Spatial Structure of Soil Texture and its Influence on Spatial Variability of Nitrate Leaching

by

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ABSTRACT

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Field scale variability of soil texture can influence crop yield and movement of soil water in the field. The objective of this study was to investigate the spatial structure of soil texture in relation to the variability of nitrate-N leaching using geostatistics. Soil textural fractions showed strong spatial autocorrelations from surface to 60 cm depth. Random variability of soil texture increased with depth. Soil water content, as well as total carbon, total nitrogen and soil organic carbon of top 15 cm, also showed spatial autocorrelations similar to soil texture. Elevation, relative slope position and vertical distance to channel network showed significant influence on the distribution of soil texture. Soil texture at 90 cm depth correlated best with cumulative percolated water and cumulative nitrate leached in field lysimeters. Our results showed that soil layers with low hydraulic conductivity control the water and nitrate movement through the soil profile.

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FOREWORD

Guidelines of Department of Soil Science, University of Manitoba were taken into account in the preparation of this thesis in manuscript format. Chapter 1 consists of an extensive literature review of nitrate leaching and spatial variability of soil texture along with the objectives of this research. Chapter 2 describes the micro scale spatial variability of soil texture in an Orthic Black Chernozem soil in both vertical and horizontal directions. Chapter 3 explores the relationships between soil variables, terrain derivatives, water percolation and nitrate leaching. Chapter 4 summarizes the findings of the research, their impacts and suggestions for future research. Chapter 2 and chapter 3 will be combined to form a manuscript and will be submitted to Soil Science Society of America Journal. The figures which show the interpolated soil variables will be converted to greyscale before the submission.

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ABBREVIATIONS

N - Nitrogen

NO_3^- - Nitrate

NO_3-N - Nitrate-nitrogen

TN - Total nitrogen

TC - Total carbon

SOC - Soil organic carbon

ADA - Assiniboine delta aquifer

CV - Coefficient of variation

AiC - Akaike's information criterion

VIP - Variable importance on partial least squares projections

DEM - Digital elevation model

PlC - Plan curvature

PrC - Profile curvature

SAGA WI - SAGA wetness index

VDCN - Vertical distance to channel network

RSP - Relative slope position

PLS - Partial least squares

JSI - Johnson Sl

1. INTRODUCTION

1.1. Nitrate leaching

Crop production in agriculture is sustained by the addition of nitrogen (N) in both inorganic and organic forms. However, excessive application of N can negatively affect the environment (Smith and Schindler, 2009) and human health (Townsend et al., 2003). Nitrate (NO_3^-) can affect surface water and groundwater through the processes of runoff and leaching (Elrashidi et al., 2005). A significant portion of organic N can also be mineralized into nitrate and leached from the soil profile. The importance of runoff and leaching in inorganic N losses has been studied in a wide range of environments (Elrashidi et al., 2005).

When water percolates through the soil, it also transports dissolved inorganic N forms. NO_3-N is the dominant form of inorganic N involved in this process (Dinnes et al., 2002) since ammonium-N is quickly converted to NO_3-N in most soils. Because of their negative charge, NO_3^- ions are less likely to be retained by mostly negatively charged minerals in temperate soils. As such they move downwards with water in a process known as nitrate leaching.

1.1.1.Factors which influence nitrate leaching

The amount of leachable NO_3^- is determined by the excess amount of NO_3^- present in the soil and the water balance (Di and Cameron, 2002). Nitrtate leaching is influenced by both the properties of the soils, and crop and soil management practices (Dinnes et al., 2002). Di and Cameron (2002) reviewed the influence of agricultural production systems, organic amendments, soil and climatic factors on NO_3^- leaching. In many cases, intensive vegetable producing systems showed the highest NO_3^- leaching than any other agricultural cropping systems. Hayed grasslands seem to produce reduced amounts of leachate relative to grazed pastures and intermittently ploughed pastures. High variability in N content makes it difficult to compare the influence of various organic amendments on NO_3^- leaching. However the contribution of amendments to leaching was significant due to increased mineralization by enhanced soil microbial activity. The effect of tillage and catch crops on NO_3^- leaching was studied by Hansen and Djurhuus (1997). In this study, rye grass, as a catch crop, reduced NO_3^- leaching in ploughed plots. However, legumes, when used as cover crops increased NO_3^- concentration in leached water (Campiglia et al., 2010). Beaudoin et al (2005) showed a significant reduction in NO_3^- leaching with the use of catch crops, and reported the relative efficiency of different catch crop rotations. Cover crops and no-till operations efficiently reduce NO_3^- leaching over the long and short term (Beaudoin et al., 2005). Early tillage of crop residue (late summer or early fall) increased the potential and duration of N mineralization and enhanced NO_3^- leaching (Di and Cameron, 2002). Amendments of straw influenced mineralization and immobilization rates thus affecting NO_3^- leaching (Beaudoin et al., 2005). Allaire-leung et al (2001) reported that NO_3^- leaching and irrigation depth, irrigation uniformity and percolation were not correlated in a study with sprinkler irrigation systems on a loamy sand soil.

In general NO_3^- leaching is reduced in fine textured soils relative to coarse textured sandy soils. This is attributed to lower drainage and higher denitrification in fine textured soils (Di and Cameron, 2002). Leaching increased by three-fold in shallow sandy soils relative to deep loamy soils (Beaudoin et al., 2005). Increased N mineralization was also observed for disturbed loamy soils and clay soils in an incubation study (Hassink, 1992) with a commensurate increase in available nitrate-N. Furthermore, denitrification increased in poorly-drained clay soils relative to well-drained sandy soils (Groffman and Tiedje, 1989). Increased denitrification indicates a decrease in available NO_3^- for leaching. Shahandeh et al (2011) reported the influence of soil texture and residual NO_3^- on the yield of corn. This study showed that corn yield, clay content and mineralizable N are spatially dependent. However their study did not find any significant relationship between soil texture (clay content) and residual NO_3^- due to initial NO_3^-, variability in seasonal precipitation and variability in management. Furthermore macro-pores transport more solutes into the deeper layers. Depth to the ground water table is also important since shallow ground water aquifers are more prone to NO_3^- contamination. Most temperate soils consist of predominantly negatively charged minerals that repel negatively charged NO_3^- , thereby increasing the potential for leaching (Di and Cameron, 2002). However, tropical soils with predominantly positively charged minerals delay leaching by adsorbing NO_3^- ions into their mineral surfaces (Di and Cameron, 2002).

Nitrate leaching is seasonal (White et al., 1983; Di and Cameron, 2002). Higher NO_3^- leaching was observed in fall than spring where organic N inputs were applied in spring and fall, respectively (Di et al., 1999; Sørensen and RubAEk, 2012). This increase was attributed to lower N use efficiency of fall crops than spring crops, lower evapotranspiration and the high availability of mineralized organic N. Decau et al (2004) found higher NO_3^- leaching in fall than summer and spring in their study with repacked lysimeters where N was applied as cow urine in spring, summer and fall to evaluate leaching. However higher spring NO_3^- leaching was observed in the study of Nikiema et al (2013) in the Prairie region, following a single application of N fertilizer in spring, due to high soil water content levels related to snowmelt during a period with lower evapotranspiration. Leaching is generally low in summer relative to spring due to higher plant uptake, though it may be high after major thunderstorm events during the summer (Di and Cameron, 2002).

Spatial and temporal variability of applied N can also affect leaching. Leaching increases rapidly when effluent application exceeds recommended rates. However, N application below recommended rates does not necessarily reduce leaching (Beaudoin et al., 2005). Split application of N fertilizers in pasture systems reduces NO_3^- leaching relative to blanket applications (Di and Cameron, 2002).

1.1.2.Quantification of nitrate leaching

NO_3^- leaching should be quantified precisely on a volumetric basis in order to identify management strategies, which minimize leaching. In laboratory experiments (Gaines and Gaines, 1994), soil columns are saturated with NO_3^- ions, and leached water percolated is then collected in order to quantify the amount of NO_3^- that is leached. However, experiments with packed soil columns do not reflect the actual field scenario. In field studies, lysimeters directly measure leached NO_3^- and water for a soil volume. Lysimeters, suction cups, and resin cores are used to collect soil solution from predefined soil depths (Lehmann and Schroth, 2003). Suction cups yield only the concentration of leached nitrogen (Beaudoin et al., 2005) not the water flux. Furthermore, the concept of macroflow in the soil profile decreases the accuracy in suction cup measurements leading to over estimations (Hansen and Djurhuus, 1997). Wang et al (2012) observed that NO_3^- leaching with suction cups was affected by sampler size and the associated volume of soil pores. The resin core technique is still under development (Lehmann and Schroth, 2003). Allaire-leung et al (2001) estimated cumulative NO_3^- leaching with anion exchange resin bags at 1 m depth, though some data were discarded due to contamination. Nitrate leaching is commonly measured using field lysimeters (Sun et al., 2008; Sørensen and RubAEk, 2012; Wang et al., 2012; Nikiema et al., 2013). Aronsson and Bergstrom (2001) found higher leaching in lysimeters located in clay soils compared to those in sand. Errors in packing and construction of lysimeters combined with high levels of initial NO_3^- could affect leaching. A lysimeter study (Silva et al., 1999) found significantly higher amounts of NO_3^- in leachates from intact cores treated with cow urine, relative to a control. Similar results were reported in the repacked lysimeter study of Decau et al (2004) for the effects of cow urine on NO_3^- leaching. Leaching was highest in fall compared to spring and summer, similar to the results of the study by Wachendorf et al (2005). Increased microbial activity and soil organic matter also resulted in high levels of NO_3^- leaching in urine patches (Wachendorf et al., 2005). It was observed that high salt concentration and urea in cow urine dissolved soil organic matter, which released more NO_3^- into the leaching pool (Wachendorf et al., 2005). Sørensen and Rubaek (2012) reported high fall NO_3^- leaching due to untreated hog slurry applied in a repacked lysimeter study. Guillard and Kopp (2004) reported nitrate-N leaching was highest in a treatment with inorganic N fertilizer in a lawn turf with lower levels where slow releasing urea fertilizer and organic amendment (aerobically composted turkey litter) were applied in a zero-tension funnel lysimeter study. An interesting study of

Campiglia et al (2010) found increased NO_3^- leaching when leguminous crops were used as mulch than non-leguminous mulch crop in peppers using sub-surface drainage cylinder lysimeters. Nyamangara et al (2003) combined manure (aerobically composted cattle manure) and N fertilizer to reduce nitrate-N leaching while maintaining dry matter yield in their repacked lysimeter study. Sun et al (2008) evaluated the effect of rainfall and N inputs in NO_3^- leaching through a lysimeter experiment. They then simulated inter-monthly variation in total leached NO_3^- and drainage using the Water and Nitrogen Management Model (WNMN). Results of their study showed higher impact of rainfall in NO_3^- leaching than crop uptake. Wang et al (2012) demonstrated the suitability of intact core lysimeters for measuring cumulative NO_3^- leaching over suction cups.

A variety of methods have been used to estimate and measure NO_3^- leaching losses. Beaudoin et al (2005) used a simulation model called LIXIM to quantify NO_3^- leaching based on the N concentrations and water content obtained from frequent soil sampling. Their study investigating the influence of soil types in NO_3^- leaching found lowest leaching in deep loamy soils and highest leaching in shallow sandy soils. Olatuyi et al (2012a; 2012b) used bromide ions and labelled N fertilizer as tracers to detect NO_3^- movement in both vertical and lateral directions in a hummocky landscape. Nitrate leaching was higher in the lower slopes of the landscape relative to middle and upper slopes, where the crop response to N fertilization significantly reduced NO_3^- leaching. They also observed that during the study period, soil NO_3^- levels were almost unchanged. This observation demonstrates the inadequacy of using only soil NO_3^- levels in leaching studies. Delgado and Bausch (2005) combined soil sampling with Geological Information Systems (GIS) and remote sensing to identify areas with varying residual soil NO_3^- and areas prone to NO_3^- leaching in a corn field. They found lower residual soil NO_3^- and higher NO_3^- leaching in sandier regions of the field .

1.2. **Spatial variation of soil properties**

The importance of variability of soil properties within a landscape is well understood from both agricultural and environmental perspectives. Soil variation is categorized into temporal and spatial variability. The first accounts for the variation with time and the other represents the variability in measured soil property or parameter over distance. Most soil-landscapes show varying degrees of spatial variation. This variability is due to the combined action of glaciation, physical, chemical, or biological processes of soil formation that operate with different intensities and scales. Some of this variability may also be induced by tillage and other soil management practices and are in many cases influenced by factors such as soil erosion and deposition. Moreover, variability of available plant nutrients can influence yield (Mallarino, 1996).

Various studies have reported the existence of spatial variability of soil properties. Campbell (1978) reported spatial variability of particle size distribution in diverse soils. Hydraulic properties have numerous sources of variability related to spatial, temporal and management related processes (Van Es et al., 1999). Mzuku et al (2005) have found that soil physical properties exhibit significant positive spatial auto-correlation across continuous corn irrigated production fields. Campbell (1978) reported that the pH of soil samples which are separated by only 10 m were spatially independent. Rockstrom et al (1999) identified two different types of spatial variability of soil chemical properties. One is variability over short distances, and the other is field-scale variability related to spatial pattern of infiltration. Stolt et al (2001) measured the spatial distribution of chemical properties and particle size distribution of different alluvial wetlands. The spatial distribution of soil chemical parameters, such as organic carbon and soil Kjeldahl N were primarily a function of site characteristics such as vegetation, topographic relief, water chemistry and hydrology. Particle size distribution and soil chemical properties were significantly related to soil depth and relative elevation in each site. Mehlich-3 phosphorus concentrations were strongly spatially correlated in different small sized (1 ha) fields in a watershed Needelman et al (2001). Mallarino (1996) observed both low and high frequency patterns in the distributions of soil phosphorus and potassium in eight no-tilled corn and soybean fields. He attributed high frequency (<1 m) patterns in some fields to repeated banded applications of fertilizers and low frequency patterns (15-18 m) to broadcast fertilizer. A study in Central Iowa showed that soil organic carbon (SOC), pH and total nitrogen (TN) were also strongly spatially dependent (Cambardella et al., 1994).

1.2.1. **Spatial variation of soil texture and its influence on nitrate leaching**

The influence of soil texture on various soil physical, chemical and biological processes is well understood. Various studies have been conducted to investigate the influence of soil texture on soil N dynamics and infiltration. Cote et al (2000) reported a negative correlation between nitrogen mineralization and clay content. Gaines and Gaines (1994) and Vinten et al (1994) investigated the influence of soil texture on leaching. In general, sandy soils leached more NO_3^- into deeper layers than clay and loam soils. Delgado and Bausch (2005) used remote sensing and geographical information systems (GIS) to explain the influence of soil texture on NO_3^- leaching. A significant negative correlation

(r^2 = 0.55) was observed between soil residual NO_3^- levels and sand content. Mamedov et al (2001) found the impact of wetting rate on aggregate disintegration and seal formation is higher in soils with high clay content than in soils with high sand content.

Some studies focused mainly on the spatial variation of soil texture (Iqbal et al., 2005; Kerry and Oliver, 2007). These studies were generally focused on finding an appropriate scale for the spatial structure of soil texture with reduced sample size. In general, determination of soil texture is resource intensive but its relationship to other soil properties and soil processes cannot be ignored (Baxter and Oliver, 2005). Meul and Van Meirvenne (2003) mapped the variation in top soil silt content of an 8 × 18 km area of land using various interpolation methods. Their study revealed small-scale and large-scale spatial variation of silt content is related to elevation. Although elevation showed a strong correlation (r=0.69) with silt content, the relationship (r=0.08) with silt content in small scales was poor due to considerable variability around the mean. Similarly, Gobin et al (2001) used soil landscape models to estimate the spatial variability of soil texture in a 589 km^2 study area. In this study, clay and silt particles were significantly correlated with slope, and they recommended the use of slope and compound topographic index to predict soil texture. However, the sample size in this study was relatively small (72 samples from a 589 km^2 study area) and small-scale variability in particle size distribution was not assessed. Iqbal et al (2005) evaluated the spatial structure of both clay content and sand content with exponential model semivariograms, and showed a moderate spatial autocorrelation (except surface sand which showed a strong autocorrelation). Increasing nugget values of sand and clay contents along the soil profile indicated increasing random variability with depth, which Iqbal et al (2005) attributed to surface tillage and depositional events. They suggested a sampling interval of 400 m to determine the spatial variability of sand, silt and clay content based on the range values of their semivariograms. However, Grote et al (2010) reported sand (%) was spatially correlated at small distances (up to 35 m) in loamy soils of a field where the topographic variation was negligible. Lopez-Granados et al (2005) reported a moderate spatial correlation of sand and clay (%) in a 6 ha cultivated field. In contrast, the silt (%) showed a pure nugget effect (no structured variability). In contrast, Kerry and Oliver (2007) showed clay (%) was better spatially correlated at smaller sampling intervals (20 m) than larger sampling intervals (40m, 60 m and 80 m). For the majority of the data, spatial structure of clay percent was explained by spherical, exponential and circular type semi variograms, which indicated existence of high short scale spatial variability. Consequently, Kerry and Oliver (2007) could not reduce sample size without decreasing precision. Zuo et al (2008) evaluated the spatial structure of soil texture in a 5-year grazed sand dune and in a 20-year old recovered sand dune. Particle size fractions showed a better spatial autocorrelation in recovered sand dune than grazed sand dune, which was attributed to the impact of grazing and vegetation in the spatial structure of soil texture.

Soil N is also spatially correlated. Kurunc et al (2011) reported that soil NO_3-N and well water NO_3^- were strongly spatially dependent in a study on a 36 000 ha of intensively cultivated land. The distribution of soil NO_3-N was patchy due to crop management practices and soil forming factors. The variation of soil NO_3-N (1.89 -106.4 $mgkg^{-1}$) and water NO_3-N (0.01 - 106.4 mgL^{-1}) was also significant. Zuo et al (2008) reported a strong spatial autocorrelation of TN in grazed sand dunes similar to the distribution of particle size distribution, and an increase in spatial variability of TN with the time of grazing. Soil organic carbon was positively related to TN content in crop fields (Shahandeh et al., 2011) and grazed sand dunes (Zuo et al., 2008). However SOC and soil NO_3^- were not spatially correlated. Cordova et al (2012) used the variation of SOC to predict the spatial variability of mineral N, but failed to find a structured variation of mineralized N.

1.3. Lysimeter study at Carberry (Background research)

A lysimeter study was established in a field 10 km northwest of Carberry (legal location SW-19-11-15W), Manitoba in 2002. The soil at this site was classified as the Fairland series, an Orthic Black Chernozem. The generalized soil profile of this series includes medium textured upper 75-90 cm thick loamy sand with an underlying sandy loam to loamy soil in a gently rolling landscape. The area is in the grassland transition (Gt2) ecoclimatic region with a mean annual precipitation of 472 mm.

The objectives of the lysimeter study were to directly measure the loss of water percolates and nitrate through the root zone over Assiniboine Delta Aquifer, and to evaluate the effect of swine manure and chemical fertilizer application on nitrate leaching (Nikiema et al., 2013). The study also established a protocol for estimating the probability of nitrate leaching. The experimental field included an area of 65 × 55 m, divided into 24, 10 × 10 m plots. Fertilizer and liquid swine manure treatments (six treatments with control, 4 replicates) were applied to the plots from 2002 to 2013. Intact soil core lysimeters were installed in each plot in order to monitor the leaching of NO_3^-, phosphorus and carbon through the soil column.

Leached water and nitrate varied considerably in the study, both spatially and between replicates of the same treatment. Nitrate leaching followed the leaching pattern of soil water in most cases and was generally attributed to the distribution of soil texture though clear spatial trends were not identified due to insufficient data. In general, lysimeters in the southern part of the field produced greater amounts of leachate than those in the northern part of the field (Akinremi et al., 2005). .

This thesis describes a detailed analysis of spatial structure of soil texture in relation to spatial trends in nitrate leaching observed in the previous lysimeter study.

The objectives of this study are;

1) To investigate the spatial distribution of soil texture in both vertical and horizontal directions

2) To determine the relationship between soil texture and the nitrate-N leaching in field lysimeters.

Hypotheses:

1) Spatial distribution of soil texture varies within the field.

2) This variability affects nitrate leaching in the field.

1.4. References

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2. SPATIAL AND STATISTICAL VARIABILITY OF SOIL PROPERTIES IN AN ORTHIC BLACK CHERNOZEM

2.1. Abstract

Micro spatial variability existing across the field should be taken into account for successful site-specific management with little impact on the environment. Soil texture is an important soil property, which influences other properties and processes in soils. The objective of this study was to investigate the spatial structure of soil texture and other soil properties in a Prairie field. A geospatial sampling scheme was designed in order to capture micro-spatial variability. One hundred and seventy eight (178) soil cores were sampled with a Giddings soil probe to 120 cm depth. Particle size distribution, soil water content, total nitrogen % (TN), total carbon % (TC) and soil organic carbon % (SOC) were determined and spatially interpolated with kriging based on semivariograms calculated with GS+. The results showed that soil particle size distribution was strongly spatially dependent in the surface layers and the strength of the spatial dependency declined with depth. Spatial autocorrelation, or proportion of spatially structured variance to total variance of sand content declined from 96% at surface (0-15cm) to 93% at 30 cm, 90% at 45 cm, 80% at 60 cm, 53% at 90 cm and 68% at 120 cm depths. The spatial autocorrelation of clay at the surface (0-15 cm) was 84%; 88% at 30 cm; 90% at 45 cm 81% at 60 cm; 59% at 90 cm and 82% at 120 cm depth. The range of the semivariograms for clay and sand also decreased with soil depth. Kriged maps clearly showed this textural variation within the field in vertical and horizontal directions. Soil water content also varied spatially similar to soil texture. Surface TC, TN and SOC were also spatially

autocorrelated where TC varied from 0.74 % to 2.86 % and TN varied from 0.07 % to .22 %.

2.2. Introduction

Soil properties vary spatially and temporally within a landscape and within the soil profile. This variability reflects environmental and agricultural processes. In the field, soil properties exhibit varying degree of spatial variability. Soil properties measured from samples taken in close proximity are often highly correlated relative to samples taken further apart. This spatial variability can affect the available plant nutrients leading to variability in yield (Mzuku et al., 2005; Shahandeh et al., 2011) and the distribution of contaminants (Needelman et al., 2001; Masetti et al., 2008; Wu et al., 2008; Glendell et al., 2014). Knowledge on this spatial structure will help to interpolate soil properties and implement site-specific management.

