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THE EFFECT OF DEEP RIPPING IN COMBINATION WITH A LIME AMENDMENT ON THE PHYSICOCHEMICAL PROPERTIES OF A SOLONETZIC SOIL IN SOUTH CENTRAL ALBERTA

by

LESLIE G. WETTER

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
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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 THE EFFECT OF DEEP RIPPING IN COMBINATION WITH A LIME AMENDMENT ON THE PHYSICOCHEMICAL PROPERTIES OF A SOLONETZIC SOIL IN SOUTH CENTRAL ALBERTA submitted by LESLIE G. WETTER in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in SOIL CHEMISTRY.

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Supervisor

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M. Nyborg

Co-Supervisors

Date: Dec 10, 1986

DEDICATION

This thesis is dedicated to my father, Gordon Wetter, and my grandfathers, as well as countless other farmers, past and present, who have tried to earn a living farming Solonetzic soils.

ABSTRACT

Crop production on Solonetzic soils is limited by an acid Ap and a dense slowly permeable Bnt horizon. The purpose of this study was to investigate the effects of ripping and liming, alone and in combination, on selected physicochemical characteristics and relate changes to differences in crop growth. Treatment plots were established in 1981 on a Brown Solodized Solonetz located in east-central Alberta.

Soil samples were taken by horizon for physical and chemical analyses in July, 1984. In the ripped treatments paired samples were taken from within and between the shanked zone. Gravimetric moisture sampling was done to the depth of ripping from May, 1985 to April, 1986. Paired samples for a root mass comparison between ripped and non-ripped treatments were obtained in August 1985. The treatments were continually cropped to wheat from 1982 to 1985 and yields were monitored by Alberta Agriculture.

The main differences observed between treatments were due to ripping. Over the four years monitored, ripping increased wheat yields by 0.9 t ha^{-1}, ripping+liming by 0.8 t ha^{-1} and liming by 0.2 t ha^{-1}. Ripping lifted calcium salts from depth and increased downward leaching of sodium thus decreasing SAR values and improving soil structure in the Bnt horizon; root penetration and spring moisture status were increased. Ripping increased the breaking strength of the Ap, and hence the potential for surface crusting, through an elevation of clay from lower horizons. An elevation of carbonate salts increased the pH of the Ap to a greater extent than the surface application of lime. Ripping on 61 cm shank spacings provided uniform subsurface shattering. There were no significant yield or physicochemical differences between ripping alone and ripping and liming in combination. In this study ripping was the economically superior treatment; surface acidity was neutralized and subsurface soil structure was improved.

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Firstly I would like to acknowledge my mother Lea Wetter and my sister Josie, as well as friends and relatives, too numerous to mention, who have provided needed emotional support throughout my studies.

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1. Introduction

Solonetzic soils are found on every inhabited continent and occupy approximately 200 million hectares worldwide (Szabolcs 1979). Canada has over 7 million hectares, (Research Branch, Canada Department of Agriculture 1977) of which more than 4 million hectares are found in the province of Alberta (Alberta Agiculture 1981). Approximately 2.8 million hectares are located south-east of Edmonton, on relatively flat terrain which is a highly desirable trait for mechanized agricultural production (Pawluk 1982).

Much research worldwide has been done on the amelioration of Solonetzic soils. In Hungary attempts at amelioration date to the early 19th century (Szabolcs 1971). Amelioration research in Canada has spanned less than thirty years, and large scale amelioration attempts at the farm level have only occurred in the last ten. Historically, amelioration attempts have been physical (deep plowing, ripping) and chemical (lime and/or gypsum applications).

Deep plowing has been considered by several researchers to be the most promising amelioration technique for Alberta soils. It has not, however, been accepted by the farm community. The most popular form of amelioration currently in use is ripping or subsoiling. The reasons for this are largely economic as the initial capital expense of ripping is lower than deep plowing. Extension personnel with Alberta Agriculture have reported that deep plowing generally increases yields more than ripping. They caution, however, that extensive soil tests should be done before deep plowing to ensure that the soil will benefit (Alberta Agiculture 1981). Increases in yields due to ripping are less than those from deep plowing but the probability of doing extensive damage through an inappropriate operation are also reduced (Jerome Lickacz person. commun. 1986).

The actual acreage ripped in Alberta is unknown but it is believed to be considerable. Although the practice is widely applied, very little reseach has been done on ripping, and its physicochemical effects have been documented at very few sites. Lime has been used in Hungary as an ameliorant of sodic soils for over a century (Szabolcs 1971). To date little research has been done in Canada on its effects in conjunction with ripping.

This study was designed to document selected physicochemical changes in the soil due to ripping and liming, alone and in combination. Selected physical and chemical field and laboratory soil analyses were performed. Moisture status was monitored to the depth of ripping from May 1985, to April 1986. Root mass, and distribution by depth, for a ripped and a non-ripped treatment was measured in August of 1985. Tissue analysis was performed on crop samples gathered in June of 1985. Crop yields were monitored by Alberta Agriculture from 1982 to 1985.

The specific objectives of this study were:

(1) To compare selected physical and chemical changes between treatments, at different depths, and to correlate these with moisture status, rooting patterns, and above-ground crop yields.

(2) To compare physical, chemical, and moisture differences, in the shank track and between the shank track, and determine if uniform fracturing occurred with the 61 cm shank spacings used.

Treatments were: Ripped on shank (ROS), Ripped intershank (RIS), Ripped+Lime on shank (RLOS), Ripped+Lime intershank (RLIS), Control (C) and Limed (L). A study site was selected on the advice of staff of the Soils

Branch of Alberta Agriculture Edmonton. The results of the investigations at this site are reported in the following pages.

2. Literature Review

2.1 Genesis of Solonetzic Soils

The term solonetz is Russian in origin. It was first introduced in the late 1800's to describe a soil commonly found on the Russian steppes. The word, according to Gedroits, as quoted by Kelley, refers to a "high percentage sodium saturation" (Ehrlich and Smith 1958). There is some controversy as to what constitutes a Solonetzic soil, but two main morphological characteristics are generally accepted (Pawluk 1982).

(1) Solonetzic soils have a compact columnar-prismatic macrostructure and a blocky mesostructure, with dark staining on the peds. The columnar-prismatic macrostructure is of varying distinctness, thickness and alkalinity.

(2) A layer of salts containing lime, gypsum and more soluble sodium or magnesium salts are found below, or in the B horizon. An eluvial layer may also be present above the B horizon.

Solonetzic soils generally have ratios of exchangeable calcium to exchangeable sodium of ten or less (Research Branch Canada Department of Agriculture 1977). To classify a Solonetzic soil by chemistry is extremely difficult and many unresolved controversies exist, one being the role of exchangeable magnesium. Some authors have suggested that morphology alone should be used to define a Solonetz (Ehrlich and Smith 1958). The exchangeable Ca to exchangeable Na ratio of ten or less should be taken as a general guideline, not a hard and fast rule.

2.1.1 History of Genesis Research

The general theory on the genesis of Solonetzic soil dates to the early twentieth century and the work of Gedroits. While other workers such as Hilgard, de Sigmond, Kelly, Vil'yams and Glinka also contributed to the theory, Gedroits is credited with its formulation (Ivanova and Bol'shakov 1972). Gedroits demonstrated experimentally that Solonetzes are formed from saline Regosols which are high in soluble sodium (sodium Solonchaks), and that Solods are formed from Solonetzic soils. This research defined three classical soil forming processes; salinization, solonization and solodization (Pawluk 1982).

The foregoing processes still provide a basis for a stepwise progression of mechanisms responsible for the formation of Solonetzic soils. Since Gedroits many other workers too numerous to mention have added concepts to his original theory, which forms the basis of our current understanding of the genesis of these soils.

2.1.2 Salinization

Through a variety of processes soluble salts accumulate at the soil surface. This accumulation is called salinization. Salts may be concentrated in areas of former saline water bodies, or formed by in situ chemical weathering of silicate minerals. Saline material may be deposited in glacial drifts, or uncovered by glaciation or erosion. While these processes are important in other areas of the world, in Canada salinization most often occurs through groundwater flow (Pawluk 1982). By this process salts are formed from the dissolution of materials within geological strata along the flow path. Groundwater serves as the solvent and medium of transport, as well as a reactant in the formation of some salts. The degree of salinization through groundwater flow is influenced by three elements, hydrological, hydrophysical, and physicochemical (Pawluk 1982).

Hydrological elements control the movement of water and salts along the flow path to the water table. In western Canada flow systems can be either local, intermediate, or regional in extent (Tóth 1962). A local flow system has a recharge area at its highest elevation and a discharge area at its lowest. These areas are adjacent to each other. An intermediate flow system has its topographic high and low separated by the recharge and discharge of one or more local systems. Regional flow systems are deep and may contain many intermediate and local systems. If the local landform is relatively flat, as in most of the Solonetzic soil areas of south and south-central Alberta, regional flow systems will dominate. Easterly moving water from the Rocky mountains leaks upward as a result of artesian pressure. Discharge may appear random and unrelated to the contour of the land due to the differential permeability of bedrock (Maclean 1974). If local relief is substantial, local and intermediate flow systems intercept this upward moving water and salinization occurs in local discharge areas (Maclean and Pawluk 1975).

Hydrophysical elements control the changing soil moisture properties in the unsaturated zone. Moisture losses through evapotranspiration are generally greater than precipitation in continental climates with subarid and subhumid moisture regimes. Where favorable hydrological conditions exist such as; shallow water tables, perched water tables, or ground water surface discharge, water and salts will move upward. The water evaporates leaving salt encrustations on the surface or in salic horizons. The upward movement of water and deposition of salt in response to evapotranspiration and evaporation at the surface is counter balanced by salt removal through precipitation and downward leaching. Therefore the net movement of salts is determined by the balance between evapotranspiration and precipitation. The Altithermal period, 9000-6000 B.P., which followed the last ice age is believed to have been warmer and drier than the present period (Harris and Pip 1973). This warm dry period enhanced the upward movement and retarded the downward movement of salts, thus increasing salinization.

Physicochemical elements are responsible for differing concentrations and compositions of salts in groundwater and the soil solution. In Alberta local shallow flow systems mainly carry bicarbonates and sulphates of calcium and magnesium. This material originates within the glacial drifts (Bowser *et al* 1962). Regional deep flow systems mainly carry bicarbonates and sulphates of sodium and magnesium. These salts originate within the Elk Point Formation of Devonian age (Hamilton 1971). The salts are dissolved and moved eastward by water originating in the Rocky mountains.

Russian researchers place a large amount of emphasis on the presence of sodium bicarbonate in the ground water, as it is believed to be particularily important in the formation of Solonetzic soils (Kovda and Samoilova 1969). This has not been confirmed by Canadian research, which has shown that Solonetzic soils can form under the influence of sodium sulfate (Cairns and Szabolcs 1973).

The concentration of salts will affect water movement through the soil. Salts present in upward moving groundwater flocculate the soil and maintain capillary pores. Downward moving low-salt water, from precipitation events, causes dispersion and leaching is inhibited (McNeal and Coleman 1966).

In the Altithermal period salinization occurred extensively. Warmer, drier temperatures increased evapotranspiration over relatively flat areas where integrated drainage systems had not yet developed. Sodium sulphate and sodium bicarbonate salts were deposited along the capillary fringe. This period was the first stage in the evolution of Solonetzic soils in Western Canada.

2.1.3 Solonization

Solonization refers to a process by which a Saline Regosol becomes a Solonetz. The characteristic solonetzic Bnt horizon is formed during this process. For solonization to proceed there must be a gradual reduction of salts throughout the profile, or a 'desalinization'. Desalinization occurs as a result of environmental changes. Solonization not only requires desalinization for it to proceed but expandible clay minerals and sodium ions must also be present in significant quantities.

In Western Canada desalinization, was initiated following the Altithermal period. Changing environmental conditions such as decreased temperature and increased precipitation, coupled with the development of an integrated drainage system, initiated desalinization (Pawluk 1982). As the temperature dropped, surface matric potential increased due to reduced evapotranspiration. With increasing precipitation surface gravitational potential increased, and the balance shifted from a net upward movement of salts and water to a net downward movement. An integrated drainage system developed as post glacial meltwaters created new channels or downcut pre-existing ones. Water tables were lowered and existing recharge-discharge flow systems were disrupted and modified.

As desalinization proceeded, the electrolyte concentration in soil solution decreased. Under conditions of high sodium and low salt, dispersion and swelling occurs in an expandible clay mineral (McNeal and Coleman 1966). The degree of dispersion will depend on the electrolyte concentration, the amount of 2:1 clay minerals present, and the amount of sodium on the exchange complex. De Sigmond (1938) reported that dispersion would occur if the total salt content is 0.10 - 0.15 percent, and if the exchangeable sodium percentage (ESP) is greater than 10 - 15.

With the onset of dispersion stable clay aggregates break down into fine clay particles. During periods of desalinization, when net water movement is downward, particles are leached into the B horizon where they clog soil pores and form an illuvial claypan. At this time the soil profile is alkaline due to the hydrolysis of sodium clays or 'alkalization'. Exchangeable sodium is replaced by hydrogen which in turn is displaced by aluminum, released from chemical alteration of clay minerals (Arshad 1964).

$$\text{Na-clay} + H_2O \quad <=> \quad \text{H-clay} + Na^+ + OH^-$$

$$OH^- + CO_2 \quad <=> \quad HCO_3^- \qquad \text{(after Pawluk 1982).}$$

Under basic conditions organic constituents form mobile sodium humates, which also leach into the B horizon, forming black stains on the soil peds.

Alternating periods of salinization, in response to dry or frozen conditions, recharge the soil profile with sodium ions (Landsburg 1981). This causes additional dispersion, and the downward movement of clay and humates into the B horizon continues. Over time a dense compact illuvial Bnt horizon with fine pores develops. The A horizon is coarser in texture with larger pores.

Due to the discontinuity in pore size the capillary fringe will now extend only to the surface of the B horizon, and the A is no longer periodically salinized with sodic groundwater. As a result, alkalization in the A horizon proceeds to completion, with hydrogen and aluminum ions displacing sodium ions on the soil colloids. In time the biocycling of calcium and magnesium by plants will lead to the partial replacement of hydrogen and aluminum by these elements. An acidic A horizon, and an alkaline B horizon, are typical of solonetzic soils (Research Branch Canada Department of Agriculture 1977).

In wet periods a perched water table will form on top of the B horizon. Hydrolysis occurs followed by slow leaching through the coarser pores. In dry periods the interface area is resalinized with sodium from groundwater rising by capillary action through fine pores. Alternating acidic and alkaline conditions result in intense weathering, consequently an eluvial, coarsely textured, platy, ashy coloured Ae horizon develops. The appearance of an Ae marks the transition to the third pedogenic process 'solodization'.

2.1.4 Solodization

The process of solodization reflects a decrease or a cessation of the influence of groundwater on the soil profile. According to the Canadian system of soil classification a solodized solonetz forms if the Ae is thicker than 2 cm. A Solod forms if the Ae is thicker than 2 cm and an AB horizon is present (Canada Soil Survey Committee 1978). Under this definition continuity with the watertable may still exist, and in cases where an Ae has not developed but the groundwater no longer influences the soil solum, the soil might still be classified as a Solonetz. Pawluk (1982) argues that solodization should only be considered to occur after the capillary fringe is no longer located in the soil solum, and no continuity with the water table exists.

