THE REDISTRIBUTION OF MANURE AND CHEMICAL FERTILIZER NUTRIENTS ON SLOPING CROPLAND IN SASKATCHEWAN

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ABSTRACT

Organic and inorganic fertilizers in combination with water facilitate higher crop production. A major change occurring rapidly across the Prairies is the increase in intensive livestock operations. Such livestock operations generate a high volume of manure which is a recyclable nutrient source for crop production but mismanagement in field application may be of environmental concern. The present study focuses on the use of hog manure as a crop fertilizer and the potential for accumulation of residues on an undulating landscape. The purpose of this study is to assess fertilizer residues and how they change with time and space. This assessment is focused on manure and chemical fertilizer residues for different landscape positions over a one year period on a seasonal basis (spring and fall) under two different manure application rates and one chemical fertilizer application rate. The study was conducted under field conditions with normal agricultural practices of the land owner. There were three treatments: a control receiving only chemical fertilizer (spring applied); and two receiving 78.7 and 112.4 m^3/ha of injected hog manure respectively (fall applied) along with a reduced chemical fertilizer application in spring. These fertilizer treatments were applied on three nearby small watersheds and the impact of the study treatments was assessed by monitoring soil chemistry, soil moisture and crop yield on different slope positions of one sample transect within each watershed. Composite soil chemical properties (EC, pH, and SAR) varied over the study period, however, the observed changes were found irrespective of the fertilizer treatments showing no adverse effect of manure application. Consideration of specific ions and elements found that chloride and nitrate concentrations increased on manure

treatments as compared to the control, and the pattern of these anions can be attributed to soil moisture distribution processes on the undulating landscape as indicated by redistribution of soluble chloride and nitrate. At the end of study period (fall 2000), there was an increase in the 30-60 cm depth interval for the bottom slope positions of the manure treatments for chloride while nitrate increased on all the treatments and slope positions with a relatively higher increase on the manure treatments. For the rest of the anions (phosphate, sulphate) and cations (calcium, magnesium, potassium, sodium), the concentrations continued to vary on different dates showing no correlation with the fertilizer treatments. Levels of exchangeable calcium, magnesium, and potassium were stable showing no significant changes while exchangeable sodium was undetected. In addition a higher canola crop yield was observed on manure treatments as compared to the control receiving the chemical fertilizer, but the relative increase in crop yield was not uniform between slope positions. Generally, the concentration of fertilizer residues for different slope positions and soil depths during the study period (one year) has shown that the chemical fertilizer and manure application rates adopted by the farmer were safe for the environment and lead to above average canola yield on study transects (1611 to 2120 kg/ha) as compared to the crop district (1396 kg/ha). However, continuous use of such rates may potentially pose problem of nitrate accumulation and leaching at bottom slope position and requires further study.

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1. INTRODUCTION

1.1. Background Concepts and Issues

Development of sustainable agricultural management systems will depend, in part, on the ability to better use renewable resources, such as animal manure (Eigenberg et al. 2002). Land application of animal manure offers the potential for beneficial recycling by using the nutrients available in the manure for plant growth in place of conventional inorganic fertilizers (Vellidis et al. 1996). Organic (such as manure) and inorganic (chemical) fertilizers are used to meet the nutrient requirement of crops. A fertilizer may be defined as any organic or inorganic material of natural or synthetic origin which is added to a soil to supply nutrient elements essential to the growth of plants (SCSA 1982). Soil fertility is the status of a soil with respect to its ability to supply elements essential for plant growth without a toxic concentration of any element (Foth and Ellis 1997).

Because of inherent variability and inefficiency of the soil-water-plant system, fertilizers can also be a source of undesirable residues (nutrients) in the environment causing instability of ecosystem health. Monitoring and evaluation of the impact of fertilizers on a short-term basis can provide information about any changes in sensitive chemical properties of soil, which are useful for future fertilizer application decisions.

Soil systems are dynamic (Larson and Pierce 1994), with various components, such as energy, water, and chemical elements, constantly entering and leaving the system in a cycle (Smith and McRae 2000). Dynamic systems require a dynamic assessment approach in which a management system is assessed in terms of its actual performance determined by measuring attributes of soil quality over time. As an alternative approach, comparative assessments may appear reasonable, but they are limited for a number of reasons. If only outputs are measured, it provides little information or inference about the processes that created measured condition. It is also not possible to determine if the system that produced the result was poorly designed or operated in a way that was unstable and could not produce the desired output (Larson and Pierce 1994). On such guidelines, an attempt is made to integrate the dynamic and comparative approaches, for the purpose of studying the impact of different fertilizer treatments over time.

In a dry environment and in the absence of irrigation, crop yield also depends on the availability of soil moisture, which also serves as a medium of nutrient uptake by plants. Moreover in a rolling landscape, soil moisture varies with slope positions because of variability in runoff losses or contribution. Such variability in soil moisture may lead to different rates of nutrient assimilation by crop roots. As a result, the expected variability in the accumulation of fertilizer residues in the root zone and over the landscape creates questions which are of interest in the present work. This research work is focussed on assessing the nutrients (residues) of fertilizers in time and space on sample transects within small watersheds with seasonal measurements.

In the root-zone soil profile, fertilizer residues may mainly exist in total, dissolved and exchangeable forms. Nutrient mineralization from applied manure depends on temperature, soil moisture, soil properties, manure characteristics, and microbial activity (Eghball et al. 2002). A seasonal account of the residues requires consideration of their different forms to assess an overall balance. The balance can be assessed from input-output relationships for defined boundaries in space and time or it can be ascertained by observing the relative changes from snapshot measurements on specific locations. The later technique is preferred in the present study due to its simplicity and lesser cost. Also, this monitoring process can provide information on significant changes in concentrations of certain residues, which can be adapted as indicators or tracers for similar research work and planning for subsequent fertilizer applications. The present analysis will also identify those residues showing potential to be used as indicators for seasonal evaluation of fertilizer residues. While considering the limited field applicability and cost factor of intensive experimental studies, the present study is based within the framework of farmer managed systems under their routine agricultural practices. This approach has maintained present study interest in easily identifiable causes for which quantified measurements be readily made from locally available research facilities and finally, some worthwhile actions that may be possible by the farmers.

Necessary criteria in a systematic approach to improve manure management systems need to consider the following factors which are grouped in different categories (Laguë 2002):

1. Agronomic – relate to animals, plants and soils from an agricultural production perspective;
2. Economic – viability of the livestock operations;
3. Environmental – impact of the manure-management system on air, soil, water, fauna and flora;
4. Social, and Health and Safety – impact of the manure-management system on humans both on and off the farm;
5. Technical – the "nuts and bolts" operational requirements of the manure-management system.

Once a livestock operation is in place, manure management requires an interrelated set of decisions involving three components: biological treatment, effluent transport, and crop selection (Roka et al. 1995). These decisions stay at the farmer's discretion in the present study which is restricted to monitor nutrients and salts at the field level. At the field level, van Noordwijk (1999) has noted a functional link between the harvested part and external organic or inorganic inputs, with a financial linkage of costs and benefits. This is named as the 'replenishment efficiency' and is defined as the amount of nutrients acquired by the farmer per unit nutrient in yield products harvested from the field. Success in achieving a better level of this efficiency depends upon 'target soil fertility' which is considered to be a function of different objectives such as production level, soil fertility maintenance, soil and water quality, and the quality of agricultural products (Janssen 1999). However, Stoorvogel (1999) has stressed that from an economic point of view soil nutrient stocks should be kept between certain critical levels for an optimum crop production and soil fertility maintenance system.

A number of short and long term experimental studies in Canadian prairies have shown promising results of using animal manure on flat lands under irrigated and rainfed conditions (Chang et al. 1990; Charles 1999; PAMI 2001a, 2001b; Assefa 2002; Mooleki et al. 2004). Research results are also available about the fate of residues from animal grazing and fertilizer inputs on hilly pastures and rangelands (Christie 1987; Whitehead 2000; Pastl et al. 2001). The present study is focused on sloping cropland to assess the redistribution of added fertilizers and manure nutrients (residues) in time and space for a span of one year.

1.2. Objectives

The general purpose of this study was to assess fertilizer nutrients (residues) and how they change with time during a one year period under the normal agronomic practices of the farmer. This assessment was focused on manure and chemical fertilizer residues for different landscape positions on a seasonal basis (spring and fall) under different manure and chemical fertilizer application rates. The specific objectives were:

1) To characterize the background status of the study site for soil chemical properties and landscape features so as to establish a base for the present experiment,
2) To assess the seasonal changes and redistribution of fertilizer nutrients in soil originating from hog manure and chemical fertilizer applications,
3) To evaluate the changes and redistribution of fertilizer nutrients for different landscape positions, and
4) To identify and evaluate indicators for managing fertilizer nutrients in a semi-arid environment from seasonal data set.

2. LITERATURE REVIEW

In reference to the objectives of this study, the following is a literature review on related aspects. This chapter is divided into five main sections: sections 2.1 and 2.2 are focussed on the rationale of the present study by explaining the task of maintaining sustainable agriculture on prairie landscape; sections 2.3 and 2.4 are presented to develop an understanding of fertilizers and soil chemistry; and section 2.5 elaborates research efforts towards maintaining environmentally productive agriculture with the main focus on the livestock manure – crop production interface.

2.1. Prairie Agriculture

2.1.1. Landscape

Agriculture represents a managed agro-ecosystem that was converted from a natural ecosystem with the ultimate objective of benefiting humans by increasing productivity of selected plant or animal species in a sustainable fashion (Acton et al. 1998). The spatial and temporal scales at which transformation and transport of nutrients occur are diverse (Mulla et al. 2003). Landform analysis is one important method for classifying smaller divisions within macro-ecosystems (Acton et al. 1998). The necessity of such classification arises with an objective to develop effective strategies to maintain soil fertility and environmental quality. Agriculture on slopes of greater than 3 % increases the risk of soil erosion, and this can lead to increases in nutrient and sediment loadings to surface waters (Jones et al. 2001). A number of other factors such as type of soil, vegetation, agronomic and climatic variables may affect and change the threshold slope for erosion (Professor Claude Laguë, Personal Communication), and are beyond the scope of this review.

For the prairie landscape (Fig. 2.1), Pennock et al. (1987) have presented a classification of different landform elements based on topographic data about the gradient, profile (downslope) curvature, and plan (across-slope) curvature. The study has recognized seven landform elements as convergent and divergent shoulders, backslopes, and footslopes, and level elements. Parameters like soil moisture, thickness of A horizon and depth to calcium carbonate are shown to be greater in convergent elements as compared to divergent ones for individual profile groups (e.g., footslopes, shoulders). The same parameters have also shown an overall increase in the slope position sequence as: shoulders < backslopes < level < footslope (Pennock et al. 1987). Grigal et al. (1999) have described that where hydrologic processes are a major factor influencing soil formation and subsequent variability within physiographic regions, watersheds are appropriate spatial units to further partition variability. Soil variability within watersheds may be further subdivided according to repeating patterns of soil variability occurring along hillslopes. These repeating patterns are described as soil catenas and are often linked to topographic variability. The authors, Grigal et al. (1999) have used similar, to Pennock et al. (1987) sets of terrain attributes (slope gradient, aspect direction, plan and profile curvature, and catchment area) to define the shape and orientation of the topographic surface. The catchment area of different slope positions (Table 2.1) indicates the potential accumulation of water and water-soluble materials by runoff and by throughflow from upper positions.

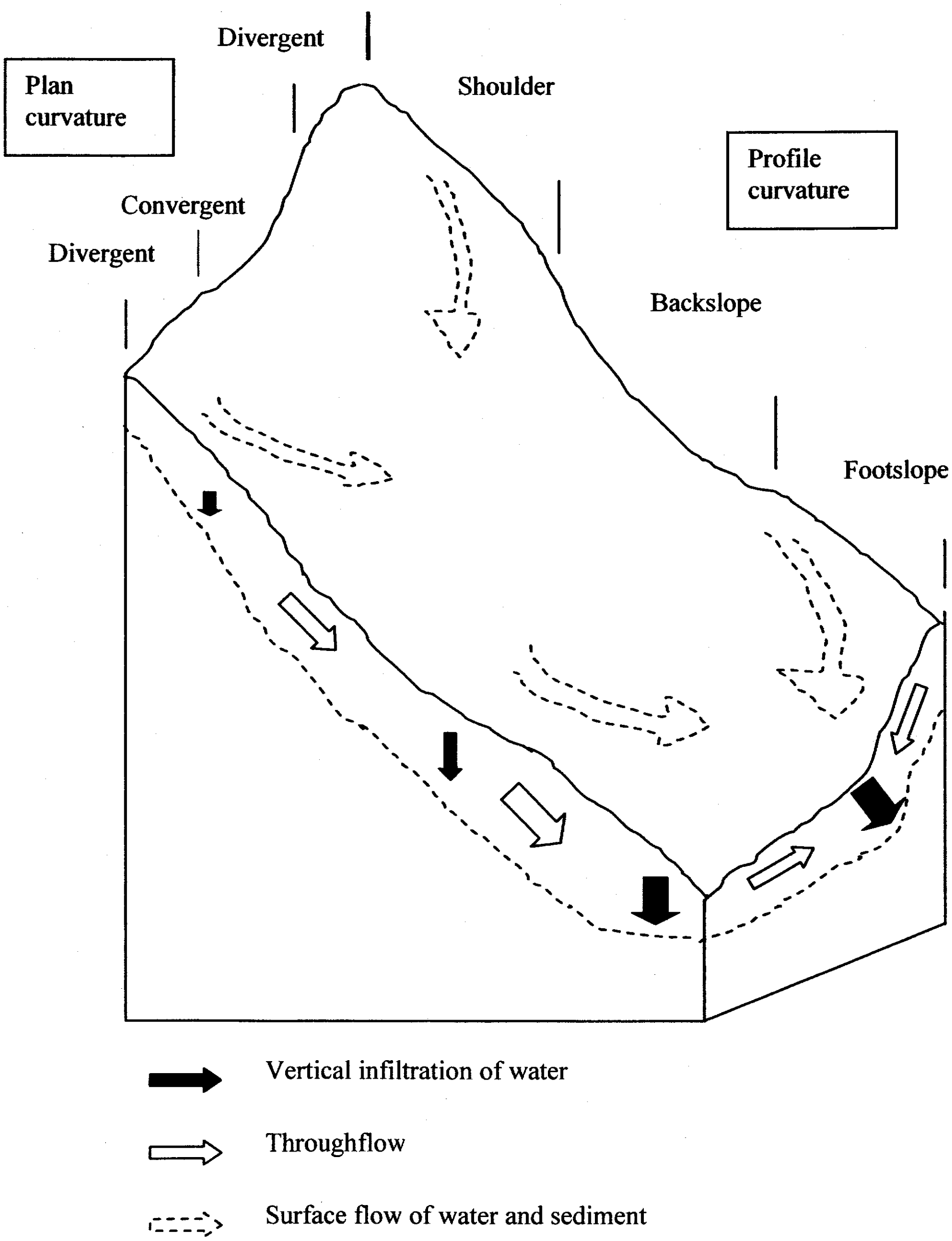


Fig. 2.1. Summary diagram of probable water movement and concentration associated with different landform elements in a hillslope system (Adapted from Pennock et al. 1987).

Table 2.1. General description of cross-sectional hillslope positions (Grigal et al. 1999).

Hillslope Position	Slope Gradient	Profile Curvature	Catchment Area
Summit	Low	Straight	Lowest
Shoulder	Moderate	Convex	Low
Sideslope	Steep	Straight	Moderate
Footslope	Moderate	Concave	Moderate
Toeslope	Low	Concave	High
Depression	Low	Concave	Highest

2.1.2. Hydrology

In the Prairie region of Saskatchewan, the average annual precipitation, generally increases from southwest to northeast and ranges from roughly 300 to 500 mm per year. Most of this precipitation occurs as late spring and summer storm events. Winter precipitation occurs as snowfall, which usually remains all winter, melts rapidly in early spring and creates the major runoff event of the year. This represents a much different pattern than is found in most other agricultural regions of the world. The entire Prairie region experiences an annual water deficit (evapotranspiration exceeds precipitation) which is most severe in the southwest. Non-irrigated, agricultural yields are limited by this moisture deficit. Large fluctuations in temperature and precipitation from year to year may produce periods of drought or extreme wet conditions (Hilliard et al. 2002).

An important hydrologic event on the Canadian Prairies is the winter snowpack development and subsequent spring melt, infiltration and runoff. Elliott et al. (2001) have found that tillage and cropping systems do not affect snow accumulation but surface cover does affect snow distribution. Water from snowmelt recharges the soil root-zone and groundwater. It has been found that snowmelt infiltration is inversely related to the total soil moisture content (water+ice) of the frozen soil at the time of melt (Gray et al. 1985). Sharratt et al. (1999) while studying the snowcover, frost depth and soil water across a prairie pothole landscape summarized that thawing of the soil profile was most rapid in the bottom of the depression and appeared to be accentuated by infiltration of surface water through localized unfilled soil pores or cracks. Zhao et al. (2002) have indicated that frozen unsaturated agricultural soils of the Canadian Prairies during snow ablation demonstrate (a) poor association between the amount of infiltration of meltwater released by the seasonal snowcover and soil texture and (b) small differences in cumulative amounts among soils of widely different textures indicating less variability of overall water infiltration.

From results obtained by a simulation model using 30 years of climatic data, (Maulé and Gray 1994) suggest that Prairie snowmelt infiltration may not vary widely, ranging from 17 to 23 mm in fallow and from 23 to 33 mm in stubble fields, whereas average annual snowmelt runoff may range between 10 mm and 40 mm for fallow and between 15 and 55 mm for stubble. These infiltration and runoff patterns were reported in response to annual water equivalent of snowcover ranging between 25 mm and 60 mm on fallow land and between 35 mm and 85 mm on stubble land.

After the completion of spring snowmelt infiltration and runoff, the redistribution of soil water within the vadose zone starts. Hillel (1998) has defined the terminology for vadose zone water movement as ‘internal drainage’ or ‘redistribution’. Internal drainage is movement in the presence of a high water table. Redistribution is where the water table is too deep to affect water movement in the root zone. Arya et al. (1999) have attributed the changes in soil moisture resulting from different drainage phases to macro- and micro-pores. Due to the deep water table of most prairie landscapes, the post snowmelt period of soil water movement is that of redistribution. Zebarth and de Jong (1989), in a study near Saskatoon, have reported that topography tends to maintain temporal stability of water distribution within the landscape by the redistribution of water as snow, runoff and interflow. For the same study area as reported in this thesis, Ward (2003) has shown that the active zone depths are 1.1 m and 1.4 m for upper and lower landscape positions respectively (the active zone is defined as the depth where seasonal volumetric water content changes are greater than 3%). The same study suggests that recharge rate (as based upon bomb tritium measurements) is between 0.0 and 18.7 mm/yr with no clear distinction between landscape positions, however differences were found in landscape positions with regard to electrical conductivity (EC) of 2:1 soil extracts, with lower slope positions have much lower EC values than upper slope positions – indicating a higher level of leaching. The present study is focused on the surface 60 cm of the active zone by dividing it into three intervals (0-15, 15-30, and 30-60 cm).

In other water balance studies focussing on small prairie watersheds, the quantity and quality of runoff have been attributed to land use on the surrounding uplands (Hayashi et al. 1998a, 1998b; van der Kamp et al. 1999). These studies have generally considered the natural water or solute (chloride) cycles. Still, the impact of crop production with manure application needs to be considered to monitor changes in nutrients and salts residues in the root zone, which may or may not contribute adverse affects on the prairie ecosystem. To meet with the present study objectives in an optimal way, this study is planned to focus on only sample transects of the watersheds under different treatments.

2.2. Environmental Issues

As with any production process, agriculture generates residuals and byproducts (Braden and Lovejoy 1990). Driving forces that influence agricultural activities can be classified into environmental factors (soil, weather) and technological factors (fertilizers, pesticides). Environmental risks from agriculture can be controlled and desirable environmental outcomes achieved through careful management of the forces affecting agriculture. Agriculture, perhaps more than most other economic activities, is intimately linked to the natural environment (Smith and McRae 2000). Farmland activity, over the last 50 years, has intensified and become more specialized, with larger farms, more area in crops, and increased mechanization. These changes, coupled with the introduction of new crop varieties and management practices, have resulted in increased productivity. In some instances, however, these developments have been accompanied by increased environmental impacts, such as degraded soils, contaminated water bodies, and changing biodiversity. Moreover, livestock manure constitutes one of the principal non-point sources of nutrient pollution in Canada (GOC 1991).

Manure management on cropland will remain an economic and environmental challenge in Canada because of the diversity in livestock operations. Livestock concentration is not necessarily linked to large livestock populations. Several high-density areas appear to be due to a rather limited amount of livestock associated with an even smaller farmland base (Beaulieu et al. 2001). Livestock in high-density areas were more likely to be on very large feedlot operations in Alberta, small dairy and pig farms in Quebec, and small dairy and beef cattle farms in Ontario (Beaulieu 2001). Smaller family-run farms are often operating under tight margins, making the capital investments required for sound environmental and manure management practices difficult. The perception that smaller family-run farms represent a lesser threat may not be valid because the cumulative impact of several non-intensive small farms may be comparable to the impact of a few large intensive farms (Beaulieu et al. 2001; Beaulieu, 2001). Consideration of manure as a beneficial by-product and not a waste is evident from that 93% hog producers personally utilize all the manure from their hog operations but also a concern that over 90% did not test the manure produced by their operations for nutrients (CETAC – West 2001).

Rainfed agricultural systems in prairie environments are particularly prone to major shifts in soil quality parameters which include physical (bulk density, soil redistribution), chemical (pH, EC, inorganic carbon), and biochemical (organic carbon, total soil N) parameters (Pennock et al. 1994). Environmental pollution generally involves damage to a shared resource, such as soil, water, or air. Both surface and underground water need to be considered. Damage to soils also may be of concern in certain situations; however, because the soil is commonly fixed in space, pollution takes on a more restricted meaning (Miner et al. 2000). The definition and quantification of soil quality are complicated by the fact that soil is not directly consumed by humans and animals, as are air and water for which there are legislated quality standards (Doran et al. 1999). In prairies, apparently with no manure application on adjacent land, the problem of nutrients and salt accumulation in farm dugouts (Cessna and Elliott 2000) may be attributed to the agricultural activity on the adjacent catchment areas or the soil profile parent material. In other parts of the world, contamination of water in wells, pasture-drainage conduits and rivers are shown to be most severe in areas of highest livestock density and highest frequency of slurry application (Vidal et al. 2000). Manure is also a carrying medium for bacteria and biological species that can alter the water environment of streams, ponds, and groundwater and that of soils (Morin et al. 1996). While one in four Canadians relies on groundwater and the remainder on surface water, the quality and quantity of both sources are increasingly threatened (SERM 1997a). Water quality objectives are the recommended safe conditions, or limits, designed to protect each type of water use, such as drinking, recreation and irrigation, or to protect freshwater aquatic life. Objectives may be site specific or general, and are developed using available scientific literature and water quality criteria (SERM 1997b).

The present study is focused on the soil tillage zone often considered the first line of defense to control environmental pollution from surface applied chemicals and manure (Johnson 1995). Vellidis et al. (1996) has suggested that nutrient loading rates, which do not exceed the assimilative capacity of the application site, are a function of the nutrient uptake rates of plants and microorganisms, the physical and chemical adsorption properties of soils, the climate, and the management regime. Loading rates that exceed the assimilative capacity of land application sites can adversely impact the environment by providing significant loading of nutrients to receiving soils and waters. Another issue that needs attention in an analysis of sustainability is 'balanced nutrition', that is, the situation in which the various nutrients (micro-, macro-, and trace) are offered in proportions matching the needs of the crop. It is a prerequisite for optimum nutrient use efficiency and sustainability. The fact is that the excess of one nutrient goes together with, and may be the consequence of, the shortage of another nutrient. Disproportions in nutrient supplies aggravate depletion of one nutrient and emissions to the environment of others (Janssen 1999). This complexity of soil-plant-environmental systems stress necessity of identification and resolution of specific problems pertaining to different locations such as the manure management under cultivated crop system on a rolling landscape.

2.3. Chemistry of Fertilizers

The contents of conventional chemical fertilizers are normally predetermined during their production process. This makes it easy for their selection and deciding the application rate. More complexity arises in managing the animal waste for crop production. Livestock manure generally includes feces and urine, which may also include spoiled feed ingredients, silage drainage, or other materials only partially consumed in a livestock or poultry operation (Miner et al. 2000). Animal manure in solid and/or liquid form contains nitrogen, phosphorus, potassium, sulfur, calcium, iron, magnesium and solids (organic and inorganic) in proportions that depend on the origin of the animal feed, the type and age of animal and the amount of dilution by water (Morin et al. 1996).

An analysis of major nutrients in different manures within Saskatchewan is given in Table 2.2, which shows total concentration values of respective major nutrients (N, P, K, and S). With some additional characteristics (EC, pH, Total Solids) and nutrients of hog manure, Table 2.3 provides a summary of results from other studies. In a recent Saskatchewan study on hog and cattle manure application at two sites, more detailed results are available from a field study done by Charles (1999) (Table 2.4) while results from Dagnew (2002) are based on samples collected directly from lagoons with or without agitation (Table 2.3). Dou et al. (2001) have cautioned that with agitation, three to five samples were adequate for a representative composite sample for reliable testing of total N and P; whereas for farms without agitation, at least 40 samples would be required.

There may be differences between nutrient test results of analysed samples and the nutrient value of manure being applied due to different sampling methods, locations, timing and manure sample handling (SAF 1999a). This type of variability in manure nutrients can be noticed from the data given in Tables 2.5 and 2.6, which shows the analysis from samples collected annually and with shorter intervals in a sequence related to particular sites and storages. Moreover, as the results are from specific project studies coordinated by the same personnel, the common sources of variability created by sampling techniques and lab analysis may have been avoided in the repeated samples. Therefore, other factors such as animal diet and gaseous losses can be attributed to the existing variability in manure analysis results (Tables 2.5 and 2.6).

Table 2.2. Average nutrient values of different manure types (SAF 1999a).

	Liquid Swine	Liquid Dairy	Liquid Poultry	Solid Beef	Solid Swine	Solid Poultry
Units:	liquid manure (kg/1000L) and solid manure (kg/tonne)					
No. of samples	76	14	4	47	5	2
No. of Sites	18	5	3	9	1	2
Nitrogen (N)	3.0	2.3	3.2	6.3	8.4	9.0
Phosphorus (P)	0.9	0.6	3.5	1.9	4.6	13.0
Potassium (K)	1.0	2.0	3.4	6.2	10.8	8.2
Sulphur (S)	0.4	0.4	0.9	1.4	3.2	2.9

Table 2.3. Composition of hog manure.

	Edwards and Daniel (1993)	Pote et al. (2001)	Dagnew (2002)
pH	7.4	7.7	-
EC (dS/m)	36.0	81.8	-
Total Solids (%)	4.9	2.1	3.6
	(mg/l)	(mg/l)	(mg/g)
Total N	5800	1643	4.2
NH_4-N	4142	1160	2.3
NO_3-N	84	23	-
TP	1200	825	0.72
K	3800	-	1.47

Note: Missing entries are not reported in the respective studies.

Table 2.4. Nutrient composition of hog and cattle manures (Charles 1999).

Nutrient	Burr hog manure ($\mu g/cm^3$)	Dixon hog manure ($\mu g/cm^3$)	Cattle manure on both sites ($\mu g/g$)
Samples	*7*	*5*	*5*
Total N	2941 (583)	1931 (29)	12460 (2693)
Organic N	1829 (715)	485 (219)	10728 (2555)
NH_4-N	1153 (52)	1447 (195)	1733 (286)
Total P	829 (696)	175 (18)	4045 (862)
Resin P	190 (179)	82 (16)	212 (95)
Total K	1393 (82)	1006 (11)	12952 (2816)
Total S	-	-	7758 (2251)
Resin SO_4-S	14 (4)	430 (11)	1366 (211)
Total Mg	615 (527)	164 (12)	10783 (2965)
Total Ca	1230 (611)	407 (10)	30792 (7325)
Total Cu	23 (13)	4.3 (0.2)	87 (7)
Total Mn	14 (12)	2.4 (0.5)	265 (73)
Total Zn	42 (27)	6.1 (0.5)	155 (41)
Total Fe	172 (128)	20 (2)	4487 (1328)
Total B	-	1.9 (1.0)	45 (13)
pH	8.5 (0.1)	-	-

Note: Reported values are means with standard deviations in brackets. Organic N is assumed to be Total N minus NH_4-N due to undetected NO_3.

Table 2.5. Concentrations in hog manure from samples collected on annual basis in fall season (PAMI 2003).

	MCS 1999	LLCS 1999	MCS 2000	LLCS 2000	MCS 2001	LLCS 2001
Units: $\mu g/ml$						
Total N	1770	2618	2986	1524	3292	3451
NH_4	1590	1818	2182	901	2284	2502
NO_3	nd	nd	nd	nd	nd	Nd
Total P	38	604	65	393	75	78
Avail. P	1	272	27	366	32	34
K	1212	1047	1325	660	1279	1330
Ca	613	504	478	276	502	458
Mg	117	293	139	203	136	136
Na	341	301	454	176	452	494
Fe	13	51	12	16	13	14
Mn	1.2	7.9	1.3	4.8	1.7	1.9
Zn	1.7	12.7	2.9	1.5	4.3	5.1
B	5.2	8.3	0.7	2.0	0.7	2.4
Cu	0.2	1.4	0.9	0.2	1.0	1.1

MCS: Melfort Crop Site (Saskatchewan); LLCS: Loon Lake Crop Site (Saskatchewan); nd: not detected.

Table 2.6. Concentrations in hog manure from samples collected within short intervals in spring season (PAMI 2004).

	Leroy Post Emergent Site1 2001			Dixon Post Emergent Trial 2002		
	May 31	June 13	June 27	June 7	June 21	July 4
Units: µg/ml						
Total N	3397	5188	5350	3255	2853	3377
NH_4	2199	3249	2310	1974	1633	2209
NO_3	nd	Nd	nd	nd	nd	nd
Total P	139	963	802	127	116	96
Avail. P	61	71	73	4	3	3
K	1472	1993	1987	1319	1132	1306
Ca	407	1047	778	345	368	467
Mg	117	616	533	139	129	383
Na	1026	1476	1413	576	507	720
Cu	4.4	12.7	14.3	1.2	1.1	1.0
Fe	13.9	51.5	55.6	31.3	18.2	19.2
Mn	2.2	14.0	12.8	2.2	2.1	2.6
Zn	17.6	40.0	45.8	2.3	2.2	13.4
B	2.1	2.4	2.8	nd	nd	nd

Briefly, animal species, storage type, physical attributes (liquid or solid), inclusion and/or exclusion of other materials (bedding, feed refusal, barnyard runoff, etc.) and manure handling systems need to be given due consideration while using results from different studies. To avoid potential confusion associated with the use of common terms such as slurry, effluent, semi-solid, solid waste, animal waste, farm yard manure, etc., manure classification as based on moisture content (Table 2.7) leads to selection of an appropriate manure application system.

Table 2.7. Classification of manure by moisture content (SAF 1999a)

Type of manure	**Moisture content**	**Ease of pumping**
Liquid manure	> 90 %	easy to pump
Semi-solid manure	80 – 90 %	May be difficult to pump
Solid manure	< 80 %	Cannot be pumped

2.4. Properties of Soils

The nature of the soil parent material is usually the main influence on the amounts of the nutrient elements, other than N and C, present in a soil. The influence is due partly to the amounts originally present in the parent material and partly to the ability of the soil constituents to retain soluble forms of the elements against loss by leaching. Agricultural practices also contribute to the inherent soil fertility and the residual effects, which in turn depend on nutrient mobility as well as biological and chemical transformations under given soil and climatic conditions (van Noordwijk 1999).

Foth and Ellis (1997) have described that calcium, magnesium, sulfur, and chlorine, along with nitrogen, phosphorus, potassium and sodium, are the eight most-abundant elements taken up by plants from soils. Calcium, Mg, K, and Na are taken up as cations and N, P, S, and Cl are taken up as anions, except for the uptake of some N as NH_4^+. Generally, the total charge of the cations taken up is about equal to that of the anions, except where NH_4^+ is abundant. Calcium, Mg, S, and Cl are generally taken up in lesser amounts than N, P, and K, but in much greater amounts than other micronutrients.

2.4.1. Soil Properties Under the Use of Chemical Fertilizers

On a level and low slope landscape with limited variation in soil moisture, soil physical and chemical properties can be easily attributed to different agricultural practices such as tillage, crop rotations and fertilizer inputs. Campbell et al. (1984) observed the soils receiving fertilizer N and P applications according to soil test recommendations did not increase leached N but instead reduced it. They also observed less NO_3 below 90 cm where a deep rooting forage was included in the rotation. Such data suggest that assuring rooting activity through fertilizers or species selection increases either uptake of previously leached NO_3 or reduces leaching of NO_3 during the current crop year. A major control on NO_3 accumulation is therefore rooting activity, which is different from the general perception that NO_3 leaching includes a linear link between NO_3 added and leaching (McGill and Myers 1987). Similar results on residual soil concentrations are reported in a Saskatchewan study comparing the effects of tillage systems and fertilizer inputs in which no consistent difference in available N or P in the surface soil (10 cm) have been found despite considerable higher use of fertilizer on zero tillage basins as compared to conventional tillage (Elliott et al. 2001). However, improvements in soil organic carbon (SOC) have been reported under continuous cropping and crop rotations (Boehm and Anderson, 1997; Campbell et al. 2000) (Table 2.8).

Crop production with chemical fertilizers may affect composite soil properties (pH and electrical conductivity) with certain soil-plant interactions. Boehm and Anderson (1997) have shown that the pH of A horizons was lower in continuously cropped soils than in either crop-fallow or extended rotation soils. The pH of Ap horizons on the shoulder and divergent backslope landform elements was higher in the crop-fallow and extended rotation fields, probably due to erosion and exposure of carbonate-rich subsoils, which have become mixed with the Ap horizon by tillage.

Table 2.8. Summary of studies on landscape and soil characteristics in Saskatchewan.

Reference and study years	Study parameters	Soils, Crops and Landscape	Study results
Boehm and Anderson (1997) 65 years	Crop rotation and indicators of soil quality	Dark Brown Soil, Level to gently undulating slope (<2%)	Continuous cropping increased SOC, aggregate size and stability, microbial biomass, resin-sorbed N and P, nitrification potential; and decreased bulk density and infiltration time.
Campbell et al. (2000) 10 years	Carbon sequestration and cropping frequency	Orthic Brown Chernozemic; Wheat, Lentil, Rye, Fallow	Soil organic carbon increased by annual cropping in 0-15 cm and no change in deeper depth.
Campbell et al. (1984) 15 years	Crop rotation, fertilizers and nitrate leaching	Same as above	Two and three year wheat rotations lost the most NO_3 while a fallow-rye-wheat rotation reduced loss.
Elliott and Efetha (1999) 11 years	Tillage systems, slope positions and soil properties	Dark Brown Chernozemic, Broad rounded hills with long slopes (6 – 30%)	As compared to CTCF, ZTCC showed higher SOC, aggregate size and stability, and infiltration rate. The differences were most pronounced at the shoulder positions.
Martz (1992)	Hillslope erodibility	Cultivated grasslands; hummocky glacial till	High erodibility on upper and low on lower slope positions.
Miller et al. (1998) 22 years	Tillage systems and soil porosity	Dark Brown Chernozemic clay loam	Porosity was higher for CT than NT for the surface soil but it was reverse for subsoil.
Moulin et al. (1994) 1 year	Cultivated and native transects for soil properties	Dark Brown soil zone and hummocky terrain	Silt and clay fractions, humic to fulvic acid ratios, total N and SOC all increased with distance down slope in the cultivated transect but the trend was absent in native transect.
Pennock and de Jong (1990)	Soil redistribution and slope gradient	Brown, Dark Brown and Black soil zones	Erosion losses (both net and mean) were highest in Dark Brown and lowest for Black soil zone.
Pennock et al. (1994) 12, 22, and 80 years sites	Soil redistribution and soil properties	Gently rolling hummocky till	Despite significant changes in soil properties because of soil redistribution and cultivation, the changes are not problematic for crop production with the exception of losses of SOC and total soil nitrogen.

SOC: Soil Organic Carbon, CT: Conventional Tillage, NT: No Till, CTCF: Conventional Tillage Crop Fallow, ZTCC: Zero Tillage Continuous Crop

Boehm and Anderson (1997) have also explained that the lower pH of A horizons of continuously cropped soils may be caused by increased organic matter and, therefore, organic acids at the soil surface, and to placement of NH_3-N fertilizer near the soil surface. If nitrification occurs near the soil surface, followed by leaching of NO_3 and plant uptake at a lower depth in the soil, net acidification can occur at the site of nitrification. The same study has shown some saline soils in the crop-fallow fields, and to a lesser extent in the extended rotation fields. The saline soils occurred in convergent footslope and convergent backslope positions which have been attributed to downslope movement of soil water and dissolved salts influenced by the farming practices. Especially, in the crop-fallow system, soils are generally filled to field capacity during latter part of the fallow year and winter. As a result, more water runs off accumulating in lower positions where it infiltrates and raises the water table locally, resulting in an upward flux of water to bare soil surfaces and increased salinity on adjacent convergent elements.

In addition to cultivation practices, soil properties on high sloping landscapes are also affected by erosion and soil redistribution processes (Table 2.8). Elliott and Efetha (1999) have shown that the distribution of organic C in the landscape is different within two tillage treatments. On the zero tillage continuous cropped (ZTCC) plot, similar organic C levels are found in the surface 0.1 m depth on converging backslopes (CB), diverging backslopes (DB) and shoulder (SH) positions, while more organic C is found in the footslope (FS) elements. Organic C is similar on CB, DB and FS elements of the conventional tillage crop fallow (CTCF) plot but is less at the SH positions. Past losses or organic C due to erosion are no longer evident at the SH position of ZTCC plot, but accumulations at the FS position reflect both past erosion and residue additions. Biomass production and, hence, residue additions are generally greater at FS positions (Elliott and Efetha 1999).

2.4.2. Soil Properties Under Use of Manure and Chemical Fertilizers

2.4.2.1. Flat Land

Manure application studies have shown good response to soils and crop yield related to a range of climatic factors and management practices (Table 2.9). However, problems exist in comparing results of different studies due to the complexity of manure in itself and interactions in soils. Further, different studies have been conducted with specific objectives and some areas are not having a definite answer. For example, injection of liquid manure is considered a best management practice with regard to efficient N capture and reduced environmental degradation. Injection can also create a unique soil chemical-biochemical environment because manure injection bands are not further disturbed in no-till systems and thus impact only about one-tenth of the soil in a field (Laboski and Lamb 2003). Field studies (Table 2.9) on small experimental plots (Charles 1999; Assefa 2002) are based on random sampling of manure injection treatments and even under repeated manure treatments (Mooleki et al. 2002) for which there is no indication about alignment of injection passes. Moreover, studies conducted in different environment and crop conditions report different rates of nutrients mineralization and residual concentrations. Therefore, instead of presenting a comparative literature from different environments, the related prairie studies have been reviewed to support the results of present study.

Table 2.9. Summary of studies with manure application.

Study reference, years, soil, and area information	Study parameters and treatments	Study results
Chang et al. (1990), 11 years field study, clay loam soils (Dark Brown Chernozemic) Lethbridge, AB.	Soil EC, pH, and soluble salts; Solid cattle manure at 0, 30, 60 and 90 Mg/ha to non-irrigated and at 0, 60, 120 and 180 Mg/ha to irrigated plots. Three methods of incorporation were used: plowing, rototilling, or cultivating plus disc.	The tillage methods of manure incorporation have not shown significant differences. Various soluble constituents from the annual applied manure accumulated in the soil under both irrigation regimes even at recommended rates. The rates of change with time were mostly linear.
Charles (1999), Assefa (2002), Mooleki et al. (2002), Wen et al. (2003), Mooleki et al. (2004), Qian et al. (2004), 1-5 yr studies on different aspects of same experiment, Black Chernozemic, Burr (sandy loam) and Dixon (loam) sites, SK. Assefa (2002) had an additional part (1st yr of a 3 yr study) on Gray soils, Falher (silty clay loam) and Fairview (silt loam) sites, AB.	Soil and crop response to; rate, frequency and application method treatments of swine and cattle manures with respect to chemical fertilizers and controls. Annual and reduced frequency, separate treatments of cattle and swine manures equivalent to approx. 74 to 790 kg total N/ha. Urea fertilizer treatments received 50, 100, 200 kg N/ha. Crops were canola, wheat, barley, and canola for respective years of 1997, 1998, 1999, and 2000. Single application of swine manure at low (183 kgN/ha) and high (811 kgN/ha) rates. About same rates for cattle manure and chemical fertilizer treatments. Low and high rates selected to match the 1 and 3 year requirements.	With respect to annual cattle manure application rates, a linear increase in grain yield was observed with no effect on grain N concentration. Swine manure showed similar increase in yield with higher grain protein. For cattle cumulative NUE was low (7-10%) with no difference among treatments and for swine, NUE was highest (50-60%) for low annual application and lowest (10-30%) for high annual application rates. The total P concentration in the surface soil (0-15 cm) was significantly increased only by the addition of cattle manure and only in the medium and high rate treatments. There was no effect of cattle manure incorporation timing and type of opener used to inject swine manure. Single manure treatment had shown limited impact on soil salinity and sodicity while repeated applications have slight impact.
Laboski and Lamb (2003), 9 months lab study, Seven Minnesota soils.	Changes in soil test phosphorus; Liquid swine manure at rates of 0, 120, and 240 mL manure/kg soil with respect to equivalent fertilizer P treatments. The manure rates were equivalent to common field applications of 37,300 and 74,500 L manure/ha by injection.	Phosphorus from liquid swine manure was more available than fertilizer P from 1 through 9 month of incubation. The study suggest as injection of manure is considered a best management practice but at the same time, manure injection may create bands of soil with high P availability.
Paré et al. 1999, 3 years field study, silty clay loam (Orthic Black Chernozemic) at Melfort, SK.	Tillage systems, quality of SOM; Cattle Fresh Manure (FM) applied in the beginning at 23 Mg/ha and then annually at 4.5 Mg/ha, whereas stockpiled manure (SM) with equal N concentration to FM also on same dates and rates with respect to a control with inorganic fertilizer.	No affect on the mass of SOM in the 0-15 cm depth. Quality of SOM affected by the increased amounts (21%) of unbound lipids in CT soils as compared to NT. Also, NT contained higher concentration of less stable SOM than CT.

