University of Alberta

Leaching potential variability within a
hummocky agricultural landscape in Central Alberta, Canada

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Abstract

Intensive agricultural practices can result in contaminated groundwater via leaching, and groundwater quality has become a major issue for rural communities in Alberta. This research project examined the long and short-term spatial and temporal variability of leaching processes within two hummocky agricultural landscapes in Central Alberta, Canada. Analysing the distribution of soil profiles within a landscape, we created a leaching potential index based on a soil profile index and plan curvature measurements. We assessed the accuracy of the index using the redistribution of bromide after a snowmelt event, and a growing season. The index accurately differentiated locations of high leaching potential from low and very low leaching potential. This index will become a useful tool to determine the variability of leaching within agricultural landscapes to identify areas of high leaching potential, to determine agricultural best management practices, and to reduce or to maintain contamination of groundwater at an acceptable level.

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1.1 Introduction

Over the last few years, the province of Alberta has experienced significant economic development based on the agricultural and petroleum industries. In addition, Alberta's population growth rate increases every year, reaching 1.9 % in 2002 (Statistics Canada, 2005). Intensification of economic sectors and population increases create pressure on the quantity and the quality of water supplies.

The economy of Alberta is directly dependent on the quality and quantity of groundwater, and Natural Resources Canada qualifies this water resource as vital for the Canadian economy and ecosystems. In Alberta, currently 80-90 % of the rural population relies on groundwater for their domestic water supply and farming activities (Alberta Government, 2002a). Groundwater is the dominant source of water for livestock, and it provides significant water supplies for the mining and petroleum industries. The significant pressure on the water resources is a concern for the government and groundwater quality has become an important issue.

In 1995, the Alberta government, in collaboration with the Canadian government, started an intense groundwater quality survey in rural Alberta, under the Canada-Alberta Environmentally Sustainable Agriculture (CAESA) Agreement (Alberta Government, 2002b). The survey provided evidence of the high groundwater contamination risks associated with intense agricultural management. Protection of groundwater quality has become a priority, and the Government of Alberta is committed in the Water For Life strategy to the wise management of Alberta's water quality and quantity for the benefit of Albertans now and in the future (Alberta Government, 2002c).

Characterization and understanding of local flow systems within agricultural landscapes are the keys to developing sustainable landscape management strategies to improve agricultural practices and minimize groundwater contamination. Agro-chemicals that are applied within agricultural landscapes move first through local flow systems. Depending on the specific conditions of the site, the agro-chemicals can reach the groundwater and move through the intermediate or regional flow systems. Once the agro-chemicals are in the groundwater flow system, they can be transported over great distances and chances are increased that these agro-chemicals reach domestic wells, farm wells, rivers, and lakes.

1.2. Literature Review

1.2.1 Spatial and temporal variation of leaching

Leaching consists of the mobilization and translocation of materials within an entire soil profile (Buol et al., 1989). Percolation or eluviation consists of the translocation of material within a section of a soil profile. Eluviation can also be considered as partial leaching; therefore, in this document, the term leaching also refers to percolation. The intensity of leaching is measured according to the concentration of solute in the soil water (mobilization) at certain depths of a soil profile (translocation) (Diggle and Bowden, 1990; Gerakis and Ritchie, 1998; Malterre et al., 1998). Therefore, the relative intensity of leaching refers to the comparison of the mobilization and translocation of solutes among locations, and leaching potential refers to the comparison among locations of their inherent capacity for leaching.

Infiltration of water is the initial step of leaching. In the western prairies, evapotranspiration is often higher than precipitation during summer, and the main events of water input generally occur during snowmelt, while the soil is still frozen or partially frozen, and during summer storm precipitation. During these events, water is distributed within the landscape, such that some areas accumulate water while other areas dissipate water. Therefore, leaching intensity can vary locally.

The variability of infiltration within an agricultural hummocky landscape creates a wide range of leaching potentials on a local scale. For example, the reduced infiltration capacity of frozen soils causes snowmelt water to run off hillslopes and accumulate in depressions, wetlands and ephemeral ponds, where it infiltrates and evaporates at variable rates. In early spring, it is common to see accumulation of water in low areas within agricultural, hummocky landscapes. In a study in Saskatchewan, Hayashi et al. (1998a) estimated that 30 to 60 % of the water accumulated in a wetland comes from snowmelt run-off, and that approximately 75 % of the water accumulated in ephemeral ponds leaves by infiltration. A three year study in Saskatchewan by Hayashi et al. (2003) estimated the infiltration rate in ephemeral ponds to be 0.6 to 0.8 mm/h under frozen soil conditions and 3 to 6 mm/h under unfrozen soil conditions. Thus, there is variability of the rate of infiltration and leaching among ephemeral ponds formed within hummocky landscapes.

Within a short time period, leaching is spatially variable over a large scale across landscapes, a small scale within a landscape, and a micro-scale within soil pore systems (Phillips, 1994). Studies have shown that leaching and water movement are highly variable within a landscape, from depressional areas to the surrounding uplands (Zebarth and De Jong, 1989). In a hummocky landscape, Zebarth and de Jong (1989) reported groundwater movement from 10^{-8} m/s in the depression to 10^{-10} m/s in the upland. These authors also mentioned important spatial variability in the direction of the water movement at a local scale, such as from vertical to lateral movement, and spatial variability of leaching at a micro-scale, such as matrix flow to preferential or by-pass flow.

The intensity of leaching processes is variable over time, and the estimation of leaching depends on the time interval between the moment when solute and water were added to the soil and soil sampling (Russo et al., 2003). Zebarth and de Jong (1989) reported changes in the flow direction in depressional areas within hummocky landscapes over time. A significant quantity of water that infiltrated the soil during the snowmelt can move laterally during the growing season in response to evapotranspiration. Hayashi et al. (1998a) estimated that only 1 % of the annual precipitation reaches the aquifer underlying ephemeral ponds and wetlands in western prairies.

The spatial and temporal variability of leaching from wetlands to surrounding uplands has been demonstrated in many studies (Hayashi et al., 1998a; Parsons et al., 2004; Zebarth and De Jong, 1989), but very little research has been conducted to quantify variation of leaching on a small scale, over agricultural hummocky landscapes. The next sections look at two different experimental approaches to investigate the spatial and temporal variability of leaching within a hummocky landscape: (1) according to hydropedology, and (2) according to water tracers.

1.2.2. Hydropedology

The combination of soil science and hydrology is referred to as hydropedology (Lin et al., 2005). Hydropedology is based on the principle that "the interactions of soil and water are so intimate and complex that they cannot be studied in a piecemeal manner, but rather as a system across spatial and temporal scales" (Lin et al., 2005). These authors discussed fundamental issues of hydropedology such as soil horizons as indicators of leaching, and soil profile development as a signature of hydrology.

Differences in soil properties among landscape elements can be largely explained by differences in water movement and distribution of water within hillslope systems (Hayashi et al., 1998a; Manning et al., 2001; Pennock and Bedard-Haughn, 2002; Pennock et al., 1987; Zebarth and De Jong, 1989).

Zebarth and de Jong (1989) related the variation in thickness of soil A horizons, thickness of soil eluviated horizons, and depth to carbonate to the variation in hydrological processes within a hillslope in a hummocky agricultural landscape. Bell et al. (1992) predicted the location of the regional soil recharge based on parent material factors and a variety of topographical data. Quisenberry et al. (1993) found a link between water and solute transport, and soil structure, texture and clay mineralogy, while Olson and Cassel (1999) found a relationship between potential leaching depth and clay content profile, as well as a correlation between leaching depths and soil water content profiles within a Piedmont toposequence. Manning et al. (2001) showed that soil pH was reduced in strongly leached surface horizons because of the downward movement of the basic ions. Richardson and Vepraskas (2001) indicated that the study of hydric soil morphology and genesis can impart important information about the nature of wetland hydrology. Lin et al. (2005) mentioned that soil formation processes such as leaching are a major driving force behind pedogenesis, soil morphology, and soil distribution.

Studies have investigated the accuracy of spatial distribution of soil horizon and profile development to indicate the spatial variability of leaching. Miller et al. (1985) demonstrated that it is possible to predict hydrological characteristics of a soil from its landscape position, morphology, and classification. Lin et al. (1999b) showed that the horizon texture had a major impact in soil matrix hydraulic properties; while Reuter et al. (2003) mentioned that the thickness and colour of surface horizons are strong indicators of landscape hydrology within a hillslope in Southern Minnesota. Finally, Lin et al. (2005) reported that soil morphology reflects profile hydrology, and is an indication of long-term persistent flow and leaching.

Numerical analysis

Multivariate structural analysis such as clustering, ordination, discriminant analysis, and canonical correlation have been used for many years by ecologists to study distribution patterns of various landscape elements (Legendre and Legendre, 1983). Spatial distribution patterns are the basis of landscape analysis. Once the patterns are understood, it is possible to focus on the elements that determined these patterns (Jongman et al., 1995). Ecologists have developed a multitude of statistical analyses, to discover spatial patterns within landscapes. Numerical analysis represents a wide group of statistical analysis that provides the basis for landscape modelling (Legendre and Legendre, 1983).

Pennock et al. (1987) looked at the variation of soil distribution within a hummocky landscape with multivariate regression and structural statistical analysis. The results of the multivariate regression analysis illustrated the limitation of this type of analysis to describe soil profile properties within a complex landscape such as hummocky terrain. However, the multivariate structural statistical analysis, a canonical discriminant analysis in this case, was able to distinguish soil profiles among groups within hummocky agricultural landscapes. Florinsky et al. (2002) showed the limitation of regression-based prediction of the spatial distribution of soil properties within a hummocky landscape.

Cluster analysis is a numerical analysis that is used to group or cluster elements to minimize the within-group variability and to maximize the among-group variability, and simultaneously to perceive separation or distinctions among clusters (Legendre and Legendre, 1983). Relatively new for soil science purposes, cluster analysis has been used to refine soil classification systems (Arkley, 1976; Young and Hammer, 2000). Arkley (1976) mentioned that soil clustering is very effective for a small number of soil groups (small scale study), but is hardly applicable when many different soil groups are present (regional scale study). He suggested that a coordinate system based upon cluster analysis is the most promising technique to produce an effective numerical soil classification.

Generally, datasets for cluster analysis contain sites in columns and site characteristics in rows (Arkley, 1976; Jongman et al., 1995; Legendre and Legendre, 1983). The characteristics have to be chosen according to the purpose of the clustering, which is, in this case, to highlight the distribution pattern of soil profile layering and development. An analogy with ecological studies that look at the distribution of species and their abundance on a landscape can be made for soil profile development, as a soil horizon can be considered as a species and the depth of the horizon can be considered as the abundance of the species (Fuller, 2002). In this case, the characteristics that will determine the clustering will be the type of horizon present in the soil profile, as measured by the depth of each horizon.

There are several options in cluster analysis such as distance coefficient, and sorting strategy (Arkley, 1976; Jongman et al., 1995). Arkley (1976) reported that the Euclidean distance is most appropriate to measure similarity or difference among clusters related to soil science. He also reported that the farthest neighbour or complete linkage clustering was an effective sorting strategy to distinguish among the soil distribution clusters. A common way to present the results of sorting procedures is with a two-dimensional dendrogram, where the length of the branches is proportional to the degree of dissimilarity.

An important use of the cluster analysis is to do an external analysis, which is to detect relations between communities and environment by analysis of the groups formed by the cluster analysis with respect to the environmental variables (Jongman et al., 1995). Tests of significance such as analysis of variance (ANOVA) can be performed on clusters to determine whether any environmental variables might control or mimic the distribution pattern of the landscape elements (Jongman et al., 1995). Accessible environmental or soil-landscape factors such as relief and soil classification that are related to the soil horizon distribution pattern provide effective information for land use and land management.

Relief

Soil forming processes such as leaching are under the influence of soil forming factors such as climate, parent material, time, vegetation, climate, and relief (Jenny, 1941). A various combinations of soil forming factors result in various combinations of soil forming processes, and therefore various sequences of soil horizons over a landscape (Bockheim and Gennadiyev, 2000). Considering an agricultural landscape where similar parent materials are under alteration for an equal period of time, and where the climate and the vegetation are consistent across the landscape, relief becomes the main soil forming factor that influences the distribution of the soil forming processes.

Typical post-glacial northwest prairie landscapes are undulating, gentle rolling, and hummocky, which represent a regular sequence of gentle slopes, a very regular sequence of moderate slopes, and very complex sequence of slopes, respectively (Soil Classification Working Group, 1998). Landscape relief has been described using an association of topographic features. Generally, elevation in meters, slope gradient in degrees (maximum rate of change in elevation within a digital elevation model grid cell), slope aspect in degrees (azimuthal bearing of the gradient), plan curvature in degrees / m (rate of change of aspect along a contour line), and profile curvature in degrees / m (rate of change of gradient) are used to classify relief (Florinsky et al., 2002; MacMillan and Pettapiece, 2000; MacMillan et al., 2000; Pennock et al., 1987).

Relief has an important impact on the redistribution of precipitation and infiltration, and influences landscape pedology, as well as landscape hydrology. Robust new tools for describing and segmenting landscape into landscape elements based on remote sensing data and digital elevation models (DEMs) have been developed in Alberta (MacMillan and Pettapiece, 2000). Combining analyses of DEMs and remotely sensed data from landscape and soil investigation lead to advanced studies of landscape and topography (Florinsky, 1998). Topographic features have been used in models to describe and predict the distribution of soil properties and watershed hydrology for a wide range of purposes such as nutrient management and solute movement. Florinsky (1998) mentioned the potential application of this technology in the prediction of the migration and accumulation zone of water and solutes. Pennock et al. (1987) used a landform classification based on topographic data to describe the distribution of soil within hummocky landscapes. Burrough et al. (1992) used a fuzzy method to predict soil property variability and surface drainage networks based on a DEM. MacMillan and Pettapiece (2000) developed a landform classification based on a DEM that includes fuzzy method estimates of landscape hydrology within hummocky landscapes. Manning et al. (2001) showed that certain soil properties such as depth of carbonates, A horizon thickness, and solum thickness are predictable from topographic features. They also found landform classifications based on a DEM useful to predict gross variability in soil properties within hummocky landscapes, but which may not present sufficient precision for a local scale study. These authors concluded that topographic features alone are not sufficient to model the occurrence of any given soil profile attribute or hydrological process. Florinsky et al. (2002) showed that topographic features are related to soil properties for the upper layer of soil, but the relationship weakens with depth. They also indicated that often the scales of these landscape prediction models were broader than the scale at which soil property variability occurred, and that the prediction models were only useful in capturing gross variability in soil hydrology within a field scale.

Soil classification

Processes of soil formation include a complex sequence of events that intimately affect soil development. Soil development can follow two main trends: (1) horizonation, and (2) haploidization (Buol et al., 1989). Horizonation is the result of processes by which parent materials are differentiated into soil profiles with many horizons. Haploidization is the result of processes by which the horizonation is inhibited, delayed, or by which the horizons are mixed or disturbed. While a soil profile is under constant development towards equilibrium, current soil properties and morphology can be explained in terms of the result of previous soil forming processes such as leaching (Manning, 1999).

Buol (1989) reported four fundamental processes of soil formation, including (1) addition of organic and mineral materials, (2) losses of these materials, (3) translocation of these materials, and (4) transformation of these materials. These processes all involve water in some way; therefore, soil is the perfect media to study water movement (Richardson and Vepraskas, 2001). Buol (1989) considered eluviation as a translocation process from an upper to a lower soil horizon, and leaching a process of material losses throughout the entire soil profile; however, the two processes are often referred to as leaching. Melanization, lixiviation, pervection or lessivage, and cheluviation are three main types of leaching. Melanization refers to the movement of organic matter through a soil profile, while lixiviation refers to the movement of soluble salts through a soil profile (Duchafour, 1982). Base cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) are often the first soluble salts to be leached from a soil profile because of their high affinity to water. Movement of base cations from the soil profile, referred to as decarbonation in the case of calcium salts movement, often disperses clay and partially acidifies the soil profile. Lessivage refers to the downward movement of dispersed clay particles in suspension in soil water (Duchafour, 1982). Cheluviation refers to the movement of metallic ions generally associated with strong weathering and specific environmental conditions such as low pH within the soil matrix (Duchafour, 1982). Melanization, lixiviation including decarbonation, lessivage, and cheluviation replace one another as the amount of water infiltrating a soil profile increases (Duchafour, 1982), and the intensity of each process affecting the development of a soil profile is related to the intensity of water movement within the soil profile. High infiltration of water generally creates greater profile development (horizonation); while low infiltration of water generally inhibits profile development (haploidization) (Manning, 1999; Richardson and Vepraskas, 2001).

The American (Soil Survey Division Staff, 1993) and Canadian (Soil Classification Working Group, 1998) soil classification systems are based on specific soil horizon properties to describe and classify soil profiles. In these systems, specific definitions of soil horizons are based on a generalization of properties of soil horizons that are known to be representative of the main soil classes, reflect the soil development process, and indicate the degrees of soil development (Soil Classification Working Group, 1998).

The American and Canadian soil classification systems are well adapted for soil inventory and soil mapping, but may not be ideal to understand and quantify spatial variation in soil forming processes related to leaching. Lin et al. (2005) mentioned that the American Soil Taxonomy System (Soil Survey Division Staff, 1993) does not relate soil to landscape components, does not allow quantification of variability within taxonomic categories and soil map units, does not consider dynamic soil properties, and is viewed as very complex by non-pedologists. A study on the Canadian prairies reported substantial variability in soil profile development within soil series membership (Manning et al., 2001). A study in Germany concluded that soil classification can be associated with some ecological variables, but neither the World Reference Base (WRB, successor of the FAO-UNESCO-ISRIC Revised Legend of the Soil Map of the World) nor the American Soil Taxonomy system (Soil Survey Division Staff, 1993) provide adequate descriptions of pedogenic processes such as leaching within all soil types of a catena (Fiedler et al., 2002).

Numerical soil classification

The increasing use of models and digital data management system requires quantification of soil data, and some soil scientists have been working to find a way to progress from classification to mathematical formulation (Buol et al., 1989).

Soil scientists have used various combinations of soil properties to develop numerical systems of classification. In 1960, Hole and Hironaka introduced the concept of "numerical classification" and developed a soil classification system based on a simple ordination method (Buol et al., 1989). In 1962, Sneath and Sokal developed a computer program to classify soil profiles according to the similarity of the sequence of soil horizons; however, their numerical classification received harsh criticism from the soil community (Buol et al., 1989). Very few such numerical classifications have been developed.

After many years, scientists have used soil properties and soil formation to initiate a numerical soil classification according to soil development and water movement within soil profiles (Quisenberry et al., 1993). These authors developed a soil classification system based on the soil texture of the A horizon, along with soil structure and clay content, to predict solute leaching susceptibility within Piedmont landscapes in North Carolina, U.S.A. Lin et al. (1999a) proposed a numerical classification system based on a quantitative description of texture, structure, soil moisture, macroporosity and root density for characterizing water flow and solute transport within a soil matrix. Thompson and Bell (1996) developed a profile darkness index based on A horizon thickness and colour to indicate wetland hydrology; Reuter and Bell (2003) reported good correlation between this profile darkness index and the hydrologic variability of a wetland basin in south-central Minnesota, U.S.A. Finally, Manning (1999) developed a profile development index (PDI) based on the B horizon soil forming processes and thickness to successfully assess variations in pedologic characters within a hummocky landscape.

Scientists have been working on various ways to adapt soil classification systems to predict solute movement and leaching within agricultural landscapes. Utilization of existing soil survey databases and digital terrain model datasets for characterizing solute transport in field soil has practical value in evaluating the leaching potential of an area. However, the lack of a proper means for quantifying soil morphology related to hydrology limits its incorporation into digital models (Lin et al., 1999a).

1.2.3. Water tracers

Non-reactive water tracers can be used to describe the direction and flux of water movement within the subsurface. The concentration profile of environmental tracers such as pedogenic salts is commonly used to estimate the location and the rate of recharge, or leaching that has occurred over many years (Allison et al., 1994; O'Brien et al., 1996), while the concentration profile of new tracers such as stable anions is commonly used to study the infiltration and redistribution of the water within a short period of time.

Tracer profiles have been used as indicators of leaching by many scientists (Beke et al., 1994; Dyck et al., 2003; Ghidey and Alberts, 1999; Hayashi et al., 1998b; Kravchenko et al., 2000; O'Brien et al., 1996; Russo et al., 2003; Salzmann and Richter, 1995; Wang and Anderson, 2000). In areas where leaching occurs, the concentration of a tracer is relatively low in the upper layers of the soil profile.

Studies of non-reactive tracers give precise information on the spatial and temporal variability of leaching on a small scale. However, tracer analyses are time-consuming, expensive, and non-reactive tracer studies may not necessarily be applicable for large-scale studies.

Long-term leaching

The spatial variability of long-term leaching can be investigated with natural tracer profiles, and many studies have demonstrated that it is possible to detect the leaching potential of an area according to concentration of pedogenic salts in a soil profile (Dyck et al., 2003; Ghidey and Alberts, 1999; Hayashi et al., 1998b; O'Brien et al., 1996; Russo et al., 2003; Salzmann and Richter, 1995; Wang and Anderson, 2000). Post-glacial materials on the Canadian prairies are rich in pedogenic salts (Hendry et al., 1986; Van Stempvoort et al., 1994). Dyck (2001) mentioned that sulphate was an excellent tracer to describe the variability of long-term leaching. Indirectly, electrical conductivity (EC) can also indicate the movement of salts within the soil matrix. Kravchenko et al. (2000) and Trianttafilis et al. (2003) estimated the soil drainage risk on a small scale via the electrical conductivity profile with a high level of precision.

The analyses of the concentration of natural tracers in a soil profile improve our understanding of the variability of the local recharge and leaching within agricultural landscapes. However, soil sampling and analysis for sulphate and EC profile description are labour intensive, time consuming, and can be very expensive.

Short-term leaching

Leaching can be investigated by following the movement of an applied tracer through a soil profile (Tyler and Walker, 1994). This type of study gives control to the experiment and allows specific conditions of leaching to be studied according to the type of tracer, the areas of application, the application and sampling schedule, and the selection of the soil condition before and after the application of the tracer.

Applied tracers are useful to follow short-term water movement, as well as to determine the main processes or pathways that drive water movement in the soil. Solutes moving downward into the subsurface can follow two pathways: macroporous (by-pass flow), or meso-microporous (matrix flow). The water moving by by-pass flow transports solutes through only a small proportion of the soil volume at a velocity that greatly exceeds the average in the surrounding matrix (Flury, 1996). Studies of by-pass flow have shown that a fraction of a chemical application can migrate to a substantial depth with only a small amount of water input (Jury et al., 1991). Therefore, solutes transported by by-pass flow are more likely to reach the aquifer over a short period of time. Solutes leached through the soil matrix are likely to be immobilized and accumulate in an illuvial horizon. However, over time, solutes accumulated in the illuviated horizon can be removed and leached to groundwater. Matrix flow occurs at much lower rates than by-pass flow; therefore, the transport of solute by matrix flow to aquifers is expected to take much more time.

Field studies of leaching have often found by-pass flow to be responsible for the migration of an applied tracer below the root zone shortly after the tracer application (Bronwijk et al., 1995; Dyck et al., 2003; Heppell et al., 2000). The combination of the two solute transport processes can cause greater spatial and temporal variability of leaching; thus, the assessment of the transport processes should be investigated considering the spatial and temporal variability of short-term leaching.

Bromide is commonly used as a conservative tracer for studying leaching because of its chemical stability within soil (Bathke et al., 1992; Bronwijk et al., 1995; Bruce et al., 1985; Butter et al., 1989; Olson and Cassel, 1999). On northern prairies, bromide is particularly useful because of its low background concentration (Walton et al., 2000). Bromide tracer can also be applied at any position of the landscape, which is an important characteristic when studying the spatial variability of water movement (Walton et al., 2000).

1.3 Study objectives

The goal of this study was to assess the spatial and temporal variability of leaching within hummocky, agricultural landscapes. In order to meet this goal, we developed four main study objectives.

1. We investigated the relationship between spatial variability of long-term leaching potential and soil profile development. From a soil classification survey, we grouped soil profiles that showed similar leaching potential based on the degree of the soil profile horizonation. Then, we compared the leaching potential attributed to each group of soil profiles to natural tracer profiles indicating leaching intensity via sulphate and electrical conductivity profiles. Assessing the spatial leaching variability within agricultural landscapes was an important step to recognize the intensity of the long-term leaching variation at a local scale. This objective is explored in Chapter 3.

2. Soil-landscape factors, characteristic of the leaching potential groups, were analysed to determine distinctive values that represented each leaching potential group. The results of these analyses were then used to develop a leaching potential index. Leaching potential indices are useful to evaluate the leaching potential of agricultural landscapes and to develop landscape management strategies. This objective is explored in Chapter 3.

3. We investigated the spatial and temporal variability of leaching after one snowmelt event, and one growing season using bromide as a tracer. We analysed the variation in leaching intensity between two distinct landscapes, each representing a type of agricultural landscape management. We also assessed the variation of leaching intensity among three slope positions for three slopes within each landscape. Our objective was to quantify the range

of leaching intensity within agricultural landscapes after various periods of time. This objective is explored in Chapter 4.

4. We tested the accuracy of the leaching potential index to assess the spatial variability of short-term leaching and its consistency over time by comparing it to the leaching intensity as shown by the bromide profiles after one snowmelt event, and after one growing season. Our objective was to evaluate the performance of the leaching potential index to predict leaching intensity within a local scale, and examine its potential as a tool useful for landscape management. This objective is also explored in Chapter 4.

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2. Study site description

To meet the research objectives, the study area was selected according to the following criteria, presented in no particular order of importance:

- Agriculture system representative of Central Alberta
- Hummocky landscape developed on glacial till
- Simple watershed
- Accessibility to the site
- Participation of the owners

2.1 Geography and landscape description

The study site was situated in the Bittern Lake area in Central Alberta (Figure 2.1), Canada, 86 km southeast of Edmonton, on the west shore of Bittern Lake, at a latitude of 53° 4' north and a longitude of 113° 0' west.

The study site was on average 750 m above the sea level. The elevation of the landscape decreased 50 m from the highest (775 m) to the lowest (725 m) point (Government of Canada, 2002b). The study site involved two landscapes: (a) NE 8 landscape located between 750 to 775 m of elevation, about 3.5 km west of the lake, and (b) SE 9 landscape located between 750 to 725 m of elevation, about 1.6 km west of the Lake (Figure 2.2).

The NE 8 landscape was hummocky to gentle rolling, and the SE 9 landscape was rolling to undulating (Bowser et al., 1962) (Figure 2.3). A hummocky landscape is a complex sequence of rounded depressions of various sizes to conical knolls where the surface generally lacks concordance between depressions and knolls, and where the slope inclination varies between 5 to 35°. A rolling landscape is a very regular sequence of moderate slopes producing a wavelike pattern, where the slope length is greater than 1.6 km and the slope gradients are greater than 3^o. An undulating landscape is very similar to a rolling landscape, with the exception that the slope length is generally less than 0.8 km, and the slope gradients are generally 1 to 3^o (Soil Classification Working Group, 1998).

2.2 Climate and hydrology

The climate in the Bittern Lake area is continental, with warm and dry summers followed by long and cold winters (Alberta Government, 2003). The average air temperature measured from 1971 to 2000 at the Camrose Weather Station, situated approximately 15 km east of the study site, was 2.7 °C with an average maximum of 8.4 °C and a average minimum of –3.0 °C (Figure 2.4) (Government of Canada, 2002b). Mean annual precipitation recorded from 1971 to 2000 was 477 mm with 354 mm of rainfall and 123 mm of snow water equivalent (Government of Canada, 2002a). The surface of the soil was usually covered with snow from October to May (Government of Canada, 2002a) (Figure 2.4).

The Bittern Lake watershed covers an area of approximately 425 km^2 (Alberta Government, 1980). Snowmelt and rainfall drain into numerous ephemeral sloughs or ponds before reaching the lake (Bowser et al., 1962). On a regional scale, the Bittern Lake watershed is situated in the Battle River watershed (Figure 2.5). The Battle River runs northeast throughout central Alberta, to discharge into the North Saskatchewan River in Saskatchewan. The Battle River watershed covers approximately 30 000 km^2, and is currently under a Water Management Plan of Alberta Environment (Alberta Government, 2001).

2.3 Vegetation and cropping system

Bittern Lake is located in a transition zone, between the grassland and the boreal zones, called the Parkland area. The study site has been used for annual cereal and oilseed production, perennial forage production, and pasture. The lands situated directly on the shore of the lake are not suitable for agricultural crops because of the high salt concentration accumulated in the soil.

The NE 8 landscape includes a hay field composed of legumes, such as alfalfa (*Medicago sativa L.*) and clover (*Trifolium L.*), and grasses, such as brome (*Bromus L.*), fescue (*Festuca L.*), and ryegrass (*Lolium L.*), during the growing season of 2003 and 2004. On average, hay is cut twice during the growing season. Hay production is semi-permanent, and the field is tilled when the production of hay decreases, approximately every 5 to 10 years. The SE 9 landscape was under canola (*Brassica napus L.*) in 2003 and barley (*Hordeum L.*) in 2004, and the field is under long-term no-till, direct seeding management.

2.4 Geology and soil description

The bedrock material underlying the hummocky moraine (till) of the study site is of the Horseshoe Canyon formation (Alberta Government, 1980). This formation typically contains a mix of sandstone, clay rich mudstone, shale, ironstone beds, and coal and varies in thickness between 12 and 45 m (Alberta Government, 1980). The till left by the last glaciation was primarily enriched in sulphate salt due to oxidation of reduced sulphur (Hendry et al., 1986). The top layer of this glacial till was composed of a compressed mixture of clay, sand, and silt, and contained many pebbles and boulders, lenses of sand, and pockets of gravel.

The soil survey of the study site revealed a variety of soil series according to the morphology of the landscape (Bowser et al., 1962) (Figure 2.6). The tops of the hillslope are generally Orthic Black Chernozems from the Peace Hills soil series, the backs of the hillslope are Eluviated Black Chernozems from the Angus Ridge soil series, and the depressions are Black Solodized Solonetz from the Camrose and Kavanagh soil series (Table 2.1).