If the Bnt is no longer resalinized by sodic groundwater alkalization of sodium clays will proceed without reversal. Biocycling of calcium and magnesium will increase with improving soil structure and plant growth. Over time an AB horizon will form from the Bnt and the profile will approach that of a 'zonally normal' soil.

Amelioration techniques have a greater chance of success where a continuity with the water table no longer exists and solonization is not an active process (Szabolcs 1971). It is pertinent to note that under the current Canadian system of soil classification this distinction is not made. Its usefulness as a predictive tool, for the likely results of amelioration attempts negative or positive, is thus limited.

2.2 Amelioration of Solonetzic Soils

The main agronomic difficulty with Solonetzic soils lies in their physical properties (Tyurin *et al.* 1960). The hard compact Bnt horizon limits water infiltration, aeration, and rooting depth. After a substantial precipitation event, or snowmelt, a perched water table forms on top of this hardpan layer. As a result, water will be lost through evaporation; poor aeration will inhibit root growth and enhance denitrification. Plant rooting depth is shallow and crops are unable to stand periods of drought. Tyurin *et al* (1960) states:

> "Roots of cultivated plants must remain within the thin surface layer .... similiar to potted plants. More or less satisfactory crops will then be obtained only in rainy years or under irrigation."

Wilting point is increased by high exchangeable sodium while hydraulic conductivity is decreased to such a degree that, even when water is available it cannot be supplied to the plants quickly enough to prevent moisture stress.

In addition to poor subsurface structure, poor surface tilth resulting in crop emergence problems are often encountered when the Ae is mixed, by cultivation, into the Ap. The Ap is generally shallow and low in organic matter.

Problems other than poor physical structure may be encountered. High electrical conductivities (E.C.) in the subsoil result in decreased osmotic potential and decreased available water. Russian researchers note that certain cations and anions such as sodium and carbonates have a particularily deleterious effect on plant growth (Tyurin *et al* 1960). In Canada, soluble magnesium to calcium (Mg/Ca) ratios greater than 1, or soluble calcium to total cations (Ca/TC) ratios, of less than 0.15, have been shown to induce calcium deficiency in barley. Deficiencies are induced independent of the E.C. or the individual concentrations of calcium and magnesium (Carter *et al* 1979). Similarily Szabolcs (1971) observed that small amounts of calcium amendment, placed with the seed increased yields, while no discernible change in physicochemical properties were observed. This could be evidence of a calcium deficiency.

In Carter *et al* (1979) it was observed that low calcium to sodium ratios caused a decrease in the uptake of potassium. Although potassium deficiencies may occur due to high sodium levels, in general, low potassium status has not been documented on Solonetzic soils (Cairns and Bowser 1969; Szabolcs 1971).

While Solonetzic soils respond well to the application of nitrogen it is not clear whether problems other than low organic matter, due to a thin Ah horizon, are responsible (Robertson 1982). On the basis of 63,000 samples of the Ap received by Alberta Soil and Feed Testing Laboratory (A.S.F.T.L) from 1962 to 1969, Solonetzic soils could not be differentiated from associated Chernozems by their nitrate nitrogen (NO_3-N) status (Cameron and Toogood 1970).

Cairns *et al* (1962) noted that less NO_3-N was released on incubation of a Solonetz than on an associated Chernozem. Rice (1978) suggested decreased mineralization of nitrogen as the result of acidity in the Ap. An amelioration technique which raises the pH of the surface will therefore increase available plant nitrogen. A flush of nitrogen may also occur from the breakdown of organic matter in the Bnt after deep plowing or ripping (Robertson 1982). This may be partially responsible for the "magic" crop response noted by some farmers in the year following deep tillage (Len Solick person. commun. 1984).

Cameron and Toogood (1970) using A.S.F.T.L. data found extractable phosphorus to be higher in the Solonetzic soil zone than in the Chernozemic. There is no reason to believe that a Solonetzic soil is particularily deficient in phosphorus, but yield increases have generally been observed through fertilization (Alexander 1973; Toogood 1978). Although other factors limit the agronomic potential of a Solonetzic soil, the decisive limiting factors are its physical properties, and their effects on the moisture regime (Szabolcs 1971). Plant nutrients may be available, but a lack of water will prevent their uptake, as plants need these nutrients in aqueous solution.

Amelioration attempts can be described under two broad headings, physical and chemical, although these are not mutually exclusive. An undesirable chemical condition leads to poor physical properties which in combination with a hydrogeological situation reinforces the original chemical condition. The aim of physical and chemical amelioration techniques is to break this cycle.

If the hydrogeological conditions, which led to the original Solonetz formation, are still present soil improvement is doubtful. In eastern Europe, drainage is considered an essential pre-requisite to any ameliortion attempt where the profile is permanently linked with groundwater. If the profile is temporarily linked, drainage may not be necessary depending on the intensity of solonization (Szabolcs 1971). Very little drainage has been done in Western Canada, but research has shown that high water tables and restricted drainage will decrease the effectiveness of deep plowing (Webster and Nyborg 1984).

2.2.1 Amelioration - Chemical

Chemical amelioration is aimed at replacing sodium on the exchange complex with calcium. Where X refers to the exchanger phase, the defining equation for Na^+ - Ca^{2+} exchange can be written:

$$CaX + 2Na^+ <=> Ca^{+2} + (Na)_2X$$

(after Bresler *et al* 1982).

An equilibrium constant can be defined for this equation (parenthesis denote activities, or effective concentrations):

$$K = (Ca^{2+})(Na_2X) /(Na^+)^2(CaX)$$

(after Bresler *et al* 1982).

Cation exchange reactions are considered to be reversible, although partial covalent bonding, fixation, and preferential divalent bonding occurs. Calcium is preferentially adsorbed due to its high valence and small hydrated radius. Exchange reactions are virtually instantaneous, therefore in soils, diffusion will be the rate determining step. Hysteresis can occur due to the tortuosity associated with diffusion (Bohn *et al* 1979). The Na^+ - Ca exchange reaction can be driven right or left by flooding the system with either cation according to the Le Chatelier's principle and the law of mass action.

If the solution is diluted the retention of calcium is favoured by the law of valence dilution. This law can be demonstrated by rearranging the equilibrium constant equation as follows:

$$k\,(Na^+)^2/(Ca^{2+}) = (Na_2X)/(CaX).$$

The squared term on the left side of this equation demonstrates that the ratio of exchangeable sodium to exchangeable calcium will change with total, as well as with relative salt concentration (Bohn *et al* 1979).

For calcium to exchange with sodium on the soil colloids two conditions must be met:

1. A calcium source must be present.
2. The ratio of calcium activity to sodium activity must be above certain levels determined by the stability constant for the exchange reaction and the law of valence dilution.

Amendments may be classified as direct or indirect. Soil conditions as well as economic considerations determine the kind and amount to be used (United States Salinity Laboratory Staff 1954). A direct amendment contains a calcium source, an indirect amendment changes soil conditions such that the solubility, and hence the activity of calcium ions released from native or applied sources, is increased.

Direct amendments which have traditionally been used are calcium chloride ($CaCl_2$), calcium nitrate ($Ca(NO_3)_2$), gypsum ($CaSO_4 \cdot 2H_2O$), and lime ($CaCO_3$). Historically lime and gypsum have been considered the main chemical ameliorants for sodic soils (United States Salinity Laboratory Staff 1954; Tyurin *et al* 1960; Bower 1969; Szabolcs 1971). Their use as ameliorants is partially due to their chemical and physical characteristics, but a large component of their popularity has been their availability at economic prices. These ameliorants will be discussed later, in separate sections.

Indirect amendments are used alone, on a calcareous soil, or in combination with lime and/or gypsum on a non calcareous, alkaline soil (United States Salinity Laboratory Staff 1954). Indirect amendments are generally acids, or acidifiers, which increase the solubility of the calcium salt and hence the activity of the calcium ion. Sulfur, sulfuric acids, iron sulfates, aluminum sulfates, and acid petroleum resins have been used. The application of these substances has been popular in the U.S. and eastern Europe (United States Salinity Laboratory Staff 1954; Tyurin *et al* 1960; Szabolcs 1971). Sulfur has been used experimentally in western Canada (Cairns 1961; McCready 1982). Generally researchers have felt other amelioration methods hold more promise but as Alberta has large reserves of sulfur, derived from the petrochemical industry, further investigation of its suitability on alkaline calcareous soils might be in order.

The efficiency of chemical ameliorants will be greatly enhanced if surface application is followed by leaching (Bower 1969). This technique is highly successful under irrigated conditions where drainage is adequate.

Where irrigation is not available methods such as snow entrapment have been used for the same purpose (Tyurin *et al* 1960). These methods could be used in western Canada.

2.2.1.1 Lime as an Ameliorant

In a technical sense lime is CaO, in practice any amendment that will reduce soil acidity, and contains calcium or magnesium, may be referred to as lime (Hausenbuiller 1978). In soils, lime is a general term for ground limestone, it most often refers to calcite ($CaCO_3$).

Lime may be applied as an ameliorant on Solonetzic soil for more than one reason. It may be used to raise the pH of an acidic Ap, or it may be used to supply calcium for exchange reactions and plant nutrition. Where lime is used to neutralize soil acidity the following reactions will occur:

$$\text{H,Al-clay} + 2CaCO_3 + 3H_2O \Leftrightarrow$$
$$\text{2Ca-clay} + 2H_2CO_3 + Al(OH)_3\ (ppt) \Leftrightarrow$$
$$\text{2Ca-clay} + Al(OH)_3\ (ppt) + 2H_2O + 2CO_2$$

(after Hausenbuiller 1978).

Exchangeable aluminum is precipitated as $Al(OH)_3$ while exchangeable hydrogen is ultimately inactivated as water. Calcium may exchange directly with sodium on the exchange complex through the following reaction:

$$\text{4 Na-clay} + 2CaCO_3 + CO_2 + H_2O \Leftrightarrow$$
$$\text{2 Ca-clay} + 2\ NaHCO_3 + Na_2CO_3$$

(after Bower 1969).

Lime has been used extensively in eastern Europe as a chemical ameliorant of sodic soils for over a century. The earliest recorded use was by Samuel Tessedic (1742-1820), and is referred to as the "digo-earth" method. A subsoil rich in lime and gypsum is spread on the soil surface at a rate of 500 to 600 m^3ha^{-1} (Szabolcs 1971). The use of lime and gypsum fell out of favour in the mid 1800's but by the turn of the century interest in it had revived. In Hungary limestone powder is now applied on non-calcareous acid or slightly alkaline soils at a rate of 15 to 30 t ha^{-1}. Lime sludge from sugar factories or moors is also used but at a higher rate due to its lower calcium carbonate content (Szabolcs 1971). De Sigmond as reported in Tyurin *et al* (1960) cites an example of the complete disappearance of solonetzic properties from a soil profile 160 years after lime was applied. In eastern Europe lime in conjunction with gypsum is applied to non calcareous, slightly alkaline soils. On calcareous alkaline soils lime is not used as an ameliorant unless it is combined with an acidifier such as petroleum resins or sulfur (Szabolcs 1971). These guidelines are reinforced by research done in the United States. Soils with pH values of greater than 7.5 will not respond well to lime, but good results are reported on acidic, or slightly alkaline Solonetzes (United States Salinity Laboratory Staff 1954).

In soils, the calcium originally contained in lime, is found in three forms, these are shown below:

$$CaCO_3 \text{ (solid)} <=>^1 \text{Ca (soluble)} <=>^2 \text{clay-Ca (exchangeable)}$$

(after Hausenbuiller 1978).

Different processes govern the rates of reaction 1 and reaction 2. Reaction 1 is determined by factors affecting the solubility of lime. The rate of reaction 2 is a function of the relative activity of the calcium ion.

Calcite is built of alternating calcium and carbonate ions which have strong bonding energies; for this reason it is sparingly soluble in water. If the soil solution is acidic the hydronium ion will diffuse rapidly to the surface of the crystal and calcium bicarbonate will form. The time of breakdown of the lime is dependent on the speed with which the hydronium ion moves to and reacts with the crystal, which is proportional to its concentration, soil water status, and the surface area of the crystal. The partial pressure of carbon dioxide (PCO_2) will determine the level of hydronium ion activity at which solid calcium carbonate will be in equilibrium with the soil solution. Increasing the PCO_2 will drive the following reaction right :

$$CaCO_3 + CO_2 + H_2O <=> Ca^{2+} + 2HCO_3^{-1}$$

(after Bohn *et al* 1979).

Bohn *et al* (1979) points out that this reaction will be driven left by low soil water and a high concentration of calcium ions even if the PCO_2 is high. For this reason the PCO_2 is more important in aqueous solutions and under geochemical conditions than in the soil. Even so the PCO_2 will play a role in the solubility of lime in soil; an increase will lower the pH of the equilibrium solution and increase the solubility of the solid phase. Tyurin *et al* (1960) states:

> "When the carbon dioxide content in the soil air reaches figures that are usual in the lower horizons the solubility of calcium carbonate is slightly less than twenty five percent of the solubility of gypsum in water".

Eastern European researchers encourage the growth of crops with high organic matter content, such as grasses, following an amelioration event which adds calcium carbonate to the soil. The decaying organic matter will increase the PCO_2, thus enhancing the solubility of lime. In an acid soil the dissolution of lime is rapid at first, but it declines as soil acidity decreases and finer lime particles disappear. A near equilibrium state is reached where other factors play a role.

As has been mentioned lime is a general term, most often referring to calcite, although it may mean vaterite and aragonite which are polymorphs of calcite and which have slightly higher solubilities, due to a less stable crystal structure (Dixon and Weed 1977). Calcite may have up to five percent magnesium in its crystal structure through isomorphic substitution.

In a soil system, it is very unlikely that pure calcite will be formed and the K_{sp} for calcite is only an approximation of the calcareous precipitate found in soil. Generally the forms found in soil are more soluble than calcite (Olsen and Watanabe 1959; Doner and Pratt 1969). For this reason amelioration techniques that mobilize native lime, such as the digo method or deep plowing, may have an advantage over techniques where calcite is applied from an external source.

Factors other than the foregoing may affect the solubility of the crystal. Szabolcs (1971) notes that calcite added to the soil becomes less soluble due to the formation of organo-mineral complexes, of very low solubility, on the lime crystal surface. For this reason more lime is added to the soil in eastern European reclamation than theoretically should be needed

One cannot assume a situation exists in which lime is allowed to reach, and stay, in equilibrium with water. Leaching will increase the dissolution of lime while evapo-transpiration will concentrate the calcium and carbonate ions in soil solution, and cause precipitation to occur. In soil solution, calcium carbonate may not be the only source of calcium. Where other calcium sources are present such as gypsum, increased calcium ion activity will decrease the solubility of lime through the "common ion effect" (Frear and Johnson 1929).