SOC: Soil Organic Carbon, CT: Conventional Tillage, NT: No Till, NUE: Nitrogen Use Efficiency

Overall, liquid hog manure has a greater effect on increasing nutrient availability in the short term (1st year of manure application) than cattle manure (Charles 1999) and this was evident even from the mid season plant tissue analysis (Assefa 2002) (Table 2.9). About 500 and 200 kg/ha of residual soil inorganic N was reported after the 1st year crop harvest at the high hog manure rate (790 kgN/ha) and fertilizer rates (200 kg/ha) respectively at Burr. The low (204 kgN/ha) hog manure application rates injected using a 30 cm spacing was most effective at Burr as compared to the medium rate (147 kgN/ha) at Dixon while application rates of hog manure in excess of 134 kL/ha (~ 400 kg N/ha) may cause crop damage and excessive residual N in soil. The high cattle manure rates (70 Mg/ha for Burr and 40 Mg/ha for Dixon) are considered effective by broadcast and incorporation method. Nitrate levels increased with hog manure application at both sites, but only in the top 30 cm, and there was no evidence of deep leached nitrates (60-120 cm) at any application rate (Charles 1999). For Gray Luvisols soils, injection of hog manure at low rate 40 kL/ha (~ 183 kg N/ha) is considered fine and the high rate 175 kL/ha (~ 811 kg N/ha) intended to supply 3 years of nutrient requirement in single application resulted in high residual nitrate levels posing a leaching concern. Moreover, 5 to 10 Mg/ha rate of cattle manure (dry basis) is suggested for optimal crop production under the climatic conditions of the study period (Assefa 2002).

Short term studies have reported that other nutrients (P, K, and S) generally remained unaffected in the soil but plant tissue concentrations have shown response to manure application resulting in higher grain and straw yields at low application rates which decreased with increasing the fertilizer or manure application rates. Charles

(1999) has reported that although extractable soil P and K levels were not significantly affected by manure additions, crop P and K uptake and straw concentrations increased with application rate. Increase in crop S uptake is also reported in chemical fertilizer treatments as compared to control and this increase is attributed to the growth response of added N since no fertilizer S was added to these plots and also to the high indigenous levels of plant-available S. In Gray Luvisols, both hog and cattle manure increased P concentrations in the plant tissue but only the hog manure increased concentrations of K and only the cattle manure increased the concentrations of S in the plant (Assefa 2002). In Gray Luvisols, there were no significant differences in the yield among the low and high rate manure treatments. However, for Black Chernozemic soils, a reduction in yield is reported with increasing fertilizer application rates and the reduction is attributed to ammonium toxicity, seedling damage and apparent stand reduction. Generally, manure treatments showed a greater yield response when compared to fertilizer treatments with similar N application rates.

In Black Chernozemic soils, soil pH and soluble salt levels were unaffected by hog and cattle manure additions at both sites in the 1st year of application (Charles 1999) (Table 2.9). Also, as reported by Assefa (2002), the same soils, after receiving four annual applications of hog and cattle did not affect the pH of the soils except at the Burr hog manure site where a slight decrease in the pH was observed. A non-significant but linear trend towards increased electrical conductivities of these soils became apparent following the four repeated manure applications at Burr and the EC increased significantly only at the Dixon cattle manure site at medium application rate (15.2 Mg/ha). Both hog and cattle manure increased the sodium adsorption ratio

(SAR) in these soils indicating that, although not yet of concern after four years of application, there is a potential for increased sodicity with continued applications of manure at high rates. The organic C content in the 0-30 cm depth, was not significantly increased by manure application. This was not unexpected, given the large sampling interval (0-30 cm) and the inherently high level of indigenous organic C in these Chernozemic soils. In contrast, a single manure application on Luvisolic soils did not affect salinity and sodicity properties but tended to improve other soil properties such as soil structure as indicated by increased aggregate size, aggregate stability, and cumulative water infiltration and decreased crust strength (Assefa 2002). None of the Saskatchewan manure application studies have accounted for chlorides which have been reported to increase in soils receiving manure applications (Chang et al. 1990) and also in groundwater of a shallow sand aquifer under manured fields (Rodvang et al. 2004) in southern Alberta. Apart from crop uptake aspect, being a conservative ion, soil is neither considered a source or a sink for Cl and it is assumed that the same amounts that are naturally deposited on surface with precipitation, will eventually will leave the soil with groundwater (provided that evapotranspiration does not exceed leaching) (Johansson et al. 2001).

Briefly, the availability of manure applied nutrients in the first and subsequent years needs to be worked out for local field conditions which varies with the type of manure (Table 2.10). While studying efficiency parameters of nitrogen in hog and cattle manure after two years of application in Saskatchewan, Wen et al. (2003) found equally efficient use of residual hog and cattle manure N in producing grain yield by the second year wheat crop, but a higher grain N concentration with cattle manure which they attributed to the availability of more N from mineralization of cattle manure due to its high C : N ratio. Motavalli et al. (1989) attributed the recovery of manure nutrients to several possible causes, including lower availability of organic nutrients in the manure; greater quantity of nutrients applied with the manure, especially for N and P; differences in nutrient placement (injecting manure in bands vs. broadcasting fertilizer; and greater denitrification losses from manure.

Table 2.10. Estimated mineralization of manure organic N and availability of total N in the first and second year after application (Eghball et al. 2002).

Manure	Organic N mineralized 1st yr (%)	Total N available 1st yr (%)	Total N available 2nd yr (%)
Cattle feedlot	30	40	15
Composted manure	18	20	8
Poultry (hens)	55	90	2
Poultry (broiler, turkeys)	55	75	5
Swine	40	90	2
Dairy	21	32	14

2.4.2.2. Sloping Land

Several textbooks and regulatory advisories can be found related to manure application on sloping land. Similarly, there are a number of studies focused on sloping grasslands and pastures reporting about accumulation, leaching, and runoff of manure residues. However, it is difficult to find any study on cultivated sloping cropland with manure application and its effects on soil chemistry at different slope positions. As the catchment area of different slope positions varies (Table 2.1), slope positions may vary in terms of fertility and moisture conditions. Under sloping conditions, one way of looking into manure residue dynamics is to consider the effect that differences in moisture content can have. To illustrate this, the results of a study by Rolston et al. (1978, 1979) are presented next.

A short-term microplot study on the impact of manure on NO_3 transformations and soil N cycle by ^{15}N labeling was undertaken by Rolston et al. (1978). The study was conducted on $1m^2$ plots of well-drained Yolo loam soil in California in relation to the influence of soil-water content, organic carbon source, and soil temperature. Soil-water contents were maintained constant near saturation differing for high and low temperature conditions with a spray irrigation system activated at frequent time intervals. The upper 15 cm of soil was maintained at soil-water pressure heads (h) of -15 and -70 cm of water for the two different water regimes of the summer season experiment conducted at an average soil temperature (5 cm depth) of 23°C. Soil-water pressure heads were maintained at -8 and -50 cm for the two water regimes of the winter season experiment conducted at an average soil temperature (5 cm soil depth) of 8°C. The entire plot area was covered with an open greenhouse type structure to prevent rain from reaching the plots. The study was conducted in both summer and winter and included a manure treatment, a ryegrass cropped treatment, and a control (1.2% OC in surface) to establish three different carbon levels. The manured plots received the equivalent of 34 Mg/ha of beef feedlot manure (about 40% C) which was incorporated into the surface 10 cm of soil two weeks before the addition of KNO_3 enriched with ^{15}N which was added at 300 kg N/ha. No crop was grown on either the manured or control plots. The undisturbed soil profile (1.2 m) of plots was monitored to estimate leaching and denitrification of labeled N as well as its organic and inorganic fractions in the soil profile. Ammonia loss was not a factor in this study since the labeled N was in the NO_3 form. The data based on warm summer months (average temperature of 23°C) has shown (Fig. 2.2) following particular points:

- Manure markedly increased losses of N (labeled) due to denitrification (from 3% to 79%) when the soil was very wet (-15 cm pressure head). Increased denitrification with manure was also associated with a decreased leaching loss of labeled N (from 87% to 12%). Cropping the high moisture plots was not sufficient to prevent 66% of the $^{15}NO_3$ from leaching below the 60 cm root zone. Cool-season ryegrass was not an efficient N trap during warm months of the summer study.
- On the -70 cm pressure head plots, manure moderately increased denitrification (from 6% to 26%), increased soil organic N (from 8% to 21%), caused a reduction of labeled residual NO_3 (from 86% to 53%), and no leaching occurred at this moisture level.

Winter season (average temperature of 8°C) data showed (Fig.2.3) that:

- For high water treatment (-8 cm), the fate of labeled N was markedly different in the cool winter season where leaching dominated as compared to the warm summer season where denitrification dominated. However, growing a cool-season grass with high water levels during winter reduced leaching to 39% due to N accumulation in the above ground crop (35%) and immobilization of N in roots and soil organic matter (23%).

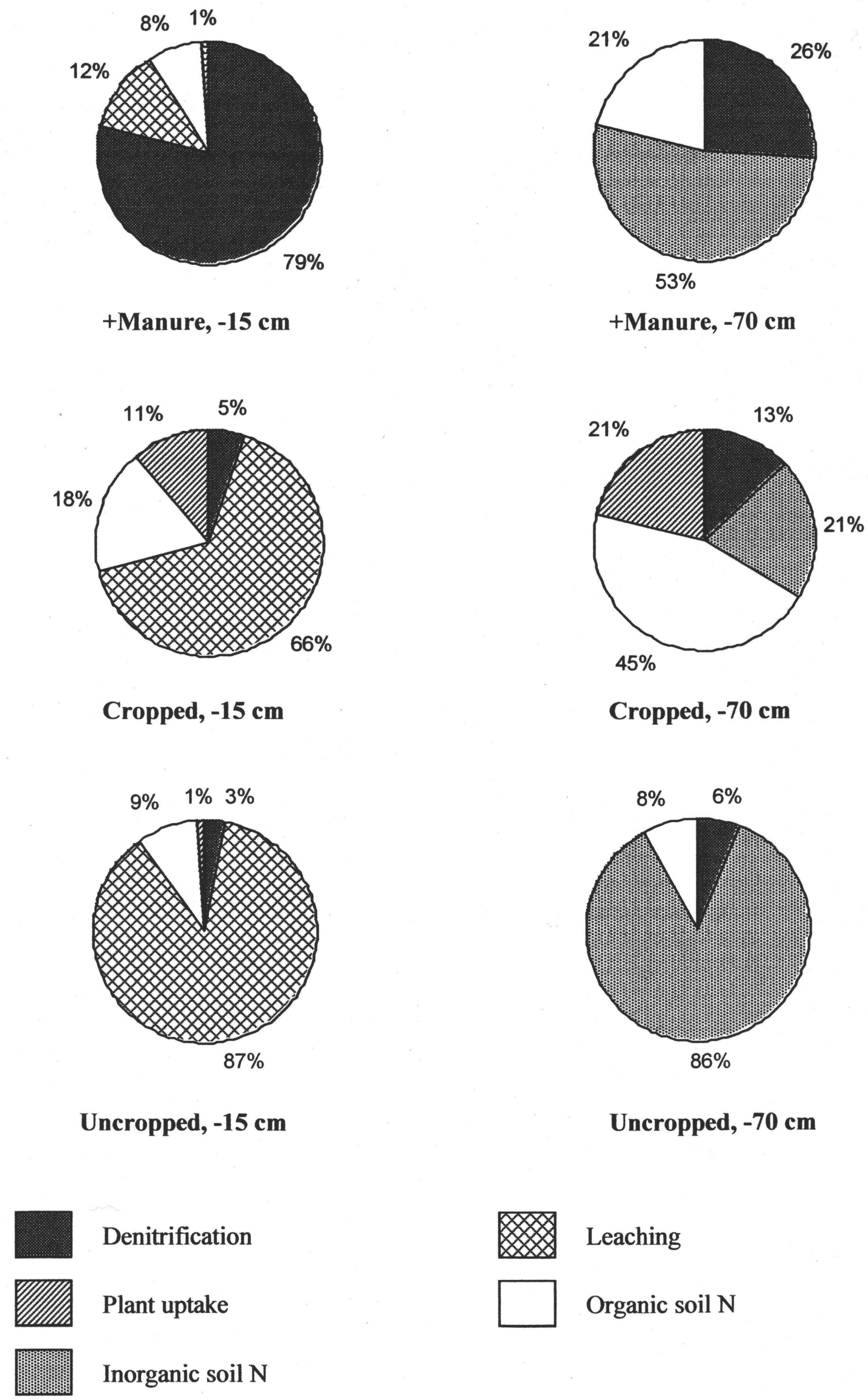


Fig. 2.2. Nitrogen budgets for an uncropped, ryegrass, and beef feedlot manure treated plots during summer months at two soil moisture tensions (Data adapted from Rolston et al. 1978, 1979; Cited in Sharpley et al. 1997).

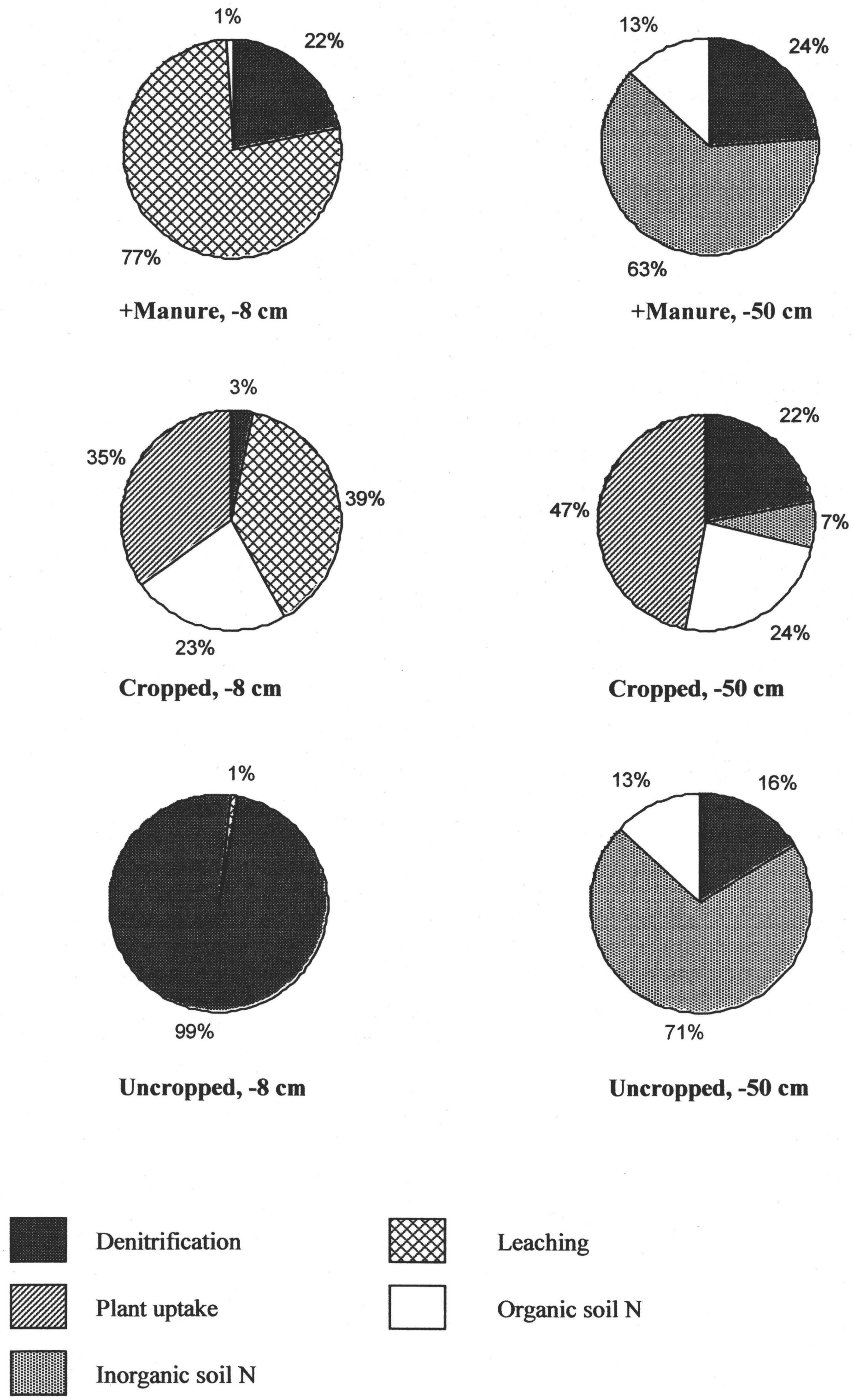


Fig. 2.3. Nitrogen budgets for an uncropped, ryegrass, and beef feedlot manure treated plots during winter months at two soil moisture tensions (Data adapted from Rolston et al. 1978, 1979; Cited in Sharpley et al. 1997).

- For low soil moisture level (-50 cm), leaching losses were negligible and inorganic N accumulated in the soil if uncropped. Denitrification losses increased also due to a longer residence time of the labeled N.

The above study has shown that the fate of NO_3 is strongly affected by factors such as available C (which affects microbial activity and oxygen demand), soil water (which affects leaching and oxygen content), temperature (which affects microbial activity, crop growth, and water use), cropping practices (which create sinks for N and water, and soil properties which interact with all of the above factors (Sharpley et al. 1997). Under field conditions of the prairies, climate and soil moistures changes throughout during a year. Although the climate is considered semi-arid, there are brief wet periods during spring snowmelt and summer storm events (Hilliard et al. 2002) which can briefly create wet conditions similar to the experimental study of Rolston et al. (1978) especially at lower slope positions. Under a range of agronomic practices in Saskatchewan (specifically with no manure treatment), Elliott (1990) has reported the proportion of water filled pores at field capacity a good indicator of denitrification potential. The same study has reported annual losses up to 100 kg N/ha at low level slope position by denitrification during a fallow year. However, the field averages are reported to be markedly lower such as 3, 20, and 4 kg N/ha under wheat, fallow and canola crop, respectively. The contribution of such losses on the fate of manure residues on non-level landscape remain to be resolved specifically when manure can act as a catalyst to denitrification providing an additional source of carbon.

2.5. Impact Assessment Techniques

Assessing the health of an agroecosystem is a complex challenge and in this perspective, Xu and Mage (2001) have classified the health criteria into four groups relating to agroecosystem structure, function, organization, and dynamics (Table 2.11). The present study is limited to the health of the soil compartment of an agroecosystem and appropriate indicators of soil quality depend on the specific application or the issues concerned (Table 2.12) (Lal 1999). The variability of soil properties in space and time presents a challenge for site assessment and the detection of changes within and amongst sites. Spatial variation includes horizontal variation across a landscape and vertical variation with horizon depth. Temporal changes may reflect seasonal and annual variations in climate and microclimate as well as management regime (e.g., plowing and manuring, fertilization, liming, etc.) and alterations of the amounts and chemical quality of organic matter inputs (Boone et al. 1999).

Table 2.11. General criteria for assessing agroecosystem health (Xu and Mage 2001).

Structural criteria	Functional criteria	Organizational criteria	Dynamics criteria
Resource	Productivity	Integrity	Stability
Availability	Efficiency	Self-organization	Resilience
Accessibility	Effectiveness	Autonomy	Capacity to respond
Diversity		Self-dependence	
Equitability			
Equity			

Table 2.12. Soil quality indicators (Lal 1999).

Objective/Issue	Key indicators
Crop growth and agricultural productivity; Environmental quality and natural resource base; and Multiple uses	Available water capacity, infiltration capacity, soil organic carbon, cation exchange capacity and exchangeable bases, electrical conductivity and total salts, effective rooting depth, pH, soil texture and structure, microbial biomass, soil biodiversity.

Preliminary assessments by mapping of soil properties can be useful for planning process. Griffin (1999) has shown that grid sampling improves nutrient map accuracy. To design a grid, yield maps are a good starting point for gathering this information although care should be taken to collect a number of years of information before attempting to define distinct patterns. There is also potential to use soil survey type maps or soil textural class maps in the same way. The results of intensive grid sampling are also subject to substantial variation and these depend on the laboratory conducting the soil tests, on the grid used for sampling, and especially on the sampling date. When the spatial distribution of soil nutrients is related to the respective crop yield, no correlation between nutrient supply and yield can be found in some studies (Moulin et al. 1994; Brenk et al. 1999) and a good correlation is reported in other studies (Tables 2.7, 2.8).

In precision agriculture studies, Mulla and Bhatti (1997) have shown that the variability in crop yield was a particularly sensitive indicator of spatial patterns in nitrogen fertilizer requirements, but was insensitive to variations in phosphorus requirements. In contrast, the variability in surface organic matter content was moderately sensitive to variations in nitrogen fertilizer requirements, and highly sensitive to variations in phosphorus fertilizer requirements. According to Khakural et al. (1996), depth to free $CaCO_3$, surface available P, relative elevation, and slope gradient were the most important variables affecting corn and soybean yields. The observations of Solohub et al. (1996) suggest that fertilizer application can be manipulated as based on landscape – scale management units to minimize inputs, while maintaining yield. Beckie et al. (1997) have shown the advantage of higher fertilizer use efficiency ($10 per ha) under variable rate inputs based on residual nitrate, organic carbon and topography. The factors, which might be considered when investigating variability within field, are generally the same as those taken account of when assessing variability between fields. The fundamental difference is that for the latter, the average value of the variable over the whole field is measured; for the former, values for points or relatively small areas are required (Dawson 1997).

For a Dark Brown Chernozemic clay loam soil having typical knob and kettle topography (6-9% slope) near Hanley SK, Dumonceaux (2001) conducted a field-scale and incubation study to investigate the potential of using spring soil moisture measurements and hot KCL-extractable N as predictors of N availability and yield response to fertilizer N applied using conventional (uniform) and variable rate application (VRF). The field component of the study found promising results from the selected N indicator for both treatments and superior for the VRF treatment agronomically, but the spring soil moisture did not exhibit a landscape pattern and was not well correlated with yield and N uptake in either treatment. However, a growth chamber experiment conducted on intact cores from upper and lower landscape positions under two water treatments simulating wet and dry years showed that increasing the N fertilizer rate and water application improved wheat yield on lower slope cores but not on upper slope cores. The results from both experiments indicated that water is not necessarily the limiting yield factor on upper slopes, and in some years, may be less important than N mineralization potential or other unidentified factors when estimating variation of crop yield potential in non-level landscape.

The preparation of the mass balance of a nutrient element, on an annual basis, can provide useful evidence of the extent to which the requirement for a specific output of herbage or livestock product is being met. It may also suggest how to improve the efficiency of use of the element and how to minimize losses (NRC 1997; Whitehead 2000). The preparation of a mass balance can also assist in modeling the cycling of a nutrient element, particularly if balance data are available for a range of situations. The soil component of the balance may be expressed in terms of the total amount or the plant-available amount of the nutrient element, the latter requiring estimates of the amounts of the nutrient released through the decomposition of OM and weathering of parent material and of the amounts immobilized in non-available forms in the soil. The complexity of the balance varies with the element, and is greatest for N and least for the micronutrient cations, whose loss from the soil is usually negligible (Whitehead 2000). Simply, the choice of a method to calculate nutrient balances strongly depends on the purpose, which may lead to selection of simple black-box model for higher spatial scale to create awareness for policy makers or dynamic compartment models for spatial scales at the plot to farm levels to evaluate the environmental impact of different management practices (Smaling and Oenema 1998). Mulla et al. (2003) have noted that the performance of spatial up-scaling techniques does not seem to depend as much as on the magnitude of upscaling as on the relative similarity between the smaller unit that is upscaled and the larger unit.

Nutrient balances alone cannot act as safe and reliable guidelines for farmers, scientists and policy-makers. Depending on the soil fertility level, negative and positive balances of a particular nutrient may or may not be desirable. Not only the balance, but also the absolute and relative sizes of individual budget items need attention to appreciate the sustainability of an agroecosystem. It is not justified to use the nutrient balance, alone or in relation to the nutrient stock, as a yardstick for sustainability, or as a guideline to set targets for the future. Not only when the balance is negative or positive, but even when it is neutral, it may represent a non-sustainable situation (Smaling and Oenema 1998).

Nutrient budgets may relate to different spatial and temporal scales. These scales depends upon the objectives, however, long term studies are suggested for manure management systems (Wood and Hattey 1995). Within a field, soil and crop may be distinguished for residual levels and crop uptake respectively, and in the soil there are compartments like soil solution, soil organic matter, soil minerals and adsorption sites for cations and anions. At each scale, nutrient flows may be classified into inputs, outputs and internal flows. A particular flow, for example animal manure, may be an input for arable land, an output for grazing land, and an internal flow for a farm (Smaling and Oenema 1998).

Another issue that needs attention in an analysis of sustainability is 'balanced nutrition', that is, the situation in which the various nutrients (micro, macro, trace) are offered in proportions matching the needs of the crop. It is a prerequisite for optimum nutrient use efficiency and sustainability. The fact is that the excess of one nutrient goes together with, and may be the consequence of, the shortage of another nutrient. Disproportions in nutrient supplies aggravate depletion of one nutrient and emissions to the environment of others (Janssen 1999). Recommendations for N are fraught with more problems than those for any other element, because its availability is subject to greater changes. Recent studies on manure N recovery and performance have reported the applicability of indirect (difference, fertilizer equivalence) methods (Wen et al. 2003) which have been reported unreliable due to their wide variation in getting N estimates (-60 to 148%) in comparison with the direct method based on ^{15}N labeling (Muñoza et al. 2004). Wolf (1999) has noted that in the cold regions of North America, serious N deficiencies can arise in the spring when soils are too cold for N release from organic matter (OM). Eliminating or greatly reducing the N application because of large amounts of soil OM can seriously limit crop yields. A better approach for these and other areas is to measure the available NO_3 and NH_4-N and eliminate or greatly reduce the N application only if high levels of available N are present. Generally, the amount added should be enough to bring available soil N from a 'poor' (0-14 ppm) or a 'fair' (15-24 ppm) to a 'good' (25-75 ppm) level. For example, if only 10 ppm of $NH_4 + NO_3$ were present, it would be desirable to raise the available N to midway in the 'good' range, and so 40 ppm (80 lb/ac ~ 74 kg/ha) would be needed (Wolf 1999).

The question that remains is to decide the suitability of impact assessment methods based on precision agriculture concepts and/or mass balance techniques to assess and evaluate the impact of the present study treatments. The presented methods are for multiple treatments on flat land and for sloping land under the precision agriculture concepts. In the present study, fertilizer treatments were applied uniformly over the whole watersheds according to the farmer decision. Moreover, it is easy to monitor boundaries for mass balance studies in lysimeters, which seems difficult in field condition especially on hillslope with runoff, runon and subsurface flow components. Keeping in view all the above sections, it has been concluded that the above methods are either difficult or un-applicable in the present study due to differences in slope positions in terms of topography and hydrology.

Therefore, the present study is mainly focused on assessing the status of fertilizer residues in time and space on a number of subsequent dates, important for the crop and hydrologic cycles of the study area, during a period of one year. As described above, complete mass balance of nutrient cycles require an enormous effort for data collection on all the inputs and outputs. Also, evaluation of soil fertility or contamination requires monitoring of a wide range of physical, chemical, and microbiological parameters, which may be very difficult to interpret on the basis of parameter-by-parameter analysis (Vidal et al. 2000). Complete evaluation of a single parameter may involve an enormous effort; for example soil N availability is related to a host of processes including mineralization, immobilization, denitrification, volatilization and leaching, and each of these processes is, in turn, influenced differently by separate controls (Walley et al. 2001). Therefore, the present study is limited to the minimal data required for a regular fertility-monitoring program which may be accomplished by the farmers under their existing management practices.

3. MATERIALS AND METHODS

3.1. Site Description

3.1.1. Study Locale

The study site is located in the rural municipality of Perdue, 60 km west of Saskatoon, Saskatchewan, Canada (Figure 3.1). The area falls in the Moist Mixed Grassland Ecoregion, which is a sub-classified region of mixed grasslands of prairie plains. The legal location of the study area is Township (35), Range (12), west of the Third Meridian. There are three watersheds represented by one transect each (three treatments) on them (Table 3.1). Watershed A is located in the SE quarter of section 28, watershed B is in the NW quarter of section 27, and watershed C is in the SE quarter of section 34. The area comes under Crop District 6b and Rural Municipality 346. The study site was selected in the fall of 1998 as a part of a research project by the Department of Agricultural and Bioresource Engineering at the University of Saskatchewan.

3.1.2. Study Treatments

Experimental cropland encompassing the study transects are located adjacent to a hog barn belonging to Heartland Bear Hills Pork Producers (Table 3.1, Figure 3.2). These transects are the three study treatments as follows:

Transect A: Application of chemical fertilizer (control)

Transect B: Application of hog manure at a rate of 78.7 m^3/ha (7,000 gal/ac)

Transect C: Application of hog manure at a rate of 112.3 m^3/ha (10,000 gal/ac)

With these different types and rates of fertilizer inputs, all other agronomic practices are the same for the three transects.

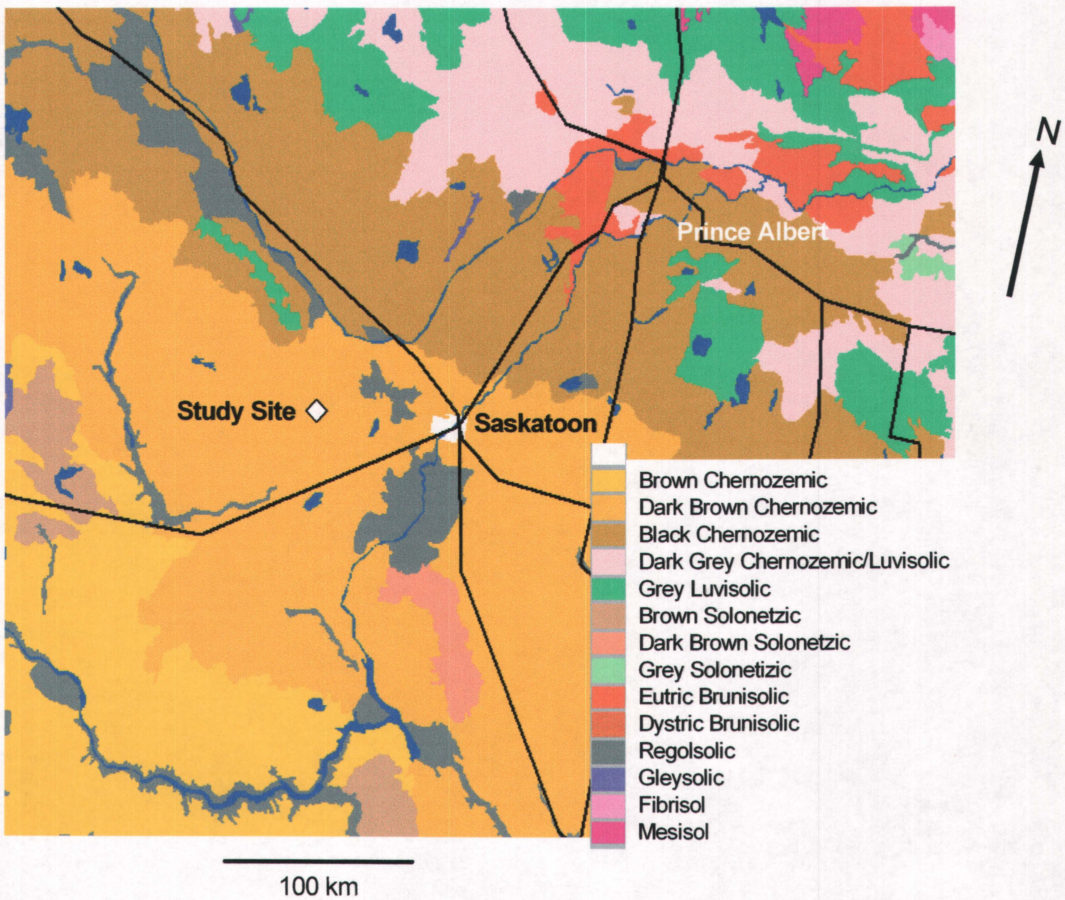


Fig. 3.1. Soils of Saskatchewan (Agriculture and Agri-Food Canada, 2002).

Table 3.1 General characteristics of watersheds at Perdue.

	Fertilizer treatment	Area (ha)	Elevation change (m)	Average slope (%)	General aspect	Location
A	Chemical	6.9	9.8	2.7	SW	SE -28-35-12-W3
B	Manure	4.4	13.0	3.3	NE	NW-27-35-12-W3
C	Manure	6.3	11.9	3.8	N	SE -34-35-12-W3

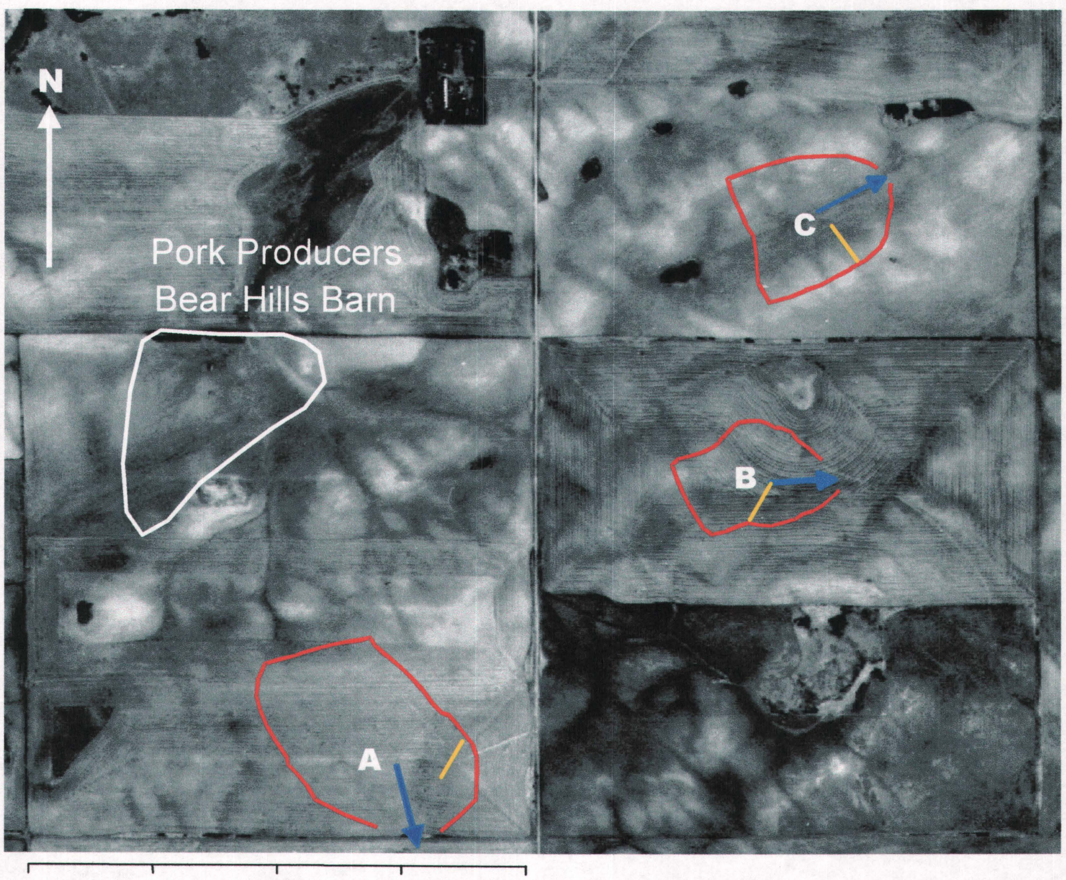


Fig. 3.2. Location of watersheds at Perdue.
Note: Red outlines are watershed areas; Blue arrows are direction of runoff; Yellow lines are study transects; and White outline is the location of hog barn.

3.1.3. Soil Physical Characteristics

The study area represents the gently sloping hummocky glacio-lacustrine landscapes dominating in the southern part of Bear Hills landscape area (Acton et al. 1998). The soils are Dark Brown Chernozemic of the Keppel Association which formed under grassland vegetation and developed in medium to fine moderately fine textured lake modified or sorted glacial till that occurred on rolling morainic landforms (Acton and Ellis, 1978) (Fig. 3.1). As their name implies, these Dark Brown soils have a dark-coloured surface layer (A horizon) that is higher in organic matter than soils in the adjacent Brown soil zone in the south, but lower than those in the Black zone in the north. Typically, this layer is separated from a grayish-brown layer (C horizon), which represents the soil parent material, by a reddish-brown layer (B horizon) that is free of carbonates of calcium and magnesium (Acton et al. 1998).

The study area soils tend to be thin and lower in organic matter on upper slopes, becoming progressively thicker and higher in organic matter on mid and lower slopes, in response to an increased supply of soil moisture and plant growth. Brown Chernozemic soils occur on prominent south-facing local and regional slopes where more arid conditions result in reduced growth. Black Chernozemic soils occur on prominent north-facing slopes and in lower-slope positions on steeply sloping topography (Acton et al. 1998). Surface textures of the Keppel soils are predominantly loam and clay loam. Permeability is moderate to low and the soils are commonly well drained. Surface runoff is moderate to low. Keppel soils are considered to be in Land Capability Class 3 having moderately severe limitations for agriculture. Lack of precipitation and somewhat limited moisture holding capacity are the principal factors which generally affect the agricultural capability of these soils (Acton and Ellis, 1978).

3.1.4. General Chemical Characteristics of the Soils

The soil deposits of the Keppel Association are moderately to strongly calcareous and generally low in salts. The Orthic Dark Brown series predominates in nearly all areas. It has a low to moderate content of organic matter, mildly alkaline reaction, low available phosphorus and high available potassium content (Acton and Ellis, 1978).

3.2. Data Collection

3.2.1. Manure Sampling and Analysis

Manure was first applied to the fields in the fall of 1999 (other details are presented in section 3.2.3). Multiple manure samples were collected for analysis at the time of application. In total, four manure samples were taken from two injection tanks at full and prior to empty stages. The samples were frozen immediately after their collection in the field. Chemical analysis of the samples was done using water extraction and H_2SO_4 digest by Prof J. Schoeneau's lab, in the Soil Science Department, University of Saskatchewan. Dissolved concentrations by water extraction were measured colorimetrically using Technicon Autoanalyzer II (NO_3-N and NH_4-N) and anion exchange resin membranes were used to determine PO_4-P. In the second method, H_2SO_4-H_2O_2 digestion of manure sample was followed by analysis using inductively coupled plasma emission spectroscopy (Perkin Elmer Optima 3000 DV) to determine manure constituents (P, Ca, Mg, K, B, Cd, Cu, Fe, Mn, Pb and Zn).

3.2.2. Soil Sampling and Analysis

For monitoring the fertilizer residues in time and space, soil samples were taken at the following dates:

1. Fall 1998 (baseline samples at the start of the project study)
2. Fall 1999b (before manure application, background samples for present study)
3. Fall 1999a (after manure application)
4. Spring 2000 (after snowmelt and before seeding)
5. Fall 2000 (after crop harvest)

Initially (Fall 1998), baseline soil samples were taken at the five slope positions (upper, shoulder, mid, toe, and depression) from the study transects (Figure 3.3). These sampling sites were chosen in conjunction with a hillslope analysis by H.de Gooijer of Saskatchewan Land Resource Centre. Three depth intervals were sampled; 0-15, 15-30 and 30-60 cm. In order to account for spatial variability and to obtain valid comparable data from each transect, six subsamples were collected at each slope position (Figure 3.4). Sub-samples from each of the six cores were combined for each depth segment.

