

THE SPATIAL DISTRIBUTION OF
SOIL N AVAILABILITY

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By

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ABSTRACT

The objective of this study was to examine the relationship between selected measurements of soil N availability and wheat grain yield along a single transect in a typical Saskatchewan farm field using both biological and chemical methods. In addition, these relationships were examined spatially using landform element classification and geostatistics. Soil N availability was estimated by aerobic incubation, ion exchange membranes, determination of soil inorganic N ($\text{NO}_3^- + \text{NH}_4^+$), hot KCl extractable N, and N hydrolyzed from organic matter. Soil measurements also included total soil N and C, soil organic C, spring soil moisture and permanent wilting percentage. Wheat grain yields were collected at each sample location. With the exception of inorganic N, soil N availability was related to landscape position in that it increased from upper to lower slope positions.

Soil properties with the strongest relationship to landform were organic N hydrolysable, spring soil moisture content, total C, and grain yield, all of which showed significant differences between shoulder and foot-slope positions. Total soil N, soil organic C, and N mineralized over the 16 wk incubation did not show as strong of a landscape relationship. Organic N hydrolysable showed the strongest correlation with grain yield ($r_s = 0.492$, significant to $P=0.01$). Soil inorganic N was unrelated to landscape position and to grain yield ($r_s = -0.114$, non-significant). Grain yield, organic N hydrolysable, and spring soil moisture were well correlated with the N mineralization that occurred during the first 2 wks of a long term incubation. This suggests that the rapidly hydrolysable organic N pool may be the most significant source of available N in terms of setting spring wheat yield potential. Geostatistics indicated that organic N hydrolysable, spring soil moisture, total soil C, and wheat grain yield had a geostatistical

range between 40 and 60 m. Soil properties with weaker landform distributions had a similar geostatistical range to each other but were much lower, in the order of 5 to 20 metres.

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LIST OF ABBREVIATIONS

No:	Potentially mineralizable N or the N mineralization potential.
LSH:	Low catchment shoulder (a shoulder position with a global catchment of 0 or 1).
HSH:	High catchment shoulder (a shoulder position with a global catchment >1).
LFS:	Low catchment foot-slope (a foot-slope position with a global catchment <5).
HFS:	High catchment foot-slope (a foot-slope position with a global catchment >5).
PWP:	Permanent wilting percentage.
ns:	Non-significant.
SOM:	Soil organic matter.
PRS TM :	Plant root simulator TM .
M:	Molar.
CEC:	Cation exchange capacity.
Nm:	N mineralized.
t:	Time.
k _l :	Labile rate constant.
k _r :	Resistant rate constant.
LF:	Light fraction organic matter.
HF:	Heavy organic matter.
r _s :	Correlation coefficient from Spearman rank correlation.
r ² :	Correlation coefficient from regression analysis.
C:	Structural variance.
Co:	Nugget variance.
(h):	Distance.
Zx:	Random variable.
γ:	Semi-variance.
h:	Hour(s).
wk	Week.
wks	Weeks.
d	Day(s).
min	Minutes.

1.0 INTRODUCTION

Gross soil organic N is tied up in a mixture of fresh plant and animal debris, microbial biomass, microbial metabolites and cell wall constituents adsorbed to soil colloids, and as very stable humus (Campbell et al., 1993). The soil contains thousands of kilograms of N per hectare, yet only 1 to 2% of this reserve is available to a crop each year (Campbell et al., 1993). A small portion of this N reserve is made available through mineralization of the soil organic matter (SOM) by microbial processes (Bremner, 1965). Nitrogen available to a crop includes soil inorganic N at seeding, N mineralized over the growing season, and N applied as fertilizer (Campbell et al., 1997). Plants take up the majority of their N at an early growth stage (Campbell et al., 1997); thus, the timing of the availability of these N sources and their amounts will strongly influence N uptake and crop yield (Campbell et al., 1997). Although mineralization is a significant source of mineral N for plants, it cannot meet the N needs of current yield goals; thus the application of N fertilizers is necessary (Bremner, 1965). Equal in importance are available moisture at time of seeding and weather conditions over the growing season (Campbell et al., 1997).

At the time of seeding, plant available soil N includes NO_3^- , NO_2^- and NH_4^+ , as well as N applied as fertilizer (Campbell et al., 1997). To calculate the appropriate amount of fertilizer to apply, the level of KCl extractable soil NO_3^- is commonly used to establish the amount of N available from the soil at time of seeding (Jalil et al., 1996;

Campbell et al., 1997). This does not take into account the amount of N that is made plant available by mineralization over the growing season (Jalil et al., 1996). The amount of N mineralized over the growing season is difficult to predict because of the dependency of the mineralization process on weather conditions and other soil properties (Campbell et al., 1997). The inability to predict weather and difficulty in assessing the impact of previous crop management and economic conditions can lead to inaccurate recommendations for N fertilizer applications (Keeney, 1982). Thus, under a single fertilizer rate, there is high potential for over-application of N in certain areas of a field, leading to greater N losses to the environment and unnecessary cost (Fiez et al., 1994). To develop accurate fertilizer N recommendations, it is necessary to estimate the amount of N that is mineralized from SOM during the growing season (Talpaz et al., 1981; Cabrera and Kissel, 1988a).

The inherent spatial variability of N-cycling processes makes it particularly difficult to estimate the potential N availability, even in small areas (Cabrera and Kissel 1988a; Mahmoudjafari et al., 1997). Separation of a field into management units on the basis of soil properties, such as the ability of a soil to mineralize N, will facilitate the matching of fertilizer N rates to the N needs of the crop, thereby lowering costs and minimizing environmental damage (Fiez et al., 1994). There is a requirement for reliable estimations of soil N availability mineralized from the SOM (Bremner, 1965; Cabrera and Kissel, 1988a; Sierra, 1996) and an understanding of the spatial variation influencing these processes of a soil (Goovaerts and Chiang, 1993).

Information on spatial variability of N is important for fertilizer recommendations in view of the specific needs of precision farming (Mahmoudjafari et al., 1997). The spatial variability associated with soils makes the estimations of plant

available N very difficult, yet vital to precision farming methods (Cabrera and Kissel, 1988a). Unfortunately, the spatial variability of N mineralization is difficult to model because the processes involved are dependent upon soil properties and climate (Campbell et al., 1997; Jaynes and Colvin, 1997). Management practices also have an impact on N mineralization, which contributes to the inaccuracies in estimations of N availability because of the difficulty in quantifying soil management effects (Keeney, 1982). Franzen and Peck (1995) felt that the more variability within a field, the more soil samples would be required to adequately describe this variability. However, in order to successfully implement precision farming there is a need to develop fertilizer recommendations with a minimal number of samples. An understanding of factors that influence N-mineralization, and N availability can offer a means to limit the number of samples.

The purpose of this research was to select several methods by which soil N availability is measured and assess their relationship to grain yield. It was also the purpose of this research to look at the spatial distribution of N availability in terms of each one of the selected methods and the spatial distribution of related soil properties. The goal was to identify which one of the selected methods of measuring N availability is most suitable for measuring the N contribution of the soil that is important to a crop on a spatial basis such as would be needed for precision farming applications.

2.0 LITERATURE REVIEW

2.1 Factors Affecting Wheat Yield

According to Jaynes and Colvin (1997) soil properties and rainfall are the major controls on wheat yield, however factors such as management, weeds, and disease also contribute. Moreover, they indicate that these factors vary from year to year depending on climatic conditions. This view is supported by Robertson (1974) who identified precipitation, wind, solar radiation, and minimum/maximum air temperatures as yield limiting factors for wheat. Entz and Fowler (1988) suggested that yield variation was attributable to the poor distribution of these factors within a growing season. Since yield potential varies across a field, this potential and its variation must be known in order to successfully vary the rate of fertilizer application, because the N needed is dependent upon the yield potential of the soil (Fiez et al., 1994).

Jaynes and Colvin (1997) recognized some similarities in yield results from year to year, but indicated that yields had little spatial or temporal persistence. Fiez et al. (1994) demonstrated that yield potential has a spatial distribution related to landscape, but noted that this was not the sole factor in determining the distribution of yield. Landscape or topography is, however, often directly related to the spatial distribution of yield (Sinai et al., 1981; Ciha, 1984; Simmons et al., 1989; Halvorson and Doll, 1991; McConkey et al., 1997; Solohub et al., 1999). These studies recognize that higher yields occur in lower slope positions and in concave landforms where moisture accumulates.

However it was also observed by some researchers that the control of landscape on water distribution and, in turn, yield is reduced in wet years when water is least limiting as a factor (Simmons et al., 1989). Conversely, in years where water availability is very limiting, landscape also has less control because there simply is not enough water to redistribute (Halvorson and Doll, 1991). Thus, Jaynes and Colvin (1997) cautioned that the interpretation of yield results from any one year may be misleading. They suggested that several years; i.e., more than six, may be necessary to find any consistency in results.

The effect of water stress and temperature on yield of wheat also has been studied or discussed by many researchers (Day and Intalap, 1970; Angus and Moncur, 1977; Campbell and Paul, 1978; Frank and Bauer, 1984; Frank et al., 1987; Entz and Fowler, 1988). A review of this literature reveals that high temperatures, high sunlight exposure, and water stress reduces the duration of apex spikelet development, which leads to a lower number of spikelets and lower wheat yield (Frank et al., 1987). The timing of temperature and water stress is important to yield (Entz and Fowler, 1988). For example, Day and Intalap (1970) and Johnson and Kanemasu (1982) noted reduced wheat grain yield when water stress occurred at the jointing stage. Fewer heads, and fewer kernels per head were produced. Similarly, water stress applied 12 days after emergence, and persistently higher air temperatures, significantly reduced the number of spikelets (Frank et al., 1987). Spikelet numbers cannot increase after terminal spikelet formation, which occurs 28 to 30 days after emergence. As well, the spikelets formed are still subject to environmental conditions, which may render them infertile and reduce wheat grain yields in this manner as well (Frank et al., 1987). Increased N, water, and

cool temperatures increase the time to reach double-ridge stage and increase wheat grain yield potential (Frank and Bauer, 1984).

Although many factors are known to contribute to crop yield, according to Campbell et al. (1997) soil moisture and a combination of the mineral N present at time of seeding and N mineralized over the growing season tend to dominate. Indeed, when water and other growth factors are not limiting, the first effect of applied N is to increase yield (Grant and Flaten, 1998). Thus, assessing the N availability of the soil may be a critical step in predicting the potential crop yield and determining the nutrient requirements of the growing crop.

2.2 Assessing the N Availability of a Soil

Soil N availability must be assessed to accurately estimate N availability to crops (Talpez et al., 1981). There are a variety of methods to assess soil N availability. These methods evaluate the N available at a particular moment in time or predict the amount of N that may be made available over a specific period of time through mineralization. Methods that assess N availability at a particular moment in time include the assessment of the level of NO_3^- -N in 60 cm of soil at seeding, using a KCl extraction (Campbell et al., 1988), or a one hour insertion of a Plant Root Simulator™ (PRS™) (Qian and Schoenau, 1995). The N mineralization potential (Campbell et al., 1993) or the N supply rate as measured using a 2 wk insertion of a PRS™ (Qian and Schoenau, 1995) are examples of methods used to predict the amount of N that may become available over a specific period of time. Organic matter indices have been devised and employed for the same purposes (Keeney, 1982).

Methods used to assess N availability typically are categorized as either biological or chemical. Biological methods measure the products of the microbially mediated process of mineralization of organic N to plant available inorganic N. For this reason, biological methods usually involve some form of incubation (Campbell et al., 1993). Chemical methods extract a portion of the N from the mineral and organic N pools of the soil that is thought to be representative of N that is readily available to plants or that is readily mineralizable. Chemical methods of assessing N availability are typically cheaper and faster than comparable biological methods (Gianello and Bremner, 1986a). Organic matter indices, in conjunction with other soil parameters, also have the potential to be used as predictors of N availability, but the validity of these indices has yet to be proven (Keeney, 1982).

2.2.1 Soil Nitrate and Ammonium as an Estimate of Available Soil N

Typically, N recommendations are based on a soil NO_3^- test prior to seeding (Nyborg et al., 1976). The NO_3^- test is commonly used in semi-arid areas to measure NO_3^- content in the top 15 to 60 cm of soil (Jalil et al., 1996). Current methods use this soil test with crop growth simulation models to make more accurate predictions of N requirements (Campbell et al., 1997). The NO_3^- test only indicates plant available N at time of seeding and does not account for N mineralized during the growing season, nor the effect that weather conditions have on the ability of the soil to mineralize N (Campbell et al., 1993; Jalil et al., 1996).

Typically such a test for available soil N test actually tests for both NH_4^+ and NO_3^- ; however, the amount of NH_4^+ present is often very low and it is generally felt that there is little benefit in including it (Binford et al., 1992). Binford et al. (1992)

examined the necessity to measure inorganic N over a 60 cm profile and concluded that testing to a 60 cm depth offered a marginal, economically questionable benefit as compared to testing to a 30 cm depth.

Where leaching and denitrification are not a concern, the NO_3^- test should approximate available N and therefore this test should be used (Keeney, 1982; Gianello and Bremner, 1986a). Blackmer et al. (1989) found that tests for soil available NO_3^- -N appear to correlate well with yield provided that sampling occurs when plants (corn) are 6 to 12 inches high. These authors suggested that at planting, a reduced level of N should be added, and using an NO_3^- -N test well after seeding to indicate how much extra N can be applied later as a side dress. In this way, overuse of N is controlled (Blackmer et al., 1989). Such a protocol may be successfully applied to corn; however may not be successful with wheat, considering the early stage at which the yield potential of wheat appears to be set.

Success in using inorganic N as an index of N availability appears best where the climate is such that the soil is less frequently subjected to sudden leaching events (Blackmer et al., 1989; Binford et al., 1992). In Saskatchewan, in situations where inorganic N is prone to leaching and denitrification, such as in depressions, there is more variability in inorganic N determinations (Mahli and Nyborg, 1986; Popoff and Anderson, 1991; Pennock et al., 1992). Malhi and Nyborg (1986) found that from late winter to early spring, inorganic N levels declined and they attributed this decline to denitrification in the spring.

Several researchers have reported that soil inorganic N is highly variable to the point of being randomly distributed in contrast to other soil properties, which often follow a predictable spatial pattern based on landform (Popoff and Anderson, 1991;

Pennock et al., 1992; Thicke et al., 1993; McConkey et al., 1997; Raun et al., 1998; Solohub et al., 1999). For example, Pennock et al. (1992) observed a random pattern for mineral N (NO_3^- , NH_4^+ , NO_2^-) in a 200 by 200 m area grid sampled at 144 points. Not surprisingly, it has also been reported that the relationship between inorganic N and yield or N uptake has also been observed to be weak or random (Popoff and Anderson, 1991; Thicke et al., 1993; Raun et al., 1998; Solohub et al., 1999). Popoff and Anderson (1991) found NO_3^- in foot-slope areas to be low as compared to shoulder and back-slope positions and attributed this to leaching of mobile nutrients from lower slope positions. They also found no relationship between spring inorganic N and yield. Raun et al. (1998) similarly compared inorganic N to yield of bermuda grass and found no relationship. Thicke et al. (1993) attempted to predict the fertilizer N required for a maximum observed yield using soil nitrate levels. They were unsuccessful and attributed this to variability caused by decomposing residues and denitrification. In a study of N mineralization in a forest soil, Walley et al. (1996) found that the spatial distribution of inorganic N did not appear to have a topographic control.

2.2.2 Biological Methods for Determining Available Soil N and/or Soil N Mineralization Potential

2.2.2.1 Incubation Techniques

The quantification of the active or plant available N pool through measurement of N mineralized over a set period of time; i.e., cumulative N, is called the “potentially mineralizable N” or the “N mineralization potential” of the soil (N_o) (Stanford and Smith, 1972; Campbell et al., 1997). Attempts have been made to use N mineralization potential, together with measured weather conditions and soil physical characteristics, to

estimate the contribution of N mineralization to plant available N over the growing season (Campbell et al., 1988). In addition to quantifying the size of this N pool, the N mineralization potential includes the rate (k) at which this potential N pool becomes available, and, although not constant for most prairie soils, k has been found to be, on average, $0.067 \pm 0.040 \text{ wk}^{-1}$ (Jalil et al., 1996). However, mineralization potential varies with soil type and cropping practice (Campbell et al., 1997).

Bremner (1965) wrote an extensive review of the then current methods used as indices of N mineralization potential. Bremner's compilation was followed by Keeney (1982) who reviewed more recent methods. Keeney (1982) indicated that although research into the N supplying power of the soil appears to have been on-going since the mid-1940's, a consistent method of sample and data analysis was not available until a seminal paper by Stanford and Smith (1972).

The biological methods of note at the time of the Bremner (1965) review, are embodied in 3 distinct techniques: 1) estimation of N mineralization by determining microbial growth in an incubated soil sample (Peterson et al., 1960); 2) determination of the production of NH_4^+ , NO_2^- and NO_3^- by aerobic incubation of a soil sample (Stanford and Hanway, 1955); and 3) determination of CO_2 production by incubation of a soil sample (Harmensen, 1956). Each of these methods directly measure the microbial response to organic N or the products of their responses.

Measurement of the mineral N products of an incubation were cited by Bremner (1965) as the best methods available at that time. The incubation techniques used to index N mineralization potential have several different variations such as under anaerobic or aerobic conditions, water content, size of soil sample, use of amendments, temperature, and length of incubation period (Bremner, 1965). The majority of these

methods involve the aerobic, laboratory incubation of a soil followed by nitrification and leaching with water in order to measure NO_3^- N content (Harmensen and Lindenbergh, 1949; Stanford and Hanway, 1955).

Of all the incubation methods, aerobic incubation, according to Bremner (1965), was considered to provide the most realistic determination of the N supplying power of the soil. Bremner (1965) reasoned that the biological processes that produce mineral N from organic matter during the incubation should be the same as the processes that occur in the field to provide mineral N to a crop. Aerobic incubations typically measure NO_3^- because NH_4^+ is quickly nitrified under such conditions (Thicke et al., 1993). Early studies of N mineralization usually involved continuous aerobic incubation; however, this allowed accumulation of mineral N to levels toxic for microorganisms (Stanford and Smith, 1972). To overcome this problem, Legg et al. (1971) leached the accumulated mineral N on 2 wk intervals.

A currently accepted and commonly used method of aerobic incubation is that of Campbell et al. (1993). It is based on the method of Stanford and Smith (1972), a 24 wk incubation at 35°C and field capacity, and has been used by many researchers, including Jalil et al. (1996) and Curtin and Wen (1999). The incubation temperature of 35°C is optimum for nitrification and thus this method is based on the extraction of NO_3^- (Stanford and Smith, 1972). Several incubation times have been suggested ranging from 7 to over 200 days (Keeney, 1982). Campbell et al. (1993) argued that a minimum incubation time had yet to be established because the goal is for cumulative N to reach a plateau, which generally occurs after 20 wks. Molina et al. (1980) suggest that

incubation must be longer than 12 wks to apply the first order model commonly used to calculate N_o .

Overall, biological indices provide valid representations of the ability of a soil to release available N; however, the correlation of these laboratory methods to field data has not been encouraging (Keeney, 1982). Bremner (1965) cites several problems with biological indices of soil N availability, such as soil N in form of ammonium, which may not be removed by pre-leaching, and its subsequent nitrification accompanying mineralization of N during the incubation may yield erroneous results. Incubation experiments also are often regarded as time consuming and expensive for use as routine soil tests (Rasiah, 1995). Nevertheless, Campbell et al. (1993) pointed out that, because this pool is a heterogeneous mixture of plant microbial biomass and related debris as well as animal residue, cellular metabolites and humus, the mineralization of the organic N pool is not uniform. Thus, as Campbell et al. (1993) suggested, the best way to quantify the ability of a soil to release available N is through incubation experiments.

Waring and Bremner (1964) put forth a method using anaerobic incubation to determine biological indices of N mineralization and since that time several anaerobic methods involving short; i.e., 7 to 14 days, to long term; i.e., 112 to 210 days, incubations have been developed. Keeney (1982), who undertook an extensive review of indexing methods developed since 1965, considered the anaerobic incubation method of Waring and Bremner (1964) to be superior to all other biological techniques. Anaerobic incubation is based on mineralization under waterlogged conditions, which speeds and simplifies the process by preventing the nitrification of the ammonium produced, and negates the concern of maintaining a specific water content (Bremner,

1965). Waring and Bremner (1964) found a close relationship between the estimates of mineralized N from aerobically incubated and anaerobically incubated samples

Gianello and Bremner (1986b) suggested that both anaerobic and aerobic incubation methods provide reliable indices of potential N mineralization. Bremner (1965) supported the aerobic incubation method because it can provide values for mineral N that are very closely related to values provided by anaerobic incubation as determined using the method of Waring and Bremner (1964). However, because mineralization occurs in the field under aerobic conditions, it can be argued that aerobic incubation is the only method that approximates field processes.

2.2.2.2 Ion Exchange Resins

Ion exchange resins have been in use since 1942 (Qian and Schoenau, 1997) and are commonly used *in situ* as a buried bag or under a soil core (Rouppette et al., 1994). The bag is periodically retrieved and the N content determined. Over a number of periods, the cumulative N, assumed to be from the soil core, is derived. Membranes were first used in 1964 by Saunders (Qian and Schoenau, 1997). These offered less soil disturbance than was required to place a resin bag, reducing unnecessary water and nutrient movement in the soil, which in turn can influence mineralization (Subler et al., 1995).

The Plant Root Simulator (PRS™) is a membrane coated with an exchange resin and framed in a plastic applicator for direct insertion into the soil (Qian and Schoenau, 1997). The PRS™ acts as a nutrient ion sink, by exchanging ions for counter ions in a manner that has some similarity to the action of a root, which makes use of exchange reactions to acquire nutrients. The amount of available nutrient is measured over time,

giving a supply rate (Qian and Schoenau, 1997). This technique can also be used in the lab on a soil sample at field capacity (Qian and Schoenau, 1995).

A PRSTM may be inserted for 1 h to assess the inorganic N present in the soil or for 2 wks to assess the long term nutrient supplying power of the soil (Qian and Schoenau, 1997). Subler et al. (1995) used resin membranes for 30 days. A long term assessment measures inorganic N that is already present in the soil and inorganic N released by mineralization of organic matter (Qian and Schoenau, 1997). Subler et al. (1995) found that uptake of NO₃⁻ by the resin membrane was non-linear, being rapid early in the incubation and slowing as the exchange sites are filled. Subler et al. (1995) questioned the validity of resin membranes for long term incubations because of the competition that exists for adsorbed NO₃⁻ by microbes and roots.

The soil N availability measured by PRSTM has been shown to be well correlated with soil type, soil organic matter and management practice (Qian and Schoenau, 1995), offering great potential for field mapping and showing differences in landscape positions in terms of nutrient supply (Qian and Schoenau, 1997).

Correlation between results using PRSTM and actual soil inorganic N levels may be low because the mobility of the NO₃⁻ influences the amount adsorbed (Giblin et al., 1994; Subler et al., 1995). The supply of N, as measured by PRSTM, is dependent on the moisture content of the soil (Qian and Schoenau, 1997). As moisture decreases, supply rates decrease because moisture is required to facilitate movement of ions to the membrane. This suggests that N uptake is restricted in plants under dry conditions, regardless of the fertility of the soil (Qian and Schoenau, 1997). Under the proper moisture conditions, PRSTM have been shown to correlate better with N uptake in canola than an aerobic incubation, and provide estimates of N supply that are as good as

hot KCl extractable N tests (Qian and Schoenau, 1995; Schoenau, 1998). This relationship can be improved by including the inorganic N measured using a 1 h insertion together with the 2 wk mineralization assessment of N supply (Qian and Schoenau, 1995). Giblin et al. (1994) found exchange resins could be used to identify fertility differences between soils. PRSTM are rapid and simple to employ, which may prove them to be a superior method compared to traditional methods of assessing N supplying power (Qian and Schoenau, 1995).

2.2.3 Alternative Chemical Methods for Determining Soil N Availability and N Mineralization Potential

Although aerobic or anaerobic incubations of soil, or the use of ion exchange resins, are effective methods for determining potential N availability, these methods may not be fast enough, and are too complicated for the needs of many analytical soil testing laboratories (Gianello and Bremner, 1986a; Campbell et al., 1997). A rapid, accurate and simple test, such as a chemical method, is required, (Gianello and Bremner, 1986a; Campbell et al., 1997).

Bremner (1965) was generally critical of chemical methods and suggested that these they are only attractive because of their speed and simplicity. Chemical methods do not account for differences in the chemical nature of the N mineralized by microorganisms (Bremner, 1965). These methods do not actually measure the N pools that are utilized by the microbial community; however, chemical indices are less sensitive to sample handling and storage than biological indices (Thicke et al., 1993).

At the time of Bremner's review in 1965, the permanganate extraction method developed by Truog (1954), was considered the most reliable chemical index of N availability. Keeney (1982) criticized permanganate extraction, suggesting better results

could be obtained using hot water or hot salts as an extractant. Keeney (1982) recommended autoclaving soil samples in dilute calcium chloride and measuring the ammonium released (Stanford and Smith, 1976). Since that time, extraction with 2 M hot KCl has shown promise (Gianello and Bremner, 1986a; Campbell et al., 1997). Gianello and Bremner (1986a) proposed treating soil with 2 M KCl for 4 h, heated in a stoppered tube at 100°C. They suggested that the advantage of this method included the fact that there are no filtration or transfer steps and many samples can be done at one time depending on the size of the block digester (40 or 100 tubes). Moreover, the method provides an acceptable estimate of potentially available N (Gianello and Bremner, 1986a).

