may make these simpler landscapes more feasible areas for early variable rate fertilizer adoption.

Traditional estimates of crop water use that include an estimate of soil moisture content are not useful in landscape research. As was demonstrated many times throughout this study, redistribution of soil water whether across the landscape or within the soil profile will result in over- or under-estimation of water use.

Before variable rate fertilization practices can be widely adopted much more research must be conducted. Management units which consider variability in both soil properties and crop yield and quality responses to applied nutrients must be developed. To date, most studies utilize soil properties or crop yield as the soul criteria for the delineation of management units. A consistent and reliable association between management units and crop yield and quality responses must be found before adoption of variable rate fertilization practices can be agronomically and economically feasible.

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8. APPENDICES

Appendix A

Profile and Slope Descriptions of Slope Positions Studied

Table A.1 Profile and slope descriptions – Toeslope Rep. 1, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	30	L	Gradient: 9.5%	Aspect: 212°	Landform: Undulating
AC	30	50	CL-L			
Cksgj	50+		CL-L			
				CSSC Classification:		
				GLR.BLC		

Table A.2 Profile and slope descriptions – Toeslope Rep. 2, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	25	L	Gradient: 9.0%	Aspect: 220°	Landform: Undulating
AC	25	39	CL-L			
Ckgj	39+		CL-L			
				CSSC Classification		
				GLR.BLC		

Table A.3 Profile and slope descriptions – Toeslope Rep. 3, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	9	L-CL	Gradient: 10.0%	Aspect: 202°	Landform: Undulating
Apks/Ahks	9	28	L-CL			
AC	28	43	CL			
Ck	43	60	CL			
Ckgj	60+		CL	CSSC Classification		
				GLR.BLC		

Table A.4 Profile and slope descriptions – Toeslope Rep. 4, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Ap/Ah	0	21	L-CL	Gradient: 8.0%	Aspect: 218°	Landform: Undulating
Bgj	21	44	CL			
BC	44	54	CL			
Cksgj	54+		CL			
				CSSC Classification		
				GL.BLC		

Table A.5 Profile and slope descriptions – Midslope Rep. 1, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	24	L	Gradient: 9.5%	Aspect: 212°	Landform: Undulating
AC	24	31	L			
Ck	31+		L-CL			
				CSSC Classification		
				R.BLC		

Table A.6 Profile and slope descriptions – Midslope Rep. 2, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	12	L	Gradient: 9.0%	Aspect: 220°	Landform: Undulating
AB	12	19	L			
Bm	19	29	L-CL			
BC	29	37	L-CL			
Ck	37+		L-CL	CSSC Classification		
				O.BLC		

Table A.7 Profile and slope descriptions – Midslope Rep. 3, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	19	L-CL	Gradient: 10.0%	Aspect: 202°	Landform: Undulating
AC	19	26	L-CL			
Ck	26+		L-CL			
				CSSC Classification		
				R.BLC		

Table A.8 Profile and slope descriptions – Midslope Rep. 4, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	8	L-CL	Gradient: 8.0%	Aspect: 218°	Landform: Undulating
Ap/Ah	8	15	L-CL			
Bm	15	33	L-CL			
BC	33	45	CL			
Ck	45+		CL	CSSC Classification		
				O.BLC		

Table A.9 Profile and slope descriptions – Shoulder Rep. 1, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	14	L	Gradient: 9.5%	Aspect: 212°	Landform: Undulating
Ck	14+		L-CL			
				CSSC Classification		
				O.BLC		

Table A.10 Profile and slope descriptions – Shoulder Rep. 2, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	10	CL	Gradient: 9.0%	Aspect: 220°	Landform: Undulating
Ck	10+		CL			
				CSSC Classification		
				R.BLC		

Table A.11 Profile and slope descriptions – Shoulder Rep. 3, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	10	CL-L	Gradient: 10.0%	Aspect: 202°	Landform: Undulating
Ck	10+		CL-L			
				CSSC Classification		
				R.BLC		

Table A.12 Profile and slope descriptions – Shoulder Rep. 4, Forrest 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	11	L-CL	Gradient: 8.0%	Aspect: 218°	Landform: Undulating
Ck1	11	23	L-CL			
Ck2	23+		L-CL			
				CSSC Classification		
				R.BLC		

Table A.13 Profile and slope descriptions – Nonsaline Toeslope Rep. 1, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apks	0	20	CL	Gradient: 9.5%	Aspect: 225°	Landform: Undulating
AC	20	30	SI-CL			
Ckgjs	30+		SI-CL			
				CSSC Classification		
				GLR.BLC		

Table A.14 Profile and slope descriptions – Nonsaline Toeslope Rep. 2, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apks	0	20	CL	Gradient: 8.0%	Aspect: 195°	Landform: Undulating
AC	20	30	SI-CL			
Ckgjs	30+		CL			
				CSSC Classification		
				GLR.BLC		

Table A.15 Profile and slope descriptions – Saline Toeslope Rep. 1, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apks/Ahks	0	30	CL	Gradient: 9.0%	Aspect: 210°	Landform: Undulating
AC	30	50	SI-CL			
Ckgjs	50+		CL			
				CSSC Classification		
				GLR.BLC		

Table A.16 Profile and slope descriptions – Saline Toeslope Rep. 2, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apks/Ahks	0	35	CL	Gradient: 9.0%	Aspect: 226°	Landform: Undulating
AC	35	40	SI-CL			
Ckgjs	40+		SI-CL			
				CSSC Classification		
				GLR.BLC		

Table A.17 Profile and slope descriptions – Midslope Rep. 1, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	15	CL	Gradient: 9.5%	Aspect: 225°	Landform: Undulating
Bmk	15	22	CL			
Ck	22	60	CL			
Ckgj	60+		CL			
				CSSC Classification		
				CA.BLC		

Table A.18 Profile and slope descriptions – Midslope Rep. 2, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	15	CL	Gradient: 8.0%	Aspect: 195°	Landform: Undulating
AC	15	20	CL			
Ck	20+		SI-CL			
				CSSC Classification		
				R.BLC		

Table A.19 Profile and slope descriptions – Midslope Rep. 3, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	20	CL	Gradient: 9.0%	Aspect: 210°	Landform: Undulating
Bmk	20	35	CL			
Ck	35+		SI-CL			
				CSSC Classification		
				CA.BLC		

Table A.20 Profile and slope descriptions – Midslope Rep. 4, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	20	CL	Gradient: 9.0%	Aspect: 226°	Landform: Undulating
AC	20	25	SI-CL			
Cca	25	35	SI-CL			
Ck	35+		CL			
				CSSC Classification		
				R.BLC		

Table A.21 Profile and slope descriptions – Shoulder Rep. 1, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	9	CL	Gradient: 9.5%	Aspect: 225°	Landform: Undulating
Bmk	9	14	CL			
Ck	14	55	CL			
Ckgj	55+		CL			
				CSSC Classification		
				O.BLC		

Table A.22 Profile and slope descriptions – Shoulder Rep. 2, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	15	CL	Gradient: 8.0%	Aspect: 195°	Landform: Undulating
Bmk	15	27	CL			
BC	27	55	CL			
Ck	55+		CL			
				CSSC Classification		
				CA.BLC		