After the 1st sampling, as described above, the samples were collected from six slope positions at the middle of the adjacent baseline positions as shown on transect diagram (Fig 3.3). This was to insure that the post-baseline samples did not disturb baseline sampling locations. Post-baseline samples were taken in duplicate, on the wheat stubble, halfway between the stubble and furrow and in the furrow, totaling 6 subsamples per sampling position (Fig. 3.4) (Maulé et al. 1999).

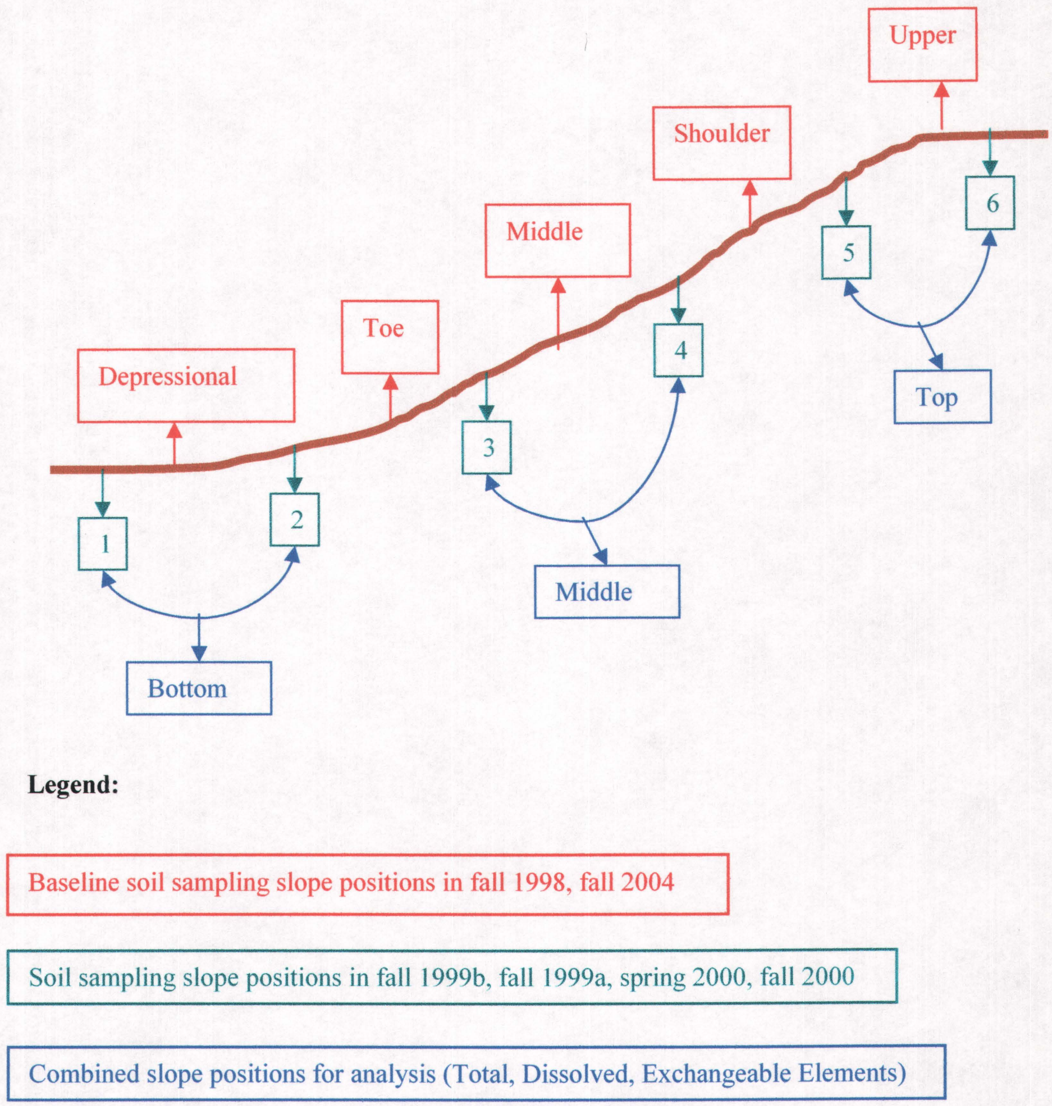
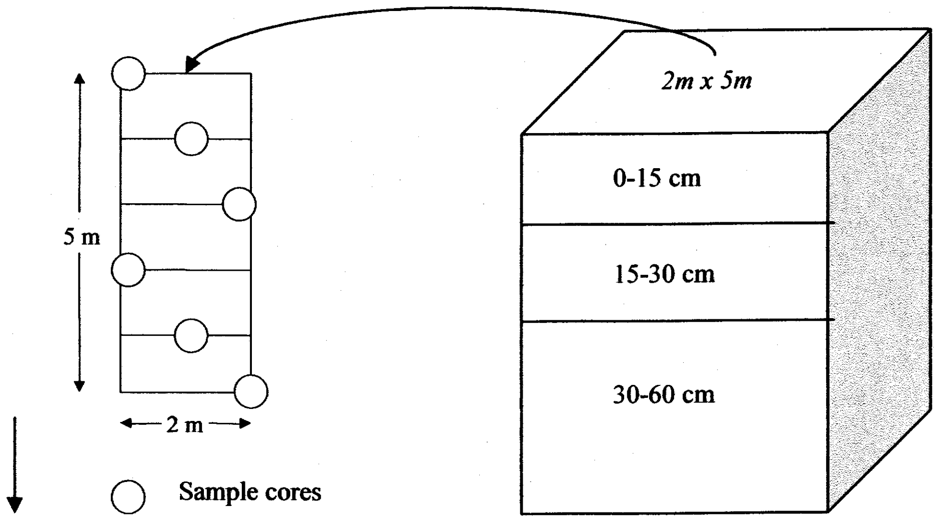


Fig. 3.3. Soil sampling locations on study transects.



Six subsamples used for determination of bulk density and gravimetric soil moisture.
Six subsamples combined for one bulked sample, ground and sieved < 2mm.

Bulked samples used for determination of soil texture and to obtain saturated paste extract.
Measured electrical conductivity and pH of extract samples.

Soil samples and extract samples mixed to represent combined slope positions (Figure 3.3).
Mixed soil samples sent for analysis of total elements (carbon, nitrogen, and phosphorus), cation exchange capacity, and exchangeable ions.
Extract samples sent for analysis of dissolved anions (chloride, nitrate, nitrite, phosphate and sulphate) and cations (ammonium, calcium, magnesium, potassium and sodium).

Fig. 3.4. Soil sampling and analysis scheme. (Note: the scheme is applicable to all sampling dates during study period. However, for baseline samples, the scheme is applicable only up to the texture measurement step. Bulk density was calculated only from samples collected in fall 2000).

Initially, for gravimetric moistures and bulk density (dry basis) calculations, the subsamples were processed separately for each slope position and depth (Figure 3.4). A summary of the soil sample analysis protocol is given in Table 3.2. In the next step, subsamples from one depth interval on one slope position were bulked and ground for saturated paste extracts. This process resulted in 54 samples from each sampling date as follows:

For each sampling date, number of samples = 3 Transects x 6 Positions x 3 Depths x 6 Subsamples = 432 = 54 (after bulking the subsamples).

After the above processing, soil samples from Fall 1998 were analyzed for soil texture by modified pipette method (Indorante et al., 1990). Soil saturated paste extracts were obtained for all the samples from each date by the Rhoades (1982) method reported in Janzen (1993). Electrical conductivity and pH readings were taken for all the extracts (Table 3.2). For further analysis, the intention was to reduce the analysis cost for a representative data set and it was decided to combine the samples in the following format from different slope positions:

1+2(bottom), 3+4(middle), 5+6(Top) = 54/2 = 27 (after combining slope positions for samples from Fall1999b to Fall 2000) (Figure 3.3)

Due to the stable nature of certain soil chemical characteristics over a short period such as Total Carbon, Total Nitrogen, Total Phosphorus, and cation exchange capacity (CEC), analysis for these properties were obtained once only using samples from Fall 1999b (Table 3.2). To compute organic carbon levels, the same set of soil samples were analyzed for Inorganic Carbon only for the top depth interval (0-15 cm).

Organic and Inorganic Carbon analysis for baseline samples (Fall 1998) was also obtained.

Table 3.2. Summary of soil laboratory analysis.

Analytical parameters	Analysis technique and source	Slope positions per transect (Fig. 3.3)	Number of samples per transect per one sampling date	Soil sampling dates
Soil texture	Modified pipette method (by student)	5 (Dep, Toe, Mid, Shoulder, upper)	5 slope positions x 3 depth intervals = 15	Fall 1998, Fall 2004
Saturated paste	Based on 250 g of soil sample (by student)	6 (1 Dep 2 Toe 3 Mid 4 Shoulder 5 upper 6)	6 slope positions x 3 depth intervals = 18	Fall 1999b, Fall 1999a, Spring 2000, Fall 2000
EC and pH	EC and pH meters (by student)	same as above	same as above	same as above
Bulk density	Soil cores volume and gravimetric mass on dry basis	same as above	same as above	Fall 2000
Total C, N, P, and Cation Exchange Capacity	C and N (Instr), P (ICP), CEC (In NH_4OAc at pH 7), (by ETL)	3 [Bottom (1+2), Middle (3+4), Top (5+6)] (+ means mixed samples)	3 slope positions x 3 depth intervals = 9	Fall 1999b
Exchangeable Cations (Ca, Mg, K, Na)	In NH_4OAc at pH 7 (after water leaching) (by ETL)	same as above	same as above	Fall 1999b, Fall 2000
Dissolved Anions (Cl, NO_2, NO_3, PO_4, SO_4)	Dionex Chromatograph (Geology Department)	same as above	same as above	Fall 1999b, Fall 1999a, Spring 2000, Fall 2000
Dissolved Cations (NH_4, Ca, Mg, K, Na)	same as above	same as above	same as above	same as above
Inorganic Carbon	Acid digestion and two end point titration (by ETL)	same as above	3 slope positions x 1 depth interval (0-15 cm) = 3	Fall 1999b
Organic and Inorganic Carbon	Combustion (SS)	5 (Dep, Toe, Mid, Shoulder, upper)	5 slope positions x 3 depth intervals = 15	Fall 1998

ETL: Envir-Test Lab, ICP: Inductively Coupled Plasma, SS: Soil Science, University of Saskatchewan
Note: All analytical analysis is based on bulked samples.

Analysis for exchangeable cations (calcium, magnesium, potassium, and sodium) was obtained for samples from the background soil sampling date (Fall 1999b) and the study end date (Fall 2000). Analysis for dissolved anions and cations in soil saturated paste extracts were performed on a Chromatograph (Chromeleon Version 6.20 Build 531, Dionex 2000) in the Geology Department (University of Saskatchewan). This analysis provided dissolved concentrations for the suite of anions (chloride, nitrate, nitrite, phosphate, and, sulphate) and the suite of cations (ammonium, calcium, magnesium, potassium, and sodium). Samples from four sampling dates over the study period (Fall 1999b, Fall 1999a, Spring 2000, and Fall 2000) were selected for this analysis.

3.2.3. Agronomic Practices

The farmer followed his normal agronomic practices in managing the crop on the study transects. Information about fertilizer inputs and crop rotations of the last three years of study were collected from the farmer (Tables 3.3 and 3.4). On transects B and C, liquid swine manure was applied at a rate of 78.7 m^3/ha and 112.3 m^3/ha respectively by a low disturbance method on October 12, 1999. From the hog manure application, transects B and C received 220 and 315 kg N/ha and, 60 and 90 kg P/ha, respectively (Elliott and Maule, 2001). Manure was injected at an average soil depth of 10 cm by low disturbance injection equipment having knife injectors on the back of a tanker truck, operated by SANDS LTD. Manure injection travel was in east-west direction which was similar to the seeding operation each year. For spring 2000, the chemical fertilizer application rates were 56 kg/ha on transect A and, 11 kg/ha on transects B and C (Table 3.3). The farmer applied chemical fertilizers with air drill during spring seeding with no other tillage operation which was same for each year. This means that the study fields were under cultivation with a minimum tillage system. The harvesting practice of the farmer leaves standing crop stubble on the field over winter.

Table 3.3. Fertilizer inputs on study transects.

Transect	Chemical Fertilizer N-P-S (kg/ha)			Hog Manure N-P (kg/ha)
	Spring 1998	Spring 1999	Spring 2000	Fall 1999
A	50-22-0	50-22-0	56-22-13	Control
B	50-22-0	50-22-0	12-11-11	220-137
C	50-22-0	50-22-0	12-11-11	315-206

N: total nitrogen, P: phosphorus (P_2O_5), S: total sulphur.

Table 3.4. Crop rotation on study transects

Transect	1998	1999	2000
A	Barley	CPS Wheat	Canola
B	CPS Wheat	CPS Wheat	Canola
C	CPS Wheat	CPS Wheat	Canola

CPS: Canada Prairie Spring

3.2.4. Crop Sampling for Yield Measurement

For the three study transects, crop samples were collected at harvest time in 1999 and 2000. Samples were collected from three slope positions (bottom, middle and top). On each slope position, four subsamples of 1 m^2 were cut to obtain average yield.

3.3. Data Analysis

Due to interrelated spatial and temporal dimensions of the study, it is intended to present the original laboratory data set for clarification of results and to avoid potential errors encountered by unit conversions from laboratory results to field conditions that could introduce another source of variability from bulk density measurements. Also, there seems little reason to express the results of soil tests other than the unit in which the sample has been measured, i.e., results obtained from volumetric analysis and weighed samples should logically be expressed in their respective units such as mg/l and mg/kg (Bates, 1993).

As a limited number of soil samples were selected for chemical analysis, the first intent is the presentation of the whole data set for obtaining a clear picture of variability in soil characteristics in time and space. This data presentation is planned in a way to compare the study treatments in terms of soil chemistry and crop yield. The data on soil chemistry is shown in different sections focussing on total, dissolved, and exchangeable elements/ions concentration. Soil moisture data is presented to help with interpretation of nutrient dynamics and crop yield (Chapter 4).

After the above data presentation, the variability of certain chemical characteristics for fertility management is analyzed and assessed. Considering different types and formats of study data, transects are compared by least significant difference (LSD) analysis (GLM procedure, SAS 2001) and Paired T-Test. Attention is given to assess the impact of study treatments by comparing them graphically based on original data and not to develop correlation or regression based relationships to study the soil variability of sloping landscape. Havens (2002) has stressed not to infer causation from correlation, until such time that ancillary studies are conducted, including a more careful consideration of the underlying processes, and optimally, controlled experimental studies.

4. RESULTS

4.1. Background Properties

4.1.1. Climate and Physical Properties

4.1.1.1. Climate

During the crop growing season (April 1 to September 30), total rainfall in the study area was 198, 277, and 348 mm for the years of 1998, 1999, and 2000 respectively (SAF 1998-2000), which shows that the crop growing season of this study in year 2000 was wetter than previous years (Appendix A). Most of this rainfall occurred during the weeks of June and July (Figure 4.1). In the three year period, there were only four weeks with more than 50 mm of rainfall and about 20 weeks are in the range of 10 to 50 mm.

Monthly precipitation for the same three years at the Saskatoon airport shows that the year of 2000 received normal precipitation (Figure 4.2). The normal precipitation data shows the summer months (May to July) receiving precipitation in the range of 40-70 mm per month. The late summer to fall months (August to October) receives precipitation in the range of 15-40 mm per month. Precipitation in winter months (November to March) was in the range of 10-20 mm per month.

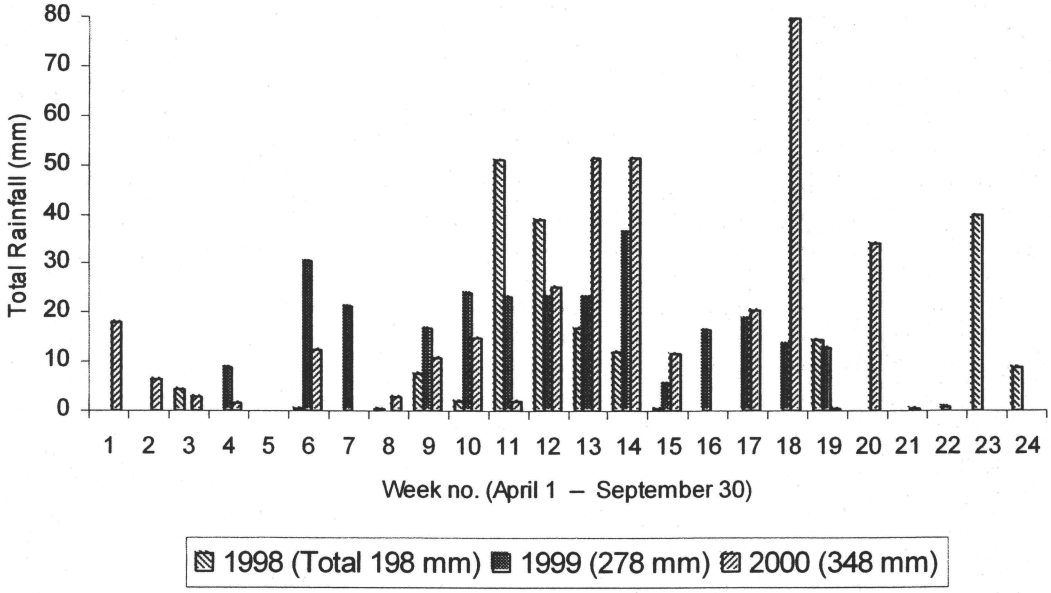


Fig. 4.1. Weekly rainfall amounts in R.M. of Perdue area during crop growing season, SAF (1998-2000) (Note: the data is grouped in 4 weeks per month).

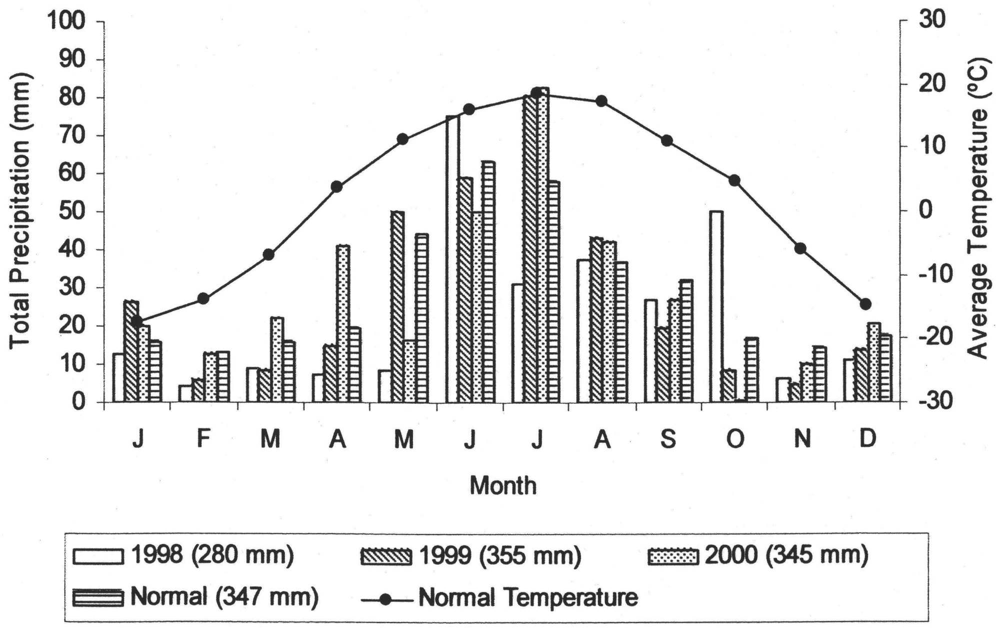


Fig. 4.2. Total monthly precipitation at Saskatoon airport, (Environment Canada, 1998-2000).

4.1.1.2. Landscape

The general aspect of the study transect in watershed A is South West, B is North East and C is North (Figures 4.3, 4.4, and 4.5). Location of the five slope positions (depression, toe, middle, shoulder, and upper) on the study transects are the same as the location of the neutron tubes shown on these figures. Study transects and their slope positions are mostly on straight lines, however, the neutron tube on upper position of watershed A is off of the transect line but the actual sample site is parallel away from the neutron tube on extended straight transect line (Figure 4.3). As all the watersheds are externally draining, the depression slope position of transect A is close to the outflow point of the whole watershed whereas for transects B and C, the depression slope position falls nearer to the starting points of the lateral slope for external drainage. Computed areas, from the topographic maps, showed the depression positions of transects A, B and C as receiving run-on contribution from an area of 4.0, 1.3 and 1.8 ha, respectively (Charles Maulé, Personal Communication).

The slope positions, where samples were taken, along the study transects are similar with regards to distance, elevation, and slope gradients (Fig.4.6, Table 4.1). Overall, the transects have slopes between 5.6 % (A) and 7.7% (C), with the overall slope for B being at 6.6%. The elevations of transect A and C differ at shoulder and upper positions by 1.7 to 2.3 m respectively, while transect B and C differ by 1.5, 1.4, and 1.2 m at middle, shoulder, and upper slope positions respectively. On all transects, elevation differences between depression versus toe and shoulder versus upper slope positions are lower (0.9 to 1.8 m) while the differences are higher between toe versus middle and middle versus shoulder positions (1.9 to 3.2 m). It means that the transect sections are steeper from toe to shoulder positions than the sections at both ends of these transects which is also evident from the gradients of individual sample positions. The steepest slope position is the middle position on transect C (13.4%) as compared to the middle position gradients on transects A (9.0%) and B (9.6%). Moreover, on all transects, distances between shoulder and upper positions are larger (39 to 45 m) as compared to all others which varies from 20 to 27 m with an exception of 33.4 m distance between middle and shoulder position on transect B. The shape of slope positions (across and down) is similar on all transects which is noted in one column for all of them (Table 4.1).

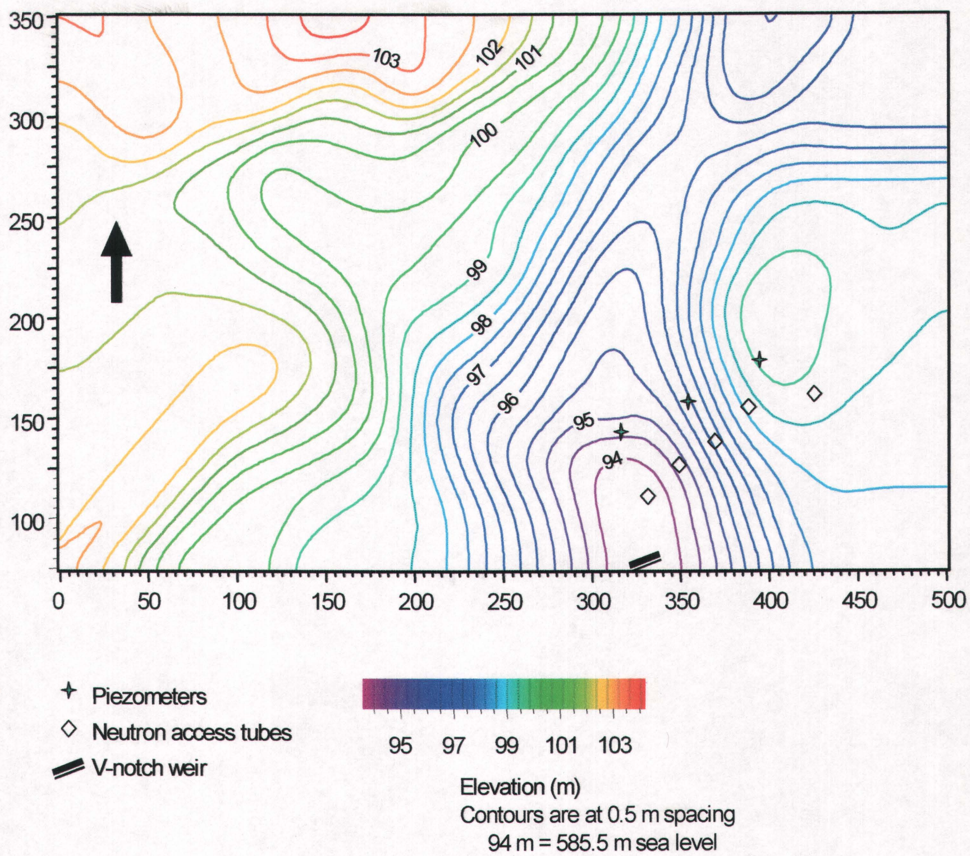


Fig. 4.3. Watershed A elevation contour map (Note: Instrumentation belongs to other components of project study. Neutron tubes are at the locations of baseline slope positions).

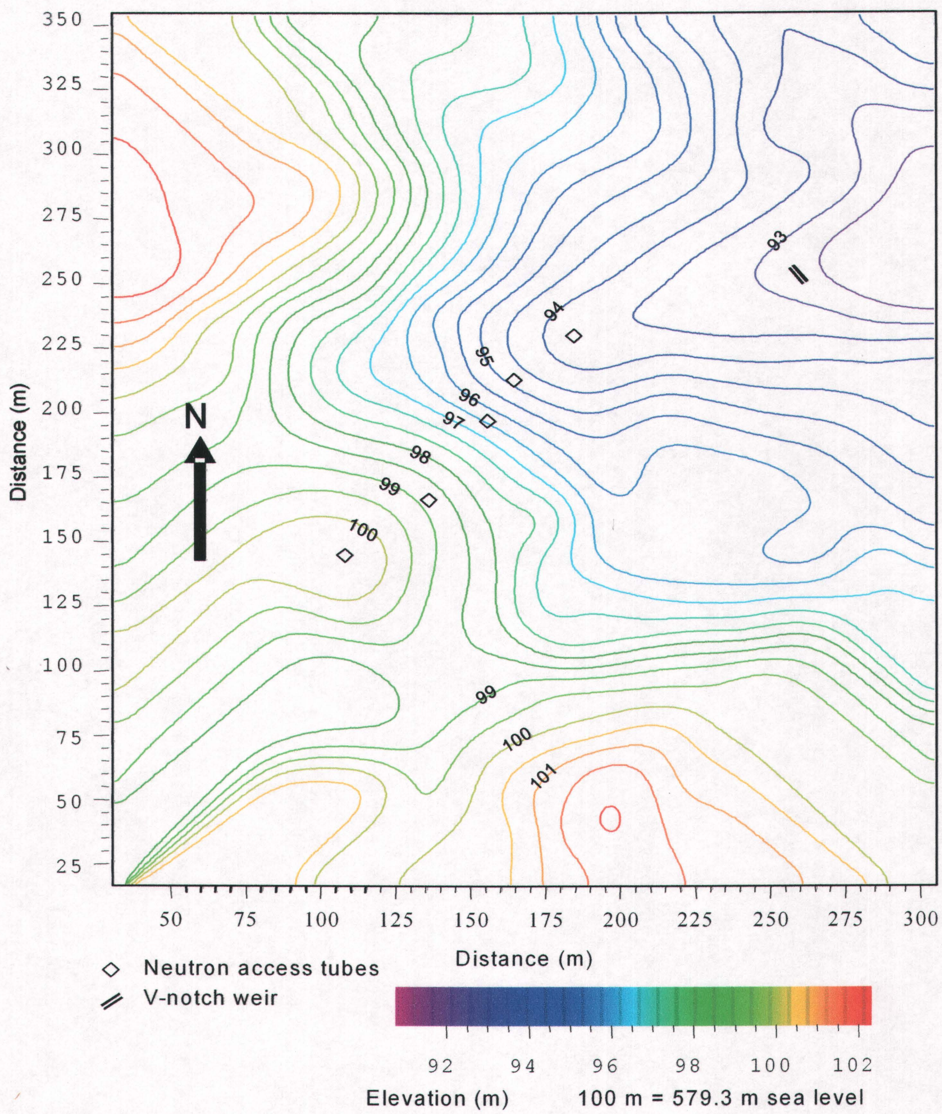


Fig. 4.4. Watershed B elevation contour map (Note: Instrumentation belongs to other components of project study. Neutron tubes are at the locations of baseline slope positions).

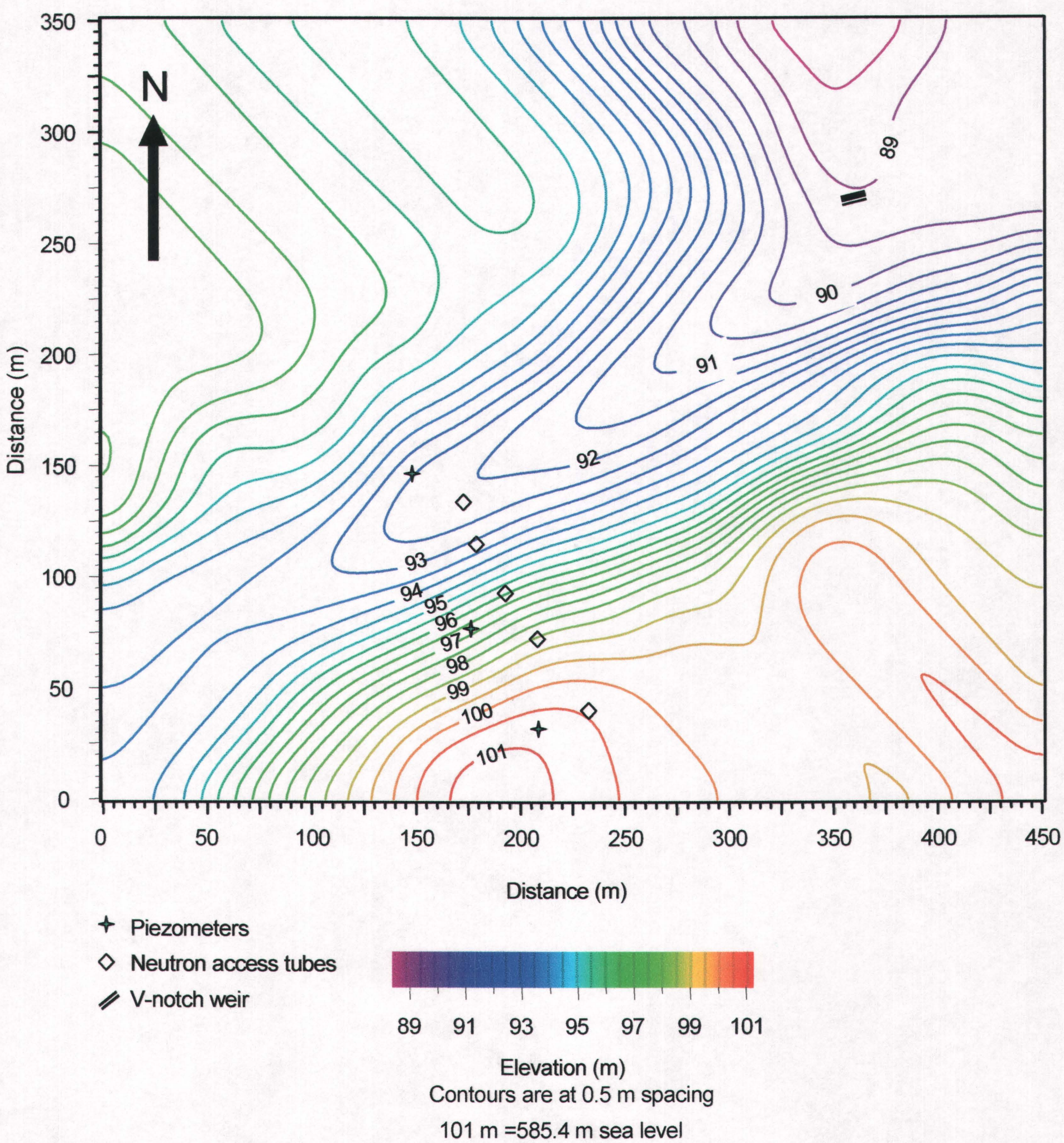


Fig. 4.5. Watershed C elevation contour map (Note: Instrumentation belongs to other components of project study. Neutron tubes are at the locations of baseline slope positions).

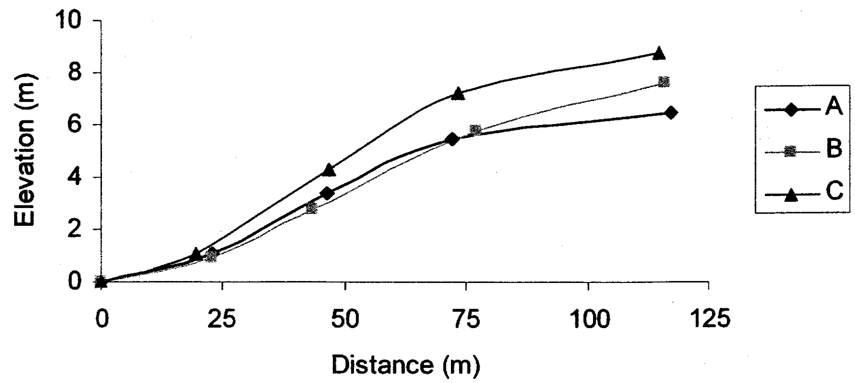


Fig.4.6. Surface topography of study transects.

Table 4.1. Landscape characteristics of sample positions on study transects.

Sample Position	**Transect A**	**Transect B**	**Transect C**	**Slope shape**
	Distance (m) and Aspect			**Across**
Depression	0.0 (SW)	0.0 (NE)	0.0 (N)	Straight
Toe	22.8 (SW)	22.8 (NE)	19.6 (N)	Concave
Middle	46.3 (SW)	43.5 (NE)	46.9 (N)	Straight
Shoulder	72.1 (SW)	76.9 (NE)	73.3 (N)	Convex
Upper	117.1 (SW)	115.9 (NE)	114.6 (N)	Convex
	Elevation (m) and Down Gradient (%)			**Down**
Depression	0.0 (2.4)	0.0 (1.5)	0.0 (1.4)	Concave
Toe	1.1 (7.3)	0.9 (7.5)	1.1 (9.0)	Concave
Middle	3.4 (9.0)	2.8 (9.6)	4.3 (13.4)	Straight
Shoulder	5.5 (6.5)	5.8 (6.2)	7.2 (8.2)	Convex
Upper	6.5 (0.5)	7.6 (2.1)	8.8 (0.4)	Convex
Overall transect gradient (%)	5.6	6.6	7.7	

Note: Distances and elevations for slope positions are cumulative values along transect. SW: South West; NE: North East; N: North.

4.1.1.3. Texture

Soil textural classes, along the transects (based on average of slope positions), are silt loam on transect A, loam on B, and clay loam on C for all depth intervals (Appendix

B). The average clay content (surface 15 cm of soil) is highest on transect C (31%) followed by transects B (24%) and A (23%). Generally, the clay content is slightly lower on toe slope positions (23%) and varies in a close range (24-29%) on all slope positions of respective transects (Figure 4.7).

Sand content (0 to 15 cm) is the highest on transect B (33%) followed by transect C (22%) and A (19%). For slope positions, the sand content is highest at the middle positions of transects B (41%) and C (30), and upper position of A (25%) while the lowest values are at the upper positions for transects B (28%) and C (15%), and transect A (13%) has the lowest sand content at the shoulder slope position (Figure 4.8). These differences have not shown much variation (22-29%) in terms of average of respective slope positions of study transects.

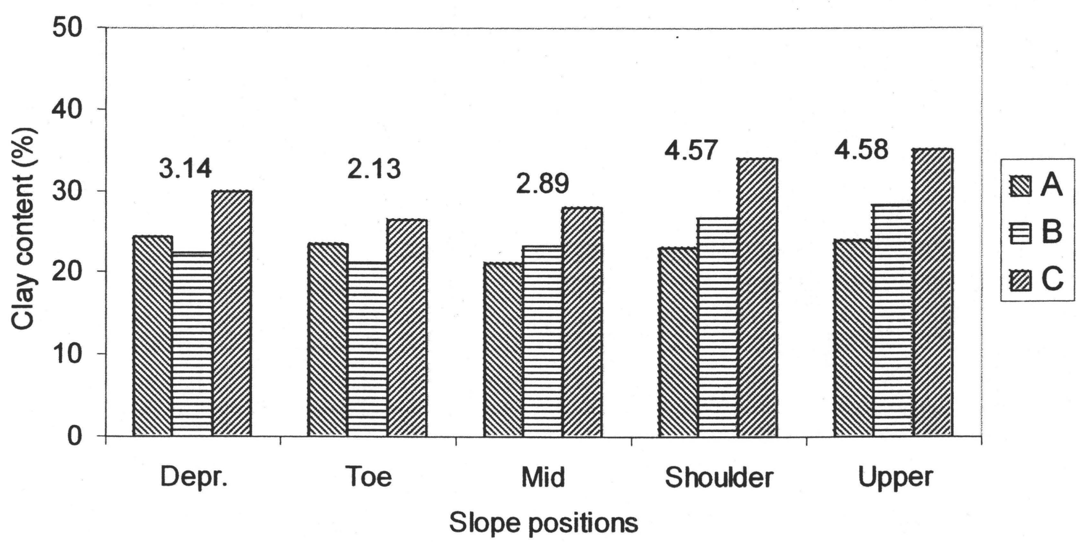


Fig. 4.7. Clay content on slope position of study transects (0-15 cm).
Note: The values shown on figure are the standard deviations based on data of three individual groups of bars.

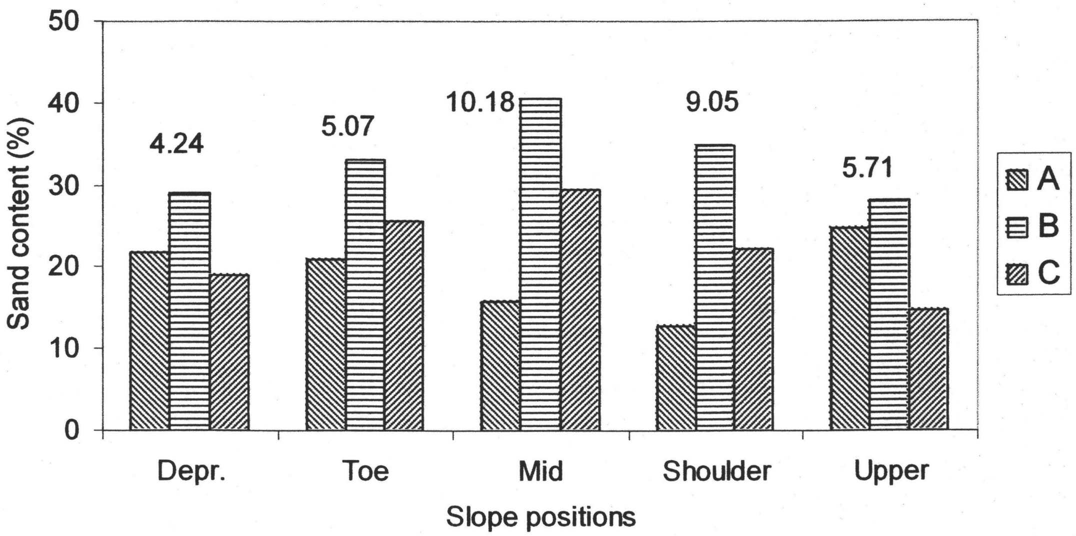


Fig. 4.8. Sand content on slope position of study transects (0-15 cm).
Note: The values shown on figure are the standard deviations based on data of three individual groups of bars.

For depth intervals, clay does not change much with depth on all the transects (Table 4.2). Sand content is consistently higher in depth profile at toe (21%) and upper position (23%) of transect A, all slope position of transect B (14 to 41%) and, toe (30%), middle (32%), and shoulder (19%) positions of transect C (Appendix B). Sand decreased with depth especially in the middle position of transect A (16, 6, and 5% for 0-15, 15-30, and 30-60 cm depth intervals, respectively) and the upper position of transect C (15, 6, and 6% for the respective depth intervals). A paired t test for separate depth intervals showed some significant differences ($\alpha = 0.1$) between transects for clay: A = B, A $\neq$ C, and B $\neq$ C, and for sand: A $\neq$ B, A = C, and B $\neq$ C, for the 0-15 cm interval while the other depth intervals (15-30 and 30-60) did not have significant differences between the study transects.

Table 4.2. Clay and Sand content of study transects.

	Depth (cm)	Transect A	Transect B	Transect C
Clay (%)	0-15	23(1.1)	24(2.6)	31(3.4)
	15-30	24(2.5)	25(4.9)	32(8.4)
	30-60	21(3.7)	26(4.7)	33(7.0)
Sand (%)	0-15	19(4.3)	33(4.5)	22(5.1)
	15-30	15(6.7)	30(3.5)	21(10.6)
	30-60	18(7.7)	25(8.0)	19(11.7)

Note: The values are average of five slope positions with standard deviations in parenthesis.