The presence of salts other than lime or gypsum in the equilibrium solution will not always decrease solubility. Through the "foreign ion effect", lime solubility quadruples in a one normal solution of sodium sulfate (Tyurin *et al* 1960). This phenomenon is due to the association, and ion pairing, of sodium and carbonate, and calcium and sulfate. As a result, the activities of the calcium and carbonate ions decrease, and more calcium carbonate comes into solution. Nakayama (1971) states that, if the ionic strength effects and the complex formation of the solid constituents are not taken into account, the tendency is to underestimate the solubility of the solid. Carter *et al* (1978) used the foreign ion effect to enhance the solubility of gypsum through its simultaneous application with ammonium nitrate. This technique increased the depth of penetration of soluble calcium.

Although the solubility of lime will be an important factor in determining the rate of exchange reactions the activity of the soluble form is more important. As has been previously noted a certain percentage of the soluble calcium is attracted to anions present in the soil solution and these "ion pairs" behave as if un-ionized (Adams 1971). The degree of ion-pairing depends on the concentration and type of anion present, as well the pH. At a neutral pH or less $CaSO_4^o$ will be the dominant pair. At a higher pH, a greater fraction of total dissolved calcium is complexed, and the predominant species are $CaCO_3^o$ and $CaHCO_3^+$ (Nakayama 1969).

Divalent cations form ion pairs at a much higher rate than monovalent cations. Alzubaidi and Webster (1983) determined the degree of ion pairing on a Duagh Solonetz: approximately 42 percent of calcium and magnesium in solution occurred as ion pairs, while less than 4 percent of sodium paired. Activity coefficients were calculated through the Debye Hückel equation after compensating ionic strength according to the amount of ion pairing. In the Bnt1 26.6 percent of all soluble calcium and 79.2 percent of soluble sodium was in the active form. Nakayama (1969) states that the degree of ion pairing may explain why amelioration of alkaline sodic soils through the application of calcium salts proceeds at such a slow rate:

> "namely, that a large part of the calcium that eventually gets into solution is not in the Ca^{2+} form and consequently is unavailable for sodium replacement".

As has been discussed, Carter *et al* (1978) noted that gypsum applied in combination with ammonium nitrate was more soluble than gypsum alone, and calcium moved to a greater depth in the soil profile. Gypsum alone however, was as effective at lowering the ESP and hence promoting amelioration. The foreign ion effect may increase the solubility of a calcium salt, but not the activity of the calcium ion.

2.2.1.2 Gypsum as an Ameliorant

Many of the principles previously discussed in relation to the use of lime as a chemical ameliorant also apply to gypsum. Historically gypsum has been used as an ameliorant for as long as has lime, and researchers worldwide have reported lower ESP following application (United States Salinity Laboratory Staff 1954; Tyurin *et al* 1960; Graveland and Toogood 1963; Obrejanu *et al* 1970; Szabolcs 1971). Reported rates of application vary from 6 to 30 t ha^{-1}.

Theoretically the solubility of gypsum is not dependent on pH and under equilibrium conditions, at standard temperature and pressure (S.T.P.), it is approximately 240 times more soluble than lime. As has been discussed many factors influence the solubility of lime which are not taken into account by S.T.P. conditions. Even so, gypsum is considered a more soluble calcium source, and hence a better ameliorant than lime.

Due to the solubility of gypsum; the electrolyte concentration of the soil solution is increased above the flocculation value; this enhances hydraulic conductivity, and ultimately cation exchange. Keren *et al* (1980) found a surface application of gypsum to be very effective at increasing infiltration: in contrast, the hydraulic conductivity following an addition of lime remained low. The flocculation value is specific to each soil and is very sensitive to ESP. Where ESP is greater than 20 to 25 percent, the flocculation value will not be reached, and gypsum is not effective in increasing hydraulic conductivity and hence amelioration (Graveland and Toogood 1963). Carter *et al* (1977) cited the increased solubility of gypsum when applied in combination with ammonium nitrate as a possible technique for use on these highly sodic soils.

Soil pH is not directly involved in the solubility of gypsum. However, in an alkaline environment, a lime crust may form on the surface of the gypsum crystal and as a result solubility will decline (Tyurin *et al* 1960). Alternatively gypsum can decrease the pH of the soil solution through the exchange of calcium for aluminum and hydrogen ions on the exchange complex (Webster and Cairns 1978). The pH of the soil should be taken into account when applying gypsum. If the soil is alkaline, gypsum could be applied in combination with an acidifier such as sulfur. If the soil is acid, gypsum and lime might be applied together.

Although a considerable amount of encouraging research has been done in Alberta, the use of gypsum has not been adopted by the farming community. An economic supply has not been available even though reserves of phosphogypsum, a by-product of the fertilizer industry, are stockpiled throughout Alberta. Phosphogypsum contains some radioactive materials, and it has only recently been cleared by Environmental Authorities for agricultural use (Jerome Lickacz, person. commun. 1986). Phosphogypsum is considered a better quality gypsum source than mined gypsum due to its high rate of dissolution (Keren and Shainberg 1981). An additional source of gypsum may be available in the future as an end product in the removal of sulfur dioxide (SO_2) emissions from gas and heavy oil plants. Currently SO_2 is released into the atmosphere though it can, however, be reacted with lime to form gypsum. While the technology for this process is available, its implementation will depend on changes in environmental laws governing acceptable atmospheric emission levels for SO_2 (Albert Leim person. commun. 1986). Transportation expenses are significant in the overall costs of applying gypsum, therefore sources which are scattered throughout the Solonetzic soil areas, such as gas plants, would significantly influence the economic feasibility of this technique.

2.2.2 Amelioration - Physical

Physical amelioration is aimed at a massive physical disruption of the sodic claypan layer. The physical disruption is accomplished through deep tillage, or working of the soil deeper than is encountered in normal cultural practices. Historically a variety of deep tillage implements has been used and differing results can often be traced to the type of tool, as well as to the type of soil, and the interaction between these two factors. In regard to deep tillage, Henderson *et al* (1981) state:

> "Although predictions can be made from previous research, only actual experience under local conditions will show the practice that should be followed".

In western Canada deep tillage implements which have been used are the deep plow and the "texas ripper", or subsoiler.

2.2.2.1 Amelioration by Deep Plowing

Deep plowing is best described as the displacement and mixing of the A, B and C horizon (Harker *et al* 1977). The ultimate aim is the physical and chemical destruction of the Bnt horizon and a transition to a "zonally normal" soil. Initially the physical disruption of the Bnt allows for greater root and water penetration (Rasmussen *et al* 1972; Unger 1979). The lime salt layer of the C horizon is elevated and mixed throughout the soil profile. The amount of native calcium salt which can be mobilized through this procedure is considerable. By plowing to a depth of 60 cm on a Duagh Black Solonetz, approximately 27 t ha^{-1} of gypsum, and 67 t ha^{-1} of calcium carbonate equivalent would be elevated (Cairns 1961). These amendments decrease surface acidity and enhance calcium sodium exchange in the A and B horizon through an increase in the soluble Ca^{2+}:Na^{+} ratio (Harker *et al* 1977; Webster and Nyborg 1984). Clay content generally increases in the Ap due to the elevation of illuvial horizons (Ballantyne 1983; Buckland and Pawluk 1985a).

In eastern Europe deep plowing of sodic soils was first initiated in the 1930's (Tyurin *et al* 1960). The first Canadian research began in the mid 1950's (Cairns 1962). In this study a Daugh Black Solonetz was mixed to a depth of 60 cm and a yield increase of 33 percent was subsequently observed in wheat and barley crops. Further research confirmed yield increases due to deep plowing (Bowser and Cairns 1967). In 1973 the Soils Branch of Alberta Agriculture undertook a "Solonetzic Soil Deep Plowing Feasibility Study". Approximately 120 four hectare plots were deep plowed throughout the Solonetzic soil zone of Alberta. Yield results have been variable, but generally positive. Increased average wheat yield, based on 33 site years, was 0.74 t ha^{-1} (Hermans 1981). Yield increases are generally more substantial in years where water has been limiting (Burnett and Hauser 1968; Unger 1979; Hermans 1981; Ballantyne 1983; Buckland and Pawluk 1985b). In the study by Buckland and Pawluk (1985b) yield increases on deep plowed areas were attributable to increased tillering and yield per head, characteristics associated with reduced moisture stress.

Surface soil crusting may be encountered in the Ap after deep plowing. This appears to be correlated to low exchangeable Ca:Na ratios, increased clay content and low organic matter in the surface horizon (Cairns 1976;

Buckland 1983). The single bottom, "classical" deep plow, mixes and buries the Ap horizon. In an attempt to improve surface tilth two prototype topsoil saving plows were designed by Engineering and Home Design of Alberta Agriculture and manufactured by Kellough Bros Ltd., of Stettler Alberta (Hermans 1981). The three layer topsoil saving plow was not effective in retaining the Ap on the soil surface and did an inferior job compared to the single bottomed deep plow (Lavado and Cairns 1980). The topsoil saving wheel plow was more efficient in saving the surface layer but it has remained a prototype. High upkeep costs, and low demand, have discouraged the manufacturer from producing more units (Fred Kellough person. commun. 1986).

Although promising experimental results have been obtained through deep plowing it has not been widely accepted by the western Canadian farm community. High costs, coupled with the slowness of the operation, and the inability to retain the Ap on the soil surface, have discouraged farmers from plowing large acreages. In the late 1970's subsoiling or ripping began to grow in popularity and since that time substantial acreages have been ripped (Plett 1982). Farmers estimate initial subsoiling costs at approximately 25 percent of deep plowing (High 1979). The custom rate for ripping is approximately $74^{.00}\ \$ha^{-1}$, and while custom deep plowing is not commercially available it is estimated that a fair rate of return for a custom operator would be $250^{.00}\ \$ha^{-1}$ (Hermans 1979).

Subsoiling is much faster than deep plowing; a 5 shank subsoiler can work 1.2 ha hr^{-1}, while a deep plow can work .3 ha hr^{-1} (Drever and Wiens 1980). In 1986 Kellough Bros. Implements had built and manufactured approximately 11 deep plows and 140 subsoilers (Fred Kellough person. commun. 1986). While other implement manufacturers have marketed rippers in western Canada, no other commercial manufacturer has marketed deep plows. Taking into account the ha hr^{-1} that can be worked, it is obvious why substantial acreages have been ripped, and why the relative acreage in proportion to areas deep plowed is large.

2.2.2.2 Amelioration by Ripping

In the literature ripping is used interchangeably with deep loosening, subsoiling or chiseling. This term generally means a deep working of the subsoil without bringing material to the surface (Duley 1957). Lavado and Cairns (1980) define a ripper as follows:

> "a chisel with wide blades designed to elevate and mix some of the Csk with the Bnt horizon while retaining most of the Ap on the surface."

Under ideal circumstance ripping will shatter the Bnt thus increasing aeration, water infiltration, water holding capacity and root penetration. While some of the lime-salt layer may be elevated throughout the profile, the amount is thought to be much less than that lifted by deep plowing. A physical disruption without provision for chemical amelioration has not been considered likely to have long term results. For this reason calcium salts, such as gypsum and lime, are often added in combination with ripping (Szabolcs 1971).

The effectiveness of ripping will depend on the extent to which the claypan is shattered. The degree with which this objective will be met depends on:

1. implement design,
2. depth of operation,

3. soil moisture at the time of subsoiling,
4. number and direction of operations.

While ripper designs vary, they follow a general trend. Most have curved standards which reduce draft, as the effective pressure is upward from the point rather than a direct horizontal pressure on the standard (Nichols and Reaves 1958; Aleksandrian 1980). The upward pressure from the point encourages the development of a "shear plane", similiar to a wedge being driven into a fracture. This shear plane should develop at, or below, the interface of the Bnt and C horizon. A variety of subsoilers are used in western Canada and the most popular model is the Kello-Bilt Subsoiler manufactured by Kellough Bros. Ltd. This ripper is available with 3, 5 or 7 curved standards arranged in a "V" design. Early models were capable of operating to a depth of 48 cm with shank spacings, center to center, of 61 cm (Drever and Wiens 1980). Later models are theoretically able to reach a 60 cm depth; shank spacings are 76 cm, center to center (Fred Kellough person. commun. 1986).

For maximum shattering to occur, White and Gartner (1981) suggested the spacings between ripper teeth should correspond to the dimensions of the stable dessication cracks surrounding the large columns in the Bnt. If horsepower is a limiting factor some farm operators remove intermediate shanks, effectively doubling shank spacings. Where this procedure was followed, it was found that the wide shank spacing caused poor intershank disruption, resulting in less homogeneous physicochemical characteristics throughout the soil profile (Riddell 1986). Wide shank spacings may result in variable crop growth with a ranker more vegetative growth on the shanked, as compared to the inter-shank, zone. The ranker growth comes to maturity later, thus complicating harvest management (Jerome Lickacz person. commun. 1986).

The correct depth of ripping will depend on the depth and thickness of the claypan layer. In the Bnt, upper columns of small diameter merge at depth into larger columns. The smaller columns are less stable and dessication cracking occurs at irregular locations; a physical alteration in these small columns will have little lasting influence (White and Gartner 1981). Permanent fracture planes are located between the large columns (Holmes and Stace 1968). For amelioration to be effective the depth of ripping, and hence uplift, must be below these large columns (White and Gartner 1981). Lavado and Cairns (1981) cite the thickness of the Bnt as being partially responsible for poor physicochemical properties on a site where ripping was deemed unsuccessful. As ripping depth increases a critical depth is reached at which draft increases rapidly. This critical depth corresponds to the point at which plastic flow shear, or soil movement by plastic flow around the standard, [illegible]ns and the development of a shear plane ceases (Trouse and Humbert 1959). In the region of plastic flow shear the walls of the vertical grooves cut by the ripper become compacted, to a higher bulk density. Maximum disruption occurs in the shear plane zone, therefore soil should be ripped to a depth where shear plane development is maximized, and plastic flow shear is minimized. In practice ripping depth is often limited by lack of power, and/or slippage (Len Solick person. commun. 1986).

If the soil is moist ripping, will not be effective (Nichols and Reaves 1958; Unger 1979; White and Gartner 1981). Disruption will be minimized as shear plane development will occur at a shallow depth (Trouse and Humbert 1959). Alexandrian (1980) set the critical gravimetric moisture content for ripping below 20 percent. Alternately, if the soil is excessively dry, management problems arise from large clods of Bnt left on the surface. Soil moisture content at the time of ripping is the most important management variable determining success or failure of the operation. Riddell (1986) speculates that a lack of disruption and alteration of soil chemical properties at one study site may have been due to high moisture, present in the profile, at the time of ripping.

The majority of ripping is done in a single tillage operation. Where horsepower and/or traction is not sufficient to rip to the desired depth, or a more complete shattering is desired, multiple passes could be used. Research has shown that double cross operations, or three individual passes, are more effective than single cross operations; cross ripping at a 45 degree angle provides the greatest amount of shattering (Trouse and Humbert 1959).

Subsoiling research began in the United States in the late 19th century (Duley 1957). In Russia research was initiated in the 1930's (Tyurin *et al* 1960). Research began relatively late in Canada, with the first reported work occurring in the early 1970's (Riddell 1986).