Table 2.1 Soil series description (Soil Classification Working Group, 1998)

Soil Series	Horizon	pH	Texture	Structure	Drainage
Angus	Ah	6.6	Loam	Weak coarse prismatic	Well drained
Ridge Loam	Ae	5.6	Loam to fine sandy Clay loam	Weak platy	
	AB	5.6	Clay loam	Medium subangular blocky	
	Bt	5.2	Loam to clay loam	Medium prism. To subangular blocky	
	Ck	7.8		Massive to large subangular blocky	
Camrose	Ah	6	Loam	Weak coarse prism. To granular	Fairly well to well
Loam	Ae	6.6	Loam	Platy	
	Bnt1	7.3	Clay	Strong round topped column. (hard, stained)	
	Bnt2	7.3	Clay loam	Hard columnar to blocky	
	Csk	7.8	Loam to clay	Massive	
	C	7.7	loam	Massive, slightly hard till	
Kavanagh	Ah	5.9	Loam	Loose granular	
	Ae	6.4	Sandy loam	Platy	
	Bnt	6.7	Loam to sandy clay	Flat topped columnar to blocky	
	Csk	7.8	Loam to clay	Massive to coarse blocky	
	C	7.8	Sandy and clayey	Shales	
Wetaskiwin	Ah	5.7	Silty clay	Granular to weak prismatic	
	Ae	5.6	Silty clay loam	Platy	
	Bnt	6.5	Clay	Hard columnar to fine blocky	
	Bntj	7.4	Clay	Massive to coarse blocky	
	Csk	8.1	Silty clay	Massive	
	C	7.9	Silty clay	Massive	
Peace Hills	Ah1	7.2	Sandy loam	Weak coarse prismatic to loose granular	Well to excessively drained
	Ah2	7	Sandy loam	Weak coarse prismatic to weak platy	
	Btj	6.3	Sandy loam	Irregular prism. to prim. Subangular blocky	
	C/Ck	7.7	Loamy sand	Weak coarse prism. To single grain	
	IIC	7.6	Clay loam	Massive to subangular blocky till	
Bittern Clay	Ahj				Well to imperfect
	C				

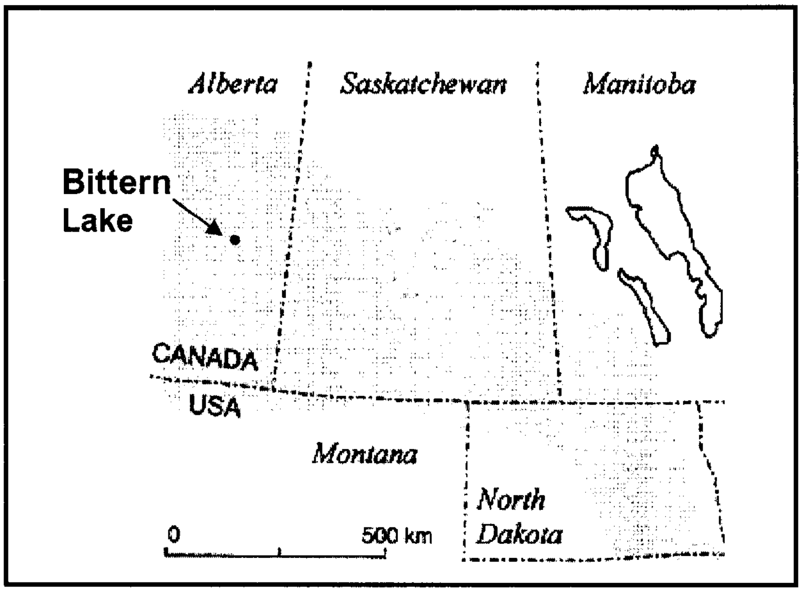


Figure 2.1 Location of Bittern Lake study site; the shaded area represents the northern glaciated prairie region; adapted from Hayashi (2003)

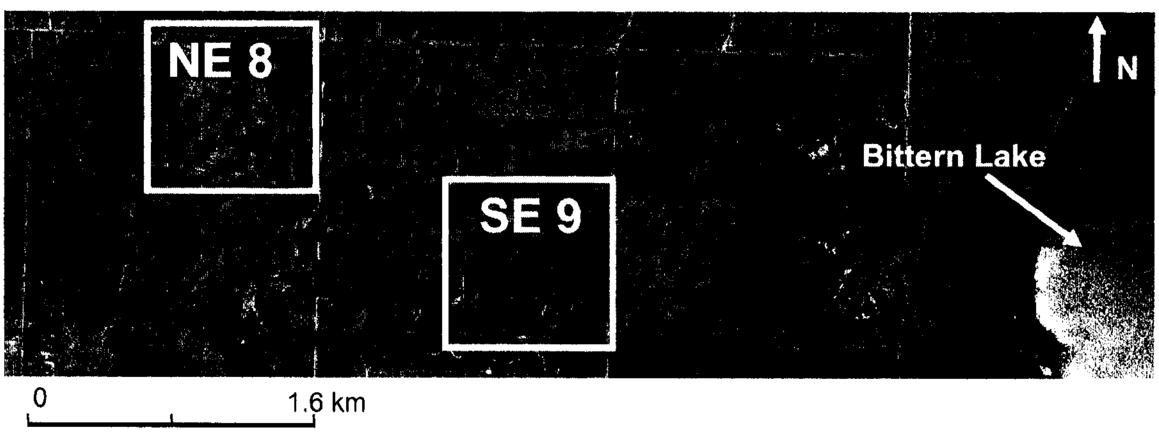


Figure 2.2 The study site at Bittern Lake, Alberta

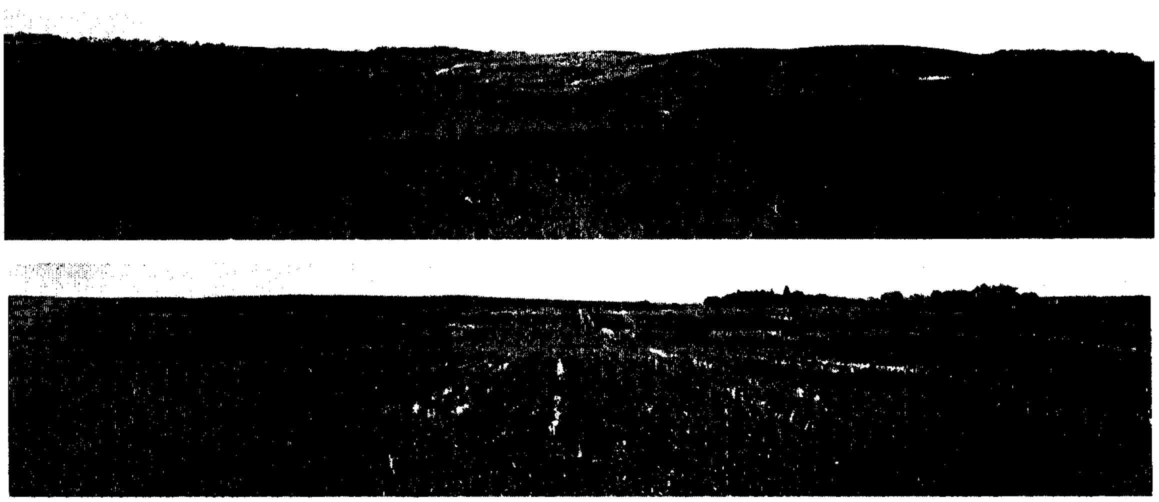


Figure 2.3 Landscape morphology: Top NE 8, Bottom SE 9

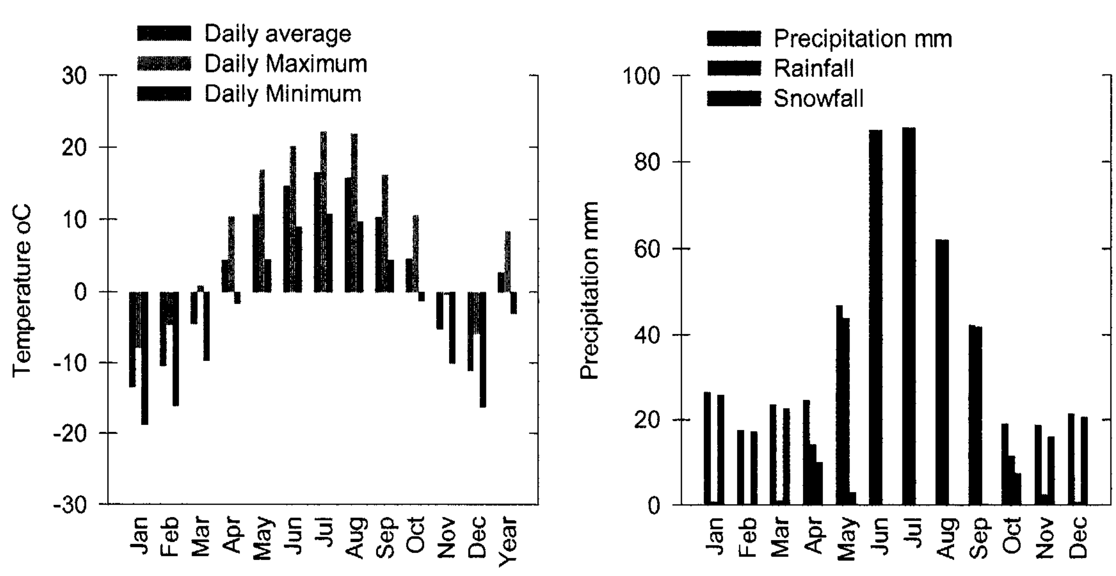


Figure 2.4 Temperature and precipitation average from 1971 to 2000, Camrose Weather Station, Alberta, Canada

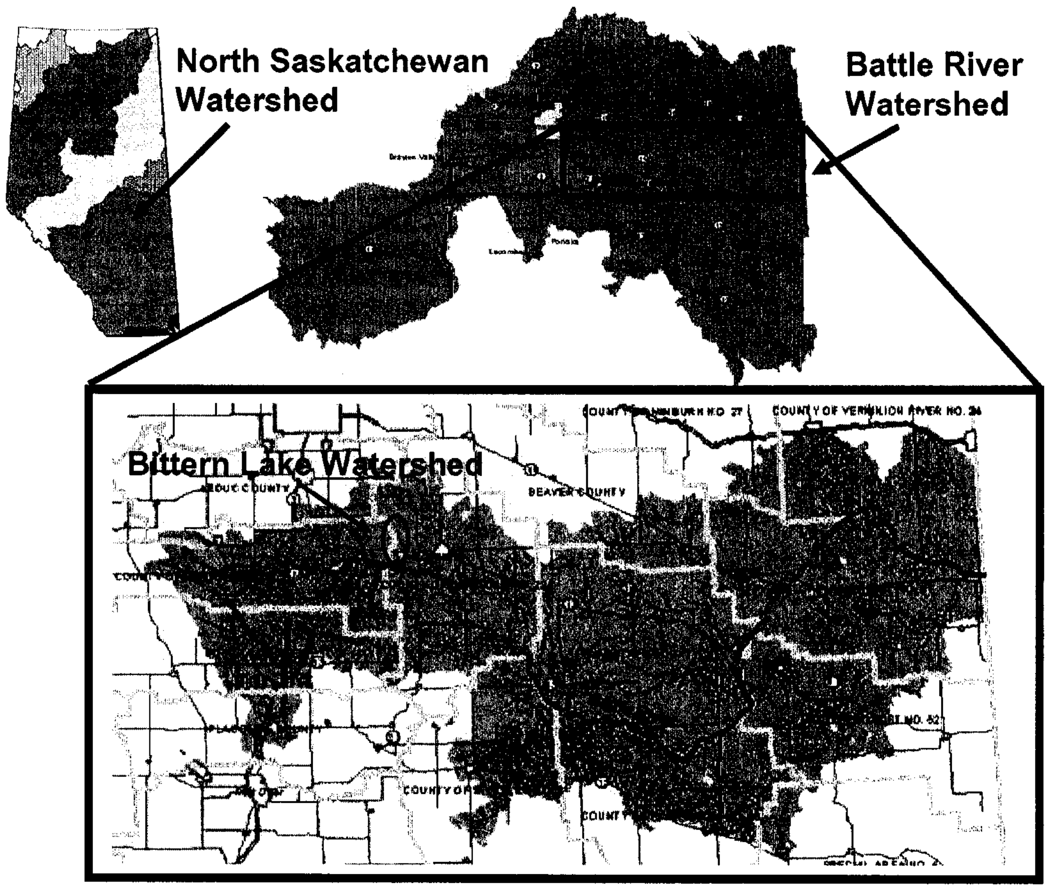
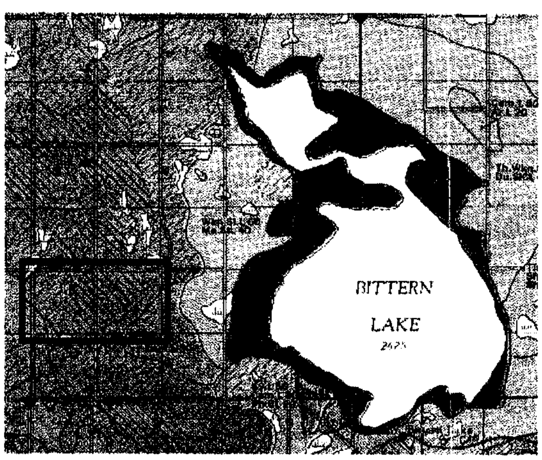


Figure 2.5 Alberta main watersheds, North Saskatchewan watershed, Battle River watershed, and Bittern Lake watershed (http://www.albertawatersheds.org)



Soil Series Legend

- Angus Ridge Loam (80 %); Camrose loam and Kavanagh loam (20 %)
- Wetaskiwin silt to silty clay loam (60%); Malmo silt loam (40%)
- Peace Hills Series
- Bittern Clay
- Marsh

Figure 2.6 Soil classification of the study site according to the Canadian Soil System of Classification, after Soil Classification Working Group (Soil Classification Working Group, 1998).

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3. A classification system to determine long-term leaching potential within a hummocky agricultural landscape

3.1 Introduction

Formation of ephemeral ponds after snowmelt is common in hummocky landscapes on the Canadian prairies. These ponds play an important role in hydrology and ecology (Conly and Van Der Kamp, 2001; Hendry, 1988), and they contribute to groundwater recharge. During a three year study in Saskatchewan, Hayashi et al. (2003) estimated the infiltration rate in ephemeral ponds to be 0.6-0.8 mm/h under frozen soil conditions and 3-6 mm/h under unfrozen soil conditions. The focused infiltration and high leaching potential under the low parts of hummocky landscapes contrasts with the leaching potential from higher elevation, but the spatial variation of long-term leaching within a hummocky landscape is not well documented (Brooks et al., 2003).

The spatial variability of long-term leaching can be investigated with natural tracer profiles such as pedogenic salts, which post-glacial material in the Canadian prairie is rich in (Hendry et al., 1986; Van Stempvoort et al., 1994). Dyck (2001), in a study in Saskatchewan, mentioned that the sulphate concentration within a soil profile is a good tracer to measure the variability of the intensity of long-term leaching. Also, studies have estimated the variability of the intensity of leaching using electrical conductivity (EC) to measure the salt concentrations within a soil profile (Kravchenko et al., 2000; Nissen et al., 2000). However, soil sampling and analysis of sulphate concentration and electrical conductivity (EC) within the soil profile are costly and often not suitable for local-scale study.

The spatial variability of long-term leaching can likely be estimated by considering the spatial variability of the soil profile (Lin et al., 2005), since water movement largely explains the variation among soil profiles (Pennock et al., 1987). Assuming no significant change in the water movement pattern since the deposition of the parent material, the distribution of soil horizons through a landscape represent the long-term leaching potential pattern (Zebarth and De Jong, 1989).

Cluster analysis is a statistical classification procedure that groups elements to minimize the within-group variability and maximize the among-group variability. This analysis allows the discovery of spatial patterns underlying landscapes (Jongman et al., 1995). Relatively new to soil science, cluster analysis has been used to refine soil classification systems (Young and Hammer, 2000). Soil horizon distribution patterns within landscapes may be translated into clusters of long-term leaching potential which may be used as an interesting tool to assess landscape management.

Soil classification systems are useful tools to describe physical and chemical properties of soil horizons, but are not adequate for landscape management purposes. The Canadian System of Soil Classification (Soil Classification Working Group, 1998) gives little information on processes of soil formation. Young and Hammer (2000) mentioned that, at a local scale, the relevance of the family and series classes from the United States Taxonomy system (Soil Survey Division Staff, 1993) to natural distribution is diminished. Increasing use of mathematical models to describe contaminant movement in soil for landscape management purposes increases the need for a numerical soil classification system. Therefore, Quisenberry et al. (1993) developed a soil classification system based on soil texture and structure from soil series in South Carolina, U.S.A., to describe short-term by-pass flow. Manning (1999) introduced a soil profile development index (PDI) providing a relative measure of the degree of soil profile development to assess differences in pedogenic characteristics among landscape elements.

In addition to soil horizons, topographic features play an important role in the spatial variability of leaching within agricultural landscapes. Many studies have looked at topographic features to describe and predict soil properties and water movement within a hummocky landscapes (Conly and Van Der Kamp, 2001; Florinsky et al., 2002; MacMillan and Pettapiece, 2000; Park and Burt, 2002; Pennock et al., 1987). However, the use of these models on a local scale has not been explored.

The local spatial variability of soil horizon distribution, and how soil profile variability can be portioned into small homogenous clusters representing levels of long-term leaching potential, were explored in this study. We also looked at the potential of a soil profile index (SPI), which is a modified version of the PDI (Manning, 1999), and the potential of different topographic features to describe the long-term leaching potential pattern within an agricultural landscape.

The hypotheses were that, at a local scale:

1. The soil horizon distribution pattern represents the spatial variability of long-term leaching potential and coincides with sulphate and EC profiles, and
2. Long-term leaching potential clusters are distinct from each other according to specific soil-landscape factors.

3.2 Methods

This study was based on a survey of the distribution and the development of soil profiles within a hummocky agricultural landscape to analyse the variability of long-term leaching. The data from the survey were grouped according to similar soil profile development. Each group (cluster) was then associated with a level of leaching potential attributed to the degree of soil profile development. Sulphate and electrical conductivity (EC) profiles were used to estimate the leaching intensity of each cluster, and validate the association between the cluster and the level of leaching potential. Finally, we used soil-landscape parameters to describe the variation of leaching potential among clusters.

In this chapter, leaching potential defined the estimation of the intensity of leaching, which in turn defined a direct measure of leaching within the soil matrix as shown by sulphate and EC profiles.

3.2.1 Study site

The study site is situated in Central Alberta, Canada, in a Black Chernozem soil area. The landscape varies from hummocky to rolling and undulating, typical of glacial till deposition (Figure 2.3). The climate is continental with warm short summers and long cold winters; an annual mean air temperature of 2.7 ^{0}C and annual precipitation of 477 mm, with 123 cm of snow. Soil profile surveys were established on two landscapes, under a traditional local rotation (Government of Canada, 2004). The first landscape (NE 8) was under continuous forage, and the second landscape (SE 9) was under canola in 2003, and barley in 2004. Elevation of the study site decreases 50 m from the NE 8 landscape to the SE 9 landscape.

3.2.2 Soil sampling

Soil sampling positions along two 500 m transects (Figure 3.1) were chosen according to the relief of the landscape, in order to capture the complete range of soil-landscape variations (Young and Hammer, 2000). Soil cores were collected at intervals of 10 m (Zebarth and De Jong, 1989) to a depth of 2 m, during October 14 and 15, 2003 with a truck-mounted hydraulic 4.6 cm diameter coring device. Each landscape was represented with 50 independent soil cores. Each soil core sampling point was recorded with a global positioning system device (GPS), and all intact soil cores were kept in PVC pipes at ambient temperature until soil classification. Soil classification was conducted according to the Canadian System of Soil Classification (Soil Classification Working Group, 1998) under the supervision of a senior soil scientist. Particular attention was given to the eluviated horizon (Ae), evidence of illuviated clay (Bt), carbonate distribution, and evidence of water table fluctuation (oxy-reduction) (Zebarth and De Jong, 1989). Solum thickness was determined to be the total thickness of the A and B horizons.

3.2.3 Cluster analysis and leaching potential

Cluster analysis was used to define similarity and differences of development among soil profiles. Complete linkage cluster analysis was preferred over simple cluster analysis to find clear discontinuity in the clusters, and to enhance the precision of the analysis (Legendre and Legendre, 1983). The SAS cluster procedure (SAS institute Inc., 1999) was used to perform the complete linkage analysis. A cluster cubic criterion (CCC) versus number of clusters was used to determine an adequate number of clusters (SAS institute Inc., 1999). Each cluster was associated with a relative degree of long-term leaching potential according to the degree of soil development within the cluster. The degree of profile development was quantified with a soil profile index (SPI).

A SPI value was calculated from the result of the soil classification for each sample. The SPI is an adapted version of the profile development index (PDI) first used by Manning (1999) to measure the degree of soil development due to water movement of the soil profile (equation 1). The PDI was based on the degree of development of each horizon, and the depth of development measured by the solum depth; however, the PDI did not consider the A horizon and the solum depth. Many studies mentioned the impact of spatial variability of leaching on solum thickness and depth to carbonates (Manning et al., 2001; Pennock et al., 1987). The SPI accounts for the horizon differentiation within a control section of 1.2 m, equivalent to the accepted rooting depth for annual crops on the Canadian Prairies (Dyck et al., 2003).

$$SPI = [\Sigma W_i (T_i/S)] * [S/1.2 \text{ m}] \tag{1}$$

Where

W_i: Weighting factor for horizon i

T_i: Thickness for horizon i (m)

S: Solum depth (m)

The solum depth (S) includes the depth of the A and B mineral horizons, and weighting factors (W_i) are relative values given to types of horizons according to the degree of pedologic development, where the least developed horizons are given a weighting value of 0.5, and the most developed horizons a value of 5 (Table 3.1). The weighting scheme was based on sequences of horizon differentiation from the parent material (Fanning and Fanning, 1989; Duchafour, 1982). The horizons within the study site are derived from glacial till rich in carbonates and clay material. Therefore, lixiviation, including decarbonation, and melanization are the first horizonation processes, followed by lessivage and cheluviation (Chapter 2). The intensity of each process affecting the soil development was recorded in the soil horizonation (Buol et al., 1989; Fanning and Fanning, 1989; Duchafour, 1982), and can be interpreted or deduced from the horizon characteristics.

The presence of the A horizon indicates a degree of horizonation attributed to the melanization process; therefore, the weighting factor attributed to an AC horizon was 0.5. The Ahk and Apk horizons represented an intensity of melanization greater than that of the AC horizon, and a weighting factor of 1 was assigned to these horizons. The Ah and Ap horizons indicated a similar intensity of melanization, with a higher intensity of decarbonation than for the Ahk and Apk. Therefore, the weighting factor for Ah and Ap horizons was 2. The Ahe horizon confirmed intense lixiviation and lessivage, and the weighting factor value was 3. The Ae horizon was evidence of an advanced degree of lixiviation and lessivage when compared to the Ahe. The weighting factor attributed to the Ae horizon was 4. The highest intensity of leaching occurring within the A horizons was assigned to the AB horizon; where the B horizon was breaking down, and the Ae horizon was prolonging within the B horizon. The weighting factor given to the AB horizon was 5.

Similarly, the presence of a B horizon indicated differentiation from the parent material, and the weighting factor assigend to the BC horizon was 0.5. The Bmk and Bk horizons confirm a higher intensity of horizonation than BC, and the weighting factor attributed to these horizons was 1. The Bm, Bn and Bg horizons indicated a higher intensity of decarbonation and lixiviation within the soil matrix than the Bmk or the Bk horizons. The weighting factor assigned to the Bm, Bn and Bg horizons was 2. The Btj horizon is an indication of weak lessivage, and the weighting factor assigned to this horizon was 3. Finally, the Bt horizon indicated intense lessivage, and the weighting factor given to this horizon was 4 (Manning, 1999).

3.2.4 Long-term leaching intensity

Soil samples to a depth of 6 m were extracted October 20 and 21, 2003, and November 8 and 9, 2004 within sites located in each leaching potential cluster from the SE 9 landscape for sulphate concentration and EC analysis. Soil samples were taken at 30 cm increments, and the samples were kept in sealed plastic bags at 4 ^{0}C until prepared for analysis.

Samples were air-dried, ground, and passed through a 2 mm sieve. Sub-samples were oven-dried at 105 ^{0}C for 48 hours for moisture content analysis. Sub-samples of 250 g of the air-dried soil samples were mixed with deionised water for soil-paste extraction (Rhoades, 1996). The extract was passed through a 0.45 μm pore size Whatman® filter, poured into a scintillation vial, and analysed with an ion chromatograph (IC) along with standards to determine sulphate concentration (Tabatabai and Frankenberger, 1996). The remainder of the soil paste extract was then used for electrical conductivity measurement (Rhoades, 1996).

An ANOVA was completed using the SAS mixed procedure with a repeated statement (SAS institute Inc., 1999) to test the variation from the sulphate and EC profiles attributed to the long-term leaching classification. The type of covariance was selected according to the Bayesian information criterion (BIC) (SAS institute Inc., 1999).

The average sulphate concentration and EC profiles for the long-term leaching potential classes or clusters were analysed to determine the leaching intensity of each cluster. The sulphate concentration and EC for a soil under a high intensity of leaching was expected to be relatively low within 0 to 120 cm of the soil profile, as the soluble ions were leached from the profile over the years. On the other hand, higher concentration of sulphate and EC within this depth indicated low intensity of leaching, as relatively less removal of soluble ions occurred in these profiles. The sulphate concentration and EC for a mid intensity of leaching was expected to be higher than that for a high leaching profile, and lower than that for a low leaching profile. The concentration of sulphate and EC at a depth below 120 cm was not considered for the leaching intensity analysis because of the variation of sulphate concentration and EC due to the possible fluctuation of the water table.

3.2.5 Soil-landscape factors

Soil-landscape factors including SPI, elevation, slope gradient, plan curvature and profile curvature were analysed to determine the distinction among each leaching potential cluster. Landscape factors including elevation, slope gradient, and plan and profile curvature of each sampling location were obtained from a digital terrain model (DTM) built on a 5 m grid (MacMillan, 2004; MacMillan and Pettapiece, 2000; Zebarth and De Jong, 1989). Elevation was given in metres relative to sea level. Slope gradient was the maximum inclination in percent within the 25 m^2 cell grid of the sampling point. Plan curvature was the change of slope in the across-slope direction given in degrees / 100 m, while profile curvature was the change in the down-slope direction given in degrees / 100 m.

The SAS general linear model (GLM) (SAS institute Inc., 1999) procedure was used to perform an analysis of variance (ANOVA), and the discontinuity of soil-landscape factors among clusters was determined according to Student-Newman-Keuls (SNK) analysis (Jongman et al., 1995).

3.3 Results

3.3.1 Soil profile survey

There were more horizon types and greater soil diversity in the NE 8 than SE 9 landscape (Table 3.2). The elevation range for the NE 8 landscape (7 m) was approximately twice that measured for the SE 9 (3 m). Similarly, the plan and profile curvature ranges for the NE 8 landscape (40 to 44 degrees / 100 m) were, on average, twice those for SE 9 (23 to 25 degrees / 100 m). However, the slope degree range for the NE 8 landscape (7°) was only slightly greater than that for SE 9 (5°). Finally, the range of SPI for the NE 8 landscape (4) was two thirds that for SE 9 (6) (Table 3.2).

3.3.2 Cluster analysis and leaching potential

For each dataset (NE 8, SE 9, and all data) CCC analysis indicated two distinct levels of cluster. The first level of cluster presented a higher degree of distinction among each cluster; however, the second degree of clusters showed a higher precision in the distribution of the soil horizon patterns, related to a finer degree of long-term leaching potential (Tables 3.3, 3.4, and 3.5). According to the average degree of profile development, quantified with the SPI, within each cluster, the first level of cluster included high, mid and low leaching potential, and the second level included very high, high, mid, low and very low leaching potential.

The leaching potential, defined according to the degree of soil development, corresponding to the first level of cluster for the NE 8 landscape and SE 9 landscape datasets, was consistent with the leaching potential associated with the second level of cluster (Tables 3.3 and 3.4); which was not the case for the dataset composed with the data from both landscapes (Table 3.5). The cluster analysis of this dataset tended to group sites from the same landscape together, instead of a mix of both landscape sites within groups. The degree of soil development, quantified with the SPI, was variable between the landscapes, and the NE 8 and SE 9 landscape datasets were treated separately for the leaching potential analysis.

3.3.3 Leaching intensity versus leaching potential

The ANOVA for the first level of clusters did not reveal significant variation among sulphate profiles located within each cluster. However, the average sulphate concentration profile within each leaching potential cluster revealed relatively high, intermediate, and low sulphate concentrations for the low, mid and high leaching potentials, respectively (Figure 3.2). The ANOVA of the second level of cluster revealed a significant difference between the very high leaching potential and very low leaching potential (*P=0.0036*), and the average sulphate concentration profile showed relatively higher concentration of sulphate for the very low leaching potential profile compared to the concentration for the very high leaching potential (Figure 3.3). However, there was no significant variation among the high, mid and low leaching potential clusters, and there was no clear distinction among the sulphate concentration profile characteristic of these leaching potential clusters.

ANOVA of EC profiles for the first level of clusters indicated a significant difference between low and high long-term leaching potentials ($P=0.0355$), but revealed no significant variation between EC profiles for the second level of cluster.

3.3.4 Soil-landscape factors

First level of cluster for the NE 8 landscape (Table 3.3) showed that the elevation ($P=0.0133$), slope gradient ($P=0.0213$), and SPI ($P<0.0001$) characteristics of each leaching potential cluster were significantly different, and can describe the soil horizon distribution pattern. Analysis of the second level of cluster showed significant variation of plan curvature ($P=0.0148$), elevation ($P<0.0001$) and SPI ($P<0.0001$) among each leaching potential cluster.

ANOVA analysis of the first level of clusters for SE 9 landscape showed that SPI ($P<0.0001$), plan curvature ($P=0.0079$) and profile curvature ($P=0.0218$) were significantly different among the leaching potential clusters. However, the SNK analysis showed that only the SPIs were significantly different among leaching potential clusters (Table 3.4). Only SPI ($P=<0.0001$) and plan curvature ($P=0.0433$) were significantly different among leaching potentials at the second level of cluster.

For both landscapes, the range of elevation, slope gradient, plan curvature, profile curvature, and SPI values attributed to each leaching potential cluster overlapped (Tables 3.3 and 3.4). However, on the first level of cluster, SPI values characteristic of the high leaching potential were clearly distinct from those characteristic of the low leaching potential. Similarly, on the second level of cluster, the SPI value characteristic of the very high leaching potential was clearly distinct from SPI value characteristic of the very low leaching potential (Figures 3.4 and 3.5).

Within the SE 9 landscape, the plan curvature values were not specific for any particular cluster. However, for the first level of cluster, the plan curvature average was > 0 for low leaching potential, and < 0 for mid and high leaching potential, while for the second level of cluster, the value was > 0 for very low and low leaching potential, and < 0 for very high and high leaching potential (Figure 3.5).

3.3.5 Leaching potential index

Within the SE 9 landscape, the very high and very low leaching potentials from the second level of cluster corresponded to the leaching intensity described by the sulphate and EC profile for that landscape, which was not the case for the high, mid, and low leaching potential clusters. Therefore, the soil profiles within each of these leaching potential clusters had to be regrouped in order to obtain a leaching potential index that represented leaching intensity as described by sulphate and EC profiles.