4.1.2. Soil Chemical Properties

4.1.2.1. Carbon

For both data sets (combined and individual slope positions) organic carbon content is highest for the depression slope positions and makes up the greatest proportion of total carbon (77% for A and, 100% for B and C) whereas inorganic carbon is highest on the upper slope positions (Table 4.3). Organic carbon remains in higher concentrations in the whole 0-60 cm depth at depression positions on all transects while for other positions, it decreases beyond the 0-15 cm depth interval. For the depression positions, organic carbon is unchanged throughout the soil profile on transect A, remains unchanged for the 0-30 cm depth intervals and then decreases in the 30-60 cm depth interval of B, and is highest in 15-30 cm of C. On other slope positions, organic carbon decreases beyond the 0-15 cm depth. Generally, inorganic carbon shows an increase with the increase in elevation and also with depth. A paired t-test performed for individual depth intervals has not revealed any significant difference ($\alpha = 0.1$) between all combinations of the three transects.

Table 4.3. Organic and Inorganic Carbon (% by mass) in the soil profile on different slope positions (Fall 1999, before manure application).

Slope	Transect A		Transect B		Transect C	
	Organic	**Inorganic**	**Organic**	**Inorganic**	**Organic**	**Inorganic**
For 0 – 15 cm, combined slope positions*						
Bottom	2.07	0.23	3.49	0.21	2.21	0.29
Middle	0.64	0.96	1.49	0.51	0.80	0.70
Top	0.93	0.37	0.66	1.04	0.91	1.59
For 0 – 15 cm, specific slope positions						
Depression	2.68	0.80	5.02	0.00	2.87	0.03
Toe	2.06	0.02	2.74	0.00	1.68	0.17
Middle	1.29	0.23	1.39	0.06	1.46	0.37
Shoulder	0.76	1.70	1.31	1.12	1.05	1.32
Upper	N/A	N/A	1.57	1.46	1.06	1.75
15 – 30 cm						
Depression	2.59	0.21	5.09	0.00	3.41	0.11
Toe	0.87	0.09	0.90	0.04	1.11	1.04
Middle	0.87	1.27	0.71	0.36	0.87	1.85
Shoulder	0.69	1.45	0.54	1.75	0.57	1.59
Upper	N/A	N/A	0.78	1.76	0.74	1.88
30 – 60 cm						
Depression	2.72	0.13	2.26	0.15	1.81	0.11
Toe	0.71	0.15	0.41	0.26	0.44	0.66
Middle	0.55	1.55	0.61	0.83	0.30	1.81
Shoulder	0.46	1.07	0.42	1.33	0.14	1.59
Upper	N/A	N/A	0.40	1.39	0.13	1.60

*Combined slope positions (bottom, middle, top) were the result of reducing six slope positions to three as described in chapter 3 (Fig.3.3).
Slope position transect: 1 Depression 2 Toe 3 Middle 4 Shoulder 5 Upper 6
Combined slope positions: 1+2(Bottom), 3+4(Middle), 5+6(Top)
N/A: not available

The data set from the combined slope positions shows that the concentration of total carbon on the three study transects varies in a similar pattern related to slope position with the bottom positions having the greatest concentrations (Fig. 4.9) for the 0-15 cm depth interval (Appendix C). Transect C shows a different pattern with the lowest organic C level at the middle position for the 0-15 cm depth interval. With regards to total carbon changing with depth, transect A shows little change in concentration from the 0-15 to the 30-60 cm depth intervals, while B and C show some decrease in total carbon content with depth, except for the top of transect B and the middle of transect C. Comparison between the transects shows that transect B (2.14%) has the highest overall carbon content due to the high values for the bottom and middle slope positions as compared to A(1.84%) and C(1.98%). Uniformity of total carbon in the soil profile at bottom slope position of transect A is because of no change in organic carbon with depth as it was shown for depression position in Table 4.3. Apart from some variability described above, the transects have no significant differences (paired t – test: $\alpha = 0.1$) for any form of carbon concentration between their respective slope positions at different depth intervals.

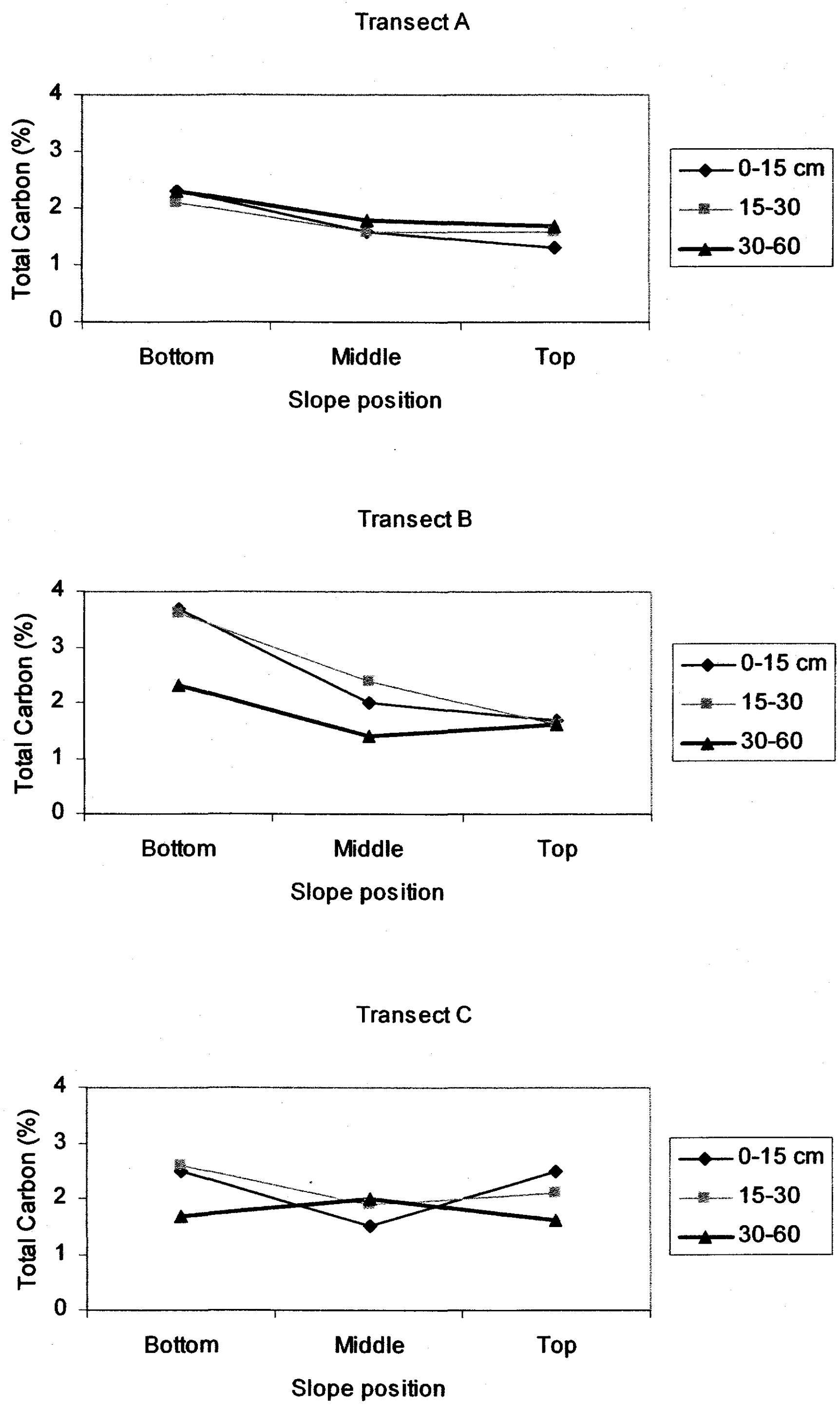


Fig. 4.9. Total carbon on study transects in soil samples taken in fall1999 before manure application.

4.1.2.2. Total Nitrogen

Similar to organic carbon, total nitrogen also has the highest contents in the bottom slope positions and in the surface depth interval (Fig. 4.10). All transects have a strong decline in nitrogen content from the bottom to the middle slope positions (e.g., from 0.35 to 0.18 % for transect B) but with little or no difference between the middle and the top positions (Fig. 4.10). Nitrogen concentration is highest in the 0-15 cm depth, showing a strong correlation [TN(%) = 0.084 OrgC(%) + 0.0585, $R^2 = 0.982$)] with Org C (Table 4.3). Total nitrogen decreases with depth on all slope positions. The exception is the bottom slope positions of transect A for the whole 0-60 cm depth and 0-30 cm depth of transects B and C, respectively where total nitrogen did not decrease with depth which is similar to organic carbon at these locations. Overall, a paired t-test did not result in any significant differences ($\alpha = 0.1$) between the transects.

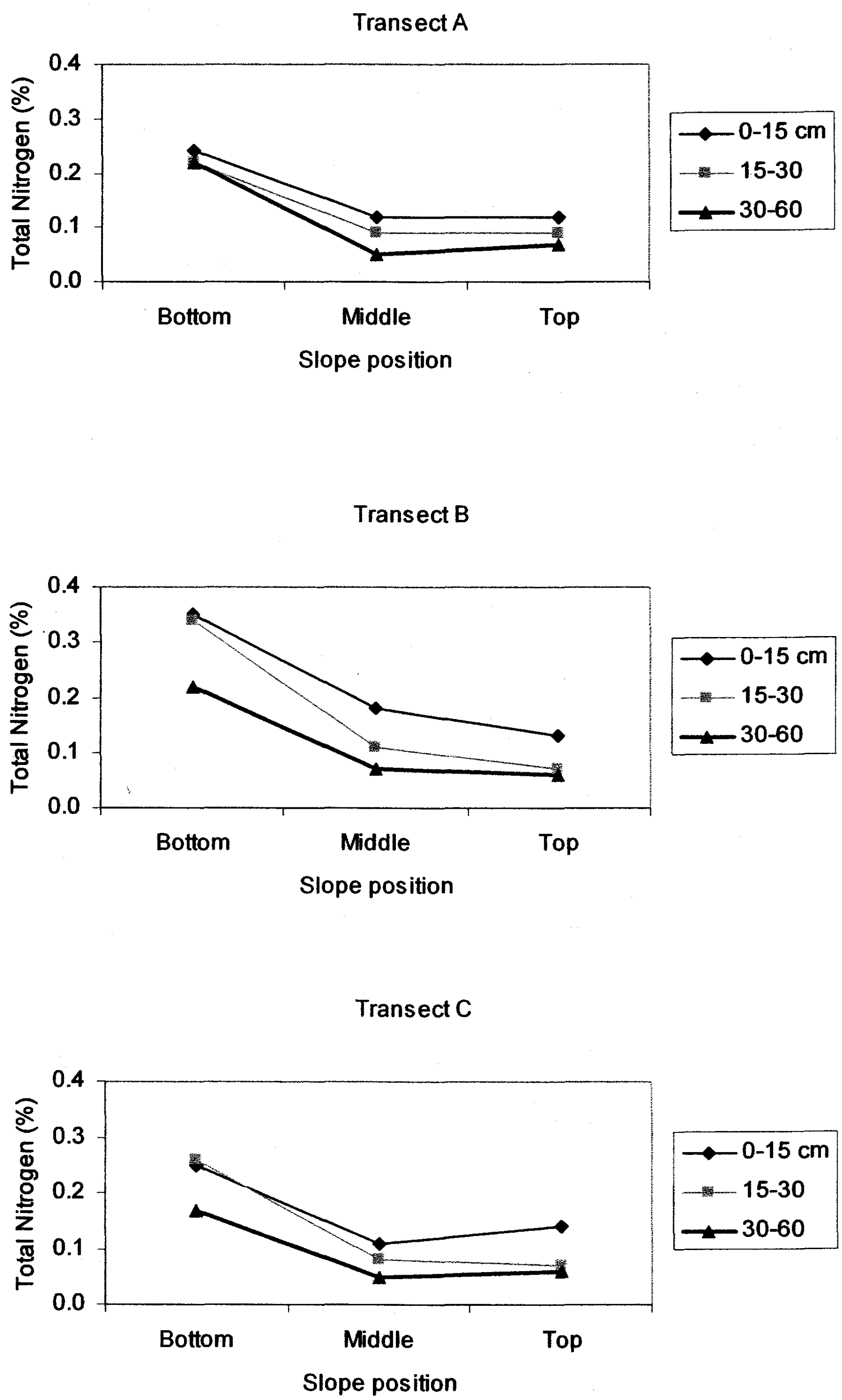


Fig. 4.10. Total nitrogen on study transects for soil samples taken in fall 1999 before manure application.

4.1.2.3. Total Phosphorus

Total phosphorus levels on the study transects also has the highest values in the bottom slope positions (with exception of the top position for transect C), however it shows little change with depth (Figure 4.11). For transect A, there is very little decrease in P concentration from bottom to top slope positions, but transect B has shown a sharp decrease. Transect C has high concentrations at bottom and top slope positions while low concentration at middle position especially in 0-15 cm depth interval showing an erosion problem on this steepest sample position. When transects are compared to each other there are no significant differences between them based on paired t-test.

4.1.2.4. Soil Cation Exchange Capacity

The general pattern of CEC for the study transects is similar to total C, N, and P; the highest values are found at bottom slope positions (Figure 4.12) with values of 20-23 meq/100g, whereas middle and top slope positions are in the range of 15 to 20 meq/100g (Appendix C). There are certain exceptions such as on transect A, where the top slope position has higher CEC (0-15 cm) relative to the middle (same as organic carbon). There are no significant differences ($\alpha = 0.1$) of CEC between the transects based on a paired t-test.

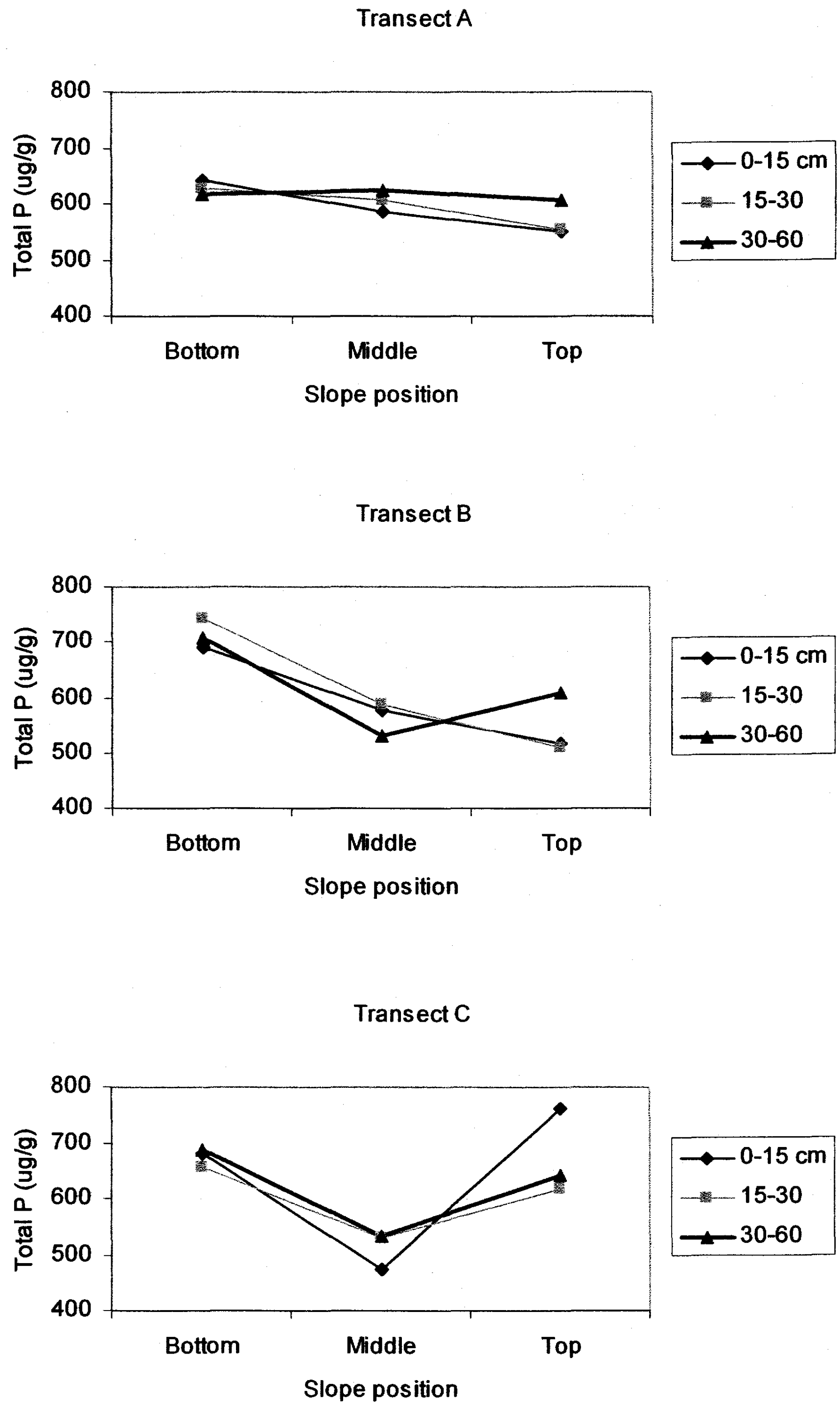
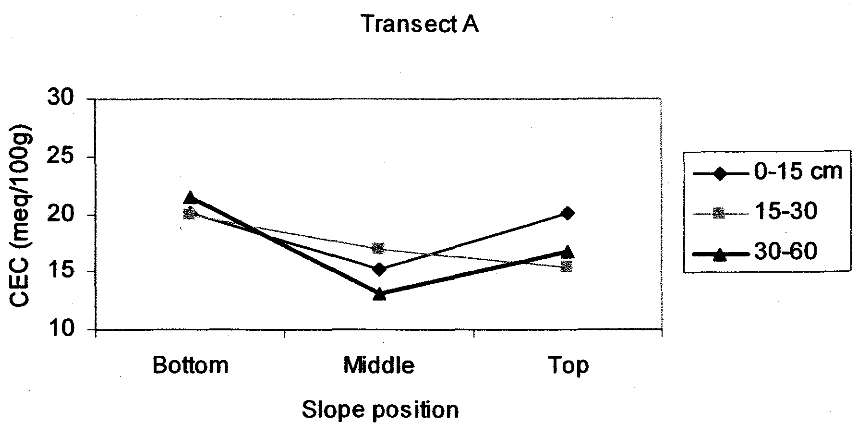
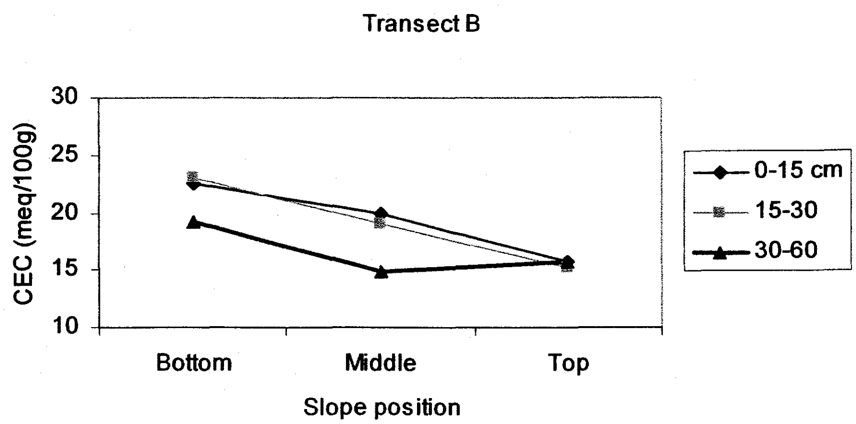


Fig. 4.11. Total Phosphorus on study transects in soil samples taken in fall 1999 before manure application.





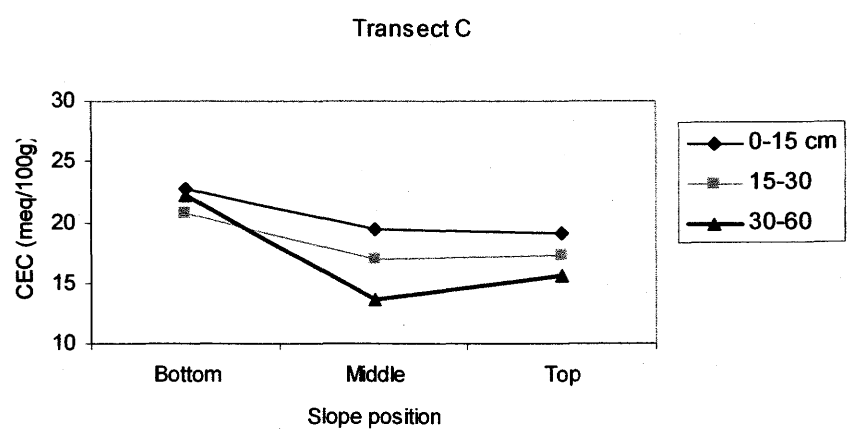


Fig. 4.12. Cation Exchange Capacity of study transects from soil samples taken in Fall 1999 before manure application.

4.1.3. Manure Chemistry

The manure was injected in October 1999 by a method of low disturbance injection using knife openers on the back of trucks operated by SANDS Ltd. at an average depth of 10 cm. The manure was applied at rates of 78.7 and 112.4 m^3/ha (7,000 and 10,000 gal/ac respectively) on watersheds B and C respectively. Four samples were collected and analyzed for total (acid digestion) and soluble (water extraction) ions (Table 4.4). The ion values of subsample 1 are higher than the other three samples all of which have similar values. The analysis shows a high concentration of water soluble ammonium nitrogen (1889 µg/g of NH_4-N), chloride (753 µg/g of Cl), and phosphorus (72 µg/g). The manure samples also contained high amounts of total N (2766 µg/g) and total P (573 µg/g).

Table 4.4. Chemistry of hog manure applied on study transects (µg/g).

Parameter	Method	Sample 1	2	3	4	Average
pH		7.61	7.88	7.89	7.88	7.82
NH_4-N	H_2O Extraction	2159	1714	1737	1948	1889
P	"	107	74	62	47	72
Cl	"	968	512	701	830	753
N	H_2SO_4 Digest	2900	2690	2703	2772	2766
P	"	1068	504	535	653	690
Ca	"	1141	448	499	679	692
Mg	"	357	213	207	233	253
K	"	1432	1468	1467	1477	1461
P(WAL)	"	886	421	441	542	573
Na	"	390	388	395	400	393
Fe	"	87	43	47	50	57
Zn	"	77	45	42	46	53
Mn	"	14.49	6.23	6.81	8.65	9.05
Cu	"	4.84	3.48	3.62	3.65	3.90
B	"	3.49	4.31	4.75	5.08	4.41
Pb	"	0.08	0.07	0.07	0.07	0.07
Cd	"	0.04	0.04	0.04	0.04	0.04

WAL: Western Agricultural Lab.

4.2. Study Treatments and Soil Saturated Paste Chemistry

The soil sample dates shown on all the charts in this section are abbreviated as follows:

F99b: Fall 1999 before manure application

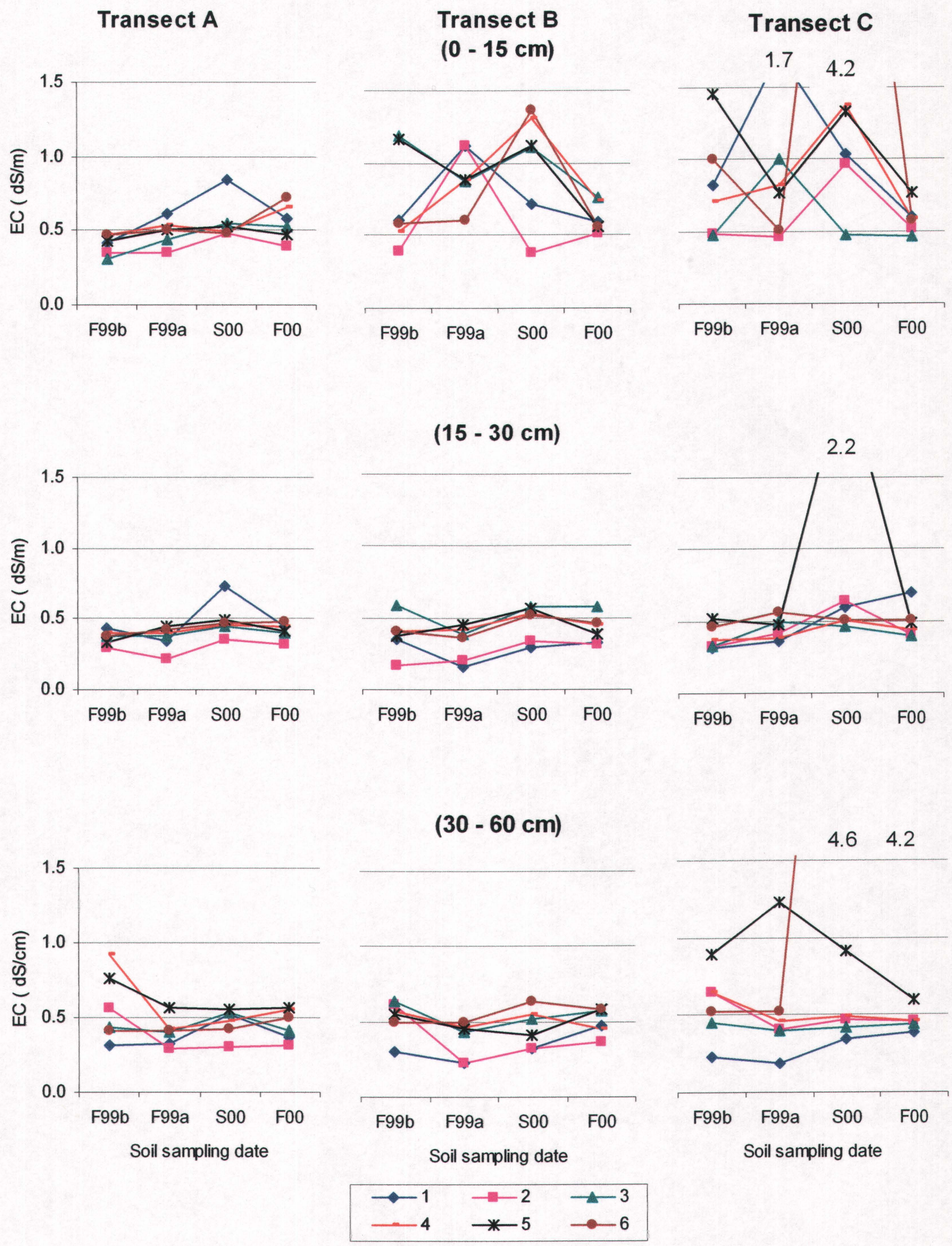
F99a: Fall 1999 after manure application

S00: Spring 2000

F00: Fall 2000

4.2.1. Soil Electrical Conductivity and pH

Electrical conductivity (EC) of soil saturated paste extracts for the surface 15 cm have similar low background (F99b) values for transect A (0.31 – 0.47 dS/m) but high and variable values for B (0.39 – 1.19 dS/m) and C (0.47 – 1.46 dS/m) (Figure 4.13, Appendix D1). For the 15-30 cm depth interval, the background EC values are similar to each other for all transects and for 30-60 cm depth interval, the transects differ from each other with low variability. The EC averages (of slope positions) increase in value for the 0-15 cm depth on all the transects from Fall 1999, before manure application, to Spring 2000 and then there is a decrease in Fall 2000 (Table 4.5). This increase is higher on transects B and C with manure application but it can not be clearly attributed to manure application because of the high variability in EC for these two transects, especially as their background values were high and variable.



Slope position legend (Fig.3.3): Bottom (1,2), Middle (3,4), and Top (5,6)

Fig. 4.13. Electrical conductivity of saturated paste extracts of soil samples.

Table 4.5. Average EC and pH values of saturated paste extracts.

Depth (cm)	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
Electrical conductivity (dS/m)					
0-15	A	0.41 by (0.1)	0.49 bxy (0.1)	0.56 ax (0.1)	0.56 ax (0.1)
	B	0.74 ax (0.3)	0.91 ax (0.1)	1.00 ax (0.3)	0.62 ax (0.1)
	C	0.83 ax (0.3)	0.88 ax (0.4)	1.58 ax (1.2)	0.59 ax (0.1)
15-30	A	0.37 ay (0.0)	0.37 aby (0.1)	0.49 ax (0.1)	0.42 axy(0.1)
	B	0.38 ax (0.1)	0.33 bx (0.1)	0.47 ax (0.1)	0.42 ax (0.1)
	C	0.39 ax (0.1)	0.45 ax (0.1)	0.83 ax (0.6)	0.49 ax (0.1)
30-60	A	0.57 ax (0.2)	0.40 ax (0.1)	0.47 ax (0.1)	0.45 ax (0.1)
	B	0.53 ax (0.1)	0.38 ax (0.1)	0.46 ax (0.1)	0.50 ax (0.1)
	C	0.57 ax (0.2)	0.53 ax (0.3)	1.21 ax (1.5)	1.08 ax (1.4)
pH values					
0-15	A	8.2 ax (0.1)	7.9 by (0.3)	7.3 az (0.4)	8.0 bxy (0.1)
	B	8.0 ax (0.3)	8.1 bx (0.6)	6.9 by (0.2)	7.8 bx (0.3)
	C	7.7 by (0.2)	8.5 aw (0.2)	7.3 az (0.3)	8.2 ax (0.3)
15-30	A	8.2 ax (0.1)	8.2 ax (0.3)	7.2 ay (0.5)	8.0 ax (0.1)
	B	8.0 abx (0.2)	8.3 ax (0.6)	7.2 ay (0.4)	7.8 ax (0.3)
	C	7.8 byz (0.3)	8.5 ax (0.3)	7.5 az (0.4)	8.0 ay (0.3)
30-60	A	7.2 ay (0.3)	8.2 ax (0.3)	7.5 ay (0.6)	8.0 ax (0.2)
	B	7.4 ayz (0.3)	8.3 ax (0.5)	7.5 az (0.6)	8.1 axy (0.2)
	C	7.5 ay (0.3)	8.5 ax (0.5)	7.2 ay (0.4)	8.3 ax (0.4)

Note: Each value is an average of 6 slope positions of respective transects with standard deviation in bracket.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'w, x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

Despite some average EC values being quite different (e.g. transect C for the 30-60 cm depth, between the sampling dates of Fall 1999a and Spring 2000, Table 4.5) the results of the least significant difference (LSD) analysis ($\alpha = 0.1$) by SAS (2001, GLM procedure) do not show any significant difference because of the high variability of EC values. Actually, this variability is induced by a few extremely high values which are reported close to their respective points on Figure 4.13.

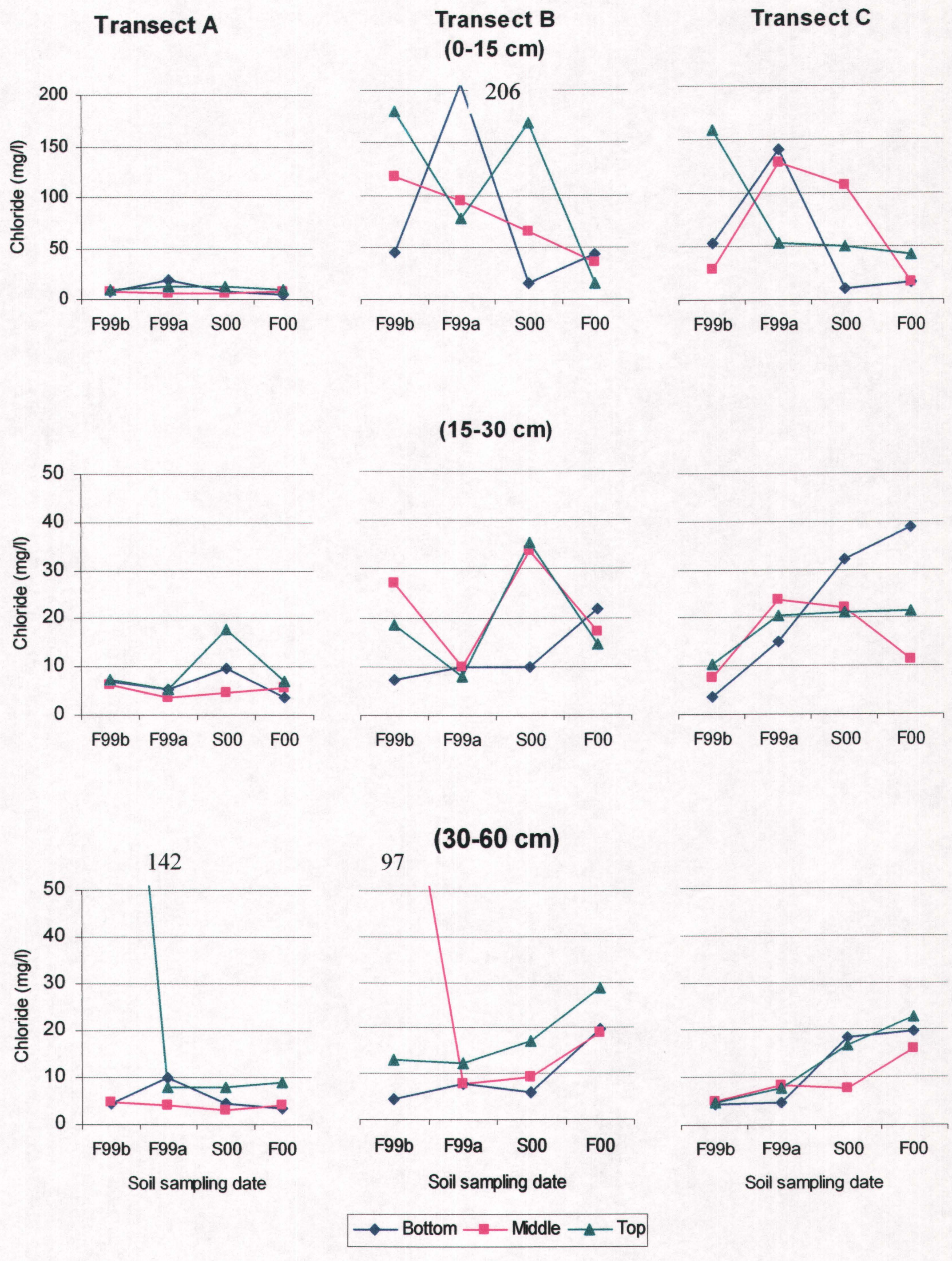
Average pH values range from about 6.9 to 8.5 on different dates, slope positions and depth intervals (Table 4.5) with the lowest measured value being 6.3 and the greatest being 9.0 (Appendix D2). Generally, fall 1999a has higher pH values, e.g., for 0-15 cm depth, the pH values for transect A, B, and C are 7.9, 8.1 and 8.5, respectively which reduced in spring 2000 having values 7.3, 6.9 and 7.3, respectively. These dates (fall 1999a and spring 2000) also have higher variation on slope positions depicted by higher standard deviations (Table 4.5) as compared to fall 1999b and fall 2000. LSD analysis has shown that there are significant differences among (all transects for same date) and within (one transect for different dates) transects especially in the 0-15 cm depth over the study period (Table 4.5). The significant differences are found on all the transects and may be attributed to the general hydrologic cycle instead of the study treatments.

4.2.2. Concentration of Dissolved Ions

The following subsections provide results of dissolved ion concentrations of the same saturated paste extracts for the EC and pH data of the previous section. The same sampling seasons are used but the slope positions have been combined from six to three in order to reduce sample costs (Section 3.2.3), and each data point represents the result of a single sample run in an ion chromatograph.

4.2.2.1. Chloride (Cl^-)

Transect A has overall low chloride concentrations as compared to transects B and C, especially the 0-15 cm interval which had a before manure application (F99b) an average of 8.5 mg/l as compared to 114 and 80 mg/l respectively for transects B and C (Figure 4.14, Table 4.6 and Appendix E1). Moreover, chloride concentrations at transects B and C show a greater variation in values between slope positions for the 0 to 30 cm depth intervals than that of transect A. For the 15-30 cm depth, transects B and C show a continuous increase of chloride content with time at the bottom slope positions, but remained varying at other positions. The deeper depth interval (30-60 cm) has a lower range of values between seasons than the shallower depths. For the 30-60 cm depth interval only two points were greater than 30 mg/l, one on transect A, and another on transect B. However, the chloride contents in this depth (30-60 cm) for transects B and C generally have shown a successive increase on all slope positions for the dates following manure application, whereas there were no such increases for transect A. Because of varying background concentrations (F99b), it is difficult to differentiate the impact of low and high manure application rates on transect B and C from their Cl concentration levels. By LSD analysis ($\alpha < 0.1$) significant differences are found between transects for a similar date (fall 1999a) and, between different dates for transect C, at 15-30 and 30-60 cm depth intervals (Table 4.6). Similar to EC, there are some apparently high differences in Cl concentration among (e.g., on fall 1999b sample date) and within transects (e.g., for transects B and C: 0-15 cm), but the LSD analysis has shown these differences (both for among transects on same date and for a transect on different dates) as non significant due to high variability.



Note: Charts are on different scales.

Fig. 4.14. Chloride ions in soil saturated paste extracts on study transects.

Table 4.6. Average chloride content of saturated paste extracts (mg/l)

Depth (cm)	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	8 ax (0)	12 bx (5)	8 ax (2)	7 ax (1)
	B	114 ax (54)	125 ax (57)	83 ax (64)	31 ax (11)
	C	80 ax (56)	107 ax (39)	55 ax (40)	25 ax (12)
15-30	A	6 ax (0)	4 cx (0)	10 ax (5)	5 ax (1)
	B	17 ax (8)	9 bx (1)	26 ax (11)	17 ax (2)
	C	7 ay (2)	19 axy (3)	25 ax (5)	23 ax (11)
30-60	A	50 ax (65)	7 ax (2)	5 ax (2)	5 bx (2)
	B	38 ax (42)	9 ax (2)	10 ax (4)	22 ax (4)
	C	7 ay (0)	6 ay (1)	14 ax (4)	18 ax (2)

Note: Each value is an average of 3 slope positions of respective transects with standard deviations in brackets. Standard deviation < 1 is reported as 0.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

4.2.2.2. Total Inorganic N ($NO_2 - N$ plus $NO_3 - N$ plus $NH_4 - N$)

It is recommended to incorporate observed soil levels of ammonium, nitrite and nitrate to report as total inorganic nitrogen (Dr. J. Schoenau 2004, personal communication). The background (fall 1999b) concentration of total inorganic nitrogen (N) is similar on all slope positions and depth intervals of the study transects (Fig. 4.15). After manure application the inorganic nitrogen increased on fall 1999a and spring 2000 dates, and returned back to background levels on fall 2000 in 0-15 cm depth. The highest N concentration levels were observed on transects B and C for the 0-15 cm depth. The bottom slope position of transect C has also shown some increase in the 15-30 and 30-60 cm depths on study end date (fall 2000).

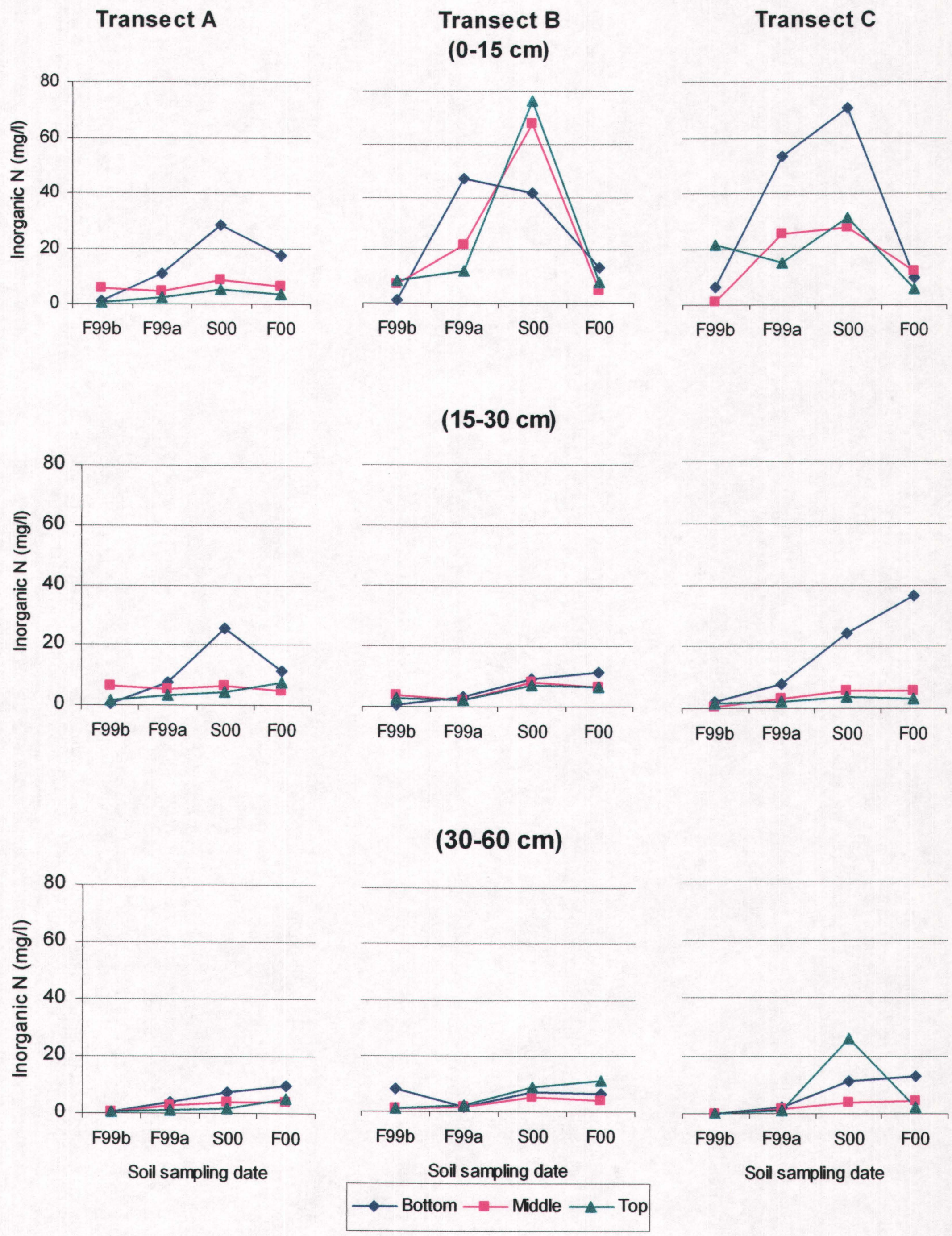


Fig. 4.15. Inorganic N ($NO_2 - N$ plus $NO_3 - N$ plus $NH_4 - N$) in soil saturated paste extracts on study transects.