Variable yield results from ripping have been reported in the literature. Generally favorable agronomic results have been reported in eastern Europe (Obrojanu *et al* 1970; Bocskai 1974). In the U.S., Sandoval (1979) and White *et al* (1981) reported increased crop yields due to deep ripping, while Rasmussen *et al* (1972) found no changes. It appears to be very difficult to predict success based on experience at another location. Bocskai (1974), in reference to subsoiling, states:

> "The data relating to soil reclamation are, as a matter of course, only applicable to Hungarian conditions."

In Canada, Cairns and Lavado (1981) reported an increase in oat yields from ripping under field conditions and barley under greenhouse conditions at one site, and a decrease in barley yields under greenhouse conditions at another. Webster and Nyborg (1984) found yield increases of 45 and 50 percent for barley and alfalfa respectively at one site, but a slight decline in yields at another. Due to the lack of data correlating yields and ripping under Canadian conditions, the Soils Branch of Alberta Agriculture in cooperation with local Agricultural Service Boards began to establish plots in the late 1970's, comparing ripping and ripping in combination with lime and gypsum (Hermans 1979). More than 30 plot sites have been established and preliminary results indicate ripping increases yield substantially, but the role of lime and gypsum is less clear (Jerome Lickacz person. commun. 1986). Bocskai (1974) found ripping in combination with a surface lime application and a subsurface injection of gypsum increased yields over ripping alone. Webster and Nyborg (1984) reported similiar results for chiselling in combination with surface applications of lime or gypsum. In addition, the combined chiselling gypsum treatment gave higher barley yields than deep plowing at one site. The soil at this site, a Duagh Black Solonetz, was poorly drained with high subsurface salinity; poor surface tilth depressed yields in the plowed treatment.

Theoretically ripping should increase hydraulic conductivity by increasing the proportion of large continuous macropores (Saveson and Lund 1958). Surface material may fall, or material from depth may be lifted, into cracks and ruptures in the Bnt. If this material has a low ESP it will not disperse and infiltration will increase along these planes (White and Gartner 1981). Increased water infiltration on sodic soils, following ripping, has been reported in the literature (Abraham and Bosckai 1971; White *et al* 1981;

Riddell 1986; Yakowlev 1983), while other researchers have found no change (Rasmussen *et al* 1972). Lavado and Cairns (1980) reported a decreased infiltration rate in the Ap, but an increased rate in the Bnt.

It is generally reasoned that subsoiling will not generate the types, or magnitudes, of physicochemical changes experienced with deep plowing (Rasmussen *et al* 1972; Webster and Nyborg 1984; Riddell 1986). Reports in the literature are scanty and contradictory, but they generally support the hypothesis that ripping may elevate material from depth. The altered physicochemical changes associated with this elevation may not be positive (Lavado and Cairns 1980; Riddell 1981). Research also indicates that ripping will enhance the penetration and ameliorating action of surface applied calcium salts (Rasmussen *et al* 1972; Webster and Nyborg 1984).

A question uppermost in the minds of farm operators, extension personnel, and researchers is the magnitude and duration of beneficial effects of ripping; the economic feasibility of this practice hinges on the answers (Hermans 1981). Eastern European researchers believe ripping must be repeated at approximately four year intervals (Obrejanu *et al* 1970; Bocskai 1974). Other researchers feel that if solonization processes no longer exist, or are very weak, amelioration may be permanent (White and Gartner 1981). For this reason, Hermans (1981) identifies soils with low sodium levels in the hardpan as the most eligible for amelioration through subsoiling. Other questions to be answered are:

1. Will enough calcium carbonate be brought to the surface to raise the pH of the acidic Ap, or is liming necessary?
2. Will germination problems result, similiar to those encountered on some deep plowed sites?

Hopefully this thesis will at least partially answer these and other questions.

3. Materials and Methods

3.1 Site Description

3.1.1 Location - Climate - Vegetation

The study site (NE - 25 - 36 - 16 - W4) is approximately 15 km south of Halkirk, Alberta (Figure 1). The climate of the region is continental, characterized by long cool summers and cold winters. Average yearly precipitation is 380 mm with approximately one quarter of this as snow (Le Breton 1971). The average moisture deficit is approximately 200 mm. Using climatological data from various sources, Buckland (1983) demonstrated that a large percentage of summer precipitation in this region occurs within a short time period. Under these conditions timing of the rainfall, as well as the rate of infiltration and water storage capacity, will determine the effectiveness of growing season precipitation.

The study area falls on the extreme southern edge of the aspen parkland vegetative zone, a transition area between the northern deciduous/coniferous forests and the southern short and midgrass prairies. The semiarid climate, in combination with soil properties, limits plant growth. Stalker (1960) in reference to this region states:

> "the amount and type of vegetation, both natural and cultivated, are strongly affected by the lower precipitation, the higher rate of evaporation and the rather impermeable soil formed from shallow clayey bedrock."

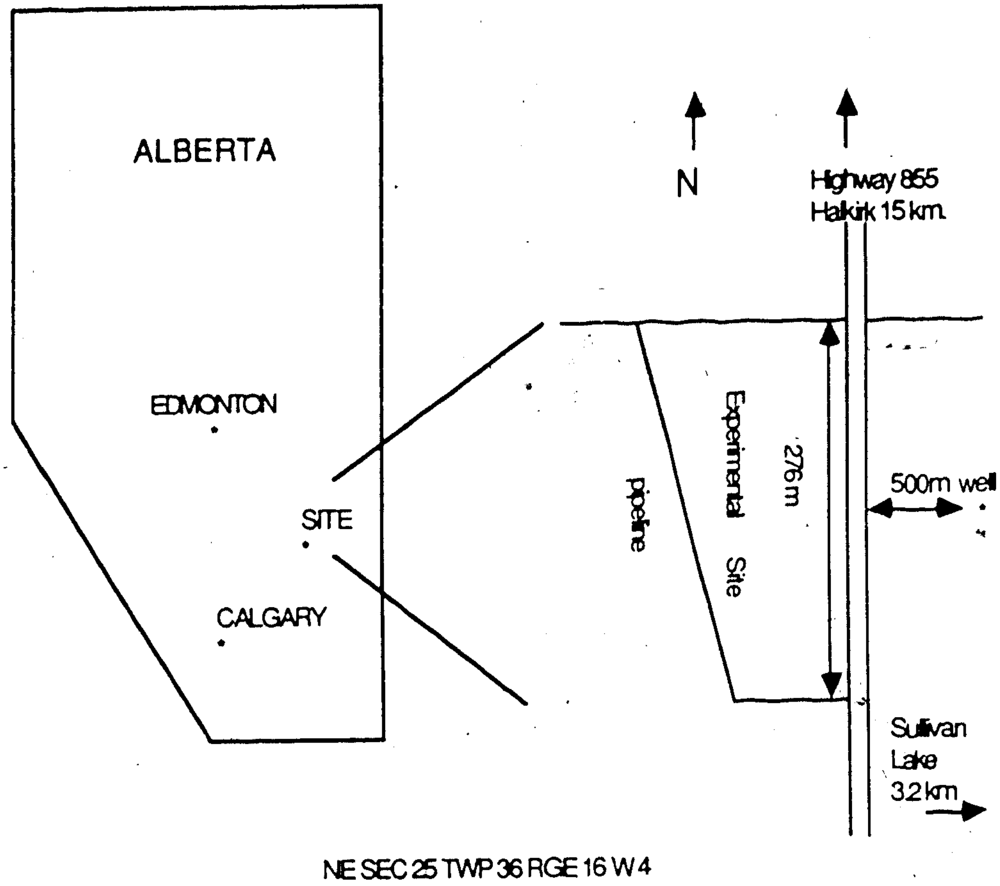


Figure 1: Location of Experimental Plots*

*not to scale

3.1.2 Bedrock and Surficial Geology - Physiography - Hydrogeology

The bedrock unit underlying the study site is the Edmonton formation of Upper Cretaceous age (Stalker 1960). The formation consists of clay, shale, argillaceous silt, sandstone, sand, and coal seams; it is of brackish and freshwater origin. The overlying glacial drift material is thin and composed of modified bedrock. The Torlea flats are the physiographic division encompassing the study site. This region contains rolling plains, dry lake basins, and small scattered hills; it is a "monotonous area of low relief" (Stalker 1960).

The study site is located on flat terrain at an elevation of 844 m. Following the last glacial stage, the Wisconsin, the maximum expanse of Glacial Lake Gough was approximately 3 km south. The northernmost boundary of present day Sullivan Lake is 3.2 km directly east of the study site; the difference in elevation between lake and site is 37 meters. With the retreat of the ice pack Glacial Lake Gough drained rapidly in a north eastward direction into present day Sullivan Lake (Stalker 1960). The study site is less than 3 km north of the drainage channel as a result, local groundwater at the site would have dropped rapidly following deglaciation.

Recharge water for regional flow systems in the Torlea flats is generally believed to have its origin in the high lands surrounding, and west of, Red Deer, Alberta (Le Breton 1971). The general trend is to view the interior plains region as a discharge area (Pawluk 1982); local conditions and features may confound the issue however. Le Breton (1971) found groundwater levels to decline with increasing depth in the flat country surrounding Halkirk. He speculates that groundwater movement is generally downward in this region.

Site specific investigations into the direction of groundwater flow, or depth to groundwater, were not undertaken in the present study, but no evidence exists: such as springs, or artesian wells, that groundwater is moving upward due to hydrostatic pressure. Surface topography suggests that local flow systems will discharge into Sullivan Lake; upward moving water from regional and intermediate flow systems would be intercepted by these local systems. Groundwater flow for the area is termed as "sluggish" (Le Breton 1971); an average well will yield 4.5 - 22.5 L min^{-1}.

The major soluble salts found at a depth of less than 70 m are $NaHCO_3$ and Na_2SO_4, with $NaHCO_3$ being usually dominant. At a depth of greater than 70 m Cl^- is the major anion and Na^+ the major cation (Le Breton 1971). In the present study groundwater was obtained from a shallow well, less than 70 m in depth located approximately 500 m east of the study site (Figure 1). A routine chemical analysis was carried out by the Water Analysis Section Alberta Environmental Center, Vegreville, Alberta according to procedures outlined in Tarus *et al* (1971). The results are listed in Appendix 1; sodium, expressed in me L^{-1} constituted 96% of the total cations and bicarbonate 98% of the total anions.

3.1.3 Soil

The soil, at the experimental site, was recently mapped as a Halkirk-Torlea series, a Dark Brown Solodized Solonetz, with minor inclusions of Dark Brown Solods, Solonetzic Dark Brown Chernozems and Gleysols. The parent materials are clay loam to clay till veneer, occasionally discontinuous, over residual or modified residual shale (Wells and Nikiforuk 1984). A Halkirk series developed on till, while a Torlea developed on residual material.

3.2 Plot Design

All plots were established in the late fall of 1981, on private land, by the Soils Branch of Alberta Agriculture in cooperation with the farm owner operator, Len Solick, of Halkirk Alberta. Plot layout and size are shown in Figure 2.

The effectiveness of ripping and liming, alone and in combination, were to be determined through crop response. The entire plot area was treated as one field for management purposes and the plots have been in continuous wheat since their inception. The study site was designed as one repeat in an overall experiment involving many sites; these sites were to serve as a demonstration, as well as a yield experiment. Visual observations and some preliminary chemical analyses were done to establish that the plot site was fairly uniform; data for the chemical analyses, performed by Alberta Soil and Feed Testing Laboratory (A.S.F.T.L) are presented in Appendix 2.

3.2.1 Liming Treatment

Agricultural limestone($CaCO_3$) or "lime", in the common language, was applied at a rate of 5.6 t ha^{-1}. A lime requirement test based on a buffered method (McKeague 1978), as performed by A.S.F.T.L., had determined 4 tha^{-1} to be sufficient to raise the pH of the Ap over 6.5 (Appendix 2). Lime was applied in a powdered form (<250 um) with a rotary fertilizer spreader; the application was immediately followed by shallow cultivation to a depth of 10 cm. All work was performed by the cooperating farmer under the direction of

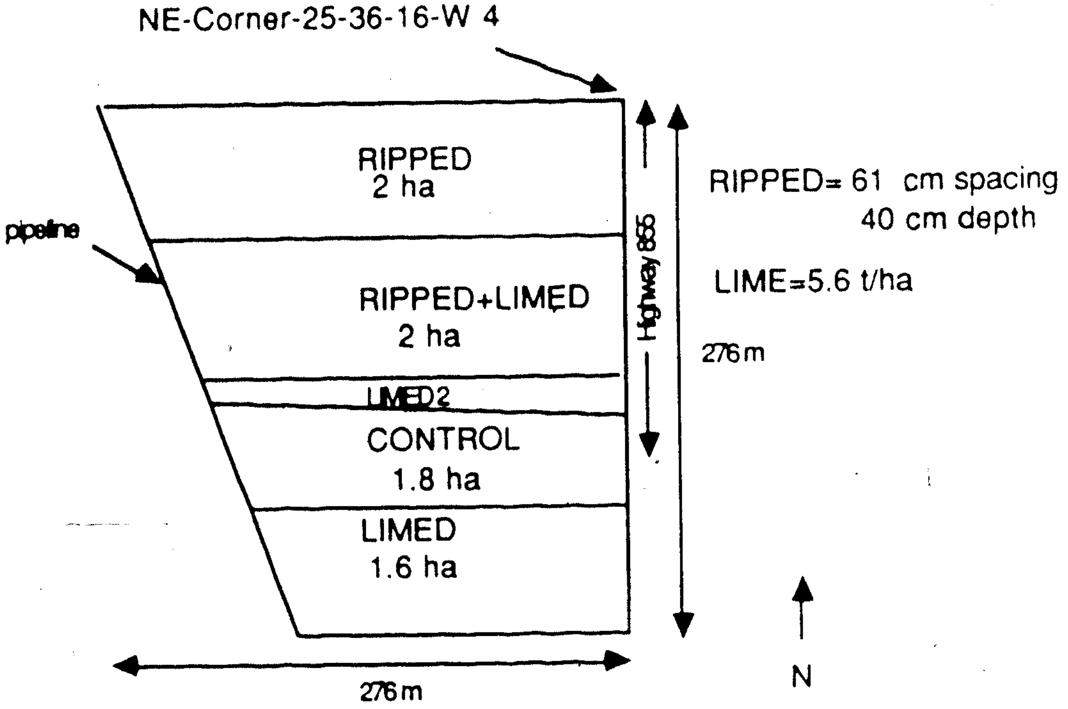


Figure 2: Field Layout of Ripped and Limed Plots*

* not to scale

Alberta Agriculture in the fall of 1981. The rotary applicator's width of spread was 11.9 m. To achieve uniformity of spread, lime was applied in two passes in a 1/2 overlap pattern: as a result the outside 5.9 m of each treatment received only 2.8 t ha^{-1}. This pattern in combination with some drifting of lime gave an indistinct "edge" effect which was determined through pH testing, at intervals, across the boundary of limed and control plots. .

3.2.2 Ripping Treatment

Subsoiling was done one week after liming operations by the cooperating farmer. A wheat crop had been grown the previous summer as a result subsoil moisture conditions were low and considered ideal for ripping. Substantial shattering of the Bnt was observed (Len Solick person. commun. 1985). A single pass was made with a five shank, Kello-Bilt model 5000, subsoiler; the ripping depth was approximately 40 cm, with a shank spacing of 61 cm, center to center.