Table A.23 Profile and slope descriptions – Shoulder Rep. 3, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	12	CL	Gradient: 9.0%	Aspect: 210°	Landform: Undulating
AC	12	20	SI-CL			
Ck	20	55	SI-CL			
Ckgj	55+		SI-CL			
				CSSC Classification		
				R.BLC		

Table A.24 Profile and slope descriptions – Shoulder Rep. 4, Zero Tillage Farm 1996.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	15	L-CL	Gradient: 9.0%	Aspect: 226°	Landform: Undulating
Bmk	15	26	CL			
Ck	26+		SI-CL			
				CSSC Classification		
				CA.BLC		

Table A.25 Profile and slope descriptions – Toeslope Rep. 1, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apks	0	15	CL	Gradient: 7.0%	Aspect: 222°	Landform: Undulating
AC	15	25	CL			
Ckgjs	25+		CL			
				CSSC Classification		
				GLR.BLC		

Table A.26 Profile and slope descriptions – Toeslope Rep. 2, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apks/Ahks	0	25	CL	Gradient: 7.0%	Aspect: 215°	Landform: Undulating
AC	25	35	CL			
Ckgjs	35+		CL			
				CSSC Classification		
				GLR.BLC		

Table A.27 Profile and slope descriptions – Toeslope Rep. 3, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apks	0	20	CL	Gradient: 9.0%	Aspect: 230°	Landform: Undulating
AC	20	50	CL			
Ccagjs	50	60	SI-CL			
Ckgjs	60+		CL			
				CSSC Classification		
				GLR.BLC		

Table A.28 Profile and slope descriptions – Midslope Rep. 1, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	15	CL	Gradient: 7.0%	Aspect: 222°	Landform: Undulating
AC	15	20	CL			
Cca	20	30	CL			
Ck	30	60	CL			
Ckgj	60+		CL	CSSC Classification		
				R.BLC		

Table A.29 Profile and slope descriptions – Midslope Rep. 2, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	12	CL	Gradient: 7.0%	Aspect: 215°	Landform: Undulating
Bmk	12	20	CL			
Ck	20+		CL			
				CSSC Classification		
				O.BLC		

Table A.30 Profile and slope descriptions – Midslope Rep. 3, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	15	CL	Gradient: 9.0%	Aspect: 230°	Landform: Undulating
Bmk	15	25	CL			
Cca	25	40	SI-CL			
Ck	40+		CL			
				CSSC Classification		
				CA.BLC		

Table A.31 Profile and slope descriptions – Shoulder Rep. 1, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	10	CL	Gradient: 7.0%	Aspect: 222°	Landform: Undulating
Bmk	10	14	CL			
Cca	14	20	CL			
Ck	20+		CL			
				CSSC Classification		
				O.BLC		

Table A.32 Profile and slope descriptions – Shoulder Rep. 2, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	9	CL	Gradient: 7.0%	Aspect: 215°	Landform: Undulating
Bmk	9	15	CL			
Ck	15+		CL			
				CSSC Classification		
				O.BLC		

Table A.33 Profile and slope descriptions – Shoulder Rep. 3, Forrest 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	8	L	Gradient: 9.0%	Aspect: 230°	Landform: Undulating
Bmk	8	12	CL			
Cca	12	20	SI-CL			
Ck	20+		CL			
				CSSC Classification		
				O.BLC		

Table A.34 Profile and slope descriptions – Toeslope Rep. 1, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	40	CL	Gradient: 11.0%	Aspect: 120°	Landform: Hummocky
AC	40	50	SI-CL			
Ckgj	50+		SI-CL			
				CSSC Classification		
				GLR.BLC		

Table A.35 Profile and slope descriptions – Toeslope Rep. 2, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	25	CL	Gradient: 9.5%	Aspect: 115°	Landform: Hummocky
AC	25	35	CL			
Ckgj	35+		SI-CL			
				CSSC Classification		
				GLR.BLC		

Table A.36 Profile and slope descriptions – Toeslope Rep. 3, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	20	S-CL	Gradient: 10.0%	Aspect: 130°	Landform: Hummocky
Ckgj	20	90	S-CL			
Ckgj	90+		S-FS			
				CSSC Classification		
				GLCU.HR		

Table A.37 Profile and slope descriptions – Toeslope Rep. 4, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	40	CL	Gradient: 10.0%	Aspect: 115°	Landform: Hummocky
Ckgj	40	80	S-CL			
Ckgj	80+		S-FS			
				CSSC Classification		
				GLCU.HR		

Table A.38 Profile and slope descriptions – Lower Midslope Rep. 1, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	15	CL	Gradient: 11.0%	Aspect: 120°	Landform: Hummocky
Bm	15	27	CL			
BC	27	35	CL			
Ck	35	55	SI-CL			
Ckgj	55+		SI-CL	CSSC Classification		
				O.BLC		

Table A.39 Profile and slope descriptions – Lower Midslope Rep. 2, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	25	CL	Gradient: 9.5%	Aspect: 115°	Landform: Hummocky
AC	25	30	CL			
Ckgj	30+		CL			
				CSSC Classification		
				GLR.BLC		

Table A.40 Profile and slope descriptions – Lower Midslope Rep. 3, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk/Ahk	0	23	CL	Gradient: 10.0%	Aspect: 130°	Landform: Hummocky
AC	23	30	SI-CL			
Ckgj	30+		SI-CL			
				CSSC Classification		
				GLR.BLC		

Table A.41 Profile and slope descriptions – Lower Midslope Rep. 4, Minnedosa 1997.

Horizon	Upper Limit (cm)	Lower Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	15	CL	Gradient: 10.0%	Aspect: 115°	Landform: Hummocky
AC	15	25	CL			
Ck	25	50	CL			
Ckgj	50+		CL			
				CSSC Classification		
				R.BLC		

Table A.42 Profile and slope descriptions – Upper Midslope Rep. 1, Minnedosa 1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	15	L-CL	Gradient: 11.0%	Aspect: 120°	Landform: Hummocky
Bm	15	27	CL			
Cca	27	35	SI-CL			
Ck	35+		CL			
				CSSC Classification		
				O.BLC		

Table A.43 Profile and slope descriptions – Upper Midslope Rep. 2, Minnedosa 1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	15	CL	Gradient: 9.5%	Aspect: 115°	Landform: Hummocky
Bm	15	30	CL			
Ck	30	55	CL			
Ckgj	55+		CL			
				CSSC Classification		
				O.BLC		

Table A.44 Profile and slope descriptions – Upper Midslope Rep. 3, Minnedosa 1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics		
Ap	0	15	CL	Gradient: 10.0%	Aspect: 130°	Landform: Hummocky
Bm	15	29	CL			
Ck	29+		CL			
				CSSC Classification		
				O.BLC		

Table A.45 Profile and slope descriptions – Upper Midslope Rep. 4, Minnedosa 1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	11	CL	Gradient: 10.0%	Aspect: 115°	Landform: Hummocky
Bmk	11	16	CL			
Ck	16+		SI-CL			
				CSSC Classification		
				O.BLC		

Table A.46 Profile and slope descriptions – Knoll Rep. 1, Minnedosa 1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	8	CL	Gradient: 11.0%	Aspect: 120°	Landform: Hummocky
Ck	8+		CL			
				CSSC Classification		
				O.BLC		