Comparison by LSD analysis has shown that there is a significant difference of inorganic N concentration in the 0-15 cm depth between transects in spring 2000, with the manure treated transects (B and C) being significantly different from A (Table 4.7). Significant differences are also observed within transects B and C with respect to samples dates only in the 0-15 cm depth. Caution is required while seeing LSD designators between dates in 30-60 cm depth where at $\alpha < 0.1$, transect A is showing significant differences for having $P = 0.063$ whereas B and C are showing non significant differences due to having same $P = 0.106$ for both of them which is little higher than the selected significance level. As indicated in previous sections, the variability in replicate values for transects B and C indicated by their higher standard deviations result in higher LSD probabilities leading to show non significant differences.

A relatively high amount of nitrite ions occurred in extract samples on chromatograph runs (Fig. 4.16, Appendix E2). This could be due to the longer holding time (10 days) of saturated paste extract samples than recommended (2 days) by Dionex (2000). This concentration ranged from 80 mg/l to less than 5 mg/l on different transects. For all transects (including the control, transect A) at all depths there is a general increase in nitrite content after the date that manure had been added, with the highest concentrations occurring for the spring 2000 date.

Table 4.7. Total Inorganic N ($NO_2 - N$ plus $NO_3 - N$ plus $NH_4 - N$) content of saturated paste extracts (mg/l)

Depth	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	2.5 ax (2.3)	6.1 ax (3.6)	14.1 bx (10.3)	9.2 ax (6.0)
	B	5.6 az (3.1)	26.9 ay (14.7)	61.8 ax (14.8)	8.7 ayz (3.8)
	C	9.7 ay (8.6)	31.3 axy (16.0)	43.2 ax (19.3)	9.3 ay (2.5)
15-30	A	3.0 ax (2.8)	5.5 ax (1.8)	12.3 ax (9.4)	8.1 ax (2.7)
	B	2.3 ay (1.2)	2.5 ay (0.6)	8.2 ax (0.9)	8.2 ax (2.2)
	C	1.4 ax (0.7)	4.4 ax (2.6)	11.4 ax (9.4)	15.0 ax (15.2)
30-60	A	0.6 az (0.1)	2.7 ayz (1.1)	4.5 axy (2.4)	6.4 ax (2.5)
	B	3.5 ax (3.3)	2.0 ax (0.5)	7.1 ax (1.6)	7.1 ax (2.9)
	C	0.1 ax (0.1)	1.8 ax (0.3)	13.8 ax (9.0)	6.7 ax (4.6)

Note: Each value is an average of 3 slope positions within their respective transect with the standard deviation in brackets.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

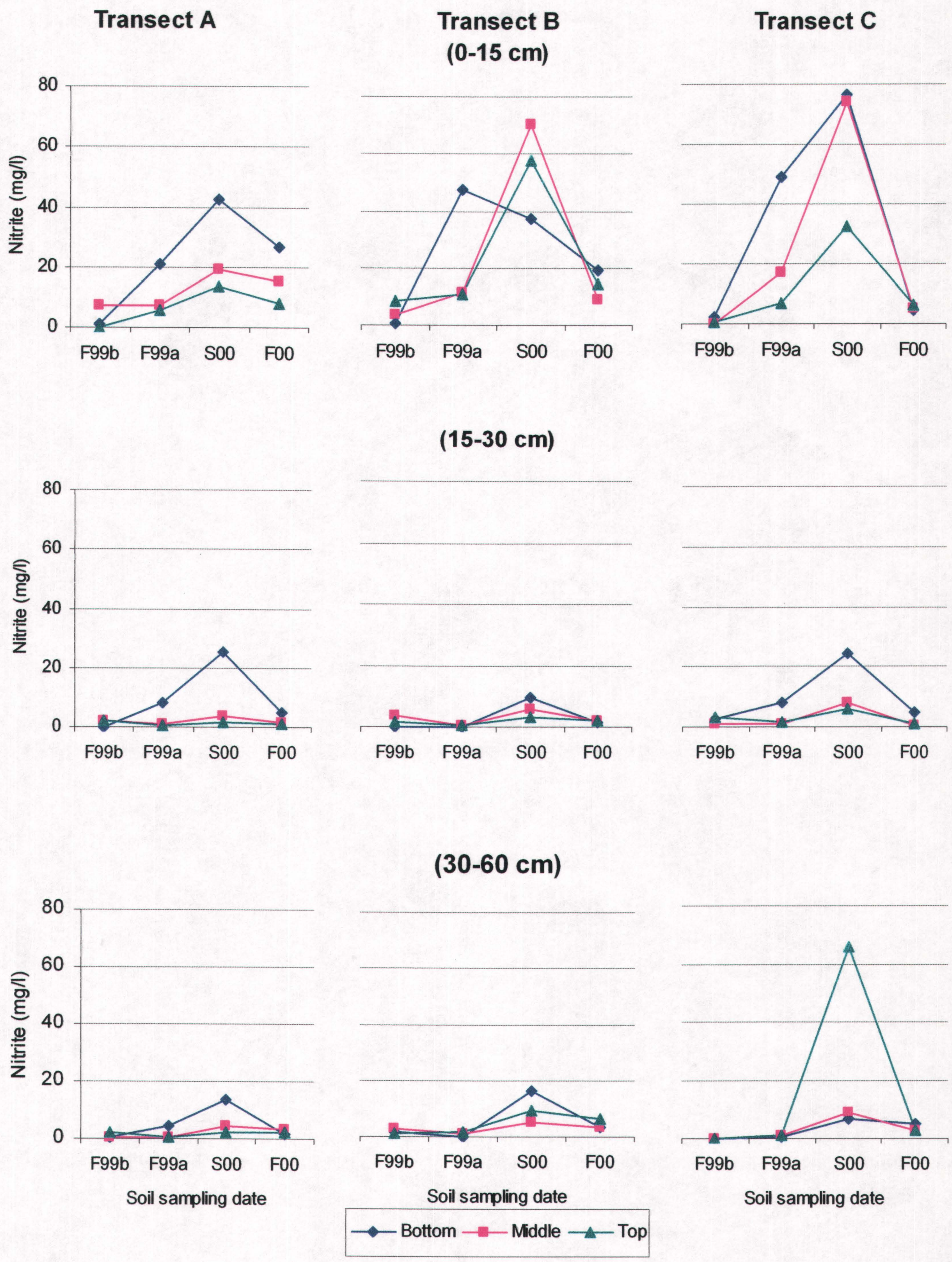
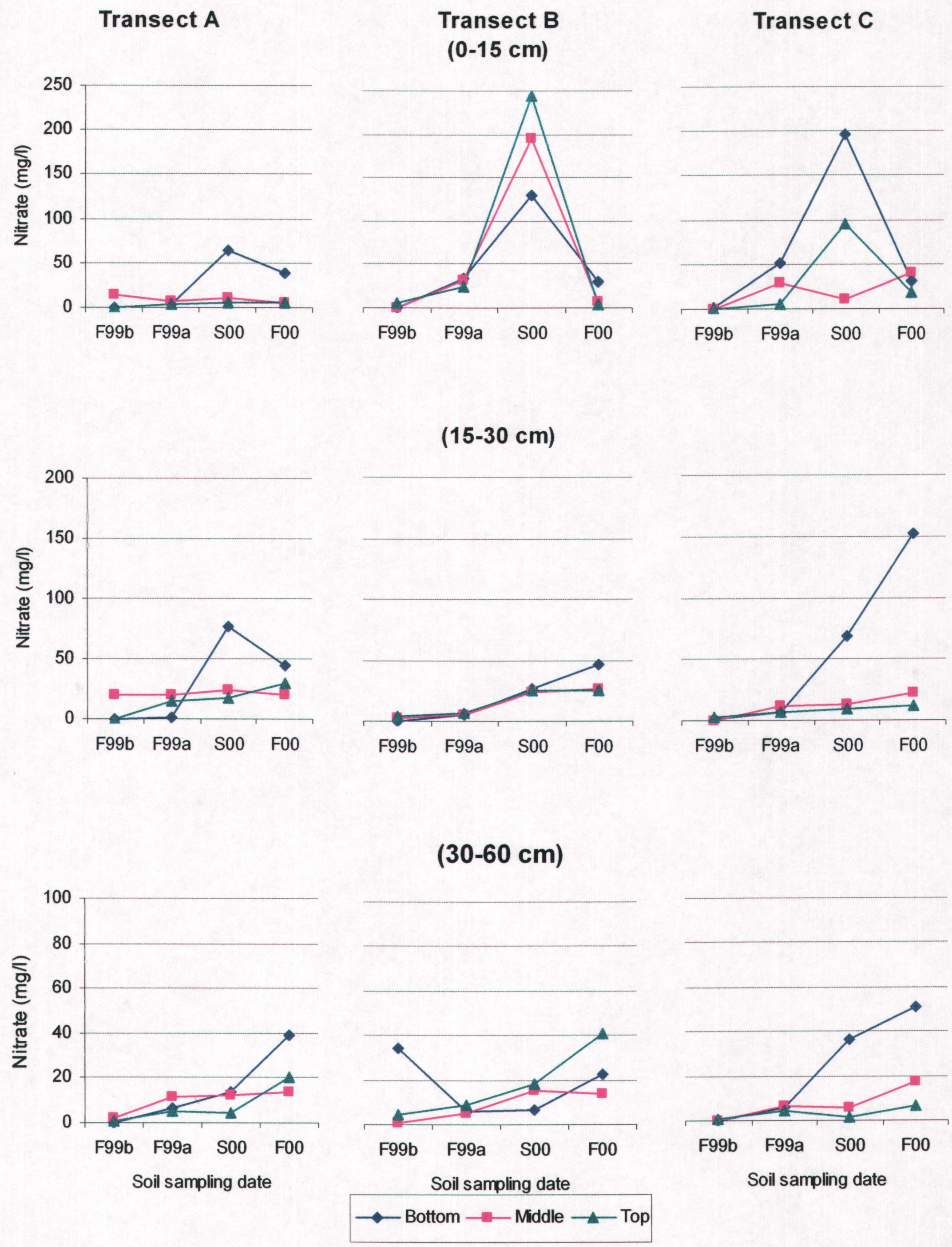


Fig. 4.16. Nitrite (NO_2) ions in soil saturated paste extracts on study transects.

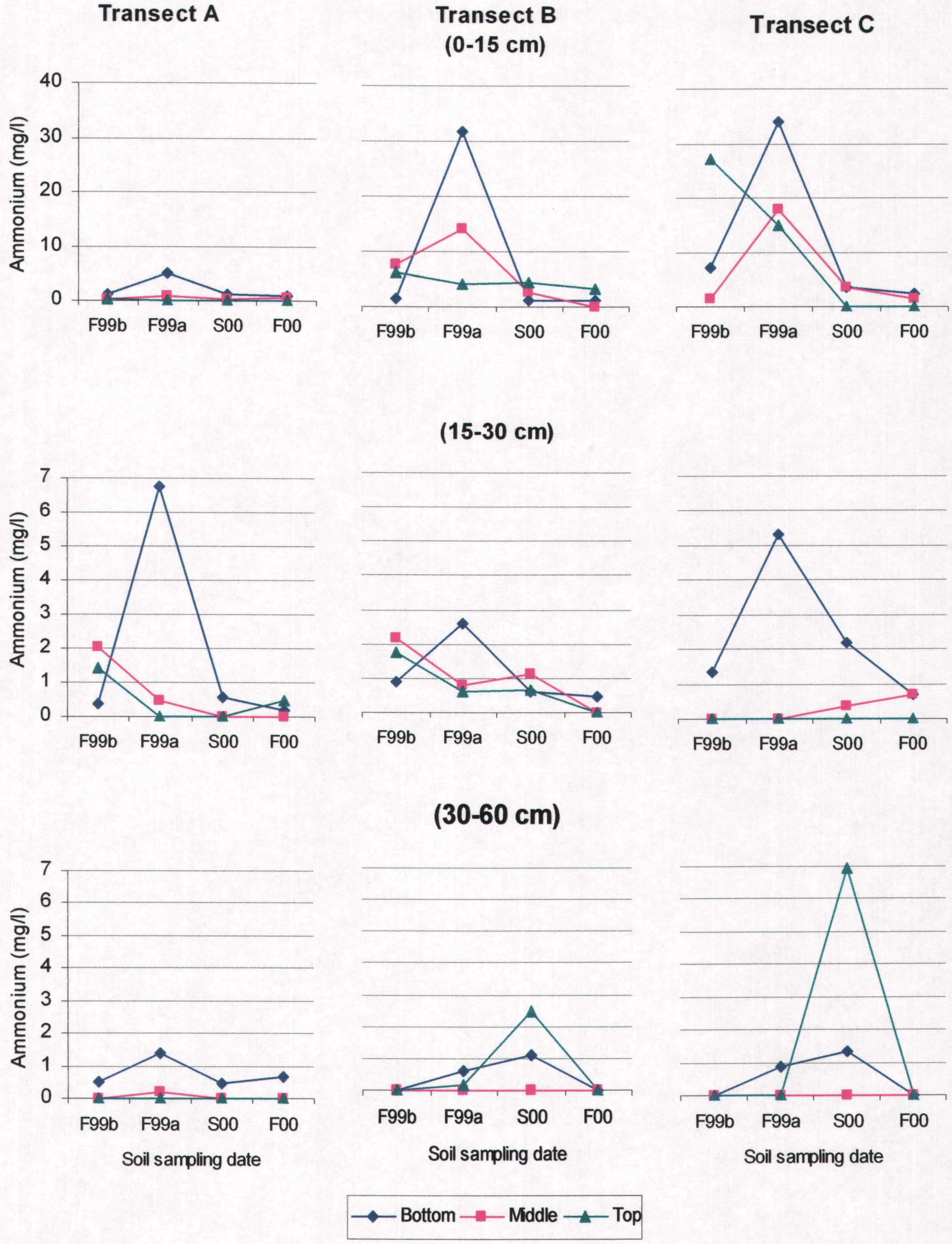
Nitrate ion concentrations (Figure 4.17 and Appendix E3) have values ranging from less than 0.1 to 245 mg/l with the lowest values occurring for fall of 1999 before manure application. Immediately following manure application there was a definite increase in nitrate for the 0-15 cm depth interval for transects receiving manure. This increase continued until spring 2000 (S00) when the manured transects increased to the range of 95 to 245 mg/l. Although transect A also had higher nitrate values (increased from an average of 5 to 26 mg/l) in spring 2000 the increase was much less than that in the manured transects (Fig. 4.17). By fall 2000 the surface interval for all transects had decreased to values near that of background values. For the deeper depth intervals there appeared to be a trend of increasing nitrate contents with time for the manured transects, especially for transect C for the bottom slope position (Figure 4.17). It is noted that transect A also showed an increase in nitrate value for the bottom slope position at the 30-60 cm depth.

For ammonium, values ranged between 0 and 34 mg/l with the higher values occurring in the 0-15 cm depth interval for transects B and C immediately following manure application (F99a) (Fig. 4.18 and Appendix E4). By spring 2000 (S00) the high values for transect B and C had dropped to similar levels before manure application. For the deeper depth intervals all values were below 7.6 mg/l with most below 2 mg/l. For all depth intervals and transects the bottom slope positions had higher ammonium values following manure application (F99b). For 15-30 cm, ammonium peaks are prominent on bottom slope position and only for the sampling date after manure application. The 30-60 cm depth interval had distinct peaks at the top and bottom slope positions on transects B and C in spring 2000.



Note: Charts are on different scales.

Fig. 4.17. Nitrate (NO_3) ions in soil saturated paste extracts on study transects.



Note: Charts are on different scales.

Fig. 4.18. Ammonium (NH_4) ions in soil saturated paste extracts on study transects.

4.2.2.3. Sulphate (SO_4^{2-})

A general overview of sulphate data (Fig. 4.19, Table 4.8) shows that the sulphate concentration on all the transects and depth profiles did not seem to show any fluctuation with that of fertilizer treatment and time. The top slope position on transect C is showing extremely high concentrations of sulphates in all the depth intervals. This also occurred with the EC values (Figure 4.13). The data has high variability, as evident from the standard deviations, likely due to natural soil variability. A LSD analysis for differences between transects did not result in any significant differences despite the much larger average for C. This can be attributed to the high standard deviation found in transect C. Between different dates, transect A (0-15 and 15-30 cm depths) and transect B (30-60 cm) have shown significant differences perhaps due to overall less variability.

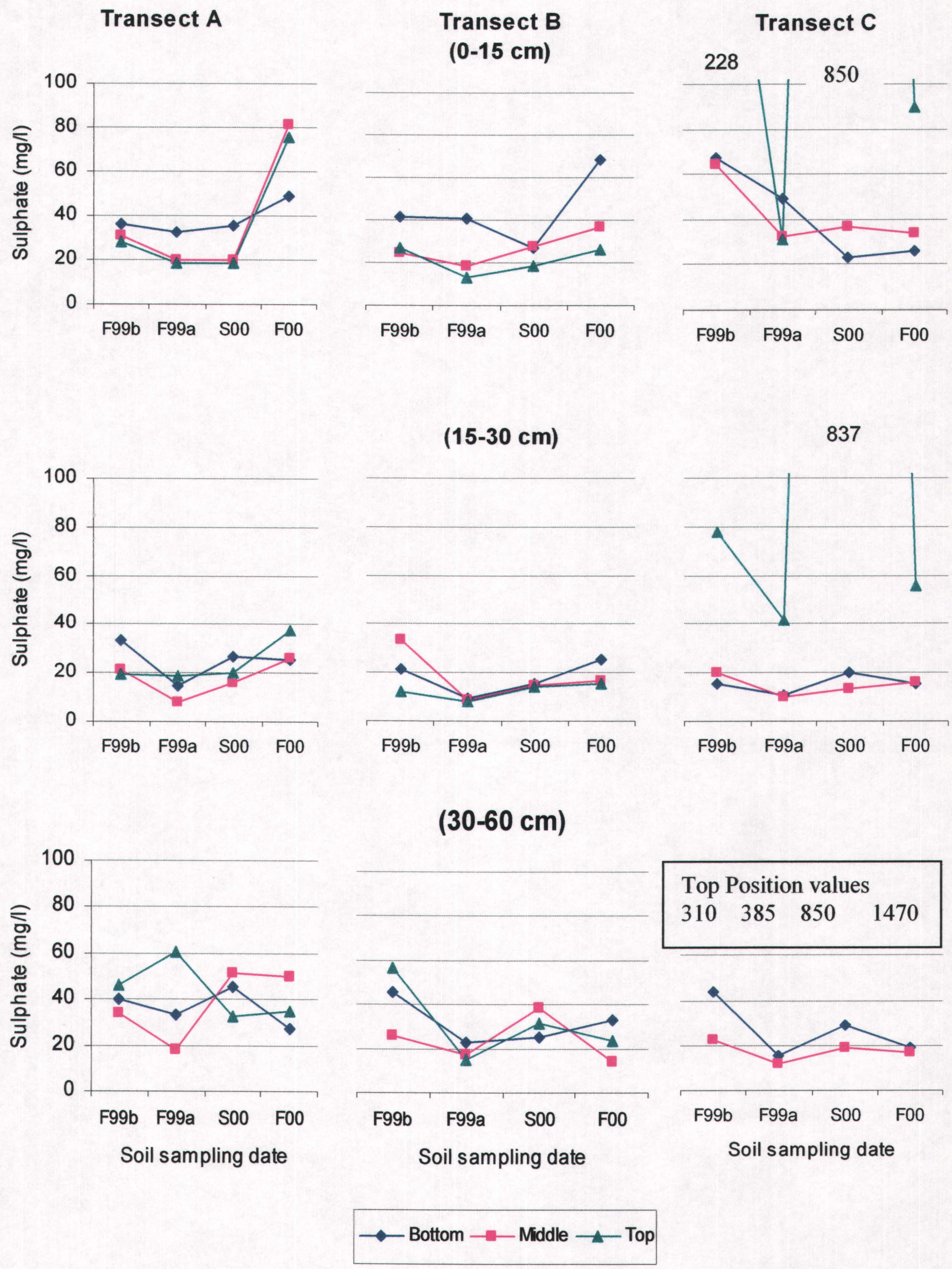


Fig. 4.19. Sulphate ions in soil saturated paste extracts on study transects.

Table 4.8. Sulphate content of saturated paste extracts (mg/l)

Depth	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	32 ay (3)	24 ay (6)	25 ay (8)	69 ax (14)
	B	31 ax (7)	24 ax (12)	24 ax (4)	44 ax (18)
	C	120 ax (76)	38 ax (8)	303 ax (387)	50 ax (29)
15-30	A	25 ax (6)	14 ay (4)	21 axy (5)	30 ax (6)
	B	23 ax (9)	9 ax (1)	15 ax (1)	19 ax (5)
	C	38 ax (28)	21 ax (15)	290 ax (387)	29 ax (19)
30-60	A	40 ax (5)	38 ax (18)	43 ax (8)	37 ax (10)
	B	43 ax (13)	18 ay (3)	32 axy (5)	24 ay (8)
	C	126 ax(131)	137 ax (175)	299 ax (389)	502 ax (684)

Note: Each value is an average of 3 slope positions of the respective transect with standard deviation in brackets.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

4.2.2.4. Phosphate (PO_4^{3-})

On most of the sample dates and locations, phosphate remained below detection limit (< 0.1 mg/l). Concentrations above detection limit were primarily found at bottom slope positions of transects B and C (Table 4.9). Although, the detection limit of the chromatograph is 0.1 mg/l it seems that the chromatograph was ineffective in detecting values in the range of 0.1 to 1.0 mg/l as the only values reported were > 1.0 mg/l.

Table 4.9. Phosphate content of saturated paste extracts (mg/l) for 0-15 cm depth.

Transect and slope position	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
Transect B				
Bottom	2.70	<0.1	<0.1	1.06
Transect C				
Bottom	3.97	13.00	5.06	4.32
Top	1.63	<0.1	<0.1	<0.1

Note; all transects and slope positions were analyzed like other anions but only those samples that had values above the detection limit of 0.1 are shown.

4.2.2.5. Calcium (Ca^{2+})

Calcium on all the transects decreases with depth in the soil profile (Figure 4.20). Calcium values range from 9 to 271 mg/l, with most of the values around 70 mg/l (Appendix E5). The manure was high in calcium (692 mg/l, Table 4.4) and there are some significant differences on transects B and C in the 0-15 cm depth after manure application (fall 1999a) (Table 4.10). However, this increase had occurred on all the transects in spring 2000 sample date (S00) and caution is required to interpret the average values in comparison to the individual values (Appendix E6) which vary on slope positions. As with EC and sulphate, transect C in the 30-60 cm depth had some very high values in the upper slope positions.

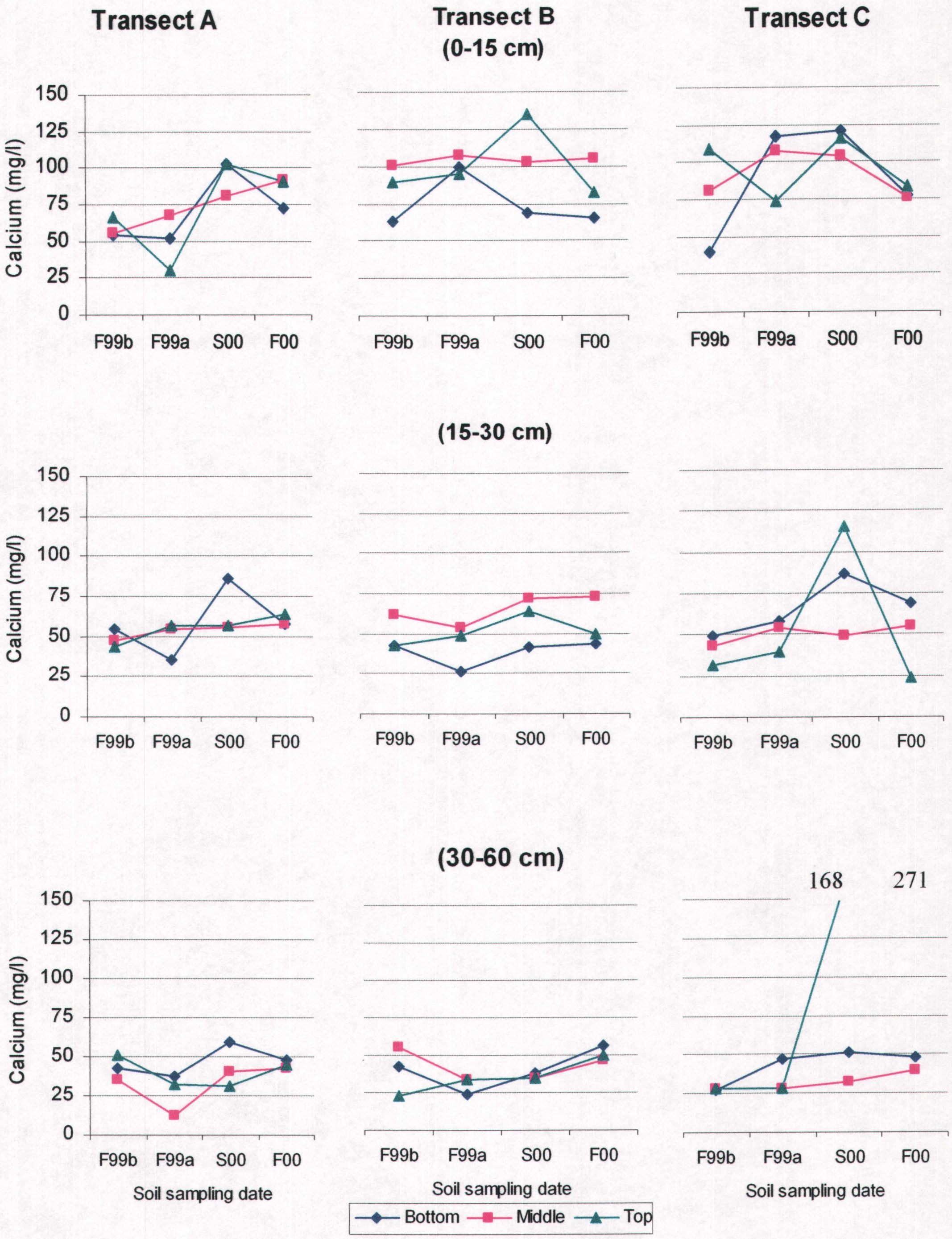


Fig. 4.20. Calcium ions in soil saturated paste extracts on study transects.

Table 4.10. Calcium content of saturated paste extracts (mg/l).

Depth	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	59 az (6)	50 bz (15)	96 ax (10)	85 ay (9)
	B	84 ax (16)	101 ax (5)	102 ax (27)	84 ax (16)
	C	76 ay (28)	100 axy (19)	113 ax (7)	79 ay (3)
15-30	A	49 ay (5)	49 ay (10)	66 ax (14)	60 axy (3)
	B	49 ax (9)	43 ax (12)	60 ax (13)	55 ax (13)
	C	42 ax (7)	51 ax (8)	84 ax (27)	49 ax (19)
30-60	A	43 ax (7)	28 ax (11)	44 ax (11)	45 ax (2)
	B	40 ax (14)	30 ax (4)	36 ax (1)	51 ax (4)
	C	28 ax (1)	35 ax (9)	84 ax (60)	120 ax (107)

Note: Each value is an average of 3 slope positions of respective transects with standard deviation in bracket.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

4.2.2.6. Magnesium (Mg^{2+})

The magnesium concentrations range from that of 2.7 to 215 mg/l with the lowest average value on transect A and the highest on C (Figure 4.21, Table 4.11). The top slope position of transect C has the highest and the most variable readings both with time and depth (Appendix E6). All bottom slope positions and depths (with exception of transects B and C 0-15 cm depth interval) had an increase in magnesium contents for after the manure application (F99a) and spring 2000 (S00). Figure 4.21 shows a higher increase of Mg on manure treatments as compared to the control at the bottom positions (15-30 and 30-60 cm depth) especially at the end date (Fall 2000). These changes were found to be non significant by LSD analysis at $\alpha = 0.1$ (Table 4.11).

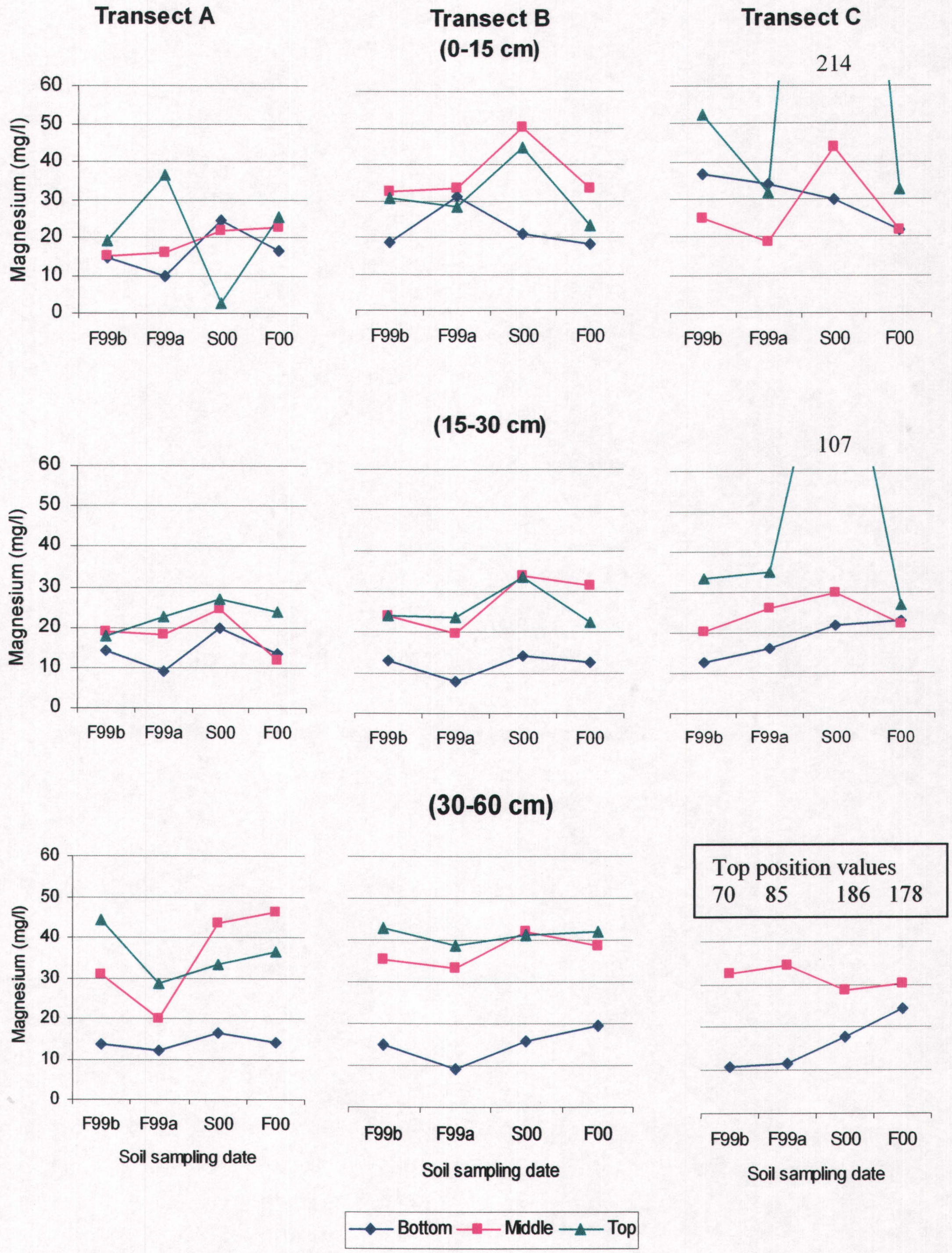


Fig. 4.21. Magnesium ions in soil saturated paste extracts on study transects.

Table 4.11. Magnesium content of saturated paste extracts (mg/l).

Depth	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	16 ax (2)	21 ax (11)	16 ax (10)	22 ax (4)
	B	27 ax (6)	31 ax (2)	39 ax (13)	25 ax (6)
	C	38 ax (11)	28 ax (7)	96 ax (84)	25 ax (5)
15-30	A	17 ax (2)	17 ax (6)	24 ax (3)	17 ax (5)
	B	20 ax (5)	17 ax (7)	27 ax (9)	22 ax (8)
	C	22 ax (8)	26 ax (8)	53 ax (38)	24 ax (2)
30-60	A	30 ax (13)	20 ax (7)	31 ax (11)	32 ax (13)
	B	31 ax (12)	27 ax (13)	33 ax (12)	33 ax (10)
	C	38 ax (25)	44 ax (31)	77 ax (77)	78 ax (71)

Note: Each value is an average of 3 slope positions of their respective transects with standard deviation in brackets.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

4.2.2.7. Potassium (K^+)

Overall the transect averages have dissolved potassium contents of about 10 mg/l with occasional high values on transect C (Figure 4.22, Table 4.12). Potassium concentrations shows greater variability for the 0-15 cm depth interval than other depth intervals with the exception of less variability for middle slope position (Appendix E7). According to agronomic practices, no potassium fertilizer has been applied on transect A while transect B and C has received potassium in manure application. There appears to be no consistent pattern of potassium concentration which may be related to the manure concentrations which were generally about 1460 mg/l (Table 4.4). LSD analysis showed only one significant difference among dates and this occurred at the 15-30 cm depth for transect C (Table 4.12).

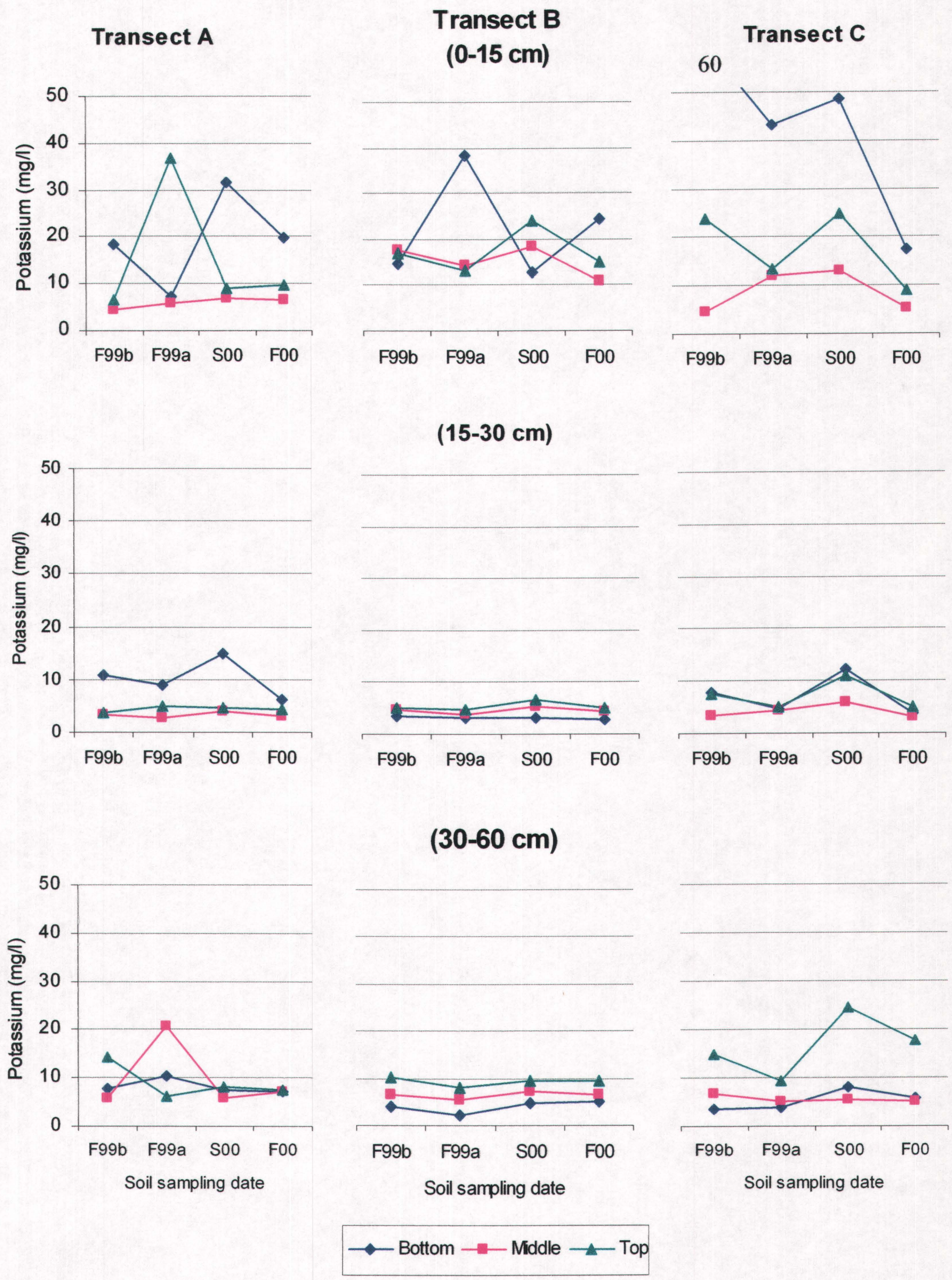


Fig. 4.22. Potassium ions in soil saturated paste extracts on study transects.

Table 4.12. Potassium content of saturated paste extracts (mg/l).

Depth	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	10 ax (6)	17 ax (14)	16 ax (11)	12 ax (6)
	B	16 ax (1)	22 ax (12)	18 ax (5)	17 ax (6)
	C	30 ax (23)	23 ax (14)	29 ax (15)	11 ax (5)
15-30	A	6 ax (3)	6 ax (2)	8 ax (5)	5 ax (1)
	B	4 ax (1)	4 ax (1)	5 ax (1)	4 ax (1)
	C	6 ay (2)	5 ay (0)	10 ax (3)	4 ay (1)
30-60	A	9 ax (4)	13 ax (6)	7 ax (1)	7 ax (0)
	B	7 ax (3)	5 ax (2)	7 ax (2)	7 ax (2)
	C	8 ax (5)	6 ax (2)	13 ax (8)	10 ax (6)

Note: Each value is an average of 3 slope positions of respective transects with standard deviation in bracket.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

4.2.2.8. Sodium (Na^+)

Overall sodium ions concentration remained stable with time with the exception of the top slope position on transect C. Transect A shows low sodium ions in the upper 30 cm depth and comparatively high values for the 30 – 60 cm depth (Table 4.13, Figure 4.23). Transects B and C have similar sodium contents within their depth profile, and higher values occur on the top slope position for transect C (Fig. 4.23, Appendix E8). LSD analysis found significant differences between transects (A different than B and C) on fall 1999a and fall 2000 sample dates (0-15 cm depth) (Table 4.13). Transect C have quite different values especially in spring 2000 but the results are shown non-significantly different due to high variability.

From the above results, it can be noted that the high values of Na, Mg, Ca, and SO_4 – and the high ECs all occur for the same samples, which generally are all transect C top slope position. As common soil salts are $CaSO_4$, $MgSO_4$, $NaSO_4$ – this is likely the origin of these high readings (Professor Charles Maulé, Personal Communication). Excluding the variability of top position on C, the general patterns did not differ from each other showing any sign of additional variability from manure salts.

Table 4.13. Sodium content of saturated paste extracts (mg/l).