Soil texture influences soil physical quality and is correlated with pore size distribution (Dexter, 2004) which affects root penetration (Tracy et al., 2013) and plant water uptake (Hultine et al., 2006). Mamedov et al (2001) found that the impact of wetting rate on aggregate disintegration and seal formation is higher in soils with high clay content than in sandy soils. N mineralization is greater in sandy soils (Cote et al., 2000) relative to clay soils which can influence NO_3^- leaching to groundwater (Delgado and Bausch., 2005; Kurunc et al., 2011; Nyamangara et al., 2003). Clay soils have a greater potential for denitrification of NO_3-N than sandy or loamy soils because of slower gas diffusivity (Gu et al., 2013). Chardon and Schoumans (2007) observed high P accumulation and leaching in sandy and peat soils, while clay soils showed a greater surface runoff P losses. Chau et al., (2011) reported that sandy soils facilitate more soil microbial diversity than soils with high clay content.

Because of this vast influence of soil texture on other properties and processes, researchers have attempted to investigate the spatial structure of soil texture within the landscape, at the field scale and in both landscape and field levels (Gobin et al., 2001; Meul and Van Meirvenne, 2003; Iqbal et al., 2005; Mzuku et al., 2005; López-Granados et al., 2005; Shahandeh et al., 2005; Delbari et al., 2011; Shahandeh et al., 2011; Pongpattananurak et al., 2012). Various sampling strategies and different geo-statistical and interpolation tools have been used to estimate soil texture in unsampled locations. Meul and Van Meirvenne (2003) mapped the variation in top soil silt content of a 8 × 18 km area to determine the small and large scale spatial variation of silt content as related to elevation. Gobin et al (2001) used soil landscape models to estimate the spatial variability of soil texture in a 589 km^2 study area. They reported clay and silt particles were significantly correlated with slope and developed a compound topographic index to predict soil texture. Pongpattananurak et al (2012) interpolated sand and clay contents of a large region (8 million ha) with three-stage least squares to assess large-scale variability, and multivariate regression trees to evaluate short-scale variability with terrain data, climatic data and satellite imagery. Both sand and clay contents showed moderate spatial dependency. Moderate to strong spatial autocorrelation of sand and clay contents were reported in an alluvial floodplain (Iqbal et al., 2005) and cultivated lands (López-Granados et al., 2005; Mzuku et al., 2005; Shahandeh et al., 2005). Mzuku et al (2005) reported strong autocorrelation of surface silt (%) in their three study sites with areas ranging in size from 19 ha to 35 ha with different soil textural classes. López-Granados et al (2005), on the other hand, found a pure nugget effect (no spatial autocorrelation) of surface silt (%) in a 40 ha field. Sampling strategy also influences the uncertainty of prediction, as samples taken at close distances are efficient in catching the spatial structure with low uncertainty than samples taken apart (Delbari et al., 2011). Kerry and Oliver (2007) computed the spatial variation of top soil (0-15 cm) clay content at four different sites where spatial autocorrelation decreased with increased sampling interval. As such, a field scale intensive sampling strategy is essential in order to determine the spatial structure of soil texture in a particular area with high precision.

Nitrogen fertilization is vital for the crop production on the Canadian Prairies (Liang et al., 2004). Although organic and inorganic amendments of N increase crop yields, excess application of N can cause pollution by leaching into groundwater (Nikiema et al., 2013). Protecting ground water aquifers such as the Assiniboine Delta Aquifer (ADA) in Manitoba, which extends to 3885 km^2, is important since it supply water for human and animal consumption and for irrigation (Burton and Ryan, 2000). However, recent studies have shown this area is vulnerable to groundwater NO_3^- pollution because of intensive cultivation practices (Burton and Ryan, 2000; Olatuyi et al., 2012; Nikiema et al., 2013). Identifying areas prone to high NO_3^- leaching through conducting leaching studies is a tedious and time-consuming effort.

Soil texture plays a crucial role in NO_3^- leaching. Slow drainage and high denitrification in clay soils yield lower NO_3^- leaching rates than in sandy soils (Di and Cameron, 2002). Beaudoin et al (2005) reported that NO_3^- leaching in shallow sandy soils is three fold greater than deep loams. Van Es et al (2006) measured NO_3^- leaching in sandy loams 2.5 times the rate reported in clay loams. Silva et al (2005) compared NO_3^- leaching within different land uses over time and also found that leaching is higher in sandy soils than clay soils. Delgado and Bausch (2005) reported that residual-N and sand content were inversely related, whereas Cote et al (2000) determined that N mineralization and clay content were negatively correlated. Higher mineralization in sandy soils eventually results in lower residual N values. As such, investigating the spatial structure of soil texture can provide insights into the potential for nitrate leaching in different parts of the field. Shahandeh et al (2011) found residual N and clay content are spatially autocorrelated. However they did not find any relationship between residual N and clay content, which they attributed to variability in initial N reserves, precipitation and management practices.

Chernozemic Prairie soils, most often, consist of horizons with contrasting soil textures (Pennock et al., 2011). In alluvial soils, Iqbal et al (2005) reported increasing nugget (random) variability in sand and clay contents with soil depth, which they attributed to tillage and depositions over time. Under such conditions, the predictions of NO_3^- leaching merely based on the spatial structure of surface soil will not be accurate as the soils in deeper layers also play a crucial role in retaining the water and nitrate-N. As such, detailed information about the variation of soil texture in deeper layers is also required for an accurate estimation of NO_3^- leaching.

In addition to soil texture, analysis of the spatial distribution of other soil properties that influences NO_3^- leaching will provide insights on how these properties are related to each other within the field, the influence of soil texture on the distribution of these properties and their possible influence on NO_3^- leaching. Soil water content influences NO_3^- leaching by affecting N mineralization. Microbial N mineralization is significantly lower when the soil is dry, increases with soil water content up to an optimum level and again declines when the soil is very wet due to oxygen deprivation (Paul et al., 2003). Soil water content showed similar spatial structure to that of sand content when the soil is near saturation (Grote et al., 2010). Determination of TN, TC and SOC will provide an idea about their distribution in the field and the influence of soil texture on their distribution. SOC showed significant positive relationship with silt+clay content in field scale (Gami et al., 2009; Plante et al., 2006; Zinn et al., 2005). TN was also significantly spatially auto correlated at field level (Shahandeh et al., 2005). However it was not correlated with soil texture in a fertilized field (Gami et al., 2009) because of mineral N fertilization.

An intact core lysimeter station was established in Carberry, Manitoba to quantify NO_3^- leaching into ADA with respect to liquid hog manure and inorganic fertilizer applications (Nikiema et al., 2013). However, significant variability in water and NO_3^- leaching was observed within the field where NO_3^- leaching was found to follow the leaching pattern of soil water in most cases. In general, lysimeters in the southern part of the field produced greater amounts of leachate than those in the northern part of the field. Although Enns (2004) showed similarities between soil texture, NO_3^- and soil water leaching, additional research was required to better understand NO_3^- leaching, by conducting a detailed analysis of spatial structure of soil texture.

Therefore the objectives of this study are

(a) to investigate the spatial structure of soil texture and soil water content in a Prairie field in both vertical and horizontal directions

(b) to determine the spatial distribution of TN, TC and OC in the surface soil.

2.3. Materials and methods

2.3.1. Study area description

The study area was located in a producer's field, 10 km northwest from Carberry (legal location SW-19-11-15W), Manitoba. This site is located in the upper pine creek basin over the ADA, which is an unconfined deltaic sand and gravel aquifer (Render, 1988). The area comes under the Grassland Transition (Gt2) ecoclimatic region. The cool sub-humid climate of this region governs the type of native vegetation and the formation of Chernozemic Black soils on well-drained positions of the landscape. The mean annual temperature is around 2.1 ^{0}C. Mean annual precipitation is 472 mm of which 351 mm is received as rainfall. High amount of rainfall is received during May – July months of the year. The native vegetation of this area is prairie grasses and shrubs.

The site consists of soils in the Fairland series, an Orthic Black Chernozem developed on lacustrine deposits (Haluschak and Podolsky, 1999). These are medium textured, well drained soils, where the upper (0 to 75-90 cm) depth increment is classified as loamy sand, and the underlying layer (> 90 cm) is sandy loam to loam. Sand content decreases with depth, from about 78% in the upper layer , while pH increases with depth from 6.37 at the surface layer and, bulk density also gradually increases from 1.31 Mg m^{-3} with depth (Enns, 2004). In general, as a result of continuous conventional agricultural practices over the ADA, high NO_3-N content and high Mehlich3-Phosphorus content have been measured in the upper layers of soil over the ADA (Burton and Ryan, 2000). The Fairland soil series primarily consists of Ap, Bm and Ck horizons. The Ap horizon with a hydraulic conductivity of 1.42 cm hr^{-1} overlays a dense B layer (K_{ave} = 4.03 cm h^{-}

^{1}). A calcareous C layer exists after the B layer with very high hydraulic conductivity of 12.36 cm hr^{-1} (Haluschak and Podolsky, 1999). The site is located in upper slope of a gently rolling landscape with a slope of 0 - 0.5 % towards the north side of the field.

The experimental field was 65 × 55 m (0.36 ha) in size. This was divided into 24 plots each measuring 10 x10 m with 5 m buffer zones separating the blocks. Intact soil core lysimeters were installed in 2002 in each plot in order to quantify the leaching of nitrate-N, phosphorus and carbon through the soil column. Intact core lysimeters have a dimension of 55.2 cm inner diameter and 106.7 cm depth (Nikiema et al., 2013). The experiment was a randomized complete block design with three levels of liquid hog manure, two levels of fertilizer treatments, and a control treatment in 4 replicates. Each plot including the lysimeter, annually received either fertilizer or liquid swine manure treatment since 2002. Buckwheat, barley and canola were grown with conventional agronomic management.

2.3.2.Sampling scheme and soil sampling

A geostatistical sampling scheme was designed to capture the short scale spatial variability of soil variables in the field, while minimizing bias (Mulla and McBratney, 2002). The number of sampling points was determined using the method developed by Zar (2010) using the variability of sand percentage at 0- 10 cm and 60 - 90 cm depth (Enns, 2004) of the field. Overall, 178 soil samples were required to detect the variability at 1 % difference with the power of test of 0.8. Then the soil sampling grid was developed by iteration by adding and subtracting sample points until the semivariogram represents all lag intervals, particularly at short distances using SAS 9.3 (SAS Institute Inc, 2011) software.

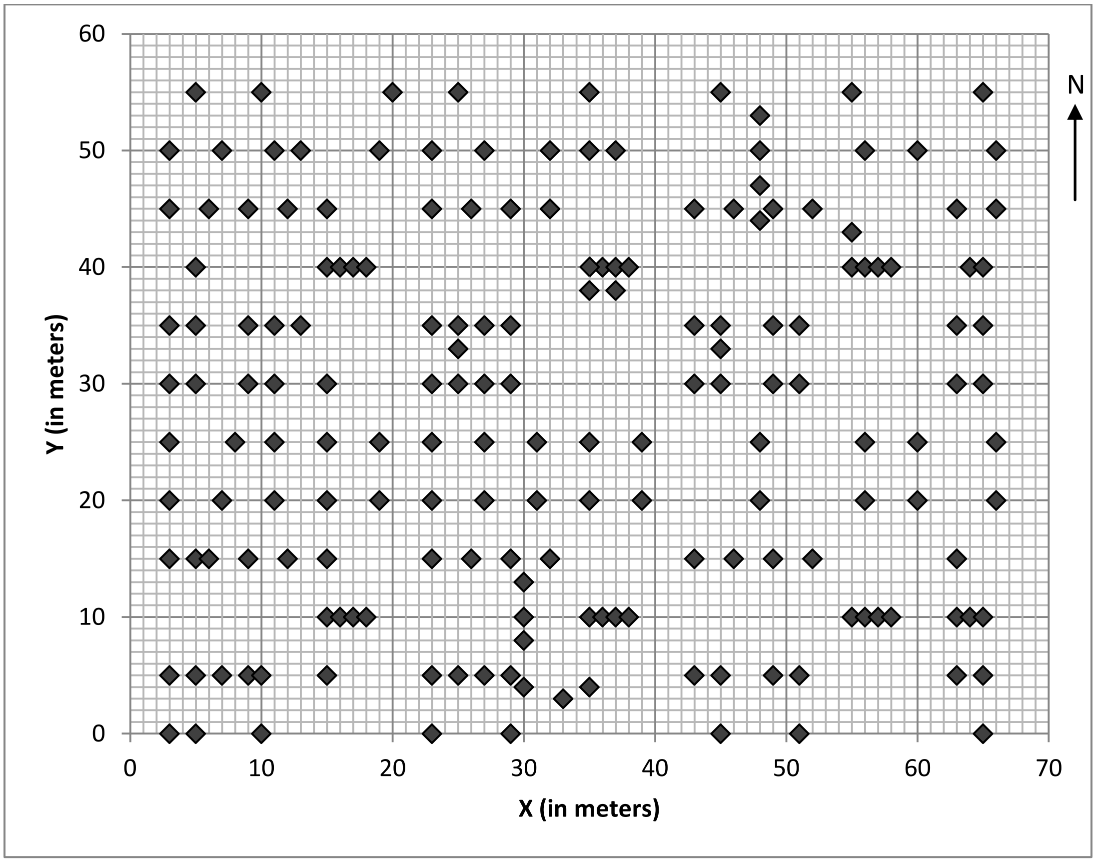


Figure 2.1Geospatial soil sampling design for the study area (178 samples)

Soil was sampled mid-May, 2013 prior to field treatment applications. Field boundaries were marked using a prism and spatial coordinates for each sample point were recorded. Soil samples were taken from 0 - 120 cm depth in 2" plastic sleeves with a Giddings hydraulic soil punch. The Giddings failed to collect soil samples below 90 cm in a few sample sites due to high sand content. From these locations, soil below 90 cm depth was collected using a Dutch auger.

2.3.3. Laboratory analysis

In order to delineate different horizons with different soil attributes, subsamples were taken from each horizon or subhorizon. Each soil sample sleeve was manually split and soil was sub-sampled according to their respective soil horizon and the depth of every soil horizon was also recorded. Visual observation (colour), determination of soil texture by hand and the reaction of soil to a dilute acid (10 % HCl) were used as aids in delineating soil horizons. Soil water content was determined by the gravimetric method (Gardner, 1986) for all subsamples before they were air-dried. Air-dried soil samples were passed through a rolling mill prior to soil textural analysis.

The particle size distribution was determined using the pipette method (Carter and Gregorich, 2008). 10 g of well-mixed soil was digested with 30 % H_2O_2 solution to remove organic matter. The soil solution was then heated on a hotplate to breakdown the remaining H_2O_2 into H_2 and O_2. Ten ml of dispersing agent (prepared by dissolving 15.88 g sodium carbonate and 71.4 g sodium hexameta-phosphate in reverse osmosis water) was added to the soil solution and thoroughly mixed for five minutes with a mixer. The soil solution was then passed through a #270 mesh sieve into a 1 l cylinder. This step separated sand portion of the soil sample which was collected in a pre-weighed beaker and oven-dried at 105 ^{o}C . Aliquots of silt + clay and clay were taken in pre-weighed beakers using a 25 ml pipette at appropriate time intervals that were calculated from Stoke's law. These samples were also dried in an oven at 105 ^{o}C overnight.

Randomly selected surface soil samples were ground for 4 minutes with a 8000D dual high energy shaker mill in preparation for chemical analysis. TN, TC and SOC were analyzed by dry combustion with a Flash 2000 elemental analyzer (Thermo Fisher

Scientific, Cambridge, UK). Inorganic carbon was removed with 0.5 ml of 2 M HCl prior to the determination of SOC, in samples placed on a hot plate at 80 ^{o}C. The process was repeated until effervescence ceased (Tiessen and Moir, 1993).

2.3.4. Statistical and Geostatistical analysis

Classical descriptive statistical parameters such as mean, standard deviation, coefficient of variation and skewness were calculated with SAS 9.3 (SAS Institute Inc, 2011) software. Normality tests were performed to test the distribution of data points. The Akaike's information criteria (Aic) and -2LogLikelihood were used to identify the best fitting distribution for soil variables (JMP 10, SAS Inc, 2012). In general, data should be normally distributed with equal variance before geospatial analysis (Moulin et al., 2014). However soil texture and moisture content data failed to show a normal distribution at 0.05 significant level (Kolmogorov-Smirnov normality test) and were transformed. Data were transformed using the Johnson Sl, Johnson Su, normal quartile and generalized log transformations in JMP version 10 (SAS Institute Inc, 2012) software. Although the log-normal transformation is commonly used in the literature (Cambardella et al., 1994; Shahandeh et al., 2005), this transform was not effective for soil texture and moisture in this study. Moulin et al (2011 and 2014) reported that continuous probability functions such as Johnson Sl, Johnson Su, normal quartile and generalized log efficiently transformed data to a normal distribution relative to a log-normal transformation. In this study, the Johnson Sl transformation yielded normal distributions in most cases when compared with untransformed, log normal, Weibull, generalized log, Johnson-Sb and Johnson-Su transformations for sand (%), clay (%), silt (%) and soil water content. Johnson Sl distribution represents lognormal distribution of Johnson system and distributions are derived from a normally transformed population (JMP 11 JSL Syntax reference, 2013). As such, Johnson Sl transformed data was used for geospatial analysis for the above mentioned parameters. However, the chemical parameters showed less skewness and approximate normal distribution, hence, they were not transformed.

Descriptive statistical parameters do not provide information about how soil samples are related to their respective locations i.e. how they are spatially autocorrelated. Geostatistical analysis, on the other hand, quantifies spatial dependency and structure of soil variables and facilitates interpolation (Mulla and McBratney, 2002). Geospatial analysis was performed with GS+ (Gamma Designs Software, 2013) software to investigate the spatial structure of soil texture and other soil properties. Semivariograms, which estimate the spatial dependency of a particular variable were generated. In a semivariogram, the nugget value (Co) quantifies the spatial variability at distances closer than the minimum sample spacing, and sampling and assaying errors (Delbari et al., 2011). The parameter "C" represents the structural or spatial variability. The sill (Co+C) is the sum of both nugget and structural variability, which is the total variability. The sill value reaches a plateau at some point and the lag distance up to that point is referred to as the range. The variable is not spatially correlated beyond the range (López-Granados et al., 2005). The ratio of C/(Co+C) explains the proportion of total variability explained by spatial autocorrelation. If the ratio is greater than 75 %, the variable it is considered to show a strong spatial dependence. A ratio between 25 -75 % indicates a moderate spatial dependence and less than 25 % indicates a weak spatial autocorrelation (Robertson, 2008; Cambardella et al., 1994). The residual sums of squares (RSS) are used to determine parameters for any given variogram model (Robertson, 2008). The model with the lowest RSS will be selected as the best fit.

Kriging is a family of generalized linear regression techniques which, with the appropriate variagram, estimates spatial variables at unsampled locations from nearby values with an error variance which is the minimum possible of any linear estimation method (Davis 2002; Mulla and McBratney, 2002). Ordinary kriging was used to interpolate and to generate maps in this study. This form of kriging does not require prior knowledge of the mean and is similar to simple kriging the mathematically least complicated variant (Davis 2002; Delbari et al., 2011)

2.4. **Results and Discussion**

2.4.1. Soil texture (Particle size distribution)

Descriptive statistical parameters of sand (%), clay (%) and silt (%) are summarized in 15 cm increments from the surface to 120 cm depth in tables 2.1, 2.2 and 2.3, respectively. In general, mean sand (%) decreased while mean clay (%) and silt (%) increased with soil depth. This change is abrupt in the 45 cm to 75 cm depth range where sand (%) decreased from 76 to 59 %, the clay (%) increased from 12 to 18 % while the silt (%) also increased from 12 to 21%. Below 75 cm depth, sand (%) declined to 51 % at 90 cm while mean clay (%) and mean silt (%) increased. Nikiema et al., 2013 also reported similar variability of sand (%), silt (%) and clay (%) with depth at this site. A main feature of a Chernozemic A horizon is the eluviation of clay particles (Pennock et al., 2012). Downward moving water eluviates finer clay particles at the surface leaving a sand-rich

A horizon, and illuviates clay in the B horizon resulting in a clay-rich B horizon (Phillips, 2001). Chernozems were formed in the Canadian Prairies on aeolian, deltaic, lacustrine and glacial till deposits with textures ranging from sandy loam to clay (Pennock et al., 2012). Sand deposited by aeolian processes at the end of glaciation (Pennock et al., 2012) likely contributed to the formation of a sandy A horizon at the study site (Haluschak and Podolsky, 1999; Phillips and Lorz, 2008).

