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PHYSICAL AND CHEMICAL PROPERTIES OF A SOLONETZIC SOIL 12 YEARS AFTER DISCONTINUING LONG-TERM AMMONIUM NITRATE APPLICATIONS

BY

LYNETTE KATHERINE MACKOWAY ESAK ©

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SUCCESS

(Adapted from Martin Buxbaum)

You can use most any measure
When you're speaking of success.
You can measure it in fancy home,
Expensive car or dress.
But the measure of your real success
Is the one you cannot spend.
It's the way your daughter and husband describe you
When they're talking to a friend.

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **PHYSICAL AND CHEMICAL PROPERTIES OF A SOLONETZIC SOIL 12 YEARS AFTER DISCONTINUING LONG-TERM AMMONIUM NITRATE APPLICATIONS** submitted by **LYNETTE KATHERINE MACKOWAY ESAK** in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** in **SOIL SCIENCE**.

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DEDICATION

To my husband and best friend, Myron P. Esak, I express deepest gratitude for his continued interest in my work and for his eternal love, patience, help and encouragement.

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ABSTRACT

The physical and chemical properties of a Solonetzic soil 12 years after discontinuing 18 years of annual NH_4NO_3 applications (305 kg ha^{-1} yr^{-1} of N) were studied in comparison with the non-fertilized control treatment. The vegetation, managed as simulated grassland, was Smooth Bromegrass (*Bromus inermis* Leyss.) and Kentucky Bluegrass (*Poa Pratensis* L.). Above ground dry matter yield was greater in the previous.y fertilized treatment, as presumably was root growth. Total N, total soluble C and soluble C were significantly higher in the fertilized Ap horizon. Bulk density was lower, and hence porosity was higher, soil aggregate size was smaller and saturated hydraulic conductivity (Ksat) was higher, in the Ap and Bnt1 horizons of the previously fertilized treatment. A one-time soil moisture sampling (June 1990) revealed lower gravimetric moisture content in soil of this treatment suggesting greater (evapo)transpiration by the higher yielding vegetation. Soil pH was significantly lower in the Ap and Bnt1 horizons of the fertilized than in the non-fertilized soil, but it had changed little during the last 24 years. The lower pH was also associated with higher concentrations of Fe, Mn, Cu, Zn and Co and lower concentration of Li in the saturation paste extracts in the Ap and Bnt1 horizons. Although base saturation was significantly lower, no individual exchangeable bases (Ca, Mg, Na and K) were significantly different in the fertilized Ap horizon. The continued greater yield on the previously fertilized treatment is interpreted as indicating feed back between plant growth and soil conditions. During the fertilization stages increased nutrient supply and accelerated solodization favored growth of the perennial crop. The increased above ground dry matter production would be expected to remove more water. From this and from the greater Ksat it is expected that greater water infiltration and percolation must also have occurred. Fertilizer treatment was later terminated, but dry matter was rarely removed so the N could be expected to recycle through subsequent crops. Such increased growth with associated water removal and deposition of litter and root debris, in turn is expected to feed back into greater water percolation, continued recycling of macronutrients and preferential recycling of Ca relative to Na.

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CHAPTER I. INTRODUCTION

1. Purpose and History

This thesis describes physical and chemical properties of a black Solonetzic soil (Duagh silty clay loam) sampled in 1990, 12 years after termination of fertilization with N at 305 kg ha^{-1} yr^{-1} as NH_4NO_3. Agronomic aspects of Solonetzic soils and the history of the study site are presented in this chapter as context for the project. Solonetzic soils are predominant in the east central to southeastern portions of Alberta and are associated with the grassland and parkland areas. Approximately 3.2 million hectares are presently delineated as containing dominantly (at least 40%) Solonetzic soils (Shields and Lindsay 1990). These areas occupy 5% of the provincial landbase.

For agricultural production, the compact Bnt horizon limits root as well as air and water penetration (Toogood and Cairns 1978). Consequently there is less storage of water for use of the plants during short droughts, which often occur during the growing season in east central Alberta. Plant roots generally concentrate in the surface soil of Solonetzic soils, rendering the plants susceptible to drought. The extreme variability of depth of the Bnt horizon (plants may be growing on a 20 cm thick A horizon or directly on a Bnt) results in a wavy plant growth pattern and added problems of variable fertility within fields (Carter and Pearen 1985). The A horizons of Solonetzic soils in this study area display low pH, low nutrient status and/or surface crusting due to low organic carbon contents (Toogood and Cairns 1978, Carter et al. 1977, Cairns et al. 1967).

Land for forage production in Alberta represents approximately 50% of the total agricultural land of the province (Malhi et al. 1993). However, only 25% of the improved pasture and hayland receives fertilizer nutrient applications (Malhi et al. 1993). Grass forage crops have a high nitrogen requirement and respond well to N fertilizer applications (Malhi et al. 1991, Malhi et al. 1986). The relatively high rate of N fertilizer can be beneficial to plant growth but the benefits are greatly affected by soil type and climate.

High rates of ammonium-based fertilizers such as $(NH_4)_2SO_4$ (Cairns 1971), NH_4NO_3 (McAndrew and Malhi 1992, Perl et al. 1982, Cairns et al. 1980, Cairns et al. 1967) or NH_4NO_3 plus gypsum (Carter and Pearen 1989, Carter et al. 1978, Carter et al. 1977) have been reported to ameliorate some of the undesirable properties of black Solonetz (Carter et al. 1978, Cairns 1971, Cairns et al. 1967) and brown Solodized Solonetz (Carter et al. 1977) soils. The underlying hypothesis is that additions of cations such as NH_4 or Ca replace Na from the Bnt horizon and increase water penetration by flocculating the clays. Although Ca is more effective than NH_4 at replacing Na, $CaSO_4$ is relatively insoluble. Carter and Pearen (1989) and Carter et al. (1978, 1977) concluded that under field conditions in central Alberta, NH_4NO_3 increased $CaSO_4$ dissolution thereby enhancing Na displacement. Consequently, high rates of NH_4NO_3 were applied over long periods at several sites in Alberta.

Sites receiving repeated application of high rates of ammonium have been studied in Alberta and elsewhere. Such treatments tend to decrease soil pH (McAndrew and Malhi 1992, Malhi et al. 1991, Schwab et al. 1989, Mahler and Harder 1984, Blevins et al. 1983, Perl et al. 1982, Blevins et al. 1977, Jolley and Pierre 1977, Cairns et al. 1967) and show a trend of lower exchangeable Ca, Mg, K (Schwab et al. 1989, Blevins et al. 1983, Blevins et al. 1977) and exchangeable Na (McAndrew and Malhi 1992). McAndrew and Malhi (1992) and Carter and Pearen (1989) reported lower sodium adsorption ratio (SAR) with N fertilization. An increase in total N with fertilization was reported by McAndrew and Malhi (1992), Blevins et al. (1983) and Blevins et al. (1977).

The oldest site receiving high rates of NH_4NO_3 in Alberta is on a Black Solonetz, on the former Agriculture Canada Vegreville Experimental Farm (SE 17-52-14-W4M; 53° 20'N, 112° 02'W) and is the focus of the work reported in this thesis. The region is on a level to undulating morainal plain with a layer of fine textured glaciolacustrine sediments overlying the till (Crown and Greenlee 1978). Directly west of the study site, a thin veneer of fine to medium textured alluvium overlies the glaciolacustrine sediments along the Vermilion River (Crown and Greenlee 1978). To the east of Vegreville is a large hummocky disintegration moraine which acts as an area of groundwater recharge with the regional flow direction westward toward the Vermilion River (Maclean 1974).

Regionally, the site is in the central part of the Alberta Plain, which is in the Third Prairie Steppe of the Interior Plains of Canada (Crown and Greenlee 1978). The land surface is level to undulating and contains many shallow depressional areas. The town of Vegreville is located at the north end of a three million hectare strip of Solonetzic soils running over 320 km south through east-central Alberta.

The present climate of the Vegreville region is characterized by relatively warm summers and cold winters. The 34 year climatic normals collected at the Vegreville Experimental Farm cite January as the coldest month with a mean temperature of - 17°C and July as the warmest month with a mean temperature of 16.5°C (Appendix A). The mean annual air temperature is 1.3°C.

The Vegreville region is within the forest-grassland transition zone (Rowe 1972). The vegetation, excluding cultivated crops, is characteristic of the Aspen Grove section. Trembling aspen *(Populus tremuloides)* is abundant in the natural stands, with balsam poplar *(Populus balsamifera)* and some white birch *(Betula papyrifera)* on moist lowlands (Rowe 1972). Interspersed with the aspen in the original vegetation are grass and meadow areas (Crown and Greenlee 1978).

The elevation at the study site is 635 m above sea level, and the soil is predominantly Duagh silty clay loam (Cairns 1961). The experimental study was established in 1960 on a simulated grassland where the seeded Smooth Bromegrass and Kentucky Bluegrass were sporadically mowed during summer on a yearly basis for dry matter yield determinations and the majority of the dry matter was left on the study site.

Smooth Bromegrass and Kentucky Bluegrass are the two grass forages common to the study area. Bromegrass is a rhizomatous, long-lived perennial, resistant to drought and has an extensive root system which can bring rapid improvement in soil structure (Walton 1983). It also tolerates impeded drainage and has a moderate tolerance of soil acidity. Under all these circumstances, water stress has little effect on the photosynthetic rates of Smooth Bromegrass and the carbohydrate reserve may increase (Walton 1983). Kentucky Bluegrass is well adapted to cool, moist climates where soils are relatively fertile and have a pH between 6.0 and 7.0 (Walton 1983). It is relatively shallow rooted which makes it suitable for the thin Solonetzic Ap horizons, but as a result is especially susceptible to periods of drought during the summer months.

The original experiment contained eight fertilizer treatments, applied annually for 18 years on a soil originally deficient in N (Cairns et al. 1962), and has been maintained without additional fertilization since 1978 (Figure 1). The present study deals only with the NH_4NO_3 treatment at 305 kg ha^{-1} yr^{-1} of N. The fertilized treatments were broadcast annually to the mixed stand of Smooth Bromegrass and Kentucky Bluegrass. Paired strips, 3 x 15 m, were selected to represent a relatively uniform area of Duagh silty clay loam. The soil selected for the initial study in 1960 was lower in exchangeable Na than described by Cairns (1961) and the Ap horizon varied from 9 to 15 cm in thickness. This study was initiated in 1990, 12 years after the last fertilizer application. The forage growth was still visibly greater; color and stand were more uniform on the fertilized treatment.

Soil physical and chemical analyses have been conducted for various reasons on this site since the experiment commenced in 1960 (McAndrew and Malhi 1992, Perl et al. 1982, Cairns et al. 1967). After a five year period, Cairns et al. (1967) found that the use of N fertilizer on the Smooth Bromegrass had significantly lowered the soluble and exchangeable Na content and increased the root content in the Ap horizon on the study site. The greatly increased Smooth Bromegrass yields prompted Perl et al. (1982) to undertake a detailed study of the soil chemical properties in 1973. Perl et al. (1982) found that after 12 years of fertilization, pH significantly decreased from 6.2 in the non-fertilized treatment to 4.7 in the fertilized treatment of the Ap horizon. Exchangeable Na, Ca, K and Mg concentrations were lower and exchangeable Mn and H levels were higher in the fertilized treatment than the non-fertilized. Under

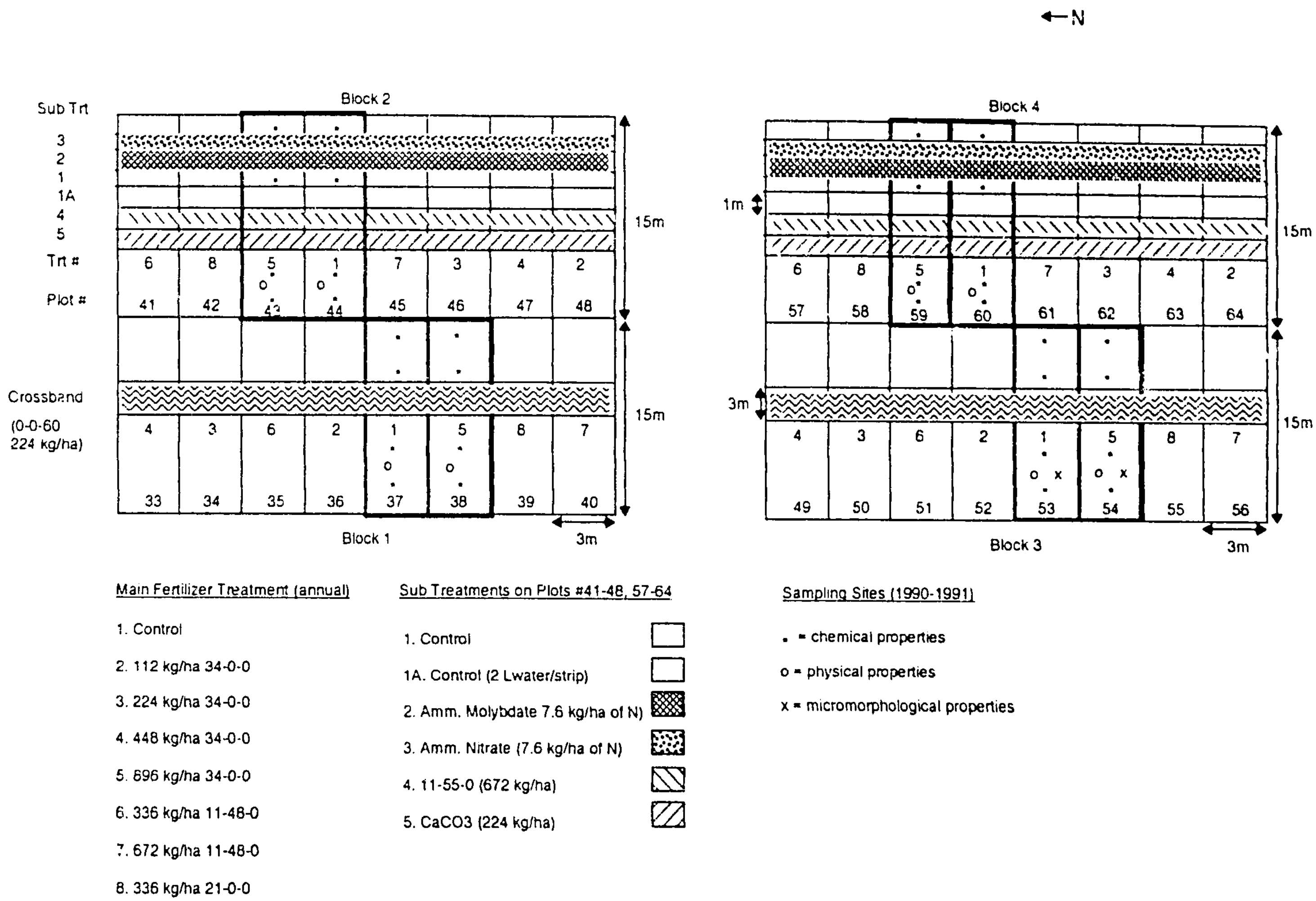

Figure 1. Site plan of the Vegreville Fertility Study.

ammonium nitrate the Ca:Na in the Ap horizon decreased while it increased in the Bnt. In the upper Bnt horizon (12 to 17 cm), pH and exchangeable Na, Mg and K were significantly higher in the fertilized treatment. Exchangeable Ca tended to be higher in the fertilized treatment, but variability was too high for any significant differences to be found.

Data from soil and plant samples collected in the fall of 1986 continued to show significant differences between the treatments (McAndrew and Malhi 1992). Soil pH was depressed from 5.7 for the non-fertilized to 4.2 in the fertilized treatments in the Ap horizon. There was a trend towards decreased sodium adsorption ratio (SAR), soluble Na and exchangeable Na and Ca, with the fertilized treatment. Total soil organic carbon (TOC) and total soil organic N increased with N application.

2. Objective

The objective of the present study was to build on work by McAndrew and Malhi (1992), Perl et al. (1982) and Cairns et al. (1967), that found solodization was increasing as a result of N fertilization of Solonetzic soils managed as a simulated grassland. Specifically this involved a detailed morphological, physical and chemical study of the site 12 years after fertilization ceased, and 4 years after the last sampling (McAndrew and Malhi 1992). It was anticipated that the higher yields of forages may be due to changes in morphological characteristics and amelioration of the physical conditions in the rooting zone.