Depth	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	9 ax (0)	7 by (1)	8 ay (1)	6 bz (1)
	B	19 ax (6)	22 ax (6)	19 ax (6)	12 ax (2)
	C	14 ax (12)	21 ax (2)	80 ax (78)	11 ax (2)
15-30	A	8 ax (0)	9 ax (2)	8 ax (2)	5 ax (1)
	B	8 ay (0)	12 ax (0)	9 ay (2)	7 ay (2)
	C	14 ax (11)	18 ax (10)	48 ax (49)	8 ax (2)
30-60	A	14 ax (9)	21 ax (9)	18 ax (11)	11 ax (6)
	B	18 ax (8)	16 ax (3)	16 ax (6)	14 ax (4)
	C	28 ax (18)	36 ax (26)	32 ax (19)	26 ax (18)

Note: Each value is an average of 3 slope positions of respective transects with standard deviation in bracket.
'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.
'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

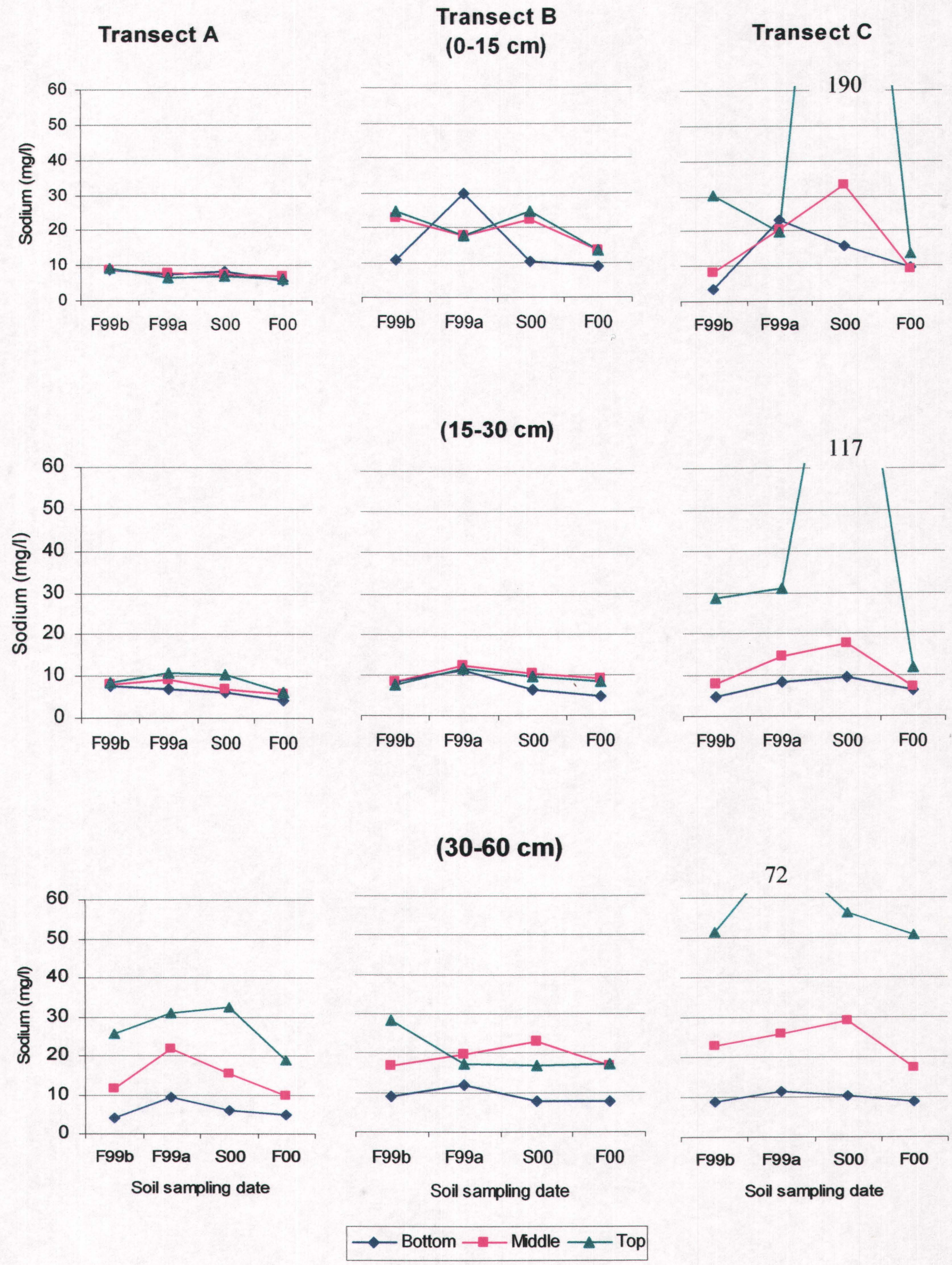


Fig. 4.23. Sodium ions in soil saturated paste extracts on study transects.

4.3. Soil Exchangeable Cations

Exchangeable cations (calcium, magnesium, and potassium) have generally shown stable patterns on slope positions and depth intervals during the study period (Figures 4.24, 4.25, and 4.26), while exchangeable sodium was below detection limit (<0.5 meq/100g). Exchangeable calcium is about equal in the 0-15 and 15-30 depth intervals but the 30-60 cm has a lower concentration (Appendix F). Statistical analysis has only shown a significant difference between dates with less value in fall 2000 for 15-30 cm depth of transect C (Table 4.14). However, individual values have shown some increase at bottom slope positions of all the transects in the 0-15 and 30-60 cm depth intervals. As these changes occurred on all transects, it may be a result of soil variability or an artifact of analysis procedure.

Table 4.14. Exchangeable cations on study transects (meq/100g).

	Depth 0-15 cm		Depth 15-30 cm		Depth 30-60 cm	
	Fall 1999b	Fall 2000	Fall 1999b	Fall 2000	Fall 1999b	Fall 2000
Calcium						
A	16.7ax(1.5)	17.4ax(1.0)	16.1ax(0.7)	16.3ax(2.3)	12.2ax(3.1)	13.0ax(3.6)
B	16.4ax(2.2)	15.6ax(2.1)	16.3ax(2.2)	15.9ax(2.7)	11.3ax(1.0)	11.6ax(1.5)
C	16.1ax(3.6)	18.1ax(1.4)	17.5ax(2.0)	14.8ay(2.6)	9.2ax(2.2)	11.9ax(2.1)
Magnesium						
A	4.8ax(0.9)	4.4bx(0.3)	4.4bx(0.3)	5.6ax(0.9)	8.8ax(3.3)	7.6ax(1.7)
B	5.6ax(1.1)	4.1bx(0.3)	4.6aby(0.6)	5.4ax(1.0)	7.1ax(2.7)	7.3ax(2.0)
C	6.8ax(1.3)	5.7ax(0.7)	6.0ax(1.2)	7.6ax(2.3)	10.0ax(3.4)	10.6ax(2.9)
Potassium						
A	0.4ax(0.2)	0.8ax(0.3)	0.6ax(0.3)	0.4ax(0.1)	0.4ax(0.1)	0.5ax(0.1)
B	0.3ay(0.0)	0.8ax(0.2)	0.6ax(0.1)	0.4ax(0.0)	0.3ay(0.1)	0.4ax(0.0)
C	0.4ax(0.2)	0.7ax(0.2)	0.8ax(0.4)	0.4ax(0.1)	0.4ay(0.1)	0.5ax(0.1)

Note: Each value is an average of 3 slope positions of respective transects with standard deviation in bracket.

'a, b, c' designators refer to the occurrence of significant differences between transects within the same year and within same depth interval, different letters mean that the transect is significantly different at a probability of $P < 0.1$.

'x, y, z' designations refer to the occurrence of significant differences between years within the same transect and within same depth interval.

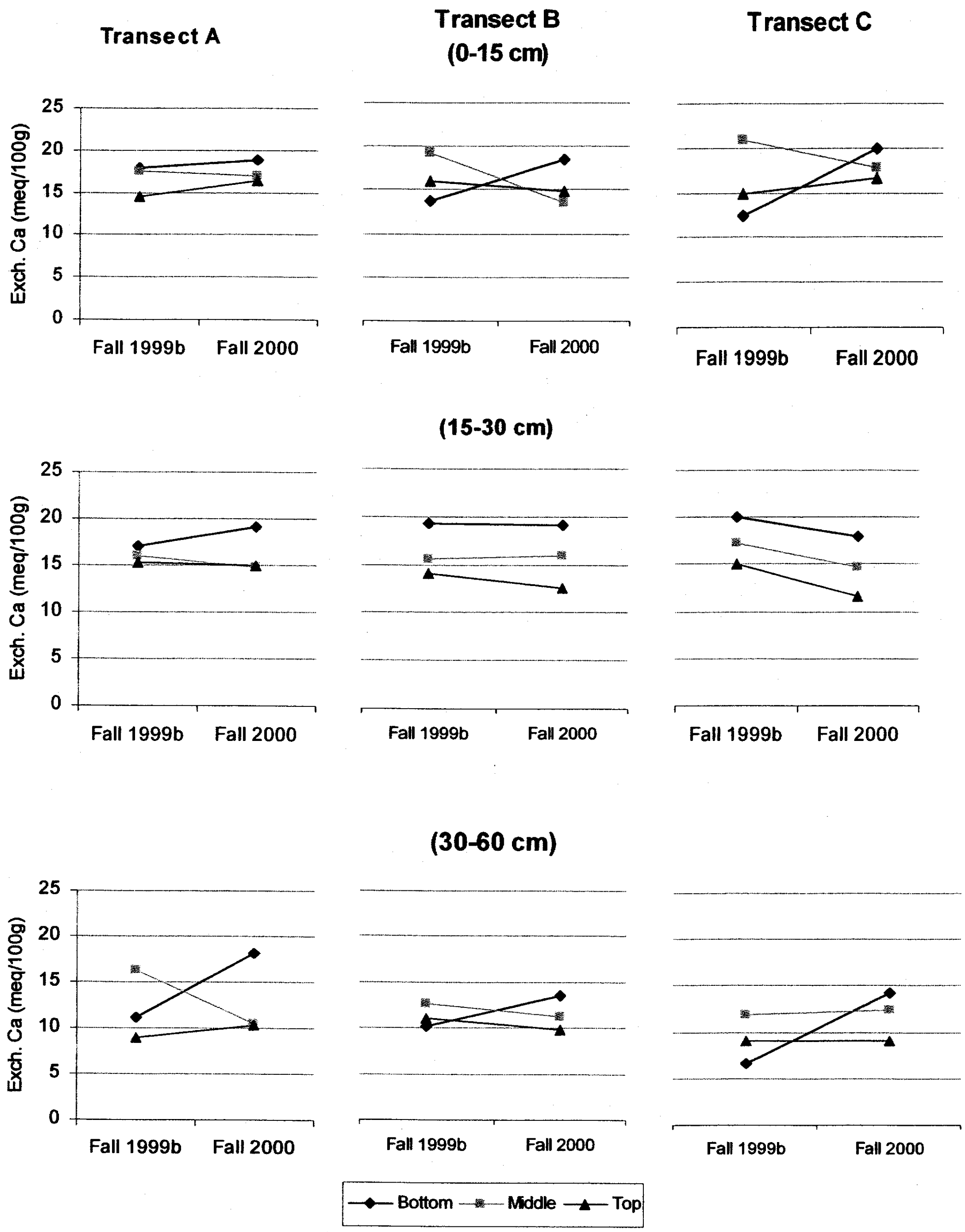


Fig. 4.24. Exchangeable calcium in soil samples on study transects.

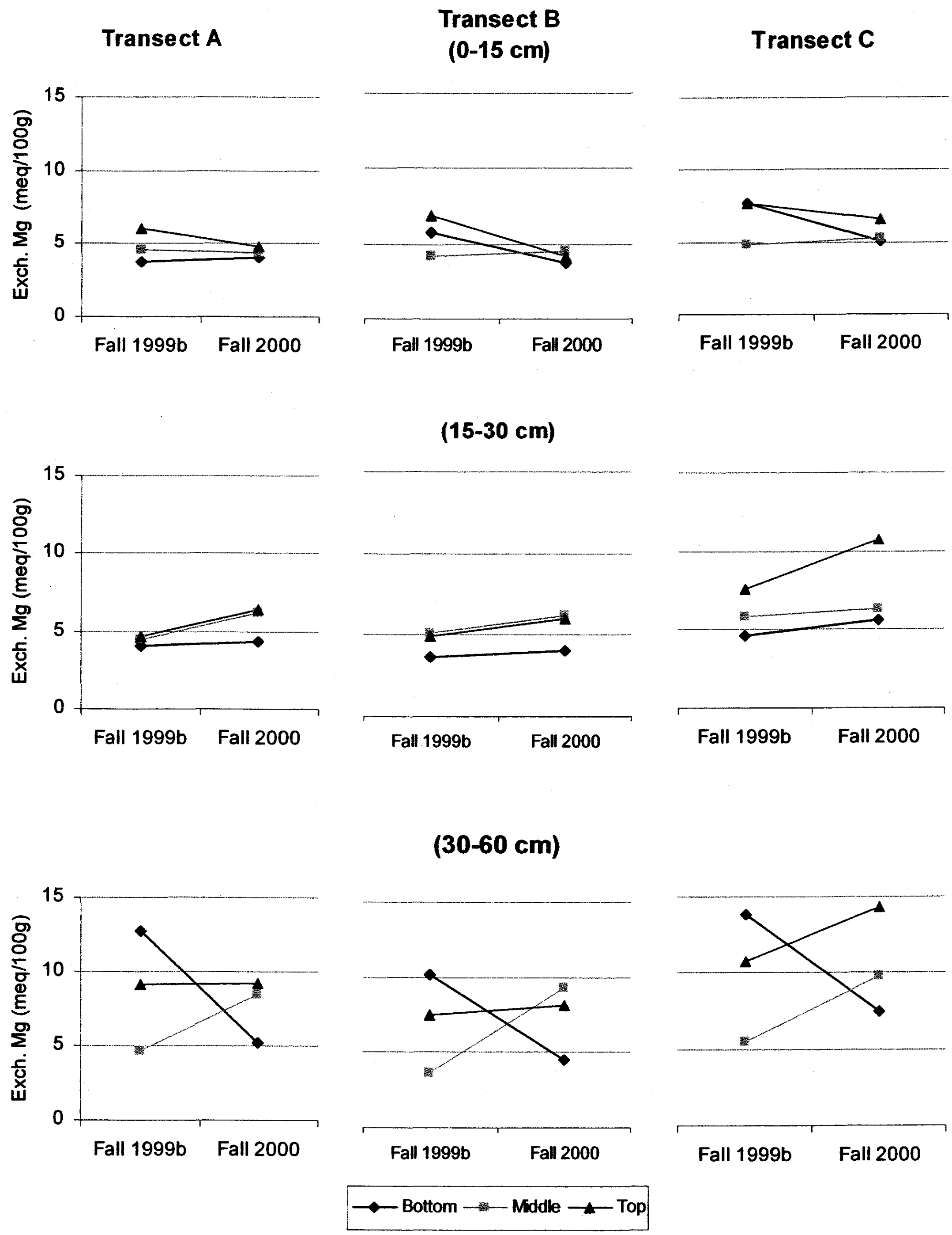


Fig. 4.25. Exchangeable magnesium in soil samples on study transects.

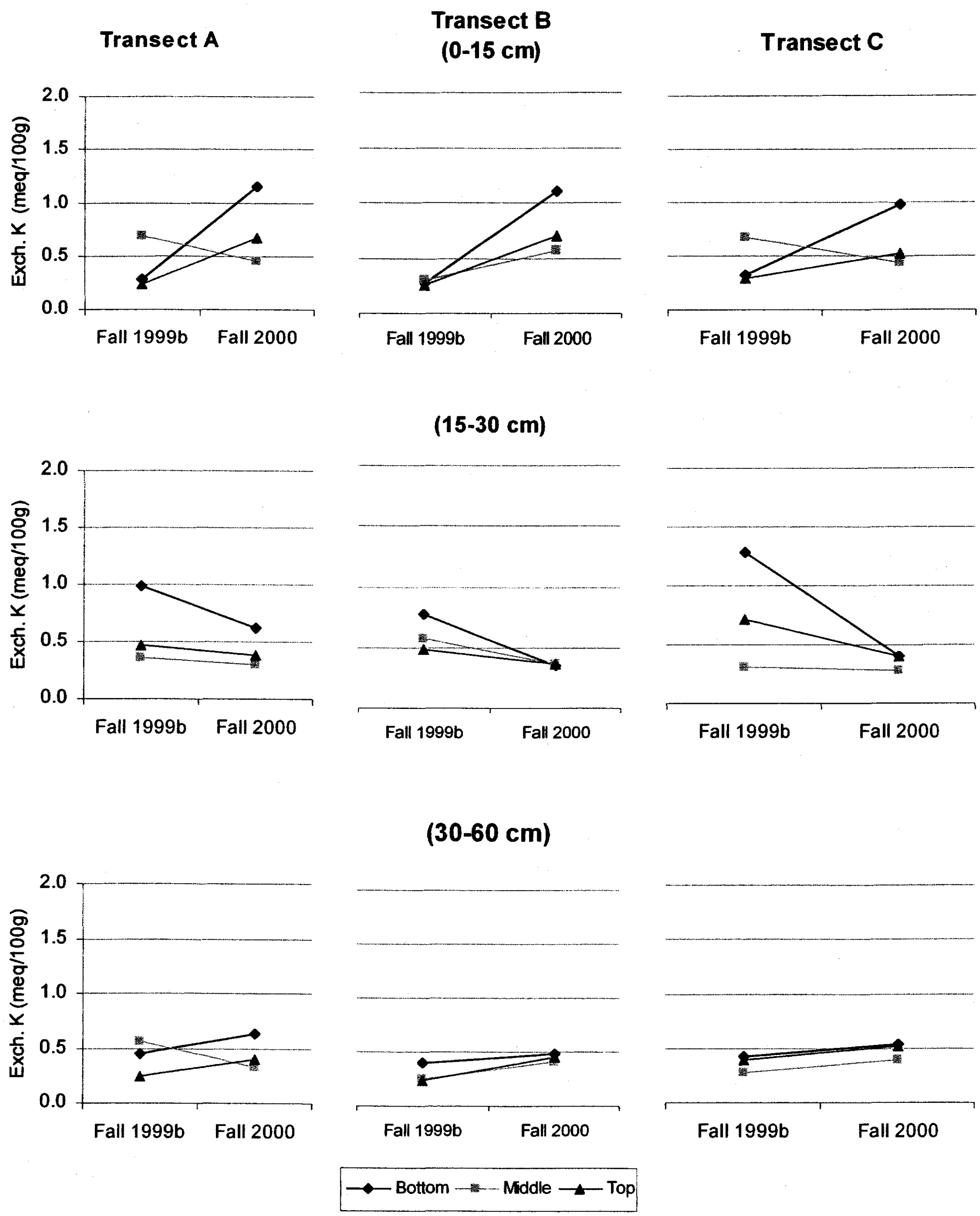


Fig. 4.26. Exchangeable potassium in soil samples on study transects.

Exchangeable Mg concentrations are about equal in the 0-15 and 15-30 cm depth intervals but the 30-60 cm depth interval has higher concentrations (Table 4.14). For all the transects at 30 to 60 cm depth interval, the bottom slope position has shown a decrease while middle and top positions have shown increase with time. There are significant differences between transects in fall 1999b (15-30 cm) and fall 2000 (0-15 cm) (Table 4.14). Moreover, transect B has shown a significant difference between dates at the 15-30 cm depth.

Exchangeable potassium is low, varying from 0.1 to 1.3 meq/100g, as compared to Ca (9 to 21 meq/100g) and Mg (3 to 14 meq/100g) (Appendix F). Individual values indicate an increase in exchangeable K in the 0-15 cm depth interval, a decrease in exchangeable K for the 15-30 cm depth, and again an increase in 30-60 cm depth on most of the slope positions of the study transects (Figure 4.26). Some of these changes are significant with time (sample dates) within transect B (0-15 and 30-60 cm) and C (30-60 cm) (Table 4.14).

4.4. Soil Moisture and Bulk Density

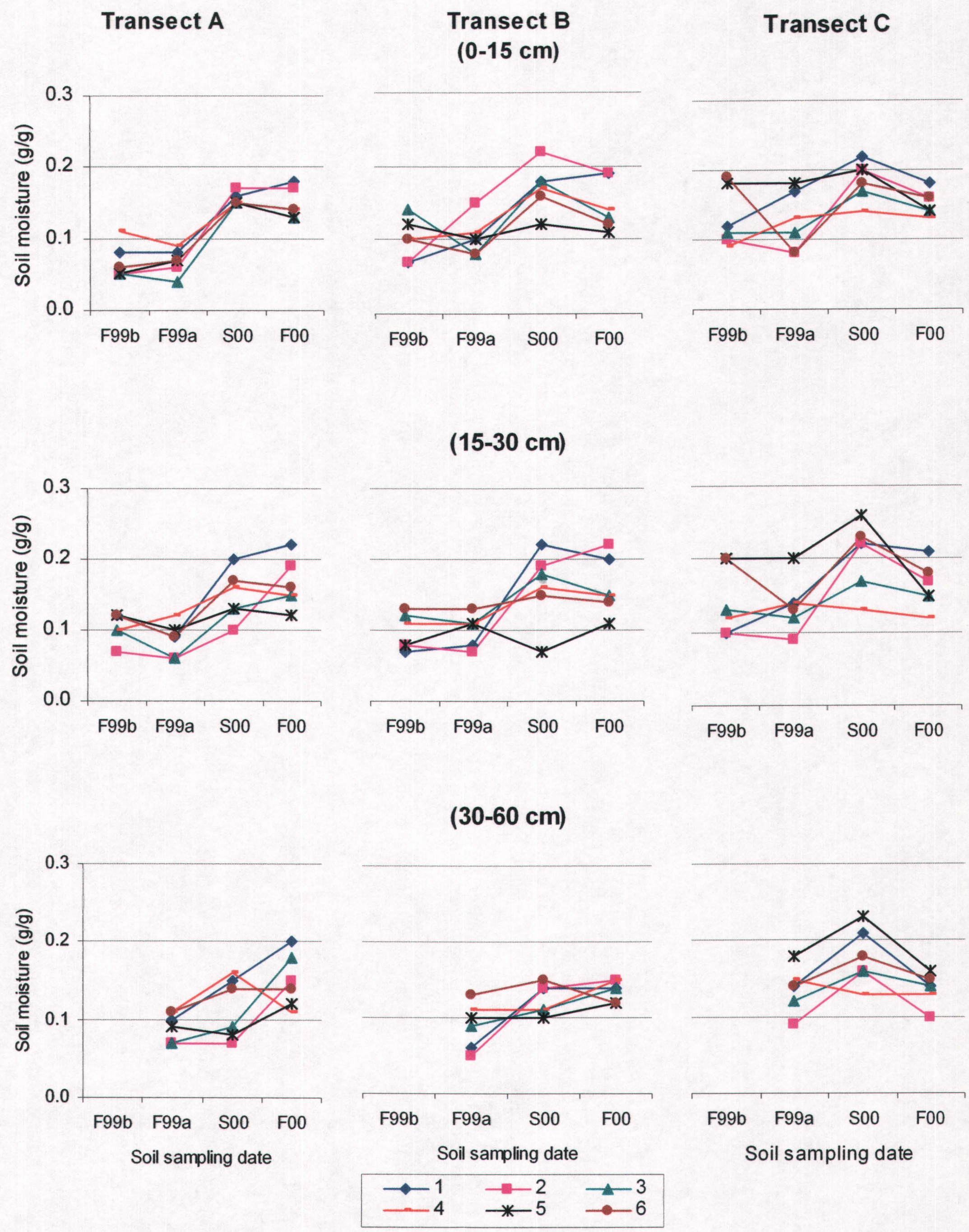
The soil bulk density ranged from 1.10 to 1.85 g/cm^3 over the slope positions and depth intervals (Table 4.15, Appendix G). As the soil samples were taken with a truck mounted hydraulic coring unit (push), there is some likelihood of soil compaction resulting in higher bulk density values, especially for the surface interval. The bulk density for transect C, 0-15 cm depth is unusually high and perhaps may be related to compaction and its slightly higher clay content (Table 4.2).

Table 4.15. Bulk density (dry basis) on study transects (fall 2000).

Transect	Depth (cm)	Bulk density (g/cm^3)	Standard deviation
A	0-15	1.47	0.09
	15-30	1.51	0.08
	30-60	1.53	0.11
B	0-15	1.32	0.16
	15-30	1.57	0.11
	30-60	1.68	0.03
C	0-15	1.68	0.10
	15-30	1.61	0.13
	30-60	1.58	0.13

Note: Each value is an average of 3 slope positions.

For different depth intervals, on all the transects, soil moisture was lowest in fall 1999 (before and after manure application) and highest in spring 2000 and fall 2000 (Figure 4.27, Table 4.16) (for the 30-60 cm depth, data is not available on sample date of fall 1999 before manure application). Amongst the transects, transect C shows higher moisture as compared to transects A and B, which could be attributed to higher retention properties of this soil, having a slightly higher clay content, or due to its more north facing aspect. Amongst the slope positions, bottom positions (series 1,2) have highest moisture in the 0-15 cm interval on all the transects (Fig. 4.27). For the 30-60 cm depth on transect C, most of slope positions have highest moisture contents in spring 2000 while transects A and B had their highest moisture in fall 2000.



Slope position legend (Fig.3.3): Bottom (1,2), Middle (3,4), and Top (5,6)

Fig. 4.27. Gravimetric soil moisture content on study transects (g/g).

Table 4.16. Gravimetric soil moisture contents on study transects.

Depth	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	0.07	0.07	0.16	0.15
	B	0.10	0.10	0.17	0.15
	C	0.13	0.13	0.19	0.15
15-30	A	0.11	0.09	0.15	0.17
	B	0.10	0.10	0.16	0.16
	C	0.14	0.14	0.21	0.16
30-60	A	N/A	0.09	0.12	0.15
	B	N/A	0.09	0.13	0.14
	C	N/A	0.14	0.18	0.14

Note: Each value is an average of 6 slope positions of respective transects.

4.5. Study Treatments and Crop Yield

For both the 1999 and 2000 crop seasons, yields were the highest for transect B (Table 4.17). Grain yields of the wheat crop (1999) on transect B is 2649 kg/ha as compared to 2013 and 1962 kg/ha on transects A and C respectively. Transect A has the highest yield on the bottom position (2706 kg/ha), whereas transect B surpassed transects A and C on the middle and top slope positions. On average the highest wheat yields occurs on the middle slope position (2366 kg/ha).

Table 4.17. Crop yield on study transects (kg/ha).

Slope position	Transect A	Transect B	Transect C	Average
Wheat (1999)				
Bottom	2706	2335	1772	2271
Middle	1863	3028	2207	2366
Top	1470	2583	1907	1986
Average	2013	2649	1962	
Canola (2000)				
Bottom	1963	2243	2615	2274
Middle	1385	2328	1178	1630
Top	1485	1790	2093	1789
Average	1611	2120	1962	

The canola crop also showed the highest yield on transect B (2120 kg/ha) as compared to transects A and C having respective yields as 1611 and 1962 kg/ha. In this case, transect C has a higher yield than A which is a shift from differences with wheat yield and perhaps may be attributed to fertilizer treatments. If the slope positions are averaged then the highest canola yield is on the bottom position which was the highest on middle position for wheat. All the three study transects have shown higher canola yields as compared to crop district yield in the same growing season and also for the last ten years average (Figure 4.28). For wheat (1999), the growing season and the ten-year (1991-2000) average crop district yields are 2475 and 2126 kg/ha respectively, which are greater than transects A (2013 kg/ha) and C (1962 kg/ha), and lower than transect B (2649 kg/ha) (Table 4.17). For canola (2000), the growing season and the ten-year (1991-2000) average crop district yields are 1522 and 1396 kg/ha respectively, which are lower than the study transects (Table 4.17).

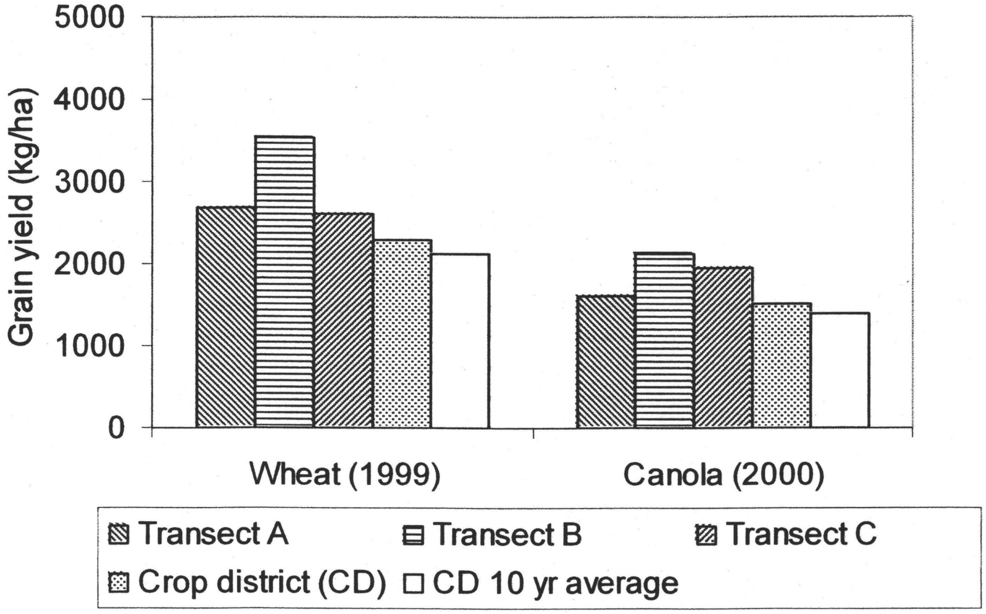


Fig. 4.28. Average grain yield on study transects and in the crop district. (Crop district data from Agriculture Statistics, SAF 2000).

5. DISCUSSION

5.1. Introduction

The study is based on three separate treatments with no replication. These study treatments are simply three watersheds which slightly differ in their area, aspect, and topography. Consideration of watersheds as study treatments in the present study is based on the concept that watersheds are logical subdivisions of physiographic regions that define portions of the landscape linked by hydrologic processes (Grigal et al., 1999). The data collection on the study treatments is based on single transects joining a low and high point within each transect and representing the respective watershed area. An equal number of study sites were selected on each transect in terms of slope position following a standard landscape classification scheme (Pennock et al., 1987). Data collection for the study period is based on the monitoring of the study sites for soil chemistry, soil moisture and crop yield on 'successive dates'. This time lapse monitoring sequence has allowed the observation of spatial and temporal field dynamics of fertilizer residues resulting from the treatment applications on the study transects.

This chapter is divided into two main sections discussing the background characteristics of the study transects (5.2) and the impact of the study treatments (5.3).

5.2. Background Characteristics of Study Transects

5.2.1. Physical Characteristics

Several physical characteristics control soil processes, and texture has great effects on infiltration and retention of water (Wolf 1999). The existing differences between the study transects in terms of clay and sand contents can be attributed to their landscape features and erosion patterns over the years. As soil texture varies to some extent among the three study transects, it can be a potential source of spatial variability for other properties to be compared over the study treatments such as comparing the impact of fertilizer treatments. As shown with clay and sand content (Figures 4.7 and 4.8, Table 4.2), the soil texture is mainly uniform on slope positions and depth intervals and is assumed an acceptable base for comparing the study treatments. For all transects, percent clay content is quite uniform between slope positions with depth in the soil profile within respective transects. However, significant differences of clay contents between transects ['A and C', 'B and C'] are only in the 0-15 cm depth and may contribute some differences to the overall root-zone soil moisture regimes. For example, in spring 2000 (Table 4.16), transect C has highest moisture contents and its clayey texture is one factor to attribute the moisture difference. Although transects A and B differ in sand contents, their soil moisture is similar probably due to similar clay contents. Moreover, an attempt has been made to reduce the influence of soil textures and other soil physical characteristics on soil chemistry assessments by sampling around the baseline positions and combining the slope positions as shown in Fig. 3.3. Firstly, the sampling scheme increased the number of subsamples from 6 to 12 to represent one bulk sample. Secondly, the scheme allowed to combine the landform elements having similar characteristics leading to greater resolution between the remaining ones e.g., each group of slope positions being combined were having similar catchment areas and the resulting combined slope positions such as bottom, middle, and top were simply having their catchment area as high, moderate, and low, respectively (Table 2.1). This is based on an initial consideration that the six slope positions of present study are in resemblance to the six positions mentioned in Table 2.1.

Several landform differences may exist on the whole area of the study watersheds due to topographic differences (Figures 4.3, 4.4, and 4.5). However, the landform elements are noted to be same on all the study transects with respect to their respective sample positions on transects (Fig. 4.6, Table 4.1). They differ from the scheme given in Table 2.1 only at upper positions which show slope shape as convex. Generally, the sample transects on the three watersheds have shown similar landform elements, equivalent variation of distances, elevations and gradients with the exception of different aspects (Table 4.1), and are assumed to be comparable as study treatments. As the transects have different aspects therefore differences in exposure to sun light may differentially affect soil-plant characteristics such as transect A facing south-west, transect B facing north-east, and transect C facing north represent all different directions. Different aspects may have an impact on soil moistures from sun radiation directly and from resulting evapotranspiration of crop which may create some differences of crop growth and nutrient dynamics. Especially, transect A facing south-west may become dryer than transects B and C with northeast and northerly aspects respectively.

5.2.2. Chemical Characteristics

The existing total C, total N, and total P contents on the study transects are a result of natural soil formation factors and agronomic practices, of which erosion patterns likely have an important role (Campbell et al. 2000; Pennock and de Jong 1990). Concentrations of total C and organic C is higher for bottom slope positions and lower for top positions (Table 4.3, Figure 4.9). This is possibly due to the lower slope positions receiving organic rich upslope sediments, from water, wind, or tillage erosion, and also to higher moisture (from upslope runoff) resulting in perhaps greater crop growth and return of biomass. The erosion mechanism over the past 50 years has been supported by cesium137 data (Fig. 5.1) showing its accumulation at bottom slope positions. Organic C is lower on upslope positions likely due to a combination of erosion removal and lower plant growths resulting from dry conditions. Inorganic C, in the form of carbonates, is low on lower slope positions due to excess water leaching and is high on upper slope positions as erosion constantly exposes it from soil profile.

Pennock et al. (1994) attribute changes in soil organic carbon (SOC) to soil redistribution and mineralization (Table 5.1) and indicate that for the range of cultivation years (12 to 80 yrs), soil organic carbon removal by mineralization is greater than additions in Chernozemic dominated footslopes. This shows that increase in cesium concentration (Fig. 5.1) may not be linked to changes in SOC but to the accumulation of other residues. The soil organic carbon changes over a period of 10 years under different crop rotations are reported to be only significant for the surface 15 cm soil depth, which have been attributed to shallow tillage practices (Campbell et al., 2000).

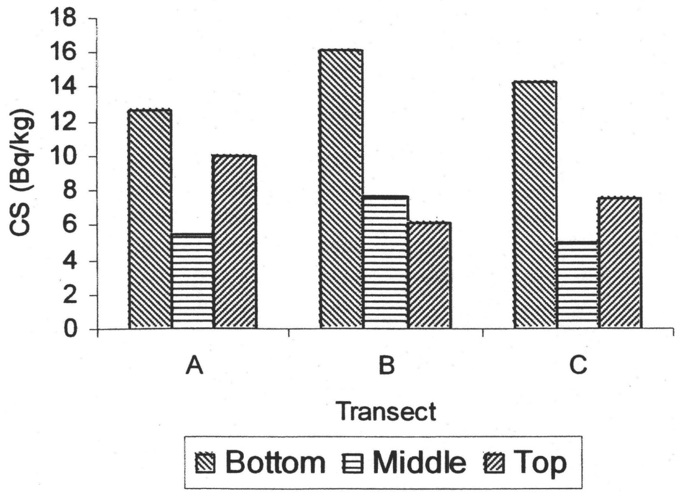


Fig. 5.1. Cesium137 variation on slope positions of study transects
(Each column represents one sample. Samples collected in 2002 by Professor Charles Maulé, and analysed by Dept of Soil Science, University of Saskatchewan).

Table 5.1. Net changes in soil organic carbon associated with landform element complexes and the causes of changes. All SOC values are in Mg/ha (adapted from Pennock et al. 1994).

	Shoulder Complexes			Chernozemic-dominated Footslope Complexes			Gleysolic-dominated Footslope and Level Depressional Complexes	
	Years of Cultivation			Years of Cultivation			Years of Cultivation	
	12	22	80	12	22	80	22	80
Observed SOC to 45 cm	96	81	53	95	104	84	98	113
Net Change in SOC to 45 relative to 0-year site	-21	-36	-64	-34	-25	-45	41[a]	56
Commulative change due to soil redistribution	-14	-19	-45	-9	-2	-18	12	25
Cumulative change due to mineralization	-7	-17	-19	-25	-23	-27	29	31

[a]For this complex the changes are calculated relative to the 12-year site.
A negative value for the net mineralization change indicates that mineralization rates are higher than rates of SOC addition to the soil; a positive value indicates that additions are higher than the soil's ability to mineralize the additions

On the present study transects, the variation of organic C and total N is strongly correlated ($R^2 = 0.982$) for the 0-15 cm depth having a linear relationship (Section 4.1.2.2). Total P content is reflective of carbon and nitrogen on slope positions with the exception of transect C (Figures 4.9, 4.10, and 4.11). Under a variable rate fertilizer application study, Walley et al. (2001) observed no significant responses for spring wheat in P treatments and it was not possible to find any other study focusing on changes in soil P in prairie landscape under conventional agricultural practices. Recently, under an experimental manure management study, of over five years duration, that took place in Saskatchewan, Qian et al. (2004) reported an increase in soil total P (0-15 cm) by repeated applications of cattle manure and no increase by liquid swine manure. However, in a Quebec, 14 years of annual liquid pig manure (LPM) use has shown an increase in total C (48%), N (60%) and P (40%) contents within one meter of soil depth with the highest rate of LPM (120 m^3/ha) (Hountin et al., 1997). In the Canadian prairies, there was no change in soil organic mass in a three year hog manure study by King (2002) and in a four year hog and cattle manure study by Assefa (2002). Also similar was the study by Paré et al. (1999), who has noted that the addition of manure did not affect the mass of organic matter in the 0-15 cm depth, however the quality of organic matter was affected by the tillage practices as indicated by the increased amounts (21%) of unbound lipids in conventional tillage soils as compared to no tillage.

5.2.3. Indicators for Background Properties

The differences in background fertility status of study transects can be ascertained from the C:N ratio which has shown certain variability over the slope positions and depth intervals (Table 5.2). For the bottom slope position, Total C : Total N ratio is lower and similar for the three depth intervals of the three transects. This can be attributed to the high Total C and Total N throughout the soil depth on the bottom position as described in section 4.2.2. The ratio varies widely on middle and top slope positions because of concomitant and inverse variations in Total C and Total N concentrations. Generally, the ratio widens from the 0-15 cm depth interval to the 30-60 cm due to the low level of Total N in deeper depths and the higher amounts of inorganic C (Appendix C). The ratio based on Organic C and Total N is more reflective of soil fertility on sloping land because it avoids the variability induced by changes in $CaCO_3$ which is a large component of TC for some slopes and depths. The highest values occur on the bottom position for transect B and it can also be seen that the same transect has lower ratio at middle position.

Table 5.2. Carbon : Nitrogen ratios on study transects in fall 1999b.

Transect	Depth	Bottom	Middle	Top
Total C/Total N				
A	0-15	10	13	11
	15-30	10	18	18
	30-60	10	36	24
B	0-15	11	11	13
	15-30	11	22	23
	30-60	10	20	27
C	0-15	10	14	18
	15-30	10	24	30
	30-60	10	40	27
Organic C/Total N				
A	0-15	11	11	6
	15-30	12	10	8
	30-60	12	11	7
B	0-15	14	8	12
	15-30	15	6	11
	30-60	10	9	7
C	0-15	11	13	8
	15-30	13	11	11
	30-60	11	6	2

Note: Ratios for bottom, middle, and top positions are based on data given for depression, middle and upper positions respectively. For transect A, top position ratio is based on data given for shoulder position (Table 4.3, Appendix C).

In reference to a CEC classification for agricultural purposes (Table 5.3), the status of soil CEC on the study transects (Figure 4.12) is in the range of 'low normal' to 'high normal' showing average conditions for crop production. The increase in CEC with a decrease in elevation of slope positions showed positive correlation coefficients with organic carbon on all the transects as A = 0.66, B = 0.93, and C = 0.99 (0-15 cm depth). However, transects B and C showed negative correlation between CEC and clay content (A = 1.0, B = -0.92, and C = -0.34) indicating an un-consistent relationship on the study transects. Therefore, for the slope positions of the study transects, CEC can be consistently correlated with organic carbon which can also contribute to soil CEC to the extent of 20-70% (Whitehead 2000). The effects of CEC pattern on study transects may become more clearer while discussing the status of exchangeable cations in a later section.

Table 5.3. CEC classification for agriculture (Yuste and Gostincar 1999).