Table A.47 Profile and slope descriptions – Knoll Rep. 2, Minnedosa 1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	7	CL	Gradient: 9.5%	Aspect: 115°	Landform: Hummocky
Bmk	7	12	CL			
Ck	12+		SI-CL			
				CSSC Classification		
				O.BLC		

Table A.48 Profile and slope descriptions – Knoll Rep. 3, Minnedosa 1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics		
Apk	0	11	CL	Gradient: 10.0%	Aspect: 130°	Landform: Hummocky
Bmk	12	15	CL			
Ck	15+		CL			
				CSSC Classification		
				O.BLC		

Table A.49 Profile and slope descriptions – Microhigh Rep. 1, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap/Ah	0	50	HC	Gradient: 0.5%	Landform: Level
Ckg	50+		HC		
				CSSC Classification	
				GLC.HV	

Table A.50 Profile and slope descriptions – Microhigh Rep. 2, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	25	HC		
Ckg	25+		HC		
				CSSC Classification	
				GLC.HV	

Table A.51 Profile and slope descriptions – Microhigh Rep. 3, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	20	HC	Gradient: 0.5%	Landform: Level
AC	20	30	HC		
Ckg	30+		HC		
				CSSC Classification	
				GL.HV	

Table A.52 Profile and slope descriptions – Microhigh Rep. 4, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap/Ah	0	35	HC	Gradient: 0.5%	Landform: Level
Cg	35	70	HC		
Ckg	70+		HC		
				CSSC Classification	
				GLC.HV	

Table A.53 Profile and slope descriptions – Microhigh Rep. 5, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap/Ah	0	35	HC	Gradient: 0.5%	Landform: Level
AC	35	70	HC		
Ckgj	70+		HC		
				CSSC Classification	
				GL.HV	

Table A.54 Profile and slope descriptions – Microhigh Rep. 6, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap/Ah	0	30	HC	Gradient: 0.5%	Landform: Level
Cg	30	60	HC		
Ckg	60+		HC		
				CSSC Classification	
				GLC.HV	

Table A.55 Profile and slope descriptions – Microlow Rep. 1, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	20	HC	Gradient: 0.5%	Landform: Level
AC	20	50	HC		
Ckg	50+		HC		
				CSSC Classification	
				GLC.HV	

Table A.56 Profile and slope descriptions – Microlow Rep. 2, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	20	HC	Gradient: 0.5%	Landform: Level
AC	20	25	HC		
Cg	25	90	HC		
Ckg	90+		HC		
				CSSC Classification	
				GLC.HV	

Table A.57 Profile and slope descriptions – Microlow Rep. 3, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	45	HC		
Ckg	45+		HC		
				CSSC Classification	
				GLC.HV	

Table A.58 Profile and slope descriptions – Microlow Rep. 4, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap/Ah	0	50	HC	Gradient: 0.5%	Landform: Level
Ckg	50+		HC		
				CSSC Classification	
				GLC.HV	

Table A.59 Profile and slope descriptions – Microlow Rep. 5, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	25	HC		
Cg	25	75	HC		
Ckg	75+		HC		
				CSSC Classification	
				GLC.HV	

Table A.60 Profile and slope descriptions – Microlow Rep. 6, Dufresne1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	30	HC		
Cgj	30	55	HC		
Ckgj	55+		HC		
				CSSC Classification	
				GL.HV	

Table A.61 Profile and slope descriptions – Microhigh Rep. 1, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	14	HC	Gradient: 0.5%	Landform: Level
Bmgj	14	26	HC		
BC	26	30	HC		
Ckgj	30+		HC		
				CSSC Classification	
				GL.HV	

Table A.62 Profile and slope descriptions – Microhigh Rep. 2, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	30	HC		
Ckgj	30+		HC		
				CSSC Classification	
				GL.HV	

Table A.63 Profile and slope descriptions – Microhigh Rep. 3, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
Bmgj	15	30	HC		
BC	30	40	HC		
Ckgj	40+		HC		
				CSSC Classification	
				GL.HV	

Table A.64 Profile and slope descriptions – Microhigh Rep. 4, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	12	HC	Gradient: 0.5%	Landform: Level
AC	12	20	HC		
Ckgj	20+		HC		
				CSSC Classification	
				GL.HV	

Table A.65 Profile and slope descriptions – Microhigh Rep. 5, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	30	HC		
Ckgj	30+		HC		
				CSSC Classification	
				GL.HV	

Table A.66 Profile and slope descriptions – Microlow Rep. 1, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	20	HC	Gradient: 0.5%	Landform: Level
Bmgj	20	26	HC		
Cgj	26	80	HC		
Ckgj	80+		HC		
				CSSC Classification	
				GL.HV	

Table A.67 Profile and slope descriptions – Microlow Rep. 2, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	18	HC	Gradient: 0.5%	Landform: Level
Bmgj	18	32	HC		
Cgj	32	100	HC		
Ckgj	100+		HC		
				CSSC Classification	
				GL.HV	

Table A.68 Profile and slope descriptions – Microlow Rep. 3, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap/Ah	0	30	HC	Gradient: 0.5%	Landform: Level
Cg	30	90	HC		
Ckg	90+		HC		
				CSSC Classification	
				GLC.HV	

Table A.69 Profile and slope descriptions – Microlow Rep. 4, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	27	HC		
Ckgj	27+		HC		
				CSSC Classification	
				GL.HV	

Table A.70 Profile and slope descriptions – Microlow Rep. 5, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	14	HC	Gradient: 0.5%	Landform: Level
AC	14	20	HC		
Ckgj	20	50	HC		
Ckg	50+		HC		
				CSSC Classification	
				GL.HV	

Table A.71 Profile and slope descriptions – Low Rep. 1, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	20	HC	Gradient: 0.5%	Landform: Level
AC	20	35	HC		
Ckgj	35+		HC		
				CSSC Classification	
				GL.HV	

Table A.72 Profile and slope descriptions – Low Rep. 2, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap/Ah	0	25	HC	Gradient: 0.5%	Landform: Level
AC	25	35	HC		
Ckg	35+		HC		
				CSSC Classification	
				GLC.HV	

Table A.73 Profile and slope descriptions – Low Rep. 3, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	18	HC	Gradient: 0.5%	Landform: Level
AC	18	30	HC		
Ckg	30+		HC		
				CSSC Classification	
				GLC.HV	

Table A.74 Profile and slope descriptions – Low Rep. 4, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	15	HC	Gradient: 0.5%	Landform: Level
AC	15	25	HC		
Cg	25	50	HC		
Ckg	50+		HC		
				CSSC Classification	
				GLC.HV	

Table A.75 Profile and slope descriptions – Low Rep. 5, Elm Creek1997.

Horizon	Lower Limit (cm)	Upper Limit (cm)	Soil Texture	Slope Characteristics	
Ap	0	12	HC	Gradient: 0.5%	Landform: Level
AC	12	20	HC		
Ckg	20+		HC		
				CSSC Classification	
				GLC.HV	

Appendix B

Relative Elevation, Spring Nutrient Distributions, and Nitrogen Mineralization Estimate Data

Table B.1 Forrest 1996.