Subsoiling was not done to its intended southern boundary in the Ripped+Lime plot, (RL). Consequently a second limed plot of approximately 25 meters in width was inadvertently established between RL and Control (C); this plot will be referred to as Limed 2 (L 2) (Figure 2). The presence and boundaries of this plot were confirmed through pH readings across the width and boundary of RL, L2 and C, and through personal communication with the farm owner.

3.3 Chemical and Physical Analyses

3.3.1 Sampling

Soil sampling for chemical and physical analyses was done in the early summer of 1984; the sampling procedure involved a series of steps. An initial sampling point (pit 1), was established in each treatment 50 m from the east boundary of the plots; this point was an equal distance from the north and south boundary of each treatment, thus eliminating any "edge effect". Nine additional pits were located at strict 10 m intervals directly west of pit 1(Figure 3).

The soil was sampled by horizon; large 4 kg samples were taken from the Ap, Bnt, BC and Cca at each sampling point. Care was taken to ensure the profile had the morphological characteristics of a Solodized Solonetzic Soil. All pits met this requirement. The soil profile was extremely shallow; the approximate thickness of the Ap was 10-15 cm, the upper boundary of the Cca horizon was generally located 25-35 cm from the soil surface. The maximum depth of ripping (40 cm) was below the interface of the B and C horizons.

In the ripped treatments, trenches were excavated perpendicular to the direction of ripping and shanked zones were located visually. More than one zone was located in each trench and measurements were taken to confirm the distance between shanked zones corresponded to dimensions between shanks. As the location of the shanked zone was established in each pit it was confirmed they were in a straight line, because the subsoiler had travelled

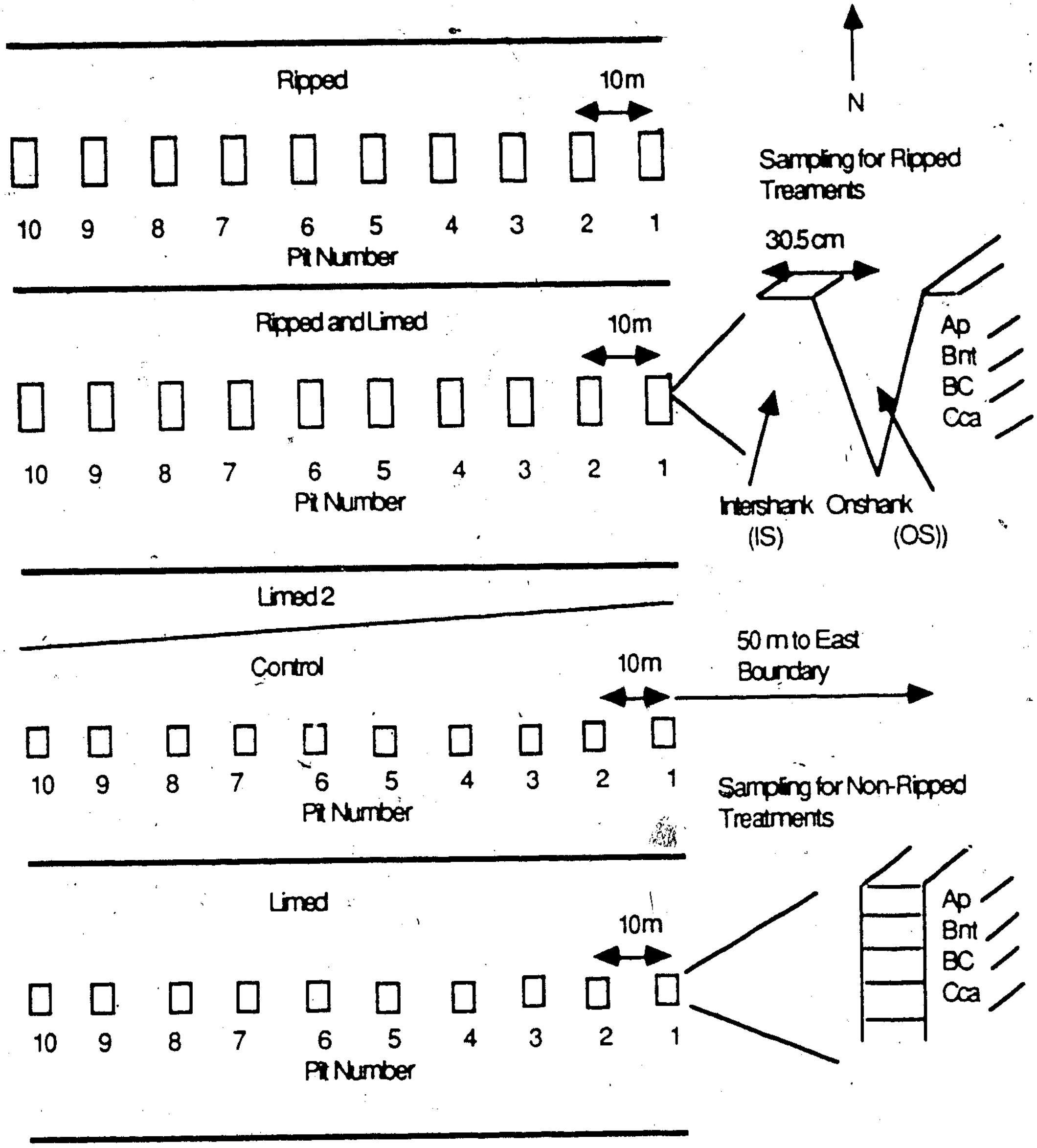


Figure 3 Sampling Procedure for Chemical and Physical Analyses*

* not to scale

in a straight east-west line throughout the field. Paired samples were obtained from the shanked area (on shank zone (OS)), and the intershank area (IS) (Figure 3).

For the non-ripped treatments C and L ten pits were sampled for each horizon, a total of 40 samples/treatment. The two ripped treatments, RL and R, were further subdivided into four treatments. They are; Ripped and Limed on shank (RLOS), Ripped and Limed intershank (RLIS), Ripped on shank (ROS), and Ripped intershank (RIS). Forty samples were obtained from four depths, for each of these treatments, thus 80 samples were obtained for each of the main treatments RL and R.

The bulk density(Db) of the Ap and Bnt was determined by the "core method" (Blake 1965), for each of the six treatments; C, L, LROS, LRIS, ROS and RIS. The Bnt was sampled in the summer of 1984 in the main sampling pits. The Ap was sampled in November, 1985. Sampling points were located 1 m west of the original pits. A Euland corer with an inside diameter of 7.6 cm was used.

In November 1985 the profile Db to a depth of 40 cm was measured through an excavation method (Blake 1965). This procedure was used in an attempt to detect differences between treatments within the total profile to the depth of ripping Five pits with diameters of approximately 25 cm were excavated 2 m north of sampling sites 1 to 5 in the C and R treatments; no distinction was made between intershank and shanked areas in the R treatment. The soil excavated from each pit was oven dried at 105 °C and a dry mass obtained. The pits were lined with thin polyethylene bags and their volume determined by filling with water.

3.3.2 Chemical Analysis

All samples taken for physical and chemical analyses were air dried at 20° C, the samples were then ground to 2 mm on a rollerball mill. Soluble anions (CO_3^{-2}, HCO_3^-, NO_3^- and SO_4^{-2}) and cations (Na^+, K^+, Mg^{+2} and Ca^{+2}) were determined for all samples, on solutions extracted from saturated soil pastes. In addition, Cl^- was determined on all samples from the Ap. Saturated pastes were prepared by standard methods outlined in McKeague (1978). Saturated pastes were thoroughly mixed at approximate field capacity and allowed to stand 24 hours before vacuum extraction. The gravimetric moisture percent of pastes before extraction, was determined by oven drying sub-samples.

Sulfate was determined by a colorimetric $BaCl_2$ method on a Technicon Auto Analyzer II™ (Lazrus *et al* 1966). Carbonate was determined by titration with .01N H_2SO_4 to the flash point of phenolphthalein; bicarbonate was determined by further titration of the sample to pH 4 using a pH meter and autotitrator. A subsequent calculation was used to compensate for bicarbonate produced during the initial carbonate titration (Anonymous 1982). Nitrate was determined by a colorimetric method involving the reduction of nitrate to nitrite and then a subsequent reaction with sulfanilamide to form a diazo compound (Grasshoff 1969). Chloride was determined by titration with $AgNO_3$ using the standard Mohr method (Harris and Kratochvil 1981). Care was taken to ensure that cations and anions approximately balanced. Where cations and anions were expressed in me L^{-1} if the balance difference was greater than 15%, as calculated by the formula below, samples were re-done.

$$\text{Balance} = |\text{cations}-\text{anions}|/|\text{cations}+\text{anions}| \times 100.$$

This procedure was in accordance with the "high quality data" definition of Bresler *et al* (1982); which is:

> "the sum of the cations in mEq/l should be approximately equal to the sum of anions in mEq/l."

A conductivity bridge was used to determine the E.C. of all samples of saturated paste extracts (McKeague 1978). The pH of all samples was determined using soil water solutions at a ratio of 1:2.5 respectively (McKeague 1978).

3.3.3 Physical Analysis

Particle size analysis was done on all samples, of all treatments, for the Ap horizon. In the Bnt and BC horizons analysis was done on C, ROS, and RIS treatments. No particle-size analysis was done on any samples from the Cca horizon. The hydrometer method as outlined in McKeague (1978) was used. Readings were taken at times of .5 min, 1 min, 3 min, 10 min, 30 min, 4.5 hr and 24 hr.

Water retention at -33 kPa and -1500 kPa was determined using pressure plate apparatus (McKeague 1978). In the Ap, all samples of all treatments were done. Samples from pits 1 to 5 were done for all treatments in the Bnt, BC and Cca horizons.

Modulus of rupture was determined on the Ap of treatments ROS, RLOS, C and L. Five replicates were done on each sample according to the procedure outlined in Richards (1953).

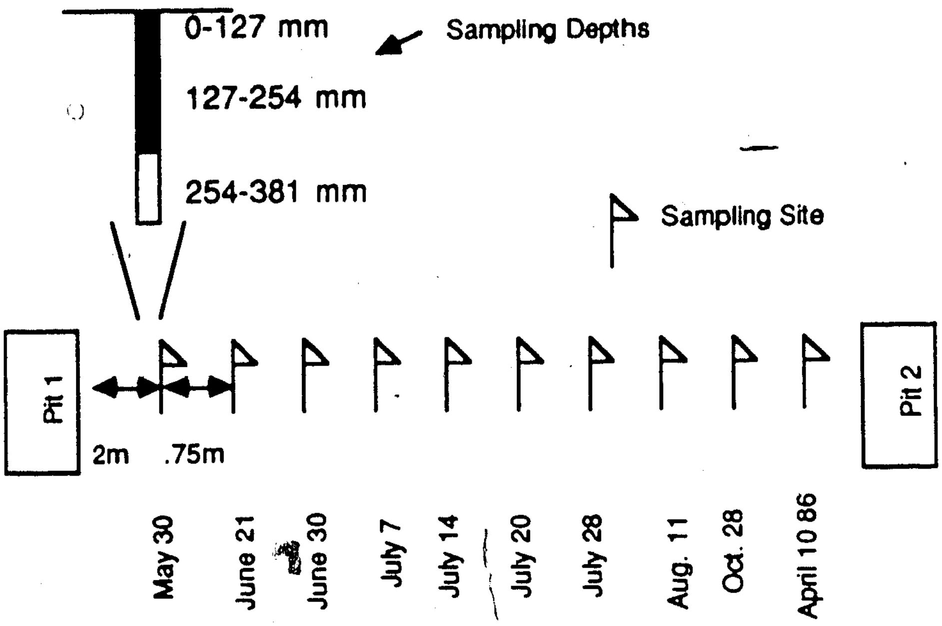
3.4 Moisture Analysis

In late May of 1985, following seeding, sampling pits for chemical and physical analyses as well as the location of shanked zones, established in 1984, were relocated. Soil moisture content was determined gravimetrically for the six treatments at ten dates from May 1985 to April 1986. Eight sampling dates were fairly closely spaced through the summer of 1985, additional sampling was done in the late fall of 1985 and the early spring of 1986. The profile was sampled in three equal intervals of 12.7 cm to a total depth of 38 cm, the approximate depth of ripping (Figure 4). A narrow diameter, 1.5 cm, Oakfield sampler was used.

On May 30, 1985, initial sampling points were established 2 m west of the former "chemistry" sampling pits. In the ripped treatment the intershank zone was sampled 30.5 cm north of the shanked zone. As gravimetric moisture sampling is site destructive each successive sampling point was relocated .75 m west of the previous point (Figure 4). Care was taken not to disturb vegetation in the future sampling area, and holes were plugged after each sampling in order to avoid any influence on soil moisture properties.

Gravimetric moisture samples were sealed in plastic bags, and kept in a styrofoam cooler in order to eliminate moisture loss during transport to the laboratory. Soil samples were weighed before, and after drying at 105°C for 48 hrs; the gravimetric moisture content for each sample was then calculated. On each sampling date 30 samples were obtained per treatment, to a depth of 38 cm, for a total of 180 samples. Daily precipitation from late May to mid August 1985, was monitored using a standard Alberta Forest Service rain guage capable of measuring to the nearest mm.

Example of Gravimetric Moisture Sampling Procedure-Non Ripped Treatments



Example of Gravimetric Moisture Sampling Procedure- Ripped Treatments

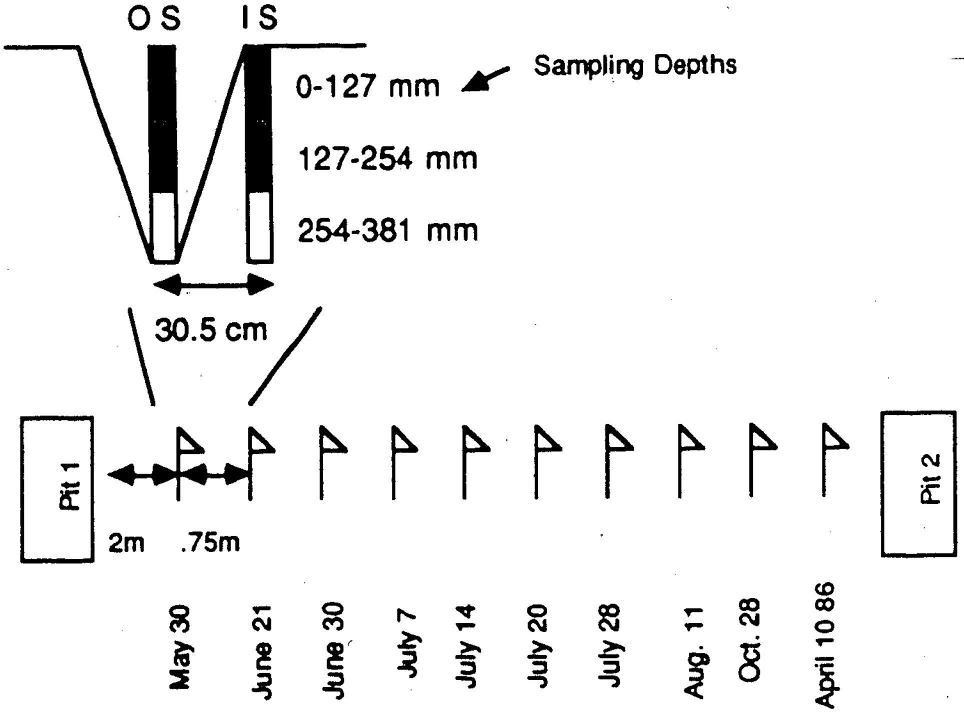


Figure 4 Gravimetric Moisture Sampling Procedure -3 depths -10 dates.