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CHAPTER II. MORPHOLOGICAL AND PHYSICAL PROPERTIES

1. Introduction

Adverse factors affecting plant growth on Solonetzic soils are mainly attributed to physical impediments within the profile which restrict root growth and movement of water and cause poor soil aeration. Consequently, there is less water being stored for future use of the plants during short droughts, which often occur during the growing season in east-central Alberta. Therefore improvement of water infiltration and percolation is an essential requirement for amelioration of Solonetzic soils.

Ammonium nitrate fertilization of Smooth Bromegrass on Solonetzic soils has been shown to favorably alter soil structure and porosity of the Ap and Bnt horizons by increased dry matter yields (DMY) (Carter et al. 1977, Cairns et al. 1967), increased TOC (McAndrew and Malhi 1992) and increased root activity (Carter et al. 1977, Cairns et al. 1967).

Although there is little research on the beneficial effect of plant roots on the physical properties of Solonetzic soils, there is considerable relevant research on forage cropping systems and annual crops under no-till on other soils. Forage crops including bromegrass have been found to decrease bulk density, increase soil aeration and increase water infiltration of fine-textured soils (Cambardella and Elliott 1993, Bauder and Brock 1992, Grevers and De Jong 1990). The extent to which forages modify these physical properties depend on the plant's root pattern and biomass, the rate of decomposition of root residues and rooting depth (Perfect et al. 1990).

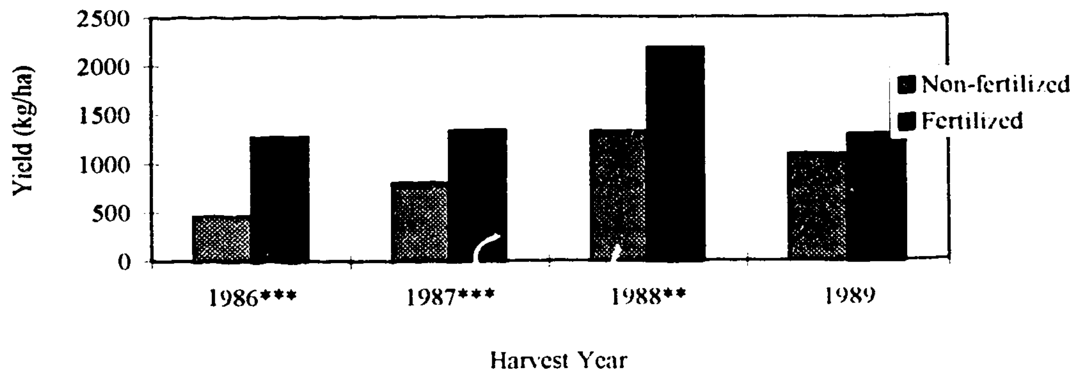
Annual crops under no-till versus conventional tillage have also been studied with regard to physical properties of soil. Research studies have reported lower bulk density (Hill 1990, Unger and Fulton 1990), increased TOC (Blevins et al. 1983, Blevins et al. 1977), increased porosity (Roseberg and McCoy 1992), decreased dry aggregate size distribution (Campbell et al. 1993), increased hydraulic conductivity (Zuzel et al. 1990) and a trend toward decreased volumetric water content at soil matric potentials between 0 and -2 kPa and increased volumetric water content at soil matric potentials from -3.9 to -40 kPa (Hill 1990). These altered physical properties could be related to the retention of crop residues with no-till (Dao 1993, Dick et al. 1989).

Roseberg and McCoy (1992) and Hill (1990) found no-till increased bulk density compared to conventional tillage in the 0 to 15 cm depth. Zuzel et al. (1990) showed that if surface sealing is prevented by a complete residue cover, the type of tillage (plow, sweep or disk) was not a major factor in reducing the infiltration capacity of the soil. Further Zuzel et al. (1990) indicated that while compaction did occur for all tillage systems, the maximum bulk density was less in the high N treatment (180 kg ha^{-1}).

There has been only limited research reported for no-tillage on Solonetzic soils in Western Canada. Malhi et al. (1992) studied the effect of ammonium nitrate fertilizer on no-till and conventional tillage systems and found more moisture in spring in soil under no-till in 2 of the 3 years studied. Andreiuk (1993) found water retention at -33 and -1500 kPa, in the surface 2.5 cm, significantly higher under zero tillage than under conventional tillage which were in effect for 4 years. However, Andreiuk (1993) also found available water holding capacity (AWHC) of the 0 to 15 cm depth was not different between the treatments and soil moisture generally did not vary among treatments during the 4 years.

At the Vegreville Experimental Farm, a research study of fertilization of forages had been conducted for 18 years, commencing in 1960. Following termination of fertilization in 1978, forage production of previously fertilized plots continued to exceed non-fertilized plots as seen in 1991 (Plate 1). For the years between 1986 to 1989 there were significantly higher yields in the fertilized plots compared to the non-fertilized plots except in 1989 (** = $P<0.01$ and *** = $P<0.001$ (ANOVA) (Figure 2) (McAndrew, personal communication).

Plate 1. Comparison of the forage stands in 1991 as affected by N fertilization: Non- fertilized treatment (left) or fertilized treatment (right).



**, *** = P<0.01 and P<0.001, respectively (ANOVA)

Figure 2. Comparison of dry matter yields of the mixed forage stand from 1986 to 1989 (McAndrew, unpublished data).

2. Objective

The objective of the study was to determine the residual effects of long-term N fertilization on several soil physical properties. The hypothesis for this study was that previous, long-term N fertilization of a grass forage altered the aggregation, porosity, water retention and transmission properties of the Solonetzic soil at the experimental site through enhanced vegetative and root biomass production.

3. Materials and Methods

3.1. Treatment Design and Layout

The experimental design, as outlined by Cairns (1961), represents a complete block design with 4 replications (Figure 1). Treatments 1 and 5, examined in this study, were arranged in paired strips 3 m x 15 m. The annual broadcast treatments included fertilization (305 kg ha^{-1} of N) and non-fertilization (0 kg ha^{-1} of N) on an established stand of grass for 18 years, beginning in 1960. Over the years, the treatment plots had several subtreatments applied but these subtreatments were not sampled. The grass stand, which had not been ploughed since the 1940's, consisted of Smooth Bromegrass and Kentucky Bluegrass. The grass stand was managed as hayland with infrequent hay removal; the grass was usually mowed and dry matter cuttings were left on the field. The soil was a Black Solonetz (Duagh series).

3.2. Field Sampling

In June 1990, a tractor mounted vibrating mechanical corer (Nelson and McAndrew 1990) was used to collect soil samples. Four cores for physical and chemical analyses were taken from each treatment (shown by • in Figure 1). Of the four samples collected per horizon, the two samples located on the east side of the treatment were combined to form a composite soil sample to ensure sufficient sample mass. This procedure was similarly followed for the 2 samples on the west side of the treatments. Therefore, the total number of soil samples collected was 64 (4 blocks x 2 treatments x 4 horizons (Ap, Bnt1, Bnt2, Cksa) x 2 pairs of samples per horizon).

Segmentation of the soil cores was based on their genetic horizons (Ap, Bnt and Cksa). The Bnt horizons were divided into two sections (Bnt1 and Bnt2) due to visible differences in structure and consistence evident between the two treatments. The samples were placed in plastic bags and kept cool in styrofoam containers during sampling. These samples, collected in June 1990, were used for organic carbon and water retention curves.

In May 1991, two profiles from Block 3 were described morphologically (Agriculture Canada Expert Committee on Soil Survey 1987) in pits (located at x in Figure 1) approximately 0.75 m wide by 0.50 m deep. Block 3 was chosen as being representative based on topography and vegetative st[illegible] of the experiment. From each of the two profiles, 4 soil monoliths were taken for soil fabric (micromorphological) analyses. The soil face was cut away to allow the undisturbed samples to be placed in tin boxes (10 cm x 10 cm x 8.75 cm). The sampling depth for each soil fabric monolith is described in Table 1.

Table 1. Sampling depth of soil fabric monoliths in block 3.

Sample Number	Treatment*	Horizon	Depth (cm)
L1	1	top Ap	0-10
L2	1	Ap-Bnt1	5-15
L3	1	Bnt1	14-24
L4	1	Bnt2-Cksa	35-45
L5	2	top Ap	0-10
L6	2	Ap-Bnt1	5-15
L7	2	Bnt1	17-27
L8	2	Bnt2-Cksa	36-46

*Treatment 1 = Non-fertilized plot (0 kg ha^{-1} of N)
*Treatment 2 = Fertilized plot (305 kg ha^{-1} of N)

In June 1991, a Uhland soil corer was used to collect soil samples (indicated with o in Figure 1). Sixteen soil samples were taken (4 blocks x 2 treatments x 2 horizons (Ap, Bnt) x 1 sample per horizon). Very low soil moisture conditions prevented the collection of additional intact samples. Aluminum coring sleeves (5.4 cm x 6.0 cm) were used. The samples were frozen until laboratory measurements were made of saturated constant head hydraulic conductivity and bulk density.

In July 1991, more soil samples of the Ap horizon were collected by spade for dry aggregate analyses. Approximately 30 cm x 30 cm x 8 cm of Ap horizons per treatment in all 4 blocks were collected and gently broken into natural clods at field moisture conditions (4 blocks x 2 treatments x 1 horizon). The grass or sod layer was left intact with the soil.

3.3. Laboratory Analysis

Gravimetric moisture content (McKeague 1978) was determined for the 64 samples taken in June 1990 and was calculated as the mass (g) water per g oven dry soil. All the soil samples collected in June 1990 were air-dried and ground to pass a 2 mm sieve. Organic carbon (g kg^{-1}) was measured by wet oxidation using the modified Walkey-Black method (Nelson and Sommers 1982). Organic carbon was calculated as [{($FeSO_4$ blank mL - $FeSO_4$ sample mL)(N $FeSO_4$ meq L^{-1})(0.003 g C meq^{-1})}/sample mass in g] [100/75 recovery x 1000 g/1 kg].

Soil monoliths were air-dried in the laboratory, impregnated with epoxy resin and each cut into one 5 x 7 cm thin section using procedures described by Brewer and Pawluk (1975). The Manual Image Analysis computer system was used in conjunction with the Mop-Videoplan version 5.41, release 1.0 software to acquire data and compute geometric characteristics by tracing images of structures such as soil aggregates, macropores and roots in the thin sections. Coordinate data were generated at the tablet for area, perimeter and maximum diameter each time a structure was outlined or when distances or locations were defined with a stylus.

Three parameters were measured: area, perimeter and maximum diameter (dmax) (Figure 3). The ocular or regular lens had a magnification of 1.25 and the

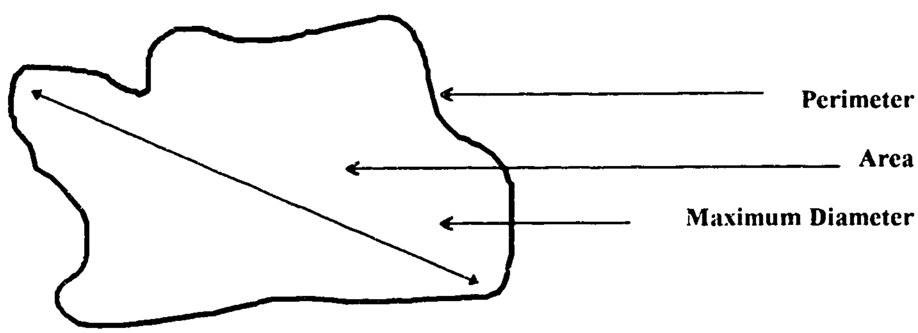


Figure 3. Area, perimeter and maximum diameter parameters used to measure soil aggregates, roots and pores of the Ap and Bnt1 horizons of the fertilized and non-fertilized treatments.

objective lens a magnification of 2.5. The active measuring area was 280 mm by 280 m. Within the active measuring area, perimeter and maximum diameter were calculated from a continuous tracing of the perimeter of all the aggregates first, followed by the perimeter of all the macropores and finally by tracing the perimeters of all roots. The maximum diameter was calculated by placing the start of the continuous perimeter trace at the extremity of the structure and returning to the starting point to terminate measurement.

Measurements were made on three active measuring areas for each thin section, and data were reported as the relative values of area mean, perimeter mean and maximum diameter mean. The relative values (Rv%) were calculated as $(Parameter_i/Parameter_s)(100)$ where $Parameter_i$ = mean parameter (area, perimeter, maximum diameter) of each individual component (aggregate, macropores or roots) and $Parameter_s$ = sum of mean parameter of the individual components. There were two sources of human error involved in manually tracing the various images for which the differences among structures were often indistinct on the computer screen. The procedure states all aggregates were to be traced first then the set of values entered into the computer by a command, then all the macropores and finally all the roots were traced. Mistakes could be made on the misinterpretation of what was an aggregate or macropore while tracing the next parameter such as macropore or root. The other source of error was that because area, perimeter and dmax were all calculated simultaneously from a single trace of an image, the extremity of the image may not have always been chosen as a starting point, which decreased the actual dmax value of the particular component (aggregate, macropore or root).

Bulk density (Mg m^{-3}) was calculated using the radius of the Uhland core sample sleeve. The calculation was (P_b - M_s/V_t where M_s {(ovendry mass + sleeve mass) - (sleeve mass)} in g; and V_t = {π(diameter of sleeve/2)^{2}height of sleeve) in cm^3 to yield g cm^{-3}. Bulk density was then converted to Mg m^{-3} by multiplying (g cm^{-3})(1 Mg/10^6 g)(10^6 cm^3/m^3) to yield Mg m^{-3}. Saturated hydraulic conductivity measurements (m d^{-1}) were taken in the laboratory using undisturbed soil Uhland cores under a constant head of water (Klute 1965).

Soil water retention characteristic curves were determined with a pressure plate apparatus at -33, -100, -500 and -1500 kPa using dried, ground (2 mm) and sieved soil. Ninety-six soil samples (4 blocks x 2 treatments x 4 (Ap, Bnt1, Bnt2, Cksa) horizons x 3 subsamples per horizon) were analyzed at each pressure (Childs 1940). Available water holding capacity was calculated as the difference in g g^{-1} between the water contents at -33 and -1500 kPa. Dry aggregate size distributions were measured on 24 samples (4 blocks x 2 treatments x 1 Ap horizon x 3 subsamples per horizon) using a RO-TAP™ paint shaker (rotary sieve machine) with 7 vertically nested sieves with openings of (6.30 mm, 4.00 mm, 2.00 mm, 1.00 mm, 0.50 mm, 0.25 mm, 0.125 mm and the pan <0.125 mm). The RO-TAP™ was used to shake and tap the soil samples for five minutes. The mean weight diameter (mm) of the eight size fractions was calculated as: $X = \Sigma x_i w_i$ where x_i is the mean diameter of aggregates of any particular size range, and w_i is the mass of the aggregates in that size range as a fraction of the total dry mass of the sample analyzed. The summation accounts for all size ranges, including the group of aggregates smaller than the openings of the finest sieve.

The total porosity relationship of soil constituents were calculated from bulk density values. Total porosity was computed as $f = 1 - P_b/P_s$ where P_b is M_s/V_t as previously defined and P_s is the average particle density of 2.65 Mg m^{-3}. Only one sample per treatment from one block was taken for gravimetric water content when the bulk density samples were taken.

3.4. Statistical Analysis

The general linear model procedure (GLM) of the SAS Institute Inc. (1989) was used to perform a two-way analysis of variance (ANOVA). Least significant difference was used to compare means where significant differences ($P \leq 0.15$) were detected by the F-test. Analysis was conducted separately for the various depths, due to differences in variability.

4. Results

4.1. Morphological Properties

4.1.1. Field Description of Soil Profiles

A mixed forage stand of dominantly smooth Bromegrass and some Kentucky Bluegrass was evident in the non-fertilized treatment and by contrast a very heavy stand of perennial grass with Smooth Bromegrass being the dominant forage species was evident in the fertilized treatment (Chapter I, Plate 1).

Similar morphological characteristics in the Ap horizons were seen in both treatments (Tables 2 and 3). Structural differences between treatments were evident in the Bnt1 horizon. There were similar colors for organic matter coatings of the peds in both treatments but the inside of the ped for the fertilized treatment was lighter in color (dull yellowish brown as compared to dark brown) as described using the Munsell Soil Color Chart. The primary structure of the non-fertilized treatment was strong large columnar as compared to strong medium columnar of the fertilized treatment. The secondary structure was strong fine blocky in the non-fertilized and strong fine-medium blocky in the fertilized treatment. The soil of the non-fertilized treatment had a very firm consistence compared to a firm consistence for the fertilized. The amount and distribution of roots was greater in the fertilized than non-fertilized treatment. There was a striking difference between the Ap and Bnt1 boundaries. The boundary was abrupt smooth for the non-fertilized and gradual smooth for the fertilized treatment.