The ANOVA results showed that SPI was a good indicator of the very high and very low leaching potentials. Also, the ANOVA revealed that SPI was distinct among the leaching potential of the second level of cluster. Also, the range for SPI characteristics of the very high and very low leaching potential clusters was distinct. However, the ranges of SPI characteristics for the high, mid and low leaching potential cluster overlapped. Therefore, the range of SPI had to be combined with other characteristics to allow a clear distinction among the high, mid and low leaching potential. The range of plan curvature tended to be >0 for the very low and low leaching potential, and <0 for the mid, high and very high leaching potential. The combination of the SPI and plan curvature helped to regroup the soil profiles into four leaching potential clusters: SPI in the very high range (SPI>4) represented a very high long-term leaching potential; SPI in the very low range (SPI<1) represented a very low long-term leaching potential; SPI in the middle classes range (4>SPI>1) combined with plan curvature < 0 denoted high leaching potential, and SPI in the range of the middle classes (4>SPI>1) combined with plan curvature > 0 denoted low leaching potential. This leaching potential classification based on SPI and plan curvature provided a leaching potential index (Table 3.7).

Within the SE 9 landscape, the leaching potential corresponded better with sulphate and EC profiles, than the cluster analysis suggested (Figure 3.6). The ANOVA revealed a significant relation between the sulphate profiles and the leaching potential index (*P=0.0346*), and there was a strong relationship between the EC profiles and the leaching potential index (P=0.0574).

The concentrations of sulphate and EC within very high leaching potential profiles were significantly different than these within the very low leaching potential profiles (*P=0.0067 and P=0.0107, respectively*). The variation of sulphate concentrations within the very high leaching potential profiles was also significantly different compared to low leaching potential profiles (*P=0.0281*), and the EC within these profiles tended to be different (*P=0.0574*). The sulphate concentration and EC within the very high leaching potential profiles were not statistically different compared to those within the high leaching potential profiles (*P=0.1033 and P=0.2331, respectively*). The sulphate and EC within the high and low leaching potential profiles (*P=0.4260 and P=0.3637, respectively*), high and very low leaching potential profiles (*P=0.2689 and 0.1427, respectively*), and low and very low leaching potential profiles (*P=0.8709 and P=0.7055, respectively*). Although not statistically significant, the concentration of sulphate and EC profiles tended to increase from very high to high, low, and very low leaching potential profiles (Figure 3.6).

3.4 Discussion

The long-term leaching potential pattern derived from the analysis of the distribution of the soil horizons varied between landscapes. Uplands are commonly viewed as being active recharge zones (Brooks et al., 2003; Fetter, 2001). However, the SE 9 landscape presented greater development of the soil profile and higher SPIs than the NE 8 landscape, which indicates greater soil development in the SE 9 than the NE 8 landscape. Park and Burt (2002) mentioned that the effects of topographic features on soil horizon distribution operate differently among landscapes. The change from grassland to agricultural land, and variations in agricultural management can have a permanent impact on water budget, infiltration capacity, and leaching (Brooks et al., 2003; Dyck, 2004). Therefore, it is important to consider the environmental context of a landscape to study water movement (MacMillan et al., 2000; Manning et al., 2001).

Within the SE 9 landscape, the leaching potential of the first level of cluster determined according to the degree of soil development showed consistency with the leaching intensity as suggested by sulphate and EC profiles. However, the distinction among the leaching potential of the second level of clusters was not consistent with the analysis long-term leaching intensity indicated with sulphate and EC profiles. The small number of sampling sites and the high variation of soil-landscape features such as SPI and plan curvature among the high, mid, and low leaching potential clusters could explain this inconsistency (Table 3.6).

SPI was a good factor to distinguish extreme intensities of leaching as described by sulphate and EC profiles. However, the range of SPI attributed to each leaching potential cluster overlapped. The combinations of topographic feature, in this case plan curvature, with SPI allowed greater distinction of leaching intensity. Young and Hammer (2000) found a relation between soil genesis and slope curvature, which could have an important effect on the detailed analysis of spatial variation of long-term leaching potential.

In this study, the leaching potential index based on SPI combined with plan curvature successfully differentiated very high, high, low, and very low long-term leaching potentials. The water movement patterns derived from the complex interactions of soil and landscape properties (Lin et al., 2005) and information from soil properties and landscape morphology can be necessary to predict leaching (Keller et al., 1988; Lin et al., 1999; Lin et al., 2005; Schoorl et al., 2002). SPI is a very site-specific landscape characteristic that can complete topographic-based landscape management models (Florinsky et al., 2002; MacMillan and Pettapiece, 2000).

Addition of sulphate and EC profiles for the study site can improve the accuracy of the leaching potential index for the prediction of long-term leaching potential. Also, the combination of various natural tracer profiles in the dataset will provide important specifications to evaluate the accuracy of the long-term leaching potential prediction index (Hendry, 1988). Finally, studies of water movement tracers such as bromide within a study site can help to assess the parallel between a long-term leaching potential prediction index and short-term leaching potential.

3.5 Conclusions

Prediction of leaching potential derived from soil profile development and soil distribution analysis was related to sulphate and EC profiles for extreme intensities of leaching potential. Considering the precision of leaching potential, we accepted the hypothesis that soil horizon distribution pattern represents the spatial variability of long-term leaching. According to the level of the cluster analysis, clusters formed with the distribution of soil horizons represent variability of long-term leaching as shown with sulphate and EC profiles within the SE 9 landscape.

Cluster analysis of the distribution of soil profiles within agricultural landscapes formed homogeneous clusters that can be described using a leaching potential index based on SPI and plan curvature measurements. This corresponds to the second research hypothesis, that SPI alone allowed distinction among clusters for the SE 9 and the NE 8 landscapes. The leaching potential index clearly delineated four clusters representing very low, low, high, and very high long-term leaching potential. The leaching potential index can be beneficially used in topographic-based landscape management and land evaluation models.

3.1 Weighting factor values

Horizon	AC	Ahk and Apk	Ah and Ap	Ahe	Ae	AB
Weighting Factor	0.5	1.0	2.0	3.0	4.0	5.0
Horizon	BC	Bk and Bmk	Bm, Bg and Bn	Btj	Bt	AB
Weighting Factor	0.5	1.0	2.0	3.0	4.0	5.0

Table 3.2 Soil profile survey

	NE 8	SE 9
Types of horizon	30	23
Types of horizon in analysis	11	8
Soil classification type	14	12
Elevation range (*average*) (m)	768 to 775 *(772)*	752 to 755 (*753*)
Plan curvature range (*average*) (degree / 100 m)	-20 to 20 *(0)*	-8 to 15 (*0*)
Profile curvature range (*average*) (degree / 100 m)	-23 to 21 *(-1)*	-12 to 13 (*0*)
Slope degree range (*average*)	0 to 7 *(3)*	0 to 5 (*2*)
SPI range (*average*)	0 to 4 *(2)*	0 to 6 (*2*)
Depth of solum range (*average*) (cm)	10 to 150 *(88)*	26 to 155 (*87*)

Table 3.3 Characteristics of cluster analysis for the NE 8 landscape

First level of long-term leaching cluster		*Second level of long-term leaching cluster*		Site n	SPI average range	Plan curvature (degree/100 m) average* range	Profile curvature (degree/100 m) average* range	Slope degree (degree) average* range	Elevation (m) average* range
1	Low	2	Very Low	14	1 c (c)	6 a (a)	3 a (a)	4 a (a)	772 b (ab)
					0 to 2	-8 to 12	-16 to 16	1 to 6	771 to 774
1	Low	4	Very Low	1	1 c (c)	-8 a (a)	-7 a (a)	5 a (a)	769 b (ab)
1	Low	3	Low	9	1 c (bc)	-5 a (ab)	-4 a (a)	5 a (a)	771 b (b)
					1 to 2	-15 to 6	-7 to 5	0 to 7	768 to 773
1	Low	1	Low	3	2 c (bc)	5 a (ab)	9 a (a)	2 a (a)	774 b (b)
					2 to 3	0 to 12	4 to 17	1 to 3	773 to 775
3	Mid	6	Mid	1	2 b (bc)	-8 a (ab)	-5 a (a)	2 ab (a)	774 b (ab)
3	Mid	7	Mid	10	1 b (bc)	-3 a (ab)	-1 a (a)	3 ab (a)	771 b (ab)
					1 to 3	-20 to 20	-15 to 21	1 to 6	768 to 774
3	Mid	8	High	3	2 b (b)	-7 a (b)	-16 a (b)	2 ab (a)	771 b (c)
					2 to 3	-10 to -3	-23 to -10	2 to 3	771 to 771
2	High	5	Very high	9	4 a (a)	-2 a (ab)	-2 a (a)	2 b (a)	774 a (a)
					3 to 4	-11 to 3	-23 to 6	1 to 4	771 to 775

*The letters beside the average represent the SNK analysis where different letters indicate significant difference between clusters: a first level of cluster, and (a) second level of cluster ($P \leq 0.05$)

Table 3.4 Characteristics of cluster analysis for the SE 9 landscape

First level of long-term leaching cluster		Second level of long-term leaching cluster		Site n	SPI average* *range*	Plan curvature (degree/100 m) average* *range*	Profile curvature (degree/100 m) average* *range*	Slope degree (degree) average* *range*	Elevation (m) average* *range*
1	Low	1	Very Low	24	1 a (a)	2 a (a)	1 a (a)	2 a (a)	753 a (a)
					0 to 3	-8 to 15	-11 to 13	0 to 5	752 to 755
1	Low	2	Low	5	2 a (ab)	0 a (a)	3 a (a)	1 a (a)	754 a (a)
					2 to 2	-2 to 2	-5 to 10	1 to 3	753 to 754
3	Mid	5	Mid	9	3 b (b)	-2 ab (a)	2 ab (a)	2 a (a)	753 a (a)
					1 to 4	-8 to 7	-12 to 9	1 to 3	753 to 754
2	High	3	High	3	4 c (c)	-2 b (a)	2 b (a)	1 a (a)	753 a (a)
					3 to 4	-5 to 1	-7 to 2	0 to 3	752 to 753
2	High	4	Very High	9	5 c (d)	-3 b (a)	1 b (a)	2 a (a)	753 a (a)
					4 to 6	-8 to 6	-8 to 4	1 to 3	753 to 753

*The letters beside the average represent the SNK analysis where different letters indicate significant difference between clusters: a first level of cluster, and (a) second level of cluster ($P \leq 0.05$)

Table 3.5 Characteristics of cluster analysis for the combined NE 8 and SE 9 datasets

First level of long-term leaching clusters		Second level of long-term leaching clusters		Site n	Landscape (%)	SPI average range	Plan curvature (degree/100 m) average range	Profile curvature (degree/100 m) average range	Slope degree (degree) average range	Elevation (m) average range
1	Low	1	Very Low	18	NE 8 (78)	1	7	5	3	768
						0 to 2	-8 to 18	-15 to 16	1 to 6	752 to 774
1	Low	4	Very Low	20	NE 8 (60)	1	-1	-1	3	764
						0 to 3	-20 to 20	-15 to 21	0 to 7	752 to 774
1	Low	5	Very Low	18	SE 9 (61)	1	-2	-4	3	760
						0 to 2	-15 to 15	-16 to 7	0 to 7	752 to 772
1	Low	6	Very Low	1	NE 8 (100)	1	-8	-7	5	769
1	Low	3	Mid	4	NE 8 (100)	2	3	8	2	774
						2 to 4	-3 to 12	4 to 17	1 to 3	773 to 775
1	Low	7	Mid	6	SE 9 (100)	2	-1	1	1	753
						2 to 5	-8 to 2	-6 to 10	1 to 3	753 to 754
1	*Low*	*2*	*Very high*	*1*	*SE 9 (100)*	*4*	*-3*	*-5*	*1*	*753*
4	*Mid*	*10*	*Low*	*1*	*NE 8 (100)*	*2*	*-8*	*-5*	*2*	*764*
4	Mid	11	High	3	NE 8 (100)	2	-7	-16	2	774
						2 to 3	-10 to -3	-23 to -10	2 to 3	771 to 772
3	Mid	9	High	9	SE 9 (100)	3	-2	-4	2	753
						1 to 4	-8 to 7	-12 to 9	1 to 3	753 to 754
2	High	8	Very high	19	SE 9 (58)	4	-2	-2	2	762
						3 to 6	-11 to 6	-23 to 6	0 to 4	752 to 775

Table 3.6 Characteristics of the sulphate and electrical conductivity sampling sites

Site	First level of cluster	Second Level of cluster	SPI	Plan curvature (degree/100 m)	Profile curvarture (degree/100 m)	Slope (degree)	Elevation (m)
14-1	Low	Very low	2	11	12	2	755
14-6	Low	Very low	0	-3	-7	1	753
14-20	Low	Very low	1	3	7	2	754
14-39	Low	Very low	1	15	7	1	753
14-48	Low	Very low	1	3	3	3	752
14-24	Low	Low	2	-2	-5	1	754
14-21	Low	Low	2	2	10	1	754
14-13	Mid	Mid	1	-3	-11	2	753
14-14	Mid	Mid	3	-6	-12	1	753
14-38	Mid	Mid	2	7	9	2	753
14-43	Mid	Mid	3	-8	-1	1	753
14-49	High	High	4	1	1	3	752
14-30	High	High	4	-4	-7	1	753
14-28	High	Very High	4	-3	-5	1	753
14-35	High	Very High	6	-8	-2	2	753
14-37	High	Very High	5	-3	4	2	753
14-42	High	Very High	5	-8	-6	2	753
14-50	High	Very High	5	-4	3	2	752

Table 3.7 Leaching potential index

Leaching potential	SPI	Plan curvature
Very High	> 4	-
High	< 4, > 1	< 0
Low	< 4, > 1	> 0
Very Low	< 1	-

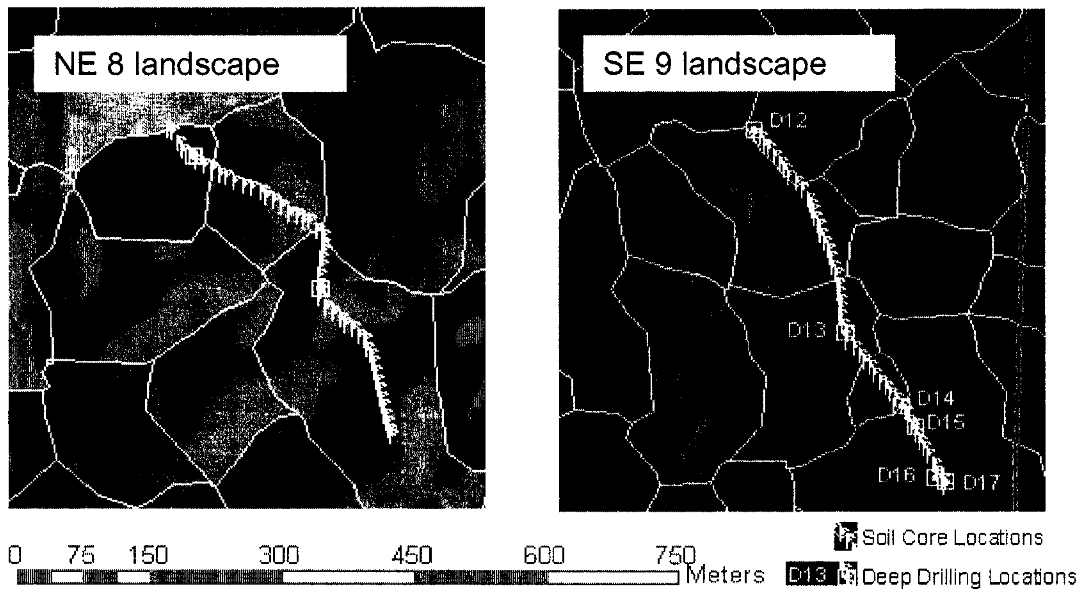

Figure 3.1 Study site at Bittern Lake area, Alberta, Canada

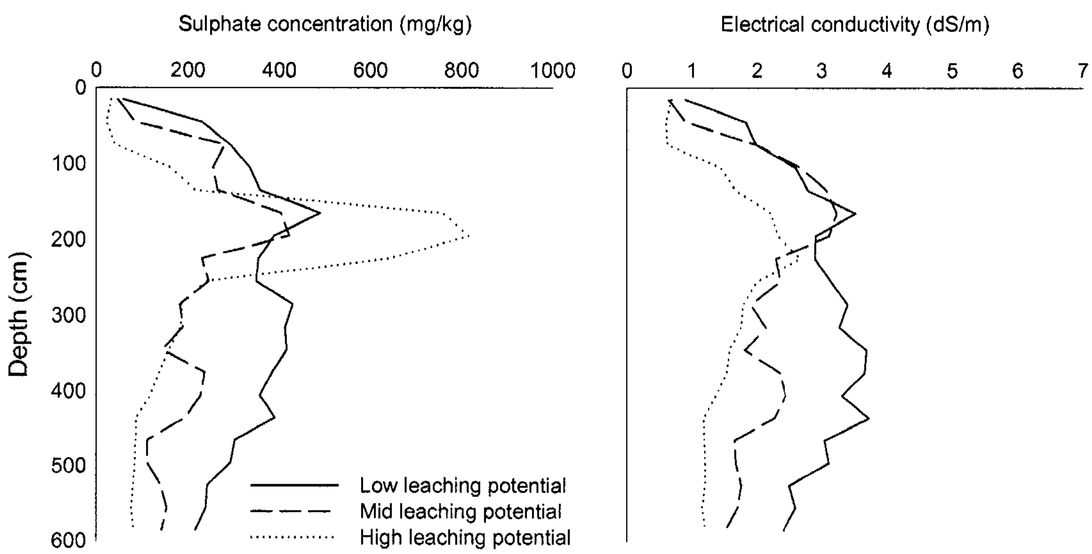

Figure 3.2 Average sulphate concentration and electrical conductivity profile from the SE 9 landscape, first level of cluster

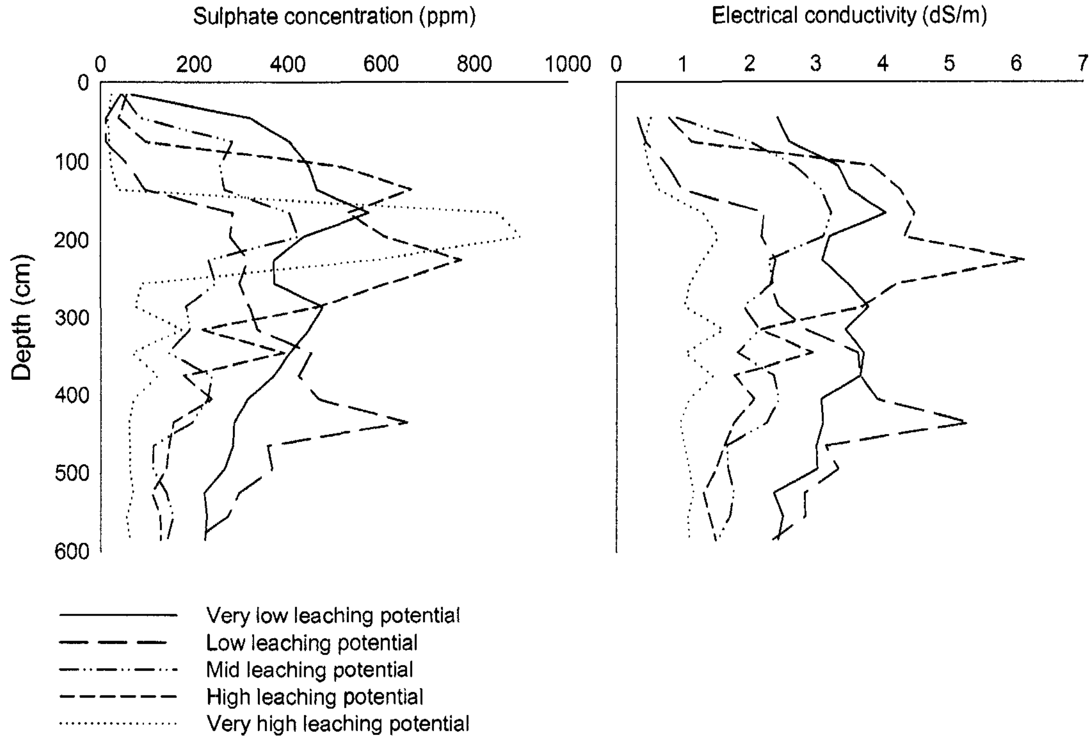

Figure 3.3 Average sulphate concentration and electrical conductivity profiles from the SE 9 landscape, second level of cluster

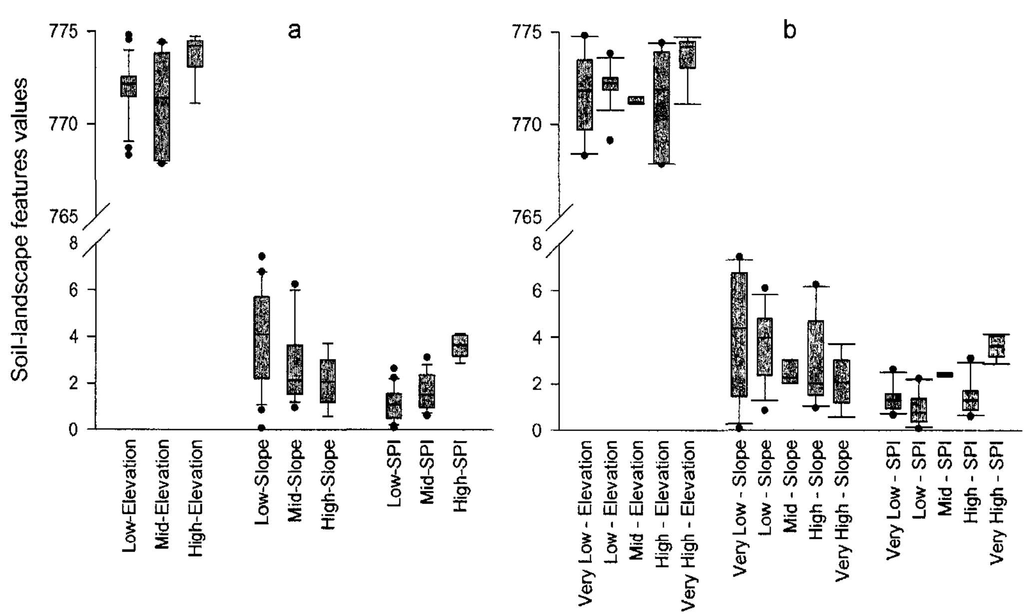

Figure 3.4 Soil-landscape factors for the NE 8 landscape: a) first level of cluster and b) second level of cluster; the line in the boxes shows the median, the boxes show the 25 and 75 percentiles, the error bars show the 10 and 90 percentiles, and the dots show the outliers

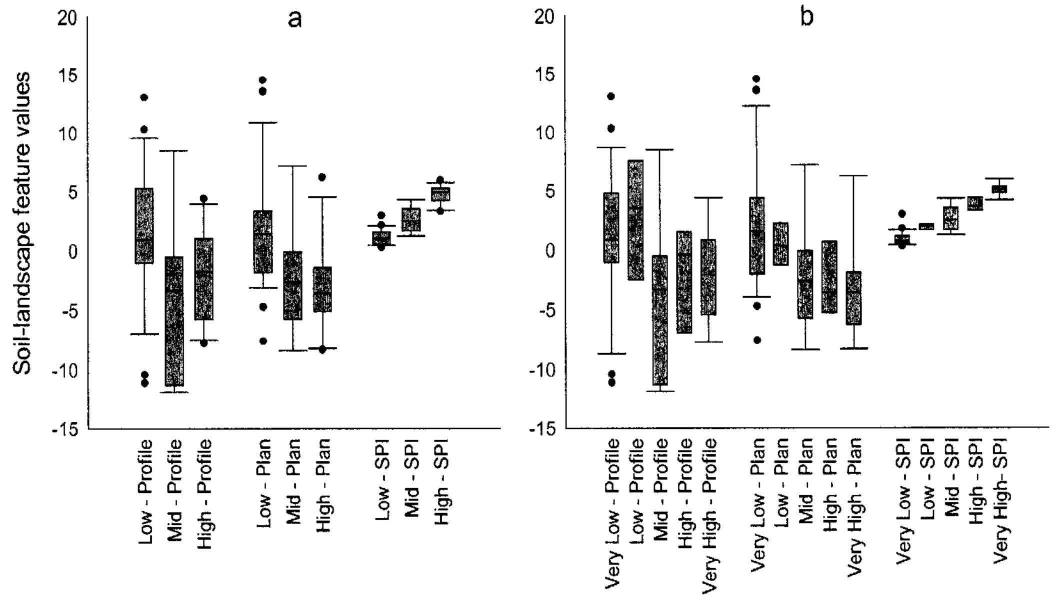

Figure 3.5 Soil-landscape factors for the SE 9 landscape: a) first level of cluster and b) second level of cluster; the line in the boxes shows the median, the boxes show the 25 and 75 percentiles, the error bars show the 10 and 90 percentiles, and the dots show the outliers

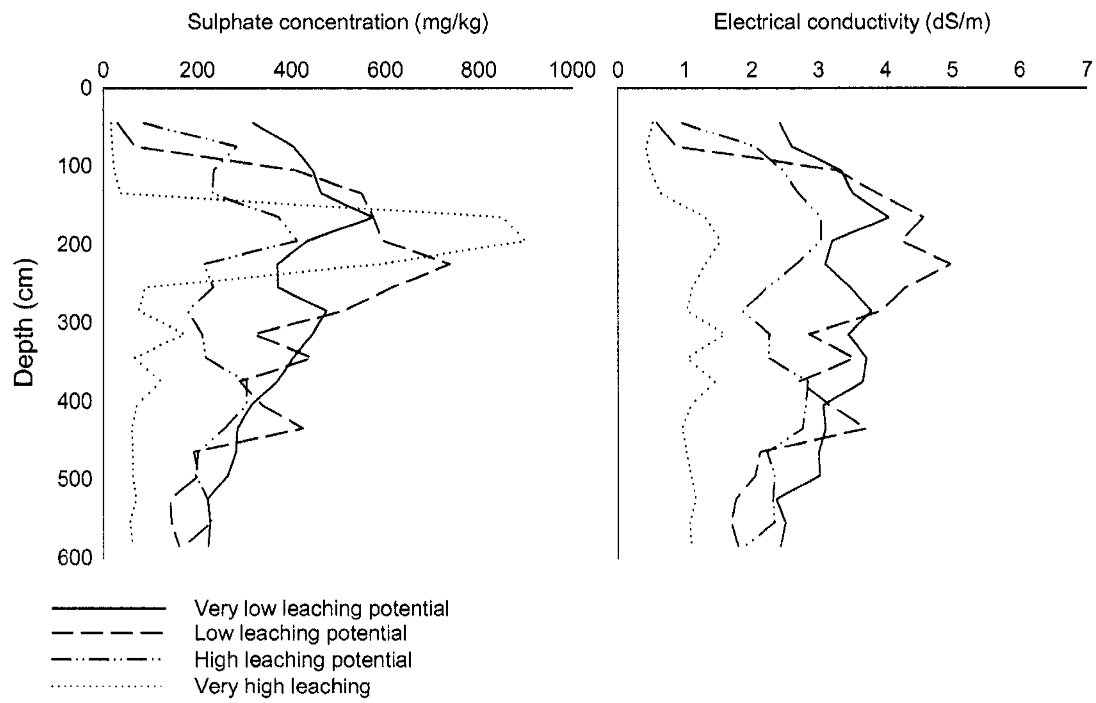

Figure 3.6 Average sulphate concentration and electrical conductivity profiles according to the second cluster analysis, SPI, and plan curvature from the SE 9 landscape

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4. Spatial and temporal variability of vertical bromide redistribution within hummocky landscapes

4.1 Introduction

There is increasing evidence that normal agricultural practices can result in low-level contamination of the groundwater via leaching of pesticides and fertilizers through the soil profile (De Jong and Reynolds, 1995). Consequently, there is a need to determine the variability of leaching within an agricultural landscape to identify areas of high leaching potential, determine agricultural best management practices, and reduce or maintain this type of contamination at an acceptable level.

Leaching refers to the downward movement of solutes within the profile soil water. Intensity of leaching is measured according to the concentration of solute in soil water at a certain depth of a soil profile (Diggle and Bowden, 1990; Gerakis and Ritchie, 1998; Malterre et al., 1998). Leaching potential refers to the prediction of the leaching intensity at a specific location.

Studies have reported significant variations of leaching potential and intensity among landscapes (Bronwijk et al., 1995; Majid et al., 1994). Within a landscape, Zebarth and De Jong (1989) found highly leached soil profiles and low soluble salt concentrations within soil profiles at low slope positions, and limited leached soil profile and high soluble salts within soil profiles at upper slope positions. Hayashi et al. (2001) and Zebarth and De Jong (1989) have found appreciable infiltration under small depressions that accumulate snowmelt water into ephemeral ponds and almost negligible infiltration on the surrounding upland. Keller (1988) mentioned that the spatial variability of leaching and infiltration rates contributed to the spatial variability of groundwater recharge within an agricultural landscape.

Investigations of leaching during the growing season revealed an important temporal variation of the intensity of leaching, which may change the interpretation and the conclusions made from the analysis of the certain leaching potential studies. Studies of wetland hydrology in the northern prairies have shown that most of the infiltrated snowmelt water flows laterally in the shallow subsurface from where some water evapotranspired during the growing season (Hayashi et al., 1998a; Parsons et al., 2004). Therefore, leaching intensity should be greater after snowmelt, and diminish during the growing season. Reuter and Bell (2003) reported differences in the water table level and hydrology of a hillslope from the top to lower slope positions, as well as from spring, after the snowmelt, to fall, after the growing season. Heppell et al. (2000) attributed the temporal variation of leaching to the swelling of clay under wet conditions, as well as to flow direction. Therefore, the intensity of leaching after snowmelt can differ from the growing season.

The spatial and temporal variability of leaching between an upland and a wetland within the same watershed have been demonstrated in many studies (Bathke et al., 1992; Butter et al., 1989; Hayashi et al., 1998a; Majid et al., 1994; Parsons et al., 2004), but the spatial and temporal variability of leaching within hummocky agricultural landscapes is still not well understood, and there is no good tool to assess this variability (Dyck et al., 2003).

The challenge in a local scale study is to accurately assess the variability of the short-term leaching at low cost (Keller et al., 1988). Tracer experiments provide direct measurement of the vertical redistribution of water after snowmelt or summer rainfalls (Hayashi et al., 1998b; Parsons et al., 2004). Bromide has commonly been used as a water movement tracer because of its low background concentration, stability in the soil, and low plant uptake (Bathke et al., 1992; Bruce et al., 1985; Parsons et al., 2004). The use of bromide as a water tracer has shown great potential in leaching studies (Bathke et al., 1992; Bruce et al., 1985; Majid et al., 1994).