Slope Position	Replicate	Relative Elevation (m)	NO_3^--N 0-30 cm (kg ha^{-1})	NO_3^--N 0-60 cm (kg ha^{-1})	NO_3^--N 0-90 cm (kg ha^{-1})	NO_3^--N 0-120 cm (kg ha^{-1})	PO_4-P (mg/kg)
Toeslope	1	1.37	53.8	115.4	170.8	230.7	12.2
Toeslope	2	0.79	42.1	91.5	113.6	129.1	6.1
Toeslope	3	0.95	58.7	125.6	221.8	302.2	10.6
Toeslope	4	0.81	54.5	87.0	107.7	128.8	
Midslope	1	2.05	52.2	105.9	222.8	323.8	6.2
Midslope	2	1.72	60.5	85.1	105.4	112.7	11.1
Midslope	3	1.62	55.5	89.8	101.0	114.2	
Midslope	4	1.74	42.9	76.0	96.0	104.1	3.1
Shoulder	1	2.7	66.3	99.2	142.1	232.5	7.3
Shoulder	2	2.47	35.8	47.3	52.9	62.0	2.0
Shoulder	3	2.5	26.3	42.6	48.4	50.4	1.2
Shoulder	4	2.64	30.3	67.1	85.4	90.6	5.5

Table B.2 Zero Tillage Farm 1996.

Slope Position	***Replicate***	Relative Elevation (m)	NO_3^--N 0-30 cm (kg ha^{-1})	NO_3^--N 0-60 cm (kg ha^{-1})	NO_3^--N 0-90 cm (kg ha^{-1})	NO_3^--N 0-120 cm (kg ha^{-1})	PO_4-P (mg/kg)	*Estimate of N mineralized (kg N/ha)
Nonsaline Toeslope	1	1.08	47.5	83.3	125.7	159.9	8.1	112.3
Nonsaline Toeslope	2	2.39	46.6	94.7	169.7	226.8	6.1	50.5
Saline Toeslope	1	1.72	44.4	92.2	151.0	218.0	12.4	-91.5
Saline Toeslope	2	2.32	92.8	184.6	237.6	263.9	6.7	159.7
Midslope	1	1.67	44.9	112.4	203.0	255.5	4.2	93.8
Midslope	2	2.26	41.4	69.0	148.6	199.1	3.9	97.5
Midslope	3	3.11	21.8	98.6	130.4	274.9	4.2	-27.7
Midslope	4	3.08	75.3	159.6	219.3	299.8	11.3	-15.0
Shoulder	1	2.16	27.4	53.8	149.5	224.1	2.5	166.0
Shoulder	2	2.93	38.7	66.5	120.9	158.7	5.3	15.2
Shoulder	3	3.73	52.8	83.9	143.6	166.5	12.0	105.5
Shoulder	4	3.65	31.6	54.4	116.3	158.2	5.4	-18.9

*Estimate of N mineralized calculated in the 0 N ha^{-1} treatments using the following formula:

(Fall NO_3^--N to 120 cm + (% N in grain * grain yield) + (% N in straw * straw yield)) – (Spring NO_3^--N to 120 cm + fertilizer N applied as monoammonium phosphate)

Table B.3 Forrest 1997.

Slope Position	Replicate	Relative Elevation (m)	NO_3^--N 0-30 cm (kg ha^{-1})	NO_3^--N 0-60 cm (kg ha^{-1})	NO_3^--N 0-90 cm (kg ha^{-1})	NO_3^--N 0-120 cm (kg ha^{-1})	PO_4-P (mg/kg)	*Estimate of N mineralized (kg N/ha)
Toeslope	1	0.46	30.3	39.3	57.3	80.8	5.8	2.1
Toeslope	2	1.109	20.0	33.2	66.7	105.2	10.3	38.1
Toeslope	3	0.854	30.4	50.1	72.3	86.5		37.6
Midslope	1	1.171	25.0	56.1	76.0	94.0	2.4	20.1
Midslope	2	1.51	21.3	88.3	218.3	275.1	1.6	-167.6
Midslope	3	1.865	29.8	68.4	140.0	191.9	3.5	285.0
Shoulder	1	1.774	15.4	29.0	57.7	100.5	2.9	38.0
Shoulder	2	2.09	19.0	30.9	51.8	77.0	8.6	76.6
Shoulder	3	2.96	24.2	34.0	40.3	53.4	2.9	101.2

*Estimate of N mineralized calculated in the 0 N ha^{-1} treatments using the following formula:

(Fall NO_3^--N to 120 cm + (% N in grain * grain yield) + (% N in straw * straw yield)) – (Spring NO_3^--N to 120 cm + fertilizer N applied as monoammonium phosphate)

Table B.4 Minnedosa 1997.

Slope Position	Replicate	Relative Elevation (m)	NO_3^--N 0-30 cm (kg ha^{-1})	NO_3^--N 0-60 cm (kg ha^{-1})	NO_3^--N 0-90 cm (kg ha^{-1})	NO_3^--N 0-120 cm (kg ha^{-1})	PO_4-P (mg/kg)	*Estimate of N mineralized (kg N/ha)
Toeslope	1	0.83	52.7	73.1	92.1	103.7	17.0	20.6
Toeslope	2	0.84	19.5	25.1	29.9	32.4	8.7	27.7
Toeslope	3	1.01	40.7	101.6	106.4	111.3	4.3	-15.4
Toeslope	4	0.99	75.4	104.4	126.7	144.6	6.4	-68.6
Lower Midslope	1	1.89	40.4	48.5	55.8	65.0	5.1	-1.6
Lower Midslope	2	1.58	27.1	32.2	35.1	39.5	3.7	28.4
Lower Midslope	3	1.95	45.1	55.7	58.1	62.0	6.7	-4.6
Lower Midslope	4	1.93	46.9	57.6	64.8	71.6	4.7	-2.0
Upper Midslope	1	3.22	15.1	18.5	21.4	24.3	2.7	26.6
Upper Midslope	2	2.44	17.6	22.3	24.7	27.6	3.5	7.7
Upper Midslope	3	2.87	29.4	37.1	41.5	44.4	5.8	-0.5
Upper Midslope	4	3.06	23.6	35.1	38.5	40.4	1.1	25.5
Shoulder	1							
Shoulder	2	3.19	20.5	24.7	27.6	29.1	1.9	17.7
Shoulder	3	3.77	25.6	28.2	30.1	30.6	3.6	6.2
Shoulder	4	3.71	14.3	19.4	20.3	20.3	2.0	2.7

*Estimate of N mineralized calculated in the 0 N ha^{-1} treatments using the following formula:
(Fall NO_3^--N to 120 cm + (% N in grain * grain yield) + (% N in straw * straw yield)) – (Spring NO_3^--N to 120 cm + fertilizer N applied as monoammonium phosphate)

Table B.5 Dufresne 1997.