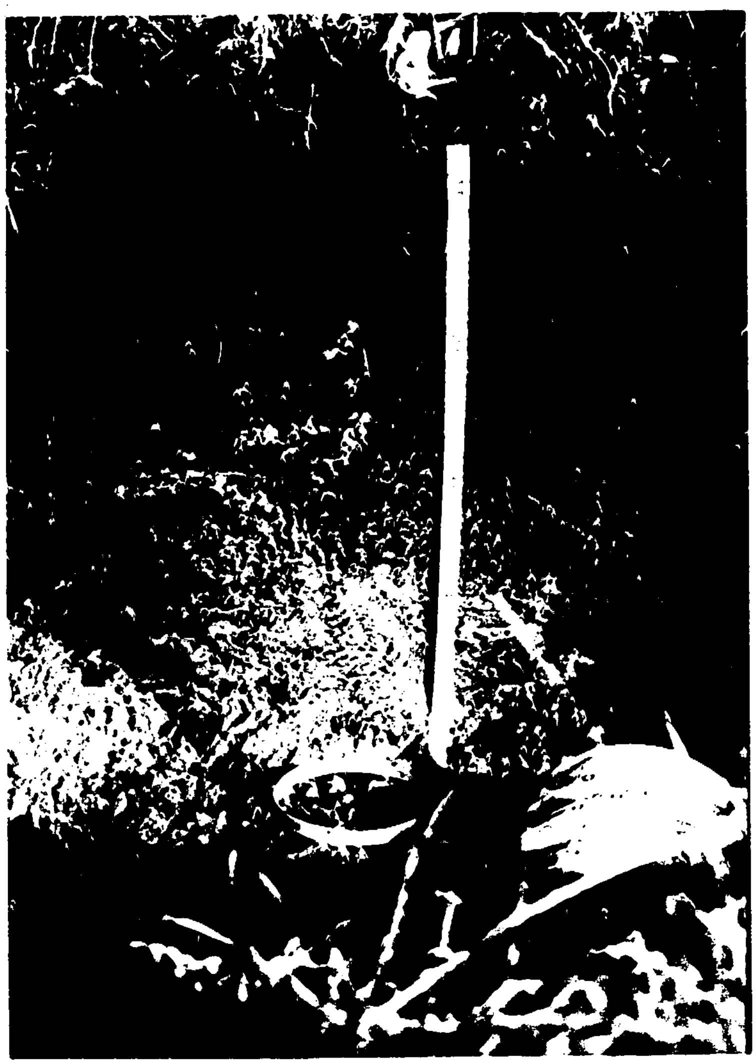


Plate 2. Soil profile of the non-fertilized treatment.

Plate 3. Soil profile of the fertilized treatment.

Table 2. Description of the soil profile of the non-fertilized treatment.

The Setting:

Condition:	hayland
Location:	Fertility Study, Block 3, Treatment 53, Agriculture Canada, Vegreville Experimental Farm, Vegreville, Alberta
Slope and aspect:	level terrain
Drainage:	seasonal ponding
Parent material:	fine textured glaciolacustrine sediments over till and saline bedrock
Vegetation:	1. Surrounding area: Excluding cultivated crops primarily trembling aspen *(Populus tremuloides)*, balsam poplar *(Populus balsamifera)*, white birch *(Betula papyrifera)* 2. Immediate area: Smooth Bromegrass (*Bromus inermis* Leyss.) dominant species; Kentucky Bluegrass (*Poa pratensis* L.) subdominant species
Elevation:	635 m
Treatment:	0 kg ha^{-1} of N

Horizon	Depth	Description
O	1-0 cm	Moderate stand of perennial grass: Smooth Bromegrass (*Bromus inermis* Leyss) dominant; Kentucky Bluegrass (*Poa pratensis* L.) sub-dominant.
Ap	0-10 cm	10 YR 2/1 m (black); strong fine granular structure; friable consistence; plentiful, fine-medium, random, inped and exped roots; silty clay loam texture; abrupt smooth Ap-Bnt boundary.
Bnt1	10-29 cm	10 YR 3/2 m (very dark grayish brown) organic matter coating; 7.5 YR 3/3 (dark brown) inside of ped; strong medium columnar primary structure; strong large blocky secondary structure; very firm consistence; many medium vertical exped roots; clay texture.
Bnt2	29-40 cm	10 YR 5/4 m (dull yellowish brown); moderate medium columnar primary structure; strong fine blocky secondary structure; very firm consistence; few medium vertical exped roots; clay texture; gradual smooth Bnt2-Cksa boundary.
Cksa	40 cm+	10 YR 4/3 m (brown to dark brown); massive; firm consistence; very few vertical exped roots; clay texture; plentiful gypsum crystals; carbonates evident at 50 cm depth.

Table 3. Description of the soil profile of the fertilized treatment.

The Setting:

Condition:	hayland
Location:	Fertility Study, Block 3, Treatment 54, Agriculture Canada, Vegreville Experimental Farm, Vegreville, Alberta
Slope and aspect:	level terrain
Drainage:	seasonal ponding
Parent material:	fine textured glaciolacustrine sediments over till and saline bedrock
Vegetation:	1. Surrounding area: Excluding cultivated crops primarily trembling aspen *(Populus tremuloides)*, balsam poplar *(Populus balsamifera)*, white birch *(Betula papyrifera)* 2. Immediate area: Smooth Bromegrass (*Bromus inermis* Leyss) dominant species
Elevation:	635 m
Treatment:	305 kg^{-1} ha^{-1} of N annually from 1960 to 1978

Horizon.	Depth	Description
0	1-0 cm	Very heavy stand of perennial grass: Smooth Bromegrass (*Bromus inermis* L.) very dominant.
Ap	0-14 cm	10 YR 2/1 d (black); strong fine granular structure; very friable consistence; plentiful fine-medium, random, inped and exped roots; silty clay loam texture; gradual smooth Ap-Bnt boundary.
Bnt1	14-26 cm	10 YR 3/2 d (very dark grayish brown) organic matter coatings; 10 YR 5/4 (dull yellowish brown) inside of ped; strong medium columnar primary structure; strong medium blocky secondary structure; firm consistence; many medium vertical exped roots; clay texture.
Bnt2	26-43 cm	10 YR 5/4 d (dull yellowish brown); moderate large columnar primary structure; strong fine-medium blocky secondary structure; firm consistence; many medium vertical exped roots; clay texture gradual smooth Bnt2-Cksa boundary.
Cksa	43+ cm	10 YR 4/3 d (dull yellowish brown); massive; firm consistence; very few fine vertical exped roots; clay texture; plentiful gypsum crystals; carbonates evident at 50 cm depth.

The Bnt2 horizon has two differences between the treatments. A strong fine blocky secondary structure was found in the non-fertilized treatment as compared to a strong fine-medium blocky secondary structure of the fertilized treatments. A very firm consistence and few medium vertical exped roots were also evident in the non-fertilized treatment, while a firm consistence and many medium vertical exped roots were found in the fertilized treatment. One would not expect firm consistence from a drier soil (fertilized) and very firm consistence from the wetter soil (non-fertilized) considering the differences in structure in the Bnt2 horizon. Although the reason for this paradox is not certain, it may relate to increased macroporosity and smaller aggregates ir the fertilized treatment. Gypsum salts were evident in both Cksa horizons. Carbonates were also present below approximately 50 cm depth in both horizons.

4.1.2. Thin Section Analysis

Photomicrographs of the thin sections are presented as 1:1 of Ap and Bnt1 horizons for non-fertilized and fertilized treatments (Plate 4) and 4 x 6 enlargements of the 1:1 prints of the Ap and Bnt1 horizons (Plates 5 and 6, respectively). Using image analyses of the soil fabric a difference between the distribution of aggregates, macropores and roots in the Ap and Bnt1 horizons of the two treatments can be seen. Relative area means, perimeter means and maximum diameters of the aggregates, macropores and roots were compared between treatments (Figures 4, 5 and 6, respectively). Complete data are shown in Appendix B.

In the general soil fabric a distinct differentiation between treatments in the Ap and Bnt1 horizons (Plates 4, 5 and 6) was evident. Finer aggregates and greater numbers of macropores and roots were observed in the Ap and Bnt1 of the fertilized than the non-fertilized treatment.

The relative area mean (%) of the aggregates in the fertilized Ap horizon was greater than in the non-fertilized treatment as determined from image analysis data (Figure 4). The relative distribution of the aggregates plus pores was lower in the

Non-fertilized Ap horizon

Fertilized Ap horizon

Non-fertilized Bnt1 horizon

Fertilized Bnt1 horizon

Plate 4. Soil fabric thin sections of the Ap and Bnt1 horizons of fertilized or non-fertilized Solonetzic soil (1:1 scale).

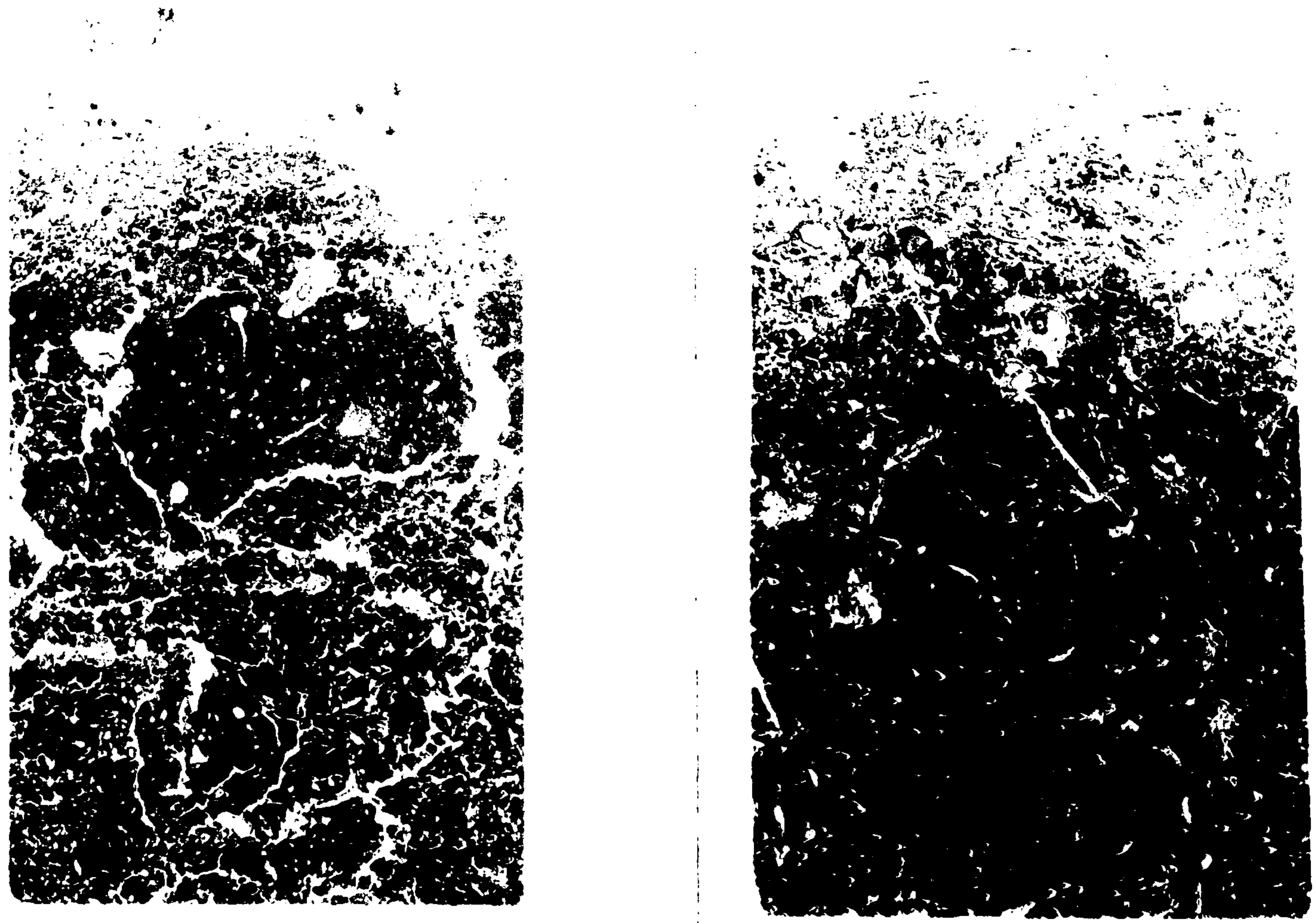


Plate 5. Soil fabric thin sections of the Ap horizon for non-fertilized (left) or fertilized (right) treatments (enlargements).

fertilized Ap horizon than in the non-fertilized. There was an increase in relative aggregate mean area of roots in the fertilized Ap horizon. The Bnt1 had lower relative aggregate mean area but greater macropores and roots means in the fertilized treatment.

Similar relative perimeter means (%) of the aggregates, macropores and roots were evident in the Ap horizon of both treatments (Figure 5). There was a difference between treatments in the relative perimeter means of aggregates, macropores and roots in the Bnt1 horizon. Relative perimeter means of the macropores and roots were greater in the fertilized treatment than the non-fertilized.

Relative maximum diameters of the aggregates, macropores and roots followed the same trend as the relative perimeter means with no distinct differences between treatments in the Ap horizon (Figure 6). In the Bnt1 horizon, the relative maximum diameters of the pores and roots were greater in the fertilized treatment than the non-fertilized.

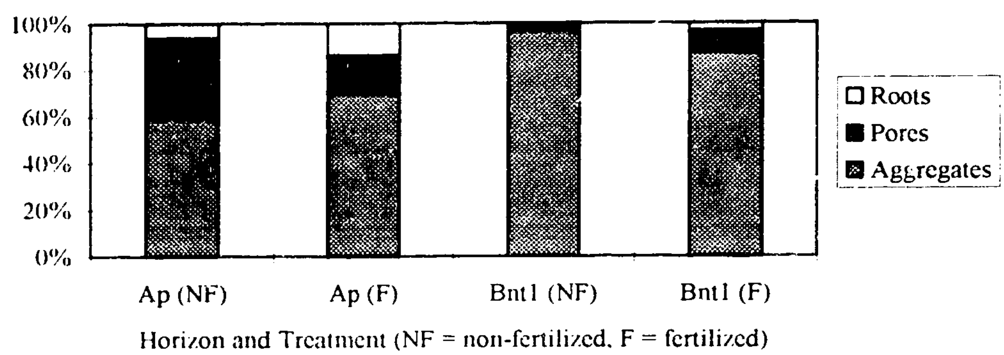


Figure 4. Relative area means of aggregates, macropores and roots in the soil fabric of fertilized or non-fertilized treatments.

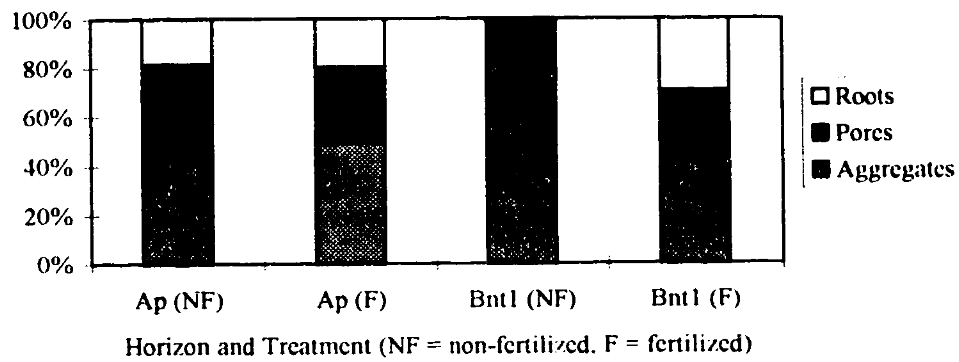


Figure 5. Relative perimeter means of aggregates, macropores and roots in the soil fabric of fertilized or non-fertilized treatments.

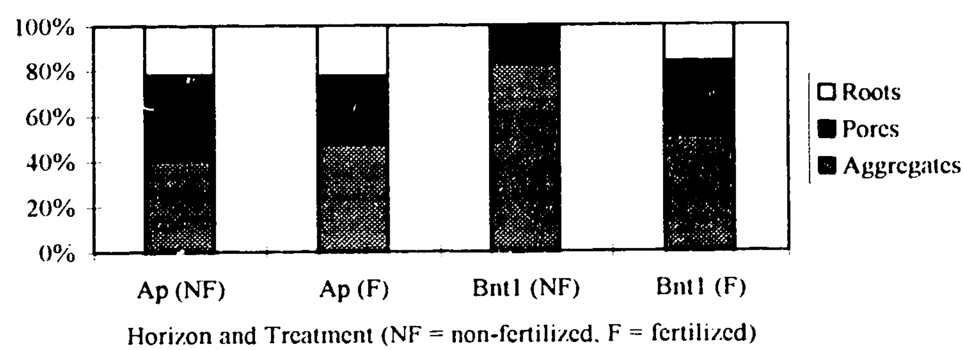


Figure 6. Relative maximum diameter means of aggregates, macropores and roots in the soil fabric of fertilized or non-fertilized treatments.