Table 2.1 Summary statistics for sand content (%) along the soil profile

Depth	**Mean**	**Standard deviation**	**Coefficient of variation**	**Skewness**	**Minimum**	**Maximum**
0 cm	73.6	6.31	8.6	-0.6	58.2	84.6
15 cm	73.9	6.80	9.2	-0.3	58.2	89.2
30 cm	76.0	9.04	11.9	-0.2	52.9	92.1
45 cm	76.2	11.4	14.9	-0.6	46.1	91.5
60 cm	71.5	16.1	22.6	-0.8	20	91.5
75 cm	59.3	19.4	32.8	0	19.9	91.5
90 cm	51.3	17.4	33.8	0.3	11.1	92.8
105 cm	49.9	18.8	37.8	0.4	10.1	92.8
120 cm	51.9	19.4	37.4	0.3	10.1	92.8

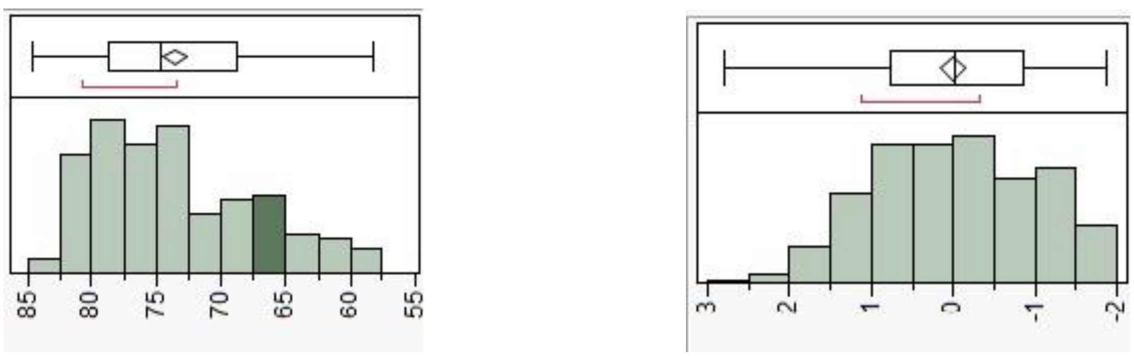
The mean and variance of soil texture fractions varied with depth. For example, the coefficient of variation (CV) for sand content increased with depth for all sites combined. For clay and silt contents, CV values increased to a depth of 60 cm then significantly decreased to 120 cm. These values exceeded the CV values of sand (%). Variability was highest in silt content at all depths when compared with sand and clay contents. The range between the minimum and maximum values also increased with depth. For example the range of sand (%) at surface (0 cm) was 58.2 % to 84.6 %, and 20 % to 91.5 % at the 60 cm depth, further increasing to 11.1 % and 92.8 % at 105 cm soil depth. The distributions of clay and silt content also show similar trends. The skewness of soil texture data varied between -1 and +1. The highest skewness of sand (-0.8) and silt (1.1) was observed at the 60 cm depth. In contrast, Delbari et al (2011) reported high CV values for sand (44 %) than silt (7 %) and clay (11 %) in a silt-rich top soil (0-10 cm). However, their data were more highly skewed than those for this study, which indicated a high level of variability of soil texture in their study. Iqbal et al (2005) reported increasing standard deviation values of soil textural fractions along soil depth in a silt-rich soil. However they did not present CV values for comparison. Most studies have focused on the distribution of soil texture in the A horizon (McLauchlan, 2006; Plante et al., 2006; Delbari et al., 2011; Pongpattananurak et al., 2012). In addition, the dynamic nature of soil texture makes it difficult to compare statistical parameters between studies.

Table 2.2 Summary statistics for clay content (%) along the soil profile

Depth	Mean	Standard deviation	Coefficient of variation	Skewness	Minimum	Maximum
0 cm	12.5	2.7	21.9	0.6	6.2	21
15 cm	12.3	2.9	23.5	0.4	5.2	21
30 cm	11.5	3.8	32.8	0.3	3.6	23.7
45 cm	11.7	4.9	42.2	0.7	4.3	26.2
60 cm	13.5	6.5	48.2	0.6	4.3	29.3
75 cm	17.5	7.3	41.5	-0.1	4.3	33.3
90 cm	20.2	6	29.9	-0.5	3.2	33.3
105 cm	19.8	7	35.2	-0.7	2.4	31.4
120 cm	19.2	7.1	37.1	-0.6	2.4	31.2

Table 2.3 Summary statistics for silt content (%) along the soil profile

Depth	Mean	Standard deviation	Coefficient of variation	Skewness	Minimum	Maximum
0 cm	13.9	4.2	30.1	0.5	5.7	25.1
15 cm	13.7	4.4	32.2	0.4	4.4	25.1
30 cm	12.7	5.7	45.4	0.4	4	30.4
45 cm	12.0	6.6	54.7	0.6	1.2	30.4
60 cm	15.3	10.3	67.2	1.1	1.2	50.9
75 cm	22.9	12.8	55.9	0.1	1.2	50.9
90 cm	29.1	12.5	42.9	0.2	4	68.3
105 cm	29.5	13.5	45.7	0.1	4	68.3
120 cm	28.8	13.7	47.6	0.2	4	68.3



(a) (b)

Figure 2.2 Histograms and box-plots showing (a) non transformed sand (%) and (b) Johnson Sl transformed sand content at surface (0 cm).

Raw data for surface sand content were skewed (0.6) and did not follow a normal distribution prior to transformation (Fig. 2.2.a). However, Johnson Sl transform (Fig. 2.2.b) yielded a normal population, which fulfilled one of the basic assumptions regarding normality for geospatial analysis. The Aic and -2Loglikelihood values for distributions of sand content at the surface (0 cm) (Table 2.4) were lower for the Johnson

Sl function relative to the normal or widely used log normal (Cambardella et al., 1994; Shahandeh et al., 2011).

Table 2.4 Best fit parameter estimates of different distributions for surface sand content (0 cm)

Distribution	-2LogLikelihood †	Aic †
Johnson Sl	1130	1137
Weibull	1134	1138
Johnson Su	1130	1138
Normal	1153	1157
Lognormal	1163	1167
Exponential	1876	1878

† - Lower values of Aic and -2LogLikelihood give the best fit.

In general, the spatial structure of soil textural components from the surface up to 60 cm depth was better represented using the Gaussian type semivariogram (Tables 2.5, 2.6 and 2.7). The spatial structure of all soil textural components below 60 cm was modeled with exponential and spherical model semivariograms.

Sand content was strongly spatially autocorrelated at all depths except the 90 to 120 cm increment. Approximately 96 % of the total variability could be attributed to spatial variability at the surface and 15 cm depths (Table 2.5). This spatial dependence decreased to 45 cm depth where 90 % of the variability was due to spatial variation, with 79 % at 60 cm depth. At 75 cm depth, the variance is represented by an exponential semi variogram with 82 % spatial autocorrelation. This decreased to a moderate spatial autocorrelation of 53 % at 90 cm depth. Spherical models explained the spatial structure of sand content at 105 cm and 120 cm depths. The shift of semivariograms with depth from Gaussian models to spherical models indicates increasing short scale variability (Grote et al., 2010). The sharp decrease in 'range' between 90 cm and 105 cm depths indicates an increase in short scale variability (López-Granados., 2005). Iqbal et al (2005) also reported strong spatial autocorrelation of sand content at the soil surface and decreasing spatial dependency along the soil profile when modeling the spatial variability of a 162 ha field with alluvial soils. In their study, sand content, which showed a strong spatial autocorrelation with a range of 438 m showed moderate spatial autocorrelation in subsurface and deeper layers with 238 m and 137 m range, respectively.

Clay content was strongly spatially autocorrelated at all depths except at the 90 cm depth where only 58 % of the total variation was explained by spatial variability. Spatial dependency of clay increased from 83 % at surface to 89 % at 45 cm depth and thereafter declined. Clay content was modeled with Gaussian semivariograms to 60 cm depth and with spherical semivariograms from 75 cm to 120 cm depth. In general, the range of clay content was greater than that of sand content in the surface layers (0 - 75 cm). Smaller ranges were observed at 105 cm and 120 cm depths, similar to sand content.

Table 2.5 Parameters for variogram models for Johnson Sl transformed sand content along the soil depth

Depth	**Model***	**Nugget variance Co**	**Sill (Co+C)**	**C/C+Co %**	**Range m**	**Spatial class****
0 cm	Gaussian	0.1	2.2	96.3	63.1	S
15 cm	Gaussian	0.1	2.2	96.6	65.3	S
30cm	Gaussian	0.1	1.9	92.6	56.2	S
45 cm	Gaussian	0.2	2	90.3	65.1	S
60 cm	Gaussian	0.3	1.7	79.8	61.4	S
75 cm	Exponential	0.3	1.7	82.2	137.4	S
90 cm	Exponential	0.6	1.2	53.3	68.8	M
105 cm	Spherical	0.2	1	75.4	13.1	S
120 cm	Spherical	0.3	1	68.4	12.1	M

* Models are all isotropic
**S = Strong spatial dependency (C/C+Co % > 75); M = Moderate spatial dependency (C/C+Co
% between 75 and 25)

Table 2.6 Parameters for variogram models for Johnson Sl transformed clay content along the soil depth

Depth	**Model**	**Nugget variance Co**	**Sill (Co+C)**	**C/C+Co %**	**Range m**	**Spatial class**
0 cm	Gaussian	0.4	2.2	83.9	75.7	S
15 cm	Gaussian	0.3	2.4	88.6	78.8	S
30cm	Gaussian	0.2	1.8	87.9	57.2	S
45 cm	Gaussian	0.2	2.3	89.5	74.4	S
60 cm	Gaussian	0.4	2	80.5	73.3	S
75 cm	Spherical	0.3	1.5	77.3	78.5	S
90 cm	Spherical	0.5	1.3	58.9	59.1	M
105 cm	Spherical	0.1	1	92.8	10.7	S
120 cm	Spherical	0.2	1	81.5	11.1	S

* Models are all isotropic
**S = Strong spatial dependency (C/C+Co % > 75); M = Moderate spatial dependency (C/C+Co
% between 75 and 25)

Table 2.7 Parameters for variogram models for silt content (JohnsonSI transform) along the soil depth

Depth	**Model**	**Nugget variance Co**	**Sill (Co+C)**	**C/C+Co %**	**Range m**	**Spatial class**
0 cm	Gaussian	0.2	2.2	90.3	68.5	S
15 cm	Gaussian	0.2	2.3	92.0	74.4	S
30cm	Gaussian	0.2	1.8	89.6	54.5	S
45 cm	Gaussian	0.2	1.9	89.2	60.5	S
60 cm	Spherical	0.4	1.6	74.2	58	M
75 cm	Exponential	0.3	1.6	83.5	120.1	S
90 cm	Exponential	0.6	1.2	50.1	51.9	M
105 cm	Exponential	0.01	1	99.0	9.9	S
120 cm	Spherical	0.4	1	64.0	12.7	M

* Models are all isotropic
**S = Strong spatial dependency (C/C+Co % > 75); M = Moderate spatial dependency (C/C+Co % between 75 and 25)

Silt content also showed a strong spatial autocorrelation up to 45 cm depth, and then declined. This observation and higher CV values of silt content at all depths when compared with sand and clay contents indicate a high variability of silt content along the soil profile and across the field.

This study showed strong spatial autocorrelation of sand, silt and clay at the surface (0-30 cm) for sampling intervals as small as 1m. Many studies in the literature report moderate spatial autocorrelation of soil textural fractions at large sampling intervals, which does not capture autocorrelation at shorter distances. Spatial distribution of soil texture varies with scale, and influences analyses at field level prior to implementing site-specific recommendations.

In general, sand (%), silt (%) and clay (%) are all spatially correlated across the study field and this spatial variability is strong in most cases, especially at shallow depths. However, short scale spatial variability increases along the soil profile and it is distinct at the 105 cm and 120 cm depths as the range declined sharply in this depth interval. Soil textural components vary within the soil profile as sand (%) tend to decrease and clay (%) increase with depth. Silt (%) varied considerably along the soil profile and across the field relative to sand and clay contents.

Soil texture varied considerably across the field (Figures 2.3 - 2.10). At the soil surface, sand content was higher in the southern part of the field compared to the northern part. The gradient of sand (%) gradually decreased in the northeast direction. A slight slope existed from the southwest to the northeast. It has been documented that soils high in clay are often observed at the lower elevations in a landscape or soil catena (Bonifacio et al., 1997; Schimel et al., 1985) due to soil erosion. A sand lens with >80 % sand content extending from the south eastern corner of the field at 30 cm depth (Figure 2.4) and occupying a significant area of the southern part of the field at 60 cm depth (Figure 2.5). In general, sand content declines below 90 cm depth (Figure 2.6). However, the uniform pattern of spatial distribution of sand content, observed in the upper layers, disappeared below 90 cm and became more random with frequent patches with very high sand content. Randomly located thin sand lenses at various depths have been previously reported on the Canadian prairies (Berthold et al., 2004; Cummings et al., 2012).

The spatial pattern of clay content in this study was the inverse of sand content as area with high sand content showed lower clay content (Fig. 2.7). For example, the northern part of the field showed high clay content values than the southern part of the field and these values increased along the soil profile. Below 90 cm depth, clay content increased in the entire field, though the autocorrelation of clay content (Table 2.6) was influenced by sand lenses. Silt content was lower in the southern part of the field relative to the northern part. Although silt content was moderate to strongly spatial dependent at all depths, the random variation of silt content in the field was greater than that of sand or clay. This trend was distinct below 75 cm (Table 2.7), and is characteristic of the Fairland soil series developed on lacustrine deposits (Haluschak and Podolsky, 1999).

In summary, soil texture was significantly autocorrelated in horizontal and vertical directions. Sand, silt and clay contents were strongly spatial dependent from the soil surface to 60 cm depth. This spatial dependence decreased below 90 cm depth.

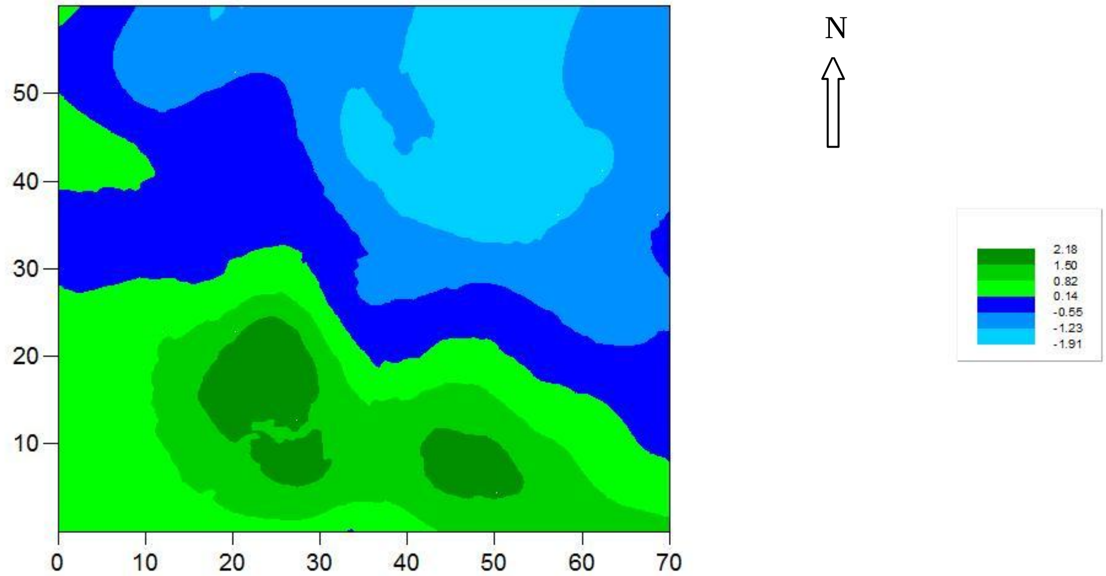


Figure 2.3 Kriged map of sand content (Johnson Sl transform) at 0 cm depth across the field. (JohnsonSl 2.18 = 83 %; 1.5 = 81 %; 0.82 = 79 %; 0.14 = 75 %; -0.55 = 71 %; -1.23 = 65 %; -1.91 = 57 %)

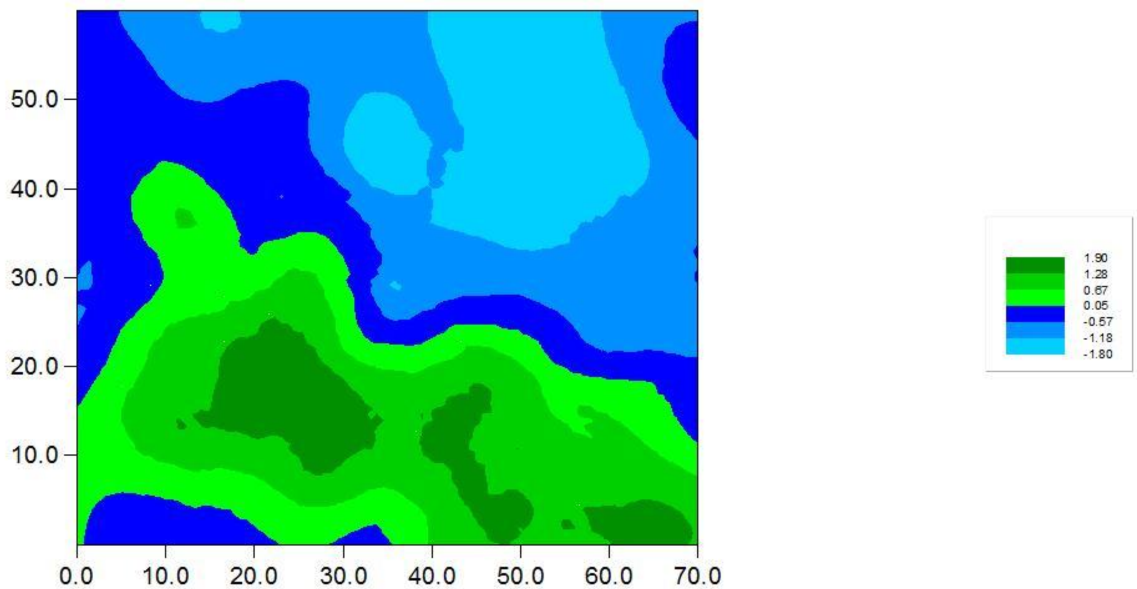


Figure 2.4 Kriged map of sand content (Johnson Sl transform) at 30 cm depth across the field. (JohnsonSl 1.9 = 91 %; 1.28 = 87 %; 0.67 = 82 %; 0.05 = 77 %; -0.57 = 71 %; -1.18 = 65 %; -1.8 = 57 %)

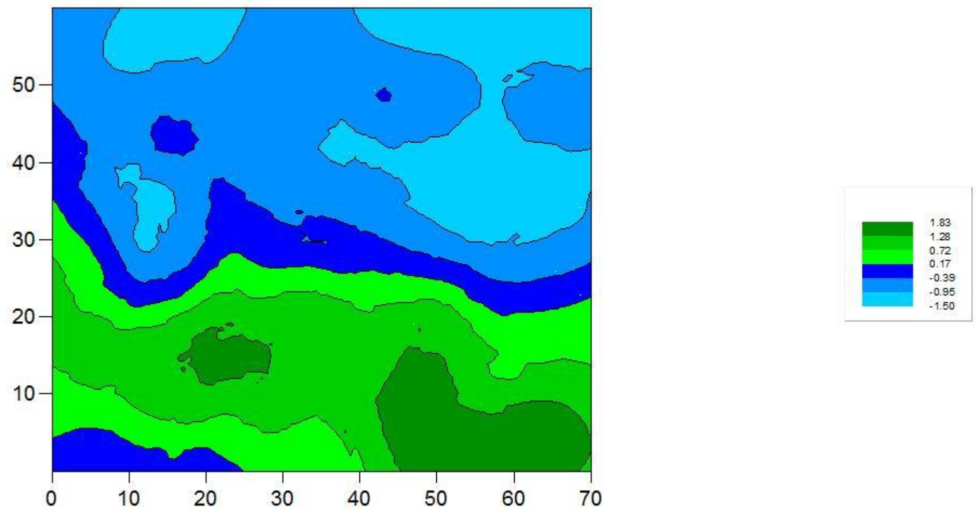


Figure 2.5 Kriged map of sand content (Johnson Sl transform) at 60 cm depth across the field. (JohnsonSl 1.83 = 90 %; 1.28 = 88 %; 0.72 = 85 %; 0.17 = 80 %; -0.39 = 71 %; -0.95 = 58 %; -1.5 = 36 %)

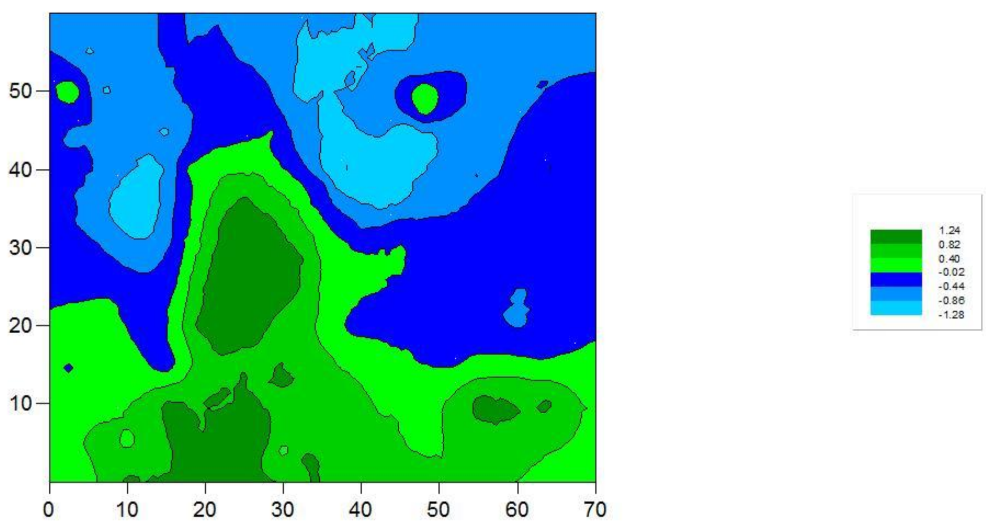


Figure 2.6 Kriged map of sand content (Johnson Sl transform) at 90 cm depth across the field. (JohnsonSl 1.24 = 73 %; 0.82 = 65; 0.4 = 57 %; -0.02 =50 %; -0.44 = 43 %; -0.86 = 36 %; -1.28 = 30 %)

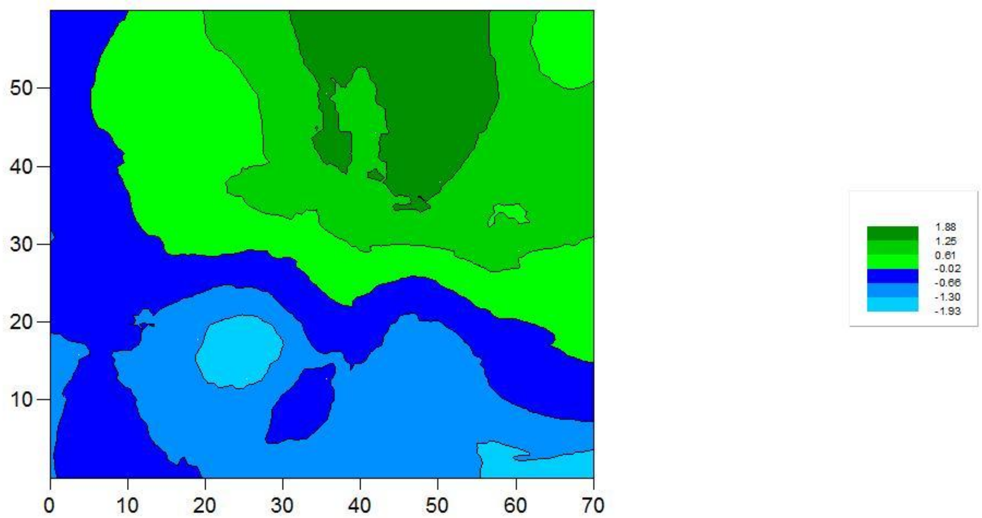


Figure 2.7 Kriged map of clay content (Johnson Sl transform) at 0 cm depth across the field. (JohnsonSl 1.88 = 18 %; 1.25 = 16 %; 0.61 = 14 %; -0.02 = 12 %; -0.66 = 11 %; -1.30 = 9 %; -1.93 = 8 %)