Through a computer program the available water content of each sample, in mm, was calculated using average bulk densities from all treatments and average wilting points values for each treatment in the surface and subsurface horizons.

3.5 Crop - Root - Tissue Analyses

The plots were continuously cropped to wheat (Triticum *aestiuum* L.) in the years following treatments. Neepawa was planted from 1982 to 1984 and in 1985 Columbus was used. Seeding rates, date of seeding, fertilizer and herbicide application were identical in all treatments; all field operations were performed by the cooperating farmer. Prior to harvest twenty (0.836 m^2) cuts were taken, at random, from the four main plots; R, RL, C and L by staff of Alberta Agriculture. Grain and straw yields were determined for each sample, following drying.

On August 12, 1985, soil cores were taken for a root mass comparison between RL and L 2. Ten paired cores were taken at 4 m intervals, 2 m on either side of the boundary separating the two treatments; the initial sampling points were 50 m from the east boundary (Figure 5). The sampling was done with a coring truck provided by the Soils Branch of Alberta Agriculture. Care was taken to randomize sampling, no attempt was made to sample directly over seed drill rows, or to avoid such points. Similarly, no attempt was made to sample consistently in the shanked zone, or the intershank zone of the ripped treatment. Cores were 6.7 cm in diameter, total core lengths were 76 cm. Each core was subdivided into 5 equal segments of 12.7 cm (Figure 5). The cores were washed in a root washer designed and built by staff of the

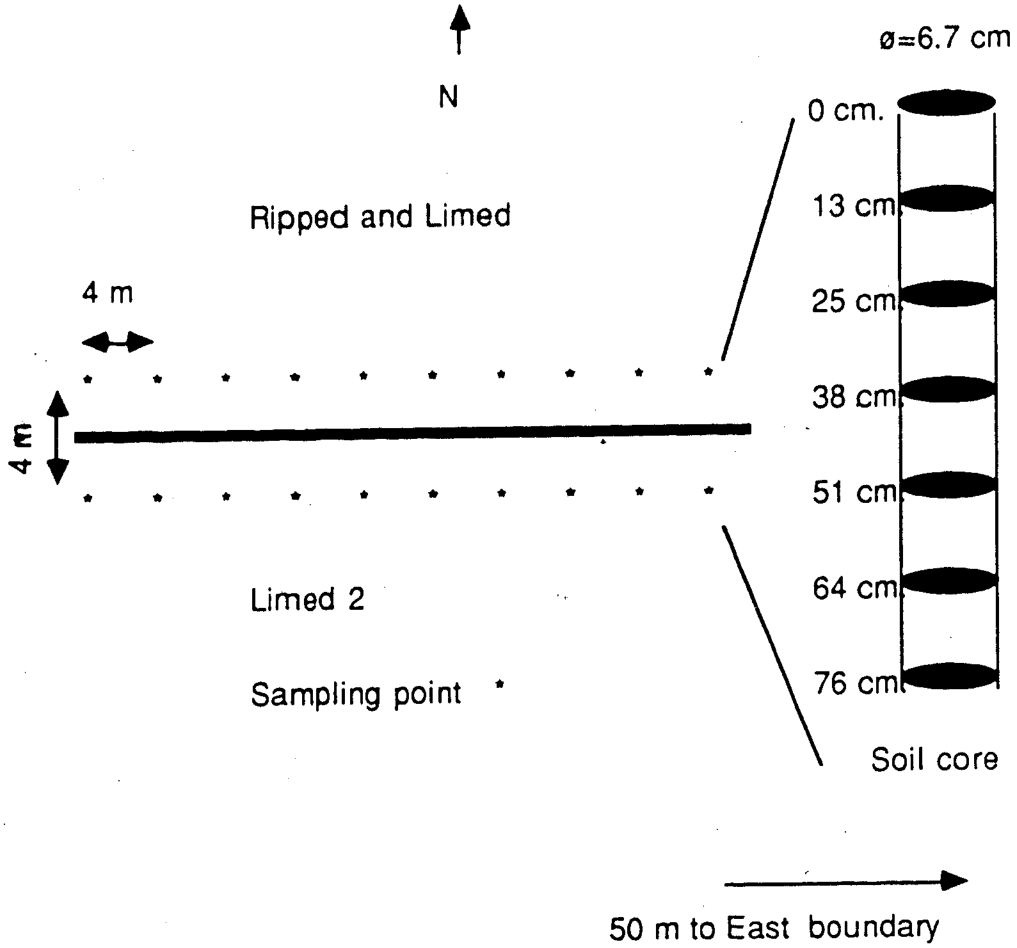


Figure 5 Root Sampling for Two Treatments and Six Depths.*

* not to scale

Plant Science Division, Alberta Environment, Vegreville Alberta. After washing, organic debris was separated from the roots by hand; the roots were oven dried at 50 °C, and dry mass obtained.

Plant samples, for tissue analysis, were taken from each of the four main treatments on June 30, 1985. Three m^2 cuts were taken for each treatment; sampling areas were located 4 m north of the first three pits in each treatment. Plant samples were analyzed by A.S.F.T.L. Total nitrogen and phosphorus were determined by a block digestion and colorimetric technique. Percent nitrogen was multiplied by a factor of 6.25 and expressed as percent protein. Calcium, magnesium and potassium were determined by atomic absorption following dry ashing. All values are expressed on a percent dry weight basis and are presented in Appendix 3. Laboratory techniques used are modifications of standard techniques and are specific to A.S.F.T.L. (A. Bollo-Kamora person. commun. 1986).

4. Results and Discussion

4.1 Chemical and Physical Analyses

Data from chemical and physical analyses for each treatment were analyzed by horizon using a one way analysis of variance. If f values for treatments effects were significant, multiple-means comparisons were obtained through the least significant difference test at a probability of ≤5%. The statistical analysis was performed on a computer using the Statistical Package for the Social Sciences (version 2.1).

4.1.1 Chemical Analysis

4.1.1.1 Soluble Cation Ratios: Sodium Adsorption Ratio, Mg/Ca, Ca/Total Cations

~~As~~ has been previously discussed exchangeable Na as expressed by ESP has a direct influence on soil physical properties. Many studies have shown that at equilibrium the ratio of cations in soil solution is proportional to the ratio of exchangeable cations (United States Salinity Laboratory Staff 1954). Soluble cations are more easily determined and with less experimental error than exchangeable cations for this reason recent researchers have recommended determining SAR rather than ESP (Bresler *et al* 1982). Sodium Adsorption Ratio (SAR) is defined as follows:

$$SAR = Na^{+}/((Ca^{2+} + Mg^{2+})/2)^{1/2*} .$$

*Ion concentrations are expressed in meL^{-1} .

When SAR is increased above a critical value poor soil physical properties will result. SAR is directly related to ESP through the formula:

$$ESP = (kSAR(100)) / (1 + kSAR)$$

(after United States Salinity Laboratory Staff 1954).

The proportionality constant k is related to soil properties, and may vary for different soils. The parameters which most influence k are clay content and organic matter (Harron 1979). If the proportionality constant does not vary, between soils, a direct relationship exists between ESP and SAR.

Carter *et al* (1979) demonstrated that soluble Mg/Ca ratios of greater than 1.0 and soluble Ca/TC ratios of less than 0.15 would induce Ca deficiency in barley. Ca/TC ratios can be viewed as the fraction of Ca in the total cation suite. The Mg/Ca ratios, Ca/TC ratios and SAR values for the six treatments and four horizons are presented in Table I. As treatments were compared statistically within each horizon, means which are not followed by the same letter within each column are significantly different at the 5% probability level according to the least significant difference test.

The difference in SAR values between any two treatments in the Ap were not significant. There was a tendency toward higher Na in the ripped treatments compared to the non-ripped treatments, but it was compensated by a similar trend toward higher Ca and Mg (Table 2). For Mg/Ca ratios in the Ap, there was a trend toward higher values in the non-ripped treatments as compared to the ripped treatments. Control had significantly higher Mg/Ca ratios than all other treatments, followed by the limed treatments: L, RLIS and RLOS. The lowest Mg/Ca ratios were found in the RIS and ROS treatments

Table 1. Multiple Means Comparisons[1] of Cation Ratios for Six Treatments and Four Horizons.

S.A.R

	Horizons			
Treatments	Ap	Bnt	BC	Cca
Ripped on shank	5.1a	6.4a	9.1ab	11.3ab
Ripped intershank	5.3a	6.1a	9.4ab	11.1ab
Ripped + Lime on shank	4.2a	6.4a	7.5a	9.0a
Ripped + Lime intershank	4.2a	6.5a	8.1a	9.0a
Control	4.4a	12.7b	12.8c	13.4b
Limed	4.8a	12.6b	12.3bc	14.4b

Mg/Ca

	Horizons			
Treatments	Ap	Bnt	BC	Cca
Ripped on shank	0.48a	0.65a	0.61a	0.72a
Ripped intershank	0.44a	0.65a	0.66a	0.70a
Ripped + Lime on shank	0.52ab	0.59a	0.53a	0.57a
Ripped + Lime intershank	0.52ab	0.68ab	0.56a	0.57a
Control	0.69c	1.02bc	0.60a	0.69a
Limed	0.59b	1.12c	0.79a	0.67a

Ca/TC

	Horizons			
Treatments	Ap	Bnt	BC	Cca
Ripped on shank	0.27bc	0.20c	0.17a	0.19a
Ripped intershank	0.26bc	0.20c	0.16a	0.22a
Ripped + Lime on shank	0.28c	0.19c	0.16a	0.20a
Ripped + Lime intershank	0.27bc	0.16bc	0.15a	0.23a
Control	0.14a	0.06a	0.09a	0.16a
Limed	0.22b	0.09ab	0.11a	0.14a

---

[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

Table 2. Multiple Means Comparisons[1] of Soluble Cations for Six Treatments and Four Horizons.

Na (meq L^{-1})

Treatments	Horizons Ap	Bnt	BC	Cca
Ripped on shank	7.8c	9.0ab	14.6b	35.2a
Ripped intershank	7.8c	7.9ab	15.4b	41.5a
Ripped + Lime on shank	6.3bc	8.2ab	8.3a	22.9a
Ripped + Lime intershank	6.0b	7.0a	9.3a	22.0a
Control	3.2a	11.1bc	13.4ab	38.3a
Limed	5.0b	13.2c	13.2ab	34.8a

Ca (meq L^{-1})

Treatments	Horizons Ap	Bnt	BC	Cca
Ripped on shank	3.3c	4.0a	4.5a	12.1a
Ripped intershank	3.1c	3.2a	4.5a	15.5a
Ripped + Lime on shank	3.1c	2.1a	1.6a	9.4a
Ripped + Lime intershank	2.8c	1.5a	1.7a	10.0a
Control	0.6a	0.8a	1.4a	9.6a
Limed	1.8b	1.2a	1.4a	8.0a

Mg (meq L^{-1})

Treatments	Horizons Ap	Bnt	BC	Cca
Ripped on shank	1.6c	2.0b	2.4bc	8.9ab
Ripped intershank	1.4bc	1.7ab	2.5c	11.5b
Ripped + Lime on shank	1.6c	1.2ab	0.9a	5.9ab
Ripped + Lime intershank	1.5c	0.9ab	0.9ab	5.4a
Control	0.4a	0.8a	0.8a	7.1ab
Limed	1.1b	1.2ab	1.0ab	5.4a

---

[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

but they were not significantly different from RLOS and RLIS treatments. Ca/TC ratios in the Ap showed proportionately more Ca in the ripped treatments as compared to the non-ripped treatments. Control had statistically lower Ca/TC ratios than all other treatments. Although there was a trend toward higher Ca/TC ratios in the ripped treatments, the non-ripped L treatment was not statistically lower than the ripped: ROS, RIS, or RLIS treatments.

SAR values in the Bnt showed very distinct statistical differences. The four ripped treatments had significantly lower SAR values than the two non-ripped treatments due to a trend toward lower Na and higher Ca in the ripped treatments . Mg/Ca and Ca/TC ratios in the Bnt showed similar trends to those found for SAR values; lower Mg/Ca and higher Ca/TC ratios were found in the ripped treatments as compared to the non-ripped treatments. The two non-ripped treatments had Mg/Ca ratios greater than 1.0 and Ca/TC ratios of less than 0.15. These ratios exceeded the limits for possible Ca deficiency in barley as defined by Carter *et al* (1979).

There was a trend toward lower SAR values for the four ripped treatments in the BC and Cca horizons as compared to the non-ripped treatments. Differences were not as clear cut between ripped and non-ripped treatments as was observed in the Bnt however. RLIS and RLOS treatments did not have significantly lower SAR values than ROS and RIS treatments in the BC and Cca horizons but they were significantly lower than C and L treatments . ROS and RIS treatments did not have significantly lower SAR values than the L treatment in the BC horizon, but they were significantly lower than the C treatment. ROS and RIS treatments were not significantly lower than L or C in the Cca horizon. Mg/Ca and Ca/TC ratios were not significantly different for any treatments in the BC or Cca horizons.

In this study Ca was available from two sources; it was elevated from depth by ripping, as $CaSO_4$ or $CaCO_3$, or it was externally applied as lime ($CaCO_3$). Ripping elevated more Ca into the Ap than was applied through the liming operation (Table 2). A negative aspect of the ripping treatment was the elevation of Na into the Ap but this was compensated by the amount of Ca concurrently elevated and hence SAR values were not affected. The lack of difference in SAR values in the Ap may be misleading due to the documented elevation of sodic clay through ripping which may have changed the proportionality constant relating ESP to SAR. This will be discussed further in sections dealing with surface soil structure.

As in the Ap there was a similar uplift of Ca in the Bnt, but a decrease in Na in the four ripped treatments as compared to the two non-ripped treatments. Although these changes were not statistically significant they produced significantly lower SAR values ($p \leq 5\%$) which denote improved soil physical properties. Similarly the low Ca and high Na status of the Bnt in the C and L treatments may induce Ca deficiency in crops. Under low moisture conditions Ca will precipitate more readily than Na, as $CaSO_4$ and $CaCO_3$, thus increasing the possibility of Ca deficiency (Carter *et al* 1979). In the L treatment surface applied lime did not appear to have penetrated into the Bnt.