4.2. Physical Properties

4.2.1. Aggregate Size Distribution

Aggregate size distribution in the Ap horizon was affected by previous fertilizer treatments (Table 4). There were significantly fewer larger aggregates (>6.3 mm) and significantly more medium-sized aggregates (2.0 to 0.25 mm) in the fertilized Ap horizon than non-fertilized treatments. This is also shown by the MWD which was 2.9 mm for the fertilized and 4.0 mm for the non-fertilized treatment.

4.2.2. Total Organic Carbon

There was a trend of higher total organic carbon contents (TOC) in the Ap horizon of the fertilized than the non-fertilized treatments (Table 5). Though the difference between TOC is not significant, the Ap depth for the fertilization treatment is greater. The TOC were similar between treatments in the Bnt1 horizon.

Table 4. Aggregate size distribution and mean weight diameter of fertilized or non-fertilized Ap horizons (July 1991).

				Relative Distribution of Aggregate Sizes mm (%)								
Hor	Trt	Avg. Depth (cm)	Grav. Water Content ($g\ g^{-1}$)	>6.3	6.3-4.0	4.0-2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.125	<0.125	MWD (mm)
Ap	NF	0-8	0.12	46.2	3.0	24.6	6.9	6.9	5.3	4.5	2.6	4.0
Ap	F	0-10	0.12	24.9	4.0	24.4	14.4	11.9	9.2	5.3	5.9	2.9
Prob			na	***	ns	ns	*	***	**	ns	ns	nc

Hor = horizon

Trt = treatment: NF = non-fertilized, F = fertilized

MWD = mean weight diameter

ns = not significant P<0.15 (ANOVA)

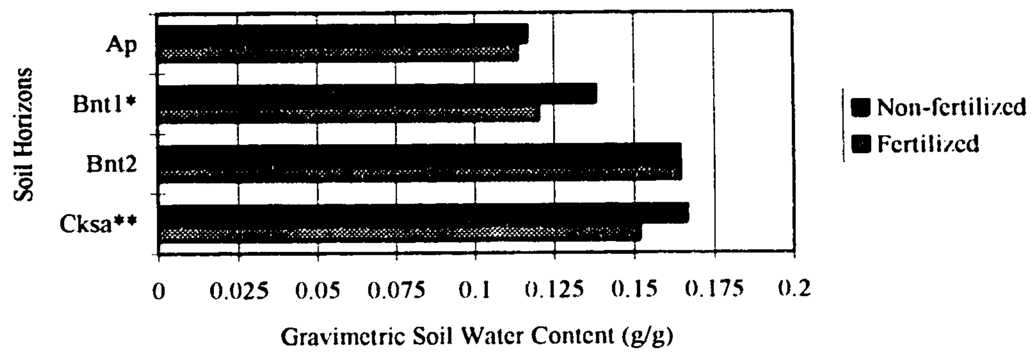
*, **, ***, P<0.05, P<0.01, P<0.001 respectively (ANOVA)

na = not available due to insufficient samples for statistics

nc = not statistically analyzed

4.2.3. Water Content and Bulk Density

The gravimetric water content of the soil samples from the Ap, Bnt1, Bnt2 and Cksa horizons taken in June 1990 at the middle of the growing season (Figure 7) was generally lower in the fertilized treatments in the four soil horizons and the differences were significant in the Bnt1 ($P<0.15$) and Cksa ($P<0.05$) horizons. At time of sampling for bulk density in 1991, the water content (Table 5) was lower in the fertilized treatments of the Ap and Bnt1 horizons than the non-fertilized. Bulk density increased with depth (Table 5) and was significantly lower in the Bnt1 ($P<0.05$) in the fertilized than the non-fertilized treatment. Total porosity was greater in the fertilized treatments in the Ap and Bnt (significantly greater at $P<0.05$) horizons.



*, **, $P<0.15$ and $P<0.05$, respectively (ANOVA)

Figure 7. Gravimetric soil water contents at sampling time (June 1990).

4.2.4. Saturated Hydraulic Conductivity and Water Retention Characteristics

Constant head saturated hydraulic conductivity (Ksat) was determined for the Ap and Bnt1 horizons. There was a trend of higher Ksat in the Ap and significantly higher ($P<0.05$) in the Bnt1 horizons of the fertilized than the non-fertilized treatments (Table 5). Ksat for the Ap horizon was greater than for the Bnt.

Soil water content at -33, -100, -500 and -1500 kPa (Table 6) and available water holding capacity (AWHC) (Table 6) for each of the four horizons and treatments were determined. In the Ap horizon, the fertilized treatment had significantly higher water content at field capacity and at wilting point than the non-fertilized treatment. However, AWHC was not different between treatments of the Ap horizon. The fertilized Bnt1 horizons had significantly lower water contents at field capacity, -100 and -500 kPa. The AWHC was also significantly lower in the fertilized than the non-fertilized Bnt1 horizon. There were no treatment effects in the Bnt2 and Cksa horizons at any of the measured pressures.

Table 5. Bulk density and associated properties, Ksat and TOC of Ap and Bnt1 horizons of fertilized or non-fertilized treatments (June 1991).

Hor	Trt	Avg. Sampling Depth (cm)	Grav. Water Content ($g\ g^{-1}$)	Bulk Density ($Mg\ m^{-3}$)	Total Porosity (f) ($Mg\ m^{-3}$ / $Mg\ m^{-3}$)	Ksat ($m\ d^{-1}$)	•TOC ($g\ kg^{-1}$)
Ap	NF	1-7	0.063	1.45	0.46	0.032	65.6
Ap	F	1-7	0.048	1.26	0.53	0.059	66.7
	Prob.		na	ns	ns	ns	ns
Bnt	NF	17-23	0.098	1.67	0.37	0.0006	38.2
Bnt	F	17-23	0.072	1.50	0.44	0.0022	37.8
	Prob.		na	***	***	***	ns

Hor = Horizon

Trt = Treatment: NF = non-fertilized, F = fertilized

Ksat = Saturated hydraulic conductivity

•TOC = Total organic carbon, Ap NF = 0-7 cm, Ap F = 0-9 cm, Bnt NF = 8-18 cm, Bnt F = 10-20 cm

na = not available due to insufficient sample numbers

ns = not significant $P<0.15$ (ANOVA)

*, **, ***, ****, $P<0.15$, $P<0.10$, $P<0.05$, $P<0.01$, respectively (ANOVA)

Table 6. Water retention characteristics and AWHC of all horizons of fertilized or non-fertilized treatments (1990).

			Water Content ($g\ g^{-1}$) at kPa				
Hor	Trt	Avg. Depth (cm)	-33 (Field Capacity)	-100	-500	-1500 (Wilting Point)	-33 less -1500 (AWHC)
Ap	NF	0-7	0.34	0.28	0.24	0.21	0.13
Ap	F	0-9	0.37	0.28	0.25	0.24	0.13
	Prob.		***	ns	ns	***	ns
Bnt1	NF	8-18	0.40	0.33	0.26	0.22	0.18
Bnt1	F	10-20	0.37	0.29	0.24	0.22	0.15
	Prob.		**	***	**	ns	***
Bnt2	NF	19-27	0.37	0.30	0.23	0.19	0.18
Bnt2	F	21-29	0.36	0.29	0.23	0.20	0.16
	Prob.		ns	ns	ns	ns	ns
Cksa	NF	50-60	0.27	0.22	0.17	0.14	0.13
Cksa	F	55-75	0.27	0.21	0.16	0.14	0.13
	Prob.		ns	ns	ns	ns	ns

Hor = Horizon
Trt = Treatment: NF = non-fertilized, F = fertilized
AWHC = Available water holding capacity
*, **, ***, $P<0.05$, $P<0.01$ and $P<0.001$ respectively (ANOVA)

5. Discussion

Many of the conventional methods of characterizing soil porosity have been based on flow measurements of fluids and/or gases through or into a soil sample. Attributes of the soil pore system were inferred from the flow dynamics using assumed relationships between pore diameters and measured volumes of fluids and/or gases. Image analysis of soil pores provided a means of characterizing the actual, rather than the inferred, morphology of soil aggregates, macropores and roots. This relatively new technique was similar to that to Grevers and De Jong (1990) who used negatives of *in* *situ* soil profiles and simultaneous images on infrared and black and white film to characterize the soil pore system by difference or stereo imagery. Other researchers have used image analysis to characterize soil porosity following no-till (Shipitalo and Protz 1987, Pagliai et al. 1984). Yanuka and Elrick (1985) were able to measure plant roots and their diameters by image analysis.

The differences in soil fabric between fertilizer treatments are more noticeable in the Bnt1 horizons than the Ap horizons. There were different amounts of aggregates, pores and roots as indicated by the three parameters: area mean, perimeter mean and maximum diameter mean in the Bnt1 horizon. As well there were larger macropores and root area means for the fertilized than the non-fertilized treatment. The increased porosity of the fertilized Ap and Bnt1 horizons was also evident in the significantly lower bulk densities which can be attributed to the greater rooting systems. The higher DMY, which was frequently left on the soil surface, dissipates the energy of rain drops before they reach the soil surface. In contrast, the non-fertilized soil with its lower DMY and less extensive rooting system was more prone to compaction than the soil in the fertilized Ap and Bnt1 horizons.

The relations between lower bulk density and increased plant growth (vegetation and root biomass) and yield are not well understood. Further, the bulk density at which root growth ceases or is restricted for a given crop varies with soil water content, soil texture and soil structure (Jones 1983). Pierce et al. (1983) developed criteria for estimating non-limiting, critical and root-limiting soil bulk densities based on basic soil physical properties. According to their estimates, the non-limiting, critical and root-limiting bulk densities for soil texture similar to those in this study (SiCL and C for Ap and Bnt1 horizons, respectively) are 1.46, 1.67 and 1.78 Mg m^{-3}, respectively. Assuming the validity of these results for conditions of the present study, the bulk density of the Bnt1 horizon for the non-fertilized treatment is critical and the bulk density of the fertilized treatment would be non-limiting to root growth.

The aggregate mean area was lower in the Bnt1 horizon of the fertilized treatment but the perimeter and maximum diameter means were relatively greater. The greater yield of bromegrass with fertilization and, therefore, the greater amount of soil-water depletion by grass roots is associated with increased areas and maximum diameter of the macropores. Grevers and De Jong (1992) found that higher yielding forages increased the soil pore area and length. The absence of differences to soil aggregation in the fertilized Ap horizon of the thinsections is not surprising because of the relatively high clay and TOC contents of this soil. Dry sieving accounted for larger aggregates in the non-fertilized Ap horizon. On the other hand, differences in aggregation in the Bnt1 horizon could be the result of soil cracks that were formed from soil desiccation by increased root activity.

There were significantly fewer dry aggregates in the larger size fraction (>6.3 mm) and a larger proportion in the smaller size fractions (2.0 to 0.25 mm) in the fertilized than the non-fertilized treatment. The MWD, which is a single index for aggregate distribution, was lower (2.9 mm) for the fertilized than the non-fertilized (4.0 mm) Ap horizon. This was consistent with how the fertilized soil handled upon drying in the laboratory as it broke down into smaller aggregates readily when handled. The Ap horizon of the fertilized treatment could allow better root growth as it has better tilth.

High TOC in both treatments, though not statistically different, could have implications for soil structural characteristics including aggregate size distribution. Blevins et al. (1983) found only small differences in organic matter content of no-till treatments and conventional tillage treatments below 5 cm depth for a silt loam (Typic Paleudalf). In my study the soil had remained undisturbed for over 50 years, such that organic carbon concentration could increase in the Ap horizon.

The data are consistent with the interpretation that the additional biomass both above and below the mineral soil surface produced by the fertilized forage helped in improving the infiltration and percolation capacity of this Solonetzic soil. Additional biomass could also include the presence of more roots penetrating the Bnt horizon and providing more macropores for water flow.

Chepil (1955) observed greater aggregation from surface residue with no-tillage than with conventional tillage. The residue placed on the surface probably continues to replenish the soil-cementing products over a longer period and protects the topsoil against rain-drop impact. Furthermore, during the winter, the greater residue cover on the fertilized Ap horizon would probably reduce the effect of freeze-drying which can be especially destructive of soil aggregates (Skidmore 1975). In other studies, the improved soil structure was attributed to an increase in soil organic carbon (Grevers and De Jong 1990), biological activity (McAndrew and Malhi 1992, Carter et al. 1986, Carter et al. 1977, Cairns et al. 1967) and the extensive forage root systems. These reported increases in TOC are in contrast to data collected in this study, where porosity increased with no significant differences in TOC in either the Ap or Bnt1 horizons of the fertilized treatment.

The water regimes in the middle of the growing season under the two fertilizer treatments reflect different water use patterns by the forage cropping system. Precipitation during the 1990 growing season for May and June was half the June normal and during the 1991 growing season for May and June was approximately 1.5 times the normal for May and June (Appendix A). Since one can assume there was equal precipitation on both treatments, the water content can be used as some evidence for greater water extraction by roots in the fertilized treatment. Of course this also assumes that there was equal infiltration of the rain on the 2 treatments, but if anything infiltration probably would be better on the fertilized treatment with the increased dry matter residue and increased soil porosity. The fertilized treatment had forages with more leaf area with increased DMY and deeper rooting systems, thus greater (evapo)transpiration resulting in significantly less water in the profile than in the non-fertilized. Grevers and De Jong (1990) found bromegrass to deplete soil water mainly from the top 70 cm of soil. The higher yielding forages on the fertilized treatment with the many fine and extensive roots could be expected to extract more soil water over the whole growing season compared to the lower yielding non-fertilized treatment.

There was a trend for greater Ksat within a horizon with the fertilizer treatment. The Ksat depends on the size and continuity of pores and not just on total porosity (Hillel 1980). Greater Ksat in no-tilled soil is an indication of better pore continuity and/or presence of large pores and biochannels in this system. Root channels, earthworm holes and large cracks can contribute greatly to the magnitude of the Ksat rate. Alteration in soil structure as a result of increased and deeper root distributions can increase Ksat as evidenced by the results observed in the Bnt horizon. The higher Ksat of the fertilized Ap and Bnt1 horizons may be attributed to greater root growth and lower bulk density. Micromorphological characteristics showed that increased roots and macropores as a result of greater growth may be the main contributing factors. Culley et al. (1987), Blevins et al. (1983) and Ehlers (1975) observed a greater Ksat under no-till which may have similarities to the fertilized treatment of this study.

The decreased water content under fertilization may reflect not only increased (evapo)transpiration but also enhanced infiltration and percolation associated with increased forage leaf growth and better pore continuity. The decrease in water content may explain the higher forage DMY in the N fertilized treatments than the non-fertilized. Moisture stress of plants during drought periods often occurs on Solonetzic soils because of the lack of stored moisture in the rooting zone due to restricted penetration of water and roots through the hard Bnt. Presumably the fertilized treatment promoted greater vegetative and root growth which may have helped the Smooth Bromegrass to grow during these short drought periods.

6. Conclusion

Nitrogen fertilization increased the above ground forage growth and presumably root growth. Evidence for this came from lower water content at sampling time and the higher DMY yields. Greater root growth improved porosity (lowered the bulk density and increased Ksat) of the Bnt1 horizon. Improved physical properties would be expected to even further increase root growth and above ground DMY. Although N fertilization was terminated, the dry matter was not removed so that the N could be expected to recycle through subsequent crops.

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CHAPTER III. CHEMICAL PROPERTIES

1. Introduction

Solonetzic soils support poor vegetative and root growth as a consequence of limiting chemical properties such as a slightly to moderately acidic A horizon, a Bnt horizon with a ratio of exchangeable Ca to Na of 10 or less and a saline B and/or C horizon (Agriculture Canada Expert Committee on Soil Survey 1987). The physical and morphological properties as altered by fertilization and grass forage cropping systems are discussed in Chapter II. Changes in chemical properties 12 years after the last N fertilizer application on a mixed stand of grass will be discussed in this chapter.