The reduction of the movement of solutes and the control of the quality of the water resources depend on our ability to predict the location and intensity of leaching within agricultural landscapes (Olson and Cassel, 1999). Many landscape management models currently use topographic features to predict water movement within landscapes. However, studies have shown a close relationship between leaching and soil properties, which indicates a great potential to accurately assess the variability of leaching using soil properties. Therefore, an index that includes topographic features as well as soil properties has the potential to correctly predict the short-term leaching potential. Bathke et al. (1992) reported that soil textural and structural properties, water content, and the rate of water infiltration can control the intensity of leaching. Other studies have found that soil moisture content and clay content are related to the variability of leaching within a hillslope (Bathke et al., 1992; Bruce et al., 1985).

The objectives of this study were to assess the spatial and temporal variability of leaching after one snowmelt event (spring) and one growing season (fall) within two hummocky agricultural landscapes, and to verify the accuracy of a leaching potential index based on a soil profile index (SPI) and plan curvature measurements (Chapter 3) to assess the relative intensity of leaching.

The hypotheses tested were:

1. For two landscapes at different relative elevations, the leaching potential intensity will increase from the lower to the higher landscape,
2. The leaching intensity will increase moving down slope within a landscape,
3. The variation in leaching intensity is related to soil physical properties such as clay content and soil moisture, and
4. The leaching intensity is correctly predicted by a leaching potential index based on SPI and plan curvature.

4.2. Methods

4.2.1. Study site

The study site is situated in the Bittern Lake area in Central Alberta, Canada, in a Black Chernozem soil area (Figure 2.1). The landscape within the study site passes from hummocky to undulating, typical of glacial till deposition. The annual mean temperature is 2.7 °C and annual precipitation is 477 mm, with 123 cm of snow (Government of Canada, 2004). Study landscapes were established on two quarter sections, NE 8 and SE 9, of 65 hectares each. The elevation of the landscapes descends 50 m from the NE 8 landscape to the SE 9 landscape.

The study was conducted from October 2003 until October 2004. During this period, the NE 8 landscape was under continuous forage mixed grass, and the SE 9 landscape was under a barley (*Hordeum L.*) crop. The first hay cut in the NE 8 landscape was made on July 16, and the second cut on September 20, 2004. The SE 9 landscape was seeded with barley on May 19 to 21, and it was harvested on September 16. The NE 8 landscape was under conventional till management, and the SE 9 landscape was under long-term no-till management.

4.2.2. Bromide application

The experiment was conducted over three slopes randomly selected within the NE 8 landscape and three slopes randomly selected within the SE 9 landscape (Figure 4.1). On each slope, three plots 300 cm wide and 30 cm long were established at the top, middle, and low slope position, oriented perpendicular to the slope direction (Whetter, 2004), similar to the design used by Bathke et al. (1992) (Figure 4.2). On October 16 2003, 500 g of crystalline potassium bromide (KBr) granules were manually spread over each plot (555 g/m^2) with a 30 cm x 100 cm frame to ensure uniform distribution (Whetter, 2004).

4.2.3. Soil-landscape factors

Clay content

Particle size analyses (PSA) were performed for each bromide plot to investigate the relation between soil physical properties and leaching potential. One soil core was extracted to a depth of 120 cm on May 26, 2004, outside of each bromide plot with a truck-mounted hydraulic 4.6 cm diameter drill for soil analysis. The core was divided into 15 cm increments to a depth of 30 cm, and 30 cm increments thereafter to a depth of 120 cm. Each depth increment was kept in a sealed plastic bag at 4 °C until prepared for PSA.

All samples collected for PSA were air-dried, ground, and passed through a 2 mm sieve. When necessary, air-dry sub-samples were pre-treated to eliminate organic matter and carbonates before the PSA analysis. The pre-treatments and the PSA were conducted according to the procedure described by Gee and Or (Gee and Or, 1996). Sub-samples were oven-dried at 105 °C for 48 hours for moisture content analysis.

Soil profile index (SPI)

To investigate the accuracy of the leaching potential index (chapter 3) to predict the intensity of leaching, another soil core was extracted to a depth of 120 cm, 1 meter beside each bromide plot with a truck-mounted hydraulic 4.6 cm diameter drill, and kept intact for SPI calculation. The SPI is an adapted version of the profile development index (PDI) first used by Manning (1999) that relatively measured the degree of soil development due to water movement of the soil profile (equation 1). The soil horizons were described according to the Canadian System of Soil Classification. The SPI accounts for the horizon differentiation within a control section equivalent to the accepted rooting depth for annual crops on the Canadian Prairies (Dyck et al., 2003). The SPI was calculated for each bromide plot using equation 1.

$$SPI = [\Sigma W_i (T_i/S)] * [S/1.2 \text{ m}] \quad (1)$$

Where

W_i: Weighting factor for horizon i

T_i: Thickness for horizon i (m)

S: Solum depth (m)

Weighting factors are relative values given to types of horizons according to the degree of pedologic development, with the least developed horizons assigned a weighting value of 0.5, and the most developed horizons assigned a value of 5. The A horizon includes AC, Ahk and Apk, Ah and Ap, Ahe, and Ae with weighting values of 0.5; 1; 2; 3; and 4, respectively. The B horizons include BC, Bmk and Bk, Bm and Bn and Bg, Btj, and Bt with weighting values of 0.5, 1, 2, 3, and 4, respectively (Manning, 1999). Transitional AB horizons presenting an important leaching effect were given a weighting value of 5. More information about SPI was given in Chapter 3.

Landscape morphology

Landscape factors including elevation, slope gradient, plan curvature, and profile curvature at each bromide plot were obtained from a digital elevation model (DEM) built on a 5 m grid (MacMillan, 2004; MacMillan and Pettapiece, 2000). Elevation is expressed in meters relative to sea level. Slope gradient is the maximum inclination in percent within the 25 m^2 cell grid of the sampling point. Plan curvature is the change of slope in the across-slope direction (degrees/100 m), while profile curvature is the change in the down-slope direction (degrees/100 m).

The spatial variation of the soil-landscape factors was analysed with a general linear model (GLM) (SAS institute Inc., 1999) to perform an analysis of variance (ANOVA). The discontinuity of soil-landscape factors among bromide plot positions was determined according to Student-Newman-Keuls (SNK) analysis (Jongman et al., 1995).

4.2.4. Meteorological parameters

Snow depth and snow density were measured on November 13 2003, and March 05 2004. The snow depth was measured at 10 locations randomly selected within each bromide plot, with a metric ruler. Snow samples were collected with a 2.4 cm diameter aluminium snow probe at two locations within each bromide plots to calculate the snow density. No correction factor associated with the snow probe was used for the snow density measurements. Snow water equivalent (SWE) was calculated using the average snow depth and snow density measurements within each bromide plots for both snow surveys, individually.

During the snowmelt period, depth and perimeter of ephemeral ponds within each study slope were recorded on a regular basis. The depth of water was measured with permanent metric rulers situated at the deepest water accumulation point of each pond. The perimeter of each ephemeral pond was measured by recording a coordinate every 2.0 m around the pond with a global positioning system (GPS) device. The coordinates were then introduced into a DEM of the study site, and the size of the pond was calculated with the DEM.

Evaporation pans 30 cm in diameter and 25 cm deep were installed at each bromide plot, and measurements of evaporation were taken on a regular basis during the snowmelt period. No correction factor associated with the evaporation pan was used for the evaporation readings. Tipping bucket precipitation gauges were installed in slope 11 of the NE 8 landscape, and slope 9 of the SE 9 landscape (Figure 4.1). Air temperature was recorded at the Camrose weather station situated 15 km east of the study site.

The snow survey and snowmelt monitoring were used to calculate a water budget at the location of each ephemeral pond according to the assumption that the change in the storage water of the ephemeral pond was equal to the water inflow (precipitation and runoff) minus water outflow (evaporation and infiltration) (Brooks et al., 2003) as shown in equation 2.

$$\Delta S = P + R - I - Q - E - T - Inf - \Delta I \qquad (2)$$

Where

ΔS: change in water storage

P: precipitation

R: runoff

I: interception of precipitation by vegetation

Q: streamflow

E: evaporation

T: transpiration

Inf: Infiltration

ΔI: change in deep seepage

During the snowmelt period, no vegetation was present on the ground, and T and I are assumed to be equal to 0. Also, ephemeral ponds are generally not connected to any stream, and thus Q was assumed to be equal to 0. Finally, ΔI was not monitored, but assumed to be equal to 0. Equation 3 shows the simplified version of the water budget equation used for the calculation of the infiltration rate.

$$Inf = P + R - E - \Delta S \qquad (3)$$

4.2.5. Spring and fall soil sampling

Spring soil sampling was conducted May 25 to 27, 2004 for the NE 8 landscape, and April 26 to 28, 2004 for the SE 9 landscape. Fall soil sampling was conducted during October 12 to 14 of 2004 for the NE 8 landscape, and October 6 to 8, 2004 for the SE 9 landscape. Three soil cores were extracted at 0, 20, 60, and 140 cm downslope from the centreline of each bromide plot during the spring sampling, and 0, 20, 60, 140, and 220 cm during the fall sampling. One soil core was also extracted 20 cm upslope from the bromide plots during spring and fall sampling to record every possible variation of bromide redistribution patterns. For each sampling event, the middle width of each bromide plot indicated the 0 cm position, and all downslope positions were measured relative to the 0 cm position (Figure 4.3) (Whetter, 2004). The three soil cores were extracted for each downslope distance, the first one from the centreline of the bromide plot, and a second and third at 75 cm to each side of the centreline. During the fall sampling, the soil cores were offset 5 cm from spring holes.

The sampling was done with a truck-mounted hydraulic 2.3 cm diameter coring device. At certain bromide plot locations, a 2.3 cm diameter Dutch auger was used to collect the soil samples due to excess compression of samples caused by the hydraulic coring device. Every hole was backfilled immediately after the soil sampling with Holeplug® 3/8" bentonite chips with a 1.5×10^{-9} cm/s permeability to prevent by-pass water movement.

The soil cores were sectioned into 15 cm increments to 30 cm of depth, and thereafter in 30 cm increments to 120 cm (rooting depth for annual crops on the Canadian Prairies), 90 cm, or 60 cm of depth, according to the sampling distance from the bromide plot (Dyck, 2004; Whetter, 2004). The soil samples were kept in sealed plastic bags at 4 ^{o}C until prepared for analysis.

4.2.6. Bromide analysis

The bromide analysis for the entire dataset was conducted on oven-dried soil according to the method described in Whetter (2004). Entire soil increment samples were weighed fresh, oven-dried at 105°C for 48 hours, and weighed to determine the gravimetric moisture content (Olson and Cassel, 1999). The oven-dried samples were then ground, and passed through a 2 mm sieve. Sub-samples of 10 g of oven-dry soil samples were mixed with 30 g of deionised water and mechanically shaken for 30 minutes. The solutions were filtered with a 0.45 μm pore size Whatman® filter, pored into a scintillation vial, and kept at 4°C until analysis (Dyck et al., 2003). The bromide concentration of the solution was measured with an ion chromatograph (IC) (Olson and Cassel, 1999) with a limit of detection of 0.02 mg/kg, with a precision of 5% or better.

Spatial and temporal variations of the bromide soil profiles were analysed with an analysis of variance (ANOVA) through a nested repeated mixed model with the statistical analysis system SAS (SAS institute Inc., 1999). The type of covariance was selected according to the Bayesian information criterion (BIC) (SAS institute Inc., 1999).

The concentration of bromide of each soil sample was considered for quantitative analyses and statistical analyses. The average concentration of the three soil cores for each depth increment at each sampling position from the bromide plot was used for trend analyses and interpretations of the vertical bromide redistribution at each bromide plot.

The intensity of leaching was analysed according to the position of the bromide front, the position of the bromide plume, and the concentration of the bromide plume. The bromide front referred to an average bromide concentration for each depth of soil (vertical movement). The average bromide concentration for each depth was determined with the results from the three cores, for each distance from the bromide plot. The position of the bromide plume referred to the depth and the distance from the bromide plot of a certain concentration of bromide (lateral and vertical movement).

Prior to the experiment a background concentration of bromide was measured to be <0.8 mg/kg over all slopes and soil sampling positions. Therefore, the bromide front was assumed to be the depth at which 1 mg/kg of bromide was detected. The bromide plume was delimited with an average concentration of 100 mg/kg of bromide, which is 100 times greater than the concentration of the bromide front, and the average concentration of bromide was provided by the maximum average concentration found in the bromide plume. These parameters were used for general comparison of leaching intensity between and within landscapes, and were not statistically analysed.

Moisture content

The gravimetric moisture content (GMC) of each soil sample collected for bromide analysis was used to determine the relation between moisture content and leaching intensity. The GMC was measured for every soil sample, and moisture content profiles were built for each bromide plot. Spatial and temporal variations of the GMC were analysed with ANOVA through a nested repeated mixed model with the statistical analysis system SAS (SAS institute Inc., 1999). The type of covariance was selected according to the Bayesian information criterion (BIC) (SAS institute Inc., 1999). The water content profiles were analysed according to the average GMC and the depth of the wetting front at each bromide plot. The wetting front represents the depth at which the moisture gradient is so steep that there appears to be a sharp boundary between the relatively moistened soil above and the relatively dry soil beneath (Hillel, 1982). The average GMC and the depth of the wetting front were used for general comparison, and were not statistically analysed.

4.2.7. Short-term leaching potential prediction

The prediction of the short-term leaching potential was made with an index developed from a study of the long-term leaching potential from the SE 9 landscape. This index used the SPI and plan curvature values to estimate a relative leaching potential, SPI < 1 indicates very low leaching potential; 1 < SPI < 4 with a plan curvature > 0 indicates low leaching potential; 1 < SPI < 4 with a plan curvature < 0 indicates high leaching potential; and SPI > 4 indicates very high leaching potential. The short-term leaching potential prediction analysis was done in SAS with ANOVA through a nested repeated mixed model (SAS institute Inc., 1999).

4.3. Results

4.3.1. Soil-landscape factors

The clay content, SPI, slope gradient, profile curvature and plan curvature were not significantly different between the NE 8 and SE 9 landscapes (P=0.471; P=0.769; P=0.382, P=0.144; P=0.882, respectively). However, the NE 8 landscape was situated at a significantly higher elevation than the SE 9 landscape (P< 0.0001) (Table 4.1). The depth of the soil cores extracted for the SPI calculation was not enough to include the C horizon in 7 of the 18 sampling positions, and, for these cases, the SPI was calculated on the incomplete soil cores with the assumption that the limit between the B and C horizon was at the end of the soil cores.

There was no significant difference in clay content between the landscapes (data not shown). However, the variation of the clay distribution among the slope positions and the soil profile depth within each landscape were significantly different (P=0.034; P=0.034, respectively). In the NE 8 landscape, there was significantly less clay at the mid slope positions compared to the top (P=0.036) and the low (P=0.013) slope positions, and clay was accumulated at depth between 30 to 90 cm at the top slope positions, 30 to 60 cm at the mid slope positions, and 30 to 90 cm at the low slope positions. In the SE 9 landscape, there was significantly less clay at the top slope positions compared to the low (P=0.025) slope positions; and the clay was accumulated at depth between 30 and 60 cm at the top slope positions, 30 to 90 cm at the mid slope positions, and 30 to 120 cm at the low slope positions. Also, the low slope positions tended to contain higher clay than the top and the mid slope positions (Table 4.2)

Within both landscapes, the SPI was significantly higher in the low slope position compared to the top (P=0.0051) and mid (P=0.036) slope positions, meaning that the degree of soil profile development was higher in the low slope position than the top and mid slope positions (data not shown).

The elevation, slope gradient, profile curvature, and plan curvature were significantly lower at the low slope positions compared to the top (P=0.0008; P=0.032; P<0.0001; P=0.003, respectively) and the mid (P=0.011; P=0.002; P=0.001; P=0.045, respectively) slope positions. Therefore, the morphology of the low slope positions was relatively flat compared to the top and mid slope positions.

There was no significant difference in SPI, elevation, slope gradient, profile curvature, and plan curvature between the top and the mid positions (P=0.228; P=0.096; P=0.081; P=0.094; P=0.113, respectively).

4.3.2. Precipitation monitoring

Snowfall survey

The snow water equivalent (SWE) was not significantly different between the landscapes (P=0.175), but was significantly different among slope positions (P<0.0001) (data not shown). In the NE 8 landscape, the top and the low slope positions did not show significant variation of SWE (P=0.095), but the mid slope position showed a significant increase in SWE compared to the low ($P<0.0001$) and top ($P<0.0001$) slope positions. In the SE 9 landscape, the SWEs in the mid and the low slope positions were significantly higher than that in the top slope positions ($P=0.005$; $P<0.0001$, respectively). The SWEs at the top and low slope positions in the NE 8 landscape were significantly lower compared to those at the top ($P<0.0001$) and low ($P<0.0001$) slope positions from the SE 9 landscape, and the SWE at the mid slope position was significantly higher in the NE 8 landscape compared to that at the mid slope position in the SE 9 landscape ($P<0.0001$).

Snowmelt survey

During spring 2004, air temperatures much above average occurred at the end of March, which drastically enhanced the snowmelt (Table 4.3). The main snowmelt event occurred from March 23 to March 31, 2004. During this period, there was no surficial water accumulation within any of the three slopes within the NE 8 landscape. However, ephemeral ponds formed in all three slopes within the SE 9 landscape, flooding only the bromide plots situated at the low slope position. The ephemeral ponds in slopes 9 and 7 dried around April 2, and the ephemeral pond in slope 8 remained until April 10 (Figure 4.2).

No precipitation or rainfall runoff occurred during the period of March 30 to April 2, and the water budget calculated for this period in the slopes from the SE 9 landscape showed that slopes 7 and 9 had a net infiltration rate of 9.8 and 6.9 mm/hr, respectively (Table 4.4). These values are 6 to 15 times greater than the infiltration rate measured by Hayashi et al. (2001) in depressions under frozen soil; however, these measurements are closer to their rate of infiltration of 2.4 to 6.1 mm/hr measured in depressions under unfrozen soils. During the same period, slope 8 had a net gain of water at a rate of 0.9 mm/hr.

Rainfall survey

The cumulative rainfall during spring and summer 2004 was 229 mm for the NE 8 landscape and 244 mm for the SE 9 landscape, which is only about 65 % and 70 % of the spring and summer rainfall normal for the area, respectively (Figure 4.4). The driest month was June with only 20 % of the monthly rainfall normal. The main rainfall event happened in July, with rainfall accumulation reaching the monthly rainfall normal. There were important rainfall variations between the landscapes during July and August; in July, the NE 8 landscape received 17 mm more rainfall than SE 9 landscape, but in August, 39 mm less rainfall.

4.3.3. Vertical redistribution of bromide concentration

Spatial variability of bromide vertical redistribution pattern

According to the repeated mixed model analysis of the bromide concentration at each sampling position, leaching was significantly variable between the landscapes (P=0.002).

The depth and the average concentration of the bromide plume were used to estimate the variation between the landscapes (Tables 4.5 and 4.6). The depth of the bromide plume at the top and the mid slope positions from the NE 8 landscape was within 30 to 60 cm, whereas the depth of the bromide plume at the top and mid slope positions from the SE 9 landscape was generally within 30 cm. On the other hand, the depth of the bromide plume at the low slope position from the NE 8 landscape was within 60 cm, whereas the low slope positions from the SE 9 landscape had intense vertical and/or lateral spreading of bromide, and no bromide concentration higher than 100 mg/kg; thus no bromide plume was found within the first 120 cm of soil.

The depth of the bromide plume at the top and the mid slope positions indicated greater leaching intensity within the NE 8 compared to the SE 9 landscape.

However, the low slope positions within the SE 9 landscape presented greater leaching intensity compared to the low slope position within the NE 8 landscape.

Spring vertical redistribution of bromide

The results of the repeated mixed model analysis of bromide concentration for spring sampling showed that the bromide vertical redistribution pattern was significantly variable between landscapes (P=0.032). However, bromide was found at a 120 cm depth in all plots, with the exception of the top slope position in slope 7 from the SE 9 landscape where bromide was not found below 90 cm of depth (Tables 4.6).

The statistical analysis showed no significant difference in leaching between the landscapes when comparing the top, mid, and low slope positions accordingly (P=0.772; P=0.099; P=0.075, respectively) (Figures 4.5 and 4.6). However, the location of bromide plumes within the low slope position varied between landscapes. The low slope position from the NE 8 landscape presented a plume situated above the 60 cm depth (Tables 4.5 and 4.6). The concentration of bromide at the low slope positions from the SE 9 landscape was generally lower than 100 mg/kg. No plume was detected, which indicated greater spreading of bromide throughout the low slope position in the SE 9 landscape than the NE 8 landscape.

Within each landscape, there were important variations in vertical redistribution of bromide among slope positions. Within slopes 10, 11, and 12 from the NE 8 landscape, the ANOVA analysis showed no significant difference of bromide redistribution between the top and the mid slope position (P=0.6642) (Figure 4.5). However, the redistribution of bromide was significantly different between the low and top slope position (P<0.0001), as well as low and mid slope position (P<0.0001). The depth of the bromide plume was around 30 to 60 cm at the top and the mid slope positions, and around 60 cm at the low slope position (Table 4.5).

Similarly, the bromide vertical redistributions within slopes 7, 8, and 9 from the SE 9 landscape were not significantly different ($P=0.3819$) at the top and the mid slope positions, but significantly different between the low and the top slope positions ($P<0.0001$), and the low and the mid slope positions ($P<0.0001$) (Figure 4.6). The depths of the bromide plume at the top and the mid slope positions were approximately 30 to 60 cm. Slope 7 showed a plume at the low slope position situated at a depth of 30 cm, but the concentrations of bromide within slopes 8 and 9 were lower than 100 mg/kg and these slopes did not show a bromide plume at the low slope position (Table 4.6).

Spring gravimetric moisture content (GMC)

The result of the ANOVA showed significantly lower GMC in the NE 8 (Table 4.9) than SE 9 landscape ($P=0.035$) (Table 4.8). The GMC was significantly variable among the slope positions ($P<0.0001$), and among depths ($P<0.0001$). However, the GMC variation among the distances from a bromide plot was not significant ($P=0.492$). In both landscapes, the GMC and the depth of the wetting front increased from the top, to the mid, and to the low slope positions.

Fall vertical redistribution of bromide

The ANOVA of the vertical redistribution of bromide concentration after a complete year showed significant differences between the landscapes ($P=0.022$) (Figure 4.5 and 4.6). Still, bromide concentrations were found at 120 cm in all bromide plots. The bromide redistribution at the top, mid and low slope positions was not significantly different between landscapes ($P=0.473$, $P=0.085$ and $P=0.115$, respectively).

The ANOVA of the bromide vertical redistribution patterns was not significantly different between the top and mid, top and low, and mid and low slope positions within either the NE 8 landscape (P=0.1011, P=0.0641, and P=0.8467, respectively) (Figure 4.5) or the SE 9 landscape (P=0.4622, P=0.2672 and P=0.7043, respectively) (Figure 4.6). The bromide plume depth within slopes 10, 11, and 12 from the NE 8 landscape was situated around 30 to 60 cm at the top and the mid slope positions, and below 60 cm at the low slope positions (Table 4.5). The bromide plume depth within slopes 7, 8, and 9 from the SE 9 landscape was situated around 30 to 60 cm at the top and the mid slope positions, but no plume was detected at the low slope (Table 4.6).

Temporal variation of bromide vertical redistribution pattern

The ANOVA showed a significant difference between the spring and the fall bromide redistribution (P<0.0001). In the NE 8 landscape, the depth of the bromide plume generally remained constants from the spring to the fall sampling; however, the concentration of the bromide plume generally decreased over time (Table 4.5). In the SE 9 landscape, the depth of the bromide plume increased from the spring to the fall, and the concentration of the bromide plume generally decreased over the growing season (Table 4.6). The change in the depth of the bromide plume indicated that the downward movement of the bromide plume over the growing season was relatively greater in the SE 9 landscape compared to the NE 8 landscape. However, there was no variation in the diminution of the concentration of the bromide plume over the growing season between the landscapes.

The variations of the bromide vertical redistribution over time were statistically significant at the top, mid, and low slope positions (all P <0.0001) (Figure 4.5 and 4.6). The differences between the bromide redistribution at the top and mid slope positions in the spring and the fall were not statistically significant in the NE 8 (P=0.7963 and P=0.3433, respectively) and SE 9 (P=0.5063 and P=0.3433, respectively) landscapes. However, the bromide redistribution between the spring and the fall was significantly different at the low slope position from the NE 8 ($P<0.0001$) and SE 9 ($P<0.0001$) landscapes.

Fall gravimetric moisture content (GMC)

The ANOVA of the variation in the GMC between the landscapes was not significant ($P=0.295$). However, according to the average GMC, the SE 9 landscape tended to have greater GMC than the NE 8 landscape (Tables 4.7 and 4.8). The GMC was relatively variable among slope positions, and among depths of sampling ($P<0.0001$ and $P<0.0001$, respectively). The GMC variation among the distance from a bromide plot was not significant ($P=0.492$). In both landscapes, the GMC and the depth of the wetting front increased from the top, to the mid, and to the low slope positions, respectively.

4.3.6. Short-term leaching potential classification

The leaching potential index based on the SPI and plan curvature measurement predicted very low to low leaching potential at the top slope position. The leaching potential of the mid slope positions varied from very low, low, and high leaching potential. The leaching potential at the low slope position was high for all slopes, in both landscapes (Table 4.5 and 4.6). No very high leaching category was predicted within the bromide plot locations.

Prediction of the variation of leaching potential during spring

The ANOVA of the bromide redistribution showed significant differences between high and low leaching potential plots, as well at the high and very low leaching potential plots during spring ($P<0.0001$ and $P=0.0001$, respectively). The bromide vertical redistribution at the very low leaching potential plots were not significantly different from those at the low leaching potential plots ($P=0.4334$) (Tables 4.5 and 4.6).

The depth of the bromide plume tended to be greater, and the concentration of the bromide plume tended to be lower within high leaching potential plots compared to the low and very low leaching potential plots. Within the 8 high leaching potential plots, 5 plots had the bromide plume located at 60 cm deep and beyond, while within the 10 low and very low leaching potential plots, 8 plots had the bromide plume located within the first 30 cm of depth. Similarly, 4 of the 8 high leaching potential plots had the maximum concentration in the bromide plume below 200 mg/kg, and all the 10 low and very low leaching potential plots had a concentration above 200 mg/kg.

There was no significant difference in bromide vertical redistribution at the low and very low leaching potential plots between the landscapes (P=0.243 and P=0.476, respectively). However, the bromide vertical redistribution pattern at the high leaching potential plots from the NE 8 landscape was significantly different than that at the SE 9 landscape (P=0.025). The depth of the centre plume within the SE 9 landscape was greater than that within the NE 8 landscape, and the bromide plume concentrations were generally higher in the SE 9 than the NE 8 landscape.

Prediction of the variation of the leaching potential during fall

There was no statistically significant difference between the high and the low leaching potential plots, between the high and the very low leaching potential plots, and between the very low and low leaching potential plots during fall (P=0.4447, P=0.5578, and P=0.9819, respectively) (Tables 4.5 and 4.6). However, the depth of the bromide plume was likely to be greater, and the concentration of the bromide plume was likely to be lower, in the high leaching potential plots compared to the low and the very low leaching potential plots. Within the 8 high leaching potential plots, 4 plots did not show concentrations > 100 mg/kg within the 120 cm of sampling depth, and within the 10 low and very low leaching potential plots, 9 plots showed concentrations > 100 mg/kg within the first 60 cm of sampling depth.

Prediction of the variation of leaching potential through time

The variation between the bromide vertical redistribution during spring and during fall was not significant for the very low ($P=0.661$) and low leaching potential plots ($P=0.692$). However, there was significant variation between the bromide vertical redistribution over the growing season at the high leaching potential plots ($P <0.0001$). The position of the centre plume during spring moved downward during the growing season in 5 of the 8 high leaching potential plots, and in 5 of the 10 low and very low leaching potential plots.

4.4. Discussion

4.4.1. Spatial and temporal variability of leaching

Leaching

After one snowmelt event and one growing season, bromide concentrations were found at 120 cm of depth in each bromide plot. Dyck et al. (2003) found a similar intensity of leaching with a chloride tracer study in hummocky landscapes. Majid et al. (1994) measured leaching effects on a bromide tracer to a depth of 60 cm to 150 cm after 560 mm of rainfall.

Deep leaching over a short period of time in the root zone has often been attributed to preferential flow (Bronwijk et al., 1995; Heppell et al., 2000; Olson and Cassel, 1999). Bronswijk et al. (1995) suggested that the short-term leaching process in heavy clay soils is mainly by-pass flow, and Heppell et al. (2000) reported that up to 86% of the vertical movement of water in the A horizon is due to by-pass flow. In this case, the depth at which 1 mg/kg of bromide was detected suggests that preferential or by-pass flows may be the main leaching process within all experimental plots.

Tyler and Walker (1994) indicated that when recharge was small, the results of tracer studies of leaching within the root zone could significantly overestimate the recharge because of variation of leaching intensity with depth. Therefore, leaching in the root zone may not be directly related to recharge. Hayashi et al. (1998b) reported that the chloride cycle occurs within 500 m to 600 m of depth, and only a very small amount of solutes escape from the cycle to enter the groundwater flow and move into deep aquifers. Dyck et al. (2003) reported that the initial movement of chloride tracer through the root zone was relatively quick and reached 134 cm within 4 years of the application, but the movement of chloride slowed down once past the root zone and moved from 134 cm to 168 cm in only 30 years. These results indicate that the intensity of leaching may drop considerately in the weathered till below the root zone.

Variation of leaching between landscapes

The variation of leaching between landscapes may derive from the variation in the water budget between the landscapes. The snow survey did not show variation in snow accumulation between the landscapes, but ephemeral ponds were formed during snowmelt only in the SE 9 landscape. The NE 8 landscape had greater elevation and different landscape morphology than the SE 9 landscape; therefore, during the snowmelt, the hydrological function of the NE 8 landscape may have been different than the SE 9 landscape. The results indicated greater infiltration along the top and mid slope position after the snowmelt within the NE 8 landscape compared to the SE 9 landscape; consequently, less snowmelt water run off the slope side in the NE 8 landscape than in the SE 9 landscape. The snowmelt water was more uniformly distributed among the slope positions within the NE 8 landscape than the SE 9 landscape, and the water within the NE 8 landscape was likely stored in the soil matrix.