The following contradictory trends account for the slightly lower SAR values observed for the four ripped treatments compared to the non-ripped treatments in the BC and Cca horizons (Table 1). In the ROS and RIS treatments soluble Na was approximately equal to the non-ripped treatments but soluble Ca and Mg were higher. In the RLOS and RLIS treatments soluble Na was lower but soluble Ca and Mg were approximately equal to non-ripped treatments. In the first case the lifting of Ca appeared responsible for lower SAR values while in the latter case the leaching of Na due to increased water infiltration may have been responsible. The slightly lower SAR values observed in the ripped+limed treatments in comparison to ripped alone were not due to increased Ca and therefore are not attributable to the lime application. Ripping and liming in combination did not improve soil structure over ripping alone. No differences were observed between on shank and intershank positions in either the ripped or ripped+limed treatments for soluble cation ratios. For ease of presentation the ROS and RIS treatments are combined as Ripped and RLOS and RLIS treatments are combined as Ripped+Lime, in a graph presenting SAR values versus depth (Figure 6.).

4.1.1.2 Soluble Anion Ratios: Alkalinity/Total Anions, SO_4/Total Anions

Anion ratios for the Ap horizon are depicted in Table 3. The ratio of alkalinity to total anions (Alk/TA) represents the fraction of the total soluble anions composed of CO_3^{2-}, HCO_3^- and OH^- as revealed by titration with H_2SO_4 to a pH of four. The fraction of sulfate to total anions (SO_4/TA) is also presented. The differences in anion ratios between treatments were non-significant, in any horizon other than the Ap.

In the Ap, the C treatment was significantly higher in percent sulfate and significantly lower in percent alkalinity than all other treatments. All of the ripped treatments were significantly higher in percent alkalinity and significantly lower in percent sulfate than the C and L treatments. The two ripped+limed treatments showed a trend toward higher percent alkalinity and lower percent sulfate than the two ripped treatments.

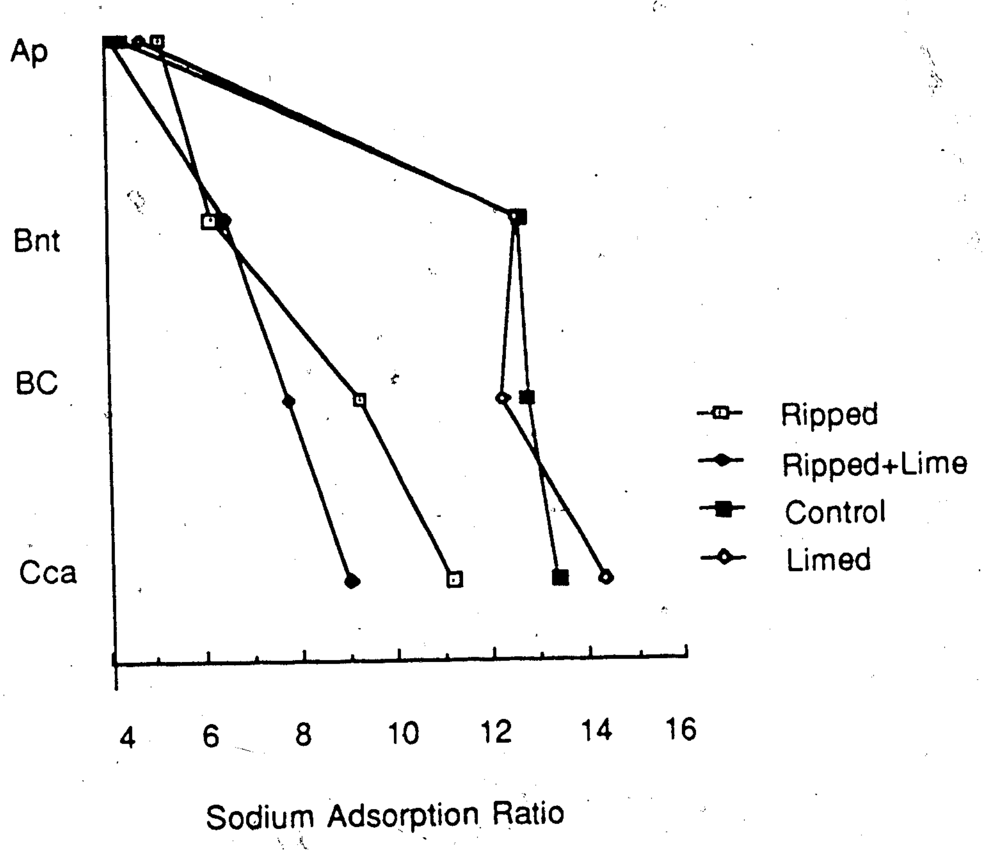


Figure 6. Sodium Adsorption Ratio versus Depth

Table 3. Multiple Means Comparisons[1] of Anion Ratios for Six Treatments and One Horizon.

Alk/TA[2]

Treatment	Ap Horizon
Control	.13a
Limed	.51b
Ripped intershank	.69c
Ripped on shank	.72cd
Ripped + Lime on shank	.79de
Ripped + Lime intershank	.82e

SO_4/TA[2]

Treatment	Ap Horizon
Control	.52d
Limed	.35c
Ripped intershank	.25b
Ripped on shank	.22ab
Ripped + Lime on shank	.16ab
Ripped + Lime intershank	.13a

---

[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

[2] Alkalinity (Alk), SO_4, and Total Anions (TA) are expressed in me L^{-1}.

The major anion in the unaltered Ap was sulfate. The lime application increased the carbonate and bicarbonate fraction but not to the degree experienced through ripping. As would be expected liming in combination with ripping gave the highest percentage of carbonate and bicarbonate in the Ap horizon. The implication of the elevation of salts from depth will be further discussed in the sections dealing with E.C. and pH.

4.1.1.3 pH

The level of hydronium ion activity as expressed by pH is reported for the six treatments and four depths (Table 4). Significant differences between treatments were observed in the Ap and Bnt horizons. In the Ap the pH of the unaltered C treatment was 5.7, this was significantly lower than the other treatments. The L treatment was significantly lower than the four ripped treatments. There was no significant difference between the four ripped treatments. These differences were mirrored in the amount of carbonate and bicarbonate in the saturation extracts of the Ap horizon (Table 5). Carbonate and bicarbonate values were higher in the ripped treatments as compared to the non-ripped treatments. In the Bnt the trend continued toward higher pH values in the ripped treatments as compared to the non-ripped treatments, although there was no significant difference between the L and RLOS treatments. The C and L treatments were not significantly different in the Bnt.

In the L treatment the pH of the Ap was raised significantly through the application of lime, but the pH was raised substantially more by the uplift of

Table 4. Multiple Means Comparisons[1] of pH values for Six Treatments and Four Horizons.

	pH			
	Horizons			
Treatment	Ap	Bnt	BC	Cca
Control	5.7a	7.7a	8.4a	8.4a
Limed	7.0b	7.9ab	8.3a	8.5a
Ripped + Lime on shank	8.2c	8.1bc	8.4a	8.4a
Ripped intershank	8.3c	8.2c	8.5a	8.4a
Ripped + Lime intershank	8.3c	8.2c	8.4a	8.2a
Ripped on shank	8.4c	8.2c	8.5a	8.2a

[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

Table 5. Multiple Means Comparisons[1] of Soluble Carbonate and Bicarbonate (me L^{-1}) for Six Treatments and One Horizon.

CO_3^{2-} (meL^{-1})

Treatment	Ap Horizon
Control	0.0a
Limed	0.2a
Ripped intershank	1.2b
Ripped + Lime on shank	1.3bc
Ripped on shank	1.3bc
Ripped + Lime intershank	1.5c

HCO_3^- ($me L^{-1}$)

Treatment	Ap Horizon
Control	0.5a
Limed	3.7b
Ripped intershank	6.5c
Ripped + Lime on shank	6.9c
Ripped on shank	6.6c
Ripped + Lime intershank	6.6c

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[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

carbonate and bicarbonate salts through ripping. As pH rises lime becomes less soluble; at pH levels found in the ripped treatments (> 8.2) little applied lime would be expected to enter soil solution (Nakayama 1969). This could account for the lack of observed differences between the ripped+limed and ripped treatments in regard to the influence of surface liming.

The pH of the C treatment was considered low and may have been deleterious to microbial and plant growth. The pH of the L treatment would be considered optimal. The pH of the ripped treatments was too high to be considered optimal; some plant nutrients may have been precipitated in less soluble forms and there may have been a negative effect on some enzyme systems within the plant (Olsen and Watanabe 1959; Bohn *et al* 1979).

In the four ripped treatments carbonate salts from depth increased the pH in the Bnt relative to the non-ripped treatments. For any practical purpose pH differences between treatments in the Bnt were minor. Surface applied lime did not penetrate into the Bnt and thus the difference in pH between the C and L treatment was non-significant. No differences in pH values were found between on shank and intershank positions. For ease of presentation and interpretation of pH values for the Ap horizon ROS and RIS treatments are combined as the Ripped treatment, and RLOS and RLIS treatments are combined as the Ripped+Lime treatment (Figure 7).

4.1.1.4 Electrical Conductivity

Electrical conductivity is reported in milliSiemens per cm (mS cm^{-1}) for the six treatments and four depths (Table 6). Differences between treatments

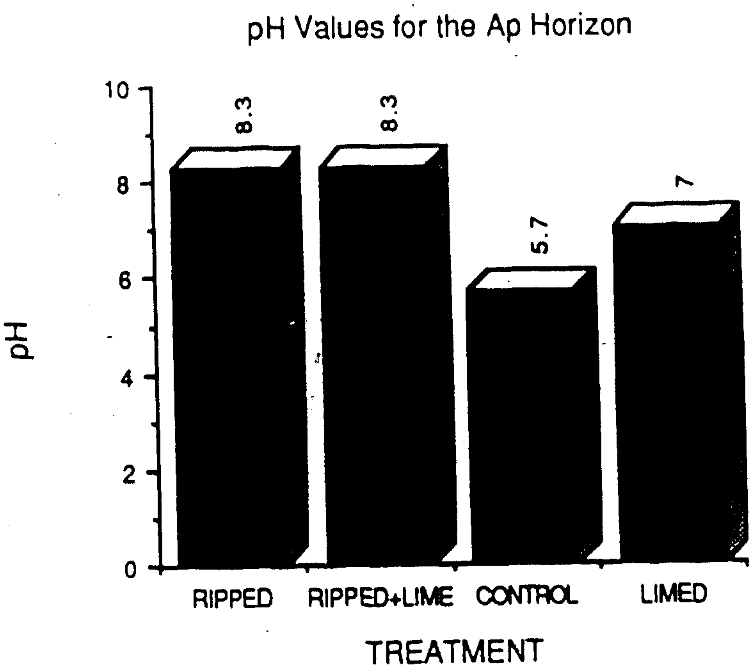

Figure 7. pH Values of the Ap Horizon.

Table 6 Multiple Means Comparisons[1] of Electrical Conductivity (mS cm^{-1}) for Six Treatments and Four Horizons.

E.C. (mS cm^{-1})

	Horizons			
Treatment	Ap	Bnt	BC	Cca
Control	0.50a	1.14a	1.35a	4.04a
Limed	0.74b	1.38a	1.35a	3.93a
Ripped + Lime intershank	0.80b	0.80a	1.05a	2.55a
Ripped + Lime on shank	0.86bc	1.01a	0.94a	2.73a
Ripped intershank	0.95c	1.04a	1.80a	5.01a
Ripped on shank	0.98c	1.19a	1.70a	4.14a

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[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

were significant only in the Ap horizon; the C treatment had a significantly lower E.C. than all other treatments. There was a trend toward higher E.C. in the ripped treatments as compared to the non-ripped although the differences between L, RLIS and RLOS were non-significant. The RIS and ROS treatments were significantly higher than L and RLIS treatments but not the RLOS treatment.

The application of lime significantly increased the E.C. in the Ap of the L treatment, over C, as did ripping. It has been suggested that resalinization of the soil surface may occur following ripping through the upward movement of capillary water bearing soluble salts (Riddell 1986). If this mechanism was responsible for observed increases in the ripped treatments the proportion of cation suite composed of Na and Mg should have increased, as their salts are more soluble than those containing Ca. This was not observed, Ca/TC ratios increased and Mg/Ca ratios decreased following ripping. The mechanical uplift of salts through ripping was responsible for the the higher E.C. observed in the Ap. The increase in E.C. was not sufficient to decrease plant growth in even the most sensitive crop plants (United States Salinity Laboratory Staff 1954). Electrical conductivities deleterious to plant growth were only observed in the Cca horizon.

The ripped+lime treatments had a lower E.C. in the Ap as compared to the other ripped treatments although the trend was not statistically consistent. A lower E.C. for ripped+lime treatments was observed throughout the lower horizons, differences were not statistically significant however. This mirrors the trend to lower SAR values throughout the soil profile for RLOS and RLIS treatments in comparison to ROS and RIS treatments (Table 1). While a trend exists in the ripped+lime treatments toward a less saline soil profile with slightly improved soil physical properties the reasons for this are not clear.

4.1.2 Physical Analyses

4.1.2.1 Particle Size Distribution, Sand, Clay

Percent sand and clay are shown for six treatments in the Ap and three treatments in the Bnt and BC horizons (Table 7). In the Ap the ripped treatments were significantly higher in clay than the non-ripped treatments. Similarly non-ripped treatments were generally higher in sand than the ripped treatments although the difference was non-significant between the L and RIS treatments. The differences between treatments for percent sand and clay in the Bnt and BC horizons were non-significant.

Subsurface material was uplifted by ripping, thus diluting the eluvial Ap horizon with clay minerals. It is highly likely that ripping caused soil from the Ap to fall into the lower horizons. This may be reflected in the trend toward lower clay and higher sand in the Bnt and BC of the ripped treatments as compared to the non-ripped; differences were not significant however.

4.1.2.2 Moisture Retention Analysis

Percent moisture retention at wilting point (-1500 kPa) and field capacity (-33 kPa), as well as percent moisture between these values (water holding capacity or available water), are shown in Table 8 for the six

Table 7 Multiple Means Comparisons[1] of Percent Clay and Sand for Six Treatments and Three Horizons.

Percent Clay

Treatment	Ap	Bnt	BC
Control	15.5a	31.7a	32.8a
Limed	18.3a		
Ripped on shank	26.5b	30.7a	31.0a
Ripped intershank	26.9b	28.5a	31.9a
Ripped + Lime on shank	28.0b		
Ripped + Lime intershank	28.0b		

Percent Sand

Treatment	Ap	Bnt	BC
Control	48.0c	35.7a	31.5a
Limed	45.8bc		
Ripped on shank	41.7a	38.1a	36.6a
Ripped intershank	42.6ab	38.4a	32.7a
Ripped + Lime on shank	39.4a		
Ripped + Lime intershank	40.4a		

[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

Table 8 Multiple Means Comparisons[1] of Percent Moisture Retention (at -1500 kPa and -33 kPa) and Water Holding Capacity for Six Treatments and Four Horizons.