Although few reports deal with chemical changes in Solonetzic soils under forages following N fertilization, there is pertinent literature dealing with soils seeded to annual crops under no-till following N fertilization and similarly fertilized soils under forage cropping systems. In the fertilized treatments as compared to the non-fertilized treatments, soil pH is reported to decrease significantly (McAndrew and Malhi 1992, Malhi et al. 1991, Schwab et al. 1989, Mahler and Harder 1984, Blevins et al. 1983, Perl et al. 1982, Blevins et al. 1977, Jolley and Pierre 1977). There is a trend toward lower electrical conductivity (EC) with reduced exchangeable Ca, Mg and K (Schwab et al. 1989, Blevins et al. 1983, Blevins et al. 1977) and Na (McAndrew and Malhi 1992) with the reduction in Na greater than that of Ca and Mg such that lower sodium adsorption ratio (SAR) has been reported (McAndrew and Malhi 1992, Carter and Pearen 1989). Trends toward higher total N (McAndrew and Malhi 1992, Blevins et al. 1983) and higher total organic carbon (TOC) may be associated with greater dry matter yields (DMY) (McAndrew and Malhi 1992, Schwab et al. 1989, Blevins et al. 1983).

Limited research has been conducted on the effect of acidification caused by ammonium nitrate fertilizer on distribution and concentrations of soluble trace elements in the soil. The research into elemental distribution under acidic soil conditions in Alberta has centered around an industrial elemental sulfur stockpile (Warren and Dudas

1992). The natural abundance of total trace elements in Alberta has been documented (Soon and Abboud 1990, Dudas and Pawluk 1980, Dudas and Pawluk 1977).

It is proposed that the ammonium nitrate fertilizer treatment gradually improves the sodic soil condition which then allows the beneficial role of plant roots to assist in the soil improvement process (Carter 1984). The extent to which plants and N fertilizer can modify the chemical properties of a soil partially depends on the rooting pattern and biomass of the crop and rate of decomposition of root residues (Perfect et al. 1990) and partially on the amount of N fertilizer (Malhi et al. 1993). Past studies have shown that increasing root growth will recycle calcium from lower soil horizons (Carter and Pearen 1989, White 1971), increase moisture extraction and sodium leaching (Carter and Pearen 1989, Cairns et al. 1967), increase crop uptake of salts (Hoffman 1986) and improve porosity, soil aeration and water percolation (Chapter II, Carter et al. 1977).

At the Vegreville Experimental Farm, fertilization of forages had been practised for 18 years, commencing in 1960. Following termination of fertilization in 1978, forage production of the previously fertilized plots continued to exceed non-fertilized plots even as late as 1991 as reported in Chapter II. Soil characterization of chemical properties and forage yields for this site over the last 30 years has been reported by McAndrew and Malhi (1992), Perl et al. (1982), Cairns (1971) and Cairns et al. (1967) as described in Chapter I.

2. Objective

The objective of the study was to determine the residual effects of previous long-term N fertilization on several soil chemical properties. The hypothesis for this study was that previous, long-term N fertilization of a grass forage acidified the Solonetzic soil at the experimental site by the release of H^+ and that Ca^{2+} cycling by plant roots replaced some of the Na^+ displaced by H^+. These processes in turn helped to increase soluble carbon, decrease exchangeable Na and increase soluble Fe, Mn, Cu, Zn and Co in the fertilized Ap horizon.

3. Materials and Methods

3.1. Plot Design and Layout

The experimental design and layout were described in Chapter II.

3.2. Field Sampling

In June 1990, a tractor mounted vibrating mechanical corer was used to collect soil samples by procedures described by Nelson and McAndrew (1990). Four samples for chemical analysis were taken from each treatment plot in the areas shown by * in Figure 1. These sample sites were chosen to avoid the subtreatment areas. Soil samples collected were: 4 blocks x 2 treatments x 4 horizons (Ap, Bnt1, Bnt2, Cksa) x 2 pairs of samples per horizon for a total of 128. Of these four samples collected per horizon, the two samples located on the east side of the treatment plot were combined to form a composite soil sample. The 2 samples on the west side of the plots were also combined. Thus 64 soil samples were analyzed.

Cores were segmented based on their genetic horizons (Ap, Bnt and Cksa). The Bnt horizons were divided into two equal sections (Bnt1 and Bnt2) due to visible differences in structure and consistence evident in the Bnt horizons between the treatments. The samples were placed in plastic bags and kept cool in Styrofoam containers. These samples, collected in June 1990, were used for measurement of: pH, exchangeable bases, total organic carbon, total N and P and saturated paste extract pH, electrical conductivity, soluble ions and soluble carbon.

3.3. Laboratory Analysis

All the soil samples collected in June 1990 were air-dried and ground to pass a 2 mm sieve. Soil pH was determined in a 1:2 ratio of soil to 0.01 *M* $CaCl_2$ solution

(Peech 1965). The soil pH in 1:2 ratio of soil to deionized water was also measured (McKeague 1978). The pH and EC of the saturation extract were measured according to Richards (1954) using a Fisher Accumet pH/EC CDM 83 conductivity meter Model 825 MP. Total nitrogen and total phosphorus were measured using the Kjeldahl method (Bremner and Mulvaney 1982) which was modified by a watch glass as a condenser during the digestion stage. The digested sample was diluted and ammonium and phosphorus concentrations measured by Auto Analyzer (Technicon Industrial Method No. 334-74W/13 1976, Revised 1977). Total N and P, in g kg^{-1}, were calculated from the μg mL^{-1} Auto Analyzer readings as [{(net μg mL^{-1}N or P) (100 mL)/mass of soil g}(1 g/10^6 μg)(1000 g/1 kg)]. Total cation exchange capacity (TCEC) was determined by saturation of the sample with NH_4^+ and then displacement of NH_4^+ as described by Chapman (1965). TCEC, in cmol+ kg^{-1} soil, was calculated as [(μg mL^{-1} NH_4^+)(250 mL/(mass of soil g)(1 mol/18.038 g NH_4^+)(1 g/ 10^6 μg) (100 cmol/1 mol)(1 mol +/1 mol NH_4^+)(10^3 g soil/1 kg soil)]. Exchangeable Na, Ca, Mg and K cations were extracted with 1*N* ammonium acetate adjusted to pH 7.0 with a 1:25 soil to solution ratio and their concentration in the extracting solution was measured using Atomic Absorption Analyzer (McKeague 1978). Each of the extractable cations was calculated as [(μg/mL dilution)(mL dilution/mL extract) (mL extract/g soil)(mol cation/ x g cation)(g cation/μg cation)(100 cmol/1 mol) (2 cmol+/1 cmol Ca and Mg cation)(10^3 g soil/1 kg soil)] where x is the molecular weight of the specific ion. Base saturation (%) was calculated as the {Σ (Exch Ca, Mg, K, Na)/TCEC} x 100 where all cations and TCEC were in cmol+ kg^{-1}.

Soluble ions were determined on the Ap and Bnt1 soil samples collected in June 1990. Saturated paste extracts were prepared using the technique outlined by Richards (1954). The extracts were filtered through #40 filter paper and then through 0.2 μm pore size filter. The samples were placed in a cooler between analyses. All the soluble inorganic ions were calculated in mmol L^{-1} as {(mg L^{-1} determined)(1 mol/ x g cation))(1 g/1000 mg)(1000 mmol/mol)} where x is the molecular weight of the specific ion. Total soluble carbon (TSC) and soluble inorganic carbon (SIC) were analyzed using a

Dohrmann Total Carbon Analyser DC-80. Soluble inorganic carbon (SIC) was first removed using acid and measured as CO_2 using an infrared detector. After the SIC was eliminated, the ultra violet light source was turned on to oxidize organic C to CO_2 which was also quantified using an infrared detector to yield SOC. The sum of SIC plus SOC is termed total soluble carbon (TSC). The instrument gave readings for TSC and SIC in mg L^{-1}.

To gain a broader understanding of the soil ion chemistry following termination of long-term fertilization, inductively coupled plasma-atomic emission (ICP) analysis was used to determine the elemental concentrations of Ca, Mg, Na, K, Si, Al, Fe, P, S, Sr, Ba, As, V, Mo, B, Mn, Cr, Li, Ti, Cd, Co, Se, Zn, Cu, Pb and Ni on saturated paste extracts (Bausch and Lomb Model 3580 AES).

Sodium adsorption ratio (SAR) was calculated using the ion concentrations in saturation paste extracts $\{SAR = [Na^+] / \sqrt{([Ca^{2+}] + Mg^{2+}]/2)}\}$. All concentrations were in mmoles per litre. An Auto Analyzer was used to measure nitrate (NO_3) using Technicon Industrial Method No. 158W-71 (1972); ammonium (NH_4) using a modified Technicon Industrial Method No. 98-70W (1973); phosphate (PO_4) using Technicon Industrial Method No. 94-70W (1973); chloride (Cl) using Technicon Industrial Method No. 99-70W (1973); and sulfate (SO_4) using Technicon Industrial Method No. 118-71W (1972). These anions were calculated in mmol L^{-1} as [mg L^{-1} determined) (1 mol/ *y* g anion)(1 g/1000 mg)(1000 mmol/mol)].

3.4. Statistical Analysis

The general linear model procedure (GLM) of the SAS Institute Inc. (1989) was used to perform a two-way analysis of variance (ANOVA). Least significant difference was used to compare means where significant differences ($P \leq 0.15$) were detected by the F-test. Analysis was conducted separately for the various depths, due to differences in variability.

4. Results

4.1. Total Nitrogen and Phosphorus

The total N concentration was significantly higher ($P<0.15$) in the fertilized Ap horizon than the non-fertilized horizon (Table 7). Total P concentrations were not significantly different between treatments in the Ap or Bnt horizons but P concentration was significantly higher in the non-fertilized than in the fertilized Cksa ($P<0.05$). There was a trend for higher TOC (Chapter III, Table 5) and the C:N ratio was significantly lower ($P<0.05$) in the fertilized Ap horizon than in the non-fertilized.

Table 7. Total N and P concentrations in the horizons of fertilized or non-fertilized Solonetzic soil.

Horizon	Treatment	Avg. Depth (cm)	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	C:N
Ap	NF	0-7	4.3	0.89	14.7
Ap	F	0-9	6.2	0.94	10.4
	Prob.		*	ns	***
Bnt1	NF	8-18	2.8	0.66	11.9
Bnt1	F	10-20	2.9	0.64	12.0
	Prob.		ns	ns	ns
Bnt2	NF	19-27	1.5	0.47	12.5
Bnt2	F	21-29	1.6	0.45	11.1
	Prob.		ns	ns	ns
Cksa	NF	50-60	0.40	0.49	20.0
Cksa	F	55-75	0.43	0.45	16.6
	Prob.		ns	***	ns

*, **, ***, ****, P<0.15, P<0.10, P<0.05, P<0.01 respectively (ANOVA)

ns = not significant, Prob<0.15 (ANOVA)

4.2. Soluble Carbon

Total soluble carbon and SOC were significantly higher in the Ap horizon of the fertilized ($P<0.05$) than the non-fertilized treatment (Table 8). The TSC and SOC concentrations tended to be higher in the Bnt1 horizon of the fertilized treatment but the differences were not significant.

Table 8. Soluble C concentrations in saturated paste extracts of fertilized or non-fertilized treatments.

Horizon	Treatment.	Avg. Depth (cm)	TSC mg L^{-1}	SIC mg L^{-1}	SOC mg L^{-1}
Ap	NF	0-7	1352.6	34.1	1318.8
Ap	F	0-9	1550.1	8.0	1542.1
	Prob.		**	ns	**
Bnt1	NF	8-18	1099.6	26.3	1073.5
Bnt1	F	10-20	1124.5	11.7	1112.8
	Prob.		ns	ns	ns

TSC = total soluble carbon

SIC = soluble inorganic carbon

SOC = soluble organic carbon

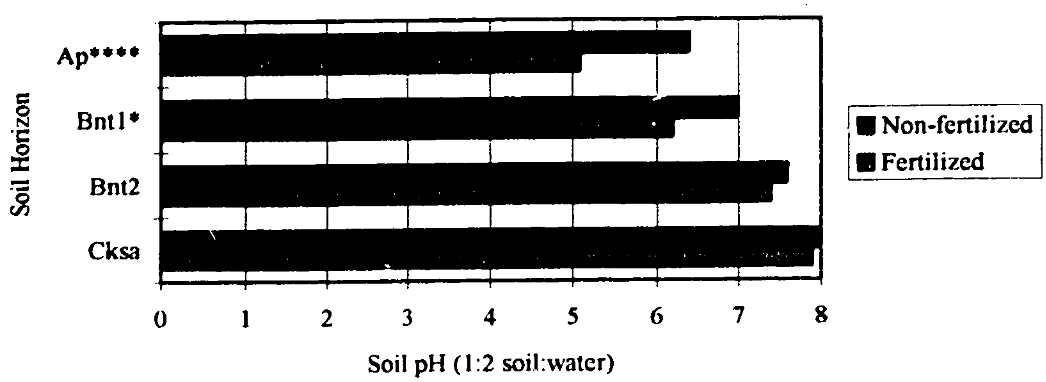
*, **, ***, $P<0.10$, $P<0.05$, $P<0.01$ respectively (ANOVA)

ns = not significant $P<0.15$ (ANOVA)

4.3. Soil pH

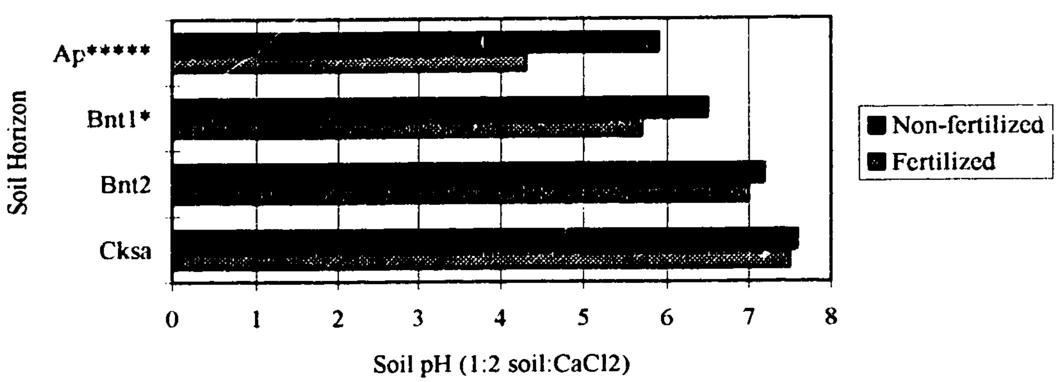
The soil pH (water and $CaCl_2$) of the Ap and Bnt1 horizons was significantly lower for the fertilized treatments than for the unfertilized (Figure 8). Lower horizons showed a similar trend.

a)



*, ****, P<0.10, P<0.001, respectively (ANOVA)

b)



*, *****, P<0.10, P<0.0001, respectively (ANOVA)

Figure 8. Soil pH for the horizons of fertilized or non-fertilized treatments a): measured in water, b) measured in $CaCl_2$.

4.4. Exchangeable Bases

Concentrations of exchangeable bases were variable (Table 9). This variability resulted in few statistically significant differences between the cation concentrations among treatments. There were significantly higher concentrations of Mg in the Bnt2 horizon of the fertilized treatment, but neither Ca nor Mg concentrations varied significantly between treatments in the Ap horizon. There was a trend for exchangeable Ca, Mg and Na to be lower in the fertilized Ap than in the non-fertilized Ap horizon. This trend is consistent with lower pH values (Figure 8). In the Bnt1 horizon, there were no significant differences in Ca, Mg or Na between treatments but exchangeable K was significantly lower in the Bnt1 ($P<0.001$) of the fertilized treatment. The base saturation was lower in the Ap horizon of the fertilized treatment. The very high base saturation values in the Bnt2 and Cksa horizons are attributed to the presence of soluble cations such as sulfates, carbonates and chlorides of Na, Mg and Ca.

The Ca:Na ratio tended to be lower in the Ap horizon of the fertilized than the non-fertilized treatment and this trend was supported by the trend toward lower pH together with negligible Na in either horizon. This Ca:Na ratio trend was reversed in the lower horizons but further interpretation is confounded by the presence of soluble ions.

The TCEC did not vary significantly between treatments or horizons (Table 9). The method used to determine TCEC (displacement of exchangeable NH_4^+) may be subject to errors which underestimate soil TCEC by: exchangeable Al and its hydroxy forms are not readily exchanged with monovalent cation saturating solutions; cation exchangers (especially fine clay particles and organic matter) may be lost during decantation; and/or NH_4^+ may be fixed within silicates (Rhoades 1982).