Slope Position	Replicate	Relative Elevation (m)	NO_3^--N 0-30 cm (kg ha^{-1})	NO_3^--N 0-60 cm (kg ha^{-1})	NO_3^--N 0-90 cm (kg ha^{-1})	NO_3^--N 0-120 cm (kg ha^{-1})	PO_4-P (mg/kg)	*Estimate of N mineralized (kg N/ha)
Microhigh	1	0.73	27.9	36.6	45.1	54.9	5.2	67.2
Microhigh	2	0.83	4.6	35.7	48.0	81.0	5.5	72.0
Microhigh	3	1.04	18.4	27.9	38.3	43.9	6.4	71.6
Microhigh	4	0.81	5.3	9.4	17.5	20.8	5.2	104.6
Microhigh	5	1.39	6.3	21.2	27.4	33.5	5.6	86.5
Microhigh	6	1.31	21.5	21.5	23.4	30.4	6.3	82.1
Microlow	1	0.70	12.0	17.7	22.0	26.2	6.9	20.1
Microlow	2	1.01	7.0	11.5	21.5	24.8	8.9	29.3
Microlow	3	1.07	19.4	32.2	34.6	38.8	5.4	61.9
Microlow	4	1.27	16.9	27.6	31.4	36.1	6.0	43.2
Microlow	5	1.25	15.1	25.5	32.1	41.6	4.6	52.3
Microlow	6	1.33	14.1	26.0	34.6	42.6	5.6	46.2

*Estimate of N mineralized calculated in the 0 N ha^{-1} treatments using the following formula:

(Fall NO_3^--N to 120 cm + (% N in grain * grain yield) + (% N in straw * straw yield)) – (Spring NO_3^--N to 120 cm + fertilizer N applied as monoammonium phosphate)

Table B.6 Elm Creek 1997.

Slope Position	Replicate	Relative Elevation (m)	NO_3^--N 0-30 cm (kg ha^{-1})	NO_3^--N 0-60 cm (kg ha^{-1})	NO_3^--N 0-90 cm (kg ha^{-1})	NO_3^--N 0-120 cm (kg ha^{-1})	PO_4-P (mg/kg)	*Estimate of N mineralized (kg N/ha)
Microhigh	1	1.07	20.5	32.7	40.7	45.4	5.1	28.1
Microhigh	2	1.21	44.0	68.8	82.4	92.2	3.8	48.3
Microhigh	3	1.08	18.8	31.8	42.1	47.3	4.1	37.5
Microhigh	4	1.05	31.7	46.3	53.8	59.0	3.9	6.7
Microhigh	5	1.02	20.6	27.8	34.4	39.9	2.3	33.0
Microlow	1	0.99	20.1	29.1	60.5	68.0	8.8	-14.7
Microlow	2	0.96	22.0	31.4	36.5	41.2	4.5	8.3
Microlow	3	0.99	23.8	34.8	42.8	48.4	3.3	24.4
Microlow	4	0.99	29.6	39.3	46.3	52.8	2.8	26.5
Microlow	5	0.97	14.7	22.4	36.9	41.1	2.3	-3.7
Low	1	0.86	19.7	28.3	33.4	36.2	4.8	1.7
Low	2	0.88	19.0	28.0	34.1	37.8	4.8	9.1
Low	3	0.80	12.8	20.5	27.6	30.4	2.9	19.6
Low	4	0.77	13.2	21.3	27.9	31.6	2.3	53.4
Low	5	0.73	15.9	25.2	31.3	35.4	4.9	25.7

*Estimate of N mineralized calculated in the 0 N ha^{-1} treatments using the following formula:
(Fall NO_3^--N to 120 cm + (% N in grain * grain yield) + (% N in straw * straw yield)) – (Spring NO_3^--N to 120 cm + fertilizer N applied as monoammonium phosphate)

Appendix C

Soil Volumetric Water Content Data

Table C.1 Forrest 1996.

		Spring Vol. Water Content (mm)				Anthesis Vol. Water Content (mm)				Harvest Vol. Water Content (mm)			
Slope Position	**Replicate**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**
Toeslope	1	144.7	275.4	409.3	522.4	131.4	247.1	350.3	440.0	125.9	253.5	377.6	498.0
Toeslope	2	124.0	253.5	423.8	546.1	106.8	217.8	335.0	432.9	107.0	223.5	338.0	452.4
Toeslope	3	124.2	255.9	379.7	489.0	74.8	174.7	288.0	384.8	103.2	216.2	333.1	446.0
Toeslope	4	116.9	233.5	346.6	462.0	84.0	186.8	275.5	357.1	84.1	174.6	291.8	374.4
Midslope	1	116.2	309.0	424.1	529.5	52.0	128.6	231.2	319.7	77.2	149.0	248.1	340.4
Midslope	2	89.0	182.4	288.1	381.8	47.7	101.9	179.7	262.7	58.9	126.0	220.3	310.3
Midslope	3	98.4	199.6	302.5	393.5	51.7	118.6	200.3		68.0	142.1	225.6	299.1
Midslope	4	100.4	200.6	315.3	413.8	47.7	98.8	171.8	254.8	96.3	159.6	264.7	365.8
Shoulder	1	101.2	216.6	310.5	444.2	53.6	127.0	206.5	291.0	70.8	153.5	242.1	331.1
Shoulder	2	92.5	184.4	284.5	374.2	51.6	116.5	202.1	283.7	63.5	131.2	211.3	296.5
Shoulder	3	88.6	190.0	285.3	368.7	52.4	112.0	190.1	273.1	76.2	158.5	232.2	311.1
Shoulder	4	98.2	198.8	298.9	384.4	55.6	118.0	184.3	249.8	74.9	143.3	223.8	301.0

Table C.2 Zero Tillage Farm 1996.

Slope Position	**Replicate**	**Spring Vol. Water Content (mm)**				**Anthesis Vol. Water Content (mm)**				**Harvest Vol. Water Content (mm)**			
		0-30 cm	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**
Nonsaline Toeslope	1	116.6	251.6	375.6	484.9	123.1	252.0	380.4	498.7	106.8	190.3	274.9	369.3
Nonsaline Toeslope	2	107.9	214.0	329.7	469.8	96.9	184.0	300.7	404.7	81.3	131.4	208.1	283.7
Saline Toeslope	1	134.5	280.5	399.3	543.0					120.5	225.7	326.4	434.3
Saline Toeslope	2	112.4	220.5	356.0	465.6	122.5	213.1	344.6	460.3	117.1	194.8	282.9	365.5
Midslope	1	105.4	190.4	329.0	445.1	102.4	201.3	288.7	366.6	67.5	140.4	204.5	275.9
Midslope	2	112.3	213.6	334.5	441.4	88.0	188.0	324.1	470.4	88.3	183.6	278.2	377.8
Midslope	3	102.2	193.2	303.9	390.8								
Midslope	4	107.1	204.6	318.0	420.7	98.7	177.9	269.1	359.9	62.3	125.7	185.9	
Shoulder	1	76.7	162.2	259.2	351.6	80.4	155.0	236.9	321.1	52.5	107.2	160.1	221.7
Shoulder	2	111.9	208.7	315.7	431.5	105.8	200.7	303.2	438.6	75.0	136.9	232.9	327.7
Shoulder	3	110.6	211.3	300.6	406.1	89.5	153.4	238.7	327.3	54.2	102.4	146.6	192.7
Shoulder	4	83.5	181.4	283.5	371.0	95.9	169.3	241.0	318.7	48.8	110.0	154.4	207.0

Table C.3 Forrest 1997.