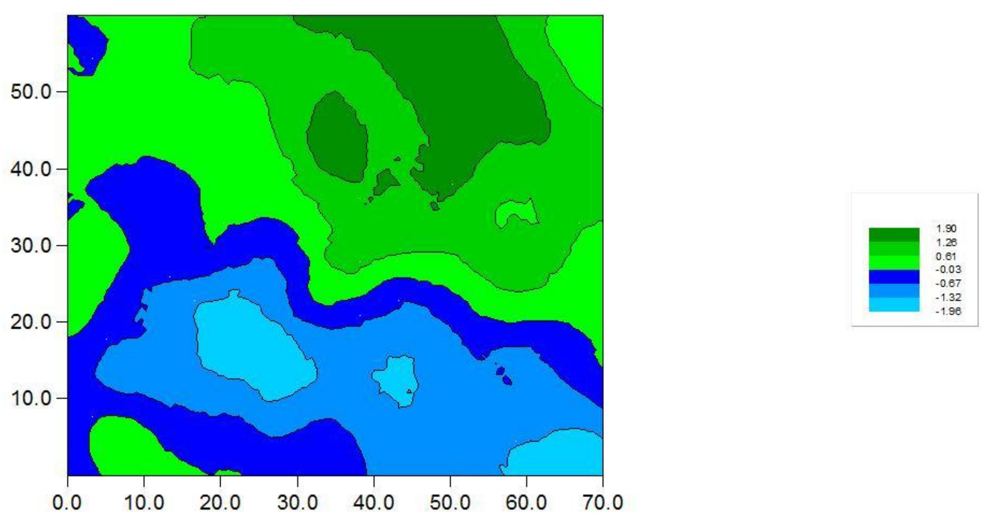


Figure 2.8 Kriged map of clay content (Johnson Sl transform) at 30 cm depth across the field. (JohnsonSl 1.9 = 19 %; 1.26 = 16 %; 0.61 = 14 %; -0.03 = 11 %; -0.67 = 9 %; -1.32 = 7 %; -1.96 = 5 %)

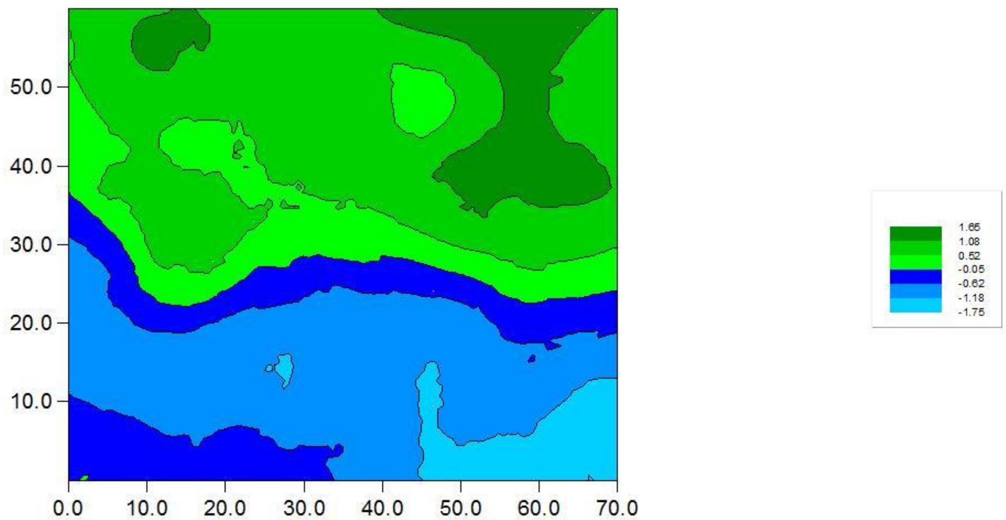


Figure 2.9 Kriged map of clay content (Johnson Sl transform) at 60 cm depth across the field. (JohnsonSl 1.66 = 28 %; 1.08 = 21 %; 0.52 = 15 %; -0.05 = 11 %; -0.62 = 9 %; -1.18 = 7 %; -1.75 = 5 %)

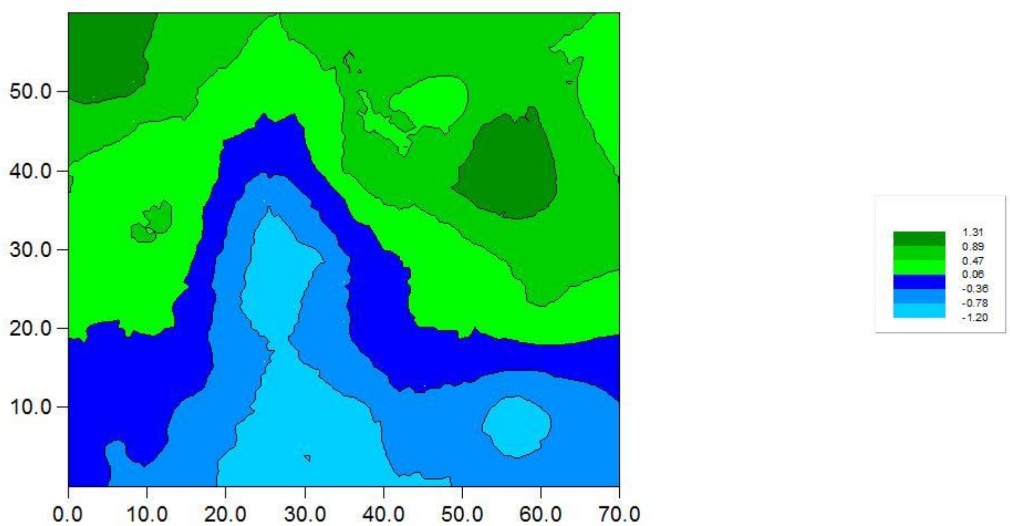


Figure 2.10 Kriged map of clay content (Johnson Sl transform) at 90 cm depth across the field. (Johnson Sl 1.31 = 28 %; 0.89 = 26 %; 0.47 = 24 %; 0.06 = 21 %; -0.36 = 19 %; -0.78 = 16 %; -1.2 = 13 %)

2.5.1. Soil water content

Soil water content was nearly constant when averaged across the field, and in the profile. The minimum mean value was 9.7% at the 45 cm depth while the maximum was 13.6% at the 90 cm depth (Table 2.8). Unlike soil texture, soil water content did not change appreciably with depth in mid-May.

Table 2.8 Summary statistics for soil water content sampled in mid-May

Depth	Mean	Standard deviation	Coefficient of variation	Skewness	Minimum	Maximum
0 cm	12.4	2.2	18.3	0.3	7.8	17.4
15 cm	12.3	2.4	19.9	0.1	6.9	17.4
30 cm	10.9	3.2	29.6	0.1	4.7	17.4
45 cm	9.7	3	31.6	0.3	4.6	16.7
60 cm	10.1	3.6	35.5	0.2	3.4	18.4
75 cm	11.8	4.3	36.6	0.1	3.4	21.5
90 cm	13.6	4	29.5	0	3.2	25.5
105 cm	13.1	4.4	33.7	-0.3	2.2	21.8
120 cm	12.8	4.8	37.5	-0.1	2.2	26.2

While texture is temporally invariant, soil water shows a high degree of temporal variation (Entin et al., 1999). Soil water content tend to increase with depth in previous spring soil sampling campaigns at this site (Enns, 2004) similar to increasing clay content with depth observed in this study. Some studies have also reported increasing soil water content in the soil profile (Qiu et al., 2001; McNamara et al., 2005). In our study, soil was sampled in mid-May just after snow melt. As a result the soil profile was still wet and soil water gradient was not established. Averages of gravimetric soil water content across the field may not reflect the relationship with depth due to higher values deeper in the profile for the south eastern portion of the field (compare Figure 2.11 with Figure 2.14). However, bulk density increased with depth at this site during the previous study (Enns, 2004), and volumetric water content should increase with depth since the gravimetric water content is nearly constant with depth (Table 2.8). The standard deviation and coefficient of variation for water content increased with soil depth, which reflects increased variability and trends within the soil profile similar to soil texture.

Table 2.9 Parameters for variogram models for Johnson Sl transformed soil water content along the soil depth

Depth	Model	Nugget variance Co	Sill (Co+C)	C/C+Co %	Range M	Spatial class
0 cm	Gaussian	0.1	2.2	95.6	64.1	S
15 cm	Gaussian	0.1	2.2	95.3	65.8	S
30cm	Gaussian	0.2	1.7	89.1	51.5	S
45 cm	Gaussian	0.3	1.8	85.0	59.2	S
60 cm	Gaussian	0.4	1.5	75.9	55.8	S
75 cm	Exponential	0.4	1.2	64.3	56.9	M
90 cm	Exponential	0.4	1	55.1	12.6	M
105 cm	Exponential	0.5	1	50.0	13.1	M
120 cm	Spherical	0.3	1	66.8	8.8	M

* Models are all isotropic
**S = Strong spatial dependency (C/C+Co % > 75); M = Moderate spatial dependency (C/C+Co % between 75 and 25)

The geostatistical parameters were a function of the spatial structure of soil water content across the field (Table 2.9). Soil water content was spatially autocorrelated from 0 to 60 cm, as indicated by the Gaussian semivariograms. For example, 95.6% of the variability was accounted for by spatial variability in the soil surface decreasing to 75.9 % at 60 cm but was between 25 and 75% below 75 cm depth where the spatial structure was represented by the exponential model semivariograms. The range also decreased with soil depth and this decrease increased at 90 cm depth (Table 2.9). These observations are correlated with the spatial structure of soil texture where increased small-scale variability was observed at depth. The occurrence of patches of dry sand lens at depth might be responsible for the increased short scale variability of soil water content with depth. McNamara et al (2005) described the possibility of existence of dry soil pockets in deeper layers of semi arid soils during winter period.

The interpolated soil water content maps are similar to the maps generated for soil clay content. The northern part of the field showed higher soil water content values when compared with the southern part of the field. However the distribution of soil water content was more random at 90 cm than the clay content (Figure 2.14).

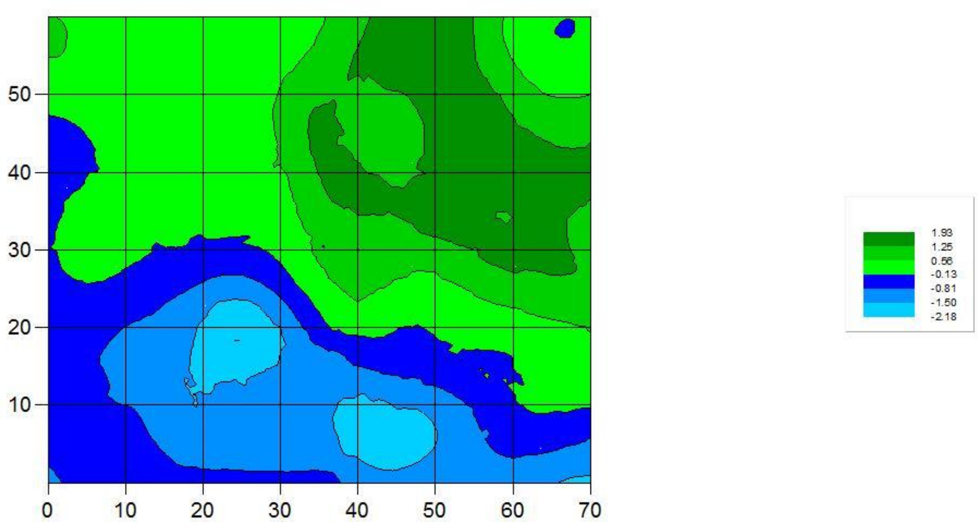


Figure 2.11 Kriged map of soil water content (Johnson Sl transform) at 0 cm depth across the field. (JohnsonSl 1.93 = 17 %; 1.25 = 15 %; 0.56 = 13 %; -0.13 = 12 %; -0.81 = 10 %; -1.5 = 9 %; -2.18 = 8 %)

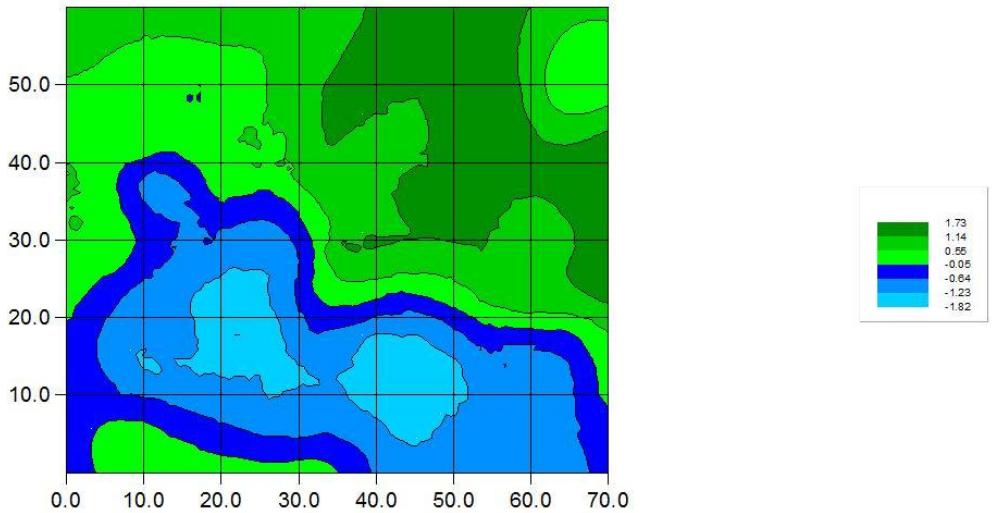


Figure 2.12 Kriged map of soil water content (Johnson Sl transform) at 30 cm depth across the field. (JohnsonSl 1.73 = 17 %; 1.14 = 15 %; 0.56 = 13 %; -0.05 = 11 %; -0.64 = 9 5; -1.23 = 7 %; -1.82 = 5 %)

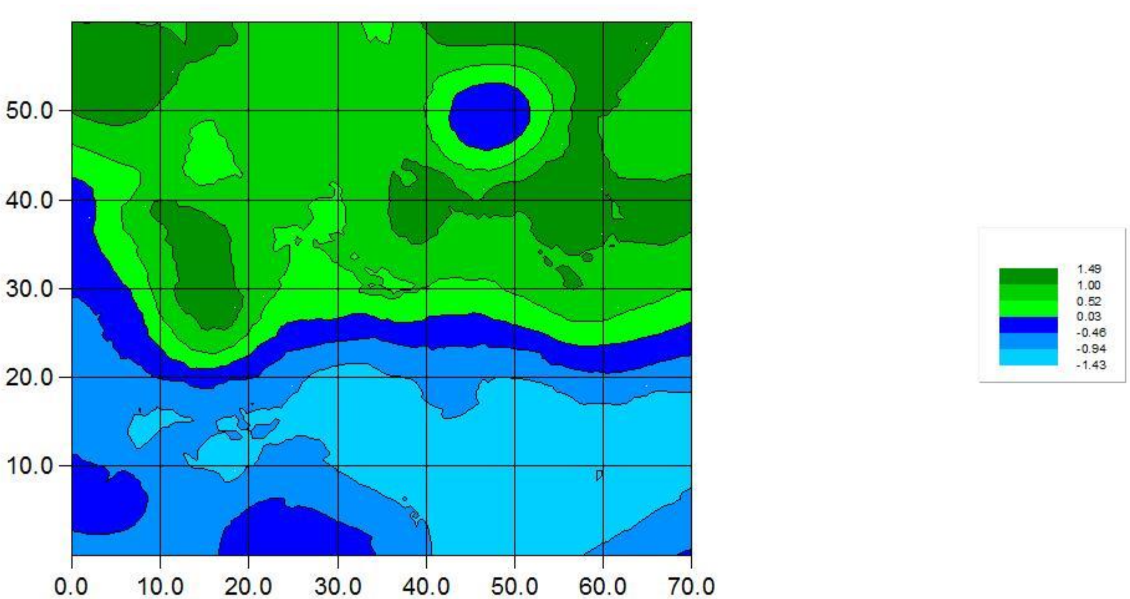


Figure 2.13 Kriged map of soil water content (Johnson Sl transform) at 60 cm depth across the field. (JohnsonSl 1.49 = 16 %; 1 = 14 %; 0.52 = 12 %; 0.03 = 10 %; -0.46 = 8 %; -0.94 = 7 %; -1.43 = 5 %)

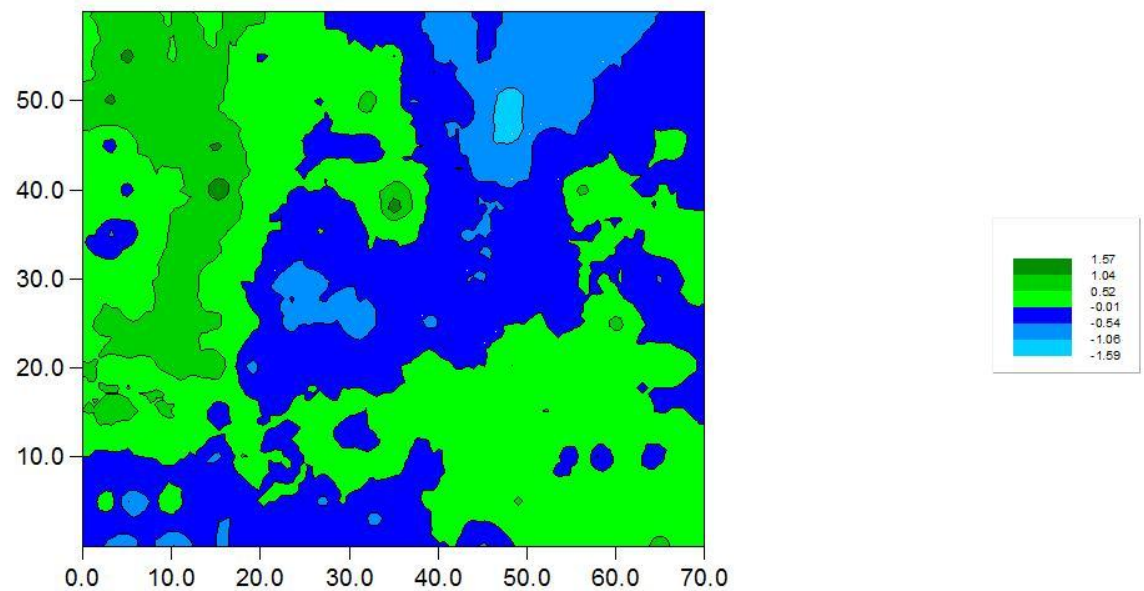


Figure 2.14 Kriged map of soil water content (Johnson Sl transform) at 90 cm depth across the field. (JohnsonSl 1.57 = 20 %; 1.04 = 18 %; 0.52 = 16 %; -0.01 = 14 %; -0.54 = 11 %; -1.06 = 9 %; -1.59 = 7 %)

2.5.2. Soil organic carbon and related properties at the surface

Maximum TN, TC and SOC were almost four times greater than minimum values at the surface. The surface TN, TC and SOC values show similar CV values (Table 2.10). This is not surprising as the TN and SOC are associated with the soil organic matter. The TN, TC and SOC were less skewed relative to surface soil texture and surface soil water content. Nikiema et al., (2013) reported topsoil (0-10 cm) average value of 2.27 % for TC before the implementation of amendments (2002) for the previous study. However, our data suggest that TC % exceed or are greater than those obtained in 2002.

Table 2.10 Summary statistics for TN%, TC% and SOC % at the soil surface (0 cm)

Variables	Mean	Standard deviation	Coefficient of variation	Skewness	Minimum	Maximum
Total nitrogen	0.14	0.04	27.8	0.2	0.06	0.22
Total carbon	1.74	0.51	29.5	0.2	0.74	2.86
Soil organic carbon	1.7	0.49	30	0.2	0.74	2.8

Table 2.11 Parameters for variogram models for TN%, TC% and SOC% at the soil surface (0-15 cm)

Parameter	Model	Nugget Co	Variance	Sill (Co+C)	C/C+Co %	Range m	Spatial class
TN	Gaussian	0.0002		0.003	90.2	56.8	S
TC	Gaussian	0.04		0.49	91.9	56.8	S
SOC	Gaussian	0.04		0.46	90.5	60.1	S

* Models are all isotropic
**S = Strong spatial dependency (C/C+Co % > 75); M = Moderate spatial dependency (C/C+Co % between 75 and 25)

These soil properties were strongly spatially correlated. Ninety % of the total variability of TN, TC and SOC was modelled with Gaussian semivariograms. This is somewhat similar to the spatial structure of sand (%) and soil water content where over 90 % of the total variation was represented by spatial variability.

Interpolated maps showed low levels of TN, TC and SOC in the southern part of the field and higher levels in the northern part (Figures 2.15 to 2.17). This was similar to the spatial distribution of soil textural fractions. TN, TC and SOC were lower in the areas with higher sand and lower clay contents and higher in areas with high clay content and lower sand content. Clay content was positively correlated with soil organic matter content and negatively correlated with mineralization of N, thus reducing the amount of N that is available for leaching. Cote et al. (2000) reported a similar relationship between clay content, soil nitrogen and carbon mineralization. Gami et al (2009) also reported positive correlation between SOC and TN with soil silt+clay content. On the other hand, a few other studies have failed to establish relationships between the clay content and SOC (McLauchlan, 2006) and between the clay content and TN (Shahandeh et al., 2011), which they attribute to temporal variability in soil organic pools.