% Moisture Retention at -1500 kPa

	Horizons			
Treatment	Ap[2]	Bnt[3]	BC[3]	Cca[3]
Control	8.9a	15.9a	17.0a	13.1a
Limed	10.0a	14.8a	14.5a	13.8a
Ripped + Lime on shank	13.8b	16.2a	17.3a	14.5a
Ripped on shank	14.0b	17.9a	17.7a	17.8a
Ripped intershank	14.1b	16.3a	17.5a	14.9a
Ripped+Lime intershank	14.1b	17.5a	17.7a	14.1a

% Moisture Retention at -33 kPa

	Horizons			
Treatment	Ap[2]	Bnt[3]	BC[3]	Cca[3]
Control	23.6a	32.8a	36.1a	30.5a
Limed	24.3a	30.6a	33.3a	30.7a
Ripped + Lime on shank	29.0c	33.5a	36.7a	33.3a
Ripped on shank	27.0b	34.6a	36.0a	31.7a
Ripped intershank	27.1b	32.9a	37.0a	29.9a
Ripped+Lime intershank	29.2c	36.2a	37.3a	31.6a

Water Holding Capacity (% Available Water)

	Horizons			
Treatment	Ap[2]	Bnt[3]	BC[3]	Cca[3]
Control	14.7b	16.8a	19.1a	17.4a
Limed	14.2b	15.8a	18.7a	16.7a
Ripped + Lime on shank	15.2b	17.3a	19.4a	18.9a
Ripped on shank	13.0a	16.8a	18.3a	13.9a
Ripped intershank	13.0a	16.5a	19.5a	15.0a
Ripped+Lime intershank	15.1b	18.7a	19.6a	17.5a

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[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

[2] Values reported are means of ten samples.

[3] Values reported are means of five samples.

treatments and four horizons. Values for the Ap are based on ten samples per treatment, as has been the norm throughout this study; values for the lower horizons are based on five samples per treatment.

In the Ap, the ripped treatments had significantly higher moisture retention at wilting point (W.P.), and at field capacity (F.C.) than C and L. The ROS and RIS treatments had significantly lower moisture retention at F.C. than the RLOS and RLIS treatments and significantly lower water holding capacity as compared to all other treatments in the Ap. Differences were non-significant between all treatment comparisons in the three lower horizons, therefore the following discussion pertains to the Ap only.

The amount of water retained under matric suction is dependant on the percentage of organic material, soil structure and soil texture (Hillel 1982). In this study moisture retention at W.P. and F.C. was positively correlated to percent clay (correlation coefficient r = .93 and .85 respectively) and negatively correlated to percent sand (-.90 and -.91 respectively). Ripping uplifted clay into the Ap and this accounted for increased moisture retention at both F.C. and W.P. in the ripped treatments. The cause of the significantly higher moisture retention at F.C. for ripped+limed treatments, as compared to ripping alone is unknown. The RLOS and RLIS treatments had higher clay and lower sand contents in the Ap than all other treatments, although they were not significantly different from ROS and RIS treatments (Table 7). This may account for the observed differences in moisture retention between ripped+limed and ripped treatments. Alternately the ripped treatments had higher E.C. values in the Ap than the ripped+limed treatment (Table 6); the increase in flocculation due to higher electrolyte concentration may account for the lower moisture retention at F.C. Available water was significantly decreased by ripping in the ROS and RIS treatments, but increased although not significantly in the RLIS and RLOS treatments. Differences in available water between ripped+limed and ripped treatments were due to the higher water holding capacity at -33 kPa for the ripped+limed treatments. Whether ripping altered water holding capacity in the Ap is unclear and cannot be answered by this study.

4.1.2.3 Bulk Density

Bulk densities for six treatments and two horizons as measured by the core method, plus two treatments to a depth of 40 cm as measured by the excavation method, are presented (Table 9). Bulk densities in the Bnt as measured by the core method were obtained in the summer of 1984. Differences between any two treatments were non-significant. Bulk densities of the Ap were determined by the core method in the fall of 1985. There was a trend toward lower bulk density in the non-ripped treatments compared to the ripped treatments, this may reflect a tendency toward greater potential compaction and poorer structure in the ripped treatments due to an uplift of sodic clay. The RIS treatment was significantly lower than all other ripped treatments. The cause for this is unknown but it does not appear to be related to the treatment. Samples in the Ap were taken following harvest, the difference may be due to uneven compaction from wheeled traffic during the harvest operation. As differences between on shank and intershank positions in the Bnt were non-significant, no attempt was made to differentiate between these treatments when bulk density was measured by the excavation method in the fall of 1985. The difference in total bulk density to a depth of 40 cm, between the Ripped and Control treatments, was non-significant. Bulk density at depth was not significantly altered by ripping.

Table 9. Multiple Means Comparisons[1] of Bulk Density for Six Treatments and Two Depths (Core method) and Two Treatments to a 40 cm Depth (Excavation method).

Bulk Density gms cm^{-3} (Core method)

	-------Horizons----------	
Treatment	Ap[2]	Bnt[2]
Ripped on shank	1.36a	1.42a
Ripped intershank	1.28b	1.47a
Ripped + Lime on shank	1.37a	1.45a
Ripped + Lime intershank	1.36a	1.50a
Control	1.27b	1.49a
Limed	1.31ab	1.54a

Bulk Density gms cm^{-3} (Excavation method)

Treatment	0-40 cm depth [3]
Ripped,	1.44a
Control	1.46a

[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

2. Values reported are means of ten samples.

3. Values reported are means of five samples.

4.1.2.4 Modulus of Rupture

Soil strength of the Ap horizon as measured by modulus of rupture is presented for four treatments (Table 10). As no significant physicochemical differences, which could be related to treatments, were found between on shank and intershank positions modulus of rupture was determined for the on shank treatments only.

The two ripped treatments, ROS and RLOS, had a significantly higher breaking strength than the two non-ripped treatments, O and L. Within the ripped treatments the RLOS treatment had a significantly higher breaking strength than the ROS treatment. Differences between the two non-ripped treatments were not significant.

Modulus of rupture is positively correlated to percent clay and soluble Na and negatively correlated to percent sand (r=.65, .53 and -.58 respectively). The correlation to SAR was not significant (r=.19); the lack of correlation may be due to the uplift of sodic clay in the ripped treatments which could significantly alter the proportionality constant relating SAR and ESP values (Harron 1979). Ibanga *et al* (1980) found modulus of rupture to be directly related to clay content although the relationship was curvilinear. In the present study the relationship between percent clay and modulus of rupture appears to be non linear, a higher correlation coefficient (r=.73) was observed when the data was fitted to a logarithmic equation (Figure 8).

Ripping has elevated sodic clay into the Ap horizon, increasing soil strength and negatively influencing soil tilth. The reason for the difference

Table 10 Multiple Means Comparisons[1] of Modulus of Rupture (kPa) with Range and Standard Deviation for four Treatments in the Ap horizon.

	Modulus of Rupture (kPa)		
Treatment	Mean[2]	Range	Standard Deviation
Control	20a	13-48	11
Limed	23a	14-41	10
Ripped on shank	49b	25-90	23
Ripped + Lime on shank	83c	39-157	35

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[1] Means within columns, not followed by the same letter(s) are significantly different according to the least significant difference test $p \leq 5\%$.

[2] Values reported are means of ten samples, five replicates per sample.

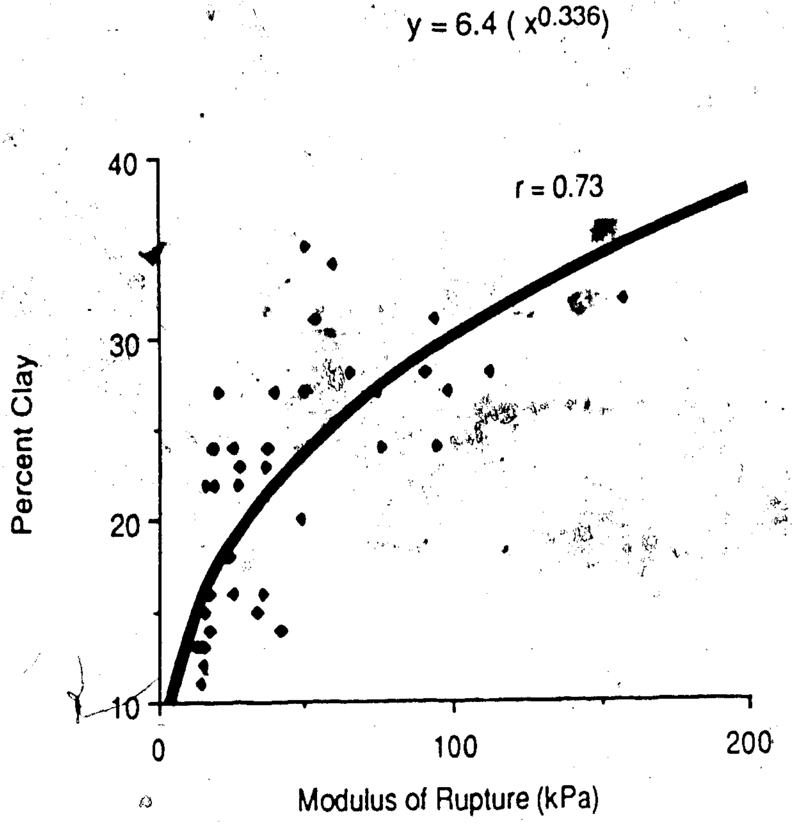

Figure 8 Modulus of Rupture versus Clay Content

between ROS and RLOS treatments is unknown. A possible explanation is the higher clay content in the RLOS treatment in combination with a lower E.C. As the electrolyte concentration decreases a sodic soil is increasingly dispersed and the strength of the crust on drying is increased (Hillel 1982). The range and standard deviation of breaking strength values were higher in the ripped treatments, as compared to the non-ripped treatments, denoting a less homogeneous soil surface. If two extreme outlying values, of 112 and 157 kPa, were discarded from the RLOS treatment differences between the RLOS and ROS treatments were no longer statistically significant.

Richards (1953) reported restricted bean emergence at breaking strength values greater than 27.3 kPa. Allison (1956) found the emergence of corn to be inhibited at crust strengths greater than 120 kPa. According to these threshold values, ripping has increased soil strength to a point where the emergence of sensitive crops may be affected. Buckland (1983) found deep plowing significantly increased modulus of rupture, at three predominantly Solonetzic sites, from 29.2 kPa to 217.7 kPa; the soils examined were located relatively close to the present study site and may be considered comparable. Although surface tilth has been negatively affected by deep ripping it has not been influenced to the degree experienced through deep plowing at similar sites in east-central Alberta .

4.1.3 Summary - Chemical and Physical Analyses

Only one physical parameter measured showed a significant difference between on shank and intershank positions. This difference was observed in core bulk density samples from the Ap horizon for RIS and ROS treatments and appears to be related to wheeled traffic during fall harvest operations, and not treatment effects. The lack of difference between on shank and intershank positions denotes homogeneous shattering at this site. Riddell (1986) reported differences between on shank and intershank positions were non-significant when a narrow (61 cm) spacing was used, although significant differences were reported when shank spacing was doubled (122 cm).

Ripping has elevated materials from depth; altered physicochemical properties were both positive and negative. SAR values in the Bnt horizon were significantly lower for ripped treatments as compared to non-ripped treatments, this denoted improved soil physical properties in the Bnt due to ripping. The pH of the Ap has been significantly increased by liming and by ripping. In this study ripping was more effective in raising the surface pH than was liming. The uplift of material from depth had a negative effect on surface tilth and may result in reduced crop emergence. Liming in conjunction with ripping does not appear to have improved soil physicochemical properties over ripping alone.

4.2 Moisture Analyses - May 1985 - April 1986

Gravimetric moisture content was determined for the six treatments at three depth increments and ten dates between May, 1985 and April, 1986. A statistical analysis of moisture data was performed on a computer using the Statistical Package for the Social Sciences (version 2.1). If interaction terms were significant valid error terms for the treatment effect were calculated by adding the sums of squares for relevant interaction terms and dividing by the sum of their degrees of freedom (Goulden 1952; Zalik 1981). Where f values were significant for treatment effects multiple means comparisons were obtained through the least significant difference test at a probability of ≤ 5%. A three way analysis of variance (treatments X depths X dates) showed highly significant differences between treatments. A two way analysis of variance for each depth (treatments X dates) showed highly significant differences between treatments in the 0-13 cm and 26-38 cm depth increments. Multiple means comparisons between treatments for the total depth, and each depth increment, are presented in Table 11.

For the total depth, 0-38 cm, the ripped treatments had significantly higher gravimetric moisture contents than the non-ripped treatments (Table 11). This pattern was also reflected in the 0-13 cm and the 26-38 cm depth increments. In the 0-13 cm depth increment there was an additional significant difference between the non-ripped, C and L treatments. The main differences between treatments were due to ripping. For the following discussion ROS, RIS, RLOS and RLIS treatments will be combined under the heading "Ripped treatment". The C and L treatments will be combined as the "Non-ripped treatment" except for the discussion of the 0-13 cm depth where

Table 11. Multiple Means Comparisons[1] of % Gravimetric Moisture, for six treatments at: 0-38 cm, 0-13 cm, 13-26 cm and 26-38 cm depth increments, and ten sampling dates, May 1985 - April 1986.

	% Gravimetric Moisture			
	Total Depth	--------------Depth Increments-------------		
Treatment	0-38 cm**	0-13 cm**	13-26 cm^{ns}	26-38 cm**
Control	15.4a	13.8a	17.5a	14.9a
Limed	15.9a	15.2b	17.4a	15.1a
Ripped on shank	17.8b	18.0c	18.3a	17.1b
Ripped intershank	17.9b	18.1c	18.6a	17.1b
Ripped+Lime intershank	18.0b	18.4c	18.7a	17.0b
Ripped+Lime on shank	18.1b	18.4c	18.7a	17.1b

[1] Means within columns not followed by the same letter(s) are significantly different according to the least significant difference test at $p \leq 5\%$.

** f value for differences between treatments is highly significant, $p \leq 1$ %.
^{ns} f value for differences between treatments is not significant.

they were significantly different. Plant available water, in mm, was calculated using average bulk densities of the surface and subsurface horizons, and average wilting point values for each of the six treatments for surface and subsurface depths.

A gravimetric moisture by time analysis for the total sampling depth (0-38 cm) and all sampling dates is presented in Figure 9. A one way analysis of variance for treatments was done at each sampling date, and the significance level of the f value is noted on the graph. The "Ripped treatment" had a higher moisture content than the "Non-Ripped treatment" at all sampling dates. This difference was highly significant in the early spring of 1985 and 1986 but declined to non-significant levels in the mid summer and late fall of 1985. This trend suggests that late fall and winter precipitation was more effectively stored in the "Ripped treatment". The additional stored moisture was then used for plant growth throughout the summer. As the moisture content of the "Ripped treatment" does not reach the level of the "Non-Ripped treatment" at any time, it appears that the extra stored moisture was not totally plant available.

Spring-summer moisture time analysis for the 0-13 cm depth increment is presented in Figure 10. Parameters shown are percent gravimetric moisture, available water (mm) and precipitation. The "Ripped treatment" was consistently higher in percent gravimetric moisture than the two non-ripped treatments, the L treatment was consistently higher than the C treatment. The difference between the "Ripped" and non-ripped treatments was due to the significantly higher clay content in the Ap of the ripped treatments. The increased clay content resulted in a stronger adsorption of water and a higher gravimetric moisture content at wilting point. An analysis of available water