Slope Position	Replicate	Spring Vol. Water Content (mm)				Anthesis Vol. Water Content (mm)				Harvest Vol. Water Content (mm)			
		0-30 cm	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**
Toeslope	1	100.8	213.0	329.8	438.3	99.4	204.2	332.8	455.7	93.8	188.9	285.4	386.3
Toeslope	2	102.6	214.5	299.7	404.6	93.7	208.8	318.8	421.8	86.9	181.9	293.1	392.3
Toeslope	3	112.3	221.3	346.1	466.4	81.5	163.8	252.5	350.3	112.3	232.2	340.2	455.9
Midslope	1	87.6	179.4	278.3	372.0	78.3	159.3	236.0	324.5	74.1	152.1	242.9	327.8
Midslope	2	90.1	189.1	292.3	391.2	69.9	163.0	251.3	342.5	63.0	141.0	236.6	322.1
Midslope	3	99.6	196.4	322.8	447.1	98.1	210.5			60.5	120.2	191.2	269.6
Shoulder	1	112.9	217.8	313.9	407.0	80.0	161.1	264.2	359.6	74.0	148.6	230.6	316.8
Shoulder	2	120.5	228.3	330.9	423.6	70.0	142.3	228.8	319.4	75.3	154.6	245.6	334.9
Shoulder	3	117.0	215.4	298.3	365.5	75.9	156.3	234.5	297.6	62.6	114.0	172.9	232.0

Table C.4 Minnedosa 1997.

Slope Position	**Replicate**	**Spring Vol. Water Content (mm)**				**Anthesis Vol. Water Content (mm)**				**Harvest Vol. Water Content (mm)**			
		0-30 cm	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**
Toeslope	1	84.2	175.1	252.9	338.9	80.2	159.6	234.4	324.7	58.5	118.5	195.9	273.8
Toeslope	2	119.1	223.2	324.6	411.4	88.5	170.5	260.9	347.2	68.2	145.9	228.9	310.5
Toeslope	3	117.3	232.3	347.9	475.5	81.6	148.6	228.6	340.5	67.5	134.9	207.4	292.7
Toeslope	4	145.9	253.7	390.1	516.8	96.8	196.7	299.6	398.5	83.0	162.5	238.9	317.6
Lower Midslope	1	82.0	156.6	227.5	305.6	67.1	118.6	178.9	246.1	55.8	104.6	168.2	237.9
Lower Midslope	2	83.4	170.0	269.1	364.6	73.7	148.6	233.1	305.4	57.6	117.4	190.9	264.3
Lower Midslope	3	104.4	184.7	270.6	412.5	69.2	144.4	236.5	342.9	64.5	135.4	248.9	357.9
Lower Midslope	4	95.8	193.3	282.6	372.0	65.6	65.6	147.3	216.8	59.4	130.3	211.1	296.4
Upper Midslope	1	75.9	140.3	205.7	273.0	61.7	114.8	170.1	223.2	52.7	98.1	154.6	213.7
Upper Midslope	2	81.9	163.1	250.0	330.8	64.0	123.3	178.6	252.5	62.0	123.2	198.3	285.8
Upper Midslope	3	64.3	131.4	215.2	288.7	54.7	117.9	183.6	251.9	46.6	92.8	148.7	214.1
Upper Midslope	4	91.7	178.4	253.4	331.4	61.9	127.5	201.7	268.2	54.9	100.3	164.5	231.5
Shoulder	1												
Shoulder	2	78.1	156.5	223.7	303.9	63.3	127.9	194.1	260.0	48.5	101.9	163.3	226.8
Shoulder	3	82.3	170.5	251.9	328.4	59.3	124.8	195.2	260.7	57.5	112.7	177.0	245.0
Shoulder	4	68.4	147.4	226.8	307.8	59.2	121.9	187.5	251.5	53.4	111.7	179.5	253.6

Table C.5 Dufresne 1997.

Slope Position	**Replicate**	**Spring Vol. Water Content (mm)**				**Anthesis Vol. Water Content (mm)**				**Harvest Vol. Water Content (mm)**			
		0-30 cm	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**
Microhigh	1	138.5	308.5	483.5	645.9	128.1	261.2	410.2	558.9	125.4	247.1	382.9	523.8
Microhigh	2	152.2	321.0	490.4	650.3	145.5	317.0	490.3	665.2	146.5	272.1	422.1	562.8
Microhigh	3	146.2	299.2	465.0	625.0	135.7	294.9	462.0	621.6	143.1	272.5	411.4	566.4
Microhigh	4	135.2	284.4	424.6	558.2	132.7	276.6	439.2	587.4	137.4	264.9	409.5	558.4
Microhigh	5	144.8	298.8	462.8	623.3	128.7	283.4	437.9	586.7	151.9	278.8	430.1	581.9
Microhigh	6	143.4	292.5	427.8	577.4	130.4	275.2	436.1	587.5	136.2	254.0	386.1	524.2
Microlow	1	138.4	300.7	470.8	638.0	151.5	321.8	505.8	664.7	136.5	288.1	459.3	641.5
Microlow	2	141.1	301.2	474.3	638.0	149.7	311.0	486.5	652.3	154.6	316.4	485.5	644.9
Microlow	3	144.5	316.8	498.5	660.8	143.5	291.6	458.6	619.4	165.0	310.1	470.3	646.6
Microlow	4	139.4	292.9	456.6	610.4	135.2	274.2	432.1	596.7	156.0	317.0	488.8	657.2
Microlow	5	137.9	296.4	464.6	624.3	136.0	271.6	433.9	597.7	146.5	292.3	441.2	602.1
Microlow	6	138.9	295.2	457.6	614.9	137.3	290.7	374.6	531.1	132.7	266.0	413.1	580.1

Table C.5 Elm Creek 1997.

Slope Position	**Replicate**	**Spring Vol. Water Content (mm)**				**Anthesis Vol. Water Content (mm)**				**Harvest Vol. Water Content (mm)**			
		0-30 cm	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**	**0-30 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**
Microhigh	1	107.6	222.2	361.4	492.5	97.4	199.4	321.8	455.5	108.4	219.8	345.3	475.6
Microhigh	2	112.8	239.2	373.0	493.4	95.6	208.1	324.7	456.4	99.2	187.4	292.7	411.1
Microhigh	3	127.8	257.7	409.1	550.4	109.3	231.1	363.6	489.9	106.5	217.4	342.6	469.9
Microhigh	4	96.1	214.9	355.5	491.7	95.8	210.0	342.2	477.4	126.0	248.8	380.0	513.6
Microhigh	5	114.4	243.8	393.5	521.1	101.0	213.4	348.4	482.2	109.2	232.0	383.2	517.2
Microlow	1	106.8	250.1	378.1	514.4	92.5	199.8	330.8	461.7	114.9	239.7	378.8	513.6
Microlow	2	108.8	248.0	387.0	515.5	99.1	209.6	335.9	469.8	103.0	214.8	345.1	481.6
Microlow	3	136.0	278.8	432.4	566.5	104.5	214.6	346.5	479.7	127.3	256.5	404.5	542.0
Microlow	4	103.2	229.1	371.0	507.7	85.2	194.5	320.4	448.6	90.3	191.7	312.3	439.1
Microlow	5	114.4	260.0	412.9	553.0	113.7	242.6	396.1	528.8	107.1	230.9	364.3	506.6
Low	1	127.0	269.8	436.3	569.9	105.0	244.6	402.0	536.7	117.1	248.3	378.2	507.8
Low	2	117.6	252.8	400.5	547.3	100.7	215.5	361.1	500.4	115.1	215.8	338.5	469.3
Low	3	119.1	252.9	411.0	544.0	111.7	241.5	379.8	507.2	118.1	239.5	374.1	501.6
Low	4	117.3	250.1	395.1	525.7	94.5	206.1	347.4	492.0	107.4	254.8	391.1	495.1
Low	5	116.6	236.4	372.8	504.4	102.2	227.0	372.7	505.0	125.1	245.9	379.4	510.7

Appendix D

Grain Yield and Grain Protein Content Data

Table D.1 Zero Tillage 1996 Grain Yield (kg ha^{-1}).