CEC in meq/100g	Class
< 5	Poor
5 – 10	Low
10 – 15	Low normal
15 – 25	High normal
25 – 40	High
> 40	Very High

5.3. Impact of Study Treatments

5.3.1. Soil Sampling and Analysis

Soil sampling and analysis is a large potential source of error in nutrient budget studies. This may especially be the case in sloping areas where nutrient losses often occur via 'hot spots' and via preferential flow patterns in soils (Oenema and Heinen 1999). A hot spot can be any point on the landscape having a higher concentration of nutrients and salts with thus a greater chance of their loss. The results on saturated paste chemistry (presented in section 4.2) have shown the bottom slope positions of all transects as potential hot spots for dissolved chloride and nitrate ions on the landscape under the present study. Bottom slope positions can be understood in the light of landscape analysis from literature. However the present study is also confronted with an unexpected source of error which is the top slope position of transect C showing large variability in soil chemical properties.

In the present study, soil sampling was done with six subsamples to obtain one bulked sample for each point. The six subsamples were collected within a grid to represent a study site (slope position) and not from the whole watershed area. On slope positions of the manure treatment, an attempt was made to equally incorporate the bottom and top of furrows created by the manure injection equipment on soil sampling date after manure application (fall 1999a) and in spring (2000). However, on the last sampling date (fall 2000), the furrows were smothered by the seeding equipment and therefore, the soil sampling cores might not had been taken uniformly over the treatments. Custom applicators injected swine manure at an average depth of 10 cm with 30 cm row spacing in present study. Research with anhydrous ammonia and urea fertilizer suggest that row space should not exceed 30 cm (12 inch) to prevent "stripping" in the crop. However, unlike urea or anhydrous ammonia, the high water volume of swine manure may result in lateral movement of the manure even when injected in a narrow slot (PAMI 2001b). Therefore, it is assumed that a bulked sample based on six samples have accounted manure uniformity in soil sampling especially due to enough mixing time resulting from natural diffusion and soil water convective movement from the time of manure application in fall of 1999 to the spring 2000 sampling date.

To assess the chemistry of soil solution on sampling dates, the saturated paste method was used because it has the advantage that it is the lowest reproducible ratio related in a predictable manner to field soil water contents (Rhoades 1982). The technique can be used to assess the quantities of nitrate and other nonsorbing ions in the soil. For elements that are highly buffered in soils, such as P, cations, and trace metals, the effects of soil water content on concentration in solution are small (Lajtha et al., 1999). Saturated paste moisture contents (Appendix E11) show some variability (overall CV 11%) in samples representing the same study sites on different dates. This may be the result of soil samples having different texture due to natural variability or non-uniform judgment criteria applied in preparation of the saturated pastes. Although the variability level is not high for soil properties, the error could be reduced by using fixed Soil:Water ratios because the extraction using a fixed ratio may be particularly useful for monitoring relative changes in solute concentration for same study sites (Janzen 1993). Therefore, most of the results have been presented in their original measurement units.

5.3.2. Soil Electrical Conductivity and pH

As the capability of EC to assess soluble salts and soil salinity is a common practice, it has been shown to be a useful property under specific soil systems such as sulphate rich soils (Chang et al., 1983) and also for assessing the soluble nutrients in soils amended with animal manure (Eigenberg et al., 2002). For a Crete silt loam soil in central USA ($EC_{1:1}$ soil-water extract = 0.55 dS/m), Eigenberg et al. (2002) reported that among the soil anions, NO_3 accounted for 25-35% of the soil conductivity signal ($EC_{1:1}$) followed in order of predominance by HCO_3 (25-30%), SO_4 (10-25%), Cl (10-15%), and PO_4 (2-5%). As the fixed ratio extraction is closely related with the saturation extract in a wide range of soils (Janzen 1993), the comparison of EC data for the present study treatments (Figure 4.13) is discussed in the context of anions and cations in the following section.

Generally, the EC values in the present study (Figure 4.13, Appendix D) have shown that the soluble salts are lower for transects A and B than that of transect C, which have high soluble salt patches especially on its top slope position. For example, on the study end date (fall 2000) and for respective depth intervals 0-15, 15-30, and 30-60 cm, the average EC values are as for transect A (0.56, 0.42, and 0.45 dS/m), transect B (0.62, 0.42, and 0.50 dS/m), and transect C (0.59, 0.49, and 1.08 dS/m). The general EC pattern over the study period has a shown a high variability for the 0-15 cm depth on transects B and C making it difficult to see the impact of manure on soluble salts. For deeper depth intervals (15-30 and 30-60 cm), the variability is less except for the top position on transect C. No other study has reported significant changes in soil EC after one year of manure application even at high rate treatments (Assefa 2002 for Gray Soils; Charles 1999 and Assefa 2002 for Black soils – Table 5.4). However, the same manure application rates on Black soils after four years have shown one case of increase in soil EC at a medium (15.2 Mg/ha) cattle manure treatment (Assefa 2002 -Table 5.4).

Table 5.4. Soil electrical conductivity and pH values for 0-30 cm depth after four years of annual hog and cattle manure applications (Assefa 2002).

Treatment	Burr site		Dixon site	
	pH	EC (dS/m)	pH	EC (dS/m)
Hog manure				
Control	8.0	0.53	7.6	0.50
Low (37.5 kl/ha)	**7.8**	0.94	7.6	0.32
Medium (75.1 kl/ha)	**7.9**	1.41	7.5	0.35
High (150.2 kl/ha)	**7.6**	0.55	7.6	0.55
Cattle manure				
Control	7.7	1.00	7.7	0.30
Low (7.6 Mg/ha)	7.8	0.64	7.8	0.53
Medium (15.2 Mg/ha)	7.8	1.88	7.7	**1.60**
High (30.4 Mg/ha)	7.6	1.12	7.9	0.70

Bold fonts values indicate significantly higher/lower mean values of a soil property than the respective control and others are non-significant ($P \leq 0.1$).

Some long term manure studies under irrigated agriculture systems have shown stable EC levels indicating that animal manure did not lead to the buildup of soluble salts and salinity (Sommerfeldt et al. 1973; Clark et al. 1998). In another manure application study (Chang et al. 1983), the accumulation of soluble salts have been reported both for irrigated and non-irrigated systems showing a lower rate of accumulation for the irrigated system and attributing it to leaching conditions with irrigation water application. As compared to the study by Clark et al. (1998), conducted under a whole year cropping environment in central California, the study by Chang et al. (1990) pertains to an half year cropping environment of Alberta which may had left more nutrients and salts in the soil due to a reduced period for crop uptake.

During the study period, significant changes in soil pH has been observed between transects on all sampling dates only for the 0-15 cm depth and also within all transects between sampling dates over the study period (Table 4.5). However, these changes seem temporal and are irrespective of fertilizer treatments. For three sampling dates (Fall 1999b, Fall 1999a, and Fall 2000), the pH values remained in the range of 7.5 to 8.5 indicating slightly to moderately alkaline conditions (Appendix D2). For spring 2000, the pH values have resulted in a lower range (7.0 to 7.5) indicating slightly acid conditions. It is not clear if it is the result of higher moisture and leached conditions after snowmelt infiltration or is just an instrumental error.

As compared to the temporal changes in soil pH, during the course of the present one year study, there was no change in pH of Gray and Black prairie soils after one year of low to high manure treatments (Charles 1999; Assefa 2002). Assefa (2002) after four years of treatment, reported a significant decrease (from 8.0 to 7.6) in Black soil pH on high hog manure treatment (Table 5.4). Some other longer term field studies (Clark et al. 1998 in California) and short-term laboratory experiments (Whalen et al. 2000 in Alberta) have reported a positive impact of cattle manure on soil pH. However, a long-term (1978-87) field study in Quebec under solid cattle manure and pig slurry treatments did not shown any significant change on the soil pH. The treatments of this study included a control, solid cattle manure (20, 40 and 60 Mg/ha) and pig slurry (60, 120 m^3/ha) applied every two years and annually, respectively, with no other fertilizer application (Ndayegamiye and Cote 1989). Slightly alkaline soils of the present study area have an average pH of about 8.0 and may not be responsive to quick changes with manure application rates used in the present study. For acidic soils (pH 4.8 to 5.6), Whalen et al. (2000) have shown persistence of a positive effect of manure on soil pH during an 8 week incubation period but the study has also cautioned the field applicability of manure amendment rates used in the laboratory experiment. The authors (Whalen et al. 2000) also suggested that the organic compounds in manure may have a positive effect on increasing the soil pH. In comparison to animal manure, chemical fertilizers are well known for their acidity and basicity-forming effects , such as the acidity caused by contained sulfur, chlorine, nitrogen, and phosphorus; whereas the presence of calcium, magnesium, potassium, and sodium in fertilizer raises the pH of the soil (Prasad and Power, 1997).

As described by Foth and Ellis (1997), cultural practices such as the method of crop harvesting, can affect soil pH. Harvesting a crop can result in removing most of the N, P, S, and Cl while leaving residues in the field that contained most of Ca, Mg, K, and Na. Thus there would be a minimum amount of acidifying elements left in the field for the production of acidity and a maximum amount of basic cations left in the field to contribute to alkalinity. In addition, it may be difficult to account for the contribution of soil processes affecting pH, such as nitrification (oxidation of NH_4 to NO_3) which acidifies the soil bringing cations into solution. The ion concentrations in solution affecting the pH levels are highly dependent on N fertility practices and would be expected to vary throughout the year (Clark et al. 1998).

5.3.3. Concentration of Dissolved Anions and Cations

5.3.3.1. Anions

The group of anions observed on the study treatments has revealed the natural variability of prairie landscape in terms of their retention, transfer and accumulation on different slope positions and depth intervals. Background levels (1999b) of chloride

(Cl) in the upper 15 cm of soil has shown similar concentrations between slope positions of transect A (8.0 to 9.3 mg/l) but on the other transects were higher and more varied (transect B: 45 to 179 mg/l and transect C: 28 to 158 mg/) (Fig. 4.14). On subsequent dates, these surface values did not show any consistent response to manure additions (which had Cl content of 753 ug/g, Table 4.4). Surface (0-15 cm) concentrations of Cl varied with sampling date quite strongly for transects B and C and thus could have masked manure additions. However, chloride accumulated under the manure treatments in the 15-60 cm depth interval especially at the bottom positions: for the 15-30 cm depth interval, transects B and C had an increase (difference of fall 1999b and fall 2000 sample dates) in Cl concentration of 14 and 35 mg/l respectively; whereas for the 30-60 cm depth, the respective increase was 16 and 15 mg/l. In comparison, the control treatment (transect A) has not shown any change (Fig.4.14). For the 0-15 cm depth, a low common point in fall 2000 for all the transects can perhaps be attributed to the Cl depletion by crop uptake and leaching down in the soil profile (Figure 4.14).

The observed Cl patterns mentioned above occurred under canola crop and a relatively wet growing season for the year 2000 (Fig. 4.1). Without showing results of any study, SAF (1999b) has indicated that the crop response to potash fertilizer (KCl) fertilizer in high potassium (K) soils may be due to the chloride in potash fertilizer (0-0-60) which contains about 47% Cl. Research results are available on Cl fertilization for spring wheat in Montana dryland indicating a 7% average yield increase and better disease control under a range of potash fertilizer treatments (Engel et al. 1994). The response of canola crop to chloride could not be found in literature. As no other short term study on manure application and chloride leaching could be found, the increase in Cl concentration in the deeper depths (15-30 and 30-60) may be a flush of Cl accumulated during previous dry years or added with manure application. Chloride continually increased in 15-30 cm depth on sample dates especially at bottom position of transect C (Fig. 4.14) and this type of change may suggest that manure constituents were present in 15-30 cm depth interval on sample date right after manure application (F99a) with the higher application rate (112.2 kL/ha).

Observed levels of both nitrite (NO_2) and nitrate (NO_3) ions showed similar accumulation pattern on all the treatments (Figures 4.16 and 4.17). Firstly considering nitrate (Fig. 4.17), in fall 1999a higher NO_3 level for the 0-15 cm depth interval is observed on slope positions of transects B (25 to 34 mg/l) and C (5 to 52 mg/l) as compared to transect A (3 to 8 mg/l) and as compared to fall 1999b. In spring 2000, nitrate values at bottom positions on transects A, B, and C are 64, 129, and 196 mg/l, respectively. For the 15-30 cm depth interval at the bottom position, the increase (relative to fall 1999b) in nitrate concentration at the end of study (fall 2000) is as given in parenthesis for transect A (44 mg/l), B (46), and C (152) (Appendix E2). Perhaps these higher nitrate values at bottom positions can be the result of either the higher organic matter contents at the lower positions and/or the runoff received from the upper slope positions. Also, nitrate ions have shown a consistent and well correlated seasonal activity on slope positions and study treatments with respect to the climatic factors as follows:

> **Fall 1999** (before manure application): The nitrate concentration level is extremely low (relative to future dates) on all the slope positions and

depth intervals. This is actually the end of a crop season and under conventional chemical fertilizer practices, there was not much residual nitrogen left in plant available form.

Fall 1999 (after manure application): This sampling date is just after an interval of one month during which hog manure was applied on transects B and C. Both transects B and C showed a concentration increase on all the slope positions in the 0-15 cm depth interval (Fig. 4.17). This may be attributed to the nitrification process during this period because the applied manure itself contained undetectable amount of the NO_3 ions, but a high concentration of ammonium. At this time of the year, ammonia loss may be minimal due to low temperatures. Even then, soil nitrate (nitrate+nitrite) is greater than ammonium on the higher manure rate treatment (Fig. 5.2).

Spring 2000 (after snowmelt and before seeding): This sampling in May 2000 came at some warm period after the completion of snowmelt, but before seeding. The high concentration peaks in 0-15 cm is likely due to both the manure and soil nitrogen transformation (Fig. 4.17) and the build up of nitrate forms of nitrogen (Fig. 5.2). There could have been some contribution due to runoff bringing greater moisture and/or some nutrients to bottom slope positions because transect A with no manure or fertilizer application during this period has also shown an increase on its bottom position.

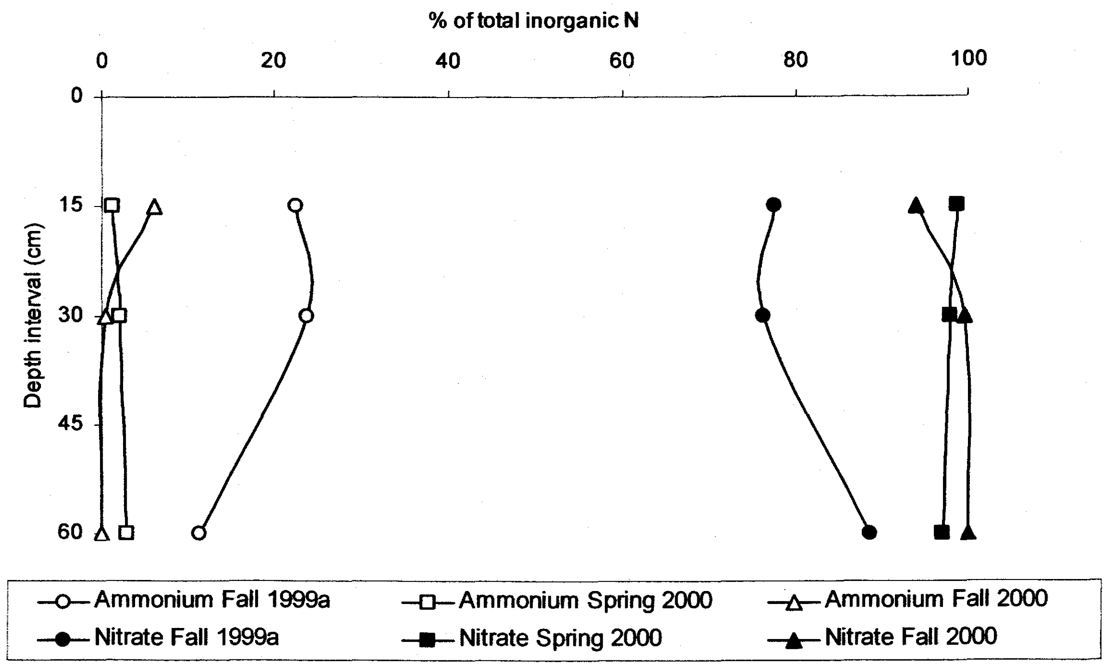


Fig. 5.2. Percentage of total inorganic N as ammonium and nitrate for bottom position of transect C.

Fall 2000 (after crop harvest): After the spring sampling, all the transects received chemical fertilizer application (Chapter 3). This fall sampling after the crop season has shown the depletion of nitrate ions in 0-15 cm from the previous level. However, the increase in nitrate level at lower depths may have been due to downward movement from the surface 0-15 cm especially at the bottom position. After one year, Assefa (2002) has shown nitrate leaching in 30-60 cm depth only under high application rates of hog manure (811 kg N/ha) on Gray soils intended to meet N crop demand for the following three years. A study by Charles (1999) found no indication of nitrate leaching in Black soils under a range of low to high cattle and hog manure rates and attributed this as being probably due to a dry year.

As the soil extract samples were stored for longer (10 days) than the recommended period (2 days at 4°C), it is possible that there were nitrite/nitrate conversions during sample storage in lab resulting in high nitrite (Fig. 4.16). The same conversions have been reported in the equipment calibration process by the manufacturer and attributed to the presence of nitrifying/denitrifying microbes in drinking water samples rather than any chromatographic resolution problems for any of the anions (Dionex 2000). The present study samples were soil extracts and microbe activity can be expected during their storage.

Nitrite is seldom present in detectable amounts, and its determination is normally unwarranted except in neutral to alkaline soils receiving NH_4 or NH_4 – producing fertilizers (Keeney and Nelson 1982, reported in Maynard and Kalra 1993). Quite high concentrations of nitrite can be expected because both the above conditions were prevailing on the present study treatments especially as swine manure contained high amounts of NH_4-N (Table 4.4), which is close to 40% of total N and is same as reported in Qian and Schoenau (2000). Morrill and Dawson (1967) (Cited in Prasad and Power 1997) studied nitrification in 116 soils of the United States ranging in pH from 4.4 to 8.8 and observed four different patterns, which are as follows:

1. In some acid soils having pH < 5.39, NH_4^+ oxidized slowly to NO_3^- without the appearance of NO_2^-.
2. In some acid soils having pH ≤ 5.39, there was accumulation of NH_4^+ with very little oxidation to NO_2^- and NO_3^-.
3. In soils having pH 5.01 to 6.38, NH_4^+ and NO_2^- were rapidly oxidized to NO_3^-.

4. In soils having pH 6.93 to 7.85, NH_4^+ oxidized to NO_2^-, which accumulated for extended periods before being oxidized to NO_3^-. This last pattern supports the occurrence of NO_2^- in the results of present study. The observed average levels of NO_3 and NO_2 in this category were reported as 77.5 ± 9.9 and 43.9 ± 6.6 µg N/ml, respectively (Morrill and Dawson 1967).

The other anions (phosphate and sulphate) did not show an apparent difference between the study treatments (Table 4.9, Fig. 4.19). Low but detectable amounts of phosphate (1 to 13 mg/l) were found on bottom positions of transects B and C, which may have accumulated by soil erosion and runoff processes from upper slope positions. A small amount of phosphate is also found on the top slope position of transect C which may be attributed to the highest clay content at this location having better capability of retaining the nutrients and salts on soil colloids especially on calcareous soils (Bolton 1999). Qian and Schoenau (2000) have reported that a single application of swine manure at low and high rates did not show a significant increase in labile P in a Black Chernozemic soil, which is similar to the results of Assefa (2002), and Charles (1999). It can be supported from Table 5.5 that 91% of P in swine manure is inorganic P, which may be just sufficient for crop uptake within a growing season. Increases in canola crop uptake of P have been reported after hog manure applications (Charles 1999; Assefa 2002) but the recoveries of the applied hog manure P in the crop were generally low and decreased with increasing manure application rate, averaging 10, 8, and 2% for the low, medium and high rates respectively (Charles 1999). For example, crop P uptake reduced from 13 to 9 kg/ha by doubling the manure P application from 111 to 223 kg P/ha at Burr hog manure trial (Charles 1999).

In short-term studies, Assefa (2002) has reported an increase in soluble sulphate levels in Gray soils with high rate hog and low rate cattle manure treatments , however there was no change observed by Charles's (1999) study attributing it to high levels of indigenous S in Black soils. Charles (1999) observed increased canola S uptake at high rates of hog and cattle manure application while Assefa (2002) observed increased uptake only on high cattle manure trial and interestingly no response to ammonium sulphate fertilizer. In Charles's (1999) study, canola crop S uptake increased from 25 to 42 kg/ha by increasing hog manure sulphate addition from 16 to 66 kg resin SO_4/ha. In Montana environment, about 20 kg S/ha was adequate for optimum seed and oil yields (Jackson 2000).

Table 5.5. The fraction of total P (TP) as organic P (OP) or inorganic P (IP) in different manure types (Eghball et al., 2002).

	OP/TP (%)	IP/TP (%)
Feedlot manure	25	75
Composted manure	16	84
Dairy	25	75
Poultry litter	10	90
Swine	9	91

5.3.3.2. Cations

Amongst the cations monitored during the study period, ammonium (NH_4^+) has shown a temporary response to manure application but the rest of the cations (Ca, Mg, K, and Na) have shown variation on different sample dates for all the transects. A high ammonium concentration at the upper slope position for the 0-15 cm interval of transect C at start date (F99b) is not understandable (Fig.4.18). However, the rest of the data shows increased ammonium concentrations on transects B and C for the sample date of fall 1999a (F99a) after manure application. In well-drained soils, oxidation of ammonium to nitrate is fairly rapid (Prasad and Power, 1997) and it might be the reason that the fall 1999a concentrations of ammonium did not persist to spring 2000. The nitrate data discussed in the previous section support this phenomena because the nitrate levels were high in spring 2000 instead of in fall 1999 after manure application (F99a) and ammonium may have converted to nitrate during this period. While looking on the whole data (Fig.4.18) and specifically the bottom slope positions, it can be deduced that observed ammonium concentrations can also be the result of mineralization because the bottom slope positions of all the transects contain high organic matter (Table 4.3). Other studies have reported results only for Fall after crop harvest (Charles 1999, Assefa 2000) and the results are similar to present study i.e., no ammonium differences between control and manure treatments, and also no sign of ammonium leaching.

Within a period of one year and under a single application of manure treatment, dissolved cation (Ca, Mg, K, and Na) concentrations at the end of study (fall 2000) remained unchanged (Figs. 4.20 to 4.23). Other short term studies under manure application and using different soil analysis methods than present study have reported changes in extractable potassium to be non-significant in Black soils (Charles 1999) but significant in Gray soils (Assefa 2002). Some long-term studies have reported that all four cation concentrations increased in manure-amended soil as compared to soil receiving no manure (Chang et al. 1990 and, Clark et al. 1998). Generally, the concentration of cations in the study transects is good for crop production except for soluble K which is low at the middle positions of transects A and C, and of moderate level on all the other slope positions of the three transects. Singh and Jones (1975) have suggested a critical soil solution K concentration of 8.7 mg/l for crops that need low amounts of K (e.g., tomatoes and beans) and 14.5 mg/l for crops such as celery and potatoes that have a high K requirement. Levels of water-soluble K below 8 mg/l may suggest K deficiency. During the first year of manure application, nearly 100% potassium, greater than 55% of Ca and Mg, and less than 40% of other micronutrients (Zn, Fe, Mn, Cu, and S) are available for plant uptake (Eghball et al. 2002).

5.3.3.3. Indicators for Dissolved Ions

The following discussion presents two composite indicators to show changes in fertilizer residues with respect to slope position and depth of the study transects.

(a) Inorganic Nitrogen

The impact of study treatments on the water soluble forms of N (ammonium, nitrate, and nitrite) has shown higher levels in the manured treatments (transects B and C) as compared to the chemical fertilizer treatment (transect A) (Table 5.6). This table is based on the inorganic N classification ranges (Wolf 1999) reviewed in chapter 2 and the inorganic N data collected by the study (Table 4.7, Fig 4.15). Inorganic N classification ranges on transect A shows most of the data points in the 'poor' category throughout the study period except for spring 2000 which have 2 data points have N in the 'good' range (Table 5.6). For transects B and C, there are more points in the higher N ranges shows higher inorganic N for plant consumption from manure application on these transects. At the end of the crop growing season (fall 2000), only one point on transect C has shown N concentration in the 'good' range. From this information the following questions and interpretations have arisen:

- Was the background (fall 1999b) pool of inorganic N (Fig. 4.15), organic carbon and total nitrogen (i.e., mineralization potential) (Tables 4.3, 5.2, and Fig. 4.10) enough to meet crop requirement It was certainly not the case due to most of the data points falling in poor N range on all the transects?
- Was the N level enough after manure application (fall 1999a)? There was some improvement on transects B and C but still more data points were in poor range and there was some mineralization potential of manure and organic matter.
- In spring 2000, it was perhaps the result of organic matter mineralization that transect A showed 2 data points in good N range (Table 5.2), and the result of both manure and organic matter showing 3 data points in good range on transects B and C. The two points on transect A having N in good range belongs to 0-15 and 15-30 cm depths at bottom position (Fig.4.15, Appendix E10) with organic carbon : total nitrogen ratios of 11 and 12 (Table 5.2), respectively.
- After passing through the growing season and hopefully meeting the crop N requirements from all sources, most of the data points went back to poor N range with the exception of one point on transect A in fair range and one on C in good range. It shows that the applied manure and chemical fertilizer rates have not shown build up of residual N and there may be a margin of using higher application rates without risk to the environment.

Table 5.6. An account of sampling points on study transects categorized to total inorganic N ($NO_2 - N$ plus $NO_3 - N$ plus $NH_4 - N$) concentration ranges in soil solution during the study period (N ranges are adapted from Wolf 1999).

N ranges (ppm)	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
Transect A				
Poor (0-14)	9	9	7	8
Fair (15-24)	0	0	0	1
Good (25-75)	0	0	2	0
Transect B				
Poor (0-14)	9	7	6	9
Fair (15-24)	0	1	0	0
Good (25-75)	0	1	3	0
Transect C				
Poor (0-14)	8	6	5	8
Fair (15-24)	1	1	1	0
Good (25-75)	0	2	3	1

Sodium Adsorption Ratio (SAR)

The calculated SAR values remained very low with respect to a 'normal soil' limit (< 3) (Table 5.7, Appendix H). In fall 1999 before manure application (0-15 cm), SAR seems to have a lower range on slope positions of transect A (0.25 to 0.27) as compared to transects B (0.30 to 0.57) and C (0.09 to 0.59). For the subsequent dates, SAR values showed small changes without a discernible pattern. For transect A, the SAR values are similar in 0-30 cm depth (0.15 to 0.30) but relatively higher in 30-60 cm depth mainly on its middle and top positions (0.25 to 1.0). For transects B and C, SAR values are also generally higher on middle and top positions as compared to bottom and varies in a similar range in the whole soil profile. Changes in SAR can be attributed to soil and analysis variability.

Table 5.7. Sodium Adsorption Ratio (SAR) on study transects.

Depth (cm)	Transect	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
0-15	A	0.26 (0.0)	0.22 (0.0)	0.19 (0.0)	0.16 (0.0)
	B	0.46 (0.1)	0.49 (0.1)	0.40 (0.1)	0.30 (0.0)
	C	0.30 (0.2)	0.48 (0.0)	1.14 (0.9)	0.27 (0.0)
15-30	A	0.25 (0.0)	0.28 (0.0)	0.21 (0.1)	0.16 (0.0)
	B	0.25 (0.0)	0.40 (0.1)	0.24 (0.0)	0.21 (0.0)
	C	0.42 (0.3)	0.51 (0.3)	0.87 (0.7)	0.25 (0.1)
30-60	A	0.37 (0.2)	0.77 (0.3)	0.51 (0.3)	0.30 (0.1)
	B	0.52 (0.2)	0.53 (0.0)	0.45 (0.1)	0.37 (0.1)
	C	0.75 (0.3)	0.89 (0.5)	0.64 (0.2)	0.45 (0.1)

Note: Each value is an average of 3 slope positions of respective transects with standard deviation in bracket.

5.3.4. Concentration of Exchangeable Cations

The soil pool of exchangeable cations is the primary reserve of cations for solution and is more stable than the soluble pool over time (Clark et al. 1998). Because of its stability, there has been little research work focused on assessing the changes in the exchangeable cation pool within a period of season or year. The results of the present study have revealed that the concentration of exchangeable ions are in the order of Ca > Mg > K > Na (Figures 4.24 to 4.26, Appendix F), which is similar to their dissolved concentration order. Over the study period, some changes in cations were observed on bottom and middle slope positions: exchangeable Ca had an increase in the order of 0.80, 4.70 and 7.50 meq/100g on transects A, B, and C, respectively at bottom positions (0-15 cm); while Mg decreased on the bottom positions (30-60 cm) on all the transects; and, K had increased on bottom and top positions (0-15 cm) on all the transects. Most of the changes are non-significant. Exchangeable Na remained below detection limit, which can be supported from Bernal et al. (1992) that the soluble-Na / exchangeable-Na equilibrium tends towards soluble – Na because of the easier retention of other cations (e.g. K) in the exchange complex. When manure is applied to the soil, the plant-availability of nutrients may increase due to mineralization or decrease due to immobilization, depending on the soil and manure properties (Eghball et al. 2002).

Therefore, the above-mentioned changes in exchangeable cations may be attributed to several processes such as the soil variability, analytical error, background conditions, treatment applications and the growing season climatic factors, which have been discussed in the previous sections. As the soil of study area is already rich in the basic cations (dissolved and exchangeable), long-term research work may be required to assess the adverse or beneficial effect of different fertilizing practices. Normally, the known composition of chemical fertilizers provide fair control on macro and micro nutrient application, while animal manure usually contains most of the nutrients readily available for crop uptake and to replenish the exchange complex (Table 4.4). The lack of options in selective application of a deficient nutrient from animal manure may require extra caution in the case of cation rich soil of the present study area while planning the manure application for supplying macronutrients on a continuing basis. Proper nutrient management for future concerns may have to consider landscape variability with use of precision agriculture concepts. Precision agriculture and variable nutrient application have shown potential benefits in sustaining soil fertility while avoiding the differential enrichment of certain landscape positions (Khakural et al.1996; Solohub et al. 1996; and, Mulla and Bhatti 1997).

5.3.4.1. Indicators for Exchangeable Cations

Ratios of individual exchangeable cations as percent of CEC has shown that on exchange sites, calcium is in the highest range (60-100%), magnesium in the middle (20-60%), and potassium is in the lowest range (1-5%) (Table 5.8). The average values of different ratios have not indicated a change during the study period. The ratios (Ca / CEC) and {(Ca+Mg+K) / CEC} exceed 100% on some points (Table 5.8) because of naturally high $CaCO_3$ content of soil which results in high exchangeable Ca values in spite of good washing of the soil samples before analysis of exchangeable cations (Lisa Groves, ETL, personal communication). Relatively, low values of the ratios at bottom positions (0-15 cm) can be attributed to naturally well-leached soil condition by excessive water accumulation in runoff from upper positions and its infiltration in the soil profile.

5.3.5. Fertilizer Nutrients and Soil Moisture

Soil water content is a critical determinant of most processes that govern the availability of nutrients in field soils (Fillery 1999) and also, soil water facilitates several processes leading to the nutrient loss (Figures 2.2 and 2.3). Soil texture is one factor to correlate with the soil moisture on the study transects (Table 5.9), which is in the order of clay content (0-15 cm) of study transects as C(32%) > B(25%) > A(23%) and leading to slight variation of soil texture classes as on transect A(silt loam), B(loam), and C(clay loam) (Appendix B). Due to textural differences, plant available water on study transects may vary to some extent with respect to a criteria used in the preparation of stubble subsoil moisture maps in Saskatchewan (Table 5.10).

Table 5.8. Exchangeable cations with respect to CEC on study transects.

Transect	Slope	Depth: 0-15 cm		Depth: 15-30 cm		Depth: 30-60	
		Fall 1999b	Fall 2000	Fall 1999b	Fall 2000	Fall 1999b	Fall 2000
Calcium / CEC (%)							
A	Bottom	90	94	86	96	52	85
	Middle	116	111	95	88	124	80
	Top	73	82	99	97	54	62
B	Bottom	61	82	84	83	53	70
	Middle	96	68	82	84	86	76
	Top	102	94	93	83	70	63
C	Bottom	55	88	97	87	30	64
	Middle	107	91	102	88	88	91
	Top	79	87	87	68	58	58
Magnesium / CEC (%)							
A	Bottom	18	20	20	22	59	24
	Middle	30	29	27	37	36	64
	Top	30	24	31	42	54	55
B	Bottom	25	16	16	17	53	23
	Middle	21	23	27	32	24	63
	Top	44	27	32	39	47	51
C	Bottom	34	22	22	27	62	34
	Middle	25	27	35	38	40	72
	Top	40	35	44	62	69	92
Potassium / CEC (%)							
A	Bottom	1.4	5.8	4.9	3.1	2.1	3.0
	Middle	4.5	3.0	2.1	1.8	4.2	2.5
	Top	1.1	3.3	3.1	2.5	1.4	2.4
B	Bottom	1.2	4.9	3.3	1.5	2.1	2.5
	Middle	1.5	2.9	3.0	1.9	1.7	2.8
	Top	1.6	4.4	3.2	2.4	1.5	2.8
C	Bottom	1.5	4.4	6.2	2.0	1.9	2.4
	Middle	3.4	2.3	1.8	1.7	2.0	2.9
	Top	1.5	2.8	4.2	2.4	2.6	3.4

In addition differences in soil moisture may also be attributed to differences in soil surface disturbance on control and manure treatments and the resulting infiltration patterns. These differences may not be large because of the similar minimum tillage system adopted on the study transects, and also because variation in infiltration and runoff patterns have been reported only under different tillage systems and especially during the spring snowmelt (Elliott and Effetha 1999; Elliott et al. 2001).

Table 5.9. Average gravimetric soil moistures on study transects.

Transect	Fall 1999a	Spring 2000	Fall 2000
Soil depth: 0-30 cm			
A	0.08	0.15	0.16
B	0.10	0.17	0.15
C	0.13	0.20	0.16
Soil depth: 0-60 cm			
A	0.08	0.13	0.15
B	0.10	0.15	0.15
C	0.13	0.19	0.15

Table 5.10. Plant available water stored per 30.5 cm of moist soil for various soil textures (adapted from SAF 2004).

Soil Texture	Centimeters of soil water per 30.5 cm of moist soil
Sand	1.9
Loamy sand	2.5
Sandy loam	3.2
Loam	3.8
Clay loam	4.4
Clay	5.1

Soil moisture observations on certain dates have helped to understand changes in some residue (Cl and NO_3) concentrations. For example, the bottom slope position at transects B and C have shown higher Cl and NO_3 concentration at deeper depth intervals (15-30 & 30-60 cm) (Figures 4.14 and 4.17). This may be attributed to several factors such as, the higher rate of these ions input in manure application, their accumulation at bottom position in surface runoff from upper positions, and also their high water solubility. *Vice versa*, the conservative ions like Cl may act as tracer of the water flow pathways because the ions are not adsorbed or converted to other ionic forms as compared to different forms of inorganic N (Jury et al. 1991). In spite of probable NO_3 accumulation at bottom positions, the higher soil moisture at this slope position may have contributed to higher denitrification losses resulting in overall low level N levels at the end of study (Table 5.6). Moreover, the chances of NO_3 leaching are minimal on prairie dryland. Rolston et al. (1978, 1979) reported that NO_3 leaching was completely diminished by reducing soil moisture content from about nearly saturated conditions (-15 cm) to partially saturated conditions (-70 cm) (Figures 2.2 and 2.3) which were not the soil moisture conditions for an extended period during the course of present study. Also the soil moistures in Rolston et al. (1978; 1979) studies were maintained constant for entire season while in actual field conditions of present study, several dry-wet cycles are expected to control denitrification, mineralization, and leaching processes.

There are no simple answers to some of the water-related processes on sloping landscape of present study. For example, there were two points (0-15 and 15-30 cm depths) at the bottom position of transect A having inorganic N in a good range for spring 2000 which were in the poor range on the previous fall 1999a sample date (Table 5.6). At the same date (spring 2000) the middle position of the same transect having about similar carbon : nitrogen ratios (Table 5.2) and soil moisture (Figure 4.27) showed soil solution N in the poor range. In this situation, the assumption is that the bottom position may have received N contribution from upper positions because inspite of similar mineralization potential, middle position has not shown such an increase.

5.3.6. Crop Yield

Crop yield is another indicator of fertilizers, and yield response to different types and rates of fertilizer application have been reported in several studies (Dormer 1997; Charles 1999; Jackson 2000; Assefa 2002). A specific interest of the present study has been to understand relationships between crop yield and fertilizer residues on different slope positions amongst the study treatments. To discuss the differences in yield requires a brief elaboration of the study treatments in terms of the actual rates of fertilizer inputs during the crop season. From the fertilizer input data, given in Table 3.3, transects A, B, and C received chemical fertilizer N at the rates of 56, 12, and 12 kg/ha respectively while transects B and C received additional manure N at the rates of 220 and 315 kg/ha showing the total N input pattern as: transect C (327 kg/ha) > B (232) > A (56). Similarly, transects A, B, and C received chemical fertilizer P at the rates of 13, 12 and 12 kg/ha respectively while transects B and C also received additional manure P at the rates of 137 and 206 kg/ha, respectively. With such fertilizer treatments, transects B and C also received several other constituents (e.g., Zn, Fe, Mn, Cu, and S) of manure (Table 4.4) which have normally good effect on crop yield.

Comparisons of spring total inorganic N to crop yield (Table 5.11) show a positive relationship with a correlation (R^2) of 0.50 between the total inorganic N in the 0-60 cm depth and yield as compared to a correlation (R^2) of 0.63 of N and yield in 0-30 cm (data not shown) (Appendix I). Soil inorganic N is total inorganic N in spring 2000 (Table 4.7, Fig. 4.15) converted to field values in kg/ha (Appendix I). The calculations are based on field bulk densities of 1.20, 1.40, and 1.59 g/cm^3 for 0-15, 15-30, and 30-60 cm depth intervals, respectively, with the bulk density values decided by considering data from present and previous studies (Professor Charles Maulé, 2004, Personal Communication). Spring 2000 soil samples were collected before spring fertilizer application.

Table 5.11. Inorganic N and canola crop grain yield on study transects.

Slope position	Soil Inorg. N in spring 2000 (0-60 cm) (kg/ha)	Application of Fertilzer N in spring 2000 (kg/ha)	Total Inorg. N for crop uptake in spring 2000 (kg/ha)	Crop grain yield (kg/ha)
Transect A				
Bottom	75.5	56	131.5	1963
Middle	27.5	56	83.5	1385
Top	14.1	56	70.1	1485
Average	39.0		95.0	1611
Transect B				
Bottom	64.0	12	76.0	2243
Middle	87.2	12	99.2	2328
Top	97.3	12	109.3	1790
Average	82.8		94.8	2120
Transect C				
Bottom	135.1	12	147.1	2615
Middle	42.7	12	54.7	1178
Top	118.2	12	130.2	2093
Average	98.6		110.7	1962

An overall comparison shows the highest yield (2615 kg/ha) on the bottom slope position of transect C having the highest total inorganic N (147.1 kg/ha) in spring 2000 and the lowest yield (1178 kg/ha) on the middle position also of transect C with the least N (54.7 kg/ha) in spring 2000. As compared to the average wheat yield pattern in 1999 (B > A > C) (Table 4.17), canola yield has shown an increase on transect C as compared to A (B > C > A), which may be attributed to higher inorganic N (Table 5.11) and also other nutrients added with manure on transect C (Table 4.4). However, transect B having similar to transect A average inorganic N shows the highest canola yield, which may be related to the higher (than transects A and C) background soil fertility characteristics such as organic carbon and total nitrogen on this transect (sections 4.1.2 and 5.2).

From the information in Table 5.11, the availability of soil N in spring at the beginning of the crop growing season has shown a strong relationship with the crop yield. However, the observed soil N in spring (the averages are 82.8 and 98.6 kg/ha for transects B and C) is much lower than the actual input from manure on transects B (220 kg/ha) and C (315 kg/ha) (Table 3.3). The manure chemistry data (Table 4.4) shows that the ammonium - nitrogen (NH_4-N) is 68% of total N. Much of the manure NH_4-N likely transformed to NO_3 in spring 2000 (Figures 4.17, 4.18 and 5.2) and might had incurred some losses showing less soil N in spring 2000. About 20% of the organic N (which is computed by subtracting ammonium from total nitrogen, Table 4.4 and is 32% of total manure N) in the liquid manure hog effluent can also become available for plant growth through mineralization over a growing season (Schoenau et al. 1999). Dormer (1997) has reported that the increase in yield with manure application may not be a phosphorus effect because hog manure application had no effect on soil P. Schoenau et al. (1999) also showed that the addition of manure had little or no impact on extractable inorganic P levels in the soil following application. The same study suggests that about 22% of P in readily soluble inorganic form is normally available in the year after a fall hog manure application. Calcareous prairie soils with high pH and CEC have an ability to strongly bind P and this relative immobility of P in the soil profile allows for building of the P reservoir in prairie soils without risk of leaching (Bolton 1999).