On the other hand, the low slope positions within the SE 9 landscape accumulated more snowmelt water than NE 8 landscape, which may explain the higher GMC there compared to the NE 8 landscape. According to the results from the snowmelt survey and the water balance, the water table situated at the areas under ephemeral ponds within SE 9 landscape may have dropped to allow water infiltration.

The variation of leaching during spring may also be caused by the variation of agricultural management systems between landscapes. Bicki and Guo (1991) found greater leaching of bromide tracer in the soil under continuous no-till management compared to that under four other types of tillage management because of by-pass flow. The impact of farming management on leaching intensity and soil water storage on upper landscape positions was also reported by Hayashi et al. (1998a).

The variation of cropping management may also be responsible for the variation of leaching between landscapes. The NE 8 landscape was under continuous forage, where deep root channels, already present in early spring, may have promoted infiltration. The SE 9 landscape was under canola previous to the experiment, and this type of crop may not have provided deep root channels within the soil profile.

Also, the crop on the SE 9 landscape was not seeded until the landscape was completely dry, whereas the forage crop on the NE 8 landscape was already growing. Hayashi et al. (1998a) mentioned the importance of the lateral subsurface water flow from the depression toward the upland after the infiltration of the snowmelt because of the plant evapotranspiration. Also, the root system and density associated with the vegetation over the landscapes may have influenced the vertical and lateral water movement. Dyck et al. (2003) referred to the relation between the root zone and the intensity of leaching within hummocky landscapes. The difference in plant establishment dates and plant types likely created variation in the demand of water in the root zone. Therefore, absorption of water by the roots and capillary movement within the soil matrix may have occurred earlier in the NE 8 than the SE 9 landscape.

The variation of rainfall quantity over the landscapes and the time at which the rainfall happened might also have been responsible for the variation of the leaching after the growing season between the landscapes. In a similar study, Bruce et al. (1985) reported the effect of the initial soil water content on the intensity of leaching caused by rainfall. In our case, the month of June was very dry compared to the average; therefore, the water soil storage capacity likely was high. The important precipitation during July likely infiltrated the soil surface, and increased the soil GMC without causing any leaching. The important rainfalls during August may have occurred while the soil GMC was higher than during July; therefore, the rainfalls may have been more likely to initiate important leaching.

Variation of leaching within a landscape

The results showed great variability of vertical redistribution of bromide within the study site, which supports the observation by Parsons et al. (2004), Majid et al. (1994), and Bathke et al. (1992).

In this study, the SWE was consistent among the slopes within each landscape, and was unlikely responsible for the variation of the leaching among the slopes. However, the water budget within the SE 9 landscape was variable among slope position. The bromide redistribution showed greater leaching intensity in low slope positions, especially where ephemeral ponds were formed, than in top and mid slope positions. These results reinforce the concept that solutes applied uniformly over the landscape may be portioned into several different plumes that will move through the soil at various intensities (Majid et al., 1994). The measurement of leaching is highly dependent on the location of the measurement; and extrapolation of few leaching measurements may introduce great errors. Therefore, landscape management systems should consider the spatial variation to accurately assess the leaching potential of a landscape.

The variation of intensity among slope position was reflected in the variation of clay content, SPI, elevation, slope gradient, plan curvature, and profile curvature. The low slope position presented different soil-landscape factors than the top and the mid slope positions. Majid et al. (1994) reported the importance of considering the landscape to accurately predict solute transport. This suggests that the interactions of topographic features with soil physical properties may capture some of the short-term leaching variations within a landscape.

The leaching intensity variation between the landscapes was consistent with the GMC variation. However, the depth of the wetting front was not consistent with the depth of the bromide front among the slopes and the slope positions. Olson and Cassel (1999) and Bathke (1992) reported a relation between the soil GMC and intensity of leaching; however, their work was conducted under high precipitation.

On the other hand, the slope position presenting high clay content also presented a high intensity of leaching. Soil enriched in clay may have swelled and cracked, according to the moisture content; which may have provided channels within the soil matrix, and promoted by-pass flow. Also, the depth of the soil layer enriched with clay particles was generally consistent with the depth of the bromide plume. Scientists have established that soil hydraulic properties vary across landscape positions due to changes in soil profile characteristics (Bathke et al., 1992), and studies have found relationships between leaching intensity and soil profile clay content (Bathke et al., 1992). Bruce et al. (1985) mentioned that the addition of physical soil properties to landscape features might explain the observed variation in bromide movement among slopes and slope positions. Therefore, it may be possible to predict short-term leaching intensity with a leaching potential prediction index based on soil properties such as clay content.

Temporal variation of leaching

The intensity of leaching likely changes over time. The variation of leaching within the slope positions was consistent among slopes and landscapes after one snowmelt event. However, this leaching variation pattern was not significant after one growing season, suggesting that an analysis of the vertical redistribution pattern at different times may give better understanding of short-term leaching compared to a one-time analysis of leaching.

The variation of the intensity of leaching through time after bromide application may be caused by the complexity of the water budget during the growing season. The change of the concentration in the bromide plume over the growing season is not directly connected to the intensity of leaching because of the effect of the evapotranspiration, rainfall, runoff, etc. Also, the soil properties and vegetative state of the crop prior to certain events such as rainfall might affect the leaching potential. Therefore, the integration of a temporal factor in short-term leaching potential prediction models may improve their precision.

In this study, the experimental design was adequate to assess the spatial and temporal variability of the intensity of leaching down to the root zone of 120 cm, between two agricultural landscapes, three slopes, and three slope positions. A mass balance recovery technique that included plant tissue analysis combined with evapotranspiration and runoff data might be needed to detect the wide range of the short-term leaching intensity after a growing season. Also, the depth of sampling should be increased to monitor the entire plume of bromide at each slope position.

4.4.2. Evaluation of the short-term leaching potential index

The leaching potential index based on the SPI and the plan curvature was able to correctly distinguish high leaching potential from low and very low leaching potential. The leaching potential index based on the analysis of long-term leaching potential corresponded to the variation of short-term leaching potential for extreme situations of leaching potential. However, the index was not precise enough to make a clear distinction between a low and very low leaching potential.

The leaching potential index distinguished the high leaching potential from the low and very low leaching potential. The calibration of the leaching potential index with data representing short-term leaching potential and by-pass flow, as well as data representing long-term leaching potential and matrix flow may improve the accuracy of the leaching potential prediction. Finally, the index should be calibrated and tested on various types of landscapes to improve the scope of the leaching potential prediction.

4.5. Summary and Conclusions

We used the bromide vertical redistribution pattern after one snowmelt event, and after one growing season to look into the spatial and temporal variation of leaching between two hummocky agricultural landscapes of different elevation, and among slope positions within the slopes. According to the relative intensity of the leaching measured with the bromide experiment, we tested the precision of a leaching potential index based on SPI and plan curvature measurements.

Concentrations of bromide > 1 mg/kg were found at 120 cm of depth at each slope position, from both landscapes, after the snowmelt and a growing season. However, the position of a bromide plume limited with a concentration of 100 mg/kg was useful to measure the relative intensity of leaching between the landscapes, among slopes within a landscape, and among slope positions within a landscape.

Significant variability occurred between landscapes. Contrary to the first hypothesis that leaching intensity will increase from the low to the high landscape elevation, the intensity of leaching at the low slope positions was greater at the lower elevation landscape than at the higher elevation landscape. The difference in the elevation between the landscapes may explain in part the variability of leaching intensity; however, other factors, such as the infiltration capacity along slope side, slope length, and agricultural management may also be partly responsible for the variation of leaching intensity between landscapes.

Over both landscapes, the intensity of leaching potential was greater at the low slope position compared to the top and the mid slope positions after one snowmelt event and one growing season. This corresponds to the hypothesis that leaching intensity increased moving downslope within a landscape. However, the variation of the intensity of leaching potential between the top and the mid slope position was not significant.

The depth of the soil layers that accumulated clay was similar to the depth that the bromide plume reached after the snowmelt, as well as after the growing season, which corresponds to the hypothesis that the variation of leaching intensity is related to soil physical properties. However, the GMC among slope positions did not reflect the intensity of leaching. Therefore, leaching intensity prediction systems based on soil properties reflecting leaching such as clay content may be closer to reality than systems based on moisture content.

Finally, the leaching potential index based on the soil profile index (SPI) and plan curvature measurements can be used to distinguish between high leaching potential, and low and very low leaching potential.

Table 4.1 Soil-landscape characteristics for each bromide plot location

Field	Transect	Plot	CSSC*	Solum Depth (cm)	Drainage	SPI	Elevation (m)	Slope gradient (degree)	Profile curvature (degree / 100 m)	Plan curvature (degree / 100 m)	Long-term Leaching potential**
NE 8	10	top	Calcareous BL	75	Well	1.6	775	2	2	4	Low
NE 8	10	mid	Calcareous BL	86	Well	2.6	774	2	-7	-4	High
NE 8	10	low	Humic LG	110	Poor	3.2	774	1	-6	-7	High
NE 8	11	top	Orthic BL	58	Well	1.0	774	5	7	2	Very Low
NE 8	11	mid	Rego BL	42	Well	0.6	773	6	-2	-3	Very Low
NE 8	11	low	Humic LG	100	Poor	2.2	772	2	-16	-7	High
NE 8	12	top	Orthic BL	50	Well	1.2	773	5	14	12	Low
NE 8	12	mid	Gleyed Eluviated BL	65	Imperfect	2.0	772	7	1	13	Low
NE 8	12	low	Humic LG	95	Imperfect-Poor	2.5	771	2	-23	-3	High
SE 9	9	top	Orthic BL	19	Well	0.3	756	0	6	23	Very Low
SE 9	9	mid	Calcareous BL	90	Moderate-Well	2.6	756	2	12	2	Low
SE 9	9	low	Humic LG	100	Poor	2.8	755	2	-3	-17	High
SE 9	8	top	Orthic BL	50	Well	1.5	754	3	14	7	Low
SE 9	8	mid	Orthic BL	45	Moderate-Well	0.9	754	4	5	3	Very Low
SE 9	8	low	Humic LG	70	Poor	1.9	753	3	-14	-6	High
SE 9	7	top	Orthic BL	56	Well	1.5	753	3	7	1	Low
SE 9	7	mid	Calcareous BL	50	Well	1.3	753	4	2	-4	High
SE 9	7	low	Humic LG	100	Imperfect-Poor	2.9	752	2	-18	-7	High

* Canadian Soil System of Classification
BL = Black Chernozem
LG = Luvic Gleysol
** SPI < 1 = Very Low; 1 < SPI < with plan curvature < 0 = Low; 1 < SPI < with plan curvature > 0 = High; SPI > 4 = Very high

Table 4.2 Total clay fractions (%)

Slope position	Depth	SE 9 Transect 7	SE 9 Transect 8	SE 9 Transect 9	NE 8 Transect 10	NE 8 Transect 11	NE 8 Transect 12	*Average*
TOP	0-15	27.9	35.5	20.3	28.2	31.6	27.7	*28.5*
TOP	15-30	25.4	28.7	27.4	25.6	28.7	21.1	*26.1*
TOP	30-60	27.4	31.5	25.2	28.1	37.9	26.9	*29.5*
TOP	60-90	33.4	33.5	30.4	31.8	30.7	20.3	*30.0*
TOP	90-120	24.5	30.2	na	32.3	27.9	23.9	*27.7*
Average		*27.7*	*31.9*	*25.8*	*29.2*	*31.4*	*24.0*	
MID	0-15	28.5	34.3	29.3	24.8	25.3	30.5	*28.8*
MID	15-30	24.8	31.0	21.4	18.4	19.2	23.1	*23.0*
MID	30-60	35.1	35.5	27.8	31.9	50.7	29.7	*35.1*
MID	60-90	23.7	25.4	35.1	32.3	52.9	17.4	*31.1*
MID	90-120	26.7	30.8	27.5	28.4	38.0	13.1	*27.4*
Average		*27.7*	*31.4*	*28.2*	*27.2*	*37.2*	*22.8*	
LOW	0-15	26.5	47.1	35.3	31.7	32.9	28.5	*33.7*
LOW	15-30	19.1	23.7	39.5	27.0	30.0	49.2	*31.4*
LOW	30-60	33.0	32.0	33.3	37.2	34.3	44.3	*35.7*
LOW	60-90	38.1	34.4	44.5	38.6	34.2	51.8	*40.3*
LOW	90-120	34.8	32.6	36.3	36.9	32.8	40.1	*35.6*
Average		*30.3*	*34.0*	*37.8*	*34.3*	*32.8*	*42.8*	

Table 4.3 Normal air temperatures (1971-2000) and 2004 temperatures from Camrose weather station

	Normal			***2004***		
Temperature (Celsius)	Average	Average Max	Average Min	Average	Extreme Max	Extreme Min
January	-13.4	-7.9	-18.8	-15.7	7.5	-41.0
February	-10.4	-4.7	-16.1	-8.2	6.5	-32.0
March	-4.5	0.9	-9.7	-2.3	[illegible]	[illegible]
April	4.4	10.4	-1.6	5.7	27.0	-6.0
May	10.7	16.9	4.5	8.8	27.0	-8.5
June	14.6	20.2	8.9	13.8	29.0	1.5
July	16.5	22.2	10.8	16.4	31.5	3.0
August	15.8	21.9	9.7	14.1	29.0	1.5
September	10.3	16.2	4.4	9.5	23.5	-1.0
October	4.6	10.6	-1.3	1.2	24.5	-16.5
November	-5.2	-0.4	-10.0	-1.3	11.0	-11.5
December	-11.1	-6.0	-16.3	-8.8	10.0	-28.0

Shaded row represents snowmelt event in 2004

Table 4.4 Snowmelt water balance from ponds survey in SE 9 study site from March 30 until April 2, 2004

Field	Transect	Change in storage mm/h	Evaporation* mm/h	Infiltration mm/hr	Net
SE 9	9	-6.91	-0.02	-6.89	Loss
SE 9	8	0.86	-0.08	0.94	Gain
SE 9	7	-9.90	-0.06	-9.84	Loss

Table 4.5 Bromide redistribution from the NE 8 landscape

Landscape		NE 8					
Transect		10		11		12	
Top slope position							
Long-term leaching potential index		Low		Very Low		Low	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Front depth*	cm	> 105	> 105	> 105	> 105	> 105	> 105
Front distance**	cm	140	220	140	220	140	220
Centre plume depth[+]	cm	30	30	60	60	30	30
Centre plume distance [++]	cm	20	0	20	20	20	20
BrMC***	mg/kg	459	367	254	218	782	420
Mid slope position							
Long-term leaching potential index		High		Very Low		Low	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Front depth*	cm	> 105	> 105	> 105	> 105	> 105	> 105
Front distance**	cm	140	220	140	220	140	220
Centre plume depth[+]	cm	30	30	60	60	30	60
Centre plume distance [++]	cm	20	60	20	20	20	20
BrMC***	mg/kg	418	263	811	269	782	142
Low slope position							
Long-term leaching potential index		High		High		High	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Front depth*	cm	> 105	> 105	> 105	> 105	> 105	> 105
Front distance**	cm	140	220	140	220	140	220
Centre plume depth[+]	cm	> 60	none	60	60	60	60
Centre plume distance [++]	cm	20	none	20	-20	20	20
BrMC***	mg/kg	154	90	306	280	664	585

*Maximum depth of bromide concentration > 1 mg/kg (bromide front)
**Maximum distance from bromide the plot of a concentration > 1 mg/kg
***Bromide maximum concentration in the plume (center plume concentration)
[+]Maximum depth of the bromide concentration > 100 mg/kg (center plume)
[++]Maximum distance from the bromide plot of a concentration > 100 mg/kg

Table 4.6 Bromide redistribution from the SE 9 landscape

Landscape		SE 9					
Transect		9		8		7	
Top slope position							
Long-term leaching potential index		Very Low		Low		Low	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Front depth*	cm	> 105	> 105	> 105	> 105	90	> 105
Front distance**	cm	140	220	140	220	140	220
Centre plume depth⁺	cm	30	60	30	none	30	60
Centre plume distance ⁺⁺	cm	20	140	20	none	-20	20
BrMC***	mg/kg	400	183	841	79	206	183
Mid slope position							
Long-term leaching potential index		Low		Very Low		High	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Front depth*	cm	> 105	> 105	90	> 105	> 105	> 105
Front distance**	cm	140	220	140	220	140	220
Centre plume depth⁺	cm	30	30	30	60	30	60
Centre plume distance ⁺⁺	cm	20	20	20	-20	20	20
BrMC***	mg/kg	246	132	267	320	994	284
Low slope position							
Long-term leaching potential index		High		High		High	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Front depth*	cm	> 105	> 105	> 105	> 105	> 105	> 105
Front distance**	cm	140	220	140	220	140	220
Centre plume depth⁺	cm	none	none	none	none	30	none
Centre plume distance ⁺⁺	cm	none	none	none	none	0	none
BrMC***	mg/kg	87	19	89	89	155	71

*Maximum depth of bromide concentration > 1 mg/kg (bromide front)
**Maximum distance from bromide the plot of a concentration > 1 mg/kg
***Bromide maximum concentration in the plume (center plume concentration)
⁺Maximum depth of the bromide concentration > 100 mg/kg (center plume)
⁺⁺Maximum distance from the bromide plot of a concentration > 100 mg/kg

Table 4.7 Gravimetric moisture content from the NE 8 landscape

Landscape		NE 8					
Transect		10		11		12	
Top slope position							
Long-term leaching potential		Very Low		Low		Low	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Average moisture content	%	9	14	8	9	9	12
Depth of wetting front	cm	15	105	0	15	15	30
Mid slope position							
Long-term leaching potential		Low		Very Low		High	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Average moisture content	%	11	13	11	14	14	18
Depth of wetting front	cm	> 105	> 105	60	105	> 105	> 105
Low slope position							
Long-term leaching potential		High		High		High	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Average moisture content	%	19	23	23	28	21	29
Depth of wetting front	cm	> 105	> 105	> 105	> 105	> 105	> 105

Table 4.8 Gravimetric moisture content from the SE 9 landscape

Landscape		SE 9					
Transect		9		8		7	
Top slope position							
Long-term leaching potential		Very Low		Low		Low	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Average moisture content	%	12	13	15	20	19	20
Depth of wetting front	cm	60	60	90	> 105	90	> 105
Mid slope position							
Long-term leaching potential		Low		Very Low		High	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Average moisture content	%	14	15	18	23	17	18
Depth of wetting front	cm	> 105	> 105	90	> 105	105	> 105
Low slope position							
Long-term leaching potential		High		High		High	
Sampling time		Spring	Fall	Spring	Fall	Spring	Fall
Average moisture content	%	22	24	23	25	22	24
Depth of wetting front	cm	> 105	> 105	> 105	> 105	> 105	> 105

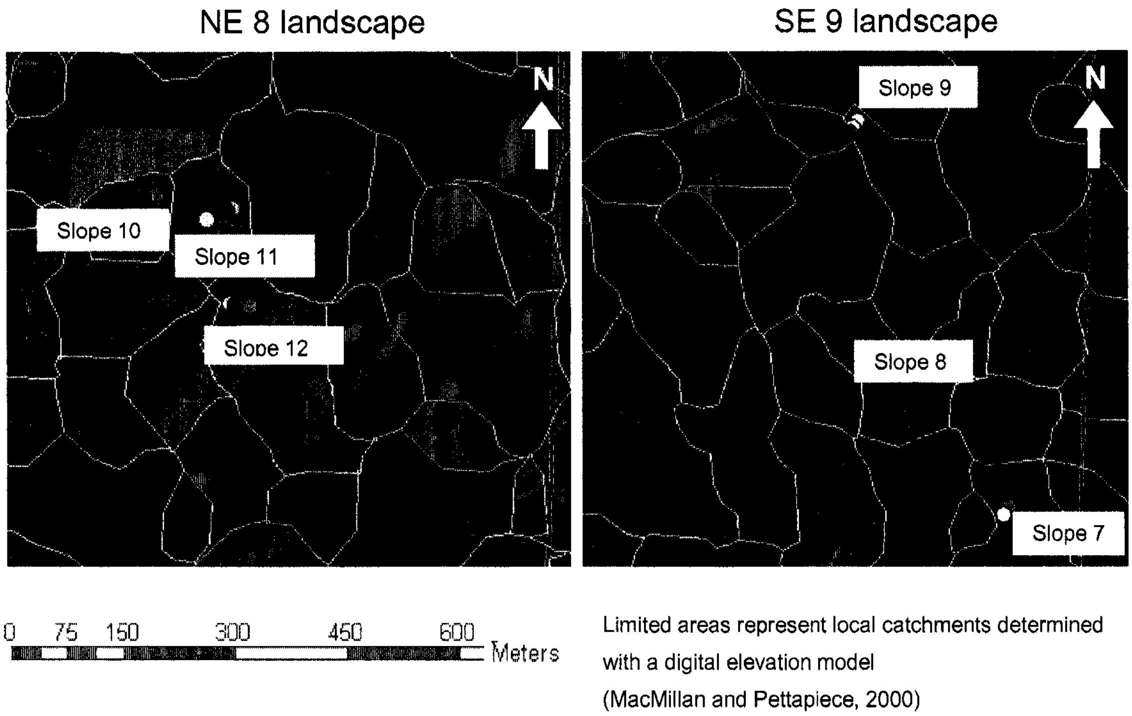

Figure 4.1 Study site, Bittern Lake, Alberta, Canada

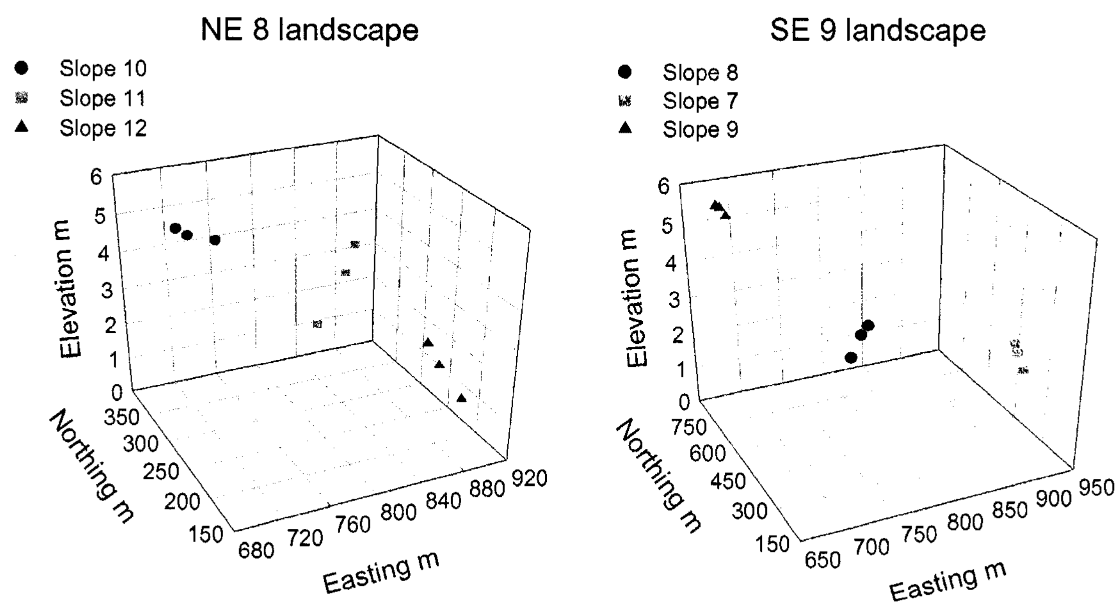

Figure 4.2 Bromide plot relative positions

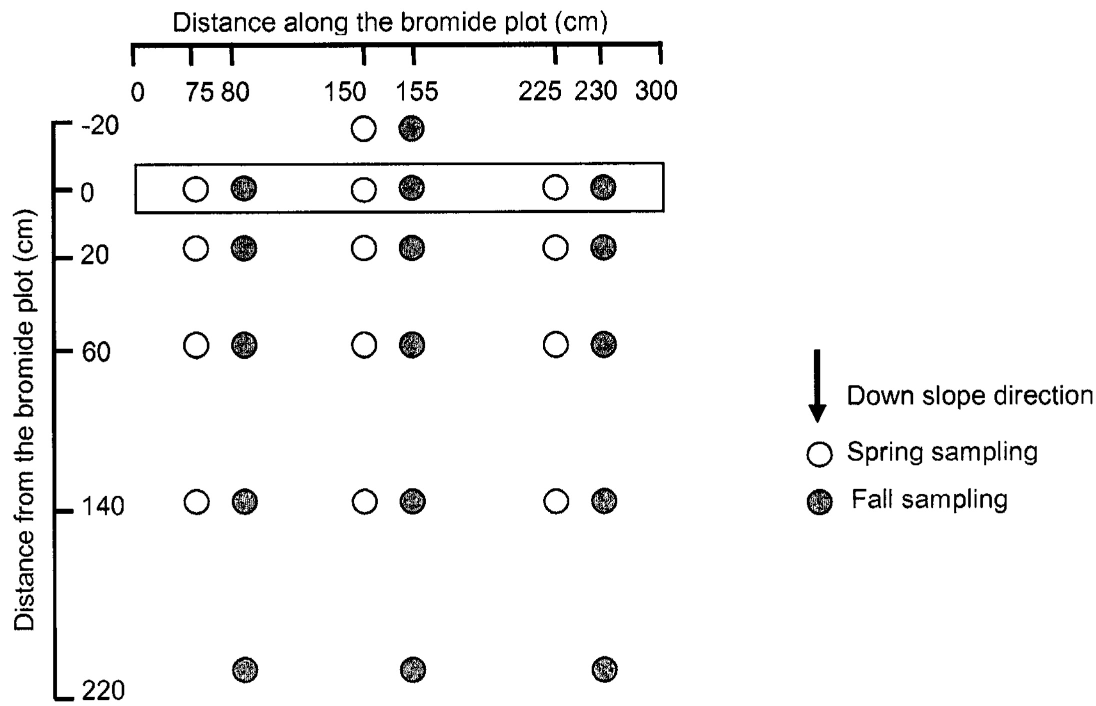

Figure 4.3 Sampling design for each bromide plot

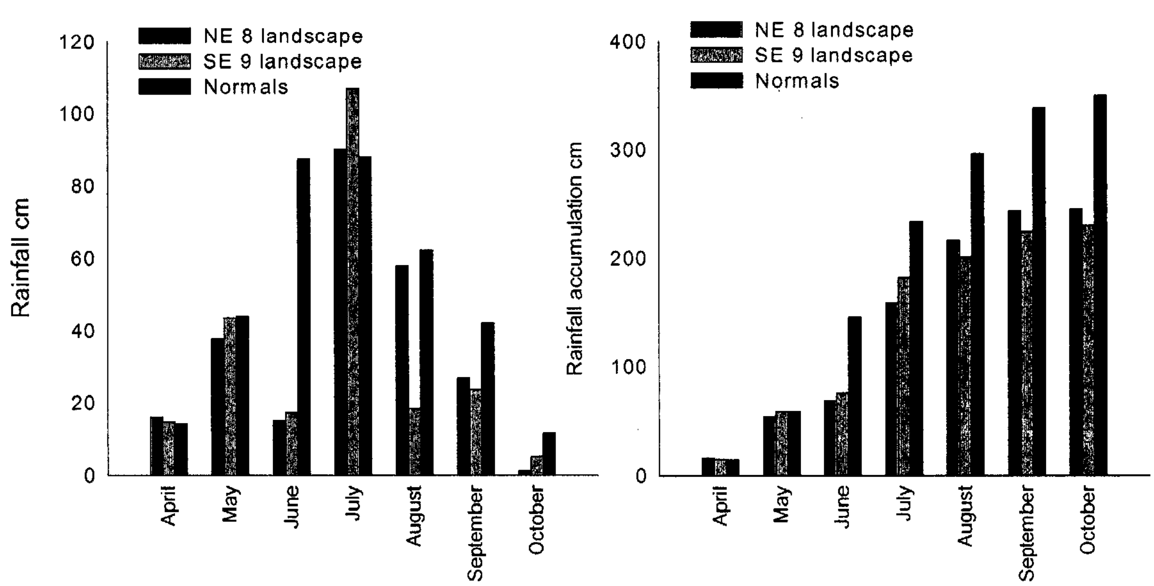

Figure 4.4 Spring and summer rainfall, 2004 (Normals from Camrose Weather Station, 15 km east of study site (Government of Canada, 2002))