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**					
		6.6	**46.6**	**86.6**	**126.6**	**166.6**	**206.6**
Nonsaline Toeslope	1	1489.1	2912.0	2470.7	2239.1	1853.1	2404.6
Nonsaline Toeslope	2	2581.0	3463.5	3110.5	2945.0	2790.6	3264.9
Saline Toeslope	1	827.3	1610.4	1577.3	1599.4	1533.2	1478.0
Saline Toeslope	2	474.3	474.3	595.6	143.4	264.7	2007.5
Midslope	1	3000.2	2978.1	2823.7	3066.4	3165.6	3088.4
Midslope	2	2415.6	2415.6	2592.1	2415.6	2978.1	2426.6
Midslope	3	3231.8	2878.9	3375.2	3540.7	3375.2	3662.0
Midslope	4	2492.8	3011.2	3143.6	2878.9	2217.1	3342.1
Shoulder	1	2415.6	2834.7	2724.4	2735.5	3408.3	2779.6
Shoulder	2	2228.1	2437.7	2117.8	2349.4	2371.5	2272.2
Shoulder	3	3077.4	3088.4	3463.5	3055.3	3220.8	3728.2
Shoulder	4	2095.7	3154.6	2967.1	3331.1	2404.6	2603.1

Table D.2 Zero Tillage 1996 Grain Protein Content.

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**					
		6.6	**46.6**	**86.6**	**126.6**	**166.6**	**206.6**
Nonsaline Toeslope	1	16.0%	17.6%	17.3%	17.3%	17.2%	17.2%
Nonsaline Toeslope	2	15.7%	16.3%	16.2%	16.8%	16.6%	17.1%
Saline Toeslope	1	15.2%	15.9%	14.5%	15.8%	16.3%	16.5%
Saline Toeslope	2						17.4%
Midslope	1	16.3%	16.8%	17.6%	16.3%	16.9%	17.0%
Midslope	2	16.1%	16.9%	16.7%	16.8%	18.1%	17.6%
Midslope	3	17.9%	17.1%	17.3%	17.3%	18.4%	17.7%
Midslope	4	15.5%	18.7%	17.0%	16.8%	17.4%	17.6%
Shoulder	1	15.6%	16.7%	15.9%	16.5%	16.4%	17.6%
Shoulder	2	16.2%	15.2%	15.7%	17.1%	15.8%	16.7%
Shoulder	3	16.7%	16.8%	17.1%	16.9%	17.0%	17.2%
Shoulder	4	14.8%	16.6%	16.4%	17.2%	17.0%	17.1%

Table D.3 Forrest 1997 Grain Yield (kg ha^{-1}).

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Toeslope	1	1376.1	1653.4	2282.8	2229.5	2634.8	2762.8	2794.8
Toeslope	2	1301.4	1642.8	2517.5	3349.5	2752.2	2752.2	2656.2
Toeslope	3	1920.1	2346.8	2634.8	2336.1	1994.8	2325.5	3136.2
Midslope	1	2197.5	2645.5	2325.5	2602.8	2410.8	2229.5	2528.1
Midslope	2	2154.8	2645.5	2954.8	2602.8	2986.8	2922.8	2720.2
Midslope	3	2624.2	2794.8	2698.8	2698.8	2634.8	2965.5	2869.5
Shoulder	1	1685.4	2197.5	2208.1	2048.1	2336.1	2250.8	2229.5
Shoulder	2	1632.1	1632.1	2848.2	2912.2	3093.5	3008.2	2837.5
Shoulder	3	2378.8	1770.8	2186.8	2069.5	2378.8	2357.5	2336.1

Table D.4 Forrest 1997 Protein Content.

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Toeslope	1	12.5%	12.6%	13.3%	14.2%	15.4%	15.8%	15.6%
Toeslope	2	12.6%	11.7%	12.5%	13.7%	14.2%	14.9%	15.3%
Toeslope	3	13.1%	14.4%	14.8%	15.8%	17.4%	17.1%	17.5%
Midslope	1	13.7%	13.1%	14.0%	16.2%	16.5%	16.6%	17.3%
Midslope	2	12.8%	15.3%	16.0%	16.6%	16.7%	16.6%	16.6%
Midslope	3	16.6%	16.2%	16.5%	16.6%	17.1%	17.1%	17.0%
Shoulder	1	13.2%	12.7%	13.5%	14.6%	16.6%	17.0%	17.2%
Shoulder	2	11.5%	12.1%	13.3%	13.3%	15.0%	15.4%	16.4%
Shoulder	3	16.0%	13.6%	14.8%	16.8%	16.5%	17.7%	17.1%

Table D.5 Minnedosa 1997 Grain Yield (kg ha^{-1}).

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Toeslope	1	3410.1	3056.3	3345.8	3367.3	3260.0	3678.2	2756.0
Toeslope	2	1715.8	1565.67	2702.4	2852.5	3120.6	2874.0	3099.2
Toeslope	3	3163.5	3678.2	2713.1	3013.4	3152.8	3849.8	3646.1
Toeslope	4	2487.9	3163.5	3088.4	2895.4	2745.3	3024.1	3260.0
Lower Midslope	1	2262.7	2026.8	2616.6	2487.9	2498.6	3281.5	2959.8
Lower Midslope	2	2734.6	2680.9	2745.3	2680.9	3045.5	3302.9	3324.4
Lower Midslope	3	2423.6	2927.6	2423.6	2176.9	2874.0	3099.2	2927.6
Lower Midslope	4	2766.7	2863.2	2723.8	2788.2	2509.4	2959.8	3613.9
Upper Midslope	1	2391.4	2616.6	2080.4	2369.9	2498.6	2777.4	2745.3
Upper Midslope	2	1565.7	2595.1	2616.6	2155.5	2831.1	2906.1	3002.6
Upper Midslope	3	1994.6	2262.7	2112.6	2584.4	2680.9	2627.3	2348.5
Upper Midslope	4	2831.1	2091.1	2112.6	2487.9	2412.8	1898.1	2520.1
Shoulder	1							
Shoulder	2	2219.8	2241.3	1865.9	2166.2	1908.8	2219.8	2134.0
Shoulder	3	1340.5	2059.0	2305.6	2498.6	2123.3	2101.9	2445.0
Shoulder	4	1233.2	1726.5	2176.9	2048.2	2144.7	2337.8	2026.8

Table D.6 Minnedosa 1997 Protein Content.