Table 9. Exchangeable bases of the soil horizons in fertilized or non-fertilized treatments.

Hor	Trt	Avg. Depth (cm)	Ca cmol+ kg^{-1}	Mg cmol+ kg^{-1}	Na cmol+ kg^{-1}	K cmol+ kg^{-1}	TCEC cmol+ kg^{-1}	Ca:Na	Base Saturation (%)
Ap	NF	0-7	11.47	5.06	0.96	1.00	19.86	15.3	92
Ap	F	0-9	5.04	3.20	0.71	0.88	21.11	9.9	48
	Prob.		ns	ns	ns	ns	ns	ns	*
Bnt1	NF	8-18	7.55	9.27	3.64	0.77	23.22	3.4	92
Bnt1	F	10-20	7.95	8.44	2.87	0.47	21.72	10.8	91
	Prob.		ns	ns	ns	****	ns	ns	ns
Bnt2	NF	19-27	14.92	11.06	3.32	0.69	22.02	4.7	148
Bnt2	F	21-29	15.87	12.04	3.09	0.54	22.67	11.2	156
	Prob.		ns	***	ns	****	ns	ns	ns
Cksa	NF	50-60	38.42	9.14	3.61	0.40	15.19	11.2	342
Cksa	F	55-75	36.43	10.46	3.79	0.35	15.79	11.0	364
	Prob.		ns	ns	ns	ns	ns	ns	ns

Hor = Horizon

Trt = Treatment: NF = non-fertilized, F = fertilized

*, **, ***, ****, $P<0.10$, $P<0.05$, $P<0.01$ and $P<0.001$ respectively (ANOVA)

ns = not significant $P<0.15$ (ANOVA)

4.5. Saturated Paste Extract Chemistry

The dominant ion species in the soil solution, from saturation paste extracts of the soil samples, were Na^+, SO_4^{2-} and Cl^- (Tables 10 (cations) and 11 (anions)). The Na and SO_4 concentrations tended to be greater, though not significantly, in the Ap horizon and lower in Bnt1 horizon of the fertilized treatment. The relative concentrations (mmol (±) L^{-1}) of the cationic and anionic species [1] followed the order:

<u>Cationic Species:</u>

Ap horizon, non-fertilized treatment:

Na >> Ca > Mg > NH_4 > K > Al >> Fe > Mn >> Sr > Li > Ba > Zn > Ti = Pb > Ni > Cu >> Cd > Co >> Cr

Ap horizon, fertilized treatment:

Na >> Mg > Ca > NH_4 > K> Al >> Fe > Mn > Co >>Zn > Sr > Ti > Ni > Ba > Ni > Cu >> Pb > V = Cr >>Li > Cd

Bnt1 horizon, non-fertilized treatment:

Na >> Mg > Ca > K > NH_4 > Al >> Fe > Mn > Li > Sr > Zn > Ni > Cu > Ti > Ba >> Co > Pb >> Cd >>V = Cr

Bnt1 horizon, fertilized treatment:

Na >> Mg > Ca > NH_4 > K > Al>> Fe > Mn > Li >> Sr > Zn > Ti > Cu > Ni > Ba >> Pb > Co >> Cd > V >> Cr

<u>Anionic Species:</u>

Ap horizon, non-fertilized treatment:

SO_4 >> Si > Cl >> B > Se >> As > Mo

Ap horizon, fertilized treatment:

SO_4 >> Si > Cl >> Se > B >> Mo > As

Bnt1 horizon, non-fertilized treatment:

SO_4 >> Cl > Si >> B > Se >> As > Mo

Bnt1 horizon, fertilized treatment:

SO_4 >> Cl > Si >> B > Se >> As > Mo

There are some significant differences between the treatments in concentrations of ions extracted from the Ap and Bnt1 horizons (Tables 10 and 11). The significant differences in cation concentrations between treatments in the Ap horizon were Fe ($P<0.15$), Mn ($P<0.15$), Co ($P<0.05$), Zn ($P<0.15$), Cu ($P<0.15$) and Li ($P<0.05$). The Ap horizon of the fertilized treatment had relatively greater concentrations of Mg, Co, Ti, Ni, Cu, V and Cr than the non-fertilized treatment when compared in the array. There were also relatively lesser concentrations of Ca, Sr, Ba, Pb and Cd in the

Table 10. Cations in saturated paste extracts of the Ap and Bnt1 horizons fertilized or non-fertilized treatments.

Hor	Trt	Avg. Depth (cm)	Ca mM	Mg mM	Na mM	K mM	NH_4 mM	Al mM	Fe mM	Mn mM
Ap	NF	0-7	2.58	1.72	11.13	0.70	0.76	0.12	0.072	0.039
Ap	F	0-9	1.11	1.26	12.92	0.51	0.86	0.28	0.144	0.053
	Prob.		ns	ns	ns	ns	ns	ns	*	*
Bnt1	NF	8-18	1.16	1.51	26.52	0.64	0.31	0.11	0.062	0.018
Bnt1	F	10-20	1.08	1.36	18.66	0.23	0.39	0.18	0.086	0.032
	Prob.		ns	ns	ns	ns	ns	ns	ns	ns

Hor	Trt	Avg. Depth (cm)	Sr µM	Li µM	Ba µM	Zn µM	Ti µM	Pb µM	Ni µM	Cu µM	Cd µM	Co µM	V µM	Cr µM
Ap	NF	0-7	9.79	9.73	3.28	2.52	2.00	2.03	1.42	1.08	0.95	0.1	0.06	§
Ap	F	0-9	5.23	0.06	2.12	5.30	5.06	0.33	2.05	1.63	0.04	12.6	0.12	0.12
	Prob		ns	***	ns	**	ns	ns	ns	**	ns	***	ns	ns
Bnt1	NF	8-18	6.22	9.73	1.45	2.75	1.65	0.14	2.35	1.73	0.04	0.17	§	§
Bnt1	F	10-20	6.22	12.4	1.50	4.23	3.34	0.27	1.63	1.83	0.05	0.11	0.02	§
	Prob		ns	ns	ns	ns	*	ns	*	ns	ns	ns	ns	na

Hor = Horizon

Trt = Treatment: NF = non-fertilized, F = fertilized

§ = below detection limits

*, **, ***, $P<0.15$, $P<0.10$, $P<0.05$ respectively (ANOVA)

ns = not significant $P<0.15$

fertilized treatment compared to the non-fertilized treatment. Cobalt had the largest change in concentrations in the Ap horizon between the treatments. The concentrations of anions in the Ap horizon showed a trend of more Si, Se and Mo and less B with the fertilized treatment compared to the unfertilized treatment.

Table 11. Anions in saturated paste extracts of the Ap and Bnt1 horizons of fertilized or non-fertilized treatments.

Hor	Trt	Avg. Depth (cm)	SO_4 mM	Si mM	Cl mM	PO_4 mM	NO_3 mM	B µM	Se µM	As µM	Mo µM
Ap	NF	0-7	2.57	0.46	0.46	§	§	7.28	1.71	0.29	0.12
Ap	F	0-9	5.33	0.66	0.48	§	§	1.97	2.42	0.28	0.29
	Prob.		ns	ns	ns	na	na	ns	ns	ns	ns
Bnt1	NF	8-18	10.61	0.12	0.50	§	§	1.97	1.12	0.28	2.45
Bnt1	F	10-20	8.79	0.37	0.38	§	§	3.76	1.48	0.23	0.19
	Prob.		ns	ns	ns	na	na	ns	ns	ns	ns

Hor = Horizon

Trt = Treatment: NF = non-fertilized, F = fertilized

§ = below detection limits

ns = not significant P<0.15 (ANOVA)

na = not available

Titanium was significantly higher (P<0.15) and Ni significantly lower (P0.15) in the Bn1 horizon of the fertilized than the non-fertilized treatment (Table 10). There were trends of increased NH_4 and Pb and decreased concentrations of K and Co in the fertilized Bnt1 horizon than the non-fertilized horizon (Table 10). Silicon tended to be higher in the fertilized than the non-fertilized Bnt1 horizon (Table 11).

The pH of the saturated extracts of the fertilized treatment tended to be lower in the Ap horizon compared to the non-fertilized treatment (5.1 and 6.3, respectively) and was significantly lower (P<0.15) in the Bnt1 (5.9 and 7.4, respectively) (Table 12). There is a trend toward lower EC for the Ap and Bnt1 horizon of the fertilized than the non-fertilized treatment (Table 12).

The sodium adsorption ratio (SAR) was higher in the Bnt1 horizon compared to the Ap horizon (Table 12). In the Ap horizon the difference in SAR between the fertilized treatment and the non-fertilized treatment (11.24 and 9.28, respectively) was not significant. In the Bnt1 horizon a reverse, but a nonsignificant trend was observed in the SAR; it was greater in the non-fertilized treatment than the fertilized treatment (15.65 and 23.39, respectively).

Table 12. pH, EC and SAR of saturated paste extracts of the Ap and Bnt1 horizons of fertilized or non-fertilized treatments.

Horizon	Treatment	Avg. Depth (cm)	Soil Saturation (%)	pH Saturated Paste Extract	EC dS cm^{-1}	SAR
Ap	NF	0-7	77.9	6.3	1.47	9.3
Ap	F	0-9	86.2	5.1	1.38	11.2
	Prob.		ns	ns	ns	ns
Bnt1	NF	8-18	66.8	7.4	2.36	23.4
Bnt1	F	10-20	69.5	5.9	1.8	15.7
	Prob.		ns	*	ns	ns

ns = not significant P<0.15 (ANOVA)
* = P<0.15 (ANOVA)

5. Discussion

Ammonium nitrate fertilization was associated with changes in some chemical properties of the Solonetzic soil 12 years after the last fertilizer application. Fertilization did not affect TOC (Chapter II) and total P in the soil horizons but significantly increased the amount of total N which was due in part to the deeper Ap horizon. McAndrew and Malhi (1992) found TOC and total N increased as a result of the residual effect of applied N at this experimental site and similar results were reported by Blevins et al. (1983) during long-term (10 years) application of 336 kg ha^{-1} of N to corn under no-tillage on silt loam (Typic Paleudalfs). Similarly, in a crop rotation study on a Brown Chernozemic soil in Saskatchewan, Biederbeck et al. (1984) observed that application of 32 kg ha^{-1} of N and adequate P to continuous wheat over 12 years maintained organic C and N content higher than did applications of P alone.

The significantly lower C:N ratio in the Ap horizon of the fertilized treatment compared to the non-fertilized treatment is consistent with the lower level of soil moisture due to grass uptake and the increased biomass (both above and below ground) production. The lower C:N ratio was probably the result of more N cycling in the soil due to the added N and perhaps higher N concentration of the dry matter that was produced. Roberts et al. (1989) found grassland soils, at any one slope position, had lower C:N ratios than the forest soils resulting from the strong influence of greater vegetation growth and increased biological activity in grassland soils.

Dry matter yield (DMY) (Chapter II) of the fertilized treatment tended to be higher. In addition to greater DMY in the fertilized treatment during 1986 to 1989, there tended also to be more mineral N (NH_4) in the soil in 1990. Soluble NO_3 was below detection limits in both treatments for most of the blocks and horizons. The greater residue cover with no-tillage annual crops and some forage crops has been reported to reduce water runoff (Hill 1990), thereby increasing potential moisture supply to crops. The forage would therefore be expected to benefit both from enhanced residual mineral N supply, perhaps through recycling, and greater moisture availability.

The high ammonium nitrate fertilizer rate of 305 kg ha^{-1} of N resulted in significantly lower soil pH (water and $CaCl_2$) in the Ap and Bnt1 horizons. Nitrogen fertilization had a beneficial effect of increasing yield with a concomitant detrimental effect of lowering pH. Other researchers have also reported depression in pH from the use of N fertilizers on Solonetzic soils (McAndrew and Malhi 1992, Carter and Pearen 1989, Perl et al. 1982, Carter et al. 1978, Cairns 1971). This was probably due to nitrification which produced H^+ and displaced basic cations from the exchange complex (Bohn et al. 1985). The soil pH of the study was similar to values reported by Cairns et al. (1967), Perl et al. (1982) and McAndrew and Malhi (1992), indicating that soil pH had changed little if any since termination of fertilization. Most Solonetzic soils have a shallow and acidic Ap horizon and fertilizer N is needed to obtain crop yields, so acidification is not desirable on these soils and suggests a need for liming.

The acidity produced by high amounts of ammonium nitrate fertilizer is readily apparent from the low pH and reduced exchangeable bases in the fertilized Ap horizon compared to the non-fertilized. Hetrick and Schwab (1992) found similar trends with decreased pH and total of exchangeable bases with N additions. Total organic carbon contributes to the TCEC of a soil (Thomas and Hargrove 1984), and one would expect that increasing TOC would result in increased TCEC (Schwab et al. 1989). Schwab et al. (1989) reported that the low pH caused by N fertilizers negated any possible increase in pH-dependent CEC resulting from higher TOC. This is probably the case in the Ap horizons of this study.

Ammonium nitrate treatments have been associated with increased water infiltration and/or percolation (van Schaik and Cairns 1974) and reduced concentrations of extractable and soluble Na in Solonetzic soils under dryland conditions (Carter et al. 1978, Cairns 1971, Cairns et al. 1967). McAndrew and Malhi (1992) reported the decrease in change of extractable Na due to N fertilizer was smaller (9 years after fertilization ceased) than previously reported for soils sampled in 1973 (Perl et al. 1982). In the present study the fertilized Ap horizon (12 years after fertilization ceased) showed only a trend toward lower exchangeable Na than in the non-fertilized Ap horizon. No significant differences in EC or SAR between fertilized and non-fertilized Ap and Bnt1 horizons were evident in this study. When McAndrew and Malhi (1992) sampled the experimental site in 1986, they reported a lower SAR in the fertilized Ap horizon (7.32) than the SAR of 11.24 which was observed in 1990 (the present study). The lower Ca:Na ratio in the fertilized Ap horizon is related to the lower exchangeable Ca, presumably due to its replacement by H and/or Al. If an exchangeable Ca:Na ratio greater than 10:1 in the Bnt represents a non-Solonetz soil (Agriculture Canada Expert Committee on Soil Survey 1987), then the transformation of Solonetz to non-Solonetz may have been completed in the Bnt1 and Bnt2 horizons as a result of N fertilization. The Ca:Na ratios should be accepted with caution because the Ca:Na ratios may have been affected by soluble ions especially in the Bnt2 and Cksa horizons.

Though not significantly different there was a trend for lower exchangeable Ca, Mg and K in the fertilized than the non-fertilized Ap horizon. This is consistent with lower pH values. The decrease in Ca and Mg with fertilizer treatment is similar to the observations of other researchers (McAndrew and Malhi 1992, Schwab et al. 1989, Perl et al. 1982, Blevins et al. 1983, Blevins et al. 1977). Although significant reduction in exchangeable K in the Bnt horizon, increases the chance of K deficiency in the soil, the K content of this soil remains well above deficiency levels.

The relative quantities of Ca, Mg, Na and K displaced from the exchange sites during the 18 years of fertilization and measured 12 years after last fertilizer treatment was applied, adhered to the classical concept of the lyotropic series for exchangeable cations (Bohn et al. 1985). According to this series, Ca is generally considered to be the most strongly retained, followed by Mg, K and Na. The results of this study demonstrate that Ca had the fewest significant concentration changes and K the most, with Na and Mg being intermediate. The reduction of exchangeable Na in the fertilized Ap and Bnt1 horizons would be expected to improve aggregation and hence percolation of water and aeration of the soil. These cations are replaced by cations such as Al^{3+}, H^+ and NH_4^+. In summary there was a direct replacement of cations by NH_4^+ but more importantly, H^+ produced by nitrification of NH_4^+ displaced more of the Ca^{2+} and Mg^{2+}.

Base saturation was significantly lower in the fertilized Ap horizon. Theoretically neither exchangeable aluminum nor exchangeable hydrogen is present in appreciable concentrations above pH 7.0 (Bohn et al. 1985), so this soil should be 100% base saturated. However, at pH 5.1 (water) base saturation of the fertilized Ap horizon was less than 48% in contrast to 92% at pH 6.4 of the non-fertilized treatment and may be indicative of presence of H and Al in the fertilized treatment.