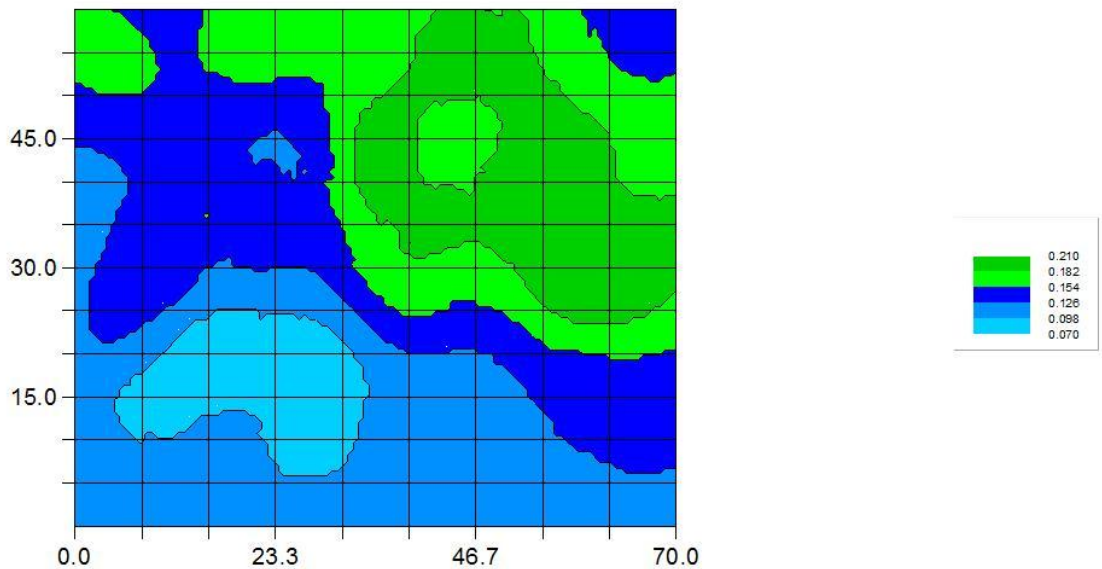


Figure 2.15 Total nitrogen (%) (0-15 cm)

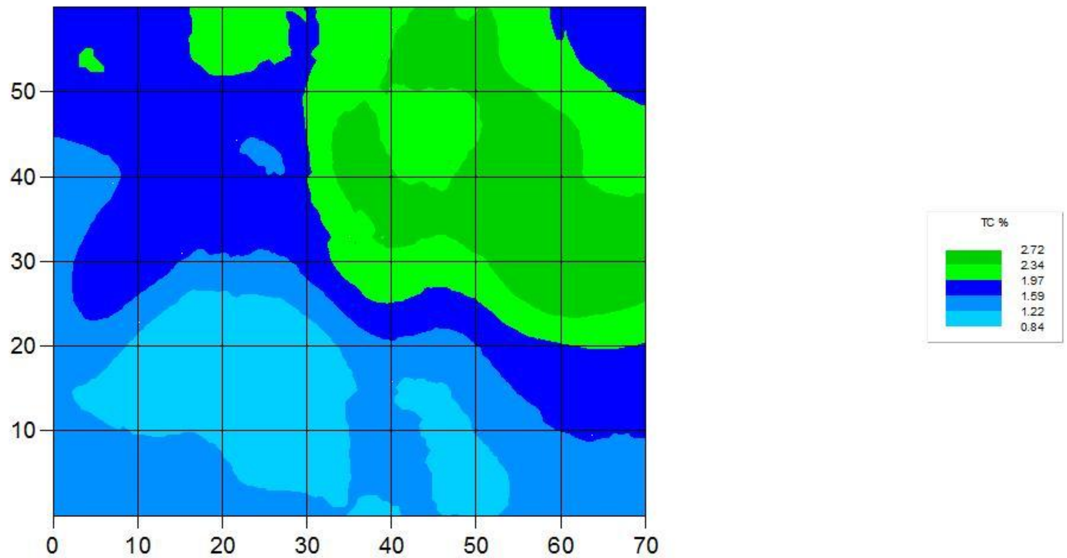


Figure 2.16 Total carbon (%) (0-15 cm)

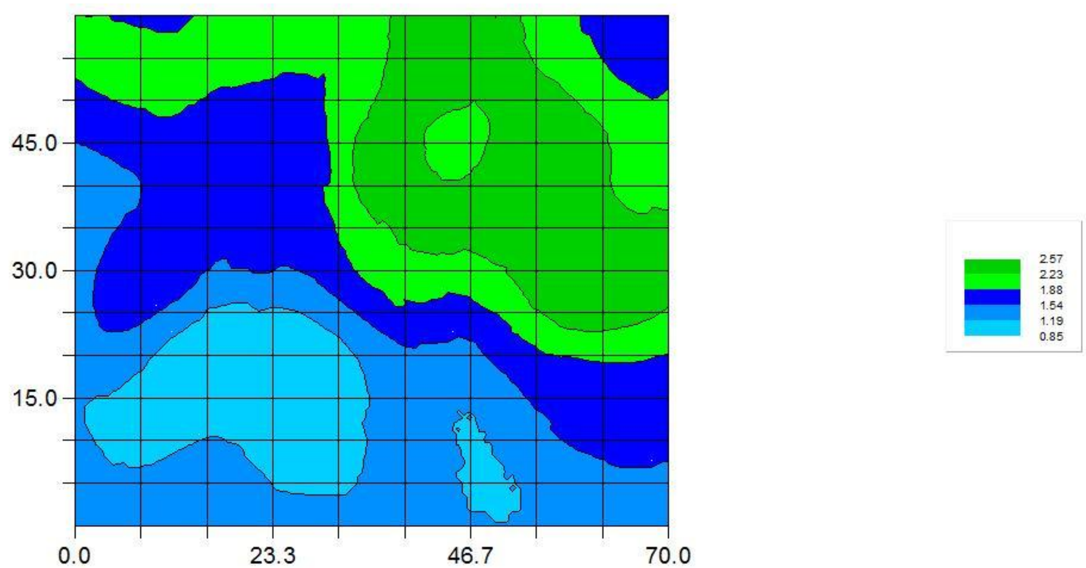


Figure 2.17 Soil organic carbon (%) (0-15 cm)

2.6. Conclusions

Sand (%), clay (%), silt (%) and soil water content were significantly spatially autocorrelated across a small Prairie field. This spatial autocorrelation decreased with depth as high random variability was observed below 90 cm. These observations show the significance of micro spatial variability in Prairie fields, which could affect the site-specific management strategies. The spatial distributions of surface TN, TC and SOC were correlated with soil texture. Further studies on possible influence of soil texture on nitrogen dynamics and water movement are required in order to determine the pattern of nitrate-N movement across the soil catena and along the soil profile.

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3. RELATIONSHIP BETWEEN SOIL TEXTURE, LEACHING AND OTHER SOIL PROPERTIES

3.1. Abstract

Determining the spatial structure of soil texture is important for site specific management and may help explain variability in leaching events across the landscape due to its influences on other soil properties and soil processes such as leaching. In this study, we investigated the relationships between soil texture and soil water content from the surface to 120 cm depth, total nitrogen (TN), total carbon (TC), soil organic carbon (SOC) in the top 15 cm, with water percolation and nitrate leaching. We also assessed the impact of terrain on soil texture and other properties with the help of digital elevation models. Simple linear correlations and partial least squares analysis were performed to establish these relationships. Soil texture significantly influenced soil water content, TN, SOC and TC. Terrain influenced the distribution of soil texture though this relationship decreased with soil depth. Elevation, relative slope position and vertical distance to channel network were the crucial terrain properties which influenced the distribution of soil texture (VIP > 0.8). Both soil texture and terrain influenced soil surface TN (R^2=0.75) and SOC (R^2=0.74) contents. Water percolation and nitrate leaching through lysimeters were positively correlated with sand content and negatively with silt and clay contents. The highest correlation was observed for soil texture at 90 cm depth with water percolation and nitrate leaching.

3.2. Introduction

To sustain crop production, inorganic N supplementation is considered as an important management option in agriculture. The application of manure N in large amounts to agricultural lands has also gained momentum in the recent past. However, excessive N fertilizer adversely affects the environment (Smith and Schindler, 2009) and human health (Townsend et al., 2003). Processes such as runoff and leaching are pathways by which inorganic N reaches surface and underground water bodies (Elrashidi et al., 2005). A significant portion of organic N is converted into inorganic forms through mineralization and leached down to groundwater bodies from the soil profile (Elrashidi et al., 2005).

Inorganic N is transported to the deeper layers of soil profile and subsequently to groundwater when water percolates through the soil. Nitrate (NO_3^-) is the dominant form of inorganic N which is involved in this process (Dinnes et al., 2002), whereas the ammonium-N is readily converted into nitrate-N in most soils. Most temperate soils, which are net negatively charged, repel NO_3^-, and as such, the NO_3^- ions move freely downwards with water in a process known as NO_3^- leaching.

Nitrogen fertilizer is crucial for sustainable crop production on the Canadian Prairies (Liang et al., 2004). Nitrogen is applied to fields in inorganic forms such as urea and mono-ammonium phosphate and organic forms such as dairy and hog manure. However, intensive cultivation and fertilizer application may result in groundwater pollution by NO_3^- (Burton and Ryan, 2000; Olatuyi et al., 2012; Nikiema et al., 2013). The Assiniboine Delta Aquifer (ADA) in Manitoba covers an area of 3 885 km^2 and supplies water for human and animal consumption and for irrigation (Burton and Ryan, 2000).

However, identifying areas which are prone to NO_3^-leaching is complex. Hummocky terrain and layered soils of the prairies make it further difficult to physically identify areas prone to NO_3^- leaching and to implement control measures. Analysis of soil properties and landscape features which influence NO_3^- leaching and water movement across the landscape and along the soil profile could provide an analytical alternative to identify areas prone to NO_3^- leaching.

Soil texture is one of the important properties affecting NO_3^- leaching. Higher leaching rates have been observed in sandy soils when compared with clay soils. High drainage and low denitrification in sandy soils may account for this observation (Di and Cameron, 2002). Beaudoin et al. (2005) observed three times greater NO_3^- leaching in shallow sandy soils than deep loams. Van Es et al (2006) reported 2.5 times greater NO_3^-leaching in sandy loam soils than clay loams. Silva et al (2005) compared NO_3^- leaching within different land uses over time. They also reported higher leaching in sandy soils than clayey soils. Remote sensing and geographical information systems (GIS) were used by Bausch and Delgado (2005) to identify a negative relationship (r^2=0.55) between sand content and residual NO_3-N. Hassink (1994) reported a negative correlation between soil N mineralization and clay+silt content in an incubation study. Griffin et al (2002) observed more NO_3^- accumulation in sandy loam soils than silty loams when they applied hog manure. These studies show an increased availability of NO_3-N for leaching in sandy soils due to increased mineralization. The relationship between NO_3^- leaching and soil texture may provide another analytical tool to identify the spatial distribution of NO_3^- leaching in the landscape.

Some authors however, report no significant relationship between soil texture and NO_3^- leaching. For example, Shahandeh et al (2011) described the spatial distribution of residual N and clay content in a 64 ha corn field, but the two variables were not significantly correlated. Variability in TN, precipitation and management may affect mineralization, and the relationship between texture and NO_3^- leaching.

Buried clay or dry sand layers can play a crucial role in water infiltration (Radcliffe and Rasmussen, 2001). In general, soil hydraulic properties such as saturated hydraulic conductivity vary within the landscapes more than soil textural components (Mulla and McBratney, 2002) and their determination is resource intensive. However, soil texture affects soil hydraulic properties by influencing soil pore size (Radcliffe and Rasmussen, 2001). So establishing a relationship with leaching and soil texture will be a possible alternative to overcome the practical issues related to the measurement of soil hydraulic conductivity.

Soil texture also influences the distribution of soil chemical parameters such as TN, TC and SOC. Geostatistical analyses in Chapter two showed a strong spatial autocorrelation for TN, TC and SOC in the top 15 cm of the soil, similar to that of soil texture. Further statistical analysis is required to find if there is a significant relationship between soil texture and the distribution of these soil chemical parameters. Significant positive relationships between SOC and silt+clay content at the field scale has been previously reported (Gami et al., 2009; Plante et al., 2006; Zinn et al., 2005). The TN has also shown a significant spatial autocorrelation at the field level (Shahandeh et al., 2005). However, TN did not correlate significantly with soil texture in a fertilized land, perhaps as a result of mineral N supplementation (Gami et al., 2009).

Soil texture is also a dynamic soil property and it varies across the field (Mzuku et al., 2005) and along the soil profile (Phillips and Lorz, 2008). Accounting for the spatial structure of soil texture in both horizontal and vertical directions would help to predict soil texture of soils in un-sampled locations, such as inside intact core lysimeters by interpolation.

Along with soil texture, NO_3^- leaching is also dynamic and is influenced by both the properties of the soils and the crop and soil management practices (Dinnes et al., 2002; Kurunc et al., 2011; Riley et al., 2001). In many cases, intensive vegetable producing systems show the highest NO_3^- leaching than any other agricultural cropping systems (Di and Cameron, 2002). Use of non-leguminous catch crops such as rye grass could significantly reduce NO_3^- leaching (Hansen and Djurhuus, 1997; Beaudoin et al., 2005) whereas legume cover crops increased leaching (Campiglia et al., 2010). Leaching loses increase rapidly after a certain level of N fertilizer of effluent application rate. However, reducing application rates below the recommended rates did not show any improvements in leaching (Beaudoin et al., 2005). In application methods, split application of nitrogen fertilizers is more efficient in reducing NO_3^- leaching than blanket applications (Di and Cameron, 2002).

Leaching also varies seasonally. Higher spring NO_3^- leaching was observed in the spring for the Prairie region, which was attributed to high soil water content and lower evapotranspiration rates after snowmelt (Nikiema et al. 2013). Crop uptake reduces NO_3^- leaching during the growing season (Sun et al., 2008). High leaching was observed after major thunderstorm events during the summer (Di and Cameron, 2002).

Soil water is another factor which affects nitrate leaching. Microbial N mineralization is significantly lower when the soil is dry, increases with soil water content up to an optimum level, and declines when the soil is very wet due to oxygen deprivation (Paul et al., 2003). Gordon et al (2008) reported that drying and rewetting events in soils significantly increased NO_3^- leaching. Prolonged dry conditions result in lower crop uptake of applied N and rewetting favors increased microbial mineralization. This increases the amount of NO_3^- available for leaching. In addition to that, higher amounts of drainage results in greater NO_3^- leaching (Di and Cameron, 2002). Soil texture plays a vital role in the spatial distribution of soil water in the fields. Chapter 2 shows that soil water follows similar distribution as sand and clay contents. Further statistical analysis is required to determine the relationship between soil water and soil texture and to see how it varying along the soil profile.

The influence of landscape in the distribution of soil properties cannot be ignored. Landscape hydrology, which often influences soil formation, is itself controlled by the terrain (Brown et al., 2004). In many cases, the position of soils in a landscape determines their behaviour and type. Regression models of Brown et al (2004) have shown an increase in sand content with slope gradient in a soil catena where poorly-drained soils can be seen. They also reported subsoil layers with higher clay contents than surface layers (texture contrast) in well-drained soils in back footslope of a landscape. Factors such as sand deposition in soil surface, clay illuviation and clay alluviation encourage the formation of abovementioned texture contrast soil layers (Brown et al., 2004).

Various studies have emphasized the importance of integrating terrain attributes with soil and crop variables when modelling yield and soil parameters (Beaudette et al., 2013; Brown et al., 2004). Sumfleth and Duttman (2008) have significantly improved the prediction of silt (%), TC and TN by incorporating terrain attributes into regression kriging in their study. Umali et al (2012) reported that the influence of terrain on SOC, electrical conductivity and coarse fraction of soil (>2mm) vary with management practices. Florinsky et al (2002) predicted residual phosphorus and soil moisture in a Canadian Prairie field by incorporating landscape attributes into regression equations. As such, deriving the terrain attributes and exploring their relationship with soil texture, soil water and leaching data will provide more insights into the spatial patterns of these parameters. Previous chapter explored the spatial variability of soil variables along and across a field on the Canadian Prairies. The objective of this study was to identify the statistical relationship between soil texture, soil water content, chemical parameters, terrain attributes and leaching observed in intact core lysimeters installed in the particular field.

3.3. Materials and methods

3.3.1.Site description

The study area is located on a cooperator farmer's field, 10 km northwest of the town of Carberry (legal location SW-19-11-15W), Manitoba. The major soils are in the Fairland series, an Orthic Black Chernozem , developed on lacustrine deposits (Haluschak and Podolsky, 1999). Further information on the study area is provided in Chapter 2, section 2.3.1.

3.3.2.Lysimeter experiment and leachate collection

The experimental field has an area of 65 × 55 m (0.36 ha). This is further divided into 24, 10 ×10 m plots with 5 m buffer zones in between. An intact field core lysimeter was installed in each plot in 2002.

Intact core lysimeters were made of schedule 80 polyvinyl chloride (PVC). The main column is 106 cm in length and 54 cm in diameter. It was separated from the collection cap by a perforated PVC plate. Leachate from the root zone was accumulated in the collection cap from the main column through perforated plate via gravity. Lysimeters were installed with the aid of a specially devised drop hammer (from USDA/ARS, State College, Pennsylvania) in a manner that can inflict little soil disturbance. Detailed information about the installation of lysimeters is provided by Enns (2004) and Nikiema et al (2013).

The objective of this lysimeter experiment was to study nitrate leaching in the ADA following liquid hog manure and fertilizer application. As such, the plots received three levels of liquid hog manure (64, 128 and 192 kg h^{-1} respectively), two levels of chemical fertilizer applications (128 and 192 kg h^{-1}) and a control,arranged in a randomized complete block design (RCBD) with 4 replicates. Lysimeters also received the same treatment which their relevant plot received every year. Leachate was collected from the collection cap with suction pumps in different times of a calendar year. Detailed information of fertilizer and manure application and collection of leachate from the lysimeters are given elsewhere (Nikiema et al., 2013)

3.3.3. Soil sampling and laboratory analysis

Soils were sampled on the 14th, 15th and 16th of May 2013. A Giddings soil punch was used to take soil samples from 0-120 cm depth in 2" plastic sleeves. A geospatial sampling scheme (Figure 2.1) was used for the above purpose. The design of the sampling scheme was elaborated upon in Chapter 2 under the section 2.3.2. Soils in the 120 cm plastic sleeves were subsampled according to their horizons or subhorizons and were analysed for particle size distribution and soil water content. Randomly selected soil samples from A horizon were analysed for TN, TC and SOC. The procedures for the above laboratory analysis were described in section 2.3.3 of Chapter 2.

3.3.4. Digital terrain modelling

Elevation data (relative altitude) were recorded with a total station (Sokkia SET). Single frequency Trimble 4600LS GPS receivers were used to calibrate the total station prior to data collection. Ordinary kriging was used to calculate a 1 m gridded DEM from elevation data (63 points). The 1 m grid interval of the regular DEM emphasized the microtopographic variability of the field. Geographic information software (SAGA version 2.12) (Conard, 2006) was used to calculate terrain derivatives including slope gradient, slope aspect, plan curvature (PlC), profile curvature (PrC), saga wetness index (SAGA WI), relative slope position (RSP) and vertical distance to channel network (VDCN). Slope gradient was defined as "an angle between a tangent plane and horizontal one at a given point on the land surface" (Florinsky et al., 2002). Slope aspect provided the gradient of the steepest slope from the north (Adhikari et al., 2013) which indicates flow direction (Florinsky et al., 2002). Plan and profile curvatures are second derivatives of slope gradient or aspect (Greve et al., 2012). Topographic convergence and divergence are calculated from plan curvature (PlC). PlC is positive when the flow diverges in positions such as ridges and is negative when the flow converges in positions such as valleys and depressions (Greve et al., 2012). Profile curvature (PrC) reflects the rate of change in slope gradient. PrC is generally positive in concave slopes and negative in convex slopes. The SAGA wetness index is interpreted as a function of specific catchment area and slope gradient (Hedley et al., 2013). High index values represent areas with high soil water content. Relative slope position (RSP) is a combined complex terrain parameter which determines the relative slope positions in the landscape (Bock et al., 2007). Each terrain derivative grid had an interval of 1 m with 3584 cells. Slope gradient, slope aspect, elevation, PlC, PrC, SAGA WI, RSP and VDCN were estimated with ordinary kriging at each of the 178 soil sampling points and locations of field lysimeters.

3.3.5.Statistical analysis

Pairwise correlations between soil variables, terrain derivatives and leaching were determined with the PROC CORR procedure in SAS (version 9.3, SAS inc, 2011) software. Correlations for transformed (Johnson Sl) sand (%), silt (%), clay (%) and soil water content by depth, and TN, TC and SOC of top 15 cm were also determined. Additional correlations were calculated with elevation and other terrain derivatives some of which were not normally distributed. These were transformed to normal or approximate normal populations with JMP (Version 10, SAS Inc, 2012) software prior to correlation analysis (Table 3.1).

Table 3.1 Transformation to normality/approximate normality for terrain derivatives

Terrain derivative	Transformation
Elevation	Johnson Sl
Slope gradient	Not transformed
Slope aspect	Johnson SU
Plan curvature	Johnson Sl
Profile curvature	Johnson SU
SAGA wetness index	Not transformed
Relative slope position (RSP)	Johnson Sl
Vertical distance to channel network	Exponential (σ= 0.24)

The relationship of percolation and nitrate leached from lysimeters (2004 to 2009) to soil variables and terrain derivatives was assessed statistically. Cumulative percolation and leached NO_3^- from 2004 to 2009 were assessed by year and season. April, May and June were classified as spring, July and August were categorized as summer, September and October as fall. Lysimeters 2 and 13 were removed from the analysis due to low leachate production during the study. Soil texture influences soil hydraulic properties by affecting the pore size distribution. In stratified soils, the layer with the lowest hydraulic conductivity determines the flow rate through the soil profile and is the most sensitive soil layer. Correlation analysis of leachate with soil texture at different depth may help to find that sensitive layer. Soil samples were not collected inside the lysimeters to avoid disturbance. Data were interpolated with kriging to estimate the texture of the soil inside the lysimeters (chapter 2). Leaching data were evaluated with terrain attributes to assess the effect of microtopography on leaching.

Linear models were determined with partial least squares (PLS) (Brereton, 2003) for the relationship between soil variables at different depths and terrain derivatives. This analysis allows the calculation of linear models with correlated independent variables (SAS Inc, 2012). Untransformed data were scaled, centered and used for the PLS analysis in JMP (Version 10, SAS Inc, 2012) software. Slope aspect was excluded from the analysis because it is a circular variable (Florinsky et al., 2002). All the other calculated terrain derivatives were tested for their relationship with sand (%), silt (%), clay (%), TN (%) and SOC (%) contents. Variables importance on PLS projections (VIP) with values greater than 0.8 were used to identify significant predictors. The statistical analysis was repeated to select a predictive model with the minimum root mean PRESS value and lowest number of predictive variables.