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Toeslope	1	17.5%	15.7%	17.0%	17.6%	18.2%	17.9%	18.0%
Toeslope	2	15.0%	16.2%	15.3%	15.9%	16.8%	17.8%	18.5%
Toeslope	3	17.9%	18.2%	18.1%	18.6%	19.5%	18.6%	18.6%
Toeslope	4	17.1%	17.1%	18.2%	18.4%	18.3%	18.2%	18.5%
Lower Midslope	1	14.6%	16.8%	16.8%	15.9%		17.7%	17.9%
Lower Midslope	2	14.3%	14.2%	16.3%	17.5%	18.3%	18.5%	18.8%
Lower Midslope	3	15.1%	14.5%	16.6%	18.1%	18.7%	18.5%	18.6%
Lower Midslope	4	15.5%	18.6%	17.6%	17.4%	18.2%	18.7%	18.5%
Upper Midslope	1	13.6%	15.7%	15.8%	16.1%	16.4%	16.8%	16.6%
Upper Midslope	2	14.2%	16.8%	15.9%	17.0%	17.9%	18.0%	17.7%
Upper Midslope	3	14.8%	15.0%	16.2%	18.1%	18.2%	17.9%	18.0%
Upper Midslope	4	15.3%	18.0%	18.0%	18.3%	18.9%	18.4%	19.7%
Shoulder	1							
Shoulder	2	15.9%		18.4%	18.0%	17.2%	17.7%	18.4%
Shoulder	3	14.4%	15.4%	16.5%	17.3%	17.8%	18.2%	18.6%
Shoulder	4	13.4%	14.5%	14.6%	17.7%	17.0%	17.7%	

Table D.7 Dufresne 1997 Grain Yield (kg ha^{-1}).

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Microhigh	1	2969.3	3367.3	3206.0	3259.8	3550.2	3485.7	3518.0
Microhigh	2	3743.9	3410.4	3700.9	3528.7	3937.5	2947.8	4066.6
Microhigh	3	2313.0	3227.5	3012.3	3647.1	3259.8	3474.9	2108.63
Microhigh	4	2829.4	3292.0	3625.5	3356.6	3335.1	3388.9	3690.1
Microhigh	5	2786.4	3302.8	2678.8	3281.3	3216.7	3485.7	3733.1
Microhigh	6	2797.2	2764.9	2904.7	2259.2	4185.0	3033.8	3356.6
Microlow	1	290.5	871.4	1097.3	936.0	1161.9	1538.4	1086.6
Microlow	2	548.7	688.5	2323.8	1280.2	1215.7	1097.3	2001.0
Microlow	3	2345.3	2366.8	3012.3	2334.5	3700.9	3582.5	2517.4
Microlow	4	1721.3		2452.9		3195.2	2657.3	
Microlow	5	2087.1	2076.4	1775.1	2377.6	2409.9	3076.9	2872.5
Microlow	6	1495.4	2054.8	2872.5	2958.5	2840.2	2528.2	2807.9

Table D.8 Dufresne 1997 Protein Content.

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Microhigh	1	12.6%	13.0%	14.6%	14.2%	15.0%	15.8%	15.9%
Microhigh	2	13.6%	14.0%	15.1%	16.1%	15.6%	16.9%	15.3%
Microhigh	3	11.8%	11.5%	12.5%	14.0%	14.6%	15.3%	16.2%
Microhigh	4	13.2%	12.4%	14.5%	14.6%	15.1%	15.5%	15.7%
Microhigh	5	12.8%	12.7%	12.9%	14.2%	15.8%	15.4%	15.8%
Microhigh	6	11.0%	12.7%	12.9%	13.3%	16.2%	14.7%	16.4%
Microlow	1	11.9%	14.6%	14.6%		15.5%	15.1%	15.5%
Microlow	2	13.1%	13.9%	14.0%	15.3%	15.3%	15.4%	15.2%
Microlow	3	12.7%	12.9%	14.7%	15.4%	15.4%	15.3%	15.5%
Microlow	4	12.4%		13.2%		14.4%	14.5%	
Microlow	5	12.6%	13.5%	15.5%	15.3%	16.0%	15.1%	15.5%
Microlow	6	13.0%	12.6%	15.6%	15.6%	15.2%	15.9%	15.3%

Table D.9 Elm Creek 1997 Grain Yield (kg ha^{-1}).

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Microhigh	1	1489.6	2320.7	1835.0	3011.6	3119.5	3432.5	2493.4
Microhigh	2	3054.7	2730.9	3421.7	3292.2	3324.6	3270.6	3464.9
Microhigh	3	1608.3	2601.4	2504.2	2450.3	3195.1	2676.9	3454.1
Microhigh	4	971.5	1781.0	2892.8	2299.1	3303.0	3065.5	3400.1
Microhigh	5	1327.7	1932.1	3249.0	2849.6	3033.1	2461.1	2493.4
Microlow	1	863.5	1208.9	1478.8	2536.6	3000.8	3130.3	2741.7
Microlow	2	809.6	723.2	1835.0	2385.5	3065.5	2018.5	2450.3
Microlow	3	1241.3	1856.6	2774.1	2450.3	2363.9	3076.3	1996.9
Microlow	4	1737.9	1208.9	1597.5	2925.2	2687.7	3043.9	2946.8
Microlow	5	269.9	1133.4	939.1	2601.4	2882.0	3087.1	3249.0
Low	1	388.6	906.7	593.7	1975.3	1662.3	1932.1	2558.2
Low	2	626.1	582.9	1176.6	1964.5	2687.7	2644.6	2504.2
Low	3	572.1	723.2	1360.1	1651.5	1781.0	1975.3	1748.6
Low	4	1403.2	2493.4	2709.3	1899.8	2331.5	3097.9	2709.3
Low	5	766.4	993.1	1241.3	2655.3	2320.7	3011.6	2784.9

Table D.10 Elm Creek 1997 Protein Content.

Slope Position	**Replicate**	**Nitrogen Fertilizer Rate (kg N ha^{-1})**						
		4.4	**34.4**	**64.4**	**94.4**	**124.4**	**154.4**	**204.4**
Microhigh	1	14.3%	12.9%	13.8%	14.7%	15.7%	15.7%	15.0%
Microhigh	2	14.8%	14.4%	15.0%	15.9%	15.9%	16.4%	16.5%
Microhigh	3	14.1%	14.2%	13.9%	15.2%	15.9%	15.6%	15.9%
Microhigh	4	15.3%	14.1%	15.1%	14.5%	15.7%	15.7%	15.7%
Microhigh	5	14.2%	13.6%	14.8%	15.7%	15.9%	15.3%	16.4%
Microlow	1	15.4%	14.6%	14.8%	14.6%	16.0%	15.7%	15.7%
Microlow	2	15.8%	15.6%	16.1%	14.8%	15.0%	15.1%	15.5%
Microlow	3	15.2%	14.2%	16.0%	14.9%	15.6%	16.3%	15.5%
Microlow	4	13.8%	15.2%	14.8%	15.2%	15.2%	16.5%	16.7%
Microlow	5	16.9%	14.8%	15.0%	14.5%	15.0%	15.9%	15.8%
Low	1	15.9%	14.9%	15.4%	15.2%	15.2%	15.5%	15.5%
Low	2	16.1%	16.2%	15.0%	15.5%	15.0%	15.3%	15.7%
Low	3	16.2%	16.5%	15.0%	15.6%	15.4%	16.1%	17.4%
Low	4	15.4%	14.0%	14.6%	15.0%	15.7%	16.4%	16.3%
Low	5	16.1%	15.0%	14.3%	14.7%	15.5%	15.7%	16.9%