Total soluble carbon and SOC were significantly greater in the fertilized Ap horizon suggesting more biologically active C compounds. Soil pH and SOC influence soil solutions because dissolved humic materials complex metals which alter metal solubility. Hesterberg et al. (1993) reported high levels of SOC increased the solubility of Zn and Cu. In the present study, the lower pH and higher SOC of the fertilized Ap horizon would be expected to increase the solubility of Fe, Mn, Cu, Zn, (Lindsay 1979) and Co and decrease the solubility of Li. Warren and Dudas (1992) found that soluble Fe and Co concentrations increased at low pH, but soluble Mn and Zn did not. Essentially there was no difference in soluble anions between treatments in either horizon in the present study.

In general, the beneficial effects on the soil chemical properties correspond to the results of previous studies conducted on similar sodic soils using high rates of ammonium nitrate (Carter and Pearen 1989, Carter et al. 1977). The reason why ammonium nitrate caused significant physical changes but little significant chemical changes in the B horizon is unclear. Other studies have shown that the beneficial effect of ammonium nitrate is associated with large increases in root growth and water infiltration into the soil (Carter et al. 1977, van Schaik and Cairns 1969, Cairns et al. 1967). As well as reducing bulk density, the ability of vigorous roots in the fertilized treatment to recycle Ca from the Cksa horizon would be expected to allow continued amelioration to occur. Shading of the soil by increased foliage along with vigorous root development could also allow greater leaching of displaced Na due to decreased evaporation and bulk density and increased infiltration and percolation into the soil profile. Thus continued better vegetative growth on the fertilized treatment is inferred to be related most closely to greater root activity.

Lower pH and lower exchangeable Ca in the fertilized Ap horizon might be expected to decrease yield but this was not found. The main agronomic effect of acidification so far reported at such sites is a change in the soil microflora and a reduced rate of soil N mineralization (Carter 1986). Overall, large additions of lime applied with the ammonium nitrate should prevent acidification. The combination of perennial grasses and N amendments can accelerate the natural process of solodization characterized by leaching of Na and addition of TSC. Increased biomass might explain some of the differences in physical properties reported in Chapter II.

6. Conclusion

There were few significant differences or trends evident in the chemical soil properties examined. Total N, TSC and SOC were significantly greater in the fertilized Ap horizon than the non-fertilized. The base saturation was significantly lower but no individual exchangeable bases concentrations (Ca, Mg, Na and K) were altered in the fertilized Ap horizon. Additionally 12 years after discontinuing N application there was still a significant reduction in soil pH, which is not desirable from a soil fertility and productivity point of view. The resulting acidification was associated with altered concentrations of elements in the saturated paste extracts of soil including significantly greater soluble Fe, Mn, Cu, Zn and Co, and significantly less soluble Li in the fertilized Ap horizon. Compared to previous studies at the study site (McAndrew and Malhi 1992, Perl et al. 1982, Cairns 1971), there was a continued trend of decreased sodicity and increased productivity of the Solonetzic soils when sampled 12 years after fertilization terminated.

7. References

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CHAPTER IV. SYNTHESIS

This study was undertaken to examine changes in physical and chemical properties 12 years after discontinuing long-term ammonium nitrate applications on a Solonetzic soil managed as a simulated grassland. Researchers studying such sites have proposed that high ammonium nitrate applications to Solonetzic soils improved the chemical properties. The fertilization treatment is proposed to increase the Ca:Na ratio by increasing salt movement (Carter 1986, Carter et al. 1978, Cairns 1971, Cairns et al. 1967), to increase water infiltration and percolation (van Schaik and Cairns 1969) and therefore to improve productivity of the crops (Cairns 1968, Cairns et al. 1967) (Figure 9.1).

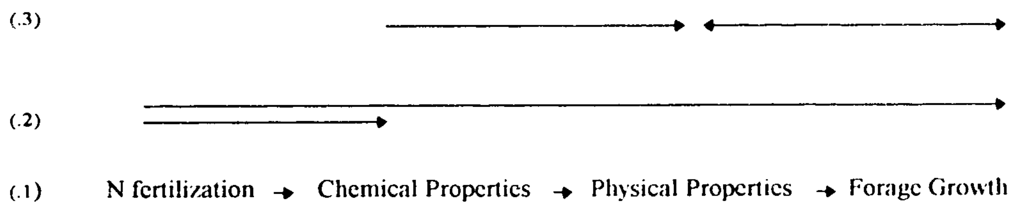

Figure 9. Schematic model of the processes involved in accelerating solodization of the Solonetzic soil with N fertilization and forage growth.

Interpretation of the data collected in this study suggested a more complex pattern than the linear model shown in Figure 9.1. The alteration in chemical and physical properties by N fertilization can be described more clearly in three phases which are not independent. Phase I (Figure 9.2) is associated with increased above ground and root biomass and acidification which occurred simultaneously with N fertilization. Between 1986 and 1989, 11 years after the last fertilization, higher dry matter yield (DMY) were higher in the fertilized treatment (McAndrew, unpublished data). Carter and Pearen (1989), Carter et al. (1977) and Cairns et al. (1967) found similar results from high fertilization rates. The ammonium nitrate fertilizer also lowered soil pH. In the present study, the pH ($CaCl_2$) of the fertilized Ap horizon was

4.3 which was significantly lower than for the Ap of the non-fertilized treatment. McAndrew and Malhi (1992), 8 years after fertilization ceased, reported pH ($CaCl_2$) of 4.2 in the fertilized Ap and 5.7 in the non-fertilized (P>0.05). Perl et al. (1982) also found lower pH in the fertilized Ap horizon 13 years after fertilization application commenced in 1960.

As a result of the higher root biomass, water percolation could be expected to increase with the higher water consumption by the perennial grasses and their extensive root system (Figure 9.2). The increased water infiltration and percolation could promote increased net leaching of Na and root growth would promote net translocation of Ca to the surface horizons by plants from the deeper rooting depth. Sodium and Ca are both taken up by the plant roots and deposited in the foliage but the net return is probably different as shown with soil data in the present study and by what other researchers have found on such high N fertilized Solonetzic soil sites with soil and plant data (McAndrew and Malhi 1992, Carter et al. 1977, Cairns 1971). The present study found Ca:Na ratio to be lower in the fertilized Ap than the non-fertilized Ap horizon. Exchangeable Ca was lower in the fertilized Ap horizon than the non-fertilized and the exchangeable Na was negligible in both treatments. The dilution of soil solution with improvement in water percolation, would be expected to increase the exchange of Ca for Na on the soil colloids in the Bnt horizon, according to the dilution and valency effect (Moss 1963). The higher Ca:Na ratios in the fertilized Bnt1 and Bnt2 horizons also supported this theory of increased net leaching of Na down the profile and increased net translocation of Ca to the surface horizons through increased vegetative and root biomass.

Research on high N fertilized sites found similar trends in Ca and Na (Carter et al. 1977, Cairns 1971). Carter et al. (1977) working on a Brown Solodized Solonetz found lower Na (1.3 fertilized:non-fertilized) in the dry matter than Ca (1.4 fertilized:non-fertilized). Thus the mass ratios of Ca:Na of the above ground dry matter was higher in the fertilized than non-fertilized treatment. Cairns (1971) in a study of $(NH_4)_2SO_4$ application on bromegrass found Na and Ca to be greater in the dry matter of the fertilized than the non-fertilized treatment. The mass ratio of Ca:Na in the fertilized (17) was greater than the non-fertilized (11) treatment. Thus the plants were recycling Ca preferentially over Na which could favor the removal of Na from upper horizons.

The greater root biomass and increased DMY improved N cycling as a result of the added N fertilizer and perhaps by the higher N concentration of the dry matter produced. The simulated grassland also helped in maintaining high TOC and TSC on both treatments because most of the dry matter remained on the site. McAndrew and Malhi (1992) confirmed that increased N cycling by plants occurred at this site. There was higher N (28 kg ha^{-1}) in the dry matter from previously fertilized treatments than in that from non-fertilized dry matter treatments (16 kg ha^{-1}) averaged over three years (1987 to 1989) (McAndrew, unpublished data).

Figure 9.3 depicts solodization processes where chemical properties are improved and the porosity and structure were altered with a decrease in aggregate size and increase in porosity. There was increased macroporosity (perimeter and maximum diameter), lower bulk densities and decrease in aggregate size distribution (perimeter and maximum diameter) in the fertilized Ap and Bnt1 than the non-fertilized horizons. The increased biomass as a result of N fertilization has been maintained after discontinuation of fertilization. Grevers and De Jong (1990) found the higher yielding forages increased the soil pore area and length but did not find differences in soil aggregation with clay soils.

Pawluk (1982) stated that solodization of the soils will continue if the water table is kept lower than needed to resalinize the site. The questions to be asked: Is the Smooth Bromegrass forage system managed as a simulated grassland a permanent solution for amelioration of Solonetzic soils at the study site? or: Will solodization continue as a permanent process at this site regardless of management? Solodization is expected to continue if the simulated grassland is continued to be maintained at the site. Continued management as a grassland would permit recycling of N, Ca, etc. by the above ground dry matter. The growth of forages would also be expected to enhance water removal. Salinization will be expected to re-occur if the area is ploughed and seeded to annual crops or if the recharge area is altered with greater precipitation as salinization can likely reoccur in the presence of a higher water table (Pawluk 1982) and the study site is in a regional discharge area (Maclean 1974). Perennial forages transpire over a longer growing period than annual crops; as well they have a more extensive rooting system (Walton 1983). Therefore, N fertilizer stimulated increased plant activity and this led to lowered water table, greater Na leaching, increased Ca return to the surface and hence increased solodization.

Therefore, accelerated solodization on this study site is likely due in part to the 18 years of annual ammonium nitrate application on a Smooth Bromegrass forage system. Although this project was one of laboratory analyses of field samples, one of the biggest questions related to amelioration of soils is the relationship of root activity and surface moisture (rooting zone) regimes to soil conditions. In all, little information is currently available pertaining to the nature and potential biological activity of roots and the mechanisms involved in soil profile moisture dynamics and their relationship to soil amelioration. Research regarding the interaction of moisture regimes in the soil rooting depth and the forage cropping system is required as this study interpreted the yield differences not to be clearly attributed only to the changes in physical and chemical properties in the soil.

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CHAPTER V. APPENDICES

Appendix A. 1990 and 1991 Meteorological Data (Vegreville Experimental Farm).

1990

Month	High Temp (°C)	Low Temp (°C)	Mean Max (°C)		Mean Min (°C)		Mean Temp (°C)		Precip (mm)		Wind (km)	
	1990	1990	1990	33 yr Avg	1990	33 yr Avg	1990	33 yr Avg	1990	33 yr Avg	1990	18 yr Avg
Jan	4.0	-36.5	-5.4	-10.9	-14.7	-22.4	-10.0	-17.1	10.9	15.3	5560	3768
Feb	7.5	-36.0	-6.1	-7.4	-19.5	-19.4	-12.8	-13.7	12.3	12.9	5741	3669
Mar	13.0	-19.5	2.6	-1.4	-7.7	-13.1	-2.6	-7.4	10.9	12.7	5277	3893
Apr	21.0	-9.0	10.0	9.9	-1.7	-2.9	4.2	3.3	22.4	15.9	6121	4362
May	28.0	-5.5	18.0	18.0	3.0	3.0	10.5	10.4	38.1	38.0	6268	5418
Jun	30.5	-1.5	22.5	21.9	7.5	7.5	15.0	14.6	48.7	72.1	4834	4342
Jul	31.0	3.0	22.7	23.9	9.2	9.8	15.9	16.5	109.8	80.0	4017	3975
Aug	35.0	1.0	22.8	22.9	8.8	8.4	15.8	15.3	80.6	63.4	4089	3786
Sep	28.5	-7.5	20.4	16.7	4.0	3.2	12.2	9.8	14.7	43.3	4535	3999
Oct	18.0	-11.5	8.5	10.8	-4.0	-2.4	2.2	4.3	8.1	15.9	5130	4184
Nov	9.5	-34.0	-3.1	-1.7	-14.0	-12.0	-8.5	-6.9	16.7	14.4	4911	3727
Dec	7.5	-40.0	-10.8	-8.7	-22.7	-19.7	-16.7	-14.5	14.5	17.6	5994	3972
Total	234.0	-197.0	102.1	94.0	-51.8	-60.0	25.2	14.6	387.7	401.5	62477	49094
Avg	19.5	-16.4	8.5	7.8	-4.3	-5.0	2.1	1.2	32.3	33.5	5206	4091

	1990	33 yr Average
Growing Season Precipitation (April-July) mm	219.0	205.8
Last Spring Frost 0°C	June 14 -1.5°C	Jun 3
First Fall Frost 0°C	Sept 18 -2.0°C	Aug 31
Number Frost Free Days 0°C	107.0	87.7
Last Killing Spring Frost -2°C	May 13 -5.0°C	May 23
First Killing Fall Frost -2°C	Sept 18 -2.0°C	Sept 10
Number of Killing Frost Free Days -2°C	128.0	110.4

1991

Month	High Temp (°C)	Low Temp (°C)	Mean Max (°C)		Mean Min (°C)		Mean Temp (°C)		Precip (mm)		Wind (km)	
	1991	1991	1991	34 yr Avg	1991	34 yr Avg	1991	34 yr Avg	1991	34 yr Avg	1991	19 yr Avg
Jan	6.5	-40.5	-8.4	-10.9	-19.0	-22.3	-13.7	-17.0	6.8	15.0	6265	3900
Feb	10.0	-21.0	1.3	-7.1	-7.9	-19.1	-3.3	-13.4	12.7	12.9	4055	3689
Mar	17.0	-28.5	0.1	-1.3	-11.9	-13.1	-5.9	-7.4	10.3	12.7	4591	3930
Apr	22.0	-6.5	13.3	10.0	-1.4	-2.8	5.9	3.4	45.6	16.8	5831	4439
May	27.0	-6.0	17.7	18.0	3.8	3.0	10.7	10.4	58.1	38.6	5491	5422
Jun	26.5	2.5	20.0	21.9	8.2	7.5	14.1	14.6	72.7	72.1	4873	4370
Jul	31.5	1.0	24.7	23.9	9.5	9.8	17.1	16.5	19.7	78.3	4732	4015
Aug	34.5	4.0	27.0	23.0	11.3	8.5	19.1	15.4	41.6	62.8	4401	3818
Sep	26.5	-8.0	18.5	16.8	4.0	3.2	11.2	9.8	13.3	42.4	5498	4077
Oct	25.0	-25.0	5.6	10.7	-6.3	-2.6	-0.3	4.2	36.0	16.5	6221	4291
Nov	6.5	-28.0	-2.3	-1.8	-11.9	-12.0	-7.1	-6.9	5.3	14.1	5036	3796
Dec	6.0	-29.5	-6.0	-8.6	-16.4	-19.6	-11.2	-14.4	17.2	17.6	5142	4034
Total	239.0	-185.5	111.3	94.6	-38.0	-59.5	36.6	15.2	339.3	399.6	62136	49781
Avg	19.9	-15.5	9.3	7.9	-3.2	-5.0	3.0	1.3	28.3	35.0	5178	4148

	1991	34 yr Average
Growing Season Precipitation (April-July) mm	196.1	205.8
Last Spring Frost 0°C	May 24 -3.5°C	Jun 3
First Fall Frost 0°C	Sept 15 -3.0°C	Aug 31
Number Frost Free Days 0°C	114.0	88.5
Last Killing Spring Frost -2°C	May 24 -3.5°C	May 23
First Killing Fall Frost -2°C	Sept 15 -3.0°C	Sept 10
Number of Killing Frost Free Days -2°C	114.0	110.5

Appendix B. Image Analysis of Soil Fabric.