3.4. Results and discussion

3.4.1.Relationship between soil texture, soil water and terrain derivatives

Soil textural fractions were significantly correlated from the surface (0 cm) to 120 cm depth (Tables 3.3, 3.4 and 3.5). These results further support our findings about the similar geospatial distribution of soil textural fractions across the field and along the soil profile.

Soil water was significantly negatively correlated with sand content ($p < 0.0001$) at all depths (Table 3.6), and positively correlated ($p < 0.0001$) with silt and clay contents. However the correlation coefficients decreased along depth. Soil texture and organic matter influence soil water content by affecting the water holding capacity (Mohanty and Skaggs, 2001; Pachepsky et al., 2001). Various studies (Gómez-Plaza et al., 2001; Grote et al., 2010; Pachepsky et al., 2001) have reported a negative relationship between soil water and sand content. Gomez-Plaza et al (2001) observed consistently significant correlation coefficients between soil water content and sand content in all three seasons when the soil water status was classified as wet, medium and dry. Available soil water was negatively related to sand content due to high surface infiltration and rapid drying and positively correlated with clay and sand. The relationships were significant for all soil water conditions except for clay during dry conditions. Grote et al (2010) reported a decrease in correlation coefficients between sand content and soil water content when the soil is near saturation.

Our study was conducted in the spring, after snow melt. There were no major rainfall events during that period. Our results addressed the influence of soil texture on soil water distribution when the soil was near field capacity. Our results also provide insights of predicting soil water content on the basis of soil texture. Previous studies have emphasized the effect of crop growth on the spatial variability of soil water content through crop water uptake and evapotranspiration (Grote et al., 2010; Hupet and Vanclooster, 2002). However, this was not a factor considered in this study as there was no crop present in spring during soil sampling in this study.

Soil properties varied throughout the study site and in relation to terrain derivatives (Table 3.2). Correlations between terrain derivatives and soil textural components were significant and reflected soil forming processes at the site. Clay and silt were negatively related ($p < 0.001$) to elevation from the surface (0 cm) to 120 cm depth. In contrast, sand content was positively related ($p < 0.0001$ from 0 cm to 90 cm; $p < 0.05$ from 90 cm to 120 cm depth) to elevation. In general, the correlation between elevation and soil textural fractions was strong (> 0.8) to moderate (0.5 to 0.8) up to 60 cm depth and reduced below at depths less than 60 cm. These correlations are attributed to erosion and redistribution of clay and silt particles to lower elevations due to water and tillage erosion similar to results reported by Moulin et al (1994) following glaciation. Lieβ et al (2012) and Cox et al (2003) reported increasing sand content and decreasing clay content with elevation. A strong negative correlation between elevation and clay content was also reported by Famiglietti et al (1998). In general, well drained sandy soils can be observed in the crest and shoulder positions of an undulating landscape and poorly drained clayey soils can be found in the toe-slope and valley positions. Our study shows the significant impact of elevation on soil texture in microtopographic level up to 120 cm depth even though it is a layered soil.

Table 3.2 Descriptive statistics of terrain derivatives for 178 sampling points

Terrain derivative	Mean	Standard deviation	Coefficient of variance	Skewness	Minimum	Maximum
Elevation, m	386.12	0.3	0.07	-0.3	385.57	386.53
Slope gradient, ^{O}	0.9	0.4	44	0	0.06	1.66
Slope aspect, ^{O}	1.46	1.9	130	1.6	0.01	6.28
Plan curvature, m^{-1}	$-1.1*10^{-4}$	$5*10^{-4}$	-515	$-7*10^{-3}$	$-2*10^{-3}$	$1*10^{-3}$
Profile curvature, m^{-1}	$1.7*10^{-4}$	$9*10^{-4}$	492	-0.1	$-2*10^{-3}$	$2*10^{-3}$
SAGA wetness index	5.4	0.5	9.3	0.1	4.3	6.4
Relative slope position	0.7	0.3	48	-0.5	0.01	1
Vertical distance to channel network	0.2	0.2	93	0.5	0	0.7

Table 3.3 Pearson correlation coefficients for sand content with soil variables and terrain derivatives

Variable	Surface 0cm	15 cm	30 cm	45 cm	60 cm	75 cm	90 cm	105 cm	120 cm
Silt	-0.93***	-0.95***	-0.97***	-0.96***	-0.96***	-0.97***	-0.92***	-0.95***	-0.98***
Clay	-0.85***	-0.89***	-0.95***	-0.96***	-0.96***	-0.93***	-0.79***	-0.84***	-0.85***
Soil water	-0.94***	-0.94***	-0.94***	-0.92***	-0.87***	-0.73***	-0.39***	-0.56***	-0.64***
Elevation	0.82***	0.8***	0.75***	0.71***	0.68***	0.48***	0.39***	0.32***	0.23**
Slope gra.	-0.34***	-0.32***	-0.26***	-0.23**	-0.4***	-0.3***	-0.18***	-0.19**	-0.23**
Aspect	0.16**	0.2**	NS	NS	NS	0.15**	NS	NS	NS
PlC	0.35***	0.4***	0.42***	0.38***	0.26***	NS	NS	NS	NS
PrC	0.71***	0.67***	0.69***	0.65***	0.58***	0.4***	0.34	0.27**	0.21**
SAGA WI	-0.25***	-0.28***	-0.3***	-0.33***	-0.14*	NS	NS	NS	NS
RSP	0.74***	0.72***	0.69***	0.64***	0.66***	0.39***	0.33***	0.29***	0.23**
VDCN	-0.83***	-0.81***	-0.77***	-0.73***	-0.71***	-0.46***	-0.38***	-0.33***	-0.24**

PlC -plan curvature; PrC- profile curvature; SAGA WI- SAGA wetness index; RSP- Relative slope position; VDCN- Vertical distance to channel network; Slope gra. - Slope gradient

*** - significant at <0.001

**-significant at <0.05

*- significant at <0.1

NS - Not significant

Table 3.4 Pearson correlation coefficients for silt content with soil variables and terrain derivatives

Variable	Surface 0cm	15 cm	30 cm	45 cm	60 cm	75 cm	90 cm	105 cm	120 cm
Sand	-0.93***	-0.95***	-0.97***	-0.96***	-0.96***	-0.97***	-0.92***	-0.95***	-0.98***
Clay	0.62***	0.72***	0.87***	0.88***	0.88***	0.89***	0.73***	0.72***	0.74***
Soil water	0.87***	0.9***	0.91***	0.9***	0.83***	0.74***	0.42***	0.54***	0.62***
Elevation	-0.75***	-0.8***	-0.73***	-0.71***	-0.67***	-0.49***	-0.38***	-0.28**	-0.19**
Slope gra.	0.25***	-0.32***	0.27***	0.2**	0.4***	0.37***	0.18**	0.19**	0.24**
Aspect	-0.12*	-0.19**	NS	NS	NS	-0.2**	-0.13*	NS	NS
PlC	-0.37***	-0.4***	-0.41***	-0.4***	-0.27***	NS	NS	NS	NS
PrC	-0.65***	-0.63***	-0.68***	-0.64***	-0.56***	-0.41***	-0.33***	-0.23**	-0.17**
SAGA WI	0.26***	0.28***	0.24***	0.35***	0.14*	NS	NS	NS	NS
RSP	-0.68***	-0.68***	-0.68***	-0.64***	-0.65***	-0.44***	-0.32***	-0.26**	-0.2**
VDCN	0.77***	0.76***	0.76***	0.73***	0.7***	0.5***	0.37***	0.29**	0.2**

PlC-plan curvature; PrC- profile curvature; SAGA WI- SAGA wetness index; RSP- Relative slope position; VDCN- Vertical distance to channel network; Slope gra. - Slope gradient
*** - significant at <0.001
**-significant at <0.05
*- significant at <0.1
NS - Not significant

Table 3.5 Pearson correlation coefficients for clay content with soil variables and terrain derivatives

Variable	Surface 0cm	15 cm	30 cm	45 cm	60 cm	75 cm	90 cm	105 cm	120 cm
Sand	-0.85***	-0.89***	-0.95***	-0.96***	-0.96***	-0.93***	-0.79***	-0.84***	-0.85***
Silt	0.62***	0.72***	0.87***	0.88***	0.88***	0.89***	0.73***	0.72***	0.74***
Soil water	0.81***	0.84***	0.88***	0.89***	0.87***	0.73***	0.42***	0.53***	0.57***
Elevation	-0.74***	-0.74***	-0.73***	-0.71***	-0.69***	-0.48***	-0.42***	-0.37***	-0.29***
Slope gra.	0.32***	0.34***	0.26***	0.2**	0.37***	0.29***	0.13*	NS	NS
Aspect	-0.15**	-0.19**	NS	NS	NS	-0.13*	NS	NS	NS
PlC	-0.28***	-0.31***	-0.39***	-0.37***	-0.2**	NS	NS	NS	NS
PrC	-0.61***	-0.6***	-0.66***	-0.64***	-0.54***	-0.38***	-0.37***	-0.33***	-0.27**
SAGA WI	0.28***	0.27***	0.32***	0.38***	0.17**	NS	NS	0.21**	NS
RSP	-0.62***	-0.64***	-0.65***	-0.62***	-0.63***	-0.4***	-0.33***	-0.3***	-0.25**
VDCN	0.72***	0.73***	0.74***	0.7***	0.69***	0.48***	0.4***	0.36***	0.29***

PlC. -plan curvature; PrC- profile curvature; SAGA WI- SAGA wetness index; RSP- Relative slope position; VDCN- Vertical distance to channel network; Slope gra. - Slope gradient
*** - significant at <0.001
**-significant at <0.05
*- significant at <0.1
NS - Not significant

Table 3.6 Pearson correlation coefficients for soil water content with soil textural fractions and terrain derivatives

Variable	Surface 0cm	15 cm	30 cm	45 cm	60 cm	75 cm	90 cm	105 cm	120 cm
Sand	-0.94***	-0.94***	-0.94***	-0.92***	-0.87***	-0.73***	-0.39***	-0.56***	-0.64***
Silt	0.87***	0.9***	0.91***	0.9***	0.83***	0.74***	0.42***	0.54***	0.62***
Clay	0.81***	0.84***	0.88***	0.89***	0.87***	0.73***	0.42***	0.53***	0.57***
Elevation	-0.81***	-0.8***	-0.72***	-0.66***	-0.63***	-0.2**	NS	NS	NS
Slope gra.	0.39***	0.38***	0.25***	0.15**	0.42***	0.3***	NS	NS	NS
Aspect	-0.19**	-0.21**	NS	NS	NS	NS	NS	NS	NS
PlC	-0.3***	-0.34***	-0.43***	-0.35***	NS	NS	0.27***	0.29***	0.26**
PrC	-0.66***	-0.64***	-0.63***	-0.61***	-0.47***	NS	NS	NS	0.16*
SAGA WI	0.19**	0.21**	0.28***	0.38***	NS	-0.16**	NS	NS	NS
RSP	-0.74***	-0.73***	-0.66***	-0.58***	-0.58***	-0.19**	NS	NS	NS
VDCN	0.82***	0.82***	0.74***	0.67***	0.67***	0.21**	NS	NS	NS

PlC. -plan curvature; PrC- profile curvature; SAGA WI- SAGA wetness index; RSP- Relative slope position; VDCN- Vertical distance to channel network; Slope gra. - Slope gradient
*** - significant at <0.001
**-significant at <0.05
*- significant at <0.1
NS - Not significant

Sand content showed a significant negative relationship with slope gradient at all depths. The correlation coefficient decreases from - 0.34 at the surface ($p < 0.0001$) to - 0.23 at 45 cm ($p = 0.0025$). Then it increases to -0.4 at 60 cm ($p < 0.0001$) and then declines to -0.18 ($p = 0.025$) at 90 cm depth (Table 3.3). Silt content is significantly positively correlated with slope gradient at all depths ($p < 0.05$) (Table 3.4). Clay content is also significantly positively correlated ($p = 0.0001$) with slope gradient up to 75 cm depth (Table 3.5). Many studies have reported a positive relationship between sand content and slope (Gobin et al., 2001; Ließ et al., 2012; Sumfleth and Duttmann, 2008) or negative relationships between clay content and slope (Bishop et al., 2006), which they attributed to the down slope and down profile removal of finer clay particles. In contrast Famiglietti et al (1998) reported a positive correlation between slope gradient and clay content. The overall slope of our study site is small (1.5 %) and can be classified as a gently rolling landscape. The smoothing of the overall slope as a result of comparatively larger measurement intervals in the upper slope area could be a reason for our results. Brown et al (2004) addressed the relationship of small convex areas to soil texture in upper slopes in the context of soil erosion. In the meantime, the study of Cox et al (2003) failed to find any relationship between slope and soil textural fractions in two of their three study fields with flat to gently rolling slope (0 - 5%). Although significant, the correlation between soil texture and slope is weaker when compared with the effect of elevation. Sand content is positively correlated ($p < 0.05$) up to 15 cm depth and thereafter was not significantly related with slope aspect whereas clay and silt are negatively correlated ($p < 0.1$) up to 15 cm depth and thereafter was not significantly related. Slope aspect often failed to provide significant correlations with soil variables which previous researchers have attributed to its circular character (Florinsky et al., 2002) and was mentioned as the least influencing attribute in predicting soil texture (Adhikari et al., 2013).

Topographic convergence and divergence of flow is determined by plan or horizontal curvature whereas profile or vertical curvature estimates the rate of change of slope angle (Greve et al., 2012). The near zero mean plan and mean profile curvature values of our data (Table 3.2) indicates that our area is in a transit zone which is neither an accumulation or a dissipation zone (Florinsky et al., 2002). Sand content is positively correlated with plan curvature ($p < 0.001$) up to 60 cm depth and thereafter was not significantly related whereas silt and clay contents showed a significant negative correlation ($p < 0.05$) up to 60 cm depth. Similar relationship was observed with profile curvature. However, the relationship between soil textural fractions and profile curvature is significant up to 120 cm depth ($p < 0.05$) with higher correlation coefficients than with plan curvature.

Sand content was negatively correlated with SAGA wetness index ($p < 0.0001$ up to 45 cm; $p < 0.1$ up to 60 cm) and thereafter was not significantly related. Silt and clay contents were significantly positively correlated with SAGA wetness index up to 60 cm depth. This is a direct relationship as clay and silt accumulate in depressions identified by the SAGA wetness index. The RSP value of 0 indicated channels and 1 indicates the ridges. Sand content was positively correlating with RSP whereas silt and clay contents were significantly negatively correlated with RSP. These correlations were significant to 60 cm depth. This shows that more sand can be seen in the upslope positions whereas more silt and clay are accumulating in the downslope areas. Vertical distance to channel network was significantly positively correlated to clay ($p < 0.0001$)

and silt ($p < 0.0001$ up to 105 cm depth and $p < 0.05$ up to 120 cm depth) contents and negatively correlated with sand content ($p < 0.0001$) from the surface (0 cm) to 120 cm depth. The correlation coefficients between RSP and vertical distance to channel network with sand, silt and clay are strong to moderate from the surface to 60 cm depth, and less so at greater depths.

The terrain control over soil water distribution is also significant and is similar to that of clay content on most occasions. Soil water is significantly negatively correlated ($p < 0.0001$ from surface to 60 cm depth and $p <0.05$ from 60 -75 cm depth) with elevation. The correlation is not significant below 75 cm depth. This is consistent with the results of the studies of Famiglietti et al (1998) and Florinsky et al (2002). Water flows from upslope to downslope in a landscape which results in the establishment of a moisture gradient. Florinsky et al (2002) also reported decreasing correlation coefficients between soil water and elevation. Slope gradient is positively correlated with soil water until 75 cm depth which contradicts the results from other studies which showed a negative relationship between soil water and slope gradient (Famiglietti et al., 1998; Florinsky et al., 2002; Gomez-Plaza et al., 2001). Runoff and evaporation rate increase with slope gradient while rainfall received per area and infiltration decrease. This results in a decrease in soil water. In our study we also found positive correlation of clay content with slope. The correlation between soil textural fractions and soil water is stronger than the correlation between soil water and terrain derivatives such as elevation and slope. This is also true for correlations with other terrain derivatives such as plan and profile curvatures, SAGA wetness index, RSP and vertical distance to channel network. The sign of the correlations of soil water content with the above derivatives is similar to that of silt and clay content. In general, soil water shows significant correlations with the above derivatives up to 45-60 cm depth, thereafter the correlation becomes weak and non-significant along the soil profile.

In summary, soil textural fractions show significant correlations with soil water and terrain derivatives which indicate the influence of terrain in the distribution of soil texture. This correlation weakens along soil depth even though it is statistically significant. Increasing random variability and influence of parent material could be the reason for the poor correlation between soil textural fractions with soil water and terrain derivatives with depth. The geospatial analysis of Chapter 2 already demonstrated increasing variability in soil textural fractions with soil depth. Both soil texture and terrain affect the distribution of soil water in the field. However the influence of soil texture in the distribution of soil water is greater than the terrain control especially in the depths below 45 cm.

3.4.2.Relationship between soil texture, soil water, TN, TC, SOC and terrain derivatives

Table 3.7 shows the Pearson correlation coefficients between soil surface (0-15 cm) chemical parameters, soil texture, soil water, and terrain derivatives. Possible influence of soil texture, soil water and terrain on soil chemical parameters is evident when we look at the results in general.

Surface TN, TC and SOC are strongly positively correlated with each other with a Pearson correlation coefficient value of 0.99 ($p < 0.0001$). In Chapter 2, we showed the existence of strong spatial autocorrelation of surface TN, TC and SOC where more than 90 % of the total variability was accounted for by spatial variation. Increased soil organic matter promotes microbial immobilization and by thus increased nitrogen immobilization (Barrett and Burke, 2000; Côté et al., 2000). This increases TN content of soil and shows a significant positive correlation between TN and SOC. Shahandeh et al (2011) also reported a significant positive correlation between TN and SOC in their study.

The interpolated maps of surface TN, TC and SOC are similar to those maps of soil textural fractions (Chapter 2). The correlation analysis results further confirms thisobservation. Sand content is strongly and negatively correlated with TN, TC and SOC whereas silt and clay contents are strongly and positively correlated with these three soil chemical properties. Figures 3.1 and 3.2 show the relationship of JohnsonSl transformed clay content with TN and SOC, respectively. In general, fine textured clay soils retain more organic matter and have more microbial biomass than coarser sandy soils. This microbial biomass convert mineral N into organic N through microbial immobilization thereby reducing NO_3^- leaching (Côté et al., 2000). This increases TN values in fine-textured soils. On the other hand, sandy soils are poor in retaining organic matter and have less microbial biomass. A significant portion of applied N will be lost through leaching, which decrease TN values, and thus gives a negative correlation between sand content and TN. Gami et al (2009) reported a significant positive relationship between silt+clay content and SOC up to 60 cm depth in both forest and cultivated soils. Similar observation was reported by Plante et al (2006) in Saskatchewan and Ohio soils. Shahandeh et al (2011) also reported a significant positive relationship between clay content and SOC. However, they failed to find any relationship between clay content and TN which they attributed to the initial nitrogen reserves and management practices. Gami et al (2009) also reported the complexity in finding a relationship between TN and soil texture due to inorganic fertilizer additions. However, our results show strong correlations between TN and soil textural fractions (Table 3.7). Study of McLauchlan (2006) describes the role of aggregates in stabilizing SOC.

Clays improve soil aggregation. But surface soil is often disturbed in the fields where conventional tillage methods are practiced. At our study site, reduced tillage was practiced as the soil was lightly tilled once a year to form a seed bed just before the seeding operation. This could have enhanced soil aggregation and the retention of SOC. A meta data study of Ogle et al (2005) also reported an increase in SOC pools in no till fields.

Soil water content showed a strong positive correlation with TN, TC and SOC contents (Figure 3.3). Correlation coefficients between soil water and the three soil chemical parameters are stronger than those between soil texture and these chemical parameters. In general, soil organic matter could retain soil water. On the other hand, soil water influences dynamics of soil organic matter and soil N by controlling microbial mediated processes such as mineralization, immobilization and NO_2 emission (Paul et al., 2003). Nitrogen in its dissolved form can also be leached with soil water into deeper soil layers. However, soil water also varies temporally and this variation makes it difficult to make conclusions about the influence of soil water on measured chemical parameters solely based on one-time measurement. We already reported strong correlations between soil water and soil textural fractions from surface to 60 cm depth. Other than that, terrain also has a significant impact on the distribution of soil water. This could have led to similar distribution of soil water and chemical parameters giving to higher correlations.