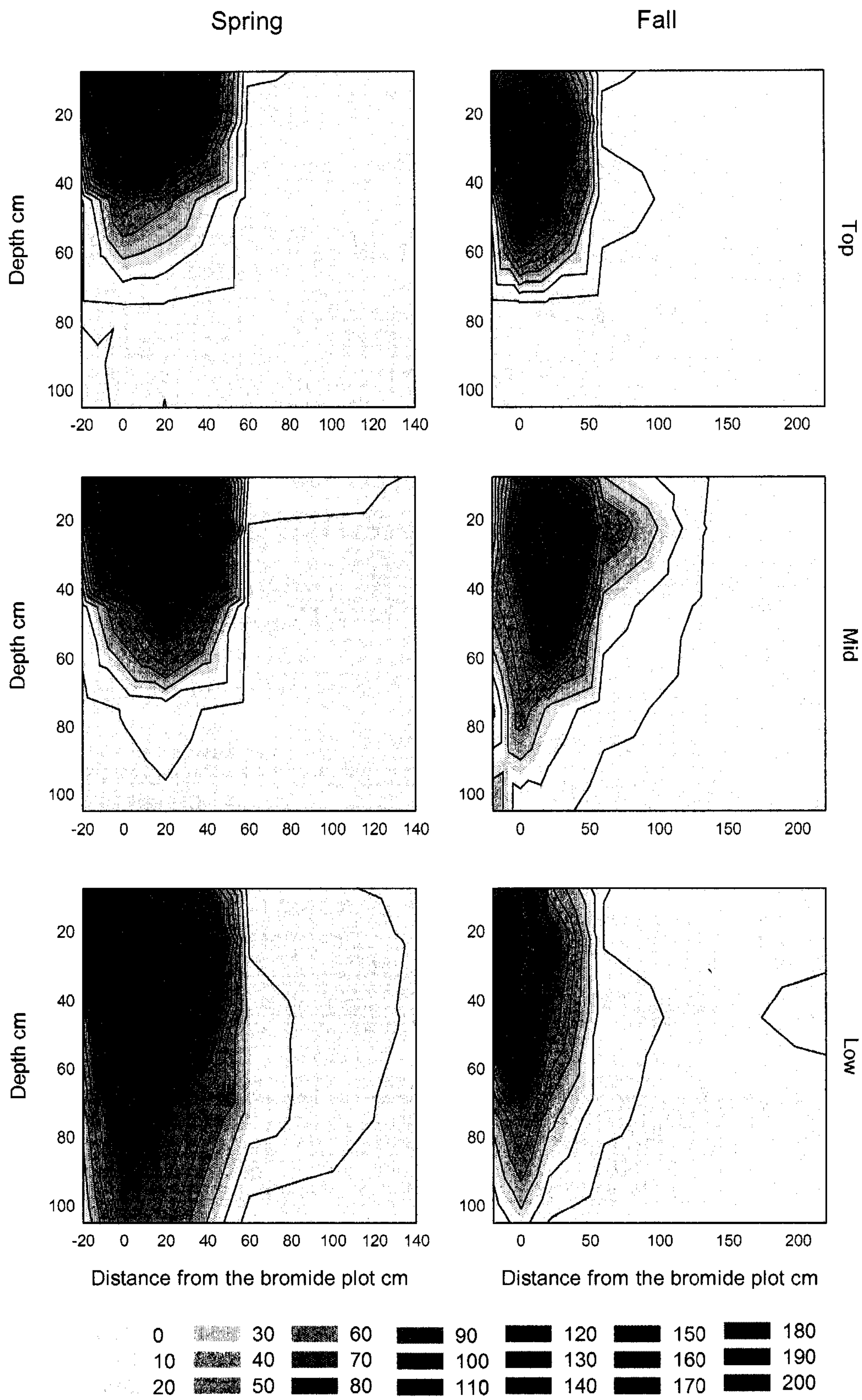

Figure 4.5 Average bromide concentrations (mg/kg), NE 8 landscape

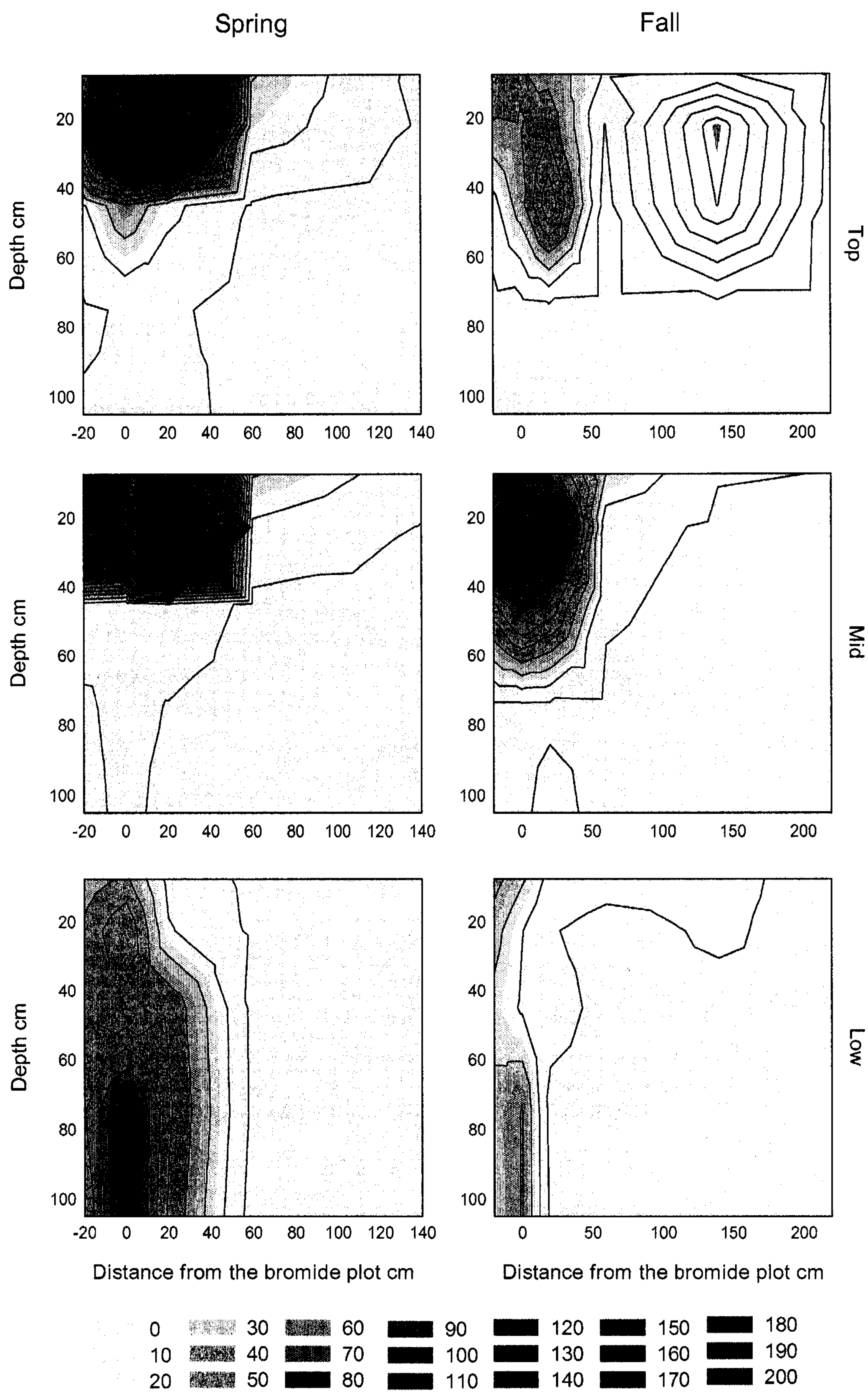

Figure 4.6 Average bromide concentrations (mg/kg), SE 9 landscape

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5. Synthesis

Groundwater quality is a main issue in Alberta, particularly for the rural communities. There is evidence that intense agricultural practices contaminate groundwater via leaching of pesticides, fertilizers, and bacteria through soil profiles. There is little information available on the variability of leaching within hummocky agricultural landscapes, and agricultural land management has generally ignored the variability of leaching.

The main goal of this study was to assess the variability of leaching within hummocky agricultural landscapes. The first objective was to measure the long-term and short-term spatial and temporal variability of leaching potential. The second objective was to build a leaching potential index based on long-term leaching to predict the short and long term leaching variability within hummocky agricultural landscapes.

5.1 Spatial and temporal variability of leaching

5.1.1. Summary

First, we investigated the relationship between spatial variability of long-term leaching and the distribution of soil profiles within two hummocky agricultural landscapes. We examined how the variety of soil profiles can be grouped into small, homogeneous clusters according to their degree of soil development. The clusters represented the variability of long-term leaching as shown with sulphate and EC profiles in one landscape.

Second, we studied the spatial and temporal variability of leaching after one snowmelt event and one growing season with a non-reactive water tracer (bromide) within two landscapes. Significant variability between landscapes and within landscapes occurred. Between the landscapes, the variation of intensity of leaching depended on the hydrological function of the landscape. Within a landscape, the intensity of leaching potential depended on the hydrology of each hillslope, and on the soil properties and topographic characteristics of each hillslope position. The combination of soil characteristics with topographic features would give an excellent estimate of the relative intensity of leaching.

5.1.2. Applications and future work

The movement of contaminants within an agricultural landscape to groundwater depends upon the intensity of leaching. Variability of the intensity of leaching among and within landscapes has been ignored in agricultural land management because of deficient information and difficulties to interpret and integrate existing information into land management systems. Information on the variability of leaching on a scale similar to a realistic unit for agricultural land management is critical to build links between research and practical integrations of knowledge in land management practices.

This study examined leaching within two hummocky agricultural landscapes from Central Alberta, Canada. Similar studies on various landscapes over time will broaden the scope of application of our knowledge, and provide important information on the limitation of our findings.

This research examined the variation of leaching that occurs on a very short-term, after one snowmelt event and one growing season, and also that which occurs on a very long-term basis, after hundred of years of soil development. However, this project does not provide information on the temporal variation of the intensity of leaching over time. Dyck et al. (2003) have showed that water movement pattern changes over time. Therefore, studies on the variation of intensity of leaching over the years will provide valuable information to accurately assess the movement of solute through the soil matrix and to evaluate the risk of groundwater contamination from agricultural land management practices.

Studies have shown that the intensity of leaching varied according to the leaching depth. Leaching may be intense in the root zone, but the intensity may be considerably reduced below the root zone (Dyck et al., 2003; Hayashi et al., 1998a; Tyler and Walker, 1994). Studies examining very short term leaching may over-estimate the intensity of leaching that occurs below the root zone, and studies looking at very long-term leaching may measurably under-estimate the leaching intensity that occurs within the root zone. Therefore, study of water movement below the root zone may improve the understanding of leaching intensity.

Finally, this project focuses on the vertical redistribution of a water tracer after a snowmelt and a growing season. Information on spatial and temporal variability of lateral movement of water may provide information to complete and improve our understanding of solute movement within the soil matrix on an agricultural landscape (Hayashi et al., 1998b; Parsons et al., 2004; Rosenberry and Winter, 1997; Whetter, 2004).

5.2 Leaching potential index

5.2.1 Summary

The variability of leaching on a short term was dependent of landscape morphology and soil profile characteristics. Soil classification systems are great tools to describe soil profile characteristics, but the integration of such descriptive classification systems in computer models or landscape management systems is complex. The soil profile index (SPI) is a numerical index based on soil classification to measure the relative intensity of soil development attributable to water interaction with the soil matrix. In this study, SPI alone was useful to differentiate dramatically different leaching potentials within an agricultural landscape. Therefore, SPI can be beneficially used to integrate soil development characteristics in topographically based landscape management and land evaluation models.

The combination of SPI with plan curvature measurements enhanced the precision of the prediction of the leaching potential, and allowed differentiating among very low, low, high, and very high intensity of long-term leaching potential. We tested the accuracy of the leaching potential index to assess the spatial and temporal variability of short-term leaching with a non-reactive water tracer (bromide) on both study landscapes. The leaching potential index was efficient to distinguish between high leaching potential, and low and very low leaching potential.

5.2.2. Applications and future work

SPI alone is an economic tool to identify locations of extreme intensity of leaching within an agricultural landscape. The precision of the index can be increased to detect a gradient of relative intensity between the extreme intensities of leaching. In this study, we used plan curvature to enhance the accuracy of the SPI prediction of leaching potential. It was not said, however, that the SPI cannot reach an acceptable level of precision without landscape morphology data, and improvement of the SPI to predict leaching potential may be achieved through further research.

The index of leaching potential was a useful tool to delineate the areas of high and very high leaching potential within a local scale. These areas represent a small percentage of an agricultural landscape, and are the ones that should primarily be targeted by land management practices to prevent movement of contaminants toward groundwater.

The leaching potential index was validated with sulphate concentration profile and electrical conductivity profile data within a single landscape. Additional water movement tracers such as tritium and oxygen^{18} may improve the accuracy of the index. Also, datasets from various landscapes will be helpful to enhance the scope of application of the index.

The leaching potential index was tested on two hummocky agricultural landscapes in Central Alberta, and additional landscapes and environments should be tested before further inferences are drawn. Also, it may be interesting to compare the prediction of leaching potential based on topographic data with the prediction of leaching potential based on the index, to evaluate the amount of precision that each technique offers, and to assess the benefit in the integration of the leaching potential index into topographically based land management systems.

The acknowledgement of the spatial variability of leaching was the key to develop a successful prediction system that will be useful to improve the agricultural practices, and maintain the quality of the groundwater resources (De Jong and Reynolds, 1995). The leaching potential index would help in the development of projects to improve agricultural practices, agricultural and environmental sustainability, and the protection of human health within the rural community.

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Whetter, D.A. 2004. Solute redistribution as influenced by soil properties in relation to landscape morphology in a glacial till landscape in Manitoba. M.Sc. thesis, University of Manitoba, Winnipeg.

Appendix A

A classification system to determine long-term leaching potential within an agricultural hummocky landscape

A1 Cluster analysis, NE 8 landscape

SAS input

```
Title "Hay field raw data-low variable";
Title2 "Hierarchical cluster analysis";
Options ls=90 ps=60 nodate nonumber formdlim='*';
data Hraw03;
input Ah     Ahk    Ahe    Ae     AC     AB     Bt     Bm     Bmk    Btj    BC;
cards;
15     0      0      0      0      0      14     0      0      48     0
12     0      0      0      0      0      0      41     0      0      0
;
run;

data sites;
input site $ @@;
Cards;
13-1 13-50;
run;

data Hraw03;
merge sites Hraw03;
run;

proc cluster method=complete data=Hraw03 ccc outtree=treeC;
var Ah     Ahk    Ahe    Ae     AC     AB     Bt     Bm     Bmk    Btj    BC;
id site;
title "Complete Linkage Clustering of the Hay field raw data-low
variable, 2003";
run;

proc tree data=treeC;
title "Complete Linkage Clustering of the Hay field raw data-low
variable, 2003";
proc print data=treeC;
run;

proc plot data=treeC;
plot _ccc_*_ncl_="*" /haxis=0 to 15 vaxis=-5 to 5  ;
title 'CCC vs Number of cluster, complete clustering, Hay field, raw
data-low variable, 2003';
run;
```

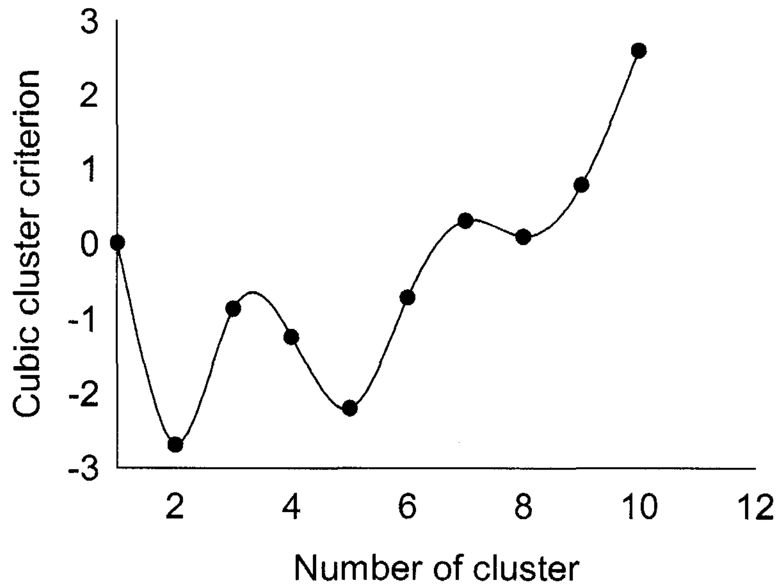

Figure A1 Cubic cluster criterion, NE 8 landscape

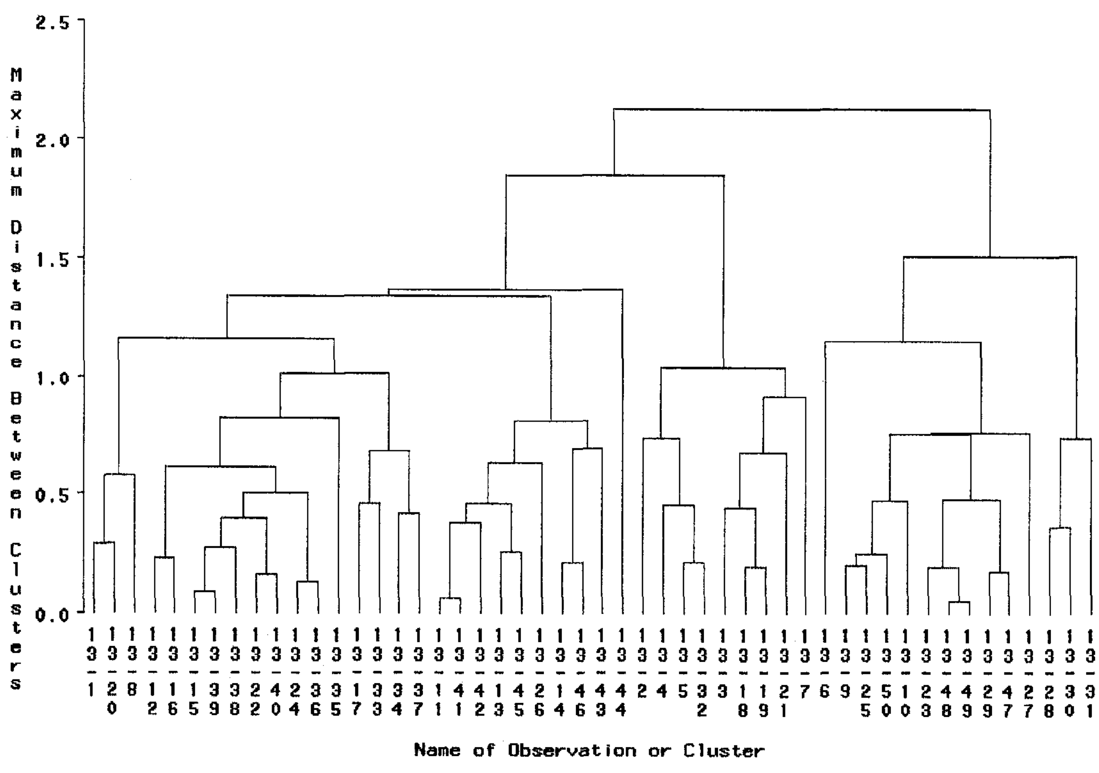

Figure A2 Complete linkage cluster analysis, NE 8 landscape

A2 Cluster analysis, SE 9 landscape

SAS input

```
Title "Canola field raw data-low variables";
Title2 "Hierarchical cluster analysis";
Options nodate nonumber formdlim='*';
data craw03;
input Ah Ahe Ahk Ae AB Bt Bm Btj Bmk;
cards;
17.00 0.00  0.00  0.00  0.00  38.00 0.00  0.00  0.00
;
run;

data sites;
input site $ @@;
Cards;
14-1 14-50
;
run;

data craw03;
merge sites craw03;
run;

proc cluster method=complete data=craw03 ccc outtree=treeC;
var Ah Ahe Ahk Ae AB Bt Bm Btj Bmk;
id site;
title "Complete Linkage Clustering of the Canola field raw data-low
variables, 2003";
run;

proc tree data=treeC;
title "Complete Linkage Clustering of the Canola field raw data-low
variables, 2003";
run;
proc print data=treeC;
run;

proc plot data=treeC;
plot _ccc_*_ncl_="*" / haxis=1 to 15 vaxis=-5 to 5;
title 'CCC vs Number of cluster, complete clustering, Canola field, raw
data-low variables, 2003';
run;
```

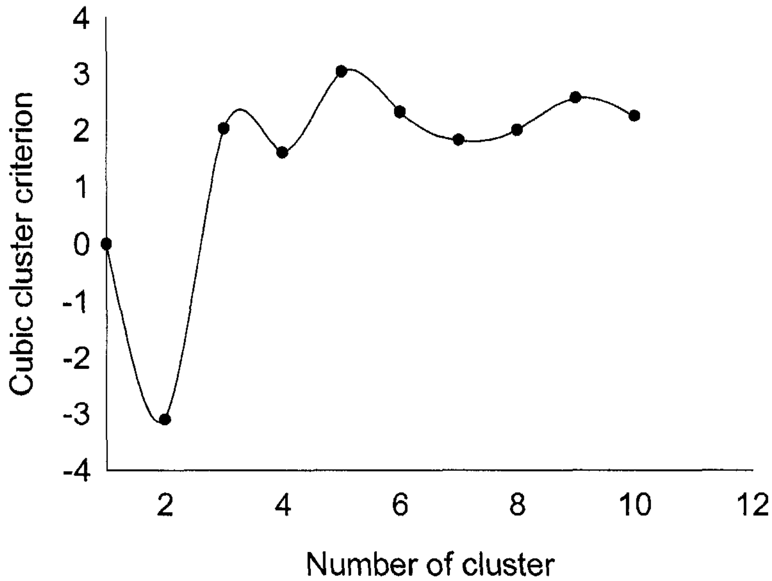

Figure A3 Cubic cluster criterion, SE 9 landscape

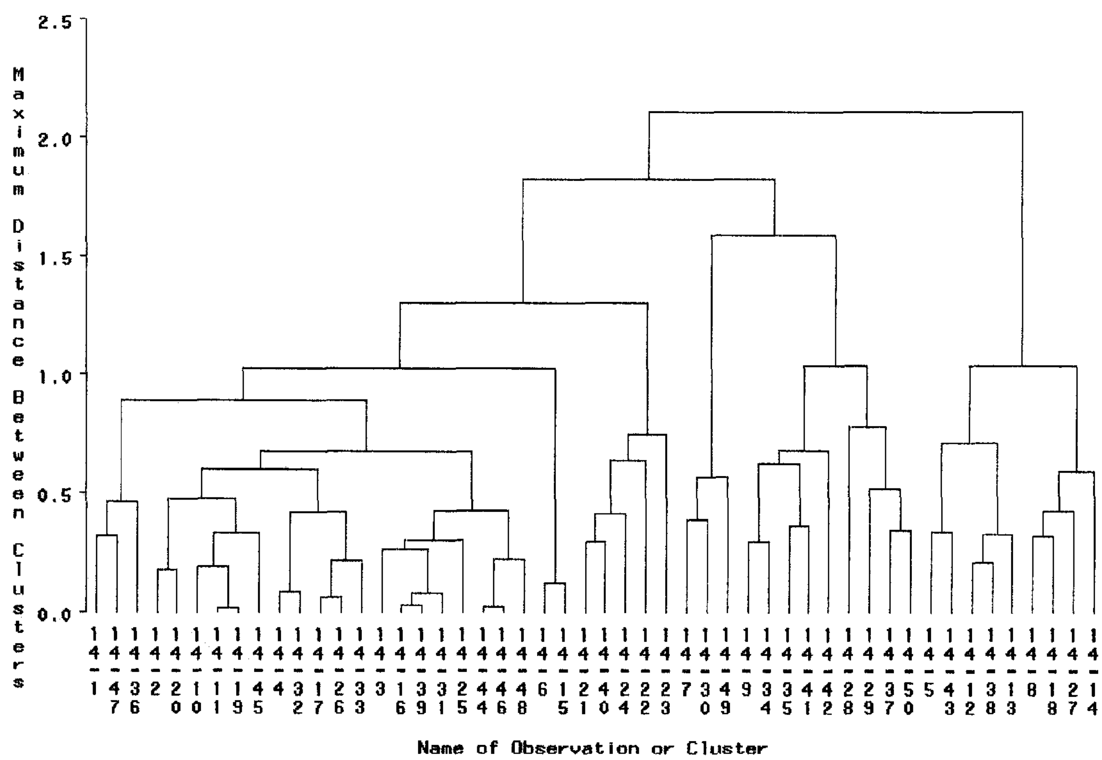

Figure A4 Complete linkage cluster analysis, SE 9 landscape

A 3 Cluster analysis, all data

SAS input

```
Title "All data raw data-low variables";
Title2 "Hierarchical cluster analysis";
Options nodate nonumber formdlim='*';
data allraw03;
input Ah Ahk Ahe Ae AB AC Bt Bg Bnt Bm Bmk Bk Btj BC;
cards;
17    0    0    0    0    0    38    0    0    0    0    0 …
;
run;

data sites;
input site $ @@;
Cards;
14-1 … 13-50
;
run;

data allraw03;
merge sites allraw03;
run;

proc cluster method=complete data=allraw03 ccc outtree=treeC;
var Ah Ahk Ahe Ae AB AC Bt Bg Bnt Bm Bmk Bk Btj BC;
id site;
title "Complete Linkage Clustering of the all data field raw data-low
variables, 2003";
run;

proc tree data=treeC;
title "Complete Linkage Clustering of the all data field raw data-low
variables, 2003";
run;

proc plot data=treeC;
plot _ccc_*_ncl_="*" / ;
title 'CCC vs Number of cluster, complete clustering, all data field,
raw data-low variables, 2003';
run;
```

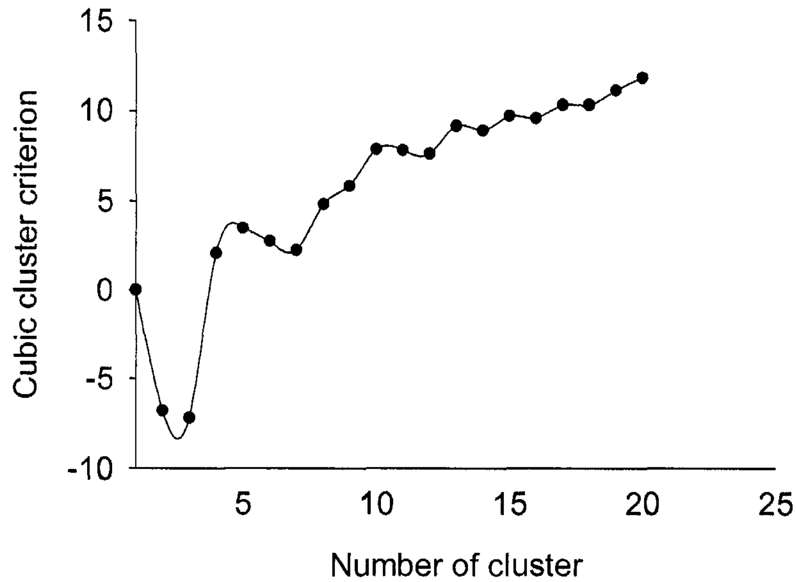

Figure A5 Cubic cluster criterion, all data

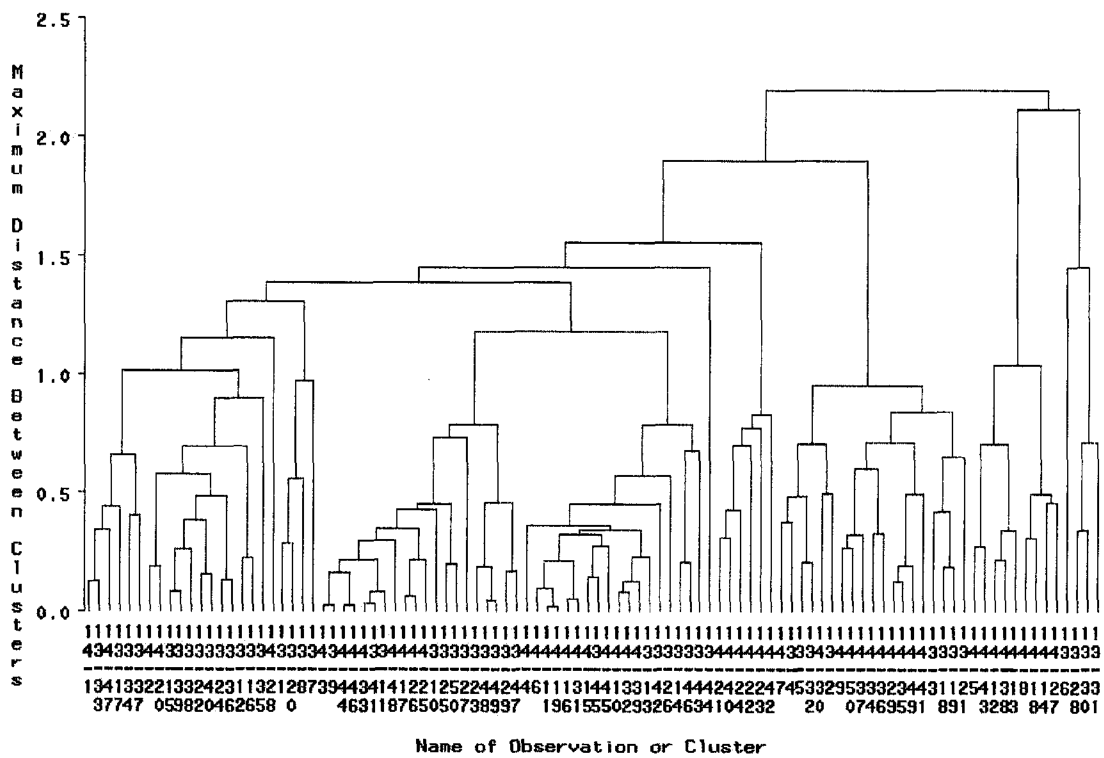

Figure A6 Complete linkage cluster analysis, all data

A4 Sulphate and Electrical conductivity (EC) analysis

SAS input example, SE 9 landscape

```
Option formdlim='*';
option LS=80 PS=64;
Title 'mixed procedure for deep drilling profile';
Title2 "EC and sulphate, first level of cluster";

data deepdrillSO4;
input leaching drilling depth sulphate EC chloride;
cards;
2     1     15    21.50 0.535 8.71
;
run;
Title3 'sulphate analysis';
proc mixed data=deepdrillSO4 covtest;
class leaching depth drilling;
model sulphate=depth leaching/ddfm=kr;
repeated depth/subject=drilling(leaching) type=ar(1) r rcorr;
lsmeans leaching/pdiff;
run;

Title5 'EC analysis';
proc mixed data=deepdrillSO4 covtest;
class leaching depth drilling;
model EC=depth leaching/ddfm=kr;
repeated depth/subject=drilling(leaching) type=ar(1) r rcorr;
lsmeans leaching/pdiff;
run;
```

Table A1 Sulphate ANOVA, leaching potential from the first level of cluster

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Depth of sample	19	309	1.62	0.0494
Leaching potential	2	42.7	0.7	0.5014

Table A2 Difference of least mean square between leaching potential from the first level of clusters, sulphate analysis

Leaching potential	Leaching potential	Estimate	Standard error	Degree of freedom	t value	Pr > t
High	Low	110.2	102.1	42.7	1.1	0.2869
High	Mid	108.2	119.8	42.7	0.9	0.3716
Low	Mid	-2.0	119.8	42.7	0.0	0.9867

Table A3 EC ANOVA, leaching potential from the first level of cluster

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Depth of sample	19	314	1.82	0.0203
Leaching potential	2	30.9	2.45	0.1030

Table A4 Difference of least mean square between leaching potential from the first level of cluster, EC analysis

Leaching potential	Leaching potential	Estimate	Standard error	Degree of freedom	t value	Pr > t
High	Low	1.2	0.5	30.9	2.2	0.0355
High	Mid	0.7	0.7	30.9	1.2	0.2546
Low	Mid	-0.4	0.6	30.9	-0.7	0.4803

Table A5 Sulphate ANOVA, leaching potential from the second level of cluster

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Depth of sample	19	51.7	0.73	0.7682
Leaching potential	4	18.9	2.89	0.0504

Table A6 Difference of least mean square between leaching potential from the second level of cluster, sulphate analysis

Leaching potential	Leaching potential	Estimate	Standard error	Degree of freedom	t value	Pr > t
High	Low	-29.5	76.9	18.9	-0.4	0.7051
High	Mid	18.1	66.6	18.9	0.3	0.7886
High	Very High	76.1	64.3	18.9	1.2	0.2512
High	Very Low	-85.3	64.3	18.9	-1.3	0.2008
Low	Mid	47.6	66.6	18.9	0.7	0.4830
Low	Very High	105.7	64.3	18.9	1.6	0.1169
Low	Very Low	-55.7	64.3	18.9	-0.9	0.3972
Mid	Very High	58.0	51.6	18.9	1.1	0.2745
Mid	Very Low	-103.4	51.6	18.9	-2.0	0.0596
Very High	Very Low	-161.4	48.6	18.9	-3.3	0.0036

Table A7 EC ANOVA, leaching potential from the second level of cluster

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Depth of sample	19	56.7	2.6	0.0029
Leaching potential	4	17.9	0.4	0.803

Table A8 Difference of least mean square between leaching potential from the second level of cluster, EC analysis

Leaching potential	Leaching potential	Estimate	Standard error	Degree of freedom	t value	Pr > t
High	Low	-0.2	0.3	17.9	-0.6	0.5853
High	Mid	0.1	0.2	17.9	0.3	0.7438
High	Very High	0.1	0.2	17.9	0.2	0.8175
High	Very Low	-0.1	0.2	17.9	-0.4	0.7127
Low	Mid	0.2	0.2	17.9	0.9	0.3433
Low	Very High	0.2	0.2	17.9	0.9	0.3810
Low	Very Low	0.1	0.2	17.9	0.3	0.7751
Mid	Very High	0.0	0.2	17.9	-0.1	0.8930
Mid	Very Low	-0.2	0.2	17.9	-0.9	0.3827
Very High	Very Low	-0.1	0.2	17.9	-0.8	0.4316

Table A9 Sulphate ANOVA, leaching potential index

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Depth of sample	19	83.2	2.44	0.0029
Leaching potential	3	155	2.95	0.0346

Table A10 Difference of least mean square between leaching potential index classes, sulphate analysis

Leaching potential	Leaching potential	Estimate	Standard error	Degree of freedom	t value	Pr > t
High	Low	-24.5	30.7	155	-0.8	0.4260
High	Very High	43.6	26.6	155	1.6	0.1033
High	Very Low	-29.6	26.6	155	-1.1	0.2689
Low	Very high	68.2	30.7	155	2.2	0.0281
Low	Very Low	-5.0	30.7	155	-0.2	0.8709
Very High	Very Low	-73.0	26.6	155	-2.8	0.0067

Table A7 EC ANOVA, leaching potential index

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Depth of sample	19	313	1.84	0.0185
Leaching potential	3	29.9	2.79	0.0574

Table A8 Difference of least mean square between leaching potential index classes, EC analysis

Leaching potential	Leaching potential	Estimate	Standard error	Degree of freedom	t value	Pr > t
High	Low	-0.6	0.7	29.9	-0.9	0.3637
High	Very High	0.7	0.6	29.9	1.2	0.2331
High	Very Low	-0.9	0.6	29.9	-1.5	0.1427
Low	Very high	1.4	0.7	29.9	1.9	0.0574
Low	Very Low	-0.3	0.7	29.9	-0.4	0.7055
Very High	Very Low	-1.6	0.6	29.9	-2.7	0.0107

A5 SPI calculation

NE 8 landscape, soil core 13-5

Ah 28 cm

Ahe 14 cm

Bg 23 cm

Btgj 85 cm

SPI=[{(Ah/150)*2}+{(Ahe/150)*3}+{(Bg/150)*2}+{(Btgj/150)*4}]*[150/120]

SPI=[{(28/150)*2}+{(14/150)*3}+{(23/150)*2}+{(85/150)*4}]*[150/120]=

SPI=(0.37+0.28+0.31+2.26)*(1.25)

SPI=3.22*1.25

SPI=4.02

SE 9 landscape, soil core 14-10

Ah 26 cm

Ahk 8 cm

Bmk 10 cm

SPI=[{(Ah/44)*2}+{(Ahk/44)*1}+{(Bmk/44)*1}]*[44/120]

SPI=[{(26/44)*2}+{(8/44)*1}+{(10/44)*1}]*[44/120]

SPI=(1.18+0.18+0.23)*(0.37)

SPI=1.59*0.36

SPI=0.58

Table A13 SPI calculation, NE 8 landscape

Weighting Factor	Horizons depth (cm)	13-1	13-2	13-3	13-4	13-5	13-6	13-7	13-8	13-9	13-10	13-11	13-12	13-13	13-14	13-15	13-16	13-17	13-18
2	Ap	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ah	15	0	16	29	28	13	16	12	20	25	33	0	43	42	19	0	14	25
1	Ahk	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	20	0	0
1	Ahkg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Ahs	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0
3	Ahe	0	7	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ahegj	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0
2	Ahg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ahgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Ae	0	19	10	6	0	0	8	0	0	0	0	0	0	0	0	0	6	11
5	AB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	AC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Bt	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	63
3	Btj	48	0	0	0	0	0	0	48	0	0	0	0	0	0	0	0	0	0
2	Bg	0	0	0	22	23	55	35	0	0	0	0	0	0	25	0	0	0	0
4	Btjgj	0	0	30	0	0	19	40	0	0	0	0	0	0	0	0	0	0	16
4	Btgj	0	70	46	65	85	0	46	0	0	0	0	0	0	0	0	0	24	0
4	Btg	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bgj	0	0	0	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0
2	Bs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Bnt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bns	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bms	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bm	0	0	0	0	0	0	0	0	28	29	23	0	0	0	0	0	0	0
2	Bmgj	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	26	0
1	Bmk	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0
1	Bmkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	10	0	0
0.5	BC	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	13
0	Om	0	0	0	0	0	0	0	0	0	0	0	46	0	0	0	0	0	0
Solum Depth (cm)		77	96	102	150	150	135	145	80	48	77	56	10	55	80	27	30	86	128
SPI		**1.9**	**3.1**	**3.1**	**4.2**	**4.0**	**2.7**	**4.0**	**1.6**	**0.8**	**1.0**	**0.9**	**0.1**	**0.9**	**1.2**	**0.4**	**0.3**	**2.2**	**3.5**

Table A13 SPI calculation, NE 8 landscape, continuous

Weighting Factor	Horizons depth (cm)	13-19	13-20	13-21	13-22	13-23	13-24	13-25	13-26	13-27	13-28	13-29	13-30	13-31	13-32	13-33	13-34	13-35
2	Ap	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ah	32	27	20	18	20	12	8	38	32	97	43	80	60	23	20	16	0
1	Ahk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Ahkg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Ahs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ahe	0	9	0	0	0	0	0	7	23	0	0	0	0	25	7	0	14
3	Ahegj	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0
2	Ahg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ahgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Ae	14	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	9
5	AB	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
0.5	AC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Bt	62	0	67	0	0	0	0	0	0	0	0	0	0	0	37	54	15
3	Btj	0	0	20	0	0	0	0	26	0	0	0	0	0	0	0	0	0
2	Bg	0	0	0	0	0	0	0	0	37	0	43	47	80	18	0	0	0
4	Btjgj	25	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Btgj	0	24	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0
4	Btg	0	0	0	0	0	0	0	0	0	0	0	0	0	84	0	0	0
2	Bgj	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0
2	Bs	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0
2	Bn	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0
3	Bnt	0	20	0	40	0	40	26	0	0	0	0	0	0	0	0	0	22
2	Bns	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0
2	Bms	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bm	0	0	0	0	56	0	0	0	0	0	0	0	0	0	0	0	0
2	Bmgj	0	0	0	0	0	0	0	0	0	53	17	0	0	0	0	0	0
1	Bmk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0
1	Bmkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	BC	12	0	33	22	0	0	0	9	0	0	0	0	0	0	0	0	38
0	Om	0	0	0	0	0	0	0	0	0	0	30	0	8	0	0	0	0
Solum Depth (cm)		145	127	140	80	76	74	63	80	147	150	103	147	140	150	64	92	98
SPI		**4.0**	**3.5**	**3.2**	**1.4**	**1.3**	**1.8**	**1.3**	**1.5**	**3.5**	**2.5**	**1.7**	**2.5**	**2.3**	**4.1**	**1.7**	**2.3**	**1.9**

Table A13 SPI calculation, NE 8 landscape, continuous

Weighting Factor	Horizons depth (cm)	13-36	13-37	13-38	13-39	13-40	13-41	13-42	13-43	13-44	13-45	13-46	13-47	13-48	13-49	13-50
2	Ap	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ah	0	0	10	24	26	31	43	69	12	38	32	30	12	28	0
1	Ahk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Ahkg	0	0	0	0	0	0	0	0	61	0	0	0	0	0	0
1	Ahs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ahe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ahegj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ahg	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0
2	Ahgj	0	0	0	0	0	0	0	0	0	0	0	19	18	0	12
4	Ae	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	AB	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	AC	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0
4	Bt	0	35	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Btj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bg	0	0	0	0	0	0	0	0	0	0	38	51	50	52	41
4	Btjgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Btgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Btg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Bnt	23	0	0	0	34	0	0	0	0	0	0	0	0	0	0
2	Bns	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bms	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bm	0	0	0	0	0	26	15	0	0	0	0	0	0	0	0
2	Bmgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Bmk	0	29	0	9	0	0	17	15	0	0	0	0	0	0	0
1	Bmkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	BC	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0
0	Om	0	0	0	0	0	0	0	0	0	0	10	0	46	34	37
Solum Depth (cm)		67	64	10	33	76	57	75	84	73	47	93	100	80	80	53
SPI		**1.8**	**1.4**	**0.2**	**0.1**	**0.9**	**0.4**	**0.4**	**0.1**	**0.5**	**0.0**	**1.0**	**1.2**	**1.1**	**0.9**	**0.9**

Table A14 SPI calculation, SE 9 landscape

Weighting Factor	Horizons depth (cm)	14-1	14-2	14-3	14-4	14-5	14-6	14-7	14-8	14-9	14-10	14-11	14-12	14-13	14-14	14-15	14-16	14-17	14-18
2	Ah	17	28	21	18	25	0	0	28	30	26	27	33	18	16	0	29	20	29
2	Ahk	0	0	0	19	0	32	0	0	0	8	0	0	0	0	30	0	0	0
2	Ahkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0
3	Ahe	0	6	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	14
2	Ahgj	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0
4	Ae	0	0	0	0	0	0	0	18	0	0	0	0	0	10	0	0	0	10
4	Aeg	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0
5	AB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Bt	38	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	17
3	Btj	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bg	0	0	0	0	70	0	0	73	0	0	0	18	38	54	0	0	0	45
2	Bgs	0	0	0	0	0	0	0	0	0	0	0	53	17	0	0	0	0	0
3	Btjg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Btjgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16
4	Btgj	0	0	0	0	0	0	88	0	0	0	0	0	0	17	0	0	0	0
4	Btgjs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Btg	0	0	0	0	0	0	0	26	65	0	0	0	0	0	0	0	0	0
2	Bgj	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	10	0	24
4	Bnt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bm	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Bmk	0	0	14	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
1	Bmkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0
1	Bkgj	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solum Depth (cm)		55	60	50	54	125	32	110	145	120	44	27	104	73	110	40	39	39	155
SPI		**1.6**	**1.3**	**0.7**	**0.8**	**2.1**	**0.5**	**3.3**	**3.2**	**3.4**	**0.7**	**0.5**	**1.7**	**1.2**	**2.5**	**0.7**	**0.7**	**0.5**	**3.3**

Table A14 SPI calculation, SE 9 landscape, continuous

Weighting Factor	Horizons depth (cm)	14-19	14-20	14-21	14-22	14-23	14-24	14-25	14-26	14-27	14-28	14-29	14-30	14-31	14-32	14-33	14-34
2	Ah	26	18	23	0	12	14	21	20	25	31	26	15	30	13	29	34
2	Ahk	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0
2	Ahkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ahe	0	0	0	7	0	0	0	0	20	29	10	7	0	0	0	0
2	Ahgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Ae	0	0	0	17	0	0	0	0	0	23	14	23	0	0	0	13
4	Aeg	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	0
5	AB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16
4	Bt	0	0	0	0	0	0	12	0	0	0	0	25	0	0	0	0
3	Btj	0	28	45	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Bg	0	0	0	0	24	0	0	0	55	0	28	0	0	0	0	0
2	Bgs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Btjg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Btjgj	0	0	0	0	38	71	0	0	0	0	0	0	0	0	0	0
4	Btgj	0	0	0	0	0	0	0	0	0	0	20	70	0	0	0	0
4	Btgjs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Btg	0	0	0	0	0	0	0	0	32	37	52	0	0	0	0	62
2	Bgj	0	0	0	0	13	0	0	0	0	0	0	0	13	0	0	0
4	Bnt	0	0	0	56	0	0	0	0	0	0	0	0	0	0	0	0
2	Bm	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0
1	Bmk	0	0	0	0	0	0	0	15	0	0	0	0	0	15	0	0
1	Bmkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26	0
1	Bkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solum Depth (cm)		26	46	68	80	87	85	55	35	150	120	150	140	43	48	55	125
SPI		**0.4**	**1.0**	**1.5**	**2.6**	**1.8**	**2.0**	**1.1**	**0.5**	**3.5**	**3.2**	**4.0**	**4.4**	**0.7**	**0.7**	**0.7**	**3.7**

Table A14 SPI calculation, SE 9 landscape, continuous

Weighting Factor	Horizons depth (cm)	14-35	14-36	14-37	14-38	14-39	14-40	14-41	14-42	14-43	14-44	14-45	14-46	14-47	14-48	14-49	14-50
2	Ah	25	29	40	33	29	38	21	20	20	28	36	29	17	24	26	29
2	Ahk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ahkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ahe	0	7	11	0	0	0	0	14	0	0	7	0	0	0	0	9
2	Ahgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Ae	18	13	15	0	0	0	0	9	9	0	0	0	6	0	12	21
4	Aeg	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0
5	AB	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Bt	0	15	0	0	0	0	0	0	0	0	0	0	25	0	0	0
3	Btj	0	0	0	0	0	58	0	0	0	0	13	0	12	0	0	0
2	Bg	32	0	0	0	0	0	15	15	97	0	0	0	0	0	0	15
2	Bgs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0
3	Btjg	0	0	0	0	0	0	23	48	0	0	0	0	0	0	0	0
3	Btjgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Btgj	0	29	40	0	0	0	0	0	0	0	0	0	0	0	32	41
4	Btgjs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0
4	Btg	75	0	39	0	0	0	62	39	14	0	0	0	0	0	0	30
2	Bgj	0	0	0	57	0	0	0	0	0	0	0	0	0	0	0	0
4	Bnt	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0
2	Bm	0	0	0	0	8	0	0	0	0	32	0	33	10	32	0	0
1	Bmk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Bmkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	Bkgj	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solum Depth (cm)		150	103	145	90	37	96	135	145	140	60	56	62	70	70	135	145
SPI		**6.4**	**3.0**	**4.1**	**1.5**	**0.6**	**2.1**	**3.7**	**3.7**	**2.7**	**1.0**	**1.1**	**1.0**	**1.8**	**1.4**	**3.7**	**4.0**

A6 Soil-landscape analysis

Table A15 Soil-landscape factors, NE 8 landscape

Soil Core	Soil profile CSSC	SPI	Elevation m	Slope degree	Profile curvature degree/100 m	Plan curvature degree/100 m
13-1	Orthic BL	1.9	774.8	1.5	5.2	11.6
13-2	Gleyed GL	3.1	774.7	2.3	6.1	3.2
13-3	Gleyed eluviated BL	3.1	774.5	2.8	-4.4	-3.4
13-4	Humic LG	4.2	774.2	1.2	-12.0	-5.6
13-5	Gleyed eluviated BL	4.0	774.2	0.6	-6.1	-10.5
13-6	Gleyed eluviated BL	2.7	774.3	1.5	-4.8	-8.1
13-7	Gleyd BL	4.0	774.5	1.3	5.8	-3.4
13-8	Orthic BL	1.6	774.5	1.2	16.7	-0.2
13-9	Orthic BL	0.8	774.4	3.3	18.7	0.4
13-10	Orthic BL	1.0	773.9	6.3	12.7	-0.9
13-11	Gleyed BL	0.9	773.1	7.4	-4.0	-6.0
13-12	Regosolic HG	0.1	772.5	5.7	-14.2	-6.2
13-13	Gleyed BL	0.9	772.0	3.0	-16.4	-6.5
13-14	Orthic HG	1.2	771.8	0.1	-5.9	-15.0
13-15	Gleyed calcareous BL	0.4	771.9	1.5	-14.9	-7.7
13-16	Gleyed calcareous BL	0.3	772.2	3.5	-7.3	-4.3
13-17	Gleyed eluviated BL	2.2	772.4	3.8	-1.8	-1.1
13-18	Eluviated BL	3.5	772.9	3.7	2.9	2.2
13-19	Eluviated BL	4.0	773.3	3.2	3.6	1.1
13-20	Gleyed black SO	3.5	773.5	2.8	4.5	3.4
13-21	Orthic BL	3.2	773.7	2.1	5.4	1.4
13-22	Black SZ	1.4	773.8	0.9	11.0	12.6
13-23	Orthic BL	1.3	773.8	2.0	21.5	20.2
13-24	Black SO	1.8	773.5	4.4	15.3	15.8
13-25	Black SZ	1.3	773.0	5.8	4.3	11.0
13-26	Eluviated BL	1.5	772.4	5.8	-4.2	6.0
13-27	Gleyed eluviated BL	3.5	771.9	4.7	-8.4	-0.2
13-28	Gleyed BL	2.5	771.5	3.0	-10.1	-9.8
13-29	Gleyed BL	1.7	771.3	1.9	-8.8	-19.9
13-30	Gleyed BL	2.5	771.2	2.3	-16.5	-8.7
13-31	Orthic HG	2.3	771.1	2.1	-22.8	-2.8
13-32	Humic LG	4.1	771.1	1.4	-23.3	-1.4
13-33	Eluviated BL	1.7	771.5	4.1	-5.2	6.7
13-34	Orthic BL	2.3	771.9	4.1	6.4	11.8
13-35	Dark grey SS	1.9	772.3	2.9	11.2	17.7
13-36	Black SO	1.8	772.5	1.8	8.3	17.2
13-37	Orthic BL	1.4	772.5	2.2	16.0	13.3
13-38	Regosolic BL	0.2	772.3	4.1	12.4	9.1
13-39	Calcareous BL	0.5	771.9	5.4	9.1	7.5
13-40	Black SZ	1.4	771.6	6.1	8.3	6.2
13-41	Orthic BL	1.0	771.0	6.8	4.5	3.2
13-42	Orthic BL	1.1	770.3	6.8	-3.9	-1.3
13-43	Calcareous BL	1.3	769.7	6.1	-7.3	-3.6
13-44	Regosilic HG	0.7	769.2	4.9	-6.7	-8.5
13-45	Regosolic HG	0.7	768.7	4.4	-5.9	-10.2
13-46	Orthic HG	1.6	768.3	3.4	-7.4	-14.8
13-47	Orthic HG	1.7	768.1	2.3	-13.2	-15.2
13-48	Orthic HG	1.3	767.9	1.0	-10.7	-14.8
13-49	Orthic HG	1.3	767.9	1.6	-15.3	-5.2
13-50	Orthic HG	0.9	767.9	1.5	-14.5	-3.7

BL: black Chernozem HG: Humic Gleysol GL: Grey Luvisol SO: Solod
SS: Solodized Solonetz LG: Luvic Gleysol SZ: Solonetz

Table A16 Soil-landscape factors, SE 9 landscape

Soil Core	Soil profile CSSC	SPI	Elevation m	Slope degree	Profile curvature degree/100 m	Plan curvature degree/100 m
14-1	Orthic BL	1.6	754.8	2.9	13.1	13.6
14-2	Eluviated BL	1.3	754.6	4.0	10.3	10.9
14-3	Orthic BL	0.7	754.1	4.8	0.2	5.0
14-4	Gleyed calcareous BL	0.8	753.6	3.9	-10.4	-1.9
14-5	Gleyed BL	2.1	753.3	2.0	-11.1	-2.6
14-6	Gleyed regosolic BL	0.5	753.2	1.0	-6.9	-3.2
14-7	Orthic HG	3.3	753.2	0.4	-0.4	-5.3
14-8	Humic LG	3.2	753.2	0.7	-3.3	-2.0
14-9	Humic LG	3.4	753.3	1.0	-1.4	6.2
14-10	Calcareous BL	0.7	753.3	1.6	5.6	5.9
14-11	Regosolic BL	0.5	753.1	2.9	3.5	1.4
14-12	Orthic HG	1.7	752.9	3.0	-3.7	-0.5
14-13	Orthic HG	1.2	752.6	1.8	-11.4	-3.1
14-14	Gleyed eluviated BL	2.5	752.6	0.9	-11.8	-6.3
14-15	Gleyed regosolic BL	0.7	752.6	1.5	-11.1	-4.7
14-16	Gleyed BL	0.7	752.8	2.3	-1.1	-2.1
14-17	Gleyed calcareous BL	0.5	753.0	1.9	1.2	-2.8
14-18	Gleyed eluviated BL	3.3	753.2	2.0	-2.7	-5.2
14-19	Rego HG	0.4	753.4	2.5	-1.1	-1.6
14-20	Orthic BL	1.0	753.7	2.0	7.1	2.7
14-21	Orthic BL	1.5	753.8	0.7	9.6	2.3
14-22	Black SS	2.6	753.8	1.2	3.5	0.3
14-23	Gleyed eluviated BL	1.8	753.7	1.3	0.5	-0.7
14-24	Gleyed BL	2.0	753.6	0.9	-5.4	-1.8
14-25	Orthic BL	1.1	753.5	0.2	-4.7	-1.0
14-26	Gleyed calcareous BL	0.5	753.5	0.6	-0.3	3.3
14-27	Humic LG	3.5	753.5	1.2	0.5	0.3
14-28	Humic LG	3.2	753.4	1.4	-4.9	-2.8
14-29	Gleyed eluviated BL	4.0	753.3	0.8	-7.7	-4.6
14-30	Eluviated BL	4.4	753.3	1.1	-7.0	-3.6
14-31	Gleyed BL	0.7	753.4	1.7	-0.9	1.7
14-32	Orthic BL	0.7	753.4	1.9	0.9	3.4
14-33	Gleyed calcareous BL	0.7	753.4	2.1	1.8	3.0
14-34	Humic LG	3.7	753.2	2.4	-1.3	-1.0
14-35	Humic LG	6.4	753.2	2.4	-2.1	-7.9
14-36	Eluviated BL	3.0	753.2	2.4	0.5	-7.6
14-37	Gleyed eluviated BL	4.1	753.3	2.4	4.4	-2.9
14-38	Gleyed BL	1.5	753.4	1.8	8.5	7.2
14-39	Orthic BL	0.6	753.4	1.4	6.5	14.5
14-40	Orthic BL	2.1	753.2	2.6	5.6	2.2
14-41	Humic LG	3.7	752.9	2.7	-4.6	-4.6
14-42	Humic LG	3.7	752.6	1.6	-6.0	-8.3
14-43	Humic LG	2.7	752.5	1.4	-1.5	-8.4
14-44	Orthic BL	1.0	752.6	1.9	0.1	-1.3
14-45	Orthic BL	1.1	752.5	2.4	0.9	-0.7
14-46	Orthic BL	1.0	752.3	3.4	1.1	-2.1
14-47	Eluviated BL	1.8	752.3	3.3	5.1	2.2
14-48	Black SS	1.4	752.2	3.1	3.9	4.7
14-49	Humic LG	3.7	752.1	2.7	1.5	0.7
14-50	Gleyed eluviated BL	4.0	752.0	2.0	3.0	-3.6

BL: black Chernozem HG: Humic Gleysol GL: Grey Luvisol SO: Solod
SS: Solodized Solonetz LG: Luvic Gleysol SZ: Solonetz

Table A17 Soil-landscape factors ANOVA, leaching potential from the first level of cluster, NE 8 landscape

Soil-landscape	Degree of freedom	Sum of Square	Mean Square	F value	P>F-value
Elevation	2	31.9	15.95	4.75	0.0133
Slope degree	2	26.3	13.16	4.18	0.0213
Profile curvature	2	316.3	158.17	1.28	0.2865
Plan curvature	2	380.1	190.07	2.21	0.1207
SPI	2	41.0	20.52	46.19	< 0.0001

Table A18 Soil-landscape factors SNK analysis, leaching potential from the first level of cluster, NE 8 landscape

	SPI	Elevation	Slope degree	Profile curvature	Plan curvature
Low	C	B	A	A	A
Mid	B	B	AB	A	A
High	A	A	B	A	A

Table A19 Soil-landscape factors ANOVA, leaching potential from the second level of cluster, NE 8 landscape

Soil-landscape	Degree of freedom	Sum of Square	Mean Square	F value	P>F-value
Elevation	7	80.9	11.55	4.45	0.0009
Slope degree	7	56.0	8.00	2.84	0.0161
Profile curvature	7	1338.9	191.28	1.68	0.139
Plan curvature	7	1244.5	177.78	2.35	0.0403
SPI	7	47.2	6.70	19.17	<0.0001

Table A20 Soil-landscape factors SNK analysis, leaching potential from the second level of cluster, NE 8 landscape

	SPI	Elevation	Slope degree	Profile curvature	Plan curvature
Very Low	C	B	A	A	A
	BC	AB	A	A	A
Low	BC	AB	A	A	A
	BC	A	A	A	A
Mid	BC	A	A	A	A
	BC	AB	A	A	A
High	B	AB	A	A	A
Very High	A	A	A	A	A

Table A21 Soil-landscape factors ANOVA, leaching potential from the first level of cluster, SE 9 landscape

Soil-landscape	Degree of freedom	Sum of Square	Mean Square	F value	P>F-value
Elevation	2	1.1	0.57	1.79	0.1800
Slope degree	2	2.5	1.25	1.32	0.2800
Profile curvature	2	247.9	123.98	4.16	0.0200
Plan curvature	2	235.2	117.58	5.37	0.0079
SPI	2	115.4	57.71	97.51	<0.0001

Table A22 Soil-landscape factors SNK analysis, leaching potential from the first level of cluster, SE 9 landscape

	SPI	Elevation	Slope degree	Profile curvature	Plan curvature
Low	C	A	A	A	A
Mid	B	A	A	B	B
High	A	A	A	AB	B

Table A23 Soil-landscape factors ANOVA, leaching potential from the second level of cluster, SE 9 landscape

Soil-landscape	Degree of freedom	Sum of Square	Mean Square	F value	P>F-value
Elevation	4	1.73	0.43	1.36	0.2621
Slope degree	4	6.9	1.72	1.92	0.123
Profile curvature	4	260.1	65.02	2.11	0.096
Plan curvature	4	243.4	60.85	2.68	0.043
SPI	4	123.3	30.83	69.57	<0.0001

Table A24 Soil-landscape factors SNK analysis, leaching potential from the second level of cluster, SE 9 landscape

	SPI	Elevation	Slope degree	Profile curvature	Plan curvature
Very Low	D	A	A	A	A
Low	C	A	A	A	A
Mid	C	A	A	A	A
High	B	A	A	A	A
Very High	A	A	A	A	A

Appendix B

Spatial and temporal variability of vertical bromide redistribution within hummocky landscapes

B1 Snow survey

Table B1 Snow water equivalent (SWE)

Transect	Plot	Density Mg/m3	Depth cm	SWE cm
10	Top	0.14	21.7	3.1
10	Mid	0.20	39.0	7.7
10	Low	0.12	29.0	3.6
11	Top	0.17	22.6	4.7
11	Mid	0.20	21.1	4.7
11	Low	0.12	24.0	3.6
12	Top	0.21	23.2	3.8
12	Mid	0.22	38.9	7.9
12	Low	0.15	27.7	3.4
7	Top	0.22	26.3	5.9
7	Mid	0.18	28.0	5.1
7	Low	0.18	30.6	5.4
8	Top	0.20	19.4	3.8
8	Mid	0.20	18.5	3.6
8	Low	0.22	30.5	6.7
9	Top	0.31	20.4	6.3
9	Mid	0.16	24.6	3.8
9	Low	0.22	26.8	5.9

Table B2 Snow density ANOVA

Effect	Numerator degree of freedom	Numerator degree of freedom	F value	Pr > F
Landscape (field)	1	4.00	5.91	0.0719
Slope position (treat)	2	26.00	4.52	0.0206
Field*treat	2	26.00	10.15	0.0006

Table B3 Difference of the least mean square, snow density

Effect 1		Effect 2		Degree of freedom	t value	Pr > t
Field	Treat	Field	Treat			
NE 8		SE 9		4	-2.43	0.0719
	Low		Mid	26	-1.84	0.0773
	Low		Top	26	-2.98	0.0062
	Mid		Top	26	-1.14	0.264
NE 8	Low	NE 8	Mid	26	-4.04	0.0004
NE 8	Low	NE 8	Top	26	-2.06	0.0492
NE 8	Low	SE 9	Low	26	-3.27	0.003
NE 8	Low	SE 9	Mid	26	-2.06	0.0499
NE 8	Low	SE 9	Top	26	-5.1	< 0.0001
NE 8	Mid	NE 8	Top	26	1.97	0.0592
NE 8	Mid	SE 9	Low	26	0.15	0.8801
NE 8	Mid	SE 9	Mid	26	1.37	0.1821
NE 8	Mid	SE 9	Top	26	-1.68	0.1058
NE 8	Top	SE 9	Low	26	-1.52	0.1398
NE 8	Top	SE 9	Mid	26	-0.3	0.7631
NE 8	Top	SE 9	Top	26	-3.35	0.0025
SE 9	Low	SE 9	Mid	26	1.44	0.1631
SE 9	Low	SE 9	Top	26	-2.15	0.0408
SE 9	Mid	SE 9	Top	26	-3.59	0.001

B2 SPI calculation

Table B4 SPI calculation, Bromide plots within NE 8 landscape

Weighting Factor	Horizon depth (cm)	10 top	10 mid	10 low	11 top	11 mid	11 low	12 top	12 mid	12 low
2.0	Ah	28	22	18	7	30	60	8	13	0
1.0	Ahk	0	0	0	0	12	0	0	0	0
1.0	Ahkg	0	0	0	0	0	0	0	0	0
1.0	Ahs	0	0	0	0	0	0	0	0	0
3.0	Ahe	14	0	18	0	0	15	0	0	30
3.0	Ahegj	0	0	0	0	0	0	0	0	0
2.0	Ahg	0	0	0	0	0	0	0	0	0
2.0	Ahgj	0	0	0	0	0	0	0	0	0
4.0	Ae	0	6	24	0	0	25	0	26	14
5.0	AB	0	13	0	0	0	0	0	0	0
0.5	AC	0	0	0	0	0	0	0	0	0
4.0	Bt	0	45	0	0	0	0	0	0	0
3.0	Btj	33	0	0	0	0	0	42	0	51
2.0	Bg	0	0	0	0	0	0	0	0	0
4.0	Btjgj	0	0	0	0	0	0	0	0	0
4.0	Btgj	0	0	50	0	0	0	0	26	0
4.0	Btg	0	0	0	0	0	0	0	0	0
2.0	Bgj	0	0	0	0	0	0	0	0	0
2.0	Bs	0	0	0	0	0	0	0	0	0
2.0	Bn	0	0	0	0	0	0	0	0	0
3.0	Bnt	0	0	0	0	0	0	0	0	0
2.0	Bns	0	0	0	0	0	0	0	0	0
2.0	Bms	0	0	0	0	0	0	0	0	0
2.0	Bm	0	0	0	51	0	0	0	0	0
2.0	Bmgj	0	0	0	0	0	0	0	0	0
1.0	Bmk	0	0	0	0	0	0	0	0	0
1.0	Bmkgj	0	0	0	0	0	0	0	0	0
0.5	BC	0	0	0	0	0	0	0	0	0
0.0	Om	0	0	0	0	0	0	0	0	0
Solum Depth (cm)		75	86	110	58	42	100	50	65	95
C Horizon Depth (cm)		0	14	0	11	8	0	20	0	0
SPI		**1.6**	**2.6**	**3.2**	**1.0**	**0.6**	**2.2**	**1.2**	**2.0**	**2.5**

Table B5 SPI calculation, Bromide plots within NE 8 landscape

Weighting Factor	Horizon Depth (cm)	9 top	9 mid	9 low	8 top	8 mid	8 low	7 top	7 mid	7 low
2.0	Ah	8	16	22	12	27	24	20	16	25
1.0	Ahk	0	0	0	0	0	0	0	0	0
1.0	Ahkg	0	0	0	0	0	0	0	0	0
1.0	Ahs	0	0	0	0	0	0	0	0	0
3.0	Ahe	0	14	24	0	0	0	0	10	0
3.0	Ahegj	0	0	0	0	0	0	0	0	0
2.0	Ahg	0	0	0	0	0	0	0	0	0
2.0	Ahgj	0	0	0	0	0	0	0	0	0
4.0	Ae	0	0	24	0	0	16	0	0	18
5.0	AB	0	0	0	0	0	0	0	0	0
0.5	AC	0	0	0	0	0	0	0	0	0
4.0	Bt	0	40	0	0	0	0	36	24	0
3.0	Btj	0	0	0	0	18	0	0	0	0
2.0	Bg	0	0	0	0	0	0	0	0	0
4.0	Btjgj	0	0	0	0	0	0	0	0	0
4.0	Btgj	0	0	0	0	0	0	0	0	0
4.0	Btg	0	20	30	38	0	30	0	0	57
2.0	Bgj	0	0	0	0	0	0	0	0	0
2.0	Bs	0	0	0	0	0	0	0	0	0
2.0	Bn	0	0	0	0	0	0	0	0	0
3.0	Bnt	0	0	0	0	0	0	0	0	0
2.0	Bns	0	0	0	0	0	0	0	0	0
2.0	Bms	0	0	0	0	0	0	0	0	0
2.0	Bm	11	0	0	0	0	0	0	0	0
2.0	Bmgj	0	0	0	0	0	0	0	0	0
1.0	Bmk	0	0	0	0	0	0	0	0	0
1.0	Bmkgj	0	0	0	0	0	0	0	0	0
0.5	BC	0	0	0	0	0	0	0	0	0
0.0	Om	0	0	0	0	0	0	0	0	0
Solum Depth (cm)		19	90	100	50	45	70	56	50	100
C Horizon Depth (cm)		51	20	0	40	30	0	34	30	0
SPI		**0.3**	**2.6**	**2.8**	**1.5**	**0.9**	**1.9**	**1.5**	**1.3**	**2.9**

B3 Soil-landscape factors analysis

Table B6 SPI ANOVA

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Landscape (field)	1	4	0.10	0.7695
Slope position (treat)	2	8	7.53	0.0145
Field*treat	2	8	0.00	0.9963

Table B7 Clay content ANOVA

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Landscape (field)	1	3.75	0.64	0.4710
Slope position (treat)	2	2.98	12.90	0.0340
Field*treat	2	2.98	10.53	0.0455
Depth of sample	4	12.7	3.66	0.0338

Table B8 Elevation ANOVA

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Landscape (field)	1	4	317.38	< 0.0001
Slope position (treat)	2	8	13.74	0.0026
Field*treat	2	8	0.97	0.419

Table B9 Slope degree ANOVA

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Landscape (field)	1	4	0.96	0.3822
Slope position (treat)	2	8	10.64	0.0056
Field*treat	2	8	4.34	0.0529

Table B10 Profile curvature ANOVA

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Landscape (field)	1	12	2.44	0.1442
Slope position (treat)	2	12	19.48	0.0002
Field*treat	2	12	0.58	0.5749

Table B11 Plan curvature ANOVA

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	Pr > F
Landscape (field)	1	4	0.02	0.8826
Slope position (treat)	2	8	8.66	0.0100
Field*treat	2	8	0.74	0.5056

B4 Bromide vertical redistribution

SAS input

```
Options ls=95 ps=64 formdlim="*" nodate nonumber;
Title1 "Bromide concentration sampling";
Title2 "Nested Repeated Mixed Model";

Data bromide2004;
Input Time$ field$ slope$ treat$ core distance depth bromide;
Cards;
Fall  NE8   10    Top   1    0     15    32.94
;
run;

proc mixed data=bromide2004 covtest;
class field time slope treat core distance depth;
model bromide = time field treat distance depth time
time*field*treat time*field time*treat treat*field /ddfm=kr;
random slope(field);
repeated  depth  /  subject  =  core(field*time*distance*treat*slope)
type=un r rcorr;
lsmeans time field treat distance depth
time*field*treat time*field time*treat treat*field /pdiff;
run;
```

Table B12 Bromide concentration ANOVA, according to the landscapes and the slope positions

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	PR > F
Time	1	353	15.54	< 0.0001
Field (Landscape)	1	352	9.91	0.0018
Treatment (Slope position)	2	351	34.22	< 0.0001
Distance from bormide plot	3	424	40.35	< 0.0001
Depth of sampling	4	386	38.1	< 0.0001
Time*field	1	352	0.00	0.9575
Time*treat	2	351	21.18	< 0.0001
Time*field*treat	2	351	0.1	0.9068
Field*treat	2	351	0.92	0.4014

Table B13 Difference of the least mean square, effect of the landscapes and slope positions

Effect 1					Effect 2					Degree of		
Landscape	Time	Slope position	Distance	Depth	Landscape	Time	Slope position	Distance	Depth	freedom	t value	Pr > t
NE 8					SE 9					352	-3.94	< 0.0001
	Fall					Spring				353	3.15	0.0018
		Low					Mid			342	6.79	< 0.0001
		Low					Top			348	7.55	< 0.0001
		Mid					Top			364	0.93	0.3556
			0					20		268	2.67	0.0081
			0					60		323	8.94	< 0.0001
			0					140		434	7.98	< 0.0001
			20					60		326	6.64	< 0.0001
			20					140		434	6.81	< 0.0001
			60					140		442	3.39	0.0008
				15					30	413	-2.15	0.0322
				15					60	414	5.31	< 0.0001
				15					90	440	8.57	< 0.0001
				15					120	448	9.56	< 0.0001
				30					60	414	6.36	< 0.0001
				30					90	433	8.67	< 0.0001
				30					120	431	9.45	< 0.0001
				60					90	403	8.65	< 0.0001
				60					120	431	10.24	< 0.0001
				90					120	210	5.39	< 0.0001

Table B13 Difference of the least mean square, effect of the landscapes and slope positions, continuous

Effect 1					Effect 2							
Landscape	Time	Slope position	Distance	Depth	Landscape	Time	Slope position	Distance	Depth	Degree of freedom	t value	Pr > t
NE 8	Fall				NE 8	Spring				344	-2.90	0.0039
NE 8	Fall				SE 9	Fall				330	2.31	0.0215
NE 8	Fall				SE 9	Spring				363	-0.54	0.5877
NE 8	Spring				SE 9	Fall				337	5.26	< 0.001
NE 8	Spring				SE 9	Spring				366	2.15	0.0319
SE 9	Fall				SE 9	Spring				358	-2.68	0.0076
	Fall	Low				Fall	Mid			322	0.40	0.6872
	Fall	Low				Fall	Top			333	2.11	0.0356
	Fall	Low				Spring	Low			323	-7.36	< 0.0001
	Fall	Low				Spring	Mid			356	1.74	0.0823
	Fall	Low				Spring	Top			361	1.36	0.1747
	Fall	Mid				Fall	Top			336	1.70	0.0900
	Fall	Mid				Spring	Low			326	-7.68	< 0.0001
	Fall	Mid				Spring	Mid			359	1.34	0.1804
	Fall	Mid				Spring	Top			364	0.97	0.3312
	Fall	Top				Spring	Low			336	-9.15	< 0.0001
	Fall	Top				Spring	Mid			366	-0.33	0.7427
	Fall	Top				Spring	Top			371	-0.65	0.5181
	Spring	Low				Spring	Mid			354	8.73	< 0.0001
	Spring	Low				Spring	Top			358	8.21	< 0.0001
	Spring	Mid				Spring	Top			381	-0.32	0.7463

Table B13 Difference of the least mean square, effect of the landscapes and slope positions, continuous

Effect 1					Effect 2					Degree of		
Landscape	Time	Slope position	Distance	Depth	Landscape	Time	Slope position	Distance	Depth	freedom	t value	Pr > t
NE 8	Fall	Low			NE 8	Fall	Mid			328	0.19	0.8467
NE 8	Fall	Low			NE 8	Fall	Top			339	1.86	0.0641
NE 8	Fall	Low			NE 8	Spring	Low			323	-5.96	< 0.0001
NE 8	Fall	Low			NE 8	Spring	Mid			324	1.16	0.2478
NE 8	Fall	Low			NE 8	Spring	Top			358	1.53	0.1259
NE 8	Fall	Low			SE 9	Fall	Low			318	1.58	0.1154
NE 8	Fall	Low			SE 9	Fall	Mid			318	1.96	0.0514
NE 8	Fall	Low			SE 9	Fall	Top			330	2.66	0.0081
NE 8	Fall	Low			SE 9	Spring	Low			326	-3.24	0.0013
NE 8	Fall	Low			SE 9	Spring	Mid			373	2.77	0.0058
NE 8	Fall	Low			SE 9	Spring	Top			363	1.86	0.0641
NE 8	Fall	Mid			NE 8	Fall	Top			345	1.64	0.1011
NE 8	Fall	Mid			NE 8	Spring	Low			330	-6.06	< 0.0001
NE 8	Fall	Mid			NE 8	Spring	Mid			331	0.95	0.3433
NE 8	Fall	Mid			NE 8	Spring	Top			364	1.33	0.1839
NE 8	Fall	Mid			SE 9	Fall	Low			325	1.36	0.1752
NE 8	Fall	Mid			SE 9	Fall	Mid			325	1.73	0.0847
NE 8	Fall	Mid			SE 9	Fall	Top			336	2.43	0.0157
NE 8	Fall	Mid			SE 9	Spring	Low			331	-3.37	0.0008
NE 8	Fall	Mid			SE 9	Spring	Mid			376	2.55	0.0111
NE 8	Fall	Mid			SE 9	Spring	Top			368	1.65	0.1002
NE 8	Fall	Top			NE 8	Spring	Low			340	-7.61	< 0.0001
NE 8	Fall	Top			NE 8	Spring	Mid			341	-0.72	0.4721
NE 8	Fall	Top			NE 8	Spring	Top			372	-0.26	0.7963
NE 8	Fall	Top			SE 9	Fall	Low			336	-0.35	0.7267
NE 8	Fall	Top			SE 9	Fall	Mid			336	0.01	0.9894
NE 8	Fall	Top			SE 9	Fall	Top			347	0.72	0.4737
NE 8	Fall	Top			SE 9	Spring	Low			339	-4.75	< 0.0001
NE 8	Fall	Top			SE 9	Spring	Mid			383	0.93	0.3551
NE 8	Fall	Top			SE 9	Spring	Top			375	0.04	0.9705

Table B13 Difference of the least mean square, effect of the landscapes and slope positions, continuous

Effect 1					Effect 2					Degree of		
Landscape	Time	Slope position	Distance	Depth	Landscape	Time	Slope position	Distance	Depth	freedom	t value	Pr > t
NE 8	Spring	Low			NE 8	Spring	Mid			325	7.05	< 0.0001
NE 8	Spring	Low			NE 8	Spring	Top			360	7.11	< 0.0001
NE 8	Spring	Low			SE 9	Fall	Low			319	7.60	< 0.0001
NE 8	Spring	Low			SE 9	Fall	Mid			319	7.97	< 0.0001
NE 8	Spring	Low			SE 9	Fall	Top			331	8.62	< 0.0001
NE 8	Spring	Low			SE 9	Spring	Low			327	1.79	0.0747
NE 8	Spring	Low			SE 9	Spring	Mid			372	8.42	< 0.0001
NE 8	Spring	Low			SE 9	Spring	Top			364	7.49	< 0.0001
NE 8	Spring	Mid			NE 8	Spring	Top			360	0.43	0.6642
NE 8	Spring	Mid			SE 9	Fall	Low			321	0.39	0.6945
NE 8	Spring	Mid			SE 9	Fall	Mid			321	0.77	0.4446
NE 8	Spring	Mid			SE 9	Fall	Top			332	1.48	0.1402
NE 8	Spring	Mid			SE 9	Spring	Low			328	-4.20	< 0.0001
NE 8	Spring	Mid			SE 9	Spring	Mid			374	1.65	0.0996
NE 8	Spring	Mid			SE 9	Spring	Top			365	0.74	0.4576
NE 8	Spring	Top			SE 9	Fall	Low			356	-0.07	0.9438
NE 8	Spring	Top			SE 9	Fall	Mid			356	0.28	0.7787
NE 8	Spring	Top			SE 9	Fall	Top			365	0.96	0.3369
NE 8	Spring	Top			SE 9	Spring	Low			353	-4.41	< 0.0001
NE 8	Spring	Top			SE 9	Spring	Mid			390	1.16	0.2485
NE 8	Spring	Top			SE 9	Spring	Top			387	0.29	0.7720

Table B13 Difference of the least mean square, effect of the landscapes and slope positions, continuous

		Effect 1					Effect 2			Degree of		
Landscape	Time	Slope position	Distance	Depth	Landscape	Time	Slope position	Distance	Depth	freedom	t value	Pr > t
SE 9	Fall	Low			SE 9	Fall	Mid			315	0.38	0.7043
SE 9	Fall	Low			SE 9	Fall	Top			327	1.11	0.2672
SE 9	Fall	Low			SE 9	Spring	Low			324	-4.60	< 0.0001
SE 9	Fall	Low			SE 9	Spring	Mid			371	1.30	0.1930
SE 9	Fall	Low			SE 9	Spring	Top			361	0.38	0.7036
SE 9	Fall	Mid			SE 9	Fall	Top			327	0.74	0.4622
SE 9	Fall	Mid			SE 9	Spring	Low			324	-4.92	< 0.0001
SE 9	Fall	Mid			SE 9	Spring	Mid			371	0.95	0.3433
SE 9	Fall	Mid			SE 9	Spring	Top			361	0.03	0.9797
SE 9	Fall	Top			SE 9	Spring	Low			332	-5.50	< 0.0001
SE 9	Fall	Top			SE 9	Spring	Mid			372	0.25	0.8029
SE 9	Fall	Top			SE 9	Spring	Top			367	-0.67	0.5063
SE 9	Spring	Low			SE 9	Spring	Mid			366	5.50	< 0.0001
SE 9	Spring	Low			SE 9	Spring	Top			356	4.71	< 0.0001
SE 9	Spring	Mid			SE 9	Spring	Top			376	-0.88	0.3819
NE 8		Low			NE 8		Mid			327	5.10	< 0.0001
NE 8		Low			NE 8		Top			350	6.39	< 0.0001
NE 8		Low			SE 9		Low			323	2.38	0.0177
NE 8		Low			SE 9		Mid			356	7.47	< 0.0001
NE 8		Low			SE 9		Top			349	7.26	< 0.0001
NE 8		Mid			NE 8		Top			353	1.46	0.1458
NE 8		Mid			SE 9		Low			327	-2.33	0.0205
NE 8		Mid			SE 9		Mid			359	2.39	0.0175
NE 8		Mid			SE 9		Top			352	2.21	0.0276
NE 8		Top			SE 9		Low			346	-3.62	0.0003
NE 8		Top			SE 9		Mid			375	0.86	0.3898
NE 8		Top			SE 9		Top			370	0.70	0.4841
NE 8		Low			SE 9		Mid			351	4.54	< 0.0001
NE 8		Low			SE 9		Top			346	4.36	< 0.0001
NE 8		Mid			SE 9		Top			369	-0.16	0.8730

B5 Bromide vertical redistribution as a function of the leaching potential index prediction

SAS input

```
Options ls=95 ps=64 formdlim="*" nodate nonumber;
Title1 "Leaching potential Bromide concentration sampling";
Title2 "Nested Repeated Mixed Model";

Data bromide2004;
Input Time$ field$ slope$ treat$ leach$ core distance depth bromide;
Cards;
Spring      NE8    10     Top    Low    1      0      15     51.86
Spring      NE8    10     Top    Low    1      0      30     116.88
;
run;
proc mixed data=bromide2004 covtest;
class field time slope leach treat core distance depth;
model bromide = time field leach distance depth time
time*field*leach time*field time*leach leach*field /ddfm=kr;
random slope(field);
repeated  depth  /  subject  =  core(field*time*distance*treat*slope)
type=un r rcorr;
lsmeans time field leach distance depth
time*field*leach time*field time*leach leach*field /pdiff;
run;
```

Table B14 Bromide concentration ANOVA, according to the leaching potential index prediction

Effect	Numerator degree of freedom	Denominator degree of freedom	F value	PR > F
Time	1	364	6.76	0.0097
Field (Landscape)	1	363	9.27	0.0025
Leaching potential (leach)	2	362	14.14	< 0.0001
Distance from bormide plot	3	427	39.77	< 0.0001
Depth of sampling	4	384	37.72	< 0.0001
Time*field	1	363	0.00	0.9540
Time*leach	2	362	8.82	0.0002
Time*field*leach	2	362	0.59	0.5543
Field*leach	2	363	0.05	0.9467

Table B15 Difference of the least mean square, effect of the leaching potential index prediction

Effect 1			Effect 2			Degree of		
Landscape	Time	Leaching	Landscape	Time	Leaching	freedom	t value	Pr > t
		High			Low	364	5.08	< 0.0001
		High			Very Low	357	3.23	0.0014
		Low			Very Low	366	-0.55	0.5815
	Fall	High		Fall	Low	344	0.77	0.4447
	Fall	High		Fall	Very Low	336	0.59	0.5578
	Fall	High		Spring	High	346	-5.53	< 0.0001
	Fall	High		Spring	Low	373	1.16	0.2479
	Fall	High		Spring	Very Low	367	0.03	0.9748
	Fall	Low		Fall	Very Low	344	0.02	0.9819
	Fall	Low		Spring	High	358	-5.95	< 0.0001
	Fall	Low		Spring	Low	380	0.4	0.6918
	Fall	Low		Spring	Very Low	371	-0.50	0.619
	Fall	Very Low		Spring	High	346	-4.53	< 0.0001
	Fall	Very Low		Spring	Low	362	0.28	0.7793
	Fall	Very Low		Spring	Very Low	361	-0.44	0.6613
	Spring	High		Spring	Low	378	6.18	< 0.0001
	Spring	High		Spring	Very Low	371	3.87	0.0001
	Spring	Low		Spring	Very Low	382	-0.78	0.4334

Table B15 Difference of the least mean square, effect of the leaching potential index prediction, continuous

Effect 1 Landscape	Time	Leaching	Effect 2 Landscape	Time	Leaching	Degree of freedom	t value	Pr > t
NE 8	Fall	High	NE 8	Fall	Low	350	0.25	0.8058
NE 8	Fall	High	NE 8	Fall	Very Low	343	-0.13	0.8993
NE 8	Fall	High	NE 8	Spring	High	329	-5.01	< 0.0001
NE 8	Fall	High	NE 8	Spring	Low	361	0.64	0.5218
NE 8	Fall	High	NE 8	Spring	Very Low	344	-0.10	0.9236
NE 8	Fall	High	SE 9	Fall	High	327	0.95	0.3421
NE 8	Fall	High	SE 9	Fall	Low	340	1.69	0.0917
NE 8	Fall	High	SE 9	Fall	Very Low	326	1.93	0.0542
NE 8	Fall	High	SE 9	Spring	High	359	-2.12	0.0345
NE 8	Fall	High	SE 9	Spring	Low	378	1.81	0.0705
NE 8	Fall	High	SE 9	Spring	Very Low	387	0.88	0.3819
NE 8	Fall	Low	NE 8	Fall	Very Low	351	-0.28	0.7806
NE 8	Fall	Low	NE 8	Spring	High	349	-5.07	< 0.0001
NE 8	Fall	Low	NE 8	Spring	Low	378	0.39	0.6993
NE 8	Fall	Low	NE 8	Spring	Very Low	352	-0.25	0.8038
NE 8	Fall	Low	SE 9	Fall	High	347	0.67	0.5039
NE 8	Fall	Low	SE 9	Fall	Low	356	1.41	0.1589
NE 8	Fall	Low	SE 9	Fall	Very Low	340	1.68	0.0941
NE 8	Fall	Low	SE 9	Spring	High	371	-2.28	0.0231
NE 8	Fall	Low	SE 9	Spring	Low	388	1.55	0.1230
NE 8	Fall	Low	SE 9	Spring	Very Low	393	0.67	0.5029
NE 8	Fall	Very Low	NE 8	Spring	High	343	-2.93	0.0036
NE 8	Fall	Very Low	NE 8	Spring	Low	356	0.53	0.5971
NE 8	Fall	Very Low	NE 8	Spring	Very Low	347	0.02	0.9808
NE 8	Fall	Very Low	SE 9	Fall	High	342	0.71	0.4806
NE 8	Fall	Very Low	SE 9	Fall	Low	347	1.21	0.2274
NE 8	Fall	Very Low	SE 9	Fall	Very Low	339	1.44	0.1513
NE 8	Fall	Very Low	SE 9	Spring	High	356	-1.29	0.1994
NE 8	Fall	Very Low	SE 9	Spring	Low	367	1.32	0.1888
NE 8	Fall	Very Low	SE 9	Spring	Very Low	376	0.74	0.4600

Table B15 Difference of the least mean square, effect of the leaching potential index prediction, continuous

Effect 1 Landscape	Time	Leaching	Effect 2 Landscape	Time	Leaching	Degree of freedom	t value	Pr > t
NE 8	Spring	High	NE 8	Spring	Low	361	5.38	< 0.0001
NE 8	Spring	High	NE 8	Spring	Very Low	344	2.96	0.0033
NE 8	Spring	High	SE 9	Fall	High	327	5.99	< 0.0001
NE 8	Spring	High	SE 9	Fall	Low	340	6.31	< 0.0001
NE 8	Spring	High	SE 9	Fall	Very Low	326	6.06	< 0.0001
NE 8	Spring	High	SE 9	Spring	High	358	2.25	0.0253
NE 8	Spring	High	SE 9	Spring	Low	377	6.22	< 0.0001
NE 8	Spring	High	SE 9	Spring	Very Low	386	4.62	< 0.0001
NE 8	Spring	Low	NE 8	Spring	Very Low	357	-0.50	0.6178
NE 8	Spring	Low	SE 9	Fall	High	360	0.26	0.7984
NE 8	Spring	Low	SE 9	Fall	Low	366	1.02	0.3086
NE 8	Spring	Low	SE 9	Fall	Very Low	349	1.32	0.1864
NE 8	Spring	Low	SE 9	Spring	High	379	-2.61	0.0095
NE 8	Spring	Low	SE 9	Spring	Low	394	1.17	0.2430
NE 8	Spring	Low	SE 9	Spring	Very Low	397	0.36	0.7207
NE 8	Spring	Very Low	SE 9	Fall	High	343	0.68	0.4996
NE 8	Spring	Very Low	SE 9	Fall	Low	348	1.18	0.2387
NE 8	Spring	Very Low	SE 9	Fall	Very Low	340	1.41	0.1592
NE 8	Spring	Very Low	SE 9	Spring	High	357	-1.32	0.1892
NE 8	Spring	Very Low	SE 9	Spring	Low	368	1.29	0.1984
NE 8	Spring	Very Low	SE 9	Spring	Very Low	377	0.71	0.4762
SE 9	Fall	High	SE 9	Fall	Low	338	0.82	0.4100
SE 9	Fall	High	SE 9	Fall	Very Low	324	1.16	0.2475
SE 9	Fall	High	SE 9	Spring	High	358	-2.96	0.0033
SE 9	Fall	High	SE 9	Spring	Low	376	0.99	0.3245
SE 9	Fall	High	SE 9	Spring	Very Low	386	0.17	0.8667
SE 9	Fall	Low	SE 9	Fall	Very Low	334	0.40	0.6918
SE 9	Fall	Low	SE 9	Spring	High	362	-3.50	0.0005
SE 9	Fall	Low	SE 9	Spring	Low	377	0.19	0.8526
SE 9	Fall	Low	SE 9	Spring	Very Low	385	-0.48	0.6339
SE 9	Fall	Very Low	SE 9	Spring	High	350	-3.57	0.0004
SE 9	Fall	Very Low	SE 9	Spring	Low	366	-0.21	0.8304

Table B15 Difference of the least mean square, effect of the leaching potential index prediction, continuous

Effect 1 Landscape	Time	Leaching	Effect 2 Landscape	Time	Leaching	Degree of freedom	t value	Pr > t
SE 9	Fall	Very Low	SE 9	Spring	Very Low	378	-0.78	0.4339
SE 9	Spring	High	SE 9	Spring	Low	381	3.56	0.0004
SE 9	Spring	High	SE 9	Spring	Very Low	387	2.46	0.0131
SE 9	Spring	Low	SE 9	Spring	Very Low	389	-0.62	0.5346
NE 8		High	NE 8		Low	355	4.01	< 0.0001
NE 8		High	NE 8		Very Low	344	2.00	0.0461
NE 8		High	SE 9		High	346	2.32	0.0210
NE 8		High	SE 9		Low	363	5.66	< 0.0001
NE 8		High	SE 9		Very Low	366	4.72	< 0.0001
NE 8		Low	NE 8		Very Low	354	-0.55	0.5823
NE 8		Low	SE 9		High	366	-1.53	0.1262
NE 8		Low	SE 9		Low	379	1.82	0.0696
NE 8		Low	SE 9		Very Low	379	1.39	0.1645
NE 8		Very Low	SE 9		High	350	-0.47	0.6379
NE 8		Very Low	SE 9		Low	358	1.77	0.0783
NE 8		Very Low	SE 9		Very Low	361	1.51	0.1323
NE 8		High	SE 9		Low	369	3.24	0.0013
NE 8		High	SE 9		Very Low	371	2.65	0.0083
NE 8		Low	SE 9		Very Low	377	-0.20	0.8429

Appendix C

Variability of air-dried versus oven-dried soil analysis

C1 Introduction

Rhoades (1996) mentioned that soil samples should not be air-dried before the water extraction of soluble salts because the heat can changes the solubility of some salts, such as sulphate. However, many studies used oven-dried soil for the water ratio extraction to determine bromide concentration (Bruce et al., 1985; Clothier et al., 1992; Majid et al., 1994; Olson and Cassel, 1999).

The objective of this study was to compare results of bromide concentration analysed from an air-dried soil samples to oven-dried soil samples

C2 Method

To assess the variability between the air-dried and oven-dried techniques, 32 soil samples were randomly selected, air-dried, ground, and passed through a 2 mm sieve. Sub-samples of 30 g of each of these soil samples were also oven-dried. Sub-samples of 10 g of air-dried and oven-dried samples were analysed for bromide concentration.

C3 Results and discussion

The difference of oven-dried bromide concentration was mostly <15% of the air-dried concentration (Table C.1), and the ANOVA showed no significant variation between the bromide concentration from an air-dried and oven-dried soil ($P=0.349$).

The results showed no significant difference in bromide concentrations between the air-dried and the oven-dried soil water extraction for the determination of bromide. Therefore, using analysis of the oven-dried soil water extraction for the bromide concentration provided reliable results.

Table C.1. Comparison of the bromide extracted from air-dried (AD) and oven-dried (OD) soil samples within study sites

Field	Slope	Slope position	Distance+ cm	Depth cm	Br ppm AD	Br ppm OD	Difference	Difference % AD
NE 8	12	MID	20	15-30	374.7	324.8	-49.9	-13.3
NE 8	12	MID	20	30-60	103.9	88.5	-15.3	-14.8
NE 8	12	MID	20	60-90	72.1	65.4	-6.7	-9.3
NE 8	12	MID	20	90-120	13.3	11.5	-1.9	-14.1
NE 8	12	MID	60	15-30	13.5	11.5	-1.9	-14.2
NE 8	12	MID	140	15-30	1.1	1.2	0.1	10.1
NE 8	12	TOP	0	0-15	784.1	734.5	-49.6	-6.3
NE 8	12	TOP	0	60-90	1.8	3.0	1.2	66.8*
NE 8	12	TOP	0	90-120	3.7	3.2	-0.4	-11.6
NE 8	12	TOP	20	0-15	14.8	11.4	-3.3	-22.5
NE 8	12	TOP	20	30-60	1.7	1.9	0.2	14.9
NE 8	10	LOW	0	0-15	21.0	20.9	-0.1	-0.6
NE 8	10	LOW	0	15-30	26.0	23.0	-2.9	-11.3
NE 8	10	LOW	0	30-60	82.6	75.5	-7.1	-8.5
NE 8	10	LOW	20	15-30	66.6	59.6	-7.0	-10.5
NE 8	10	LOW	60	0-15	4.4	4.4	0.0	-0.8
SE 9	9	TOP	-20	30-60	3.8	3.1	-0.6	-17.1
SE 9	9	TOP	-20	90-120	6.8	5.8	-1.0	-14.4
SE 9	9	TOP	0	0-15	740.2	699.0	-41.2	-5.6
SE 9	9	TOP	0	30-60	107.3	107.0	-0.3	-0.3
SE 9	9	TOP	0	90-120	14.8	12.9	-1.9	-12.8
SE 9	9	TOP	20	15-30	296.4	273.3	-23.1	-7.8
SE 9	9	TOP	20	60-90	38.2	31.6	-6.5	-17.1
SE 9	9	TOP	20	90-120	29.2	26.6	-2.6	-8.8
SE 9	9	TOP	60	15-30	12.2	10.5	-1.7	-13.6
SE 9	9	TOP	140	0-15	3.4	2.5	-0.9	-26.6
SE 9	7	MID	0	30-60	114.7	29.0	-85.7	-74.7*
SE 9	7	MID	0	90-120	3.0	2.9	0.0	-1.4
SE 9	7	MID	20	30-60	2.1	1.7	-0.4	-20.3
SE 9	7	MID	60	15-30	0.7	1.9	1.2	186.4*
SE 9	7	MID	140	0-15	1.0	1.4	0.4	41.2
SE 9	7	MID	140	30-60	0.3	0.9	0.6	222.2*

+ Distance downslope from the bromide plot (Figure 4.3)
* High variation AD-OD.