1. Aggregate, pore and root distribution of the non-fertilized Ap Horizon

3 samples taken of aggregates, pores and roots

Area Value mm^2 x 0.001x 3.125 mag μm^2

Perimeter Value mm x 0.001x 3.125 mag µm

DMax maximum diameter Value mm x 0.001x 3.125 mag µm

Form PE Form factor whereby circle = 1, ellipse <1, irregular structures <1 {(4Πarea)/perimeter^2)}

Slide: L1 Horizon: Ap Treatment: Non-fertilized

Aggregates	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	12	--	--	--	8	--	--	--
Classes	14	--	--	--	12	--	--	--
Interval	41251.05	--	--	--	77911.91	--	--	--
Minimum	22023.10	--	--	--	7693.24	--	--	--
Maximum	1999538	--	--	--	3342636	--	--	--
Laxt X	33019.12	1098.51	403.81	0.344	782714.5	6679.52	1798.81	0.220
Sum	5044598	42446.14	12229.00	4.92	5254182	40675.91	9520.06	2.33
Mean	420383	3537.18	1019.11	0.410	656772	5084.48	1190.01	0.291
St. Dev.	544804	2685.24	575.57	0.222	1127970	5037.81	1062.38	0.172
Median	304525	--	--	--	285605	--	--	--

Aggregates	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	4	--	--	--	8		
Classes	10	--	--	--	12		
Interval	4056.85	--	--	--	41073.27		
Minimum	10174.07	--	--	--	13296.80		
Maximum	50742	--	--	--	1797639		
Laxt X	13037.47	795.60	316.35	0.259			
Sum	116367	5037.32	1884.60	1.18	3471716		
Mean	29092	1259.33	471.15	0.294	368749	3293.663	893.423
St. Dev.	20508.32	766.29	274.92	0.195			
Median	38572.04	--	--	--			

Slide: L1 Horizon: Ap Treatment. Non-fertilized

Pores	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	D	F
Counts	19	--	--	--	19	--	--	--
Classes	16	--	--	--	16	--	--	--
Interval	20897.70	--	--	--	11536.67	--	--	--
Minimum	2793.74	--	--	--	2960.92	--	--	--
Maximum	337157.00	--	--	--	187547.58	--	--	--
Laxt X	23445.16	1493.93	358.87	0.132	38794.14	894.46	298.56	0.609
Sum	1315075	36261.49	11360.76	5.69	919940	30332.10	10832.71	6.82
Mean	69214.50	1908.50	597.94	0.300	48417.906	1596.43	570.14	0.359
St. Dev.	103881.07	2339.64	597.43	0.160	47541.93	1365.95	473.54	0.226
Median	2793.74	--	--	--	34109.92	--	--	--

Pores	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	10	--	--	--	16		
Classes	13	--	--	--	15		
Interval	09418.93	--	--	--	13951.10		
Minimum	20843.24	--	--	--	8865.97		
Maximum	1443289	--	--	--	655998		
Laxt X	1443147	12704.88	2642.79	0.112			
Sum	5037344	42085.20	11499.03	4.36	2020388		
Mean	503734.41	4208.52	1149.90	0.436	207122.27	2571.15	772.66
St. Dev.	544818.94	3711.03	784.49	0.225			
Median	294390.56	--	--	--			

Slide: L1 Horizon: Ap Treatment: Non-fertilized

Roots	Sample 1 Area	Perimeter	DMax	FormPE	Sample 2 Area	Perimeter	D	F
Counts	5	--	--	--	4	--	--	--
Classes	10	--	--	--	--	--	--	--
Interval	2376.15	--	--	--	--	--	--	--
Minimum	2253.61	--	--	--	10174.02	--	--	--
Maximum	26.015.16	--	--	--	50738.55	--	--	--
Last X	10114.06	749.42	304.57	0.226	13037.47	--	--	--
Sum	66822.67	2570.62	1008.24	3.31	116367.60	5037.31	1884.59	1.178
Mean	13364.53	514.12	201.65	0.662	29091.91	1259.33	471.14	0.294
St. Dev.	8622.05	213.84	89.27	0.253	--	--	--	--
Median	12946.33	--	--	--	--	--	--	--

Roots	Sample 3 Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	17	--	--	--	8.67		
Classes	15	--	--	--	--		
Interval	37242.07	--	--	--	--		
Minimum	5810.39	--	--	--	6079.34		
Maximum	564441.44	--	--	--	213731.71		
Last X	5810.39	644.43	294.18	0.176			
Sum	1210007	38079.93	12597.60	65.07	464399		
Mean	71176.89	2239.99	741.04	0.298	37877.78	1337.813	471.277
St. Dev.	132508.63	2745.78	732.92	0.215			
Median	5810.39	--	--	--			

2. Aggregate, pore and root distribution of the fertilized Ap Horizon

3 samples taken of aggregates, pores and roots

Area = Value mm^2 x 0.001x 3.125 mag = µm^2

Perimeter = Value mm x 0.001x 3.125 mag = µm

DMax = maximum diameter = Value mm x 0.001x 3.125 mag = µm

Form PE = Form factor whereby circle = 1, ellipse <1, irregular structures< 1 {(4Πarea) perimeter^2)}

Slide: L5 Horizon: Ap Treatment: Fertilized

Aggregates	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	38	--	--	--	18	--	--	--
Classes	19	--	--	--	16	--	--	--
Interval	51865.28	--	--	--	54034.26	--	--	--
Minimum	4195.44	--	--	--	73.94	--	--	--
Maximum	989635.81	--	--	--	864622.12	--	--	--
Laxt X	209172.88	2663.34	839.03	0.371	381895.25	4439.33	911.11	0.244
Sum	4840195.00	62283.00	17354.48	20.88	4408322.00	51303.84	13634.15	6.30
Mean	127373.56	1639.03	456.69	0.549	244906.78	2850.21	757.45	0.350
St. Dev.	196619.91	1785.38	375.71	0.197	271333.31	2156.34	488.34	0.199
Median	4195.44	--	--	--	135159.59	--	--	--

Aggregates	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	23	--	--	--	26.3		
Classes	17	--	--	--	17.33		
Interval	70215.92	--	--	--	58705.15		
Minimum	4960.58	--	--	--	3076.65		
Maximum	1198631.25	--	--	--	1017629.70		
Laxt X	509997.06	4754.053	1110.307	0.284			
Sum	4028266.25	50363.94	14287.62	10.51	4425594.41		
Mean	175142.02	2189.736	621.201	0.457	182474.12	2226.325	611.78
St. Dev.	265644.09	2179.028	401.316	0.225			
Median	82198.10	--	--	--			

Slide: L5 Horizon: Ap Treatment: Fertilized

Pores	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	44	--	--	--	48	--	--	--
Classes	19	--	--	--	19	--	--	--
Interval	16016.35	--	--	--	38667.89	--	--	--
Minimum	18.22	--	--	--	160.74	--	--	--
Maximum	304328.22	--	--	--	734850.62	--	--	--
Laxt X	19109.34	587.77	199.03	0.695	635.48	111.38	39.18	0.644
Sum	1281913.75	51679.36	16576.97	10.69	1622624.37	47099.20	14005.10	20.29
Mean	29134.40	1174.53	376.75	0.243	33804.67	981.23	291.77	0.423
St. Dev.	54647.92	990.83	245.99	0.200	105845.88	1183.92	275.99	0.265
Median	18.22	--	--	--	160.74	--	--	--

Pores	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	29	--	--	--	40.3		
Classes	17	--	--	--	18.3		
Interval	30212.95	--	--	--	28299.06		
Minimum	2073.61	--	--	--	750.86		
Maximum	515693.75	--	--	--	518290.83		
Laxt X	5809.316	436.986	201.959	0.382			
Sum	1787067.37	50784.87	11967.34	11.04	1563868.49		
Mean	61623.012	1751.203	412.667	0.381	41520.69	1302.321	360.396
St. Dev.	114032.81	2349.36	368.997	0.294			
Median	2073.61	--	--	-			

Slide: L5 Horizon: Ap Treatment: Fertilized

Roots	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	6	--	--	--	12	--	--	--
Classes	11	--	--	--	14	--	--	--
Interval	2554.73	--	--	--	10403.29	--	--	--
Minimum	527.28	--	--	--	6621.61	--	--	--
Maximum	33372.35	--	--	--	152267.72	--	--	--
Laxt X	9558.96	437.28	119.05	0.628	37831.82	903.58	300.12	0.582
Sum	92365.01	3116.64	1168.21	4.15	484214.72	12927.79	3662.49	6.83
Mean	15394.17	519.44	194.70	0.691	40351.227	1077.32	305.21	0.569
St. Dev.	10297.12	201.50	87.38	0.127	38899.75	703.28	155.29	0.284
Median	11657.12	--	--	--	34363.73	--	--	--

Roots	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	12	--	--	--	10.0		
Classes	14	--	--	--	13.0		
Interval	9798.68	--	--	--	7585.57		
Minimum	4844.85	--	--	--	5578.91		
Maximum	142026.36	--	--	--	109221.97		
Laxt X	8579.483	366.494	124.258	0.803			
Sum	621399	11934.48	4141.19	7.69	399326		
Mean	51783.309	994.54	345.099	0.640	35842.902	863.767	281.670
St. Dev.	47493.277	525.54	191.619	0.246			
Median	34240.89	--	--	--			

3. Aggregate, pore and root distribution of the non-fertilized Bnt1 Horizon

3 samples taken of aggregates and pores

albino roots seen in non-fertilized slide L2 of the ßnt1 horizon

Area Value mm^2 x 0.001x 3.125 mag = μm^2

Perimeter = Value mm x 0.001x 3.125 mag = µm

DMax maximum diameter = Value mm x 0.001x 3.125 mag = µm

Form PE Form factor whereby circle 1, ellipse<1, irregular structures<1 {(4Πarea)/perimeter^2)})

Slide: L2 Horizon: Bnt1 Treatment : Non-fertilized

Aggregates	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	7	--	--	--	3	--	--	--
Classes	12	--	--	--	8	--	--	--
Interval	92018.30	--	--	--	95384.36	--	--	--
Minimum	7445.70	--	--	--	1690608	--	--	--
Maximum	2311665	--	--	--	2453683	--	--	--
Laxt X	1730465	10495.347	2415.321	0.197	2453607	8259.208	2526.597	0.452
Sum	5441580	31699.66	8599.82	2.75	6223247	24428.31	7457.58	1.19
Mean	777368	4528.523	1228.545	0.393	2074415	8142.769	2485.860	0.395
St. Dev.	886487	3579.495	832.703	0.113	381520	318.205	47.155	0.81
Median	439486.84	--	--	--	2119838	--	--	--

Aggregates	Sample 3				AVG (Area)	AVG (Perim)	AVG (Dmax)
	Area	Perimeter	DMax	FormPE			
Counts	2	--	--	--	4		
Classes	7	--	--	--	9		
Interval	4550.00	--	--	--	63984.22		
Minimum	2732644	--	--	--	1476899		
Maximum	3464494	--	--	--	2743280		
Laxt X	3464421	12357.506	2977.592	0.285			
Sum	6797066	26197.95	6010.76	0.46	6153964		
Mean	3098533	13098.974	3005.379	0.232	1983439	8590.089	2239.928
St. Dev.	517444	1048.593	39.296	0.075			
Median	3359944	--	--	--			

Slide: L2 Horizon: Bnt1 Treatment: Non-fertilized

Pores	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	19	--	--	--	15	--	--	--
Classes	16	--	--	--	15	--	--	--
Interval	39947.86	--	--	--	8750.89	--	--	--
Minimum	1373.83	--	--	--	2223.64	--	--	--
Maximum	640539.62	--	--	--	133487.00	--	--	--
Laxt X	3365.995	241.623	76.015	0.725	18802.850	650.799	251.064	0.558
Sum	1179371	28469.21	8438.71	9.79	556777	17468.34	5902.15	7.74
Mean	62072.91	1498.379	444.143	0.515	37118.465	1164.556	393.477	0.516
St. Dev.	143926	2796.374	562.601	0.286	33218	1074.070	316.875	0.296
Median	1373.83	--	--	--	26288.59	--	--	--

Pores	Sample 3						
	ERROR						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts		--	--	--	11.30		
Classes		--	--	--			
Interval		--	--	--			
Minimum		--	--	--	1798.00		
Maximum		--	--	--	387013.30		
Laxt X							
Sum					868074.31		
Mean					49595.50	1331.4675	418.81
St. Dev.							
Median							

4. Aggregate, pore and root distribution of the fertilized Bnt1 Horizon

3 samples taken of aggregates, pores and roots

Area Value mm^2 x 0.001x 3.125 mag μm^2

Perimeter Value mm x 0.001x 3.125 mag μm

DMax maximum diameter Value mm x 0.001x 3.125 mag μm

Form PE Form factor whereby circle 1, ellipse<1, irregular structures<1 {(4Πarea)/perimeter^2)}

Slide: L6 Horizon: Bnt1 Treatment : Fertilized

Aggregates	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	5	--	--	--	17	--	--	--
Classes	10	--	--	--	15	--	--	--
Interval	67201.34	--	--	--	6532.52	--	--	--
Minimum	6882.02	--	--	--	1293.46	--	--	--
Maximum	1678895	--	--	--	3099281	--	--	--
Laxt X	1678728	9192.415	2646.889	0.250	3098971	9964.891	2528.658	0.392
Sum	4560666	26415.62	8022.38	2.01	4014696	22735.86	7212.95	11.34
Mean	912133	5283.125	1604.476	0.402	236158	1337.403	424.291	0.667
St. Dev.	652080	3246.799	982.170	0.158	750259	2424.896	694.896	0.195
Median	801088.37	--	--	--	1293.46	--	--	--

Aggregates	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	4	--	--	--	8.67		
Classes	10	--	--	--			
Interval	28855.58	--	--	--			
Minimum	22495.69	--	--	--	10223.72		
Maximum	2311051	--	--	--	2363076		
Laxt X	1871228	6706.911	1957.296	0.523			
Sum	4281059	24392.28	5874.59	1.73	4285474		
Mean	1070264	6098.070	1468.647	0.432	1809783	4239.532	1165.80
St. Dev.	1192461	6903.199	1289.373	0.265			
Median	1853340	--	--	--			

Slide: L6 Horizon: Bnt1 Treatment: Fertilized

Pores	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	15	--	--	--	8	--	--	--
Classes	15	--	--	--	12	--	--	--
Interval	38827.24	--	--	--	91542.04	--	--	--
Minimum	1861.42	--	--	--	3992.90	--	--	--
Maximum	584270	--	--	--	1102497	--	--	--
Laxt X	2775.526	238.397	107.805	0.614	6207.034	392.150	142.256	0.507
Sum	1372686	24293.96	6684.57	8.16	2059719	31175.45	8036.03	1.53
Mean	91512	1619.597	445.638	0.544	257464	3896.931	1004.504	0.191
St. Dev.	188962	2745.237	688.316	0.263	393436	4069.067	833.733	0.148
Median	1861.42	--	--	--	95534.94	--	--	--

Pores	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	11	--	--	--	11.3		
Classes	14	--	--	--			
Interval	14796.71	--	--	--			
Minimum	3541.74	--	--	--	3132.02		
Maximum	1610695	--	--	--	1099154		
Laxt X	7169.216	404.098	98.952	0.552			
Sum	2283612	29148.63	9259.58	3.77	1905339		
Mean	207601	2649.875	823.599	0.342	185526	2722.134	700.99
St. Dev.	469573	2918.925	724.439	0.238			
Median	3541.74	--	--	--			

Slide. 16 Horizon: Bnt1 Treatment: Fertilized

Roots	Sample 1				Sample 2			
	Area	Perimeter	DMax	FormPE	Area	Perimeter	DMax	FormPE
Counts	6	--	--	--	7	--	--	--
Classes	11	--	--	--	12	--	--	--
Interval	20944.02	--	--	--	21087.54	--	--	--
Minimum	18322.76	--	--	--	13261.44	--	--	--
Maximum	248706.97	--	--	--	266311.87	--	--	--
Laxt X	35195	853.693	278.837	0.607	266286	2981.941	619.048	0.376
Sum	563864.81	7595.02	2629.57	3.65	686237.62	9511.52	2665.14	4.94
Mean	93977.469	1265.837	438.261	0.609	98033.945	1358.788	380.734	0.706
St. Dev.	93536.508	654.755	325.491	0.156	81304.352	827.805	208.711	0.255
Median	49738.79	--	--	--	87067.83	--	--	--

Roots	Sample 3						
	Area	Perimeter	DMax	FormPE	AVG (Area)	AVG (Perim)	AVG (Dmax)
Counts	8	--	--	--	7		
Classes	12	--	--	--			
Interval	2389.08	--	--	--			
Minimum	7790.76	--	--	--	13124.99		
Maximum	36459.78	--	--	--	183826.20		
Laxt X	10005.825	364.881	117.434	0.944			
Sum	147070.73	6206.81	2095.07	4.33	465724.39		
Mean	18383.842	775.851	261.884	0.541	70131.75	2943.812	360.293
St. Dev.	9354.567	374.316	146.901	0.347			
Median	19736.19	--	--	--			

Appendix C. Clay Mineralogy

An attempt was made to characterize the clay mineralogy of the soils in the two treatments. The characterization included clay separation for X-ray defraction, heavy liquid specific gravity separation, dissolution of mineral material, surface area determination of the clay and CEC determination. The analyses failed as a result of the high organic matter content of soils bound to the clay particles during clay dispersion. This resulted in the removal of clay particles and organic matter in the supernatant. When the clay slides were X-rayed, a very high content of quartz was present.

If one was to do the mineralogical analyses for soils with very high organic matter contents, it would be important to determine the appropriate procedure for removing the organic matter besides during the siphoning of the supernatant with clay flocculation.