Table 3.7 Correlation matrix for soil surface (0-15 cm) chemical parameters with soil variables and terrain derivatives

Variable	Total nitrogen (%)	Total carbon (%)	C:N Ratio	Organic carbon (%)
Total nitrogen (%)		0.99***	0.35***	0.99***
Total carbon (%)			0.44***	0.99***
C:N Ratio				0.34***
Sand	-0.88***	-0.89***	-0.53***	-0.87***
Silt	0.81***	0.82***	0.5***	0.8***
Clay	0.79***	0.8***	0.4***	0.78***
Soil water	0.91***	0.92***	0.47***	0.9***
Elevation	-0.79***	-0.79***	-0.31***	-0.79***
Slope gradient	0.31***	0.33***	0.27***	0.31***
Aspect	-0.17*	-0.17**	NS	0.17**
Plan curvature	-0.27**	-0.28**	-0.17**	-0.28**
Profile curvature	-0.63***	-0.64***	-0.39***	-0.63***
SAGA WI	0.26**	0.24**	NS	0.25**
RSP	-0.69***	-0.7***	-0.42***	-0.69***
VDCN	0.77***	0.78***	0.42***	0.77***

SAGA WI- SAGA wetness index; RSP- Relative slope position; VDCN- Vertical distance to channel network

*** - significant at <0.001

**-significant at <0.05

*- significant at <0.1

NS - Not significant

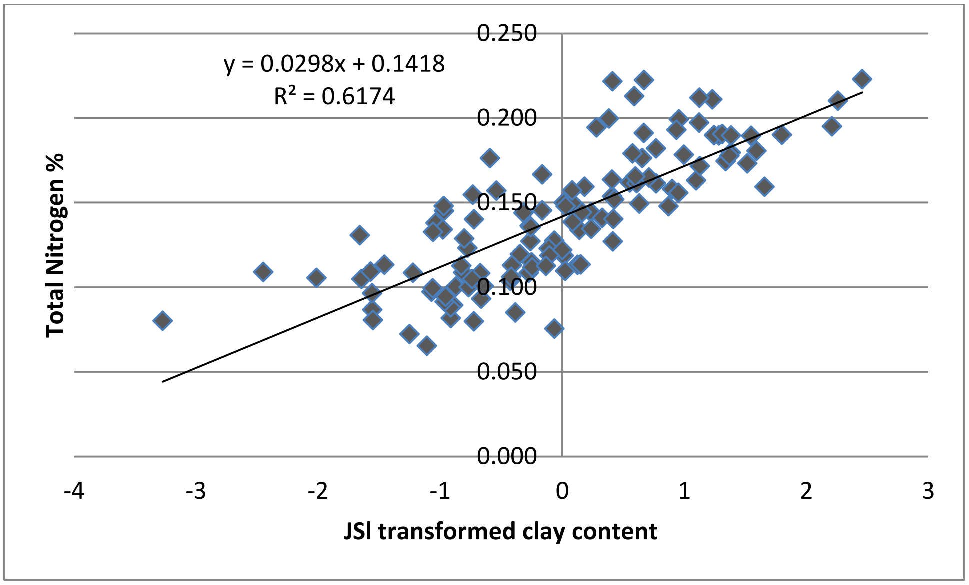

Figure 3.1 Relationship between JSl transformed clay content and TN at 0 -15 cm depth.

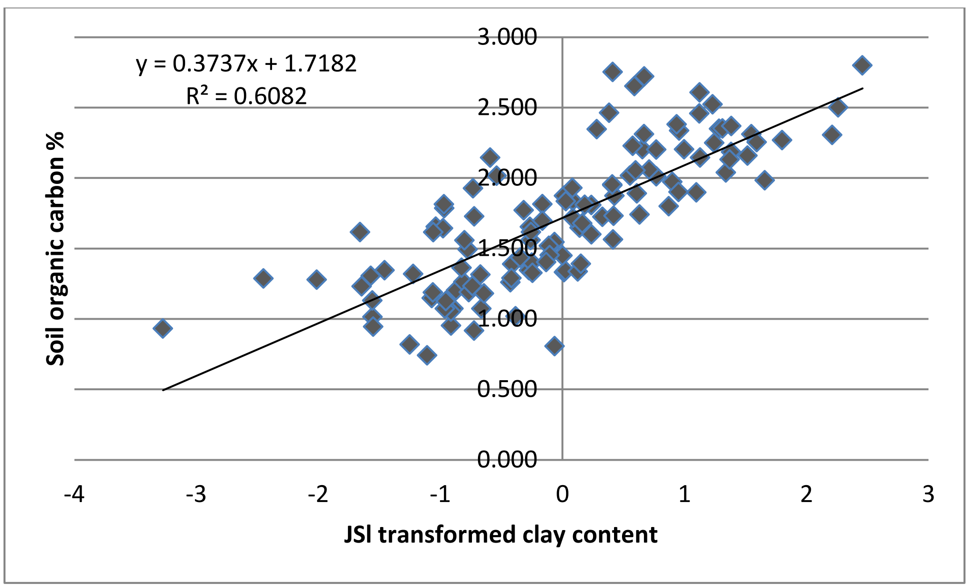

Figure 3.2 Relationship between JSl transformed clay content and SOC at 0 - 15 cm depth.

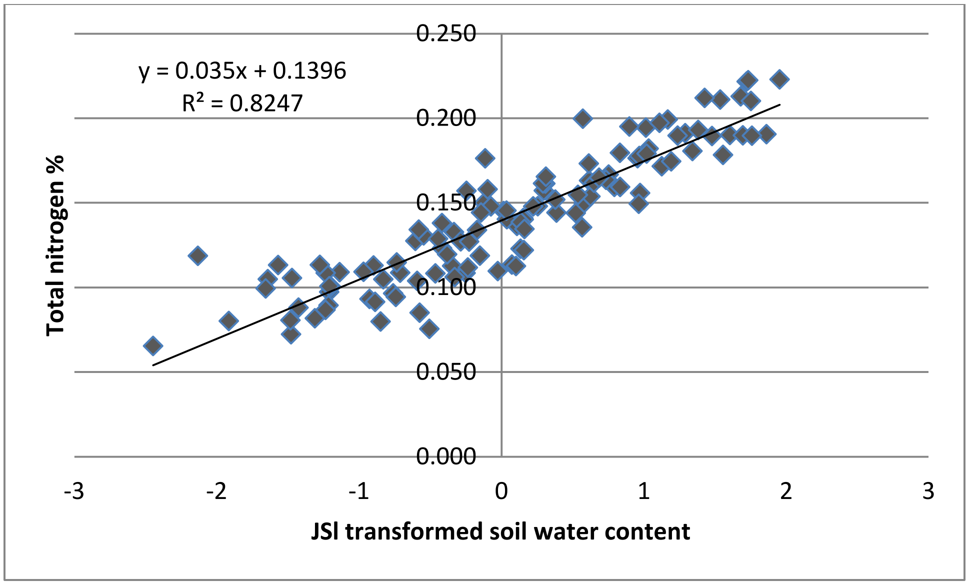

Figure 3.3 Relationship between JSl transformed soil water content and TN at 0 -15 cm depth

The TN, TC and SOC show significant correlations with terrain derivatives. Elevation, relative slope position and vertical distance to channel network show stronger correlations with chemical parameters than the other terrain derivatives. Grimm et al. (2008) reported that terrain influences the variability of SOC in surface layer (0 - 10 cm) than soil texture and this is reversed in the subsoil (10 -20 cm) where the soil texture influences the distribution of SOC than terrain. We also found a strong influence of terrain on both soil texture and chemical parameters in surface soils. Strong negative correlations of TN, TC and SOC with elevation indicates a relatively small concentration of TN, TC and SOC in higher elevation areas which then increase towards lower elevations. The results of Ritchie et al (2007) reported similar findings which they attributed to the redistribution process due to erosive forces.

3.4.3. Partial least squares (PLS) analysis between soil and terrain variables

Sand, silt and clay contents were mainly dependent on elevation, RSP and VDCN (Tables 3.8, 3.9 and 3.10) at the surface. At 0 cm, these three variables accounted for 82 % of the variability observed in sand, 70 % of the variability observed in silt and 68 % of the variability observed in clay. However the influence of these derivatives declined with soil depth as indicated by the decrease in the R^2 of the model and increased the root mean PRESS values. Slope and PrC also significantly influence the distribution of soil texture below 60 cm, though the predictability of the model decreases with depth. Models for clay and silt contents using terrain derivatives were similar to sand content. However, the R^2 values were lower than those for sand content from 0 cm to 45 cm depth. At 60 cm depth the R^2 for clay content was 0.52 whereas R^2 for sand content (0.46) and silt content (0.43) were lower in PLS analyses. Correlations of clay with terrain variables were low (Table 3.5) when compared to sand content. Deposition of sand by aeolian processes was a major pedological factor which influenced the formation of sand rich surface horizons in the Prairies (Pennock et al., 2012). Topography influenced aeolian deposition and distribution of sand which was originated from deltaic deposits in the Carberry area. The proportion of sand in soil redistributed by wind was high and consequently the probabilities for the statistical relationship of clay to terrain attributes were lower. The variability of the statistical relationship of clay content to terrain derivatives up to a depth of 60 cm was low (R^2> 0.5) relative to sand. Sand (R^2=0.46) and silt contents (R^2=0.43) had low coefficients of determination (R^2) at the same depth. Increasing soil variability and decreasing terrain control on soil texture fractions limit the use of terrain derivatives in predicting soil texture below 60 cm. A significant proportion of the variability (75%) in surface TN (%) was accounted for by sand content, elevation, RSP and VDCN (root mean PRESS = 0.53). The model explained 66 % of the total variation when the sand content was replaced with clay content (root mean PRESS =0.6). A model with elevation, RSP and VDCN explained 63 % of the total variation in clay content (root mean PRESS = 0.63). Soil organic carbon content was influenced by sand, elevation, RSP and VDCN which accounted for 74 % of the total variability (root mean PRESS = 0.53). A model with clay (%), elevation, RSP and VDCN explained 65 % of the total variation of SOC (root mean PRESS = 0.6).

Table 3.8 Significant variables (VIP > 0.8) and models describing dependency of sand content on terrain derivatives along the soil depth

Depth (cm)	VIP > 0.8	Model coefficients for centered and scaled data	R^2
0	Elev, RSP, VDCN	X= -1.16Elev -0.52RSP -2.58VDCN	0.82
15	Elev, RSP, VDCN	X= -1.44Elev -1.43RSP -3.78VDCN	0.80
30	Elev, RSP, VDCN	X= -1.89Elev -1.03RSP -3.76VDCN	0.77
45	Elev, RSP, VDCN	X= -1.83Elev -0.41RSP -3.08VDCN	0.73
60	Elev, RSP, VDCN	X= -0.49Elev -3.57RSP -4.71VDCN .	0.46
75	Elev, RSP, VDCN, PrC, PlC, Slope	X= -2.56Elev -0.72RSP -3.93VDCN -0.13PrC -0.25 PlC-0.31Slope	0.39
90	Elev, RSP, VDCN, PrC , PlC	X= -1.05Elev +0.14RSP -0.14VDCN +0.13 PrC -0.15 PlC	0.2
105	Elev, RSP, VDCN, PrC , Slope	X= 0.09Elev +0.09RSP -0.09VDCN +0.09 PrC -0.2Slope	0.14
120	Elev, RSP, VDCN, PrC , Slope	X= 0.04Elev +0.03RSP -0.04VDCN +0.09 PrC -0.05Slope	0.09

Elev. -elevation; RSP- relative slope position; SAGA WI- SAGA wetness index; VDCN- vertical distance to channel network; PlC - Plan curvature; PrC - Profile curvature

Table 3.9 Significant variables (VIP > 0.8) and models describing dependency of silt content on terrain derivatives in the soil profile

Depth (cm)	**VIP>0.8**	**Model coefficients for centered and scaled data**	**R^2**
0	Elev, RSP, VDCN	X= 1.27Elev +1.31RSP +3.4VDCN	0.70
15	Elev, RSP, VDCN	X= 1.38Elev +1.86RSP +4.06VDCN	0.71
30	Elev, RSP, VDCN	X= 1.87Elev +1.76RSP +4.44VDCN	0.72
45	Elev, RSP, VDCN	X= 1.86Elev +0.63RSP +3.3VDCN	0.71
60	Elev, RSP, VDCN, PrC	X= 1.64Elev +2.35RSP +4.48VDCN +0.38Slope +0.22SAGA WI +0.08PrC	0.43
75	Elev, RSP, VDCN, PrC, Slope	X= 2.13Elev -1.74RSP +1.12VDCN +0.22Slope -0.22SAGA WI +0.1PrC+0.23PlC	0.40

Elev. -elevation; RSP- relative slope position; SAGA WI- SAGA wetness index; VDCN- vertical distance to channel network; PlC - Plan curvature; PrC.-Profile curvature

Table 3.10 Significant variables (VIP > 0.8) and models describing dependency of clay content on terrain derivatives in the soil profile

Depth (cm)	**VIP>0.8**	**Model coefficients for centered and scaled data**	**R^2**
0	Elev, RSP, VDCN	X= 1.67Elev -1.33RSP +0.91VDCN +0.4Slope +0.27SAGAWI	0.68
15	Elev, RSP, VDCN	X= 1.98Elev -1.42RSP +1.1VDCN +0.47Slope +0.29SAGAWI	0.70
30	Elev, RSP, VDCN	X= 1.43Elev -1.22RSP +VDCN	0.70
45	Elev, RSP, VDCN	X= 1.5Elev -1.3RSP +VDCN	0.71
60	Elev, RSP, VDCN	X= 0.4Elev +3.5RSP +4.6VDCN	0.52
75	Elev, RSP, VDCN, PrC, Slope	X= 2.55Elev +2.18RSP +5.57VDCN +0.14Slope -0.18SAGA WI +0.24PrC+0.22PlC	0.39
90	Elev, RSP, VDCN, PrC	X= 2.24Elev -3.5RSP +6.4VDCN -0.16SAGA WI +0.07PrC+0.19 PlC	0.29

Elev. -elevation; RSP- relative slope position; SAGA WI- SAGA wetness index; VDCN- vertical distance to channel network; PlC - Plan curvature; PrC - Profile curvature

Table 3.11 Parameters of regression equations for the relationship of surface TN and SOC contents with terrain derivatives and soil texture

Dependent variables	**VIP > 0.8**	**Model**	**R^2**
TN %	Sand (%), Elev, RSP, VDCN	X= -0.79Sand -1.42Elev +0.94RSP -0.4VDCN	0.75
SOC %	Sand (%), Elev, RSP, VDCN	X= -0.78Sand -1.4Elev +0.96RSP -0.35VDCN	0.74

Elev. -elevation; RSP- relative slope position; VDCN- vertical distance to channel network.

3.4.4. Relationship between soil texture, water percolation, nitrate leaching and terrain derivatives

3.4.4.1. Relationship between soil texture and water percolation

3.4.4.1.1. **Cumulative water percolation**

In general, the cumulative percolated water from the lysimeter was positively correlated (Pearson correlation) with sand content and negatively correlated with clay and silt contents (Table 1 to Table 6 of Appendix 3A). Sandy layers are more permeable with greater hydraulic conductivity than clay layers. These correlations are highly significant at 90 cm depth, but rarely significant from the surface to 60 cm depth. The lack of significant correlation at depths less than 90 cm is probably due to the change in soil texture within the profile. Soil from 0 to 60 cm was sandy which facilitates the flow of water and nitrate relative to lower depths with higher clay content which restricted flow. It appears that the soil layers >90 cm highly influence water movement in this soil. Cumulative percolated water (2004 to 2009) was positively correlated with sand content ($p < 0.1$) and negatively correlated with silt content ($p < 0.05$) and clay content ($p < 0.1$) at 90 cm depth. Significant correlations were observed at 90 cm depth with all soil texture fractions in 2004 and 2007 when cumulative water (January-December, 2004 to 2009) was considered.

3.4.4.1.2. Seasonal water percolation

Water percolation in spring and summer correlated well with soil texture than in fall. Cumulative spring water percolation (2004-2009) shows a significant positive correlation with sand content ($p < 0.1$) and significant negative relationship with silt content at 90 cm depth. Silt content at 90 cm depth was negatively related ($p < 0.1$) to cumulative water percolated in summer (2004-2009). For sand and clay contents, the highest correlation coefficients for cumulative summer water percolation were observed at 90 cm depth. Cumulative water percolated in fall showed a significant negative relationship with silt content ($p<0.1$) at 75 cm depth. Moreover significant correlations were observed at 90 cm during spring 2004 (sand and silt), summer 2004 (sand, silt and clay), spring 2005 (sand and silt), spring 2007 (sand and silt), summer 2007 (silt) and summer 2008 (silt).

3.4.4.2. Relationship between soil texture and cumulative nitrate leaching

3.4.4.2.1. Cumulative nitrate leaching

The relationships (Pearson correlation coefficients) between NO_3^- leaching and soil texture were weaker than those for water percolation and soil texture (Table 7 to Table 10 of Appendix 3B). Unlike water percolation, which is mainly influenced by texture controlling hydraulic properties of a particular soil layer, NO_3^- leaching is dependent upon other factors such land use (Silva et al., 2005), season, manure and fertilizer management (Nikiema et al., 2013). Sand (positive) and silt (negative) contents were better correlated at depths of 75 cm to 105 cm relative to clay content. Nevertheless, our results indicate soil texture influenced both water percolation and nitrate leaching in layered soils. Leaching increased with sand content but decreased due to silt and clay contents. In general, smaller NO_3^- leaching losses are observed in fine-textured soils than coarse-textured sandy soils. This is attributed to slower drainage rates and higher denitrification rates in fine-textured soils (Di and Cameron, 2002). Beaudoin et al. (2005) reported three times greater leaching in shallow sandy soils than deep loamy soils. Increased N mineralization was observed in disturbed loamy soils than clay soils during an incubation study (Hassink, 1992). Studies of Van Es et al (2006), Silva et al (2005), Bausch and Delgado (2005) and Cote et al (2000) also have reported higher leaching in sandy soils than loams and clays.

3.4.4.2.2. Seasonal nitrate leaching

Nitrate leaching was better correlated with soil texture in spring and summer compared to fall. Cumulative summer NO_3^- leaching (2004 - 2009) was significantly correlated with sand content at 105 cm depth. Silt content was significantly negatively correlated with NO_3^- leaching in 2006 (90 cm and 105 cm depths) and 2009 (90 cm). Both sand and silt contents showed significant correlations with nitrate leaching in 2008 from 75 cm, 90 cm and 105 cm depths. Nitrate leaching in the summer of 2008 was also significantly correlated with sand and silt contents at 75cm, 90 cm and 105 cm depths. Significant correlations between NO_3^- leaching and soil texture were also observed in summer of 2004 (silt at 90 cm), summer 2005 (sand at 105 cm), spring 2009 (sand at 75 and 90 cm; silt at 75, 90 and 105 cm) and summer 2009 (sand at 60 cm).

Higher volumes of water, due to snowmelt in the spring, may increase water percolation and nitrate leaching. Although leaching is reduced in summer due to higher plant uptake and evaporation, major summer thunderstorms can result in large amount of leachates (Di and Cameron, 2002). In our study, the volume of leachates was considerably reduced during the fall. The seasonal change in leachate volume was attributed to low rainfall and high evaporation from the soil surface in the absence of a plant canopy.

Soil texture at the 90 cm depth accounted for most of the variability in percolation and NO_3^- leaching. The correlations of sand, silt and clay at 90 cm with water percolation and NO_3^-

leaching were high when compared with other depths. This particular soil layer was considered as the most influential soil layer for water percolation and nitrate leaching. The correlation between percolation, NO_3^- leaching and soil texture was not significant in the upper layers of the soil profile. Silva et al (2005) define the upper layer as a flux-type boundary where the influence of rainfall, evaporation, transpiration and runoff are high whereas only free drainage occurs at the bottom.

The volume of percolated water and leached nitrate was better correlated with sand and silt contents than with clay content. Although clay content was negatively correlated with water percolation this was not the case with leached nitrate. Sand and silt were negatively correlated with coefficients greater than 0.92 (Table 3.4). Clay content was moderately to stronglycorrelated with both sand and silt (Table 3.5). At 90 cm depth the correlation coefficient between clay and sand was -0.79 whereas the coefficient between clay and silt content was 0.73. However the coefficient between sand and silt at 90 cm was -0.92. The majority of studies which evaluated the impact of soil types on nitrate leaching were located in sandy or loamy soils (Silva et al., 2005; Van Es et al., 2006; Bausch and Delgado, 2005). The roles of silt and clay in nitrate leaching are difficult to ascertain without detailed information regarding clay mineralogy and surface chemistry, and silt content.

Soil texture was estimated for the lysimeter locations by kriging using the geospatial data calculated for the entire field, the variability of which increased with soil depth. The spatial distribution of sand content was relatively uniform in the upper layers but was dominated by frequent patches of very high sand content below 90 cm. Random thin sand lenses at various depths have been previously reported on the Canadian prairies (Berthold et al., 2004; Cummings et al., 2012). This increases the uncertainty of predicted soil texture for unsampled locations. Different application rates of manures and fertilizers may have reduced the relationship between NO_3^- leaching and soil texture. Variability in the uptake of $NO_3^-$by the crop in different years could also have affected the relationship between soil texture and NO_3^- leaching.

Non-equilibrium preferential water flow could be another reason for the observed variability of water percolation in field lysimeters. In general, macro-pore network in the field is responsible for preferential flow in structured soils. This macro-pore network is influenced by various factors such as aggregation, clay content, slope position, vegetation, management and faunal activity (Jarvis, 2007). However, preferential flow in less structured soils such as sands is caused by layers with different soil textures, variations in soil bulk density, trapped air and non-ponding infiltration (Hendrickx and Flury, 2001). Saxena et al (1994) reported preferential flow of ^{36}Cl in sandy soils using an undisturbed lysimeter study. Preferential flow or "fingering", has been reported in layered soils by various researchers (De Rooij, 2000, Hardie et al., 2011). In general, "fingering" effect occurs in soils where a fine coarse textured layer lays below a fine textured layer. But, a sandy loam layer overlaid relatively fine loam textured soil layer in our study. Thin sand lenses were also embedded in this loamy soil layer. A concept called "funnel flow" is used to describe preferential flow which happens in coarse textured soil embedded in relatively fine textured soil layer (Hendrickx and Flury, 2001; Walter et al., 2000) explicitly in these sand lenses. In a field study with tracer dyes, Heilig et al (2003) concluded that funnel flow at field scale is difficult to estimate without characterizing soil layers.

Several terrain derivatives were related to percolation in lysimeters (data not shown). Cumulative water percolated (2004-2009) was significantly correlated with elevation, slope, RSP, VDCN and plan curvature. Cumulative water percolated during spring (2004-2009) is significantly correlating with elevation, RSP, VDCN, plan curvature and SAGA wetness index. Cumulative summer percolation and yearly percolation were also significantly correlated with terrain derivatives.

Although the site is gently sloping with sandy textured soils, unsaturated overland flow may occur, as is common in arid and semi-arid areas (Lin et al., 2008). The existence of a water restricting, calcareous C_k soil horizon may trigger interflow (Lin et al., 2008) as water flows laterally through the soil and exfiltrates in a lower landscape position following infiltration into upper slope positions. Zhang et al (2011) found significant nitrate-nitrogen losses through interflow in a gently sloping landscape. The occurrence of preferential subsurface flows in hill slopes may also lead to spatial variation of chemical concentration throughout the landscape. Elrashidi et al (2005) reported significant loss of NO_3^- nitrogen through interflow in a moderately sloping well drained watershed. This loss was slightly less than subsurface leaching. A perched water table above the relatively impervious Ck horizon, may complicate estimation of subsurface runoff flow.