In prairie landscape, variability in inherent soil fertility and productivity of different slope positions have been reported under uniform fertilizer application treatments (Dormer 1997) and under variable rate fertilization practices (Dumonceaux 2001; Solohub et al. 1996; Walley et al. 2001). Spring soil moisture has been reported to be a major factor in determining the yield and the protein content of wheat both within different years and between different landscape positions within a given year (Walley et al. 2001). The soil moisture on slope positions may respond to crop development differently because even the subsoil drying at particular crop development stage is considered essential for movement of nutrients into the subsoil matrix (Arya et al., 1999) and for the extension of root zone (Claassen and Steingrobe 1999). Moulin et al. (1994) have reported nonlinear relationships between elevation of slope positions versus soil properties and yield measurements, which are similar to the results of present study. Moreover, Brenk et al. (1999) have noted that trials conducted simultaneously for a targeted increase of phosphate and potash fertilizer rates on sub-sites with low soil nutrient content showed no positive effect on the crop yield. In a comprehensive study under several treatments in Montana, Jackson (2000) has reported linear and quadratic relationships between canola seed yield and nitrogen application rate suggesting that the relationship between total plant yield and N reflects the tendency of canola to exhibit an indeterminate growth habit when nutrients and water are essentially unlimited with no heat stress.

6. SUMMARY AND CONCLUSIONS

6.1. Summary

Manure is a useful source of nutrients on cropland, however there is concern about the possible build-up of residues (nutrients) under certain conditions. The present study is focused on the spatial and temporal monitoring of manure residues on cropland within a prairie region of undulating landscape over a one year period from just before fall injection of manure to the fall following crop harvest. The study was conducted under field conditions with normal agricultural practices of the land owner and using a commercial manure applicator. There were three fertilizer application treatments: a 'control' receiving chemical fertilizer; and two treatments receiving injected hog manure 78.7 and 112.4 m^3/ha (7,000 and 10,000 gal/ac). These fertilizer treatments were applied on three nearby small watersheds, referred to as A, B and C on a Perdue area farm about 60 km west of Saskatoon in the Dark Brown soil zone.

The impact of the study treatments was assessed by monitoring soil chemistry, crop yield, and soil moisture on different slope positions of sample transects within each watershed. For studying the treatment effects, the slope positions on each transect were first characterized for their background properties before manure application (Fall 1999) such as landscape forms, soil texture, cation exchange capacity (CEC), and concentration of nutrients and salts (total, dissolved, and exchangeable). Relative changes in soil chemistry were observed during the study period by further soil sampling immediately after manure application, in Fall 1999, Spring 2000, and Fall 2000.

The sample study transects were comparable in terms of slope position and slope features, but had differing aspect; SW for transect A, NE for B and N for C. Soil texture, for transects A, B, and C, was silt loam, loam, and clay loam, respectively. On all transects, clay content slightly increased with increase in elevation and remained constant with depth whereas sand content showed some variation. Organic carbon content was highest at bottom positions (2.07% on transect A, 3.49% on B, and 2.21% on C) and lowest for the middle positions at A (0.64%) and C (0.80%), whereas it was lowest on the top position for B (0.66%). Similar patterns were found for other properties such as cation exchange capacity, total nitrogen and total phosphorous.

In assessing the treatment effects, soil electrical conductivity (EC) varied greatly over the study period, however, the observed changes were found irrespective of the fertilizer treatments showing no relation to manure application. The variations of soil pH were normal for a crop cycle. Sodium adsorption ratios (SAR) did not show any sodium problem, nor any response to manure application. Average total inorganic nitrogen (TIN) concentration for the spring following manure application, was significantly greater on the transects that had received manure application. By the end of the growing season (Fall 2000) average TIN was lower and similar for all three transects. The bottom slope position of all the treatments had greater increases in TIN during spring 2000 than other slope positions. For deeper soil depths (15-30 cm and 30-60 cm) for the B and C transects this increase stayed or further increased for fall of 2000. This may be attributed to more downward movement at lower slope positions as a result of runoff contribution from upper positions and/or the higher reserve of organic matter at the bottom positions. Ratios of exchangeable cations with CEC showed that there were no major changes in the addition or removal of exchangeable cations from exchange sites.

Consideration of specific ions and elements found that chloride and nitrate concentrations increased on manure treatments as compared to the control, and the pattern of these anions on different slope positions can be attributed to soil moisture distribution processes on the undulating landscape. At the end of study period (fall 2000), there were non-significant positive changes (increase) in the 30-60 cm depth interval for the bottom slope positions of the manure treatments for chloride while nitrate increased on all the treatments and slope positions with a relatively higher increase only for transect C for the 15-30 cm and 30-60 cm depths. For the rest of the anions (ammonium, phosphate, sulphate) and cations (calcium, magnesium, potassium, sodium), the fall 2000 concentration levels showed no relationship with the fertilizer treatments. Exchangeable cations showed stable conditions.

In addition a higher canola crop yield was observed on manure treatments as compared to the control receiving the chemical fertilizer, but the relative increase in crop yield was not uniform between slope positions. Generally, the concentration of fertilizer residues on landscape and in soil profile during the study period (one year) has shown that the chemical fertilizer and manure application rates adopted by the farmer were safe for the environment with above average yield in the crop district. However, continuous use of such rates may potentially pose problem of nitrate accumulation and leaching at bottom slope positions.

6.2. Conclusions

Sloping cropland in Saskatchewan has soil variability related to landscape position and the characterization of the study site in terms of physical and chemical properties was the first objective. Selected sample transects representing three study treatments were compared in terms of established terrain attributes and comparable landform elements were found on respective sample positions of the three transects with the exception of aspect. Aspects were South West for transect A, North East for B, and North for C, while all transects had low-gradient convex upper slopes, steep-gradient straight middle slope, and, low-gradient concave lower slopes. Other conclusions related to 1st objective are:

- Clay contents were similar on sample positions within each study transect and soil textural classes of individual transects were silt loam, loam, and clay loam for transects A, B, and C, respectively.
- The chemical characteristics of all the transects were similar in terms of organic carbon (OC), total nitrogen (TN), total phosphorus (TP), and cation exchange capacity.
- For all the transects, elemental concentration levels (OC, TN and TP) were highest at lower positions. Inorganic carbon was lowest at the lower positions.
- Ratio of organic carbon : total nitrogen was more reflective of background soil fertility on sloping land as compared to the total carbon : total nitrogen ratio.

To assess and evaluate changes in soil fertilizer residues upon a seasonal and landscape basis were the second and third objectives of the thesis. The findings for both the objectives together are:

- Observed levels of dissolved ions showed that by the end of the study period, fall 2000, chloride and nitrate anions increased on manured lower slope positions especially at their lower depths. This increase could be due to the lower slope positions receiving additional moisture and nutrients in runoff from upper slope positions while higher organic matter at lower positions may be another factor to contribute nutrients by mineralization. The concentration level of these anions showed a link to the fertilizer application rates which for nitrate can be either chemical fertilizer or manure but chloride is specifically related to manure application.
- The rest of the fertilizer residues (phosphate, sulphate, calcium, magnesium, potassium, and sodium) have not shown such changes.
- During the study period, exchangeable calcium, magnesium, and potassium remained unchanged on all the treatments while exchangeable sodium was below detection limit.
- The concentration of fertilizer residues in different landscape positions and within the soil profile during the study period has shown that the chemical fertilizer and manure application rates adapted by the farmer were safe for the environment with above average yield in the crop district. However, continuous use of such rates may at least pose a problem of nitrate accumulation and leaching at bottom slope positions.

Identification and evaluation of indicators for managing fertilizer residues was the last objective and the conclusions are:

- This study has found that indicators based on ratios (C/N, SAR, Cations/CEC) and composite soil properties (EC, pH) may be useful to monitor the impact of different fertilizer applications on a long term basis. The reason might be that soil chemical changes reflecting fertilizer residues may need longer times to occur. Therefore, simple relative changes in the concentration of individual residues such as chloride and nitrate may be more useful to monitor on a short-term basis and to use to manage fertilizer applications because good nitrate levels are important for crop growth, but high levels at inappropriate times and depths must be avoided due to environmental concerns. Chloride can supplement information as a tracer especially due to its presence in animal manures.
- In this study, evaluation of soil inorganic N indicator based on lab results with respect to general criteria from literature and which was also comparable directly with the lab results without lab-to-field unit conversions proved useful. The conversion of results from lab-to-field level may involve unavoidable variability of bulk densities and soil moistures found in analytical procedure of this study. Therefore, a better alternative is to recommended fertilizer N application rates based on lab results especially when the requirement of a diagnostic test procedure provide some lab results.

6.3. Recommendations

The assumption of uniform manure application in the present study can only be supported to be true from similar observed levels of residue concentrations and their distribution patterns in the control as well as the manure treatments. Further work is required to understand the diffusion mechanism of injected manure to avoid banding of manure constituents especially under minimum tillage system and repeated manure application on dry land.

With respect to the timing strategy of manure application in fall, the study found lower inorganic nitrogen in the spring than what manure added in the fall. This discrepancy is attributed to the low recovery of manure nutrients and/or losses linked to the intervening snowmelt event with no definite answer. Further work is required on manure application techniques and timing strategy to account and avoid losses. This type of research work requires to be conducted in conjunction with measurement of soil moisture and runon especially on sloping landscapes.

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APPENDIX A. PRECIPITATION AND TEMPERATURE DATA.

Appendix A1. Weekly rainfall data reported from two locations in the Perdue municipality area during crop season
(Weekly Crop Reports 1998 - 2000, Saskatchewan Agriculture and Food).

Month	**Week**	**Perdue 346 A**			**Perdue 346 B**			**Average**		
		1998	1999	2000	1998	1999	2000	1998	1999	2000
April	1	0	0	15	0	0	21	0	0	18
	2	0	0	8	0	0	5	0	0	6.5
	3	3	0	3	6	0	3	4.5	0	3
	4	0	7	0	0	11	3	0	9	1.5
May	5	0	0	0	0	0	0	0	0	0
	6	1	27	13	0	34	12	0.5	30.5	12.5
	7	0	19	0	0	24	0	0	21.5	0
	8	0	0	3	1	0	3	0.5	0	3
June	9	7	18	14	8	16	8	7.5	17	11
	10	2	10	12	2	38	18	2	24	15
	11	45	23	0	57	24	4	51	23.5	2
	12	50	16	20	28	31	31	39	23.5	25.5
July	13	29	18	35	5	29	68	17	23.5	51.5
	14	9	37	24	15	36	79	12	36.5	51.5
	15	0	3	12	1	8	11	0.5	5.5	11.5
	16	0	13	0	0	20	0	0	16.5	0
August	17	0	20	10	0	18	31	0	19	20.5
	18	0	17	83	0	10	76	0	13.5	79.5
	19	17	10	1	12	16	0	14.5	13	0.5
	20	0	0	35	0	0	33	0	0	34
September	21	0	0	0	0	0	1	0	0	0.5
	22	0	0	0	0	2	0	0	1	0
	23	26	0	0	54	0	0	40	0	0
	24	9	0	0	9	0	0	9	0	0
Total		198	238	288	198	317	407	198	277.5	347.5

Appendix A2. Monthly precipitation and temperature at Saskatoon airport (Environment Canada 2000).

Month	**Precipitation (mm)**			**Normal***	**Temperature (°C)**			**Normal**
	1998	1999	2000	1970-2000	1998	1999	2000	1970-2000
January	13	27	20	16	-18	-17	-17	-18
February	4	6	13	13	-6	-10	-11	-14
March	9	9	22	16	-7	-5	-2	-7
April	7	15	41	20	7	7	4	4
May	9	50	16	44	13	11	11	12
June	75	59	50	63	15	15	14	16
July	31	80	83	58	19	16	19	19
August	37	43	42	37	20	18	17	17
September	27	20	27	32	13	10	12	11
October	50	9	0	17	5	4	5	5
November	7	5	10	14	-4	-1	-6	-6
December	11	14	21	17	-13	-7.5	-19	-15
Total	280	335	345	347				

APPENDIX B. SOIL TEXTURE DATA (FALL 2004).

Depth	Slope positions					Mean	Texture
	Depre.	Toe	Middle	Shoulder	Upper		
Transect A							
%CLAY							
0-15 cm	24	23	21	23	24	23	
15-30	26	25	21	20	26	24	
30-60	27	22	22	16	19	21	
				Transect mean =		23	
%SAND							
0-15	22	21	16	13	25	19	Silt loam
15-30	22	16	6	8	22	15	Silt loam
30-60	14	27	5	21	23	18	Silt loam
				Transect mean =		17	
Transect B							
%CLAY							
0-15	23	21	23	27	28	24	
15-30	22	18	27	28	32	25	
30-60	22	19	33	27	28	26	
				Transect mean =		25	
%SAND							
0-15	29	33	41	35	28	33	Loam
15-30	27	35	31	32	25	30	Loam
30-60	32	36	19	27	14	25	Loam
				Transect mean =		30	
Transect C							
%CLAY							
0-15	30	26	28	34	35	31	
15-30	32	24	22	38	44	32	
30-60	39	21	28	36	39	33	
				Transect mean =		32	
%SAND							
0-15	19	26	30	22	15	22	Clay loam
15-30	17	30	36	18	6	21	Clay loam
30-60	9	35	30	17	6	19	Clay loam
				Transect mean =		21	

APPENDIX C. TOTAL CARBON, NITROGEN, PHOSPHOROUS, AND CATION EXCHANGE CAPACITY DATA (FALL 1999B).

Transect	Slope position	Depth (cm)			Depth (0-15 cm)	
		0-15	15-30	30-60	Inorg.C(%)	$CaCO_3$(%)
Total Carbon (%)						
A	Bottom	2.3	2.1	2.3	0.23	1.9
	Middle	1.6	1.6	1.8	0.96	8.0
	Top	1.3	1.6	1.7	0.37	3.1
B	Bottom	3.7	3.6	2.3	0.21	1.8
	Middle	2.0	2.4	1.4	0.51	4.3
	Top	1.7	1.6	1.6	1.04	8.7
C	Bottom	2.5	2.6	1.7	0.29	2.4
	Middle	1.5	1.9	2.0	0.70	5.8
	Top	2.5	2.1	1.6	1.59	13.2
Total Nitrogen (%)						
A	Bottom	0.24	0.22	0.22		
	Middle	0.12	0.09	0.05		
	Top	0.12	0.09	0.07		
B	Bottom	0.35	0.34	0.22		
	Middle	0.18	0.11	0.07		
	Top	0.13	0.07	0.06		
C	Bottom	0.25	0.26	0.17		
	Middle	0.11	0.08	0.05		
	Top	0.14	0.07	0.06		
Total Phosphorous (μg/g)						
A	Bottom	642	628	616		
	Middle	585	607	623		
	Top	550	554	608		
B	Bottom	689	744	707		
	Middle	578	587	530		
	Top	516	508	610		
C	Bottom	682	657	686		
	Middle	474	530	532		
	Top	762	617	642		
CEC (meq/100g)						
A	Bottom	20.1	19.9	21.4		
	Middle	15.2	16.9	13.2		
	Top	20.1	15.4	16.7		
B	Bottom	22.5	23.0	19.3		
	Middle	19.9	19.1	14.8		
	Top	15.8	15.2	15.8		
C	Bottom	22.7	20.8	22.3		
	Middle	19.5	16.9	13.7		
	Top	19.1	17.3	15.6		

APPENDIX D. ELECTRICAL CONDUCTIVITY AND pH DATA.

Appendix D1. Electrical conductivities of soil saturated paste extracts (μS/cm).

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
Transect A												
1	421	610	841	583	438	344	738	443	315	321	525	367
2	350	346	486	396	296	212	353	322	563	295	305	318
3	310	440	548	526	374	380	450	402	435	404	530	412
4	469	535	493	652	398	406	455	446	919	428	481	554
5	425	506	526	468	329	446	494	417	763	563	552	562
6	473	504	480	720	376	428	472	485	410	410	428	495
Transect B												
1	606	1116	722	594	355	163	292	330	305	222	321	475
2	389	1117	385	511	174	198	338	314	618	230	319	372
3	1191	869	1112	758	582	382	570	575	636	428	522	570
4	529	881	1314	738	403	422	532	454	575	467	548	449
5	1164	876	1120	558	377	452	569	378	551	457	409	578
6	580	606	1369	565	406	356	514	465	496	496	632	586
Transect C												
1	822	1735	1040	600	314	362	602	697	230	187	350	388
2	489	468	969	521	330	414	642	406	649	406	470	463
3	471	1005	472	464	331	494	465	397	451	401	418	439
4	713	824	1379	587	376	389	513	435	649	457	495	458
5	1456	770	1335	768	518	472	2240	487	894	1226	913	600
6	1006	509	4280	578	462	569	506	509	524	524	4630	4160

Appendix D2. pH values for saturated paste extracts.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
Transect A												
1	8.1	7.7	7.4	8.0	8.3	7.9	6.8	7.9	6.6	7.7	6.8	7.7
2	8.1	7.5	6.5	7.8	8.1	7.7	6.3	7.7	7.5	7.9	6.6	7.8
3	8.1	7.8	7.3	8.0	8.3	8.1	7.3	8.0	7.4	8.0	7.6	8.0
4	8.2	8.2	7.6	8.0	8.2	8.5	7.7	8.0	7.3	8.5	7.8	8.0
5	8.5	7.9	7.5	8.0	8.3	8.4	7.3	8.1	7.2	8.5	7.7	8.2
6	8.3	8.4	7.4	8.0	8.1	8.4	7.7	8.0	7.2	8.5	8.2	8.1
Transect B												
1	8.2	7.2	6.9	7.6	8.2	7.1	6.4	7.4	7.0	7.5	6.5	7.8
2	8.1	7.3	6.5	7.2	7.8	8.0	7.0	7.3	7.8	7.8	6.9	7.8
3	8.2	8.4	7.1	7.9	8.2	8.4	7.3	8.1	7.1	8.6	7.6	8.1
4	8.1	8.4	6.9	8.0	8.0	8.7	7.6	8.0	7.4	8.7	8.0	8.2
5	7.3	8.5	6.8	8.0	7.6	8.7	7.3	8.0	7.5	8.5	7.9	8.2
6	8.0	8.7	7.1	8.0	8.2	8.6	7.8	8.2	7.5	8.8	7.9	8.2
Transect C												
1	7.3	8.4	7.0	8.0	7.3	8.0	7.1	7.2	7.2	7.5	6.4	8.3
2	8.1	8.3	7.0	8.1	7.5	8.5	6.9	8.0	7.1	8.5	7.2	8.1
3	7.7	8.4	7.4	8.1	7.9	8.4	7.7	8.1	7.8	8.7	7.7	9.0
4	7.7	8.7	7.3	8.5	7.8	8.5	7.6	8.1	7.9	8.9	7.7	8.2
5	7.7	8.7	7.5	8.0	8.2	8.9	7.8	8.2	7.6	8.7	7.1	8.3
6	7.7	8.7	7.8	8.7	7.9	8.8	7.9	8.2	7.6	8.8	7.3	7.7

APPENDIX E. DISSOLVED IONS DATA.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
E1. Chlorides (mg/l).												
Transect A												
Bottom	8.3	19.5	7.9	5.5	7.0	5.2	9.8	3.8	4.4	10.1	4.3	3.3
Middle	8.0	6.5	5.8	8.4	6.4	3.7	4.7	5.6	4.7	4.2	3.1	4.1
Top	9.3	12.1	12.9	8.8	7.4	5.2	17.7	7.0	142.6	8.1	8.0	9.1
Transect B												
Bottom	45.5	206.6	15.3	43.9	7.2	9.8	10.0	21.7	4.4	7.8	5.9	19.9
Middle	117.9	94.3	64.9	35.9	27.1	10.0	33.7	17.2	97.6	7.9	9.3	18.9
Top	179.9	76.8	169.0	15.7	18.5	7.9	35.4	14.6	13.0	12.4	17.3	28.9
Transect C												
Bottom	53.4	141.3	9.9	17.3	3.8	15.1	32.2	38.9	4.5	4.6	18.4	19.7
Middle	28.2	129.1	107.3	16.7	7.8	23.9	22.2	11.4	5.0	8.3	7.6	16.1
Top	158.5	52.4	49.7	42.8	10.4	20.5	21.0	21.3	4.9	7.7	16.9	23.0
E2. Nitrates (mg/l).												
Transect A												
Bottom	0.3	3.4	64.6	38.7	0.2	0.7	77.4	44.7	0.1	6.8	13.8	39.4
Middle	14.6	7.6	10.2	5.3	19.8	20.4	24.3	20.4	1.8	11.9	12.1	13.8
Top	0.4	3.5	5.1	5.6	0.4	15.0	18.0	30.0	0.5	4.9	4.6	20.3
Transect B												
Bottom	0.4	34.0	129.2	30.3	0.2	5.3	26.3	46.5	34.2	5.7	6.5	22.7
Middle	0.6	32.2	196.2	8.3	3.0	5.6	24.5	26.0	0.8	5.5	15.5	13.6
Top	4.7	25.0	245.1	3.5	3.6	6.0	25.2	26.0	4.2	9.0	18.0	41.0
Transect C												
Bottom	1.0	51.8	196.4	30.4	1.0	6.0	68.3	152.7	0.0	6.2	36.5	50.8
Middle	0.4	28.9	10.5	41.2	0.5	12.4	12.8	22.0	0.0	6.3	6.2	17.5
Top	0.7	5.5	95.4	18.2	2.7	7.2	9.0	11.4	0.4	4.1	1.3	6.7

Appendix E. Dissolved ions in saturated paste extracts.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
E3. Nitrites (mg/l).												
Transect A												
Bottom	1.3	20.8	42.7	26.9	0.0	8.0	25.2	4.7	0.4	4.3	13.5	1.9
Middle	7.2	7.4	19.5	15.4	2.4	1.1	4.0	1.6	0.5	0.5	4.4	3.3
Top	0.1	5.8	13.4	7.7	2.2	0.4	1.7	1.1	2.1	0.4	2.6	2.1
Transect B												
Bottom	0.4	47.8	37.3	19.4	0.0	0.2	9.9	1.4	1.7	0.1	16.1	3.5
Middle	3.4	11.4	70.1	9.3	3.9	0.8	5.7	2.2	3.0	0.9	5.1	3.4
Top	8.3	10.7	58.0	14.6	1.4	0.8	3.1	2.4	0.9	1.5	9.3	6.1
Transect C												
Bottom	2.2	48.9	76.6	4.4	2.8	8.3	24.7	4.8	0.0	0.3	6.7	5.2
Middle	0.0	17.1	74.1	5.0	1.0	0.9	8.2	0.5	0.0	1.3	9.2	2.6
Top	0.6	7.1	32.3	6.2	3.5	1.8	6.2	1.3	0.3	1.2	65.8	3.0
E4. Sulphates (mg/l).												
Transect A												
Bottom	36.3	32.8	35.9	48.9	33.4	14.6	27.2	25.4	40.2	33.6	45.7	27.1
Middle	30.9	20.1	20.0	81.7	21.4	8.2	15.9	26.5	34.0	18.2	51.3	50.1
Top	27.9	18.6	18.4	75.5	19.2	18.7	20.0	37.7	45.9	60.9	32.5	34.8
Transect B												
Bottom	41.2	40.6	27.0	68.8	21.8	9.7	15.3	25.5	46.0	22.6	25.5	33.2
Middle	24.3	18.6	27.5	36.6	33.7	8.9	14.7	16.9	25.9	17.1	38.8	14.5
Top	27.2	12.9	18.3	26.5	12.2	7.9	13.9	15.1	56.4	14.8	31.8	24.0
Transect C												
Bottom	67.5	49.2	23.1	26.1	15.6	10.5	20.2	15.2	44.2	15.3	28.9	19.3
Middle	64.3	32.6	36.9	33.9	20.0	10.0	13.4	15.9	22.4	12.1	19.0	16.8
Top	227.5	31.2	850.0	90.1	77.5	41.6	837.0	55.6	310.1	384.6	850.0	1469.6

Appendix E. Dissolved ions in saturated paste extracts.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
E5. Ammonium (mg/l).												
Transect A												
Bottom	1.3	5.0	1.1	0.9	0.4	6.8	0.6	0.2	0.5	1.4	0.4	0.6
Middle	0.2	0.9	0.4	0.6	2.0	0.5	0.0	0.0	0.0	0.2	0.0	0.0
Top	0.3	0.0	0.0	0.0	1.4	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Transect B												
Bottom	1.4	31.7	1.2	1.3	0.9	2.6	0.6	0.5	0.0	0.6	1.1	0.0
Middle	7.6	14.2	2.6	0.0	2.2	0.8	1.1	0.0	0.0	0.0	0.0	0.0
Top	6.2	4.0	4.3	3.2	1.7	0.6	0.7	0.0	0.0	0.2	2.5	0.0
Transect C												
Bottom	7.1	34.2	3.6	2.3	1.4	5.3	2.2	0.7	0.0	0.9	1.4	0.0
Middle	1.5	18.0	3.7	1.5	0.0	0.0	0.4	0.7	0.0	0.0	0.0	0.0
Top	27.2	15.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	0.0
E6. Calcium (mg/l).												
Transect A												
Bottom	53.9	52.4	103.3	72.1	55.0	35.1	86.3	58.1	42.8	37.4	59.0	48.3
Middle	55.9	68.1	81.1	91.5	48.0	55.2	55.4	58.0	35.2	12.9	40.1	42.4
Top	66.6	30.7	102.6	90.3	43.3	57.0	56.3	63.9	51.2	32.6	31.6	45.0
Transect B												
Bottom	63.0	99.8	68.5	65.0	42.9	26.1	42.0	43.3	42.6	23.8	37.8	56.7
Middle	100.5	107.6	102.5	104.8	61.5	53.3	72.4	72.8	55.9	33.2	34.4	46.3
Top	89.8	95.3	135.7	82.2	42.5	49.0	64.3	49.9	22.4	33.4	35.2	49.6
Transect C												
Bottom	39.6	117.8	120.4	77.3	49.1	58.3	86.5	68.6	27.4	47.1	51.8	48.6
Middle	81.0	107.9	104.0	76.2	43.6	54.7	49.7	55.0	28.3	28.5	32.7	40.0
Top	108.3	73.3	115.7	83.9	32.0	39.7	115.7	23.7	28.8	28.8	168.0	271.1

Appendix E. Dissolved ions in saturated paste extracts.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
E7. Magnesium (mg/l).												
Transect A												
Bottom	14.5	9.9	24.6	16.5	14.5	9.3	19.9	13.6	13.7	12.1	16.3	14.2
Middle	15.3	15.9	21.8	22.9	19.0	18.3	24.7	12.1	30.9	20.2	43.4	46.1
Top	19.0	36.3	2.7	25.2	18.0	22.8	27.0	23.8	44.4	28.8	33.5	36.6
Transect B												
Bottom	18.7	31.1	20.8	17.9	12.9	8.0	14.2	12.7	14.8	9.4	15.7	19.4
Middle	32.8	33.5	50.3	33.4	24.0	19.9	34.0	31.7	35.4	33.3	42.1	38.5
Top	30.5	28.5	44.6	23.4	24.1	23.6	33.5	22.7	42.9	38.6	41.3	42.3
Transect C												
Bottom	36.7	34.2	30.0	22.1	12.8	16.1	22.1	23.2	10.7	11.5	17.7	24.3
Middle	25.1	18.7	43.9	21.9	20.3	26.2	30.1	22.2	32.6	34.4	28.5	30.3
Top	52.3	31.7	214.8	32.5	33.3	34.9	107.2	26.7	70.1	84.9	186.1	178.8
E8. Potassium (mg/l).												
Transect A												
Bottom	18.5	7.3	31.6	19.8	10.9	8.9	15.0	6.1	7.7	10.5	7.6	7.1
Middle	4.4	5.9	6.8	6.5	3.4	2.8	4.2	3.1	6.0	20.9	5.8	7.2
Top	6.5	36.7	9.0	9.6	3.7	5.0	4.7	4.4	14.3	6.2	8.1	7.4
Transect B												
Bottom	14.6	38.3	12.8	24.4	3.5	3.1	3.3	2.8	4.1	2.3	4.7	5.2
Middle	17.6	14.4	18.4	10.9	4.6	3.9	5.4	4.6	6.5	5.3	7.2	6.6
Top	17.0	13.2	23.9	15.1	5.1	4.8	6.6	5.2	10.2	8.0	9.4	9.5
Transect C												
Bottom	60.5	43.2	48.5	17.4	8.0	4.7	12.4	3.7	3.4	4.0	8.1	5.9
Middle	4.7	12.0	13.1	5.3	3.4	4.3	6.0	3.0	6.8	5.2	5.5	5.2
Top	23.7	13.6	24.9	9.2	7.6	4.9	11.1	5.1	14.8	9.4	24.4	17.9

Appendix E. Dissolved ions in saturated paste extracts.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
E9. Sodium (mg/l).												
Transect A												
Bottom	8.7	7.3	8.5	5.5	7.7	6.9	6.1	4.2	4.3	9.6	5.9	4.8
Middle	8.6	7.9	7.3	6.9	8.0	9.3	7.2	5.9	11.8	21.8	15.5	9.8
Top	9.0	6.4	7.1	6.1	8.3	10.8	10.4	6.2	25.6	30.8	32.3	18.8
Transect B												
Bottom	10.5	29.7	10.1	8.8	8.5	11.3	6.5	4.7	9.0	12.1	7.8	7.8
Middle	23.0	17.9	22.3	13.5	8.3	12.2	10.3	9.2	17.1	19.9	23.0	16.8
Top	24.7	17.6	24.6	13.7	7.7	11.5	9.6	8.4	28.3	17.3	16.7	17.3
Transect C												
Bottom	3.3	23.3	15.7	9.5	4.9	8.2	9.5	6.3	8.9	11.5	10.3	8.7
Middle	8.2	20.4	33.1	9.1	7.7	14.6	17.7	6.9	22.8	26.0	29.3	17.3
Top	30.1	19.8	190.0	13.6	28.7	31.2	117.0	11.6	51.6	71.7	56.2	50.7
E10. Total inorganic N (NO_2 – N plus NO_3 – N plus NH_4 – N) (mg/l).												
Transect A												
Bottom	1.4	11.0	28.5	17.6	0.3	7.9	25.6	11.7	0.6	3.9	7.6	10.0
Middle	5.7	4.7	8.5	6.4	6.8	5.3	6.7	5.1	0.6	3.0	4.1	4.1
Top	0.4	2.6	5.2	3.6	1.9	3.5	4.6	7.5	0.8	1.2	1.8	5.2
Transect B												
Bottom	1.3	46.8	41.5	13.7	0.8	3.3	9.4	11.3	8.2	1.8	7.3	6.2
Middle	7.1	21.8	67.7	4.7	3.5	2.1	8.1	6.6	1.1	1.5	5.0	4.1
Top	8.4	12.0	76.3	7.7	2.6	2.1	7.1	6.6	1.2	2.6	8.8	11.1
Transect C												
Bottom	6.4	53.2	70.5	10.0	2.1	8.0	24.6	36.5	0.0	2.2	11.3	13.0
Middle	1.3	25.8	27.8	12.0	0.4	3.1	5.7	5.7	0.0	1.8	4.2	4.7
Top	21.5	15.1	31.4	6.0	1.7	2.2	3.9	3.0	0.2	1.3	25.7	2.4

Appendix E11. Summary of saturation percentages from saturated paste data of soil samples.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
Transect A												
Bottom	42	51	53	47	43	49	55	48	46	51	52	50
Middle	42	49	55	47	44	52	58	49	42	49	56	48
Top	42	49	52	48	41	50	50	51	44	50	51	51
Transect B												
Bottom	47	51	52	56	51	47	49	56	42	40	44	45
Middle	48	47	54	49	44	47	56	48	39	45	49	47
Top	42	48	49	48	43	48	51	45	43	48	53	46
Transect C												
Bottom	48	52	59	53	48	51	58	54	41	47	56	49
Middle	44	48	51	48	43	45	51	46	40	46	55	47
Top	52	54	63	53	54	53	64	51	48	54	63	55

APPENDIX F. EXCHANGEABLE CATIONS DATA.

Transect	Slope position	Depth: 0-15 cm Fall 1999b	Depth: 0-15 cm Fall 2000	Depth: 15-30 cm Fall 1999b	Depth: 15-30 cm Fall 2000	Depth: 30-60 cm Fall 1999b	Depth: 30-60 cm Fall 2000
Calcium (meq/100g).							
A	Bottom	18.0	18.8	17.1	19.2	11.2	18.1
	Middle	17.6	16.9	16.0	14.8	16.4	10.5
	Top	14.6	16.4	15.3	15.0	9.0	10.4
B	Bottom	13.8	18.5	19.3	19.1	10.2	13.6
	Middle	19.2	13.5	15.6	16.0	12.7	11.2
	Top	16.1	14.9	14.1	12.6	11.1	9.9
C	Bottom	12.4	19.9	20.1	18.0	6.6	14.2
	Middle	20.9	17.8	17.3	14.8	12.0	12.5
	Top	15.0	16.6	15.1	11.7	9.1	9.1
Magnesium (meq/100g).							
A	Bottom	3.7	4.0	4.0	4.3	12.7	5.2
	Middle	4.6	4.4	4.5	6.2	4.7	8.5
	Top	6.0	4.8	4.7	6.4	9.1	9.2
B	Bottom	5.7	3.7	3.7	4.0	10.2	4.5
	Middle	4.2	4.5	5.1	6.2	3.6	9.3
	Top	6.9	4.2	4.9	6.0	7.5	8.1
C	Bottom	7.7	5.1	4.6	5.6	13.8	7.5
	Middle	4.9	5.3	5.9	6.4	5.5	9.8
	Top	7.7	6.6	7.6	10.8	10.8	14.4
Potassium (meq/100g).							
A	Bottom	0.28	1.16	0.98	0.62	0.45	0.64
	Middle	0.69	0.45	0.36	0.30	0.56	0.33
	Top	0.23	0.67	0.47	0.39	0.24	0.40
B	Bottom	0.27	1.10	0.77	0.35	0.40	0.48
	Middle	0.30	0.57	0.58	0.37	0.25	0.41
	Top	0.26	0.70	0.49	0.37	0.24	0.45
C	Bottom	0.33	0.99	1.28	0.41	0.43	0.54
	Middle	0.67	0.44	0.31	0.29	0.28	0.40
	Top	0.29	0.53	0.72	0.41	0.40	0.53
Sodium < 0.5 (meq/100g) in all the above samples.							

APPENDIX G. BULK DENSITY AND SOIL MOISTURE DATA.

Transect	Slope position	Depth (cm)	BD (g/cm^3)	Gravimetric moisture content (w/w)			
				Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
A	1	0-15	1.64	0.08	0.08	0.16	0.18
A	1	15-30	1.54	0.12	0.09	0.20	0.22
A	1	30-60	1.51		0.10	0.15	0.20
A	2	0-15	1.34	0.05	0.06	0.17	0.17
A	2	15-30	1.56	0.07	0.06	0.10	0.19
A	2	30-60	1.70		0.07	0.07	0.15
A	3	0-15	1.49	0.05	0.04	0.15	0.13
A	3	15-30	1.54	0.10	0.06	0.13	0.15
A	3	30-60	1.32		0.07	0.09	0.18
A	4	0-15	1.44	0.11	0.09	0.15	0.14
A	4	15-30	1.39	0.10	0.12	0.16	0.15
A	4	30-60	1.51		0.11	0.16	0.11
A	5	0-15	1.46	0.05	0.07	0.15	0.13
A	5	15-30	1.60	0.12	0.10	0.13	0.12
A	5	30-60	1.55		0.09	0.08	0.12
A	6	0-15	1.42	0.06	0.07	0.15	0.14
A	6	15-30	1.40	0.12	0.09	0.17	0.16
A	6	30-60	1.56		0.11	0.14	0.14
B	1	0-15	1.12	0.07	0.10	0.18	0.19
B	1	15-30	1.56	0.07	0.08	0.22	0.20
B	1	30-60	1.66		0.06	0.14	0.14
B	2	0-15	1.14	0.07	0.15	0.22	0.19
B	2	15-30	1.38	0.08	0.07	0.19	0.22
B	2	30-60	1.68		0.05	0.14	0.15
B	3	0-15	1.26	0.14	0.08	0.18	0.13
B	3	15-30	1.60	0.12	0.11	0.18	0.15
B	3	30-60	1.63		0.09	0.11	0.14
B	4	0-15	1.52	0.10	0.11	0.17	0.14
B	4	15-30	1.49	0.11	0.11	0.16	0.15
B	4	30-60	1.67		0.11	0.11	0.15
B	5	0-15	1.53	0.12	0.10	0.12	0.11
B	5	15-30	1.69	0.08	0.11	0.07	0.11
B	5	30-60	1.74		0.10	0.10	0.12
B	6	0-15	1.32	0.10	0.08	0.16	0.12
B	6	15-30	1.68	0.13	0.13	0.15	0.14
B	6	30-60	1.68		0.13	0.15	0.12

Appendix G. Bulk density and soil moisture data.

Transect	Slope position	Depth (cm)	BD (g/cm^3)	Gravimetric moisture content (w/w)			
				Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
C	1	0-15	1.52	0.12	0.17	0.22	0.18
C	1	15-30	1.40	0.10	0.14	0.22	0.21
C	1	30-60	1.69		0.14	0.21	0.14
C	2	0-15	1.59	0.10	0.08	0.20	0.16
C	2	15-30	1.60	0.10	0.09	0.22	0.17
C	2	30-60	1.62		0.09	0.16	0.10
C	3	0-15	1.75	0.11	0.11	0.17	0.14
C	3	15-30	1.57	0.13	0.12	0.17	0.15
C	3	30-60	1.59		0.12	0.16	0.14
C	4	0-15	1.68	0.09	0.13	0.14	0.13
C	4	15-30	1.58	0.12	0.14	0.13	0.12
C	4	30-60	1.65		0.15	0.13	0.13
C	5	0-15	1.81	0.18	0.18	0.20	0.14
C	5	15-30	1.85	0.20	0.20	0.26	0.15
C	5	30-60	1.60		0.18	0.23	0.16
C	6	0-15	1.73	0.19	0.08	0.18	0.16
C	6	15-30	1.68	0.20	0.13	0.23	0.18
C	6	30-60	1.30		0.14	0.18	0.15

APPENDIX H. SODIUM ADSORPTION RATIO (SAR).

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
Transect A												
Bottom	0.27	0.24	0.20	0.15	0.24	0.27	0.15	0.13	0.14	0.35	0.17	0.16
Middle	0.26	0.22	0.18	0.17	0.25	0.28	0.20	0.18	0.35	1.05	0.40	0.25
Top	0.25	0.18	0.19	0.15	0.27	0.30	0.28	0.17	0.63	0.92	0.95	0.51
Transect B												
Bottom	0.30	0.67	0.28	0.25	0.29	0.50	0.22	0.16	0.30	0.53	0.27	0.23
Middle	0.51	0.39	0.45	0.29	0.23	0.36	0.25	0.23	0.44	0.58	0.62	0.44
Top	0.57	0.41	0.47	0.34	0.23	0.34	0.24	0.25	0.81	0.48	0.45	0.44
Transect C												
Bottom	0.09	0.49	0.33	0.25	0.16	0.25	0.24	0.17	0.37	0.40	0.31	0.25
Middle	0.20	0.48	0.69	0.24	0.24	0.41	0.49	0.20	0.69	0.77	0.91	0.50
Top	0.59	0.49	2.41	0.32	0.85	0.87	1.88	0.39	1.18	1.49	0.71	0.59

APPENDIX I. TOTAL INORGANIC NITROGEN DATA.

Slope position	Depth interval: 0-15 cm				Depth interval: 15-30 cm				Depth interval: 30-60 cm			
	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000	Fall 1999b	Fall 1999a	Spring 2000	Fall 2000
					Unit: kg/ha							
Transect A												
Bottom	1.08	10.06	27.14	14.87	0.29	8.09	29.55	11.78	1.27	9.52	18.77	23.83
Middle	4.31	4.11	8.43	5.38	6.27	5.78	8.17	5.25	1.16	7.01	10.89	9.44
Top	0.29	2.25	4.88	3.11	1.62	3.68	4.81	8.01	1.57	2.94	4.43	12.69
Transect B												
Bottom	1.07	43.01	38.80	13.82	0.81	3.24	9.70	13.31	16.47	3.42	15.24	13.27
Middle	6.09	18.45	65.79	4.14	3.27	2.10	9.57	6.61	2.03	3.19	11.80	9.22
Top	6.37	10.38	67.31	6.63	2.33	2.08	7.65	6.22	2.51	5.94	22.37	24.43
Transect C												
Bottom	5.56	49.75	74.82	9.55	2.14	8.60	30.00	41.38	0.00	4.79	30.25	30.50
Middle	0.99	22.26	25.56	10.36	0.37	2.90	6.10	5.46	0.00	4.01	11.04	10.63
Top	20.16	14.67	35.58	5.72	1.90	2.43	5.27	3.18	0.38	3.35	77.34	6.32