Gianello and Bremner (1986b) evaluated the CaCl₂ extraction method devised by Stanford and Smith (1976), the Keeney (1982) modification of the same method, and their own proposed method of using 2 M KCl. They found the 2 M KCl method to be as accurate as the more complicated Stanford and Smith (1976) method and more accurate than the method proposed by Keeney (1982). Using 2M KCl for a 4 h extraction reduced handling of the soil, and was well adapted to multiple sample extraction. It compared very well to results obtained by incubation. Jalil et al. (1996) also found chemical extraction using 2 M hot KCl for determination of mineralization potential compared well to mineralization potential as measured by biological incubation.

Curtin and Wen (1999) found that the hot KCl method was not a good predictor of cumulative N mineralized over a 24 wk incubation ($r^2=0.13$; $P=0.01$). A closer relationship was found between the hot KCl method and N mineralized in the first 2 wks of an aerobic incubation ($r^2=0.65$; $P=0.01$) (Curtin and Wen, 1999). This relationship,

as well as a close relationship between hot KCl extractable N and the water soluble organic N, suggested that hot KCl extracted from a labile, rapidly mineralized pool of organic N (Curtin and Wen, 1999). Selles et al. (1999) concluded that hot KCl extracted from the same pool of N as did an aerobic incubation for cumulative N. Estimates using the hot KCl method have been shown to correlate closely with cumulative N, but the advantage of speed and ease makes this method more promising (Selles et al., 1999).

The N availability estimates that are determined using the hot KCl method also include any inorganic N that was present in the soil. Subtraction of this amount of mineral N from the hot KCl derived amount of N leaves what is termed “organic N hydrolysable” and this value was thought to correlate better with biological indices than estimates using hot KCl values alone (Gianello and Bremner, 1986a). However many authors feel the advantage, if any, is so slight that it does not warrant its determination (Jalil et al., 1996; Campbell et al., 1997; Schoenau, 1998).

Campbell et al. (1997) tested the hot KCl method as a means of predicting available N for fertilizer recommendations using the crop growth simulation model of Jame et al. (1993). Initially the results of the extraction were checked against the results of an aerobic incubation and found to correlate well (Campbell et al., 1997). These results were then used with a modified CERES-wheat model, in which the modification consisted of using organic N pools which were more labile and would provide greater estimates of mineralization (Campbell et al., 1997). The authors were able to predict grain yields for certain moisture conditions and soil types or zones; however, these predictions have yet to be field tested (Campbell et al., 1997).

An alternative chemical indexing method, suggested by Gianello and Bremner (1986b) is the extraction of available N; i.e., NH_4^+ -N determined using a phosphate-

borate solution buffered at pH 11.2. The phosphate-borate buffer method, considered simple and precise, is not affected by air drying of the soil (Gianello and Bremner, 1988). Phosphate-borate appears well correlated with labile fractions of soil organic N (Vanotti et al., 1995). Phosphate-borate apparently extracts the soluble as well as the adsorbed labile N (Curtin and Wen, 1999). Curtin et al. (1996) have shown that this method is pH sensitive as the high pH of the solution disrupts the bonding on soil colloids and releases adsorbed organic matter that might otherwise be protected. Clays may offer some protection to adsorbed organics from phosphate borate (Curtin et al., 1998).

Other chemical methods of interest include the permanganate distillation technique Truog (1954), which has been since modified by other researchers (Bremner, 1965). Gianello and Bremner (1986a) also refer to autoclaving the soil in CaCl_2 to determine NH_4^+ -N. The authors consider this method complicated and slow. A similar method proposed by Keeney (1982) was less complicated, but not as precise (Gianello and Bremner, 1986a).

Gianello and Bremner (1986b) compared the results using their phosphate-borate buffer method and their hot KCl method to the results of 17 other methods for the same soils. These methods included KMnO_4 (Stanford and Smith, 1978), alkaline KMnO_4 (Stanford, 1978), CaCl_2 autoclaved (Keeney, 1982), NaHCO_3 with ultraviolet absorption (Fox and Piekielek, 1978) as well as the standard anaerobic and aerobic methods. These methods have not gained the same favor as the hot KCl or phosphate borate methods because they are not as simple, and require filtration and transfer steps not required by the hot KCl or phosphate-borate methods (Gianello and Bremner, 1986b). As well, they observed that both of their methods were highly correlated with

anaerobic and aerobic incubation methods, and proved superior to the 17 other methods in terms of this correlation, speed and simplicity.

2.2.4 Models Describing Soil N Mineralization Potential

Models describing soil N mineralization potential typically are based on the results from incubation studies. Nitrogen mineralization is generally considered to be a first order reaction (Stanford and Smith, 1972; Cabrera and Kissel, 1988a; MacDonald et al., 1995; Rasiah, 1995). Models for predicting N mineralization generally take the form of a one-pool (Stanford and Smith, 1972) or two-pool (Molina et al., 1980) model. Models with more than one-pool have been shown to have an advantage when used to analyze laboratory data; however, they do not have the same advantage when dealing with data collected in the field (Campbell et al., 1993).

The one-pool model proposed by Stanford and Smith (1972) is shown as equation 2.1.

$$N_m = N_o - N_o e^{-kt} \quad (2.1)$$

where N_m is amount of N mineralized at time t (cumulative N), a value derived through the incubation of a soil sample; N_o is the mineralization potential or potentially mineralizable N (Rasiah, 1995) or the pool of mineralizable N (Cabrera and Kissel, 1988a); and k is the rate constant of N mineralization. The amount of N mineralized is the difference between N_o at time 0 and N_o at time t (Campbell et al., 1993)

Equation 2.1 is based on the assertion that the rate of N mineralization is proportional to the amount of potentially mineralizable N (Stanford and Smith, 1972). N_m is often measured directly in the lab as the amount of N accumulated from successive extractions of a soil sample over the duration of an incubation (cumulative N),

(Campbell et al., 1993). The incubation is terminated when the amount of N mineralized, in the period between each extraction, approaches zero (at approximately 20 wks) (Campbell et al., 1993). According to Campbell et al. (1993), the calculation of N_0 is only valid if incubation occurs under ideal conditions; i.e., 35°C and field capacity. Moreover, N_0 values for a particular soil sample are generally 50% greater than the cumulative N value for that same soil sample (Campbell et al., 1993). The procedure assumes there is only one active N pool. In reality there is more than one-pool, but Campbell et al. (1993) suggested that separating these N pools is not likely to be worth the effort in terms of improving estimates of potentially mineralizable N.

Stanford and Smith (1972) suggested that a common value for k could be derived that would apply to a wide range of soils. They estimated k to be $0.054 \pm 0.009 \text{ wk}^{-1}$ which means that 5.4% of the mineralizable N pool is available per wk, based on the amount of mineralizable N remaining at the end of each wk. This estimate was based on pooled regressions for 29 soils of varied types. Subsequent work has shown that k is not constant and may have to be calculated from field to field (Rasiah, 1995; Mahmoudjafari et al., 1997). Campbell et al. (1993) and Jalil et al. (1996) used non-linear regression (least squares) to calculate N_0 and k , assuming first order kinetics, and found that k ranged from 0.05 to 0.20 wk^{-1} . Initial values of k and N_0 , to start off the iterative process of the non-linear regression, can be obtained by estimating k at 0.10 wk^{-1} and N_0 as 50 % greater than accumulated mineralized N (Campbell et al., 1993).

The two-pool model of N mineralization proposed Molina et al. (1980) is as follows (Equation 2.2).

$$N_m = N_1[1 - e^{-k_1 t}] + N_2 [1 - e^{-k_2 t}] \quad (2.2)$$

According to this equation, the single N pool, N_0 , from Stanford and Smith (1972), has been broken into two-pools, N_1 and N_2 , with both pools operating in a first order manner with separate rate constants (Molina et al., 1980). Molina et al. (1980) proposed that the first pool is small, representing approximately 16 % of the total potentially mineralizable N pool. This pool is rapidly mineralized ($k = 1.131 \text{ wk}^{-1}$). The second pool is much larger, representing approximately 84% of the total potentially mineralizable pool, and is more stable ($k = 0.0424 \text{ wk}^{-1}$). The larger, second pool is akin to the single pool proposed by Stanford and Smith (1972), but separation into two-pools allowed for a better fit of the exponential model with the observed data (Molina et al., 1980).

In a comparison of disturbed (dried, ground, and sieved) and undisturbed samples, Cabrera and Kissel (1988a) found that the two-pool model best described the mineralization of disturbed samples whereas the one-pool model best described mineralization of the undisturbed sample. They suggested that the smaller pool of the two-pool model was an artifact of sample pretreatment, and related it to the flush of mineralization which occurs upon re-wetting of a dried soil sample, rather than the mineralization of a highly labile pool, as was proposed by Molina (1980).

Subsequent work by Cabrera and Kissel (1988b) used the two-pool model, but used only the parameters derived from the larger pool to describe the mineralization. Other researchers have claimed success using the model in this form (Rasiah, 1995). However, Campbell et al. (1993) found no advantage in using the two-pool model, in any form, when it was applied to field data as opposed to laboratory data. Cabrera (1993) indicated that the flush of mineralization upon wetting may be an important aspect of soil N-cycling in that it mimics natural wet and dry cycles. Cabrera (1993)

concluded that the small-pool flush is important to mineralization models and should be included.

Some researchers have proposed that the two-pool model can be further modified by using first order kinetics for the rapidly mineralized pool and zero order (linear) kinetics for the slowly mineralized pool (Goncalves and Carlyle, 1994; Vanotti et al., 1995). However, this association with kinetics may merely reflect the pool size because if the pool is small, the amount mineralized in each period will be affected by depletion, resulting in exponentially controlled mineralization (Goncalves and Carlyle, 1994). If the pool is large, such that the amount of N mineralized is small by comparison, then no effective depletion occurs and zero order mineralization occurs (Goncalves and Carlyle, 1994). Thus, in a field situation, where the organic matter pool is being continually replenished, the pool remains large and zero order kinetics should dominate (Goncalves and Carlyle, 1994).

Work by Sierra (1990) demonstrated that as N mineralization proceeds, the amount of readily mineralizable N decreases in proportion to the less readily mineralizable N, which reduces the overall mineralization rate. The rate of N mineralization is not constant because the proportion of labile organic matter is not constant; thus, linear models may overestimate the N_0 and underestimate k (Sierra, 1990). Sierra (1990) indicated that the double exponential model is an improvement upon this, but it would be necessary to account for all expected pools, each with a function, to properly model N mineralization. The number of pools to be accounted for may vary depending upon the situation and goal of the project. Moreover, Sierra (1990) cautioned that if the mineralization rate does decrease, then pools of discrete size are not possible, and must be changing as well.

Ellert and Bettany (1988) devised an incremental model to describe N mineralization in an incubation study that involved periodic leaching of the soil. They treated each incubation period as a separate biological response to the preceding leaching. They felt that a cumulative model might mask the stress on the microbial community induced by leaching which occurs in the first few intervals, before the microbial population can adapt. Ellert and Bettany (1988) reported that the stages of mineralization included a large N flush, a mineralization lag (within the first 13 wks) and a constant rate of release near the end of the incubation. Superimposed on this were continuously decreasing rates of mineralization. They concluded that the variability in mineralization rates reflected different substrate pools and pathways of mineralization.

Rasiah (1995), in seeking a reliable field method of estimating N mineralization, attempted to predict mineralizable N and the rate constant with a model that used intrinsic soil properties. This model was based on a pedotransfer function of N mineralization that relied on clay and silt content, soil organic C, pH, total soil N and cation exchange capacity. The pedotransfer function allowed the contribution of these soil properties to N mineralization to interact in the determination of the mineralization potential (Rasiah, 1995). The function was tested against one and two-pool models of mineralization in which N_0 (one-pool), N_1 , N_2 , k_1 (labile rate constant), and k_r (resistant rate constant) were predicted with confidence. However, k (one-pool) appeared to be insensitive to the soil properties, from which the author concluded that k was not constant and that a single value of k cannot be used (such as would be used in a one-pool model). Based on this understanding, Rasiah (1995) concluded that the two-pool model was a better predictive model of N mineralization potential.

Attempts to model the N mineralization potential for the purpose of predicting N mineralization in the field have involved correcting the rate constant for temperature and correcting the amount of N mineralized for water content (Stanford et al., 1973; Stanford and Epstein, 1974). Campbell et al. (1988) attempted to estimate the amount of N mineralized using a model, which included N_0 , k , temperature, and field moisture contents. It was concluded that the actual amount of N mineralized was underestimated because the method used did not account for wet/dry cycles such as would produce an N mineralization flush (Campbell et al., 1988). Through this work, Campbell et al. (1988) reasserted that a one-pool model is sufficient for estimating net N mineralization. Cabrera and Kissel (1988b) also attempted predictions based on a model which incorporated factors for temperature and water content and found that actual amounts of N mineralized were over-predicted by as much as 343%.

Research by Curtin et al. (1998) addressed the one-pool / two-pool model controversy and these authors concluded that a one-pool model was sufficient in most cases; however, they suggested that where there is an appreciable labile fraction, a two-pool model should be used.

2.3 Environmental Factors Influencing Soil N Mineralization

The literature identifies a number of factors which influence, to varying degrees, the extent to which N mineralization will occur in a soil. These include climatic factors such as temperature and precipitation (Stanford and Smith, 1972; Campbell et al., 1974; Goncalves and Carlyle, 1994; MacDonald et al., 1995). Soil properties such as soil moisture, total soil N and soil organic C, pH, clay content, pore size distribution and pore volume, and microbial biomass are also important (Herlihy, 1979; Goovaerts and

Chiang, 1993; Breland and Hansen, 1996; Franzluebbbers et al., 1996; Scott et al., 1996), as is light fraction (LF) and heavy fraction (HF) organic matter (Spycher et al., 1983; Sollins et al., 1984; Cabrera and Kissel, 1988a; Janzen et al., 1992; Sierra, 1992; Gregorich and Ellert, 1993; Boone, 1994; Sierra, 1996; Wander and Traina, 1996). Landscape is also considered to exert a significant control on soil properties, thereby influencing soil processes such as mineralization (Pennock et al., 1992, 1994). Campbell et al. (1988) and Mahmoudjafari et al. (1997) suggested that the effect of moisture, temperature, and other factors on N mineralization is due to the effect of these factors on k .

2.3.1 Moisture and Temperature

Soil moisture and temperature have been of concern for some time and generally are held constant during incubation studies (Stanford and Smith, 1972; Mahmoudjafari et al., 1997). Ellert and Bettany (1992) considered soil moisture and temperature as the most influential factors affecting mineralization rates in soil. Attempts to relate laboratory results to field conditions led to mineralization studies based on the level of soil moisture within the plant-available range and different temperatures regimes typical of growing season conditions (Herlihy, 1979; Goncalves and Carlyle, 1994). Nitrogen mineralization for SOM was slower in the field than the lab (Honeycutt, 1999). It was suggested that the main difference was that the field plots were much drier and the water content was much more variable under field conditions as compared to laboratory incubations (Honeycutt, 1999). Field conditions also have been simulated using equations for one-pool and two-pool N models which correct k for soil temperature and N_0 for soil moisture (Cabrera and Kissel, 1988b). Smith et al. (1977) attempted to

adjust N_0 for various soil water and temperature values and compared these predictions to field measurements. The adjusted N_0 correlated better with the field measurements than did other measures of N availability.

Goncalves and Carlyle (1994) found that the quantity of mineral N produced increased linearly with time for the majority of moisture and temperature combinations. The size of the mineralizable pool appeared to increase with increasing soil temperature, possibly due to the positive response of the microbial community to temperature (MacDonald et al., 1995).

Within a single growing season, water and temperature will have more influence on the rate and amount of N mineralized than will the size of the N pool itself (Goncalves and Carlyle, 1994). Herlihy (1979) observed higher mineralization values under fluctuating moisture contents or where soil was allowed to go through wet and dry cycles. Ellert and Bettany (1992) concluded that mineralizable pools changed as temperature changed. This may be due to its affect on microorganisms, substrate composition, or transport processes. Q_{10} is not the same across all soils or temperatures and assuming a Q_{10} of 2 is common, but may not be correct (Campbell et al., 1988).

MacDonald et al. (1995) studied the effect of temperature on microbial respiration and net N and S mineralization and found that mineralized N increased with temperature and that the apparent pool size was related to temperature. Rates may be dependent upon temperature which affects which pool and the size of pool that is accessed by microbes (MacDonald et al., 1995).

Davidson et al. (1990), found that nitrification and the net nitrification rate declined as soil dried, but the decline lagged behind the onset of drying and decline of nitrification potentials. Reduction in N-cycling is likely related to a decline in microbial

populations under water stress and the inability of dissolved organics and mineralized materials to diffuse from microsites. Davidson et al. (1990) also noted that microsites differ in the time it takes to reach water stress, likely due to compositional and structural differences. Microsite heterogeneity would be expected to have an effect on the distribution of N mineralization (Davidson et al., 1990).

Soil N processes such as nitrification and ammonification appear to be less sensitive to changes in moisture content than previously thought (Sierra, 1992). This may be due to micro-aggregates maintaining the moisture content through drier periods or, alternatively, the microbial population may be adapted to the seasonal moisture variations (Sierra, 1992). Thus, in dry soils, the spatial variation in N may be due to variations in soil texture as it affects moisture content (Sierra, 1992).

Kowalenko and Cameron (1976) performed an incubation experiment using clay loam to examine the impact of temperature, moisture and added NH_4^+ -N on mineralized N. They found the interaction between temperature and moisture to be very important to the amounts of N mineralized and considered it to be more important than the effect of temperature alone. Quemada and Cabrera (1997) also examined the interaction between temperature and moisture and found that the effect of moisture was enhanced as temperature increased. Kolberg et al. (1999) found that precipitation, mean air temperature, and their interaction term were the best predictors of N mineralization.

2.3.2 *Wet/Dry cycles*

Cabrera (1993) felt that the method of Stanford and Smith (1972) did not accurately reflect N mineralization that occurs in soils that undergo wet-dry cycles typical in semi-arid conditions. This is because mineralization, upon the rewetting of a

dry soil, occurs as a flush. Campbell et al. (1988) considered wet/dry cycles to be important to N mineralization in the field. According to Cabrera (1993) wet/dry cycles are a mechanism by which N is made available from less readily available pools by means of desorption of organic substrates from soil surfaces. During an incubation, the flush is represented by that portion of cumulative mineral N obtained from the first extraction, which also tends to be the largest fraction (Cabrera, 1993). Clay appears to isolate organic matter from the microbial community, but upon drying and rewetting, this protection is broken down and this organic matter becomes available (Strong et al., 1999b). Soils with clays that fix organic matter will experience a greater flush of mineral N than soils with lower clay content or clays which are less able to fix organic matter (Strong et al., 1999b). In contrast, Magid et al. (1999) found that mineralization did not increase due to increased organic matter decomposition, but probably due to the availability of microbial debris from death of microorganisms.

Samples which are not subject to the wet/dry cycles experience N mineralization that follows zero order kinetics, whereas samples which undergo wet-dry cycles demonstrate first order kinetics (Cabrera, 1993). Flushes appear to be short-term, and subside after only two or three days (Murphy et al., 1998; Franzluebbers, 1999).

Murphy et al. (1998) found that changes in gross N mineralization were correlated to the soil water content in the top 2.5 cm of soil. Changes in water content in the top 2.5 cm of soil may heavily influence N mineralization because of its influence on the microbial activity concentrated in this layer (Murphy et al., 1998). Thus, minor rain events can have a disproportionate effect on mineralization. The microbial population appears to respond rapidly to small rainfall, even with rapid drying, by

mineralizing a significant amount of N (Murphy et al., 1998), suggesting that the microbial population is adapted to the wet/dry cycling.

2.3.3 Soil Texture

The influence of soil texture on N mineralization is primarily related to clay content and, to some degree, clay mineralogy (Breland and Hansen, 1996; Franzluebbbers et al., 1996; Scott et al., 1996). Soil texture has a major influence on the soil microenvironment and on soil processes such as decomposition (Scott et al., 1996). A simple example is the positive correlation between soil organic matter and soil clay content across the Great Plains (Burke et al., 1990). It is generally agreed that coarse textured soils have a more active microbial population and organic matter is more available for mineralization than soils of finer texture (Breland and Hansen, 1996; Franzluebbbers et al., 1996; Scott et al., 1996). Franzluebbbers et al. (1996) found that the rate of basal soil respiration per unit of soil microbial biomass carbon was greatest in soils of coarse texture; as clay content increased, basal soil respiration decreased. Mineralizable C to N ratio also decreased with increasing clay content (Franzluebbbers et al., 1996).

Soil organic matter in coarse textured soils appears to be more labile, whereas in finer textured soils, the complex soil structure provides greater protection to the SOM, thus reducing the turnover of C and N (Franzluebbbers et al., 1996). As clay content increases, soil surface area and organic matter stabilization potential increases (van Veen et al., 1985). Tisdale and Oades (1982) noted that SOM tended to increase with clay content because of the increase in surface area and charge leading to more chemical and physical binding with the organic matter. Rasiah (1995) reported that mineralization was

negatively correlated with clay content and cation exchange capacity (CEC), which further suggests a decrease in mineralization with increasing protection of substrate. Clays with low surface charge, such as a kaolinite appear to have much less ability to protect adsorbed organic matter (Franzluebbers, 1999).

Cabrera and Kissel (1988a) suggested that the ratio of clay to total soil N can be used as an index of the degree of protection that clays provide to organic matter from microbial attack. A pretreated or disturbed soil of low clay content, which has a reduced ability to protect organic matter, may have mineralization values closely correlated with an undisturbed sample of the same soil. In such cases, disturbed samples could provide an accurate N mineralization index for that type of soil. For higher clay soils with good aggregation, this correlation of N mineralization between disturbed and undisturbed likely would be poor.

2.3.4 Soil Compaction and Pore Space

Soil compaction reduces the proportion of large pore spaces and increases the relative proportion of small pore spaces (Breland and Hansen, 1996). If it is accepted that organic material in the smaller pores is physically protected from microbial attack (Breland and Hansen, 1996), then the proportion of organic matter that is protected increases, and mineralization decreases as pore size decreases. Breland and Hansen (1996) found that N mineralization was, in fact, negatively correlated with the amount of small pores in a soil.

Scott et al. (1996) suggested that while small pore spaces protect organic matter from microbial attack, large pores will dry too quickly to facilitate N mineralization and diffusion of mineral N products. Medium size pores allow microbes access to organic

matter and retain water under dryer conditions. Thus, medium size pores are the most important to mineralization and their loss under soil compaction is the most serious. Strong et al. (1999a) agreed with this point of view and suggested that large pores (>10 μm) appear to protect organic matter because they do not regularly fill with water, thus, these pores cannot be easily accessed by microbes; and the biochemical process of mineralization and the transport of the products is severely limited. Strong et al. (1999a) concluded that the rewetting of a soil that has been dried in the process of sample pretreatment will collapse the soil structure, thereby reducing the number of pore spaces conducive to mineralization.

2.3.5 Total soil N and Soil organic C

Interest in total soil N is usually related to a desire to isolate the proportion of total soil N that is mineralized (Sollins et al., 1984; Serna and Pomares, 1992). It is also used as a means to determine organic N (Bremner et al., 1994) and as a soil quality indicator (Pennock et al., 1994; Campbell et al., 1997). Total soil N has also been used as a measure of N mineralization potential (Bremner, 1965); however, both Bremner (1965) and Selles et al. (1999) saw little value in total soil N for this purpose. Bremner (1965) based his conclusion on a review of literature of the time, and Selles et al. (1999) found total soil N to be poorly correlated with other measures of soil N availability, such as hot KCl extractable N. Keeney (1982) did not include total soil N as a method to index N mineralization potential in an extensive review of indexing methods. In some studies, total soil N is determined, but not interpreted (Cabrera and Kissel, 1988a). The methods used to determine total soil N sometimes are not reported (Raun et al., 1988; Stein et al., 1997).

Total soil N has been found to be positively correlated with N mineralization potential (Rasiah, 1995; Hossain et al., 1996). Selles et al. (1999) found total soil N and soil N availability to be weakly related according to an analysis of their semi-variance. However, total soil N does not appear directly related to how much or how fast the N is mineralized (Stanford, 1982). Thicke et al. (1993) observed that unless total soil N is very low, N mineralization is unrelated to total soil N. Total soil N has been found to correlate with N released by hot KCl and phosphate-borate extractants (Curtin et al., 1998). In some studies, total soil N was correlated to crop yields, such as the study by Stein et al. (1997) in which a good r^2 of 0.407 was achieved.

Soil organic C is intimately related with total soil N (Rasmussen et al., 1998) and is reported in much the same way as is total soil N. A positive relationship is always reported between N mineralization potential and soil organic C (Cabrera and Kissel, 1988a; Rasiah, 1995; Selles et al., 1999). Bonmati et al. (1991) found soil organic C to be significantly and positively correlated with total soil N. Keeney (1982) viewed organic matter as an index for N mineralization and reported that organic matter indices for N recommendations are used in several states in America. MacDonald et al. (1995), however, found mineralized N was not well correlated with soil organic C.

2.3.6 Light and Heavy Fraction Organic Matter

Soil organic matter content has been long linked to the ability of a soil to sustain plant growth (Biederbeck et al., 1994). Soil organic matter (SOM) is an olio of plant debris, humic material and residues (Biederbeck et al., 1994; Watkins and Barraclough, 1996). The various organic matter fractions each have different rates of decomposition, which can account for the observation that overall organic matter levels change very

slowly in soil in spite of a small fraction of intensely labile organic material with high turnover rates (Biederbeck et al., 1994).

For research purposes, SOM is often divided into two fractions. The first is a small pool of weakly decomposed plant debris called the light fraction (LF), and the second, a much larger pool, called the heavy fraction (HF), which is adsorbed and sequestered in organo-mineral complexes (Spycher et al., 1983; Sollins et al., 1984; Cabrera and Kissel, 1988a; Janzen et al., 1992; Gregorich and Ellert, 1993; Biederbeck et al., 1994; Boone, 1994; Bremner et al., 1994; Sierra, 1996; and Wander and Traina, 1996). Wander and Traina (1996) found that 2.6% of the total soil N was LF. Light fraction and HF constitute most of the organic matter in soils, excluding soluble organics and a small portion of the micro-flora (Boone, 1994).

The LF is usually defined on the basis of gross composition, such as organic debris in stages of decomposition from fresh to nearly humified (Janzen et al., 1992; Biederbeck, 1994; Bremner et al., 1994). It is also identified on the basis of specific gravity, being that material which floats in an NaI solution of 1.65 g cm^{-3} (Spycher et al., 1983). Heavy fraction organic material is that which is adsorbed or deposited onto mineral surfaces, and thus can be sequestered within micro-aggregates (Sollins et al., 1984). These two soil fractions are also described on the basis of C:N ratio with the C:N ratio of the LF (approximately 30:1) being higher than that of the HF (approximately 20:1) (Spycher et al., 1983; Boone, 1994; Sollins et al., 1984; Wander and Traina, 1996).

The LF has been considered by some researchers to have the lower mineralization potential and may, in fact, induce immobilization that can mask mineralization from the HF, thereby reducing net mineralization (Boone, 1994; Bremner et al., 1994). On the other hand, some studies suggest the LF can produce significant

amounts of mineralized N, or is more labile than the HF. This may be possible if the C:N ratio of initial plant debris is low, or alternatively the faster turnover may be due to the lack of protection of LF by soil colloids, allowing quick and easy degradation by soil microbes (Janzen et al., 1992; Gregorich and Ellert, 1993; Boone, 1994). It does, however, appear that the light or labile fraction is considered small but very dynamic and may account for most of the measurable fluctuations in organic matter (Biederbeck et al., 1994).

There appear to be varying opinions as to the nature of the LF. Some researchers feel that the LF is equitable to the labile pool (Bremner et al., 1994) whereas others feel a labile portion is part of the LF and must be identified to understand the impact of the LF on the immobilization – mineralization process (Sierra, 1996). According to Gregorich and Ellert (1993), the LF organic matter may account for as much as 30% of the soil organic N in rapidly decomposable material. This would represent a significant source of potentially mineralizable N. Boone (1994), however, found indications that the LF was a less available source of N than the HF and concluded that the LF only contributes in a small way to N mineralization potential *in situ*. Boone (1994) felt this was a result of the effects of the LF on immobilization, which can nullify net mineralization of the whole soil.

The differing opinions may be accounted for by differences in the physical protection of organic matter (Boone, 1994). Finer textured soils, such as those studied by Janzen et al. (1992), offer greater protection to the HF organic matter so that the LF will be relatively more exposed to microbial attack (Boone, 1994). Coarse textured soils, such as those studied by Sollins et al. (1984), offer less protection and the HF will consequently contribute more to mineralization than the LF (Boone, 1994). Boone

(1994) also indicated that part of the problem lies in the density fractionation procedure, which he suggests does not provide adequate separation of the LF and HF. In addition, the transfer between the LF to the HF is not well understood, nor is the influence of the distribution of microbes and microbial debris on the partitioning between LF and HF.

Overall, SOM does not vary significantly in the short term; i.e., 1 to 10 years; however, the proportion of LF will vary because it receives seasonal additions and is readily decomposable (Wander and Traina, 1996; Boone, 1994). These organic matter inputs, being seasonal, have been observed to cause estimates of N mineralization to vary by a factor of two over the season (Franzluebbers et al., 1996). Spycher et al. (1983), referring to a forest soil, noted that the LF is present in the highest amounts during spring and fall, and is lowest during the summer months. Hence, time of sampling for N mineralization studies is critical and it is recommended that sampling should occur in the spring or as late as possible in the fall, after the inputs of organic matter have stopped (Franzluebbers et al., 1996).

Whole soil mineralization does not appear to be as closely related to the C:N ratio as does the mineralization from the HF and LF fractions (Sollins et al., 1984). However, if mineralized N from whole soil is expressed as a ratio of total soil N, then there is correlation between whole soil C:N and N mineralization (Sollins et al., 1984). The mineralized N: total soil N ratio for the HF increases with increasing C:N ratios, which may be due to the lower C:N ratio material being sequestered in micro-aggregates and, therefore, less available for mineralization (Sollins et al., 1984). Thus extensive micro-aggregate structure should contribute to lower levels of mineralization. In fact, Sollins et al. (1984) noted that soils with more organic matter, greater fertility and more

extensive micro-aggregate structure appeared to mineralize a lower proportion of total soil N.

In the surface horizon, the LF accounts for most of the C and N as compared with the deeper layers (Spycher et al., 1983). Deeper in the profile, the proportion of C and N contributed by the HF increases and the amount of plant and microbial contributed organic matter decreases (Spycher et al., 1983).

Sierra (1996) suggested that the LF could provide a good estimate of the mineralizable N pool. Periods with low mineralization rates had low levels of available LF, such that changes in the LF could explain 40 to 50% of the variation in N mineralization at the beginning of each period. For these reasons, Sierra (1996) indicated that a better understanding of the LF will lead to better estimates of the mineralizable pool and the spatial variability of mineralization.

Curtin and Wen (1999) studied components of the LF organic matter and suggested that water soluble soil organic matter was a small, but immediate, source of nutrients in the soil. Its importance stems from the fact that, although small, this pool is continually replenished by desorption of adsorbed organic N from soil colloids. For these reasons water-soluble organic matter may be a valuable indicator of N mineralization (Groot and Houba, 1995). Curtin and Wen (1999) questioned the importance of the LF to N mineralization. They found that LF was not well related to the amount of N mineralized; however, the relationship may improve the longer the mineralization took place.

2.3.7 Management Practices

Changes in management practice can have a faster effect on mineralizable N than on total soil C or total soil N (Janzen et al., 1992). Choice of crops with residues having a low C:N ratio promote N mineralization (Rasmussen et al., 1998). For example, available N and wheat N uptake was higher on pea stubble than lentil stubble, which has a higher C:N ratio than pea stubble (Schoenau, 1998). Rasmussen et al. (1988) report that type of tillage equipment appears to affect N mineralization, likely due to the impact of tillage on soil disturbance. Sweep tilled soil appears to mineralize the most N in the field and lab as compared to disc and plow tilled soils.

2.3.8 Topography and Soil Variability

Pennock et al. (1992, 1994) demonstrated the significance of landscape variation to the development of soil properties. This variation occurs through the effect of landscape on hydrological and pedological processes, which influences the redistribution of water. The resulting patterns of soil moisture, in turn, influence the pattern of soil processes (Sinai et al., 1981; Hanna et al., 1982; Halvorson and Doll, 1991; Pennock et al., 1992). Convergent landscape elements encourage the capture and retention of moisture, leading to deeper soil profile development (King et al., 1983; Pennock et al., 1987; Halvorson and Doll, 1991). Landform brings an order of systematic, spatial variability in soil properties (Wilding and Drees, 1983). Thus a field may be divided into areas or landscape units on the basis of moisture regime. Identification of landscape units can be accomplished by determining the gradient, profile and plan curvature of a field (Pennock et al., 1987).

The use of these morphological characteristics, is superior to regression techniques for identifying soil-landform relationships (Pennock et al., 1987). Higher moisture contents can be expected in convergent elements and, in general, moisture content will increase from shoulder, back-slope, to foot-slope positions (Pennock et al., 1987). Distribution of water in the landscape is also affected, to a lesser degree, by slope direction (Hanna et al., 1982). Thus, soil properties resulting from the redistribution of water are not random and variation in soil properties is an underlying control on within-field variation of soils and the subsequent impact on crop yield (Fiez et al., 1994).

One should expect to see landscape, and its influence on water redistribution, affect the variability in N mineralization (Pennock et al., 1992; Mahmoudjafari et al., 1997). Schoenau (1998) demonstrated that landscape position had a large influence on N mineralization with the greatest N mineralization potential occurring in foot-slope positions and the lowest in shoulder positions. For precision farming techniques to be economically and environmentally successful, the sampling pattern on a field must represent this variability such that the areas that will benefit from more fertilizer can be distinguished from areas that will benefit from less (Franzen and Peck, 1995).

Soil properties are indirectly influenced through the redistribution of soil by tillage and erosion that occurs in a landscape of variable terrain. Schoenau (1998) noted that upper slopes tend to be poorer in fertility, especially where there has been a significant loss of topsoil. Tillage and erosion on a variable landscape results in redistribution of soil from upper to lower slope positions (Pennock, 1997). The gain of soil in the lower slope positions from the upper slope positions increases fertility in the lower slopes and decreases fertility in the upper slopes (Pennock, 1997).

2.4 Errors in Estimation of Soil N Mineralization Potential

The variation in conditions encountered in the field make it difficult to assess the impact of variables important to soil N processes (Campbell et al., 1974). On the other hand, laboratory experiments are not at all reflective of field conditions, which makes practical application of the resulting data difficult (Campbell et al., 1974). Regardless of the general satisfaction with the results of anaerobic and aerobic incubation methods, it has long been recognized that the soil pretreatment involved with these methods may produce erroneous or exaggerated results (Bremner, 1965; Keeney, 1982; Cabrera and Kissel, 1988a; Sierra, 1992, 1996). Indeed, various authors have recognized a problem with correlating green house incubation experiments with field results (Bremner, 1965; Keeney, 1982). Honeycutt (1999) found that laboratory predictions over estimated the N mineralization that was measured under field conditions.

In a review by Bremner (1965) it was suggested that air drying samples and length of storage time are correlated with an increase in the values for N mineralized. Research indicates that grinding the soil sample increases the availability of organic matter to microbial degradation beyond that of an undisturbed soil leading to significant increases in mineral N values (Bremner, 1965; Sierra, 1996). Cabrera and Kissel (1988a) compared mineralization values of disturbed and undisturbed samples and found that disturbed samples always produced more mineralized N. Air dried samples also had larger mineralization values than field moist samples (Marion and Miller, 1982). Sierra (1992) noted that the amount of N mineralized is affected by disruption of soil aggregates, the pool of N accessed varies according to size and stability of aggregates, which is dependent upon agricultural practices, soil type and mineralogy (Sierra, 1992).

The values obtained for potential mineralization from undisturbed cores are lower overall than from those obtained from disturbed cores (Cabrera and Kissel, 1988a). Sierra (1992) reported that disturbed samples yielded one to eight times more mineralized N than undisturbed cores for the same sample and conditions of incubation. Several authors have noted the effect of rewetting of air-dried soils, describing the resulting “flush” of mineralization that commonly results in these consistently higher values (Cabrera and Kissel, 1988a).

To reduce the effect of pretreatment on the soil samples and come closer to approximating field conditions, the practice of incubating undisturbed soil cores and determining N mineralization *in situ* was developed (Cabrera and Kissel, 1988a; Sierra, 1992; Roupette et al., 1994; Mahmoudjafari et al., 1997). *In situ* methods usually involve burial of a resin bag beneath a replaced core of soil. The resin bag traps the products of mineralization and nitrification, which are subsequently extracted with a KCl leachate (Roupette et al., 1994). It must be noted that the mineral N found in the bag may be a component of mineral N moving through the soil with water redistribution (Roupette et al., 1994). Thus the mineral N measured at a specific location may not necessarily have been mineralized in that location.

Time of sampling is very important to the mineralization potential measured, because inputs of organic matter can change N mineralization by a factor of two over the growing season, depending on the amounts added (Franzluebbers et al., 1996). The optimum time for sample collection, for the purposes of estimating potential N mineralization, is late winter or early spring (Bremner, 1965; Franzluebbers et al., 1996). Generally, N mineralization studies avoid incorporation of crop residues in the sample (Thicke et al., 1993). However, this may eliminate an important source of N

mineralized even though the first wk may not be representative of N mineralization potential (Thicke et al., 1993).

Incubations to index the N mineralization potential of SOM fractions, such as the LF and the HF, may be affected by the method used to separate the fractions. Gregorich and Ellert (1993) noted that a separation medium, such as NaI, can have a negative impact on the soil microorganisms, and this impact likely would alter the results of incubation tests. Reinnoculation with the original soil may correct this (Gregorich and Ellert, 1993).

2.5 Correlation of Biological and Chemical Indices of Soil N Mineralization Potential and/or Soil N Availability and Crop Yield

Biological techniques involving the incubation of a soil under conditions that promote mineralization of organic matter to mineral N products are generally considered to be the best methods for indexing the N mineralization potential of a soil (Bremner, 1965; Jalil et al., 1996). Alternative techniques such as chemical indices are usually compared against biological indices. Correlations between most methods are generally good to high. For example, estimates of N mineralization using phosphate-borate buffer solution have been obtained by several researchers and typically this method explains 70 to 90% of the variability in cumulative N or N mineralization potential assessed using aerobic incubation methods (Gianello and Bremner, 1986b, 1988; Vanotti et al., 1995; Jalil et al., 1996). Hot KCl extractable N, often conducted as a comparison to phosphate-borate buffer-N, explains essentially the same range of variability, but appears to correlate slightly better with the biological index (Gianello and Bremner, 1986b; Serna and Pomares, 1992; Jalil et al., 1996; Campbell et al., 1997). Results reported using the 0.01M CaCl₂ autoclave method (Keeney, 1982) are generally lower

by 10% or more than those for hot KCl and phosphate-borate buffer methods (Gianello and Bremner, 1986b; Vanotti et al., 1995).

Bremner (1965) noted that although extensive work had gone into indexing the N mineralization potential and correlating biological and chemical methods, correlation between N mineralized during incubation tests and yield response has been lacking. By the time of the Keeney (1982) review, several agricultural areas were using indices to assess N mineralization for fertilizer recommendations, but these were primarily based on inorganic N and organic matter, with very few using aerobic incubation.

Research comparing yield or N uptake to biological and chemical indices followed, gradually comparing such tests as hot KCl, aerobic incubation, phosphate borate buffer and the CaCl₂ autoclave method to yield or N uptake (Serna and Pomares, 1992; Vanotti et al., 1995; Schoenau, 1998). Hot KCl extractable N appeared to be the method which was most successful in explaining variability in yield (Serna and Pomares, 1992; Campbell et al., 1997; Schoenau, 1998). This is likely due to hot KCl extracting from a pool of N which is accessed by the crop early in the growing season, when N is most critically needed (Schoenau, 1998). Vanotti et al. (1995) has found that N released during the first few wks of an incubation period correlated best with N uptake.

Thicke et al. (1993) felt that an index of N mineralization may be able to predict or explain variability in yield, but this may only hold for the season during which the crop was grown in. As conditions for growth change from year to year, it may not be possible to use such data for predictive purposes. Biological indexes in the laboratory have good correlation with plant yield; however, in the field these correlations are

weaker, except where organic N sources have been added or under unfertilized conditions (Thicke et al., 1993).

2.6 Experimental Designs and Statistical Approaches to Studying Soil N Mineralization Potential

The choice of experimental design and statistical methods often is dictated by the goal of the research study. Research into soil N availability may be grouped into three general areas. The first group are studies comparing the N mineralization potential of various soils and/or compare indexing methods or measures of soil N availability. Such studies generally use classical statistics for description, correlation, and regressions, both linear and nonlinear (Stanford and Smith, 1972; Talpaz et al., 1981; Sollins et al., 1984; Cabrera and Kissel, 1988a and 1988b; Ellert and Bettany, 1988, 1992; Serna and Pomares, 1992; Campbell et al., 1993, 1997; Subler et al., 1995; Xu et al., 1996; Curtin et al., 1999; Strong et al., 1999a, 1999b;). These studies seldom have any experimental design, *per se*, as the soil samples are usually selected to represent many geographic locations and organic matter contents.

The second group of studies are those incorporating treatment effects into indices of mineralization potential or soil N availability and usually use a replicated design such as randomized complete block (Janzen et al., 1992; Fiez et al., 1994; Goncalves and Carlyle, 1994; Roupette et al., 1994; Vanotti et al., 1995; Franzluebbers, 1999;) or split plot (Simmons et al., 1989); however, in many cases the experimental design is not clear (Herlihy, 1979; Ciha, 1984; Rasmussen et al., 1998; Honeycutt, 1999). Statistics of choice are primarily one-way analysis of variance and general linear models.

The third group of studies examine the spatial distribution of N mineralization potential and related soil properties or yield. These studies have been approached in two

ways. One approach is to examine the distribution of these variables through landscape scale research. This approach requires identifying landform elements based on quantitative slope morphology (Sinai et al., 1981; King, 1983; Ciha, 1984; Pennock et al., 1987, 1992, 1994; Popoff and Anderson, 1990 and 1991; Halvorson and Doll, 1991; Walley et al., 1996; Solohub et al., 1999). The second approach, is to study the distribution of these variables using geostatistics, which seeks to quantify the spatial dependence of one sample location to another (Tabor et al., 1984; Raun et al., 1988; Goovaerts and Chiang, 1993; Mahmoudjafari et al., 1997; Marriott et al., 1997; Stein et al., 1997; Selles et al., 1999). Studies using geostatistics usually require intensive grid or transect sampling.

Geostatistics have been successful in describing the spatial variability of soil properties and, in turn, have been used to allocate inputs for precision farming (Stein et al., 1997). Improper sample spacing, which results in over or under sampling, can be avoided by understanding the spatial dependency of selected soil properties across the field (Selles et al., 1999).

Soil properties exhibit spatial variability, which according to Wilding and Drees (1983) can be separated into random and non-random components. The non-random component is a result of the gradual change in soil properties over distance and geostatistics seek to describe these changes. Classical statistics are based on the assumption that sample distributions are random and samples are assumed to be independent from each other, regardless of location (Selles et al., 1999). Therefore, classical statistics is not suited to deal with the non-random, dependent component of this variability. This requires that not only the value of the variable, but the location of

the values in space, is known (Selles et al., 1999). The use of geostatistical analysis meets these criterion.

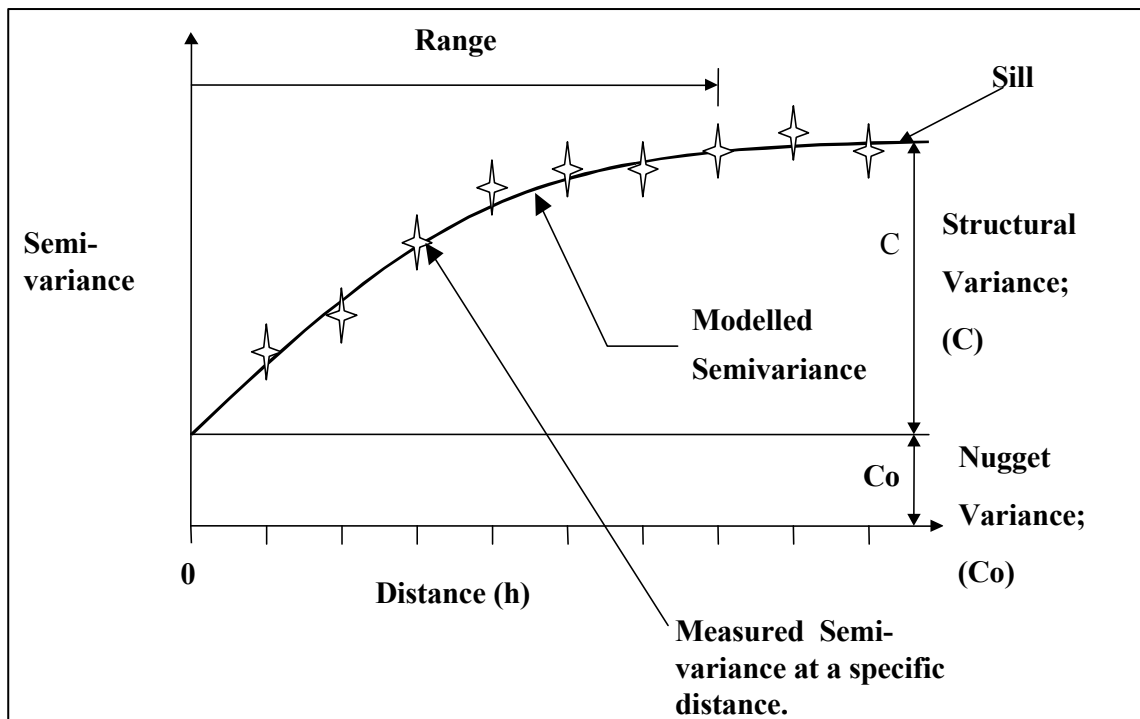
A plot showing the change in semi-variance as distance increases is known as a semi-variogram. The semi-variogram is a geostatistical tool, which allows one to determine the spatial distribution and variability of a soil property; i.e., its dependence and variance, (Selles et al., 1999). Semi-variance (γ) is defined by equation 2.3 (Tabor et al., 1984) for a one dimensional case; i.e., equally spaced samples on a transect such as used in this project. Semi-variance $\gamma(h)$ is the function of the distance between the locations of 2 random variables; $Z(x)$ and $Z(x+h)$ which are separated by the distance (h). Assuming stationarity, the expected value E is a constant (Tabor et al., 1984). The greater the distance (h) between the locations, the greater the semi-variance between the random variables.

$$\gamma(h) = \frac{1}{2} E[Z(x) - Z(x+h)]^2 \quad (2.3)$$

Figure 2.1 is an idealized semi-variogram as might be expected for most soil properties. Trangmar et al. (1985) provides a readable, concise explanation of semi-variance and semi-variograms. Unless cited, the following concepts are from Trangmar et al. (1985). Semi-variance and the semi-variogram are based on the theory of regionalized variables. This theory essentially states that the value of a variable in a specified region depends, to some degree, on its location in that region. It assumes first order stationarity, which means that the expected value of a variable in a specified region should be the same at any location in that region. It also assumes that second order stationarity exists, which means that the covariance between any two values of a

variable located in the specified region should be the same across the region. If these assumptions are met, then we can define regions, or areas of space, in which we can expect to get the same expected mean value and variance for a variable when we sample in that region. Essentially we can determine at what distance, or range samples will be independent of each other for a particular soil property. This allows one to design a sampling scheme, which can prevent the taking of more samples than are necessary to define the spatial variability the soil property in question within a given area. This has implications for assessing nutrient requirements for precision farming techniques (Stein et al., 1997).

Figure 2.1. Ideal semi-variogram for soil properties. Adapted from Wilding and Drees (1983).



As shown in Figure 2.1, as distance (h) increases, semi-variance (γ) increases. As semi-variance increases, the change in semi-variance with distance decreases. At

some point no change and the semi-variance is constant. Where the semi-variance is constant is referred to as the sill. The range of this soil property is the distance from zero to the sill. Within the distance represented by the range, we expect the soil variable measured to have the same expected value anywhere in that distance and sample locations within that distance are statistically dependent or related to each other. Sample locations farther apart than that range would be independent or statically unrelated to each other for that particular variable.

Samples taken for this type of statistical analysis are often taken on a transect, or along a line, equally spaced in one direction. The range of spatial dependence can be determined for a property in this direction, which can indicate the sample spacing necessary to describe the variability with spatially independent samples.

Semi-variograms are often modeled using an iterative computer program, which fits a curve to the semi-variance measured over distance. Several models can be used, the most common being exponential and spherical. These models smooth the data to permit a more quantitative selection of the nugget, sill, and range. However, modeling is often viewed as a subjective process in itself (Tabor et al., 1984).

The nugget variance (C_0) is the random sampling error. This is the variance between zero and the interception of the y axis by the curve. Nugget plus the structural variance (C) should equal the total variance for that set of measurements of the soil property in question. Structural variance is a combination of the systematic and random variance within the distribution of the variable, and this changes with distance between points

The use of landscape scale research and geostatistics are the latest tools in a long history of research devoted to improving the understanding of the ability of the soil to provide plant available N.

3.0 METHODS AND MATERIALS

3.1 Site Description and Sampling Strategy

The research site was located in the Hepburn area, approximately 40 km north of Saskatoon, Saskatchewan Canada at the SE quarter of Section 7, Township 40, Range 5, west of the third meridian. The site was classified as a hummocky, glacial till landscape in the Black soil zone and is classified as part of the Oxbow Association (Acton and Ellis, 1978).

The field plot (Fig. 3.1) consisted of a single, north-south transect, 300 m long and 40 cm wide with sample locations equally spaced at 3 m intervals. Immediately to either side of the sample transect, running its full length, was a 2.15 m seeded strip consisting of five inner rows of Hard Red Spring wheat (var. AC Barrie) and two boundary rows of winter wheat at a 30.7 cm spacing. The west strip was an unfertilized treatment, and the east strip was fertilized at a rate of 70 kg N ha⁻¹ applied as urea (46-0-0). This was the recommended N fertilizer rate based on a composite sample (from 10 to 15 subsamples) taken from midslope positions at the site. Soils were analyzed by Envirotest Laboratories (Saskatoon, SK) using standard methods to develop fertilizer recommendations. In its entirety, the plot measured 4.60 m by 300 m and ran across 4 east-west trending landform cycles.

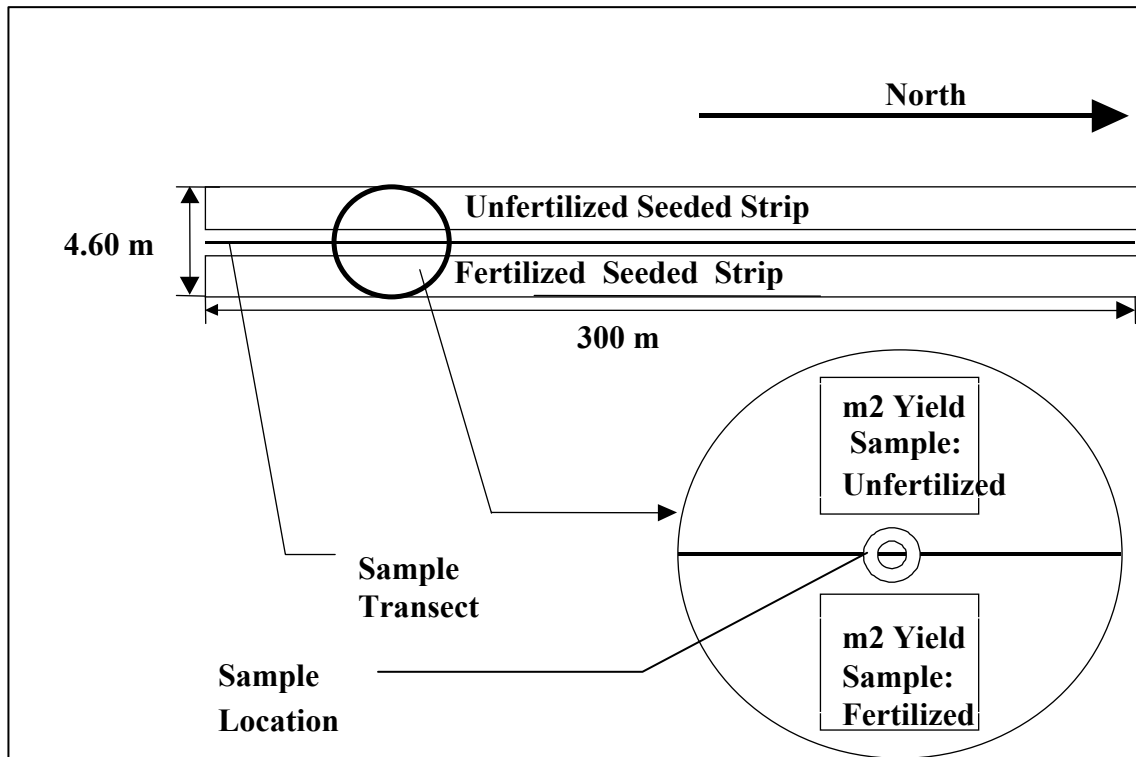


Figure 3.1. Schematic of the Hepburn wheat site (not to scale).

On May 4th and 5th of 1998, 6.5 cm diameter soil cores were extracted at each of the 100 sample locations along the transect. Cores were sampled to a depth of 60 cm using a truck-mounted soil punch. The external surfaces of the metal coring devices were lubricated with a commercial lubricant, WD-40 (WD-40 Products Canada Ltd., Etobicoke, ON.), to assist removal and avoid soil profile compaction in wet areas. At each sampling location, the soil profiles were described and the soils classified according to the Canadian System of Soil Classification (Agriculture Canada, 1987). Each core was subdivided into 3 depth increments: 0 to 15 cm , 15 to 30 cm and 30 to 60 cm . Samples were tagged and double bagged in plastic, placed in a cooler with an ice pack, and shipped as soon as possible; i.e., within eight hours of sample removal, to Saskatoon where the samples were immediately placed in cold storage (4°C). Seeding

of the fertilized and unfertilized strips took place on May 15th. On three occasions during the growing season soil samples were taken at every third sample location to a depth of 60 cm using a Dutch auger for the determination of gravimetric moisture content.

On September 3rd, at each sample location, a 1 m² yield sample was hand harvested from each of the seeded strips (Fig. 3.1) for determination of grain yield and yield parameters. The biomass samples were cut at approximately 2.5 cm above ground and the entire above-ground sample was bagged in cloth and returned to Saskatoon. The samples were allowed to air dry. The samples were moved to a hot box and dried at 60°C for 72 h, and subsequently weighed and threshed. All the grain was collected from each yield sample as well as a sub-sample of the straw. Straw weight was determined by subtracting grain weight from total biomass weight. The straw was chopped in a Wiley mill and grain was finely ground in a grain grinder so both would pass a 2 mm sieve prior to analysis for total soil N using a LECO® CNS-2000 analyzer (LECO Instruments Ltd., Mississauga, ON). Following harvest, the soils at the site were re-sampled between the seeded strips at each sample location using the truck-mounted soil punch. This second set of cores was taken within 15 cm of the original location, to a depth of 60 cm, for fall gravimetric moisture and inorganic N content.

3.2 Landform Element Classification

A topographic survey of the sample transect and surrounding landforms was accomplished by partitioning a 36 X 335 m area around the site into 3 X 3 m grid cells (Fig. 3.2). This allowed the systematic classification of each sample location into an

appropriate landform element (Pennock et al., 1987). Landform elements were then grouped into landform element complexes (Pennock et al., 1994).

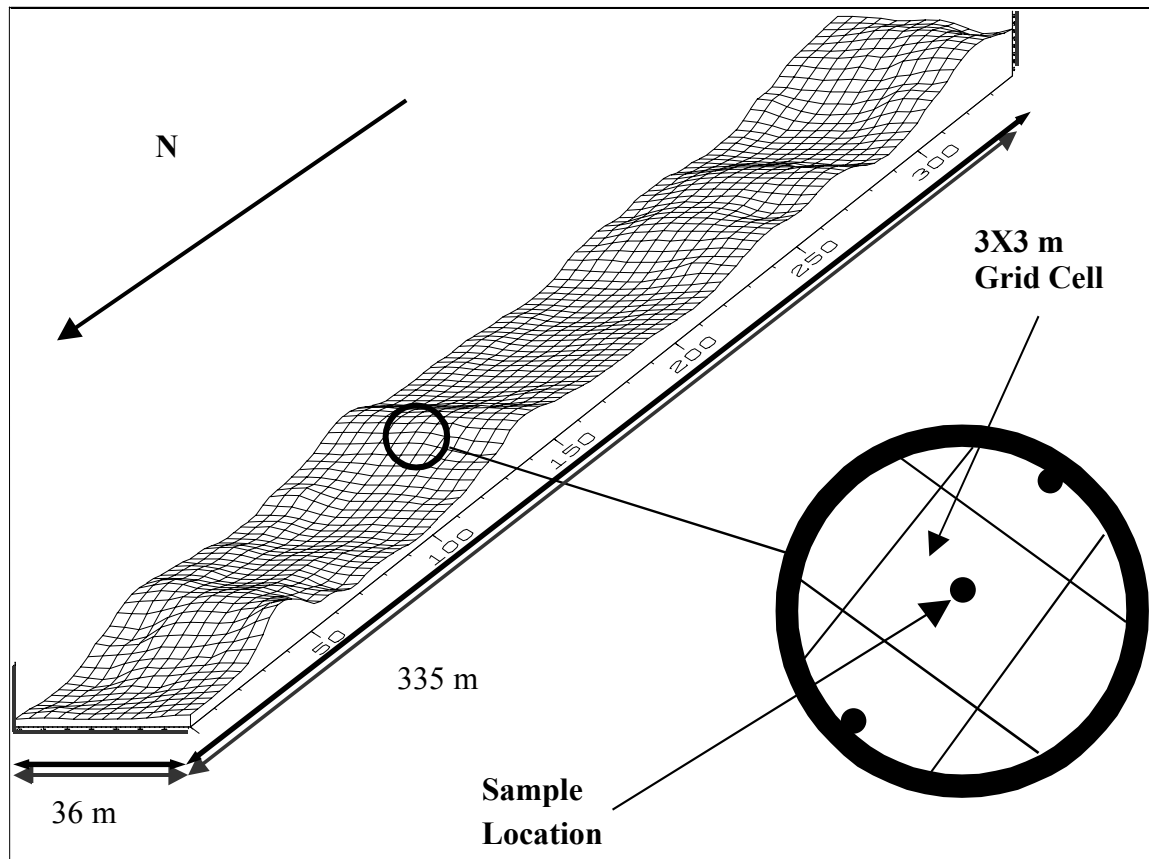


Figure 3.2. Mesh map of the Hepburn site looking SE.

The landform element complexes were identified on the basis of global catchment area using the method of Pennock et al. (1994). Because each sample location was located within a discrete 3 X 3 m grid cell and was, in turn, surrounded by grid cells identified from the survey of the broader area, a global catchment; i.e., a value representing the area about a grid cell that contributes moisture to that grid cell, could be assigned to the entire transect

Topographically high positions of low global catchment, which included both divergent shoulder, convergent shoulder, and upper level positions were grouped into low catchment shoulder complexes (LSH) and high catchment shoulder complexes

(HSH). The LSH were considered shoulder and upper level elements with a global catchment area from zero to one, and HSH were shoulder and upper level elements of a global catchment greater than one. Topographically low positions, which included foot-slopes and lower level elements were grouped into low catchment and high catchment foot-slope complexes (LFS and HFS), respectively, with global catchments below or above 5.

The majority of landform elements identified along the transect were shoulder, foot-slope and level positions. Because very few back-slope elements were identified, these were reclassified as shoulder elements. Level elements, which were primarily lower slope positions, were allocated to LFS complexes if global catchment was less than 5 and to HFS complexes if above 5.

3.3 Laboratory Analysis

3.3.1 Biological Assays of Soil N Availability and/or N Mineralization Potential

3.3.1.1 Aerobic Incubation Technique

To index the N availability using a biological method, an aerobic incubation was performed according to the procedure of Campbell et al. (1993). For each sample location, a field moist sub-sample was taken at the 0 to 15 cm and 15 to 30 cm depth increments. Incubations were not performed on samples from the 30 to 60 cm depth to maintain a manageable number of samples for the resources and time available. It was felt that the contribution of this depth increment would be sufficiently assessed by the other indexes of soil N availability.

The original intention was to use undisturbed soil cores for the incubation study; however, preliminary trials exposed a wide variation in the infiltration rates of the cores,

preventing any consistency in sampling of the leachate and incubation conditions. It became obvious that to maintain consistent intervals of incubation and facilitate extraction, the soils would have to be disturbed and therefore method using a mixture of sand and soil, as proposed by Campbell et al. (1993), was adopted.

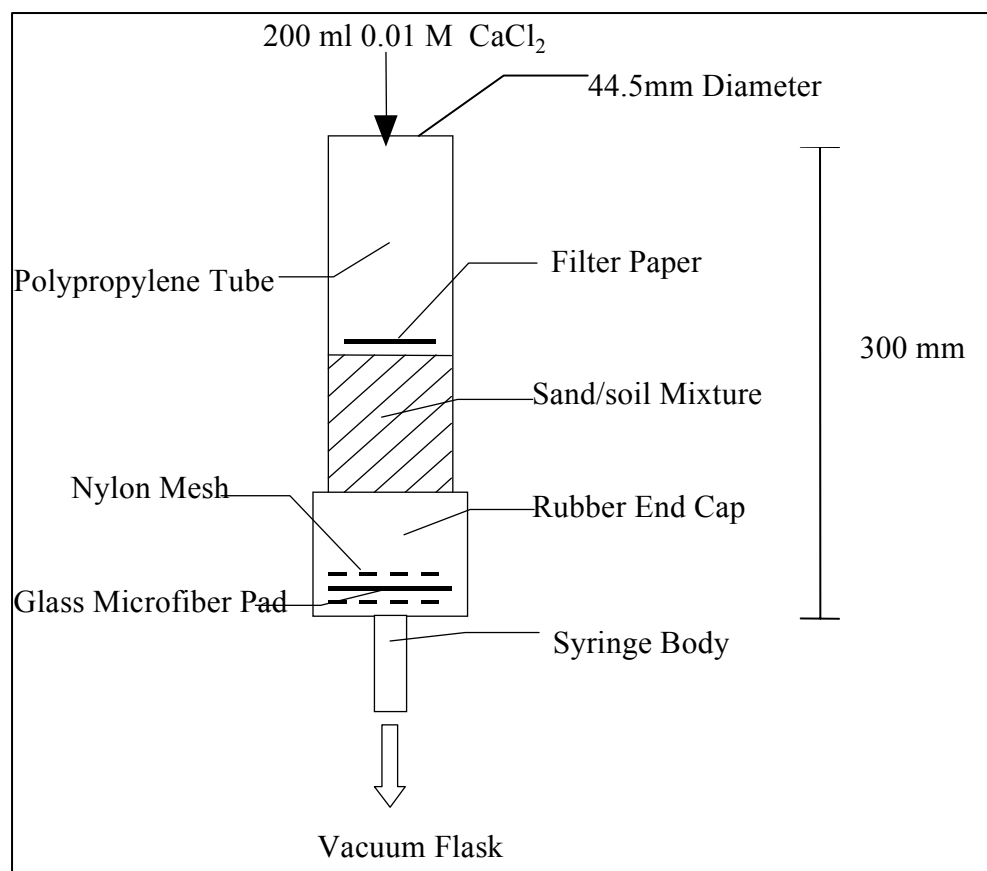
Incubation vessels (Fig. 3.3) were constructed from a 30 cm length of clear, polypropylene tube, manufactured to serve as a liner for a Gidding's tube (Gidding's Machine Company, Fort Collins, Colorado) with an inside diameter of 44.5 mm. A rubber cap was fixed on the bottom end of the tube, which was pierced by a 1 cc syringe body to facilitate drainage and aeration. A glass microfiber filter pad, sandwiched between two pieces of nylon mesh, was placed within the end cap to prevent loss of sample. The apparatus was held together with cyanoacrylate glue (Instacure™; Bob Smith Industries, Atascadero, CA). Although this design of leaching apparatus is unique in its materials, the general format satisfies the design suggested by Campbell et al. (1993).

A 200 g sample of 1:1 sand/soil mixture, using 100 g of oven dry equivalent field moist soil and 100 g of acid washed Ottawa quartz sand (Granusil®; Unimin Corp, New Canaan, CT) was placed into each incubation tube. The field moist soil had been pre-sieved to 2 mm. The mixture was carefully poured into each tube, tamped gently and covered with a Whatman # 4 filter paper to prevent dispersion during extraction.

Prior to incubation, each sample was pre-leached with 200 mL of 0.01 M CaCl₂, applied in 20 mL aliquots, and the leachate was discarded. Using a bench top vacuum, the moisture content of each sample was drawn down to 20 % by weight. In each case the actual weight was monitored. This procedure allowed for the addition of 10 mL of a

nutrient solution that contained no N, often referred to as a minus N nutrient solution (Campbell et al., 1993), and subsequent adjustment of the moisture content to 22.5 % by weight using deionized water. Campbell et al. (1993) indicated that the soil sample should be at field capacity for incubation; however, it is not clear if field capacity refers to the soil or the soil-sand mixture. As well, field capacity would not represent consistent gravimetric soil moisture content from sample to sample. For these reasons it was decided to adjust the moisture content of each sample to the same % H₂O by weight. The moisture content of 22.5% w/w was chosen.

Figure 3.3. Incubation and extraction apparatus used for aerobic incubations.



Aside from controlling moisture content, the only significant departure from the method proposed by Campbell et al. (1993) was the use of 10 mL of minus N nutrient

solution (0.002 M CaSO₄, 0.002 M MgSO₄, 0.005 M Ca(H₂PO₄)₂, and 0.0025 M K₂SO₄ after Campbell et al. (1993) rather than the 25 mL suggested. The amount of nutrient solution was reduced to facilitate the control of moisture content.

For the incubation, the open end of each tube was covered with a piece of Parafilm® and pierced to facilitate aeration. The tubes were stored in loosely covered, 76 L Sterilite® plastic containers placed in a growth chamber maintained at 35°C. Large vessels of water were placed within the chamber to maintain a high relative humidity and reduce loss of moisture from the samples. Once a week, the samples were weighed and restored to 22.5 % by weight, if necessary, using deionized water. Typically, over a one wk period, water loss in some samples was 1 to 2 % moisture by weight.

Over the course of the incubation, each sample was extracted every 2 wks for 12 wks and every 4 wks thereafter for 16 wks. The samples were extracted in the manner described above using 0.01 M CaCl₂ added in 20 mL aliquots, followed by 10 mL of a N minus nutrient solution prior to adjustment of water content and subsequent period of incubation. The majority of samples were incubated for 16 wks. The data presented for the cumulative amount of mineralized N, here on referred to as cumulative N, and potential mineralization is based on 16 wks of incubation.

Extracts from the incubation were filtered using a Whatman # 2 filter paper and analyzed for inorganic N; i.e., NO₃⁻-N + NH₄⁺-N, using a Technicon Auto Analyzer II System (Labtronics Inc., Tarrytown, NY). The extract from the first 2 wks of incubation was analyzed for both NO₃⁻ + NH₄⁺; however, the analysis for NH₄⁺ was discontinued for subsequent periods of incubation because the amounts of NH₄⁺ in the leachate were consistently low. In most cases the amount of NH₄⁺ was below detection limits. For

example, only 18 out of the entire 200 samples had detectable levels of NH_4^+ , and all of those were under $2 \mu\text{g NH}_4^+ \text{ ml}^{-1}$. At the end of the incubation, each sand /soil mixture was destructively sampled by shaking 24 g in 2 M cold KCl for 1 h to determine a final inorganic soil N content. Samples were handled in sets of 50 for which there were two blanks per set. The blanks were identical in terms of apparatus, handling and materials used, except that only 100 g of acid washed sand was incubated.

The cumulative N data collected over time was used to calculate potentially mineralizable N (No) and a rate constant (k) for each sample using a nonlinear regression iteration program assuming a one-pool model and first order kinetics as described by Campbell et al. (1993). The results were initially calculated in terms of $\mu\text{g NO}_3^- \text{ g}^{-1}$ soil and subsequently were converted to $\text{kg N O}_3^- \text{ -N ha}^{-1}$.

3.3.1.2 Ion Exchange Membrane

Using anion exchange membranes, in the form of the Plant Root Simulator (PRSTM; Western Ag Innovation, Saskatoon, SK, Canada), the N availability of the three depth increments of each soil location, was assessed in the laboratory on the basis of N supply rate (Qian and Schoenau, 1995). The anion exchange membranes simulate the action of a root by adsorbing negatively charged anions, such as NO_3^- , by exchange with a counter ion (Qian and Schoenau, 1997). The anion exchange membranes are suitable for assessing N mineralization by acting as a sink for NO_3^- produced through the mineralization of soil organic matter (Qian and Schoenau, 1995). Because the amount of NO_3^- (μg) adsorbed on the membrane is a function of time (2 wks) and surface area of the membrane itself (10 cm^2), the units of this measurement are expressed as a supply rate expressed as $\mu\text{g NO}_3^- 10 \text{ cm}^{-2} 2 \text{ wk}$ (Qian and Schoenau, 1997).

Prior to use, the membranes were prepared by bathing them in a NaHCO_3^- solution (86 g of NaHCO_3 in 1 L of deionized H_2O) four separate times over 48 h. This prepared the anion exchange sites and cleaned off any remaining anions from the previous usage (Qian and Schoenau, 1997). At the time of use, the probes were removed from the solution and rinsed in deionized water prior to insertion into the soil.

Each probe was placed in a 40 dram vial (9.7 cm X 4.5 cm diameter or 152.4 cm^3) and soil was added around the probe to the lip of the vial and tamped to ensure adequate contact between the soil and the surface of the anion exchange membrane. Each vial contained approximately 100g of soil; however, as this method yields an N supply rate, the amount of soil, by weight or volume, was not a factor.

It is important to ensure enough moisture to facilitate transport of anions to the membrane; therefore, although samples used were field moist, additional deionized water was added to sufficiently wet the sample. This was done by adding water slowly and stopping when the wetting front (faint, yet visible in a field moist soil) reached the bottom of the vial (personal communication, Schoenau, 1998). Samples were then covered with a piece of parafilm and left in darkness to incubate at room temperature on the laboratory bench top. At 1 wk after the start of the incubation, the parafilm was removed and the sample was allowed to aerate for 5 min. The parafilm was then replaced and the sample was incubated for a further 7 d prior to analysis (Qian and Schoenau, 1995).

At the end of the 2 wk incubation period, the probes were removed from the soil sample and handled as described by Qian and Schoenau (1997). Briefly, this included washing off soil adhering to the probe with deionized water, followed by elution of the probe for 1 h, in 20 mL of 0.5 M HCl. The elution removed the adsorbed anions and the

eluent was analyzed for NO_3^- using a Technicon Auto Analyzer II System. Initially, both cation and anion exchange membranes were used; however, the amount of NH_4^+ was often below detection limits and it was decided that such low levels of NH_4^+ did not warrant the extra time and resources necessary for its detection in all samples.

3.3.2 Chemical Assays of Soil N Availability and /or N Mineralization Potential

3.3.2.1 Soil Inorganic N

The inorganic N content of the soil; i.e., NO_3^- and NH_4^+ , prior to seeding; i.e., spring inorganic N, and after harvest; i.e., fall inorganic N, was determined for each sampling location at all three depth increments. A sub-sample of 24 g of field moist soil was placed in a shaker bottle with 200 mL of 2 M KCl (cold). The mixture was shaken for 1 h, then decanted and filtered through a Whatman # 2 paper. The extract was analyzed for NO_3^- and NH_4^+ using a Technicon Auto Analyzer II System. Results were converted from $\mu\text{g NO}_3^- + \text{NH}_4^+ \text{ g}^{-1}$ soil to kg N ha^{-1} and expressed in terms of the oven dry equivalent for the field moist sample.

3.3.2.2 Hot KCl Extractable N

Hot KCl extractable N was determined at all sample locations, for all depth increments. The basic method as in Jalil et al. (1996) required 3 g of air-dried soil, ground to pass a 2 mm mesh sieve, added to 20 mL of 2 M KCl. The solution was heated in a block digester for 4 h at 100°C. Once cooled to room temperature, the solution was decanted and filtered through a Whatman #2 paper, and analyzed for NO_3^- and NH_4^+ using a Technicon Auto Analyzer II System. Results in $\mu\text{g g}^{-1}$ soil were converted to kg ha^{-1} .

3.3.3 Total Soil N and C

Total soil N and C were determined at each sample location, for each depth increment, by dry combustion using a LECO® CNS-2000 analyzer (LECO Instruments Ltd, Mississauga, ON). Results were initially expressed on a concentration basis and later converted to kg ha^{-1} total soil N and total C.

3.3.4 Soil Organic C

Soil organic C was determined for all sample locations at all three depth increments by dry combustion using a LECO® Carbon Determinator CR-12 (LECO Instruments Ltd, Mississauga, ON). Results were initially expressed on a concentration basis and later converted to kg ha^{-1} soil organic C.

3.3.5 Gravimetric Water Content

Moisture content for each soil at time of sampling was determined gravimetrically. Approximately 30 g of soil, of known weight, was oven dried for 24 hours at 105°C. The sample was then re-weighed and the difference used to calculate the moisture content by weight. Using the bulk density (Section 3.3.7) for each individual sample, this was converted to moisture content by volume.

3.3.6 Permanent Wilting Point

Permanent wilting point (PWP), estimated as the water content at 15 atmospheres of suction, was determined for each sample location at all three depth increments using a pressure plate chamber. The moisture content by weight was converted to % v/v using the bulk density for each sample.

3.3.7 Soil Bulk Density

Initial processing of the samples included recording bulk density. This was determined using total oven dry weight, calculated using the weight and water content of sub-sample (Section 3.3.5) and the volume of the initial soil sample, which was based on the diameter of the coring tube (6.5cm) and the corresponding depth increment.

3.4 Statistical Analysis

3.4.1 Non-parametric Statistics

Parametric statistics operate under the assumption that the distribution of the population is normal. This allows comparison tests to be made based on mean and variance. When distributions are not normal; i.e., skewed, these tests cannot be used unless a transformation is performed to normalize the distribution. As an alternative to transformation, non-parametric statistics that focus on median values, and the rankings of these values, may be desirable. Soil properties typically display skewed distributions (Trangmar et al., 1985); therefore, many studies have employed non-parametric statistics (Pennock et al., 1992; van Kessel et al., 1993; Pennock et al., 1994; Corre et al., 1996 Pennock and van Kessel, 1997).

A skewed distribution is commonly transformed to a normal distribution for the purpose of employing classical statistical methods; however, it is important to maintain a consistent approach (Pennock et al., 1994). Therefore, to ensure the data for all the soil properties is examined in a consistent manner, Spearman Rank correlations, at 0.05 and 0.01 levels of significance, were used instead of Pearson correlations. This allowed the use of one method for the entire data set without transformation of selected data. As the

Spearman Rank correlation is a non-parametric statistical technique, Kruskal Wallis ($P = 0.20$) was used for mean separation.

3.4.2 *Geostatistics*

For each soil property studied in this research project, semi-variance was used to determine a range (m) using an exponential model fitted using an iterative program (SAS Institute, Inc, Cary, NC). A full discussion of the geostatistical approach has been provided in the Literature Review (Section 2.6).

4.0 RESULTS

4.1 Description of Soils at the Hepburn Field Plot

The catenary sequences at the Hepburn field plot consisted of a variety of soil types, which were related to specific landscape positions (Table 4.1). For example, Orthic Regosols and Rego Black Chernozems were found primarily on LSH. Calcareous Black Chernozems and Orthic Black Chernozems were found primarily on HSH and LFS. Eluviated Black Chernozems, Gleyed Black Chernozems, and Humic Luvic Gleysols were found primarily on LFS and HFS.

The landscape positions defined in this study are comparable to those defined by Pennock et al. (1994) for a similar landscape. In that study, convex shoulders positions would be equivalent to the LSH in this study, the HSH equivalent to upper level positions, LFS to foot-slope positions, and HFS to low level depressions.

To determine the appropriate method of correlating the soil properties measured, the soil properties at the Hepburn site were assessed for their skewness, both across the entire transect and by landscape position. This test revealed a mixture of skewed and normal distributions across the data set (data not shown). Pearson correlation coefficients (data not shown) were compared against the coefficients provided by Spearman rank correlation. This revealed no set trend; i.e., the use of Pearson Correlation did not result in consistently higher or lower values as compared to Spearman Rank. Based on this, Spearman rank correlation was chosen.

Table 4.1. Cross tabulation showing soil types at the Hepburn field plot and their occurrence in the landform element complexes.

Soil Class	Landform Element Complexes				Total
	LSH	HSH	LFS	HFS	
Orthic Regosol	10	1	1		12
Rego Black Chernozem	3				3
Calcareous Black Chernozem	3	4	3		12
Orthic Black Chernozem	7	9	17	5	38
Eluviated Black Chernozem			5	7	12
Gleyed Black Chernozem			7	4	11
Humic Luvic Gleysol			6	8	14
Total	23	14	39	24	100

Box-plots were used to illustrate the distribution of the different soil properties along the transect, according to landscape (e.g., Fig. 4.1), for each soil property. These plots are also a non-parametric means of displaying the data. Each box consists of a median or center line within the box, and the 25th and 75th percentiles. The whiskers represent 1.5 x the interquartile range beyond which the value would normally be considered an outlier or extreme value. Outliers and extremes were judged to be part of the natural variability of the respective soil property along the transect, and were not removed from the data sets. However, owing to the scaling problems created when displaying these values, they are not shown on the box plots. Significant differences between landform complexes are indicated by lower case letters within each box-plot. Similar letters denote that no significant difference ($P = 0.20$) existed between the respective landform complexes.

The thickness of the A horizon (Table 4.2) ranged widely along the transect with the thinnest A horizons found on topographically high landscape positions such as LSH and a general trend to increase down slope (Fig. 4.1). However, the lowest slope positions and those with the highest global catchment; i.e., HFS, had thinner A horizons in comparison to slope positions such as LFS and HSH.

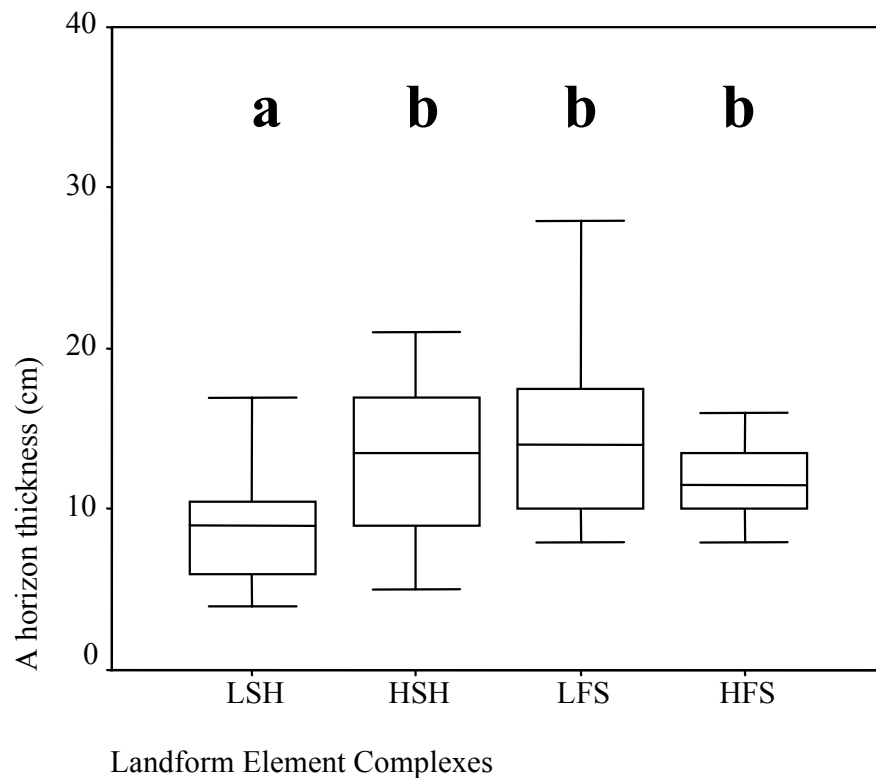


Figure 4.1. Box-plot of A horizon thickness at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

Table 4.2. Summary statistics of basic soil properties measured from all samples (n = 100) taken from the Hepburn field plot, 1998.

Variable	Depth (cm)/Trt.	Max.	Min.	Mean ±Std Err.	Median	C.V. %	Range (±Std. Err.
A Horizon (cm)	****	42	4	13 ± 6	11	46	8 ± 2
Total Soil N Mg ha ⁻¹	0-15	15	2	5 ± 1	5	29	7 ± 8
	15-30	5	1	2 ± 1	2	35	12 ± 6
	30-60	2	0.4	1 ± 0.4	1	34	19 ± 3
	0-30	16	3	6 ± 0.2	7	3	8 ± 5
	0-60	17	3.8	8 ± 2	8	25	10 ± 2
Total Soil C Mg ha ⁻¹	0-15	95	25	55 ± 13	55	23	61 ± 16
	15-30	83	9	31 ± 22	24	69	42 ± 12
	30-60	70	7	30 ± 22	22	71	41 ± 8
	0-30	174	40	87 ± 2.9	80	3	71 ± 30
	0-60	240	50	120 ± 50	100	39	68 ± 25
Soil Org. C Mg ha ⁻¹	0-15	74	22	49 ± 11	49	22	18 ± 6
	15-30	48	3	15 ± 9	13	55	16 ± 3
	30-60	19	1	6 ± 3	6	48	9 ± 2
	0-30	118	31	64 ± 2	60.6	3	16 ± 11
	0-60	131	33	70 ± 19	67	27	18 ± 7

4.2 Summary of Soil Properties at the Hepburn Field Plot

The mean value of total soil N (Table 4.2) across the transect (0 to 15 cm) was 5 ± 1 Mg ha⁻¹ or 2.4 ± 0.5 g kg⁻¹. Soil organic C and total soil C, in the 0 to 15 cm depth, had mean values of 49 ± 11 and 55 ± 13 Mg ha⁻¹, respectively (equivalent to 23 ± 5 and 26 ± 6 g kg⁻¹). Within the soil profile the mean value for total soil N, total soil C and soil organic C decreased with depth (Table 4.2).

The distribution of total soil N, soil organic C, and total soil C according to landscape position are shown in Figures 4.2, 4.3 and 4.4. LSH positions have the lowest values of total soil N (Fig. 4.2) and soil organic C (Fig. 4.3). In terms of total soil C, the

LSH positions have the highest values (Fig. 4.4). HSH positions have the highest values of total soil N and soil organic C. The value of total soil C in the HSH positions is between the values for the LSH and the lower slope positions; i.e., LFS and HFS. LFS and HFS are similar to each other in terms of total soil N, soil organic C and total soil C (Fig. 4.2 to 4.4).

The geostatistical ranges determined for total soil N (10 ± 2 m), soil organic C (18 ± 7 m), to a 60 cm depth, and A horizon thickness (8 ± 2 m) were similar in magnitude (Table 4.2). Total soil C for the same depth appeared to have a markedly wider range, that range being 68 ± 25 m. For total soil N, the range increased with depth. However, for total soil C and soil organic C the range decreased with depth, although the decrease in range for total soil C was minimal in light of the high standard error (Table 4.2).

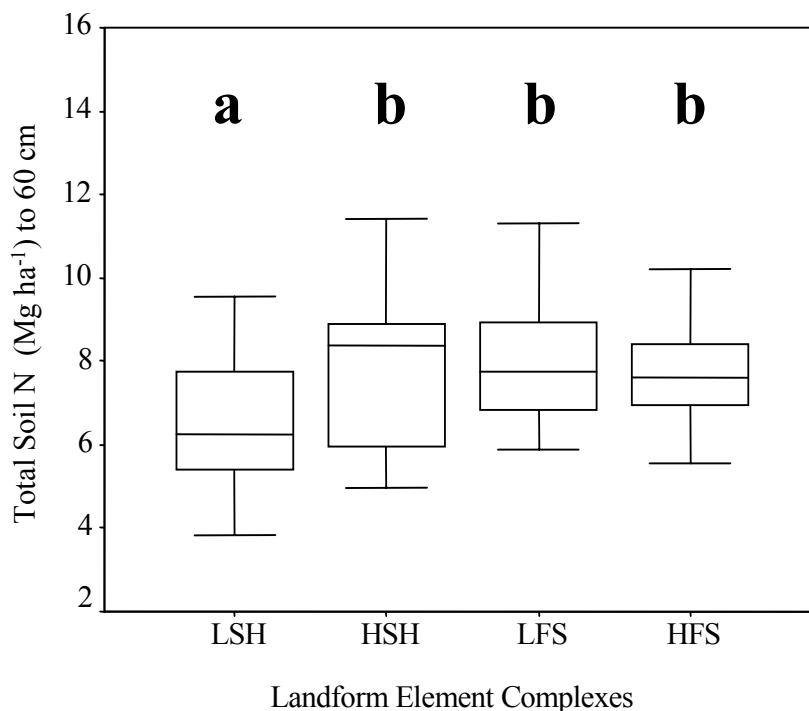


Figure 4.2. Box-plot of total soil N to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

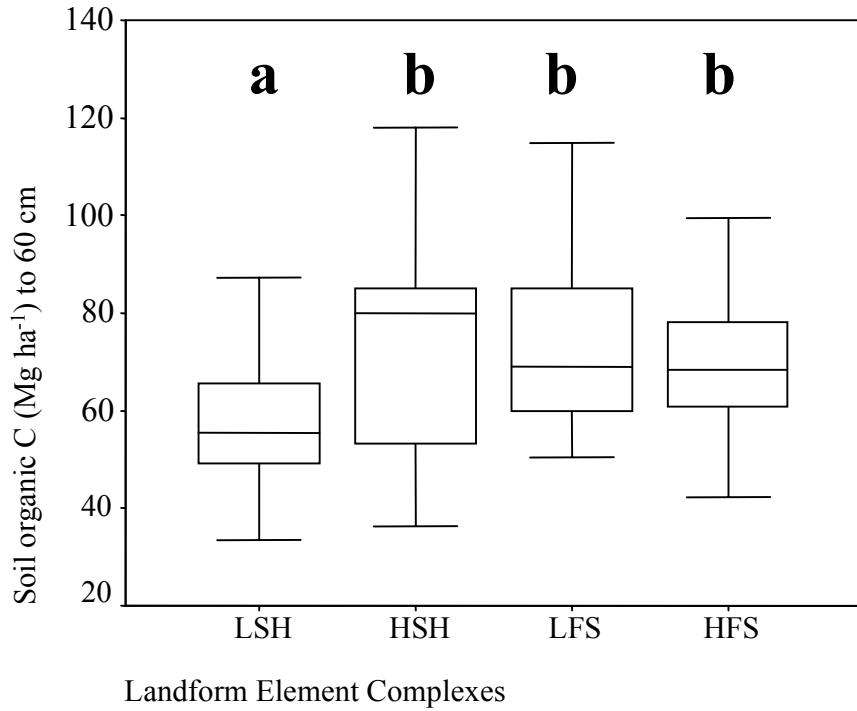


Figure 4.3. Box-plot of soil organic C to 60cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

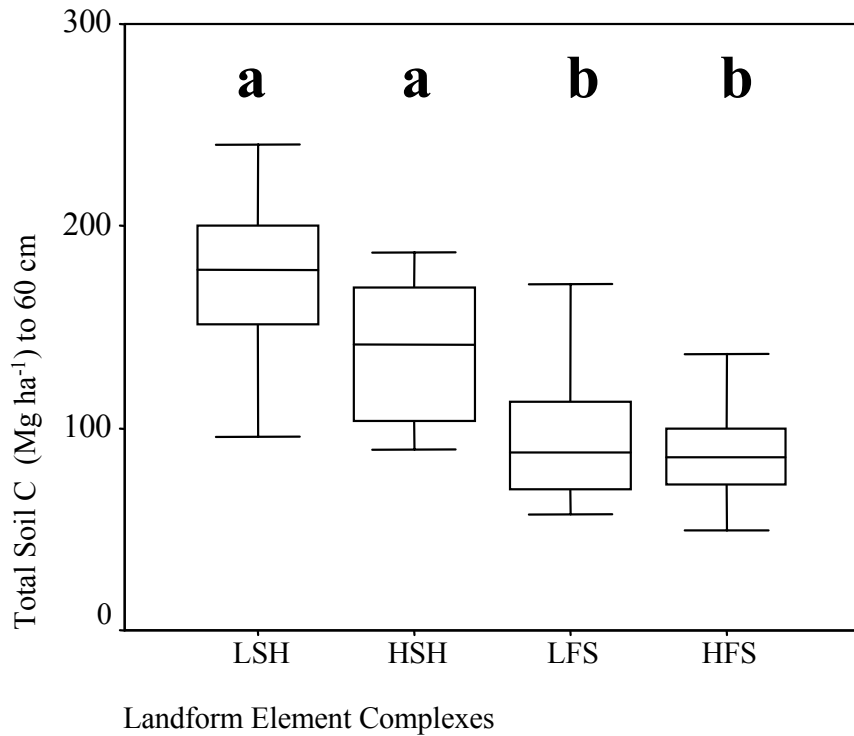


Figure 4.4. Box-plot of total soil C to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

4.3 Growing Season Soil Moisture Content

The average spring soil moisture content was 25 ± 5 %(v/v) in the top 15 cm of soil and decreased with depth (Table 4.3). Variability associated with spring soil moisture content was moderately high, but comparably lower than the other soil properties (Tables 4.2 and 4.3). This variability increased with depth with the exception of the C.V. averaged over a 30 cm depth, which was remarkably low (Table 4.3).

Gravimetric soil moisture typically increased down-slope (Fig. 4.5). In order from upper to lower slope and from driest to wettest position, the complexes were: LSH> HSH>LFS> HFS (Fig. 4.5). The shoulder units were statistically significant from foot-slope units in terms of soil moisture content.

The geostatistical ranges calculated for spring soil moisture at the different depth increments (Table 4.3) were the same magnitude as total soil C (Table 4.2). There was no set trend for the range for spring soil moisture content to increase or decrease with depth; however, the variability in the range through the soil profile was considerably lower than the range for other soil properties (Table 4.3).

Climate conditions for the Hepburn field plot during the summer of 1998 are reported in Table 4.4. The recorded days in May were hot and dry, in terms of temperature and precipitation. June, by comparison, was much cooler and wetter; however, the vast majority of the precipitation which fell in June came after the 15th day of the month (data not shown).

Table 4.3. Summary statistics of spring soil moisture measured from all samples (n = 100) taken at the Hepburn field plot, 1998.

Variable	Depth (cm)/Trt.	Max	Min.	Mean \pm Std Err.	Median	C.V. %	Range (m) \pm Std Err.
Spring	0-15	37	11	25 \pm 5	25	20	66 \pm 4
Soil	15-30	34	11	22 \pm 6	21	26	80 \pm 12
Moisture	30-60	39	7	19 \pm 7	17	36	52 \pm 4
% v/v	0-30	35	14	23 \pm 1	24	2	45 \pm 4
	0-60	35	12	21 \pm 6	20	26	52 \pm 8

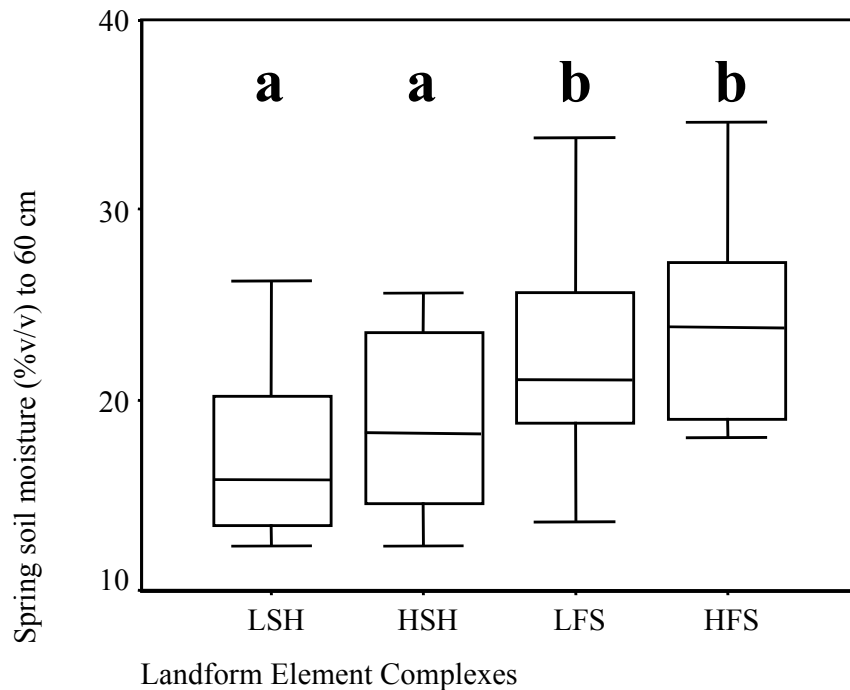


Figure 4.5. Box-plot of spring soil moisture content to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

Table 4.4. Climate data for the growing season of 1998 at the Hepburn field plot.

Month	Average Air Temperature $^{\circ}$ C	Average Soil Temperature $^{\circ}$ C	Total Precipitation (mm)
May 20-31 (seeded May 15)	17.2	7.8	1.8
June	14.8	9.5	86.2
July	18.3	13.2	34.2
August	19.4	13.6	42.2
September 1- 24 (Harvest Sept. 3)	14.2	11.7	33.5
Total			197.9

In a related study conducted on land immediately adjacent to this experiment, Pennock and Walley (1999) observed that the amount of precipitation received over the actual growing season was 169.4 cm in 1998. They further indicated that this level of precipitation was not unlike the year before; i.e., low levels of precipitation relative to the twenty year average. However, there was only 12.1 mm of precipitation for the period after seeding from May 15th to June 9th.

The maximum and minimum permanent wilting percentage (PWP) for each landform element complex to a depth of 60 cm can be seen in Table 4.5. The mean PWP did not vary much between the landform element complexes; however, the maximum PWP for each landscape position exceeded the minimum spring soil moisture contents at each landscape position (Fig. 4.5). As soil sampling was done several days before seeding, with very little moisture received during the period in between, it is likely that at several sample locations the soil was at or very close to PWP. Under these conditions, available water would have been very low to the point of stressing the crop.

4.4 Estimates of Soil N Availability and N Mineralization Potential

4.4.1 *Cumulative N and Potentially Mineralizable N*

The mean value of cumulative N extracted during the 16 wk aerobic incubation; i.e., 16 wk cumulative N, was 200 ± 80 kg N ha⁻¹ (equivalent to 96 ± 38 mg kg⁻¹) across the transect to a depth of 15 cm (Table 4.6). Potentially mineralizable N (No) displayed a lot of variability with maximum values as extreme as 2820 kg N ha⁻¹ or 1352 mg kg⁻¹ (Table 4.6).

Table 4.5. Permanent wilting percentage (%v/v) according to landform element complex to a 60 cm depth.

Permanent Wilting Percentage (%v/v)				
Landform Element Complex				
	LSH	HSH	LFS	HFS
Mean (Std. Err.)	10.8(0.4)	10.2(0.3)	9.3 (0.3)	9.4(0.6)
Median	10.7	10.1	9.6	9.1
Minimum	8.1	8.0	6.3	5.6
Maximum	14.7	13.4	12.3	22.1
C.V. %	4	3	3	6

Table 4.6. Summary statistics of results from the 16 wk aerobic incubation (n = 100) from the Hepburn field plot, 1998.

Variable	Depth (cm)/Trt.	Max.	Min.	Mean \pm Std Err.	Median	C.V. %	Range (m) \pm Std. Err.
Cumulative N 16 wk kg ha ⁻¹	0-15	380	20	200 \pm 80	210	41	14 \pm 2
	15-30	108	5	21 \pm 13	19	62	0 \pm 500
	0-30	400	30	220 \pm 84	230	39	17 \pm 3
No kg ha ⁻¹	0-15	1630	20	270 \pm 210	220	79	13 \pm 1
	15-30	2670	10	70 \pm 290	20	418	10 \pm 1
	0-30	2820	30	340 \pm 350	260	103	13 \pm 1
k wk ⁻¹	0-15	1.28	0.01	0.16 \pm 0.16	0.12	100	13 \pm 22
	15-30	0.76	0.00	0.13 \pm 0.12	0.12	92	11 \pm 1

The landscape patterns for 16 wk cumulative N, potentially mineralizable N and 2 wk cumulative N showed a trend towards increasing values from upper slope to lower slope positions (Fig. 4.6, 4.7 and 4.8). However, the variability was high (Table 4.6) and LSH positions stand out as the only significantly different landform element complex. A similar landscape pattern was observed for A horizon thickness (Fig. 4.1), total soil N (Fig. 4.2) and soil organic C (Fig. 4.3).

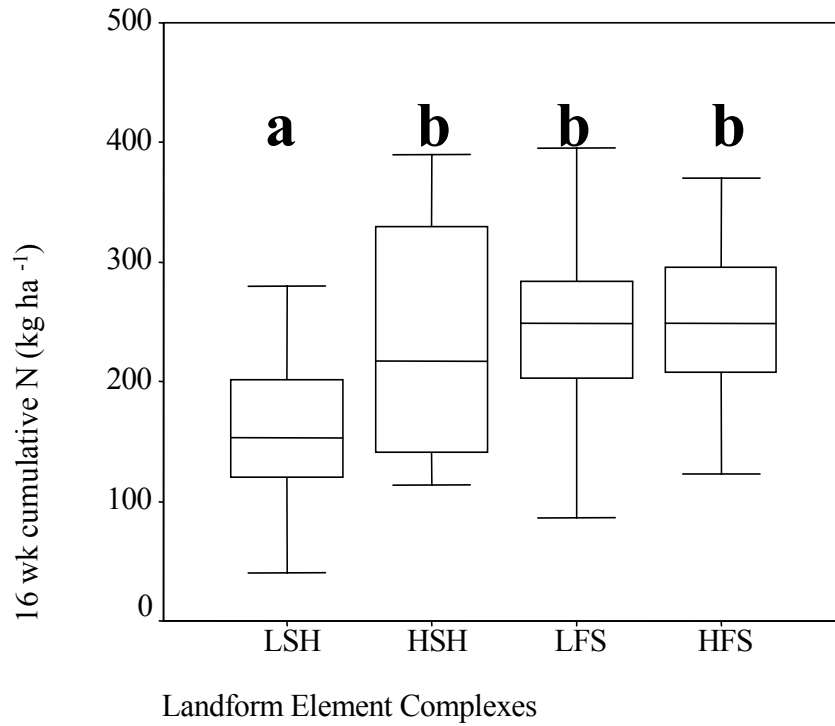


Figure 4.6. Box-plot of 16 wk cumulative N to a 30 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

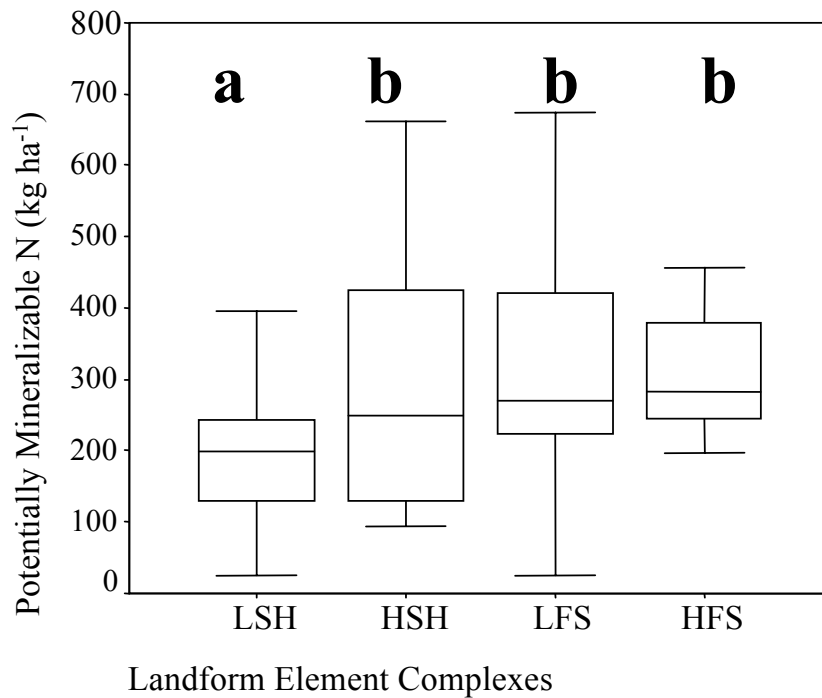


Figure 4.7. Box-plot of potentially mineralizable N to a 30 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

For comparison, the box plot showing the cumulative N collected over the first 2 wks of the incubation was included. The 2 wk cumulative N (Fig. 4.8) appeared to have a stronger relationship to landform; however, the trend is not significant such that the statistical significance between the landscape positions did not change from that of the 16 wk cumulative N values.

Geostatistically, cumulative N, potentially mineralizable N and the k value associated with the 0 to 15 cm depth (Table 4.6) had ranges similar to total soil N, soil organic C and A horizon thickness; i.e., under 20 m (Table 4.2).

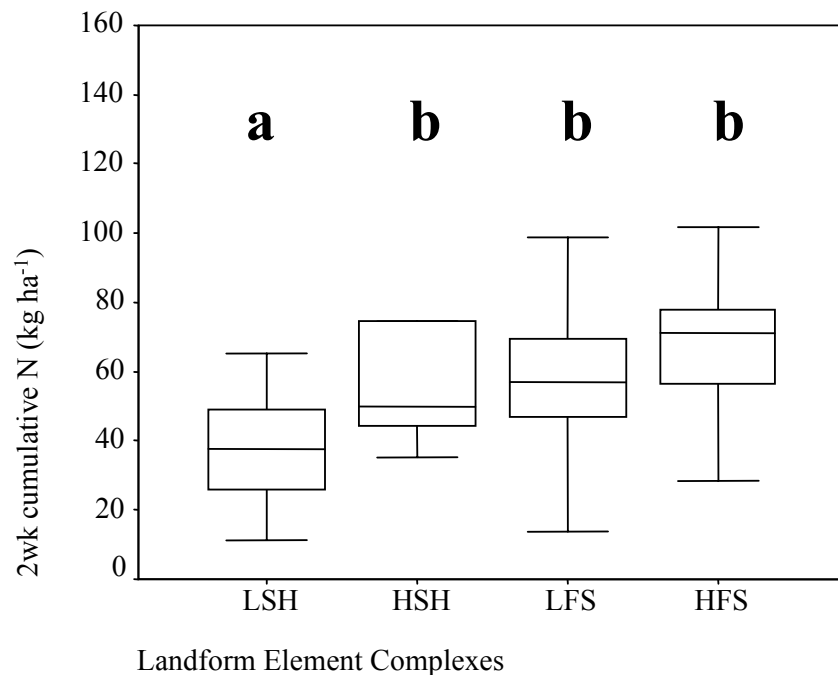


Figure 4.8. Box-plot of 2 wk cumulative N to a 30 cm depth at Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

4.4.2 *Hot KCl Extractable N*

The mean value for hot KCl extractable N in the 0 to 15 cm depth was 59 ± 16 kg $\text{NO}_3^- + \text{NH}_4^+ \text{-N ha}^{-1}$ or 28 ± 7 mg kg^{-1} (Table 4.7). The C.V. for each 15 cm depth increment was high (Table 4.7), but lower overall, and less variable for the previously described soil properties, with the exception of spring soil moisture content (Tables 4.2 and 4.3). As also seen with total soil N, total soil C, and soil organic C (Table 4.2), the C.V. for hot KCl extractable N (Table 4.7) in the 30 cm depth is 2 %, markedly lower.

The mean value of organic N hydrolysable at the Hepburn field site, for the 0 to 15 cm depth, was 39 ± 17 kg $\text{NO}_3^- + \text{NH}_4^+ \text{-N ha}^{-1}$ or 19 ± 8 mg $\text{NO}_3^- + \text{NH}_4^+ \text{ kg}^{-1}$ (Table 4.7). Organic N hydrolysable values were as low as 0 mg kg^{-1} for some samples. In in these cases, the measured inorganic N value was slightly higher than the reported hot KCl extractable N value canceling it to zero when calculating organic N hydrolysable. Both values for inorganic N and the hot KCl extractable N value were quite low overall. The C.V. values for organic N hydrolysable were slightly higher and more variable than that for hot KCl extractable N, with the profile to a depth of 30 cm also having a markedly lower C.V. of 3% (Table 4.7).

Table 4.7. Summary statistics of N availability indexes measured for samples (n = 100) taken from the Hepburn field plot, 1998.

Variable	Depth (cm)/Trt.	Max	Min	Mean ±Std Err.	Median	C.V. %	Range (m)
Hot KCl-N kg ha ⁻¹	0-15	100	27	59 ± 16	58	27	67 ± 6
	15-30	41	12	24 ± 6	24	23	19 ± 1
	30-60	59	10	27 ± 8	25	31	6 ± 1
	0-30	126	43	83 ± 2	83	2	86 ± 12
	0-60	178	62	110 ± 22	110	20	54 ± 9
Organic N Hydrolysable kg ha ⁻¹	0-15	82	0	39 ± 17	38	42	46 ± 4
	15-30	29	7	16 ± 5	16	31	42 ± 5
	30-60	41	0	17 ± 9	17	52	25 ± 2
	0-30	99	0	55 ± 2	54.6	3	54 ± 5
	0-60	118	0	71 ± 24	69	34	43 ± 4
Spring Inorganic N kg ha ⁻¹	0-15	77	10	20 ± 8	19	39	14 ± 19
	15-30	23	0	8 ± 5	8	60	34 ± 6
	30-60	39	0	11 ± 8	9	74	31 ± 6
	0-30	98	12	28 ± 1	26.2	4	57 ± 11
	0-60	118	12	39 ± 17	35	43	28 ± 5
Fall Inorganic N* kg ha ⁻¹	0-15	22	0	6 ± 5	5	79	12 ± 3
	15-30	15	0	2 ± 2	2	106	17 ± 6
	30-60	38	0	5 ± 6	3	125	7 ± 1
	0-30	28.2	0.5	8 ± 1	7	7	9 ± 5
	0-60	60	1	13 ± 10	10	73	7 ± 2
Plant Root Simulator µg·10cm ⁻² ·2wk ⁻¹	0-15	5400	100	600 ± 600	400	110	4 ± 2
	15-30	390	0	180 ± 80	170	47	19 ± 5
	30-60	510	0	60 ± 60	50	99	4 ± 1
	0-30	5630	70	730 ± 60	590	9	31 ± 1
	0-60	5700	100	800 ± 600	700	81	27 ± 13

*Fall samples were collected subsequent to the cropping season.

Landscape influenced the distribution of the hot KCl extractable N (Fig. 4.9).

The significance between landform element complexes followed a pattern that had similarities to both the pattern for total soil N (Fig. 4.2) and soil organic C (Fig. 4.3). Hot KCl extractable N values tended to increase down-slope, although the difference between landform complexes was not enough to define all shoulders complexes as

distinct from all foot-slope complexes. Unlike total soil N and soil organic C, the HSH complexes were not significantly different than the LSH complexes

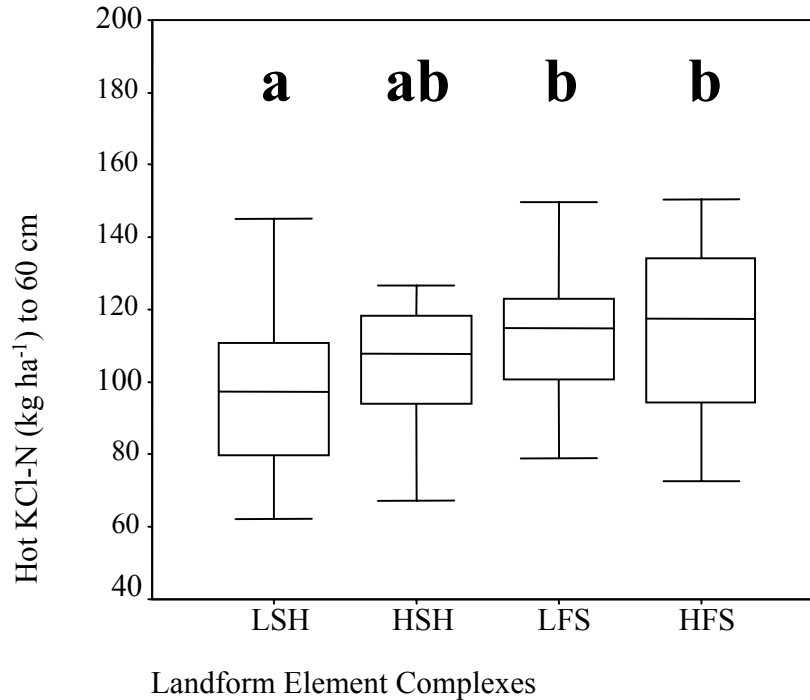


Figure 4.9. Box-plot of hot KCl extractable N to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

The pattern for organic N hydrolysable values (Fig. 4.10) had a stronger relationship to landscape than the hot KCl extractable N (Fig. 4.9). Both shoulder complexes were significantly different from both foot-slope complexes (Fig. 4.10). Although opposite in trend to the pattern of total C, it was similar in that both shoulder complexes were behaved as one unit, and both foot-slope complexes formed a second, distinct unit.

The geostatistical range for the hot KCl extractable N, to a 60 cm depth, was 54 ± 9 m whereas the range for organic N hydrolysable was 43 ± 4 m (Table 4.7).

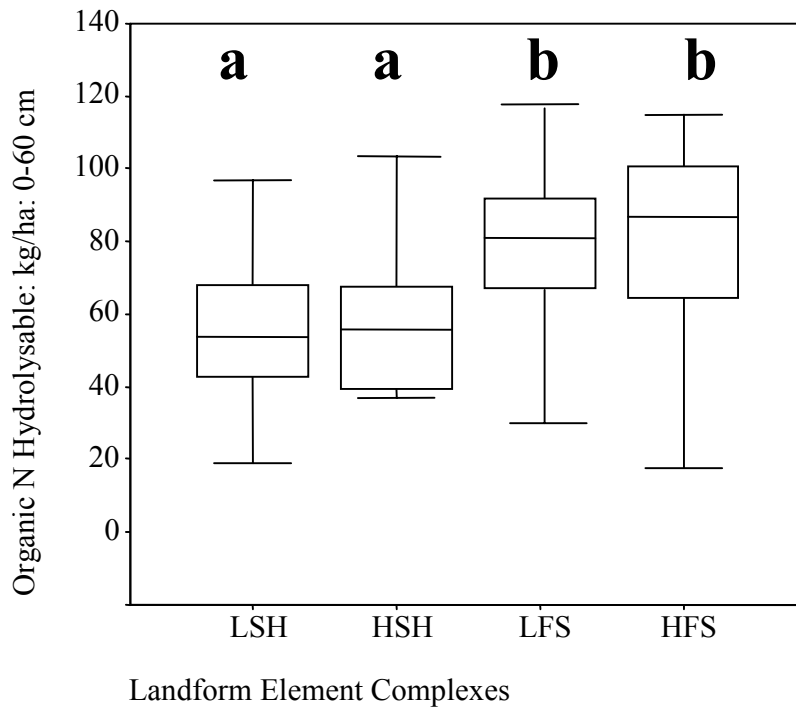


Figure 4.10. Box-plot of organic N hydrolysable to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

4.4.3 Spring and Fall Inorganic N

Spring inorganic N values had a mean value of 20 ± 8 kg ha⁻¹, equivalent to 9 ± 4 mg kg⁻¹, in the top 15 cm (Table 4.7). Fall inorganic N values were lower than those for the spring particularly in the lower 15 to 30 and 30 to 60 cm soil depths (Table 4.7).

The variability in the data, as revealed by the C.V.'s for both spring and fall inorganic N, was high (Table 4.7). The variability was higher overall, in the case of spring inorganic N (Table 4.7), than the other soil properties, with the exception of N_o and k (Table 4.6) and much higher in the case of fall inorganic N, especially in the 15 to

30 and 30 to 60 cm depth increments (Table 4.7). In keeping with several of the other soil properties, the C.V. for the 0 to 30 depth was markedly lower.

The distribution of spring inorganic N along the transect (Fig. 4.11) was markedly different from that for 16 wk cumulative N and hot KCl extractable N (Figs. 4.6 and 4.9). In particular, the LSH complexes were not the positions of lowest values, as was observed for each of the other soil properties. The HSH represented the highest values, with LFS and HFS being the positions of the lowest inorganic N values.

Fall soil sampling similarly revealed that inorganic N levels did not follow a clear or predictable landscape (Fig. 4.12). Specifically, the units defined by the significance between landscape positions were not clearly defined between shoulders and foot-slopes as they were for organic N hydrolysable and total C.

The geostatistical range for spring inorganic N to a depth of 60 cm was 28 ± 5 m (Table 4.7). Overall, this range is less than that for hot KCl extractable N (54 ± 9 m) (Table 4.7), total soil C (68 ± 25 m) (Table 4.2) and organic N hydrolysable (43 ± 4 m) (Table 4.7), yet greater than total soil N (10 ± 2 m) and soil organic C (18 ± 7 m) (Table 4.2).

Over a 15 cm depth the range for spring inorganic N (14 ± 9 m) (Table 4.7) was more in keeping with total soil N (7 ± 8 m), soil organic C (18 ± 6 m) and A horizon thickness (8 ± 2 m) (Table 4.2). Averaged over a 30 cm depth, the range for spring inorganic N is higher (57 ± 11 m), yet still lower than the range for hot KCl extractable N (86 ± 12 m), but similar to organic N hydrolysable (54 ± 5 m) (Table 4.7).

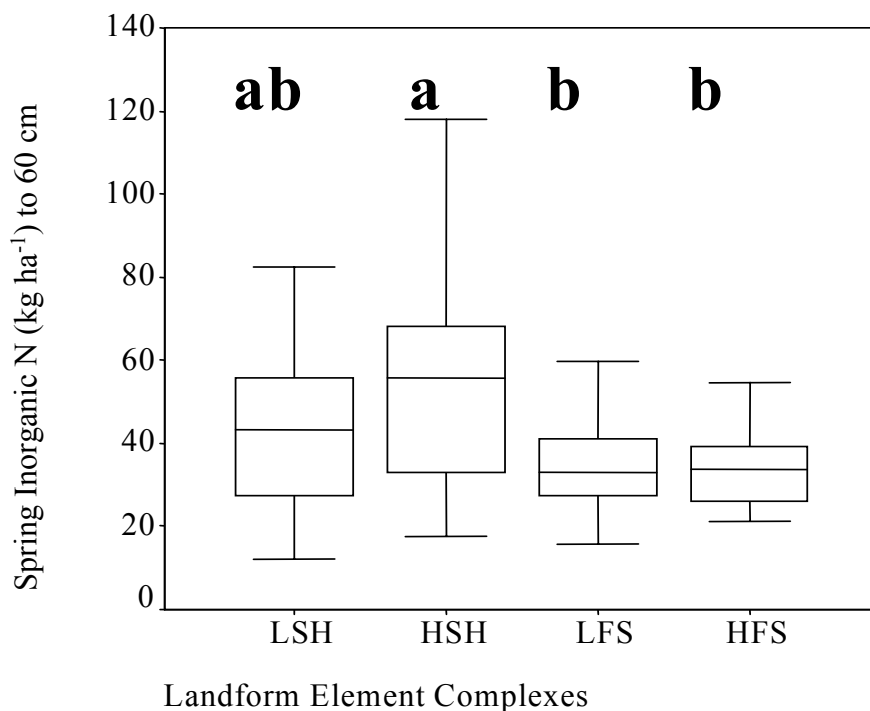


Figure 4.11. Box-plot of spring inorganic N to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

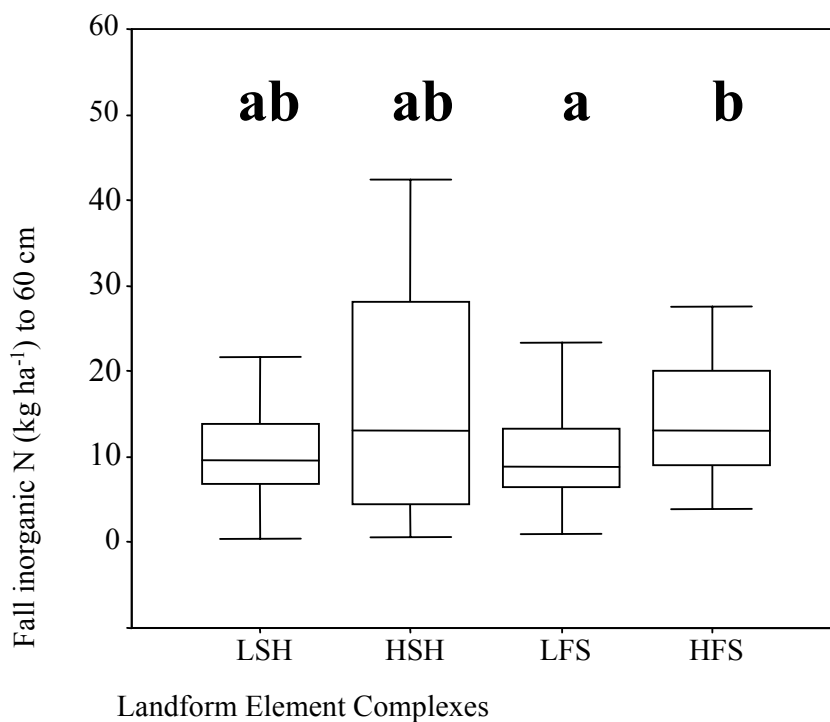


Figure 4.12. Box-plot of fall inorganic N to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

4.4.4 Ion Exchange Membranes

The mean value of NO_3^- supply, as estimated using ion exchange membranes in the form of the PRSTM, for the top 15 cm of soil was $600 \pm 600 \mu\text{g NO}_3^- \cdot \text{N} \cdot 10 \text{ cm}^{-2} \cdot 2 \text{ wk}^{-1}$ (Table 4.7). At the Hepburn site, the majority of the NO_3^- supply was in the top 15 cm of soil and estimates of NO_3^- supply decreased with depth (Table 4.7). The mean NO_3^- supply values were variable. Indeed, the C.V. for the NO_3^- supply as measured using the PRSTM-N was 110 % for the 15 cm depth. However, as observed with other soil properties, the NO_3^- supply averaged over the top 30 cm depth had a remarkably low C.V. of only 9% (Table 4.7).

It is interesting to note that the pattern of NO_3^- supply (PRSTM-N) across the landscape (Fig. 4.13) was similar to the pattern observed for hot KCl extractable N (Fig. 4.9) and 16 wk cumulative N (Fig. 4.6) in that the rate of NO_3^- supply increased down-slope.

The geostatistical range for PRSTM-N, to a depth of 15 cm ($4 \pm 2 \text{ m}$) (Table 4.7), was similar to the ranges for total soil N ($7 \pm 8 \text{ m}$), soil organic carbon ($18 \pm 6 \text{ m}$), A horizon thickness ($8 \pm 2 \text{ m}$) (Table 4.2), and 16 wk cumulative N ($14 \pm 2 \text{ m}$) (Table 4.6). The ranges for PRSTM-N over a 30 cm and a 60 cm depth ; i.e., $31 \pm 1 \text{ m}$ and $27 \pm 13 \text{ m}$, respectively, were wider (Table 4.7).

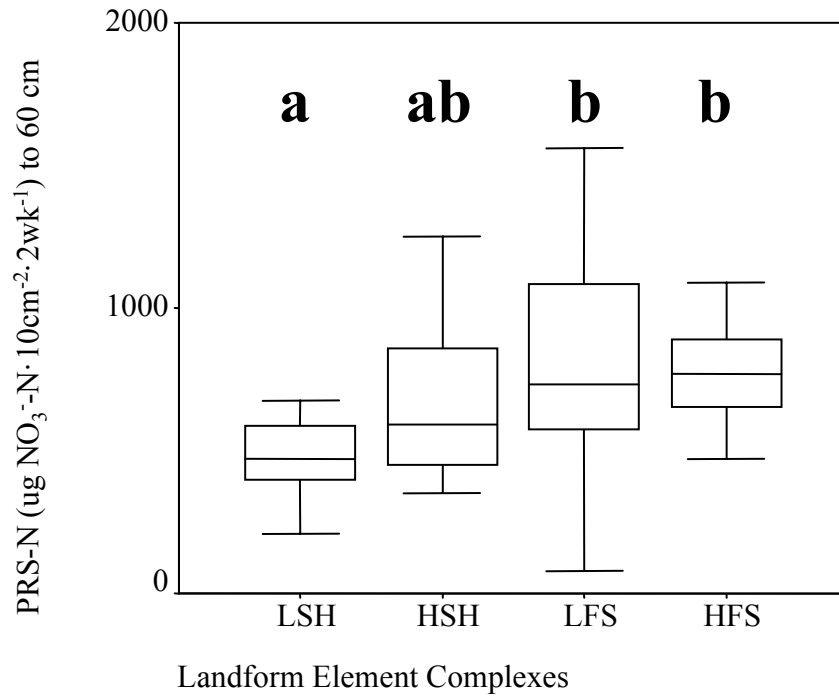


Figure 4.13. Box-plot of PRSTM-N to a 60 cm depth at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

4.4.5 Grain Yield and N Uptake

Both grain yield and crop N uptake increased from upper to lower slope positions (Fig. 4.14 to 4.17). In all landscape positions, the highest yields were achieved in the fertilized strip as compared to the unfertilized strip (Fig. 4.14 and 4.15). All shoulder complexes (LSH and HSH) were lower in grain yield than all foot-slope complexes (LFS and HFS) in both the fertilized and unfertilized strip. The differences between the shoulder and foot-slope complexes were statistically significant. This was the same landscape pattern that was observed for spring soil moisture content (Fig. 4.5), and organic N hydrolysable (Fig. 4.10).

A similar pattern between landscape positions for N uptake was observed in the unfertilized and fertilized strips (Fig. 4.16 and 4.17). It is interesting to note that the increase in fertilized N uptake, from upper to lower slope positions was more pronounced in the fertilized strip.

The geostatistical ranges determined for grain yield were very similar between the unfertilized and fertilized treatments (Table 4.8). The range for unfertilized grain yield (42 ± 5 m) was similar to that for spring soil moisture content to a 30 cm depth (45 ± 4 m) (Table 4.3) and organic N hydrolysable to a 15 cm depth (46 ± 4 m) (Table 4.7). The ranges for N uptake were markedly lower than grain yield (Table 4.8). The variability in the range was quite low for grain yield with the standard error less than 10% of the range.

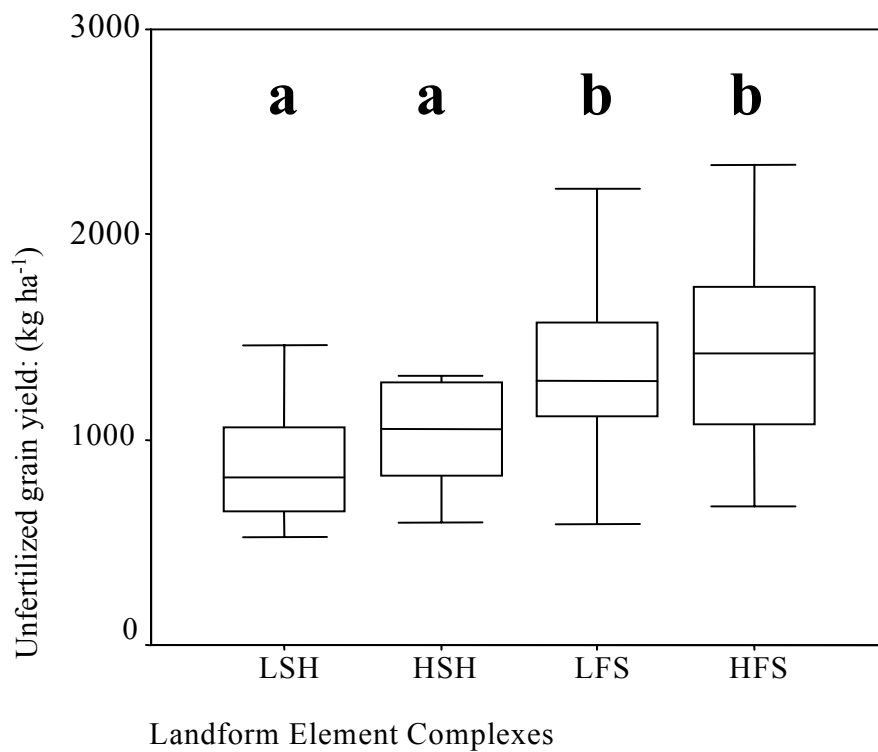


Figure 4.14. Box-plot of grain yield for the unfertilized treatment at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

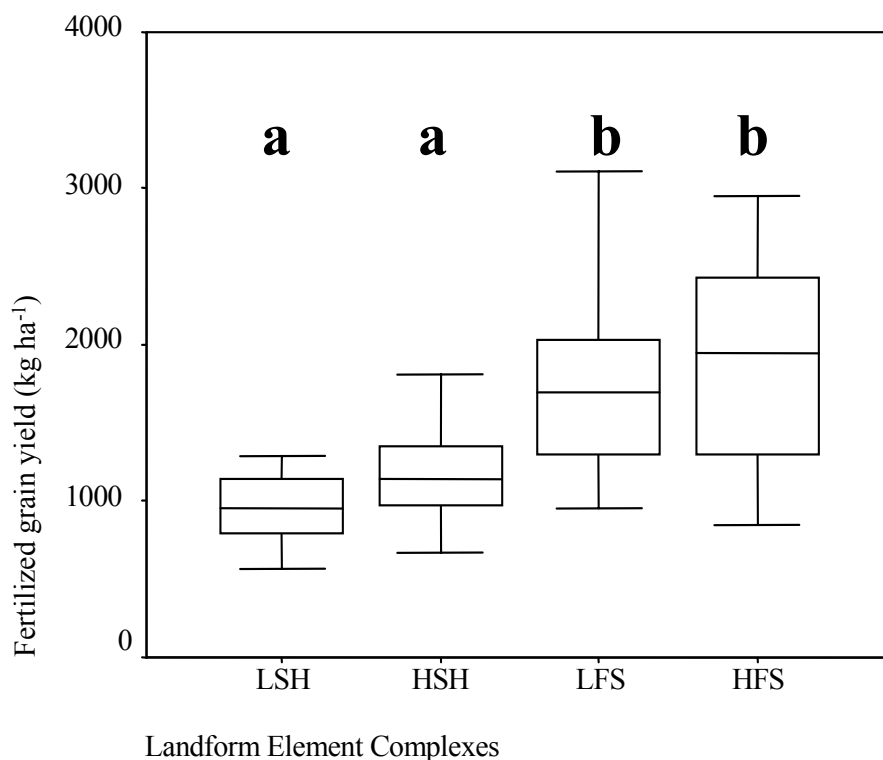
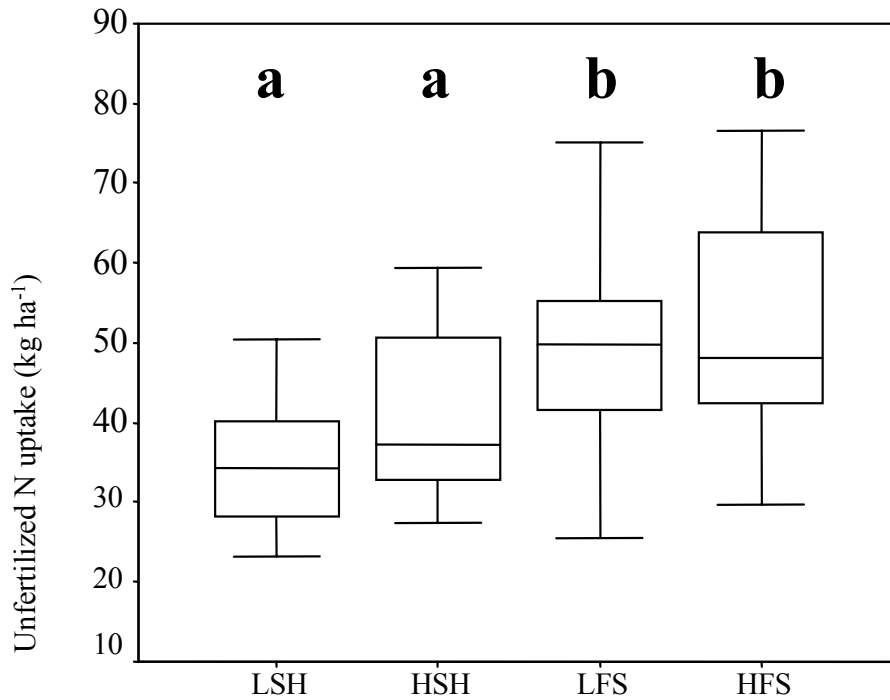
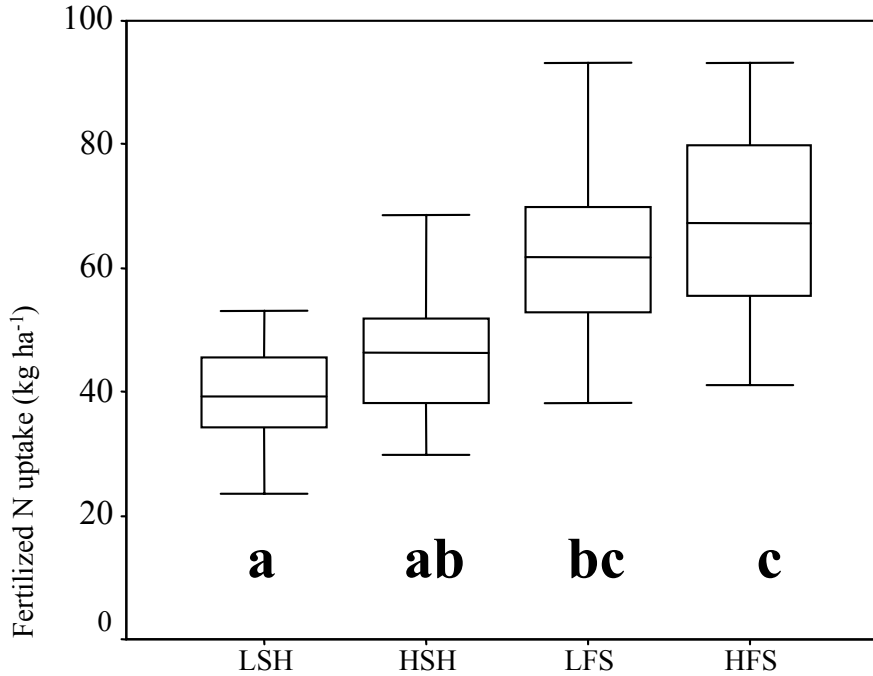


Figure 4.15. Box-plot of grain yield for the fertilized treatment at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).



Landform Element Complexes

Figure 4.16. Box-plot of N uptake for the unfertilized treatment at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).



Landform Element Complexes

Figure 4.17. Box-plot of N uptake for the fertilized treatment at the Hepburn field plot. Outliers are not shown. Letters denote significant differences between landscape positions as determined by a Kruskal-Wallis test ($P=0.20$).

Table 4.8. Summary statistics for yield parameters from metre square samples (n = 100) taken at the Hepburn field plot 1998.

Variable	Trt.	Max	Min	Mean ±Std Err.	Median	C.V. %	Range (m)
Grain yield kg ha ⁻¹	Fertilized	31	6	15±6	13	41	41 ±2
	Unfertilized	23	10	12±4	11	36	42 ±5
N Uptake kg ha ⁻¹	Fertilized	93	23	56±17	54	30	29 ±2
	Unfertilized	77	15	45±13	45	29	18 ±4

4.5 Correlations

Tables 4.9 to 4.11 display the coefficients obtained by comparing the soil properties measured for the three depths 0 to 15, 0 to 30 and 0 to 60 cm against the yield parameters collected; i.e., grain yield and N uptake, for both the fertilized and unfertilized strips. The highest positive correlation was between organic N hydrolysable in the 0 to 60 cm depth and fertilized N uptake (0.538; $P = 0.01$) (Table 4.11). Organic N hydrolysable was typically the highest correlating measurement of soil N availability with yield parameters. Exceptions are A horizon thickness with unfertilized N uptake in the 0 to 15 cm depth (0.479; $P = 0.01$) (Table 4.9) and spring soil moisture content with fertilized grain yield in the 0 to 30 cm depth (0.511; $P = 0.01$) (Table 4.10)

Table 4.9. Spearman rank correlations for A horizon thickness, soil properties in the 0 to 15 cm depth, and measurements of soil N availability in the 0 to 15 cm depth with yield parameters at the Hepburn field plot, 1998.

Variable	Grain yield		N uptake	
	Fertilized	Unfertilized	Fertilized	Unfertilized
16 wk Cumulative N (aerobic incubation)	0.316**	0.315**	0.318**	0.327**
Potentially mineralizable N	0.212*	0.245*	0.214*	0.261**
Hot KCl extractable N	0.467**	0.443**	0.480**	0.468**
Organic N Hydrolysable	0.511**	0.485**	0.508**	0.476**
Ion Exchange Membrane	0.404**	0.424**	0.374**	0.398**
Spring soil Inorganic N	-0.073	-0.021	-0.015	0.055
Total soil N	0.324**	0.300**	0.371**	0.365**
Total soil C	-0.051	-0.098	-0.048	-0.100
Soil organic C	0.419**	0.359**	0.406**	0.463**
A horizon thickness	0.407**	0.368**	0.437**	0.479**
Spring soil moisture	0.486**	0.369**	0.472**	0.375**

*Significant to $P = 0.05$; **Significant to $P = 0.01$.

Table 4.10. Spearman rank for soil properties in the 0 to 30 cm depth, and measurements of soil N availability in the 0 to 30 cm depth with yield parameters at the Hepburn field plot, 1998.

Variable	Grain yield		N uptake	
	Fertilized	Unfertilized	Fertilized	Unfertilized
16 wk Cumulative N (aerobic incubation)	0.316**	0.315**	0.324**	0.334**
Potentially mineralizable N	0.313**	0.344**	0.351**	0.325**
Hot KCl extractable N	0.420**	0.429**	0.442**	0.464**
Organic N Hydrolysable	0.508**	0.497**	0.515**	0.489**
Ion Exchange Membrane	0.423**	0.415**	0.397**	0.394**
Spring soil Inorganic N	0-.170	-0.112	-0.128	-0.030
Total soil N	0.336**	0.316**	0.376**	0.384**
Total soil C	-0.486**	-0.412**	-0.479**	-0.418**
Soil organic C	0.351**	0.303**	0.387**	0.352**
Spring soil moisture	0.511**	0.371**	0.498**	0.379**

*Significant to $P = 0.05$; **Significant to $P = 0.01$.

Table 4.11. Spearman rank correlations for soil properties in the 0 to 60 cm depth, and measurements of soil N availability in the 0 to 60 cm depth with yield parameters at the Hepburn field plot, 1998.

Variable	Grain yield		N uptake	
	Fertilized	Unfertilized	Fertilized	Unfertilized
Hot KCl extractable N	0.413**	0.391**	0.438**	0.454**
Organic N Hydrolysable	0.519**	0.492**	0.538**	0.476**
Ion Exchange Membrane	0.435**	0.420**	0.409**	.0407**
Spring soil Inorganic N	-0.105	-0.114	-0.118	-0.040
Total soil N	0.399**	0.353**	0.430**	0.404**
Total soil C	-0.671**	-0.530**	-0.662**	-0.553**
Soil organic C	0.362**	0.323**	0.394**	0.376**
Spring soil moisture	0.489**	0.303**	0.465**	0.295**

*Significant to $P = 0.05$; **Significant to $P = 0.01$.

Spring soil inorganic N, to any depth, did not correlate with grain yield or N uptake (Tables 4.9 to 4.11). In general, the correlation coefficients relating soil properties to yield were relatively low (Tables 4.9 to 4.11). However, many correlations were highly significant.

Tables 4.12 to 4.14 display the coefficients obtained by comparing the measures of the soil N availability against each other. Of note among the comparisons is the correlation between 16 wk cumulative N and the other soil variables. Comparisons of 16 wk cumulative N with hot KCl extractable N, organic N hydrolysable, ion exchange membranes and spring soil inorganic N reveals coefficients all under 0.300 ($P = 0.05$ or ns) (Tables 4.12 and 4.13). Comparisons of 16 wk cumulative N with total soil N, soil organic C, and A horizon thickness reveal coefficients well above 0.300 ($P = 0.01$) (Tables 4.12 to 4.14). Comparisons of spring inorganic N with other measures of soil N availability produced the lowest correlations, overall, with many coefficients being negative (Tables 4.12 to 4.14). Significant correlations were detected between organic N hydrolysable and ion exchange membranes although these correlation coefficients were all less than 0.500 (Tables 4.12 to 4.14).

Figures 4.18 to 4.20 show how the correlation coefficient between selected properties and cumulative N changed as the incubation proceeded. Organic N hydrolysable (Fig. 4.18), and unfertilized N uptake (Fig. 4.19) correlated most strongly with the cumulative N collected during the first 2 wks of the incubation (0.266; $P = 0.05$ and 0.431; $P = 0.01$) Correlation coefficients had a tendency to decline over time.

Table 4.12. Spearman rank correlations for measurements of soil N availability in the 0 to 15 cm depth, including A horizon thickness, at the Hepburn field plot, 1998.

	16 wk Cumulative N (incubation)	Hot KCl extractable N	Organic N Hydrolysable	Ion Exchange Membrane	Spring soil Inorganic N	Total Soil N	Soil organic C	A horizon thickness
16 wk Cumulative N (incubation)	nd	0.135	0.127	0.248*	0.031	0.334*	0.390**	0.385**
Hot KCl extractable N		nd	nd	0.403**	0.252*	0.399**	0.451**	0.278**
Organic N Hydrolysable			nd	0.433**	-0.086	0.328**	0.387**	0.234*
Ion Exchange Membrane				nd	-0.081	0.377**	0.376**	0.165
Spring soil Inorganic N					nd	0.296**	0.275**	0.237*
Total soil N						nd	nd	0.473**
Soil organic C							nd	0.578**
A horizon thickness								nd

*Significant to $P = 0.05$; **Significant to $P = 0.01$.

Table 4.13. Spearman rank correlations for measurements of soil N availability in the 0 to 30 cm depth, including A horizon thickness, at the Hepburn field plot, 1998.

	16 wk Cumulative N (incubation)	Hot KCl extractable N	Organic N Hydrolysable	Ion Exchange Membrane	Spring soil Inorganic N	Total soil N	Soil organic C	A horizon thickness
16 wk Cumulative N (incubation)	nd	0.181	0.169	0.281**	0.062	0.383**	0.456**	0.408**
Hot KCl extractable N		nd	nd	0.428**	0.235*	0.461**	0.432**	0.333**
Organic N Hydrolysable			nd	0.387**	-0.258**	0.293**	0.277**	0.247*
Ion Exchange Membrane				nd	0.017	0.428**	0.424**	0.260**
Spring soil Inorganic N					nd	0.378**	0.368**	0.262**
Total soil N						nd	nd	0.589**
Soil organic C							nd	0.643**
A horizon thickness								nd

*Significant to $P = 0.05$; **Significant to $P = 0.01$.

Table 4.14. Spearman rank correlations for measurements of soil N availability in the 0 to 60 cm depth, including A horizon thickness, at the Hepburn field plot, 1998.

	Hot KCl extractable N	Organic N Hydrolysable	Ion Exchange Membrane	Spring soil Inorganic N	Total Soil N	Soil organic C	A horizon thickness
Hot KCl extractable N	nd	nd	0.463**	0.258**	0.464**	0.454**	0.371**
Organic N Hydrolysable		nd	0.406**	-0.364**	0.301**	0.274**	0.257**
Ion Exchange Membrane			nd	0.037	0.430**	0.412**	0.285**
Spring soil Inorganic N				nd	0.302**	0.326**	0.194**
Total soil N					nd	nd	0.612**
Soil organic C						nd	0.659**
A horizon thickness							nd

*Significant to $P = 0.05$; **Significant to $P = 0.01$.

The correlations between cumulative N and both organic N hydrolysable and the unfertilized N uptake declined in a linear manner between 2 and 16 weeks. In contrast, the correlation between total soil N and cumulative N (Fig. 4.20) was weakest at 2 wks (0.247; $P = 0.05$) and strongest at the completion of the incubation (0.404; $P = 0.01$). This relationship was logarithmic and has a high $r^2 = 0.97$.

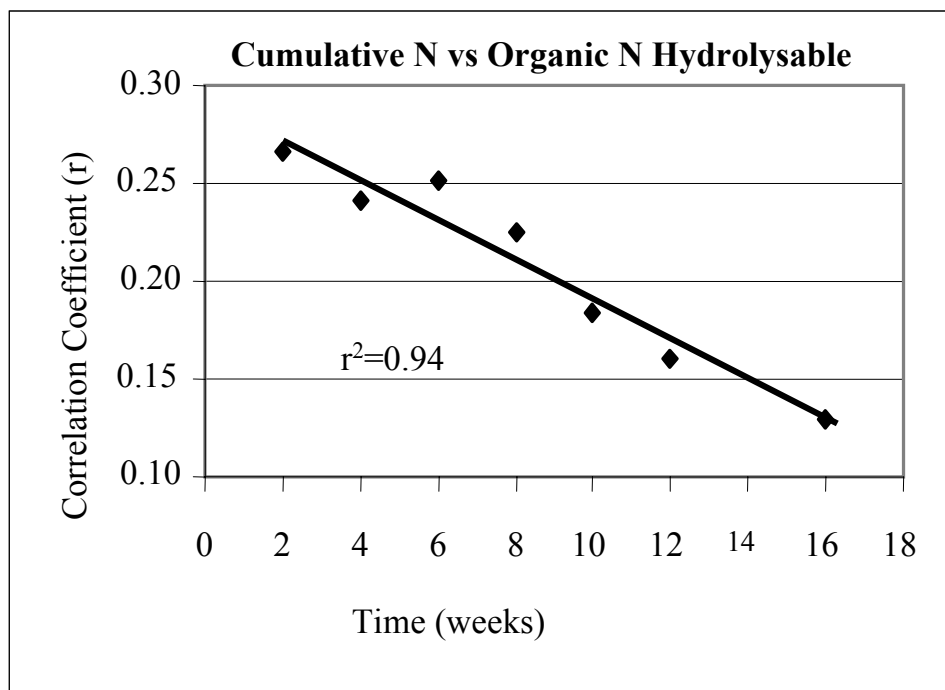


Figure 4.18. Change in correlation coefficient between cumulative N, and organic N hydrolysable during the course of the 16 wk incubation.

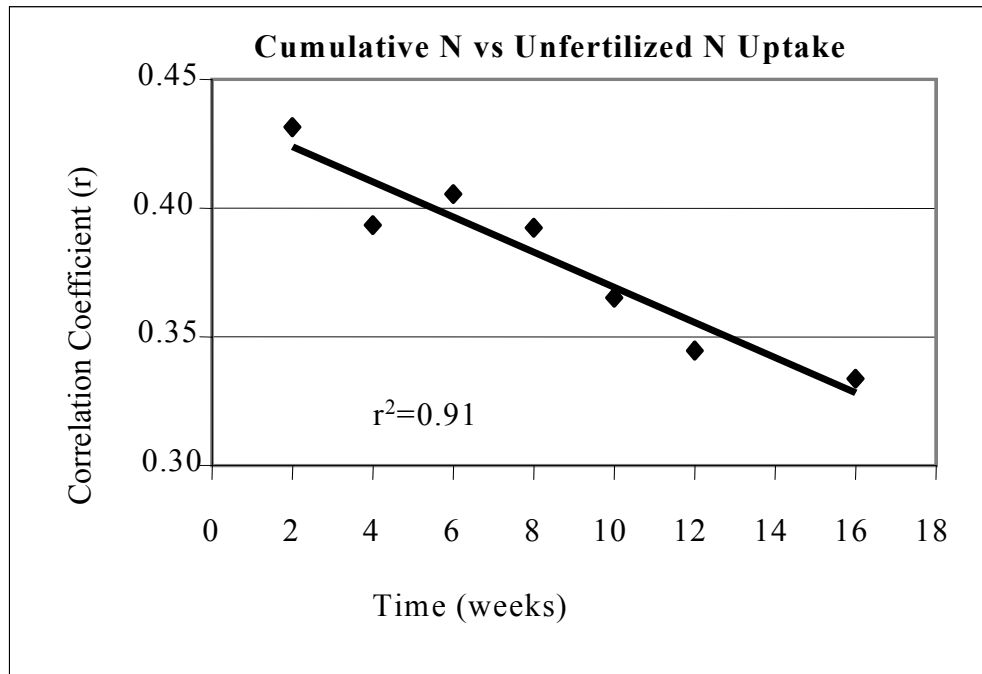


Figure 4.19: Change in correlation coefficient between cumulative N, and unfertilized N uptake during the course of the 16 wk incubation.

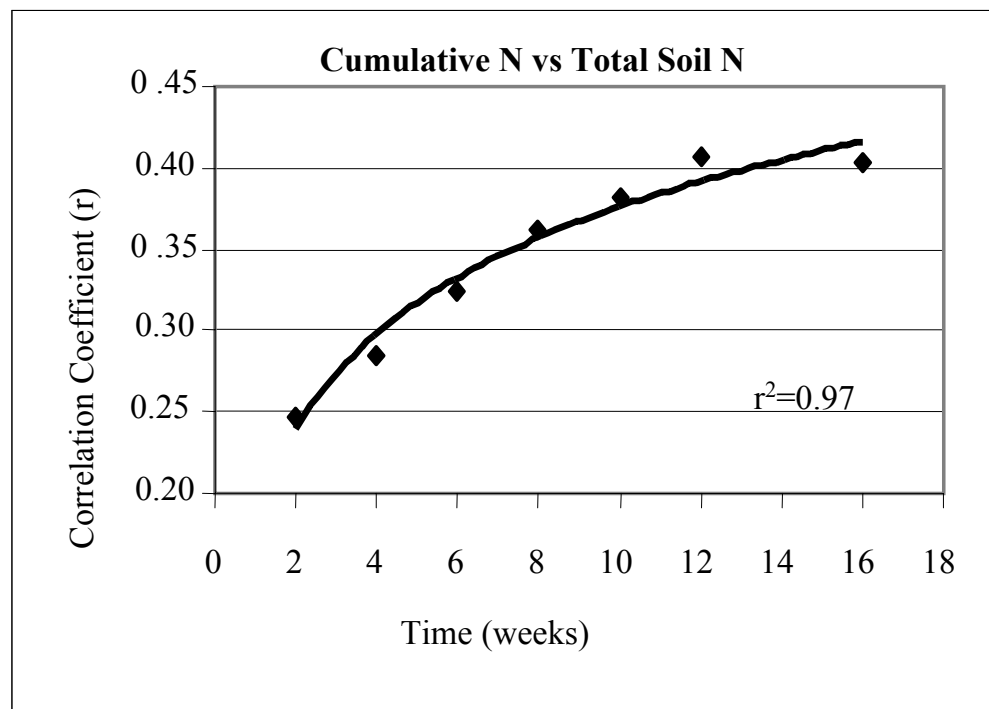


Figure 4.20: Change in correlation coefficient between cumulative N, and total soil N, during the course of the 16 wk incubation.

5.0 DISCUSSION

Soil distribution (Table 4.1) and A horizon thickness (Table 4.2) at the Hepburn site was similar to that of a glacial till site in the Black soil zone of Saskatchewan previously described by Pennock et al. (1994). They reported an increase in A horizon thickness from upper to lower slope positions. They also noted that the low level depressional positions had thinner A horizons as compared to foot-slopes except where tillage translocation of upper slope material had artificially thickened the lower slope horizon during long term cultivation. These lower slope positions were also found to be dominated by Gleysols, as they were at Hepburn (Table 4.2).

Pennock et al. (1997) reported that the predictable patterns of soil distribution within a glacial till landscape were the result of the topographically controlled redistribution of water. Examination of the spatial patterns of spring soil moisture content at the Hepburn site similarly indicated landscape controls on soil moisture content with soil moisture highest in the HFS and lowest in the LSH (Fig. 4.13). Thus, the development of soils at the Hepburn site likely reflects the influence of moisture movement and availability within the landscape. Moreover, in agreement with Pennock (1997), soil development was predictable on the basis of topographically controlled moisture redistribution.

Moisture redistribution has a great influence on soil development (Pennock et al., 1987) and hence should have a significant influence on the quantity and quality of

organic matter produced. As a consequence it might be expected that the A horizon thickness, and related properties such as soil organic C content of the soil, would be closely related to patterns of soil moisture content. However, patterns for A horizon thickness (Fig. 4.1), total soil N (Fig. 4.2) and soil organic C (Fig. 4.3) were somewhat different than the spring available soil moisture (Fig. 4.5). Specifically, available spring moisture typically was highest in lower slope positions and lowest in upper slope positions. In contrast, relatively low values for A horizon thickness, total soil N and soil organic C were associated with lower slope positions.

Several possible explanations exist for the discrepancy between the expected and observed results. Firstly, it could be argued that the data collected from the Hepburn site is anomalous in some manner. However, the numerical range of values for total soil N, soil organic C, and total soil C were similar to values obtained from similar studies. For example, the mean value of total soil N (Table 4.2) was 2.4 g kg^{-1} which is comparable to a mean of 3.3 g kg^{-1} found by Curtin and Wen (1999) for 61 Saskatchewan soils (0 to 15 cm). Jalil et al. (1996) examined soil properties for various Saskatchewan soils, including two from the Black soil zone (Meota Association), and reported total soil N values of 1.72 and 4.03 g kg^{-1} total soil N (0 to 15 cm) for these two soils. Selles et al. (1999) reported a mean value of 2.23 g kg^{-1} total soil N for a Dark Brown Chernozem developed on modified glacial till for the 7.5 to 15 cm depth increment. Total C and soil organic C in the 0 to 15 cm depth at Hepburn was equivalent to 26 and 23 g kg^{-1} , respectively (Table 4.2). Jalil et al. (1996) reported mean soil organic C values of 19.5 and 37.9 g kg^{-1} for the two Meota soils that they examined. Pennock et al. (1994) reported a range of 53 to 124 Mg ha^{-1} soil organic C over a 45 cm depth for Chernozemic soils developed on glacial till in the Black soil zone of Saskatchewan.

Thus, values for total soil N, soil organic C and total soil C from the Hepburn site fell within ranges that other researchers had previously observed suggesting that the Hepburn site was not an anomaly.

A second explanation for why spring soil moisture patterns differed from patterns for A horizon thickness, total soil N and soil organic C may be due to excessive variability in the data. Indeed, it was noted that the data were characterized by a high degree of variability. In this study, variability in soil properties was high with C.V.'s of 29% for total soil N, 23 % for total C, 22% for soil organic C and 27% for A horizon thickness. However, for total soil N, total C, and soil organic C, the C.V.'s over a 30 cm depth was noticeably lower; i.e., C.V.= 3%, than the individual depth increments and the entire 60 cm profile (Table 4.2). Research projects similar to this one have reported relatively high levels of variability for these soil properties. For example, Selles et al. (1999) reported a C.V. of 33% for total soil N (0 to 15 cm). Soil organic C values presented by Curtin and Wen (1999) had a calculated C.V. of 48% over a 15 cm depth.

Although variability may explain, in part, the differences in patterns for spring soil moisture and soil properties such A horizon thickness, total soil N and soil organic C, a more plausible explanation likely relates to previous vegetation and thus reflects cumulative soil forming processes. In particular, it is possible that the lower slope position; i.e., HFS may have been dominated by different vegetation during soil development as compared to the upper slope positions and thus organic inputs during soil development were different both in quality and quantity. Indeed, it is possible that the HFS were dominated by aspen bluffs prior to clearing and thus organic matter levels, and differences in organic matter levels within the landscape, reflect the inherent differences in organic inputs during soil formation.

Although the distributions of A horizon thickness, total soil N and soil organic C were not directly related to soil moisture, the distributions of these three properties, to a depth of 60 cm (Fig. 4.1, 4.2 and 4.3) were similar to one another. In particular, the LSH positions had the lowest values and the HSH positions had the highest values for total soil N and soil organic C. Down slope positions such as LFS and HFS were similar to each other in terms of total soil N and soil organic C, and these values typically fell between the values of total soil N and soil organic C associated with the LSH and HSH positions. Pennock et al. (1994) suggested that Gleysolic dominated foot-slopes and level depressional complexes; i.e., positions comparable to HFS typically are very low in N because of the impact of anaerobic conditions. Thus the relatively low values for total soil N and soil organic C in the HFS are not surprising because these positions were dominated by Gleysolic soils at the Hepburn site.

In contrast to the distribution of total soil N and soil organic C, the distribution of total C displayed a stronger landscape relationship with the highest values in the topographically highest positions (LSH). Total soil C decreased steadily down slope with the LFS and HFS sharing similar values that were both lower than HSH positions (Fig. 4.4). The values for A horizon thickness, soil organic C and total soil N in the LSH positions (Fig. 4.1, 4.2 and 4.3), were statistically distinct from the values for these soil properties in other landscape positions whereas for total C both the LSH and HSH were a significantly distinct group from LFS and HFS. The strong landscape pattern in total soil C was due to the fact that total soil C was dominated by inorganic C in this calcareous soil and the distribution soil inorganic carbon is known to be controlled by the redistribution of water in the landscape (Pennock et al., 1992).

According to geostatistical analysis, the three soil properties; i.e., total soil N, soil organic C and A horizon thickness, did not share the same landscape pattern as total soil C (Table 4.2). Specifically, the ranges for total soil N, soil organic C, and A horizon thickness were all under 20 m, whereas the range for total soil C was much greater, generally exceeding 40 m. Selles et al. (1999) reported a considerably higher range for total soil N of 150 to 200 m. The topographic variation within the field used by Selles et al. (1999) may have been much less than that of the Hepburn site, leading to less variation in total soil N between sample locations.

The data suggests two trends in landscape distribution of the measured soil properties at the Hepburn field site. The first trend is that distribution shared by total soil N, soil organic C and A horizon thickness (Table 4.2). Each of these soil properties had a comparatively short range. The second trend is that demonstrated by the distribution of total soil C, which had a range approximately twice that of the first three soil properties (Table 4.2). The differences in these trends suggest that these soil properties may be governed by different controls. The differences in the distributions are also expressed by the significant differences between landscape positions for each of the soil properties (Fig. 4.1 to 4.4). The distribution of total soil C shows a distinction between all shoulder positions and all foot-slope positions, whereas for the other soil properties, there was no distinction between HSH, LFS and HFS positions. It can be suggested that the second trend was the result of a greater sensitivity to the control of landscape; i.e., total soil C was more responsive to landscape than was total soil N, soil organic C and A horizon thickness.

The landscape distribution of spring soil moisture content reinforces this concept of two trends in the spatial distribution of the soil properties. Spring soil moisture content

increased progressively from topographically high positions (LSH) to topographically low positions (HFS) (Fig. 4.5). The significant differences between landscape positions for spring soil moisture content were the same as those observed for total soil C; i.e., LSH and HSH positions were statistically distinct from LFS and HFS positions. The geostatistical range for spring soil moisture content also exceeded 40m, similar to that for total soil C.

Pennock et al. (1997) demonstrated that the pattern of soil moisture is the result of the redistribution of water within the landscape. Thus, we should expect the spatial distribution of spring soil moisture content to be strongly controlled by the landscape. Similarly one might expect total soil C to share a similar pattern because total soil C was dominated by inorganic C at Hepburn (data not shown) and the distribution of inorganic C is expected to be related to the redistribution of water in the landscape (Pennock et al., 1992). It is most probable that if a soil property has a landscape pattern similar to that of total soil C; i.e., following the second trend, this property is influenced or controlled in some way by spring soil moisture. It follows that the other measurements taken in this study; i.e., soil N availability and crop yield, may be expected to exhibit a pattern that is either clearly related to the redistribution of water; i.e., the second trend, or, alternatively, has a pattern that is not directly related to spring soil moisture, but may be indirectly related to long term impact of water redistribution; i.e., the first trend.

The landscape pattern of soil N availability, as expressed by N produced biologically over a long term incubation, can be reported as cumulative N data; i.e., the actual N collected as NO_3^- collected over the course of the incubation, or as potentially mineralizable N (a value calculated from the cumulative N data). As a measure of soil N availability, cumulative N is more appropriate for assessing N availability than is

potentially mineralizable N (Selles et al., 1999). Selles et al. (1999) collected cumulative N data (referred to in their paper as Sum N) and calculated potentially mineralizable N (N_0) and k constants for a 24 wk incubation performed in the same manner as was done in this study, using the method of Campbell et al. (1993). Interestingly, Selles et al. (1999) concluded that sum N was a more useful measure of N availability than N_0 or k and reasoned that there was no advantage in using N_0 or k in terms of assessing soil N availability because N_0 was a value calculated from the sum N data, and N_0 and k were negatively correlated with each other. The N_0 values obtained from the cumulative N data for this study also appeared to offer no advantage over cumulative N, in terms of landscape relationships, geostatistics and Spearman rank correlations. Moreover, N_0 and k were also negatively correlated (data not shown).

The mean value for cumulative N determined over 16 wks (Table 4.6) (16 wk cumulative N) was equivalent to 96 mg kg^{-1} , which compares to reported cumulative N values of 56 and 147 mg kg^{-1} for two Meota soils over a 15 cm depth from a 24 wk incubation (Jalil et al., 1997). Selles et al. (1999) reported a mean value of 63.9 mg kg^{-1} (sum - N, which is equivalent to cumulative N) over 24 wks of incubation for a similar soil to a depth of 15 cm. Selles et al. (1999) similarly reported high levels of variability with C.V. values of 79% for sum - N (cumulative N). In contrast, Mahmoudjafari et al. (1997) reported much lower C.V. values such as 12% for cumulative N; however, the field site for their research was relatively level; i.e., slopes of 0 to 1%.

The values of 16 wk cumulative N (Fig. 4.6) for samples collected from the Hepburn site appeared to follow a similar spatial pattern to that of total soil N, soil organic C and A horizon thickness (Fig. 4.1 to 4.3). As with the latter soil properties, no statistically significant differences in 16 wk cumulative N were detected between the

HSH, LFS and HFS positions. Only LSH positions were significantly distinct in terms of 16 wk cumulative N. The geostatistical range for 16 wk cumulative N values was also less than 20 m, similar to that of total soil N, soil organic C and A horizon thickness. These similarities between 16 wk cumulative N and total soil N, soil organic C and A horizon thickness may be because 16 wk cumulative N was a direct reflection of the N mineralized from the overall soil organic N pool. Total soil N, soil organic C and A horizon thickness are also directly related to the same soil organic N pool. In fact, Tables 4.12 to 4.14 indicate that the correlations between 16 wk cumulative N and soil properties such as total soil N, soil organic C and A horizon thickness are comparatively strong relative to other measures of soil N availability such as hot KCl extractable N. It is possible that an explanation for the comparatively strong correlations rests in the nature of the soil organic N pool itself.

The general soil organic N pool, is made up of several smaller organic N pools (Campbell et al., 1993). Nitrogen extracted using hot KCl; i.e., hot KCl extractable N, probably represents a different and more specific pool of soil organic N than does 16 wk cumulative N. Curtin and Wen (1999) found hot KCl extractable N to be related to a small, yet active water soluble fraction of organic N. In contrast, 24 wk cumulative N was closely related to estimates of the LF, which was the largest portion of total soil N of the organic matter fractions they measured. Hence it is not unexpected that cumulative N values, extracted over a long term incubation were more closely related to total soil N than to hot KCl extractable N for soils at the Hepburn site. Simply stated, these two estimates of soil N availability may be measuring chemically different portions of the overall soil N pool.

In this study, no significant relationship between cumulative N collected from a long term incubation and hot KCl extractable N was detected ($r_s = 0.181$; ns over a 30 cm depth). These results are in agreement in agreement with Curtin and Wen (1999) who similarly reported the relationship between hot KCl extractable N and cumulative N to be weak ($r^2 = 0.130$; $P = 0.01$). In contrast, Jalil et al. (1996), Campbell et al. (1997) and Selles et al. (1999) found strong correlations between hot KCl extractable N and cumulative N mineralized over a 24 wk incubation (e.g., $r^2 = 0.790$; $P < 0.001$ (Jalil et al., 1996)). In fact, Selles et al. (1999) concluded that hot KCl extracted N from the same pool of N as did the aerobic incubation.

The differences between these studies may be related to the size of the organic N pools. If the hydrolysable organic N pool, which is accessed by hot KCl extractable N, is proportionally a large part of the overall organic N pool, then it will strongly influence the results of the long term incubation and correlate well with the cumulative N. The soils selected by Selles et al. (1999) were from a single field, mapped as Dark Brown Chernozem. Jalil et al. (1996) chose soils from a variety of soil zones, but primarily Brown Chernozems, Dark Grey Luvisols, and Grey Luvisols. Curtin and Wen (1999) also chose soil from a variety of soil zones; however, their samples appear to be represented by a larger proportion of soil from the Black soil zone. The Hepburn site was also located in the Black soil zone. The suggestion is that if a soil has a relatively large soil N pool, such as that which can be expected in a Black Chernozem versus a Brown Chernozem, then the contribution of recent crop residues to N availability; i.e., hydrolysable N as estimated by hot KCl, may be overwhelmed by the contribution of N from the resident N pool. The soil samples collected by Curtin and Wen (1999) and

those collected from Hepburn may have had proportionally larger pool of resident organic N relative to the pool of hydrolysable N; i.e., recent crop residues.

The mean value for hot KCl extractable N over a 15 cm depth was equivalent to 28 mg N kg⁻¹ (Table 4.4). This value was higher than values obtained for similar soils such as those used by Jalil et al. (1996) who found mean values of 10.7 and 12.0 mg N kg⁻¹ in the 0 to 15 cm depth for two Meota Association soils (loamy sand to sand of the Black soil zone). Curtin and Wen (1999) reported a mean value of 13 mg N kg⁻¹ for 61 Saskatchewan soils (0 to 15 cm) and Selles et al. (1999) reported a mean value of 11.7 mg N kg⁻¹ for soils in the Brown soil zone (0 to 15 cm).

The reason for these differences in hot KCl extractable N between studies again likely relates to the soil N pools that hot KCl accesses. Hot KCl extractable N includes N extracted both from an organic N pool; i.e., organic N hydrolysable, and from the inorganic N pool (Curtin and Wen, 1999; Gianello and Bremner, 1986a). The organic N pool represented by organic N hydrolysable, is highly labile and sensitive to management practices (Janzen et al., 1992); therefore, fields with different management histories in different soil zones would be expected to differ in terms of organic N hydrolysable. Inorganic N values have been known to have an impact on the hot KCl extractable N values by their inclusion (Gianello and Bremner, 1986a), although the degree or value of this impact has been contested (Jalil et al., 1996; Campbell et al., 1997; Schoenau, 1998).

Spring inorganic N values at Hepburn were not unusual for a soil in the Black soil zone with a mean value of 20 kg ha⁻¹, equivalent to 9 mg kg⁻¹, in the top 15 cm (Table 4.7). For example, this compares to reported values of 6.5 and 7.8 mg kg⁻¹ for similar soils (Jalil et al., 1996). The landscape distribution of spring inorganic N (Fig.

4.11) was such that the landscape units could not be clearly defined as they were for organic N hydrolysable, spring soil moisture, and total soil C. Specifically, LSH positions were not statistically distinct from foot-slope positions and HSH positions were not distinct from LSH positions in terms of spring inorganic N.

These observations are similar to the findings of Popoff and Anderson (1991) who reported a similar pattern for samples taken along a catena. In their study, inorganic N (NO_3^-) was considered low in foot-slope positions as compared to shoulder positions, likely due to leaching of mobile NO_3^- - N deeper into the profile. This is also in agreement with Solohub et al. (1996) who did not detect a significant difference between landscape positions for mineral N on a till landscape in the Black soil zone of Saskatchewan. It is apparent that the distribution of spring inorganic N either is not controlled by landscape at all or alternatively, the degree of control is far less than that of other soil properties. This is underscored by the lack of correlation between spring inorganic N and other measures of N availability for the Hepburn site (Tables 4.12 to 4.14). For example, to a depth of 15 cm, there was no detectable correlation between 16 wk cumulative N and spring inorganic N (Table 4.12). Because hot KCl extractable N includes the contribution of inorganic N present in the soil at the time of sampling, a significant correlation was detected between these two estimates of N availability. However, upon removal of the inorganic N (which occurs in the calculation of organic N hydrolysable) there was no detectable correlation between inorganic N and organic N hydrolysable. Interestingly, the correlation between inorganic N and N supply rate, measured using the ion exchange membrane; i.e., $\text{PRS}^{\text{TM}} - \text{N}$, was also close to zero and non-significant even though the ion exchange membrane also measure inorganic N

present at time of sampling. It is likely that the contribution of inorganic N at the time of sampling was overwhelmed by the N released during the incubation of the soil in which the ion exchange membrane was inserted.

As a result of the influence of the random distribution of spring inorganic N the landscape distribution of hot KCl extractable N (Fig. 4.9), which includes the contribution of spring inorganic N, appears to have similarities to the patterns exhibited both total soil N (Fig. 4.2) and spring soil moisture content (Fig. 4.5). The geostatistical range for hot KCl extractable N was not clearly over 40 m as is was for the latter soil properties (Table 4.7). When spring soil inorganic N values are subtracted from hot KCl extractable N values, in the calculation of organic N hydrolysable, a significant change in the landscape distribution of organic N hydrolysable was detected.

The spatial distribution of organic N hydrolysable was different from that of hot KCl extractable N in that the shoulder positions were significantly distinct from the foot-slope positions (Fig. 4.10) and that the highest values of organic N hydrolysable were found in the topographically lowest positions. This was also the same pattern observed with spring soil moisture content. The geostatistical range for organic N hydrolysable exceeded 40 m in all depth increments except that for the 30 to 60 cm increment. Thus, by removing the contribution of inorganic N, the organic N hydrolysable estimate of N availability appears to be more similar in terms of its distribution to spring soil moisture content.

Curtin and Wen (1999) suggested that crop residues break down to a LF organic matter which in turn is converted to microbial metabolites and water soluble organic N, both of which are extracted by hot KCl and represented by determining organic N hydrolysable. In a variable landscape, such as the Hepburn site, it has been shown that

greater crop yields; i.e., greater organic matter production, occurs in the convergent areas of the landscape, due primarily to the ability of these lower areas to capture and retain moisture as opposed to divergent areas (Mc Conkey et al., 1997; Solohub et al., 1999). Hence with greater crop production in depressional areas and, in turn, greater crop residues, the values of organic N hydrolysable typically were higher than other positions in the landscape. Thus, organic N hydrolysable shared a landscape pattern similar to spring soil moisture content.

The above discussion also provides an explanation for the landscape distribution of N supply rate as measured by the 2 wk insertion of the PRS™. The ion exchange membranes will adsorb mineral N that is present in the soil at time of insertion and mineral N produced by mineralization over the 2 wk period of the incubation. The organic N pool which mineralizes first during that 2 wk incubation is the highly labile pool which has been described as that accessed by hot KCl extractable N and whose distribution is expressed by organic N hydrolysable. In fact, Curtin and Wen (1999) found hot KCl extractable N to be closely related to N mineralized during the first 2 wks of incubation and not as closely related to N mineralized over the entire 24 wks of the incubation. Because PRS™ - N is influenced by spring inorganic N in the same way that the values for hot KCl extractable N are, it is not surprising that the landscape distribution of PRS™ - N is similar to that of hot KCl - N. If a 1 h incubation had been performed using the ion exchange membranes, one could have corrected for the contribution of inorganic N and likely would have seen a distribution pattern for PRS™ - N very similar to that of organic N hydrolysable.

It was assumed that the amount of crop residues increased at the Hepburn site from higher to lower topographic positions due to increased water availability. Other researchers have observed this landscape pattern in the quantity of crop residues (McConkey et al., 1997; Solohub et al., 1999). Although not measured directly, it is likely that the quantity of residues returned to the soil reflected the distribution of grain yields.

Grain yield from both the fertilized and unfertilized strips increased from LSH through to HFS positions (Fig. 4.14 and 4.15). This was also the pattern for N uptake in both the fertilized and unfertilized strips (Fig. 4.16 and 4.17). Statistically, both shoulder positions were distinct from both foot-slope positions for grain yield (Fig. 4.14 and 4.15) and had a landscape pattern similar to that of spring soil moisture (Fig. 4.5) and organic N hydrolysable (Fig. 4.10). Based on studies such as Sinai et al. (1981), McConkey et al. (1997) and Solohub et al. (1999), higher grain yields and N uptake can be attributed to greater water availability in foot-slope positions. Campbell et al. (1997) maintains that soil moisture and available N at time of seeding and the N subsequently mineralized are the dominant factors in crop yield. Based on the results at the Hepburn site increased yields in the foot-slope positions can be attributed to both spring soil moisture and to the N made available through mineralization of the labile organic N fraction expressed by organic N hydrolysable. A linear regression was performed to look at the contribution of these two factors in explaining variability in unfertilized grain yield. The result ($r = 0.583$; $P = 0.05$) is an improvement upon the r_s values obtained for each of these factors alone (Table 4.10); however, the results strongly suggest that there were other factors involved in explaining unfertilized grain yield that have not been identified in this study.

Although Campbell et al. (1997) suggested that N mineralized subsequent to seeding is one of the dominant factors affecting yield, yield parameters at Hepburn were more closely correlated to the N mineralized during the first 2 wks of incubating soil samples than the total amount of N produced during the entire 16 wk incubation (Fig. 4.19). This is in keeping with the findings of Curtin and Wen (1999) who found hot KCl extractable N to be poorly correlated with N mineralized over the duration of their 24 wk incubation in comparison with the N produced in the first 2 wks of the incubation. They suggested that the highly labile pool of water soluble organic N associated with that extracted by the hot KCl extractable N is the first to mineralize. This labile pool of N, which mineralizes first, is likely to be a significant portion of the first N available to the crop. Figure 4.19 indicates that this is likely the case because the N uptake in the unfertilized strip was best correlated with the N produced during the first 2 wks of the incubation as opposed to the N produced over the duration of the incubation. Finally, Fig. 4.20 reinforces the above assertions by indicating that total soil N is best correlated with the N produced over the entire course of the incubation, which should be expected if long term incubation represents the larger, general pool of organic N rather than the smaller pool of organic N represented by hot KCl extractable N and organic N hydrolysable.

The geostatistical range for wheat grain yield was approximately 40 m in both the fertilized and unfertilized strips (Table 4.8), which was in keeping with the ranges for the soil properties with the same landscape distribution; i.e., spring soil moisture (Table 4.3), organic N hydrolysable (Table 4.6) and total soil C (Table 4.2). The range for N uptake in both the fertilized and unfertilized strips (Table 4.8) was less than this, particularly in the unfertilized strip where the range was under 20 m. One possible

explanation for this may be in the timing of the removal of the yield samples. The period during which seeding occurred (Table 4.4) was very dry in terms of total precipitation. As a consequence, germination and seedling emergence was poor. In June, when greater amounts of precipitation occurred, a second flush of wheat seedlings emerged. Upon harvest in September, the crop was composed of wheat plants which were very mature mixed with some immature plants that conceivably were still translocating N. The greener plants made up a significant portion of the crop and may have influenced the distribution of N uptake.

Correlation between measures of soil N availability and grain yield support the indications presented by the landscape distribution and geostatistical range of these variables (Tables 4.9 to 4.11). Spring inorganic N shows no relationship to yield whatsoever with all correlations non-significant. Organic N hydrolysable, on the other hand, was the most closely correlated measure of soil N availability to yield. Schoenau (1998) found that hot KCl extractable N was the most successful in explaining variability in yield and attributed this to the ability of hot KCl extractable N to access a pool of N which is used by the crop early in the growing season when the N supply is the most important to setting the maximum yield potential.

Although the correlations between yield parameters and measures of soil N availability were highly significant in many cases, the correlations themselves were relatively low. There are several possible reasons for this. The dry growing conditions for the spring of 1998 previously discussed may have had an influence by minimizing yield differences between landscape positions. Thick et al. (1993) noted that results linking N availability to yield may only be valid for that particular year as growth conditions change from year to year. Relatively low values for the correlation may also

be due to the sampling strategy used at Hepburn as compared to other studies. Jalil et al. (1996) or Curtin and Wen (1999) used soils from several geographic locations whereas soils used in the Hepburn study came from several locations within a single field. One might expect that soils taken from within the same field would share more similarities in terms of soil properties than soils sampled from geographically distinct regions.

However, the C.V.'s associated with the soil properties at the Hepburn field site do not indicate any less variability than that of the other studies. A third possibility is in the treatment of the data itself. Stronger correlations would be obtainable with the data from the Hepburn field plot if the data was smoothed by removing outliers and extremes or grouping the data according to topography and using the means from these groupings.

However, it was decided to use the entire data set in these correlations to include the inherent soil variability and maintain the true influence of the soil properties tested.

Allowing the inherent soil variability to express itself allows the influence of all factors relating to yield and mineralization to be reflected, no matter how significant or insignificant.

Taking the previous discussion into consideration, the results of the Hepburn study suggest that organic N hydrolysable, hot KCl extractable N and PRSTM – N, as a means of testing the N availability of a soil, provided good estimates of soil N availability that appear to correlate with final grain yield and grain N uptake of wheat. Other methods of assessing potentially available N, including a biological incubation, also correlated with grain yield although these correlations were not as strong. Moreover, long term incubations are cumbersome to perform and from a commercial soil testing perspective, likely too expensive to perform. Curtin and Wen (1999) also

reported that hot KCl extractable N was an appropriate method for establishing soil N availability because it extracted from a highly labile organic N source. In contrast, the results collected from the Hepburn site strongly indicate that spring inorganic N was not a suitable estimate of soil N availability. These results are in agreement with Solohub et al. (1999) who similarly failed to detect a correlation between spring inorganic N and grain yields.

6.0 SUMMARY AND CONCLUSIONS

This research study examined several methods by which soil N availability is measured and assessed each of these methods in terms of grain yield. This assessment also examined the spatial distribution of soil N availability within a variable landscape as measured by each one of the selected methods and the spatial distribution of related soil properties. The purpose was to identify which one of the selected methods of measuring soil N availability was the most suitable for relating a soil N test to yield along a transect in a commercial field, such as would be done for a fertilizer recommendation. Studying these relationships on a spatial basis may allow these results to be applied to precision farming methods.

The field plot consisted of a single sample transect of 100 locations spaced at 3 m intervals from which soil and grain yield samples were collected. The experiment was designed to examine the relationship between various estimates of soil N availability and topographic position. Data were examined using non-parametric statistics as related to the landform element classification, and geostatistics.

The soil N availability was assessed using both biological and chemical assays. The biological assays were conducted by determining the N mineralized (termed “cumulative N”) over a long term, i.e., 16 wk, aerobic incubation. A second biological assay consisted of using ion exchange membranes, in the form of the Plant Root Simulator (PRS™) to collect N mineralized over a 2 wk period. Chemical assays of the soil N availability included hot KCl extractable N, spring inorganic N, and organic N

hydrolysable (inorganic N subtracted from the value for hot KCl extractable N).

Additional soil properties measured included total soil N, total soil C, soil organic C, and spring soil moisture. Wheat yield measurements were obtained at each sample location from seeded strips that ran on either side of the transect for its entire length.

The interpretation of the data collected indicated a firm relationship between soil N availability and topography, assessed by both by landform element classification and geostatistics. Most of the methods used to estimate soil N availability demonstrated that soil N availability generally increased from upper to lower slope landscape positions. The sole exception to this was inorganic N which did not display a predictable pattern that could be associated with topography. The relationship between soil N availability and topography was best shown by organic N hydrolysable, which indicated that all the lower slope landscape positions tested were significantly higher in soil N availability than all upper slope landscape positions tested. Interestingly, the geostatistical range for organic N hydrolysable and spring soil moisture, a soil property known to be strictly controlled by landscape, were very similar; i.e., 40 to 50 m. This was not the case for the other N testing methods.

Not all assays provided similar estimates of soil N availability. For example, using long term aerobic incubation as a means of testing soil N availability suggested that lower landscape positions and some upper landscape positions were not significantly different in their ability to supply N. This also can be said of N supply as measured by PRSTM and hot KCl without a correction for inorganic N. The distribution of inorganic N, along the transect clearly was not directly related to landform.

These results suggest that these different assays may be accessing different pools of potentially available N. For example, the long-term aerobic incubation appeared to exploit the general N pool, which likely included both fast and slowly mineralizable organic matter, whereas organic N hydrolysable appeared to represent a rapidly mineralizing pool of organic N. This distinction was made because total soil N, which can be seen as representing the overall soil N pool was more closely correlated to N mineralized over the entire duration of the incubation than to N mineralized in the first 2 wks of the incubation. Moreover, the N mineralized over the first 2 wks of the incubation; i.e., the rapidly mineralizing pool of organic N, was most closely correlated to organic N hydrolysable. This rapidly mineralizing pool of organic N appeared to be controlled more by the impact of landscape on water redistribution and the resulting inputs of recent crop residues, whereas the overall organic N pool is the result of thousands of years of soil formation.

The distribution of crop yield across the landscape appeared to be strongly controlled by topography. Each of the soil N testing methods, with the exception of inorganic N, showed to some degree a positive correlation with crop yield. However, the best correlation between soil N testing methods and crop yield was with organic N hydrolysable suggesting that the source of N most closely related to crop yield was that from the rapidly mineralizable pool of N. Crop yield was better correlated with N mineralized over a 2 wk period than N mineralized over a 16 wk incubation. Soil inorganic N showed no relationship with the crop yields obtained.

The ability of the soil to mineralize N, overall, can be characterized by a long-term incubation. Although biological assays of N availability are often assumed to provide the most accurate assessment of potentially available N, this relationship was

not observed in the present study. Moreover, it is likely that the available N that appeared to be of most importance to the crop was drawn from a particular portion of this total soil N pool and this particular portion was not properly characterized using the long term incubation assay because the highest demand for N by a crop occurs early in the growing season, therefore, the N which mineralizes first and is available at this time appears to be most important to crop yield. Apparently organic N hydrolysable best characterized this available N of all the soil N testing methods used.

Geostatistically, the semi-variograms provided further evidence of a relationship between organic N hydrolysable and crop yield. The properties with the highest ranges are those which had the strongest relation to landform. These ranges typically were similar to the scale of the landscape. Those soil properties, which had the shortest ranges, also appeared to have weaker relationships with landform, demonstrating that landform was not the only influence in their distribution.

Although the geostatistics were supportive, the results of the geostatistical analysis were not instrumental to the conclusions of the study. Geostatistics provided a means of assessing the relationship between N testing methods and crop yield, without having to observe the physical features of the field plot; however, the physical features of the field plot were readily discernable and divisible into management units; i.e., landform element complexes, which provided an equally valid means of comparing assays of soil N availability to crop yield.

In conclusion, it is recommended that the results of long-term incubations be interpreted with caution. Ion exchange membranes, such as the PRS™ would be the preferred biological method to test soil N availability. In addition, inorganic N is an

inappropriate test of soil N availability. Hot KCl extractable N should be corrected for inorganic N; i.e., organic N hydrolysable, to protect against the influences of inorganic N. Since organic N hydrolysable shows much promise as a test of soil N availability as related to crop yield, further research should be undertaken with the goal of replacing inorganic N test commonly used for the purposes of fertilizer recommendations.

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