The physical design of lysimeters likely influenced the effect of terrain features on horizontal water movement. The edge of the lysimeter core was generally a few centimeters high above the surface, and soil was completely confined by the PVC rim. Consequently the lysimeters impeded horizontal flow of water and reduced the effect of terrain features. In general, we assumed that the intact cores reflected the influence of soil formation, processes such as erosion and adjacent terrain features on soil properties prior to installation of the lysimeters. The loss of nutrients through interflow and overland flow may not be reflected in lysimeter data.

3.5. Conclusions

Soil water content was correlated with surface TN, SOC and TC and terrain significantly influenced spatial and statistical distribution of soil texture. The impact of terrain on soil textural fractions was significant. Sand content was highly correlated with terrain derivatives, more so than clay content. However this influence declined with increasing soil depth as the random variability increased. Elevation, RSP and VDCN significantly influenced the distribution of soil textural fractions from surface to 60 cm depth. Sand (%), elevation, RSP and VDCN can be used to predict soil surface TN and SOC contents.

Soil texture influences water percolation and nitrate leaching through a layered soil. The water percolation and nitrate leaching in lysimeters showed positive correlations with sand content and negative correlations with silt and clay contents. Most significant relationships were observed at 90 cm depth. In general, sand and silt contents showed better correlations for both nitrate leaching and water percolation. The relationships were not significant in the surface depths (0-60 cm) where the sand content was relatively high. Increasing soil variability along soil profile also increased uncertainty in predicting soil texture in deeper depths (60-120cm). Terrain derivatives such as elevation, RSP and slope were significantly correlated with lysimeter water percolation. However, the inhibition of landscape processes by the PVC casing of lysimeter limits the extent to which terrain derivatives can be used to estimate water percolation or nitrate leaching.

3.6. References

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4. OVERALL SYNTHESIS

Nitrate leaching and its negative impacts on the environment and human health have received increased attention in recent times. Several studies have emphasized the vulnerability of the Assiniboine Delta Aquifer for NO_3-N pollution. However, nitrate leaching is spatially and temporally variable and identifying the leaching hotspots is a very difficult challenge. Soil texture is an intrinsic soil property which influences water and pollutant movement through the soil profile. The objectives of this study are to account for the spatial variability of soil texture in both vertical and horizontal directions in a Prairie field and then to determine the relationship between soil texture and nitrate leaching observed in field lysimeters. Intensive soil sampling was conducted and samples were taken down to 120 cm. They were analyzed for soil texture and soil water content. Soil samples from the top 15 cm were analyzed for TN, TC and SOC. The topography of the field was also measured using a total station. Water percolation and nitrate leaching data from 2004 to 2009 from the intact core lysimeters which are located in the same field were compiled.

Soil texture was spatially autocorrelated and varied significantly within the field. Sand, silt and clay contents showed strong spatial autocorrelation from 0 cm to 60 cm depth where more than 75 % of the total variation was accounted for by spatial variability. However, this spatial dependence decreased with depth as the range of semi variograms decreased and RSS values increased. An increase in clay content and decrease in sand content was also observed in the soil profile. Interpolated maps clearly showed the spatial variability of soil textural fractions at the study site. However, the variability of soil texture increased at 90 cm depth. Thin sand lenses at various depths have been previously reported on the Canadian prairies (Berthold et al., 2004; Cummings et al., 2012) and could account for the increased random variability at depth.

Soil water content followed a similar distribution to clay content. Surface TN, TC and SOC contents were strongly autocorrelated. Interpolated maps clearly showed a negative correlation between TN, TC and SOC contents and high sand content, but this was positive in areas with high clay contents. These relationships were similar in the correlations for the same variables determined from soil at the sample sites. Sand content was significantly negatively correlated with TN, TC and SOC, silt, clay, and soil water content. Silt content and clay content were positively correlated with soil water content, TN, TC and SOC. Correlation and PLS analysis of soil texture with terrain derivatives revealed a significant topographic control on the distribution of soil textural fractions from the surface up to 60 cm depth ($R^2 > 0.5$). Elevation, relative slope position and vertical distance to channel network were the dominant terrain derivatives which influenced the distribution of soil textural fractions in the field. However, this topographic influence on soil texture also decreased with depth as the random variability increased. Sand content could be used as a predictor along with elevation, RSP and VDCN to determine surface TN ($R^2 = 0.75$) and SOC ($R^2 = 0.74$) contents. The influence of terrain on the distribution of soil textural fractions and other soil variables can be further improved to develop models that can predict soil properties in larger areas with ease. Furthermore terrain derivates can provide valuable information about surface and subsurface water flows in the landscape.

The cumulative percolated water from the lysimeter was positively correlated with sand content and negatively correlated with clay and silt contents. These correlations were strong and significant at the 90 cm depth ($p < 0.1$). Correlation coefficients were rarely significant from the surface to 60 cm depth. The first 60 cm are mainly sandy and as such will not restrict the flow of water and nitrate compared to the lower depth that contained significant amounts of clay which restrict flow. As such, it appears that the lower soil layers (>90 cm) highly influence water movement in this soil. The relationship of soil texture to nitrate leaching is weaker than that with water percolation. In general, leaching was positively correlated with sand content but negatively with silt and clay. Nitrate leaching in spring and summer was highly correlated with soil texture, but less so in the fall. Most of the significant correlations between nitrate leaching and soil textural fractions were observed at 90 cm depth. We obtained better correlations between water percolation or leached nitrate with sand and silt contents than with clay content in the depths below 75 cm. Although the clay content gave significant negative correlations with water percolation it showed poor correlations with leached nitrate. Furthermore leached nitrate was significantly negatively correlated with silt content in more cases than with clay content. A detailed study of the surface chemistry of silt and clay may clarify this relationship.

Although we identified the sensitive soil layer for nitrate leaching, a physical relationship between leached nitrate and soil textural fractions was not determined in this study. The main reason was the increasing random variability along the soil profile. Even though the semivariogram models gave a moderate spatial autocorrelation for soil textural fractions at depths below 75 cm, a sharp decrease in the range greatly increase the uncertainty in prediction. The attempt to use terrain derivatives to estimate soil texture also yielded poor results at depths below 60 cm. This demonstrates the extent of micro scale variability in Prairies, especially at depths below 60 cm. Micro scale variability in site specific management may account for significant nutrient losses through the soil profile. Our results emphasize the importance of micro scale variability in field and plot-scale studies. Furthermore, application rates of manures and fertilizers could have been reduced to influence the relationship between nitrate leaching and soil texture. Variability in crop uptake of nitrate in different years could also have affected the relationship between soil texture and nitrate leaching.

Our results further provide insight into water and nutrient movement in layered soils. Preferential flow in coarse textured soils is not commonly studied as most of the studies focus on water movement through macropores in loamy and clay soils. Sand lenses which were observed in the deeper layer can trigger "funnel flow" where most of the water and nutrients are transported to deeper soil layers or ground water table before they could be taken up by plant roots. This could be a reason for the anomalies observed in nitrate leaching in intact core field lysimeters.

The field core lysimeter technique that was used to collect leachates in this study influenced the data. The loss of nutrients through overland flow and unsaturated interflow may not be accounted for in the lysimeters.

In summary, the micro-spatial variability of soil texture in a Prairie field in both vertical and horizontal directions was explored in our study. Terrain derivatives are correlated with the distribution of soil texture at the surface. However, random variability of soil textural fractions increased with depth in the soil profile. Soil texture at 90 cm depth was correlated with cumulative percolated water and leached nitrate. However, the correlations between soil textural fractions and leached nitrate were not significant. Future studies in this area should focus on the nitrate and water balance in every lysimeter. This can be done by accounting for applied N, crop uptake, nitrate retained by each soil layer in relation to nitrate collected in leachate. Analysis of the water balance will help to understand the type of non-equilibrium preferential water flow mechanisms occurring within the soil profile. Overall, this study shows the spatial structure of soil texture in a Prairie field and the influence of the layer with least hydraulic conductivity on water percolation and nitrate leaching.

4.1. References

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APPENDICES

Appendix 3.A Correlation matrix of water percolation and soil texture

Table 1. Pearson Correlation Coefficients for water percolation and sand content

Depth cm	Cp0409	Cpsp	Cpsu	Cpfa	p04	p05	p06	p07	p08	p09
0	0.19	0.24	0.12	0.06	0.16	0.2	0.24	0.24	0.02	0.27
15	0.14	0.16	0.09	0.06	0.06	0.16	0.13	0.21	0.01	0.22
30	0.13	0.15	0.11	-0.06	0.04	0.17	0.18	0.17	0	0.25
45	0.18	0.2	0.15	0	0.1	0.24	0.25	0.19	0.02	0.31
60	0.16	0.22	0.09	0.02	0.15	0.14	0.19	0.25	0	0.24
75	0.24	0.24	0.17	0.33	0.27	0.07	0.08	0.35*	0.18	0.09
90	0.37*	0.37*	0.31	0.34	0.43**	0.2	0.28	0.4*	0.31	0.14
105	0.16	0.21	0.1	0.05	0.23	0	0.13	0.25	0.13	0.02

* - significant at p<0.1; ** - significant at p<0.05; Cp0409- cumulative water percolation (2004-2009); Cpsp- cumulative spring water percolation (2004-2009); Cpsu- cumulative summer water percolation (2004-2009); Cpfa- cumulative fall water percolation (2004-2009); p04- water percolation in 2004; p05-water percolation in 2005 so on and so forth

Table 2. Pearson correlation coefficients for water percolation and clay content

Depth cm	Cp0409	Cpsp	Cpsu	Cpfa	p04	p05	p06	p07	p08	p09
0	-0.26	-0.32	-0.17	-0.15	-0.2	-0.24	-0.29	-0.35	-0.07	-0.35
15	-0.21	-0.25	-0.14	-0.15	-0.12	-0.2	-0.19	-0.31	-0.06	-0.3
30	-0.17	-0.19	-0.15	0.01	-0.09	-0.22	-0.23	-0.22	-0.03	-0.25
45	-0.2	-0.22	-0.17	-0.03	-0.13	-0.23	-0.25	-0.22	-0.05	-0.28
60	-0.21	-0.25	-0.16	-0.03	-0.19	-0.2	-0.23	-0.28	-0.06	-0.19
75	-0.23	-0.23	-0.19	-0.29	-0.24	-0.11	-0.09	-0.34	-0.17	-0.12
90	-0.36*	-0.32	-0.33	-0.35	-0.37*	-0.26	-0.28	-0.35*	-0.29	-0.16
105	-0.18	-0.23	-0.1	-0.17	-0.3	-0.05	-0.22	-0.23	-0.08	-0.02

*- significant at p<0.1; Cp0409- cumulative water percolation (2004-2009); Cpsp- cumulative spring water percolation (2004-2009); Cpsu- cumulative summer water percolation (2004-2009); Cpfa- cumulative fall water percolation (2004-2009); p04-water percolation in 2004; p05-water percolation in 2005 so on and so forth

Table 3. Pearson correlation coefficients for water percolation and silt content

Depth cm	Cp0409	Cpsp	Cpsu	Cpfa	p04	p05	p06	p07	p08	p09
0	-0.19	-0.22	-0.14	-0.03	-0.16	-0.2	-0.23	-0.21	-0.04	-0.25
15	-0.14	-0.16	-0.11	-0.05	-0.07	-0.17	-0.13	-0.2	-0.031	-0.2
30	-0.11	-0.13	-0.1	0.08	-0.01	-0.16	-0.15	-0.14	0	-0.26
45	-0.17	-0.19	-0.15	0.01	-0.08	-0.25	-0.26	-0.17	-0.02	-0.32
60	-0.16	-0.24	-0.07	-0.04	-0.17	-0.13	-0.2	-0.26	0.01	-0.24
75	-0.31	-0.31	-0.23	-0.37*	-0.33	-0.11	-0.17	-0.42**	-0.26	-0.13
90	-0.41**	-0.38*	-0.39*	-0.33	-0.4*	-0.26	-0.31	-0.42**	-0.39*	-0.15
105	-0.27	-0.29	-0.2	-0.19	-0.24	-0.13	-0.27	-0.36*	-0.2	-0.17

* - significant at $p<0.1$; ** - significant at $p<0.05$; Cp0409- cumulative water percolation (2004-2009); Cpsp- cumulative spring water percolation (2004-2009); Cpsu- cumulative summer water percolation (2004-2009); Cpfa- cumulative fall water percolation (2004-2009); p04- water percolation in 2004; p05-water percolation in 2005 so on and so forth

Table 4. Pearson correlation coefficients for seasonal water percolation and sand content

Depth cm	psp04	psu04	psp05	psu05	psp06	psp07	psu07	psu08	pfa08	psp09	psu09
0	0.08	0.35	0.26	0.16	0.23	0.23	0.2	0.02	-0.03	0.32	-0.11
15	-0.01	0.26	0.12	0.16	0.12	0.2	0.19	0.01	0	0.3	-0.19
30	-0.01	0.24	0.13	0.17	0.17	0.14	0.2	0.02	-0.12	0.31	-0.14
45	0.04	0.27	0.2	0.23	0.24	0.16	0.2	0.03	-0.08	0.32	-0.03
60	0.09	0.30	0.18	0.09	0.19	0.24	0.17	0.02	-0.07	0.27	-0.08
75	0.19	0.41*	0.19	0	0.07	0.34	0.31	0.17	0.25	0.08	0.02
90	0.36*	0.53**	0.36*	0.08	0.27	0.38*	0.36*	0.32	0.23	0.11	0.07
105	0.2	0.32	0.2	-0.11	0.11	0.23	0.25	0.17	0	0.06	-0.08

* - significant at $p<0.1$; ** - significant at $p<0.05$

psp04- water percolation in spring 2004; psu04-water percolation in summer 2004;....

... ; pfa08-water percolation in fall 2008

Table 5. Pearson correlation coefficients for seasonal water percolation and clay content

Depth cm	psp04	psu04	psp05	psu05	psp06	psp07	psu07	psu08	pfa08	psp09	psu09
0	-0.13	-0.39*	-0.27	-0.19	-0.28	-0.33	-0.3	-0.06	-0.07	-0.37*	0.05
15	-0.04	-0.32	-0.19	-0.18	-0.18	-0.29	-0.29	-0.05	-0.08	-0.35*	0.13
30	-0.03	-0.27	-0.17	-0.22	-0.22	-0.19	-0.23	-0.05	0.07	-0.29	0.08
45	-0.07	-0.28	-0.21	-0.21	-0.24	-0.19	-0.26	-0.06	0.04	-0.28	0
60	-0.14	-0.3	-0.22	-0.15	-0.22	-0.27	-0.24	-0.09	0.06	-0.2	0.04
75	-0.14	-0.45**	-0.18	-0.05	-0.08	-0.32	-0.3	-0.16	-0.21	-0.13	0.02
90	-0.25	-0.57**	-0.34	-0.18	-0.27	-0.33	-0.3	-0.3	-0.2	-0.14	-0.04
105	-0.2	-0.39*	-0.26	0.07	-0.22	-0.23	-0.16	-0.12	0.04	-0.03	0.02

* - significant at $p<0.1$; ** - significant at $p<0.05$

psp04- water percolation in spring 2004; psu04-water percolation in summer 2004;....

... ; pfa08-water percolation in fall 2008

Table 6. Pearson correlation coefficients for seasonal water percolation and silt content

Depth cm	psp04	psu04	psp05	psu05	psp06	psp07	psu07	psu08	pfa08	psp09	psu09
0	-0.09	-0.35	-0.21	-0.16	-0.22	-0.19	-0.2	-0.06	0.05	-0.3	0.14
15	0	-0.27	-0.13	-0.16	-0.13	-0.18	-0.19	-0.04	0.01	-0.3	0.21
30	0.04	-0.23	-0.11	-0.16	-0.14	-0.11	-0.18	-0.02	0.14	-0.34	0.18
45	-0.01	-0.27	-0.2	-0.24	-0.26	-0.15	-0.18	-0.04	0.1	-0.34	0.06
60	-0.12	-0.31	-0.19	-0.07	-0.2	-0.26	-0.15	0	0.05	-0.27	0.06
75	-0.26	-0.46**	-0.25	-0.01	-0.11	-0.4*	-0.37*	-0.25	-0.31	-0.11	-0.04
90	-0.35*	-0.46**	-0.36*	-0.17	-0.3	-0.39*	-0.4*	-0.41*	-0.25	-0.11	-0.1
105	-0.17	-0.34	-0.29	-0.02	-0.26	-0.35	-0.29	-0.23	-0.1	-0.16	-0.02

* - significant at $p<0.1$; ** - significant at $p<0.05$

psp04- water percolation in spring 2004; psu04-water percolation in summer 2004;....

... ; pfa08-water percolation in fall 2008

Appendix 3.B Correlation matrix of nitrate leaching and soil texture

Table 7. Pearson Correlation Coefficients for nitrate leaching and sand content

Depth cm	Cl0409	Clsp	Clsu	Clfa	l04	l05	l06	l07	l08	l09
0	-0.06	-0.08	-0.02	-0.05	-0.08	-0.04	0.26	-0.19	-0.05	-0.13
15	-0.03	-0.11	0.04	-0.07	-0.13	0.01	0.15	-0.21	-0.04	-0.1
30	-0.04	-0.07	0	-0.07	-0.06	-0.02	0.18	-0.2	-0.01	-0.1
45	-0.06	-0.06	-0.04	-0.09	-0.06	-0.04	0.22	-0.25	-0.05	-0.11
60	-0.01	-0.11	0.06	-0.06	0.02	-0.01	0.21	-0.21	0.09	-0.05
75	0.07	-0.08	0.13	0.21	0.05	0.02	0.06	-0.03	0.35	0.23
90	0.14	0.06	0.13	0.21	0.2	0.06	0.35	0.09	0.37*	0.29
105	0.35	0.06	0.41*	0.13	0.17	0.32	0.23	0.05	0.41*	0.16

* - significant at $p<0.1$;

Cl0409- cumulative nitrate leaching (2004-2009); Clsp- cumulative spring nitrate leaching (2004-2009);

Clsu- cumulative summer nitrate leaching (2004-2009); Clfa- cumulative fall nitrate leaching (2004-2009)

l04- nitrate leaching in 2004; l05-nitrate leaching in 2005 so on and so forth

Table 8. Pearson Correlation Coefficients for nitrate leaching and silt content

Depth cm	Cl0409	Clsp	Clsu	Clfa	l04	l05	l06	l07	l08	l09
0	0.05	0.07	0.01	0.03	0.06	0.03	-0.25	0.18	0.02	0.14
15	0.02	0.1	-0.04	0.06	0.12	-0.01	-0.16	0.21	0.02	0.11
30	0.04	0.07	0	0.08	0.07	0.03	-0.16	0.2	0	0.08
45	0.06	0.07	0.03	0.1	0.08	0.04	-0.22	0.26	0.06	0.13
60	-0.01	0.08	-0.08	0.05	-0.04	-0.01	-0.23	0.17	-0.09	0.01
75	-0.14	-0.01	-0.16	-0.29	-0.16	-0.06	-0.11	-0.07	-0.44**	-0.33
90	-0.19	-0.21	-0.11	-0.24	-0.32	-0.08	-0.37*	-0.26	-0.44**	-0.4*
105	-0.28	-0.14	-0.28	-0.06	-0.21	-0.22	-0.35*	-0.19	-0.43	-0.31

* - significant at p<0.1; **-significant at p<0.05;

Cl0409- cumulative nitrate leaching (2004-2009); Clsp- cumulative spring nitrate leaching (2004-2009);

Clsu- cumulative summer nitrate leaching (2004-2009); Clfa- cumulative fall nitrate leaching (2004-2009)

l04- nitrate leaching in 2004; l05-nitrate leaching in 2005 so on and so forth

Table 9. Pearson Correlation Coefficients for seasonal nitrate leaching and sand content											
Depth cm	lsp04	lsu04	lsp05	lsu05	lsp06	lsp07	lsu07	lsu08	lfa08	lsp09	lsu09
0	-0.11	0.13	-0.05	-0.02	0.24	-0.21	0.04	-0.04	-0.06	0.03	-0.29
15	-0.16	0.11	-0.07	0.04	0.14	-0.22	-0.01	-0.02	-0.07	0.08	-0.29
30	-0.09	0.13	-0.04	0	0.16	-0.23	0.02	0.02	-0.08	0.06	-0.26
45	-0.08	0.1	-0.02	-0.04	0.21	-0.25	-0.07	-0.04	-0.1	0.03	-0.25
60	0	0.22	-0.13	0.04	0.2	-0.25	0.08	0.12	-0.07	0.2	-0.36*
75	0.03	0.18	-0.14	0.09	0.04	0.01	-0.2	0.35*	0.2	0.4*	-0.09
90	0.18	0.29	0	0.08	0.32	0.05	0.12	0.38*	0.19	0.39*	0
105	0.16	0.26	0.01	0.37*	0.19	0.02	0.13	0.45**	0.12	0.29	-0.1

* - significant at p<0.1; ** - significant at p<0.05

lsp04- nitrate leaching in spring 2004; lsu04-nitrate leaching in summer 2004;....

... ; pfa08-nitrate leaching in fall 2008

Table 10. Pearson Correlation Coefficients for seasonal nitrate leaching and silt content

Depth cm	lsp04	lsu04	lsp05	lsu05	lsp06	lsp07	lsu07	lsu08	lfa08	lsp09	lsu09
0	0.09	-0.13	0.04	0.01	-0.24	0.22	-0.08	0.01	0.05	-0.01	0.27
15	0.14	-0.1	0.06	-0.04	-0.15	0.23	-0.02	0.01	0.07	-0.06	0.28
30	0.09	-0.14	0.04	0.01	-0.14	0.23	-0.05	-0.03	0.09	-0.08	0.26
45	0.1	-0.11	0.02	0.032	-0.21	0.28	0.02	0.04	0.12	-0.02	0.28
60	-0.01	-0.25	0.1	-0.06	-0.23	0.21	-0.1	-0.13	0.06	-0.23	0.32
75	-0.14	-0.27	0.06	-0.11	-0.09	-0.1	0.13	-0.43**	-0.28	-0.47**	0.02
90	-0.31	-0.37*	-0.13	-0.04	-0.34	-0.2	-0.28	-0.45**	-0.22	-0.46**	-0.13
105	-0.19	-0.32	-0.09	-0.22	-0.31	-0.13	-0.27	-0.49**	-0.05	-0.44**	0.01

* - significant at p<0.1; ** - significant at p<0.05

lsp04- nitrate leaching in spring 2004; lsu04-nitrate leaching in summer 2004;....... ;

pfa08-nitrate leaching in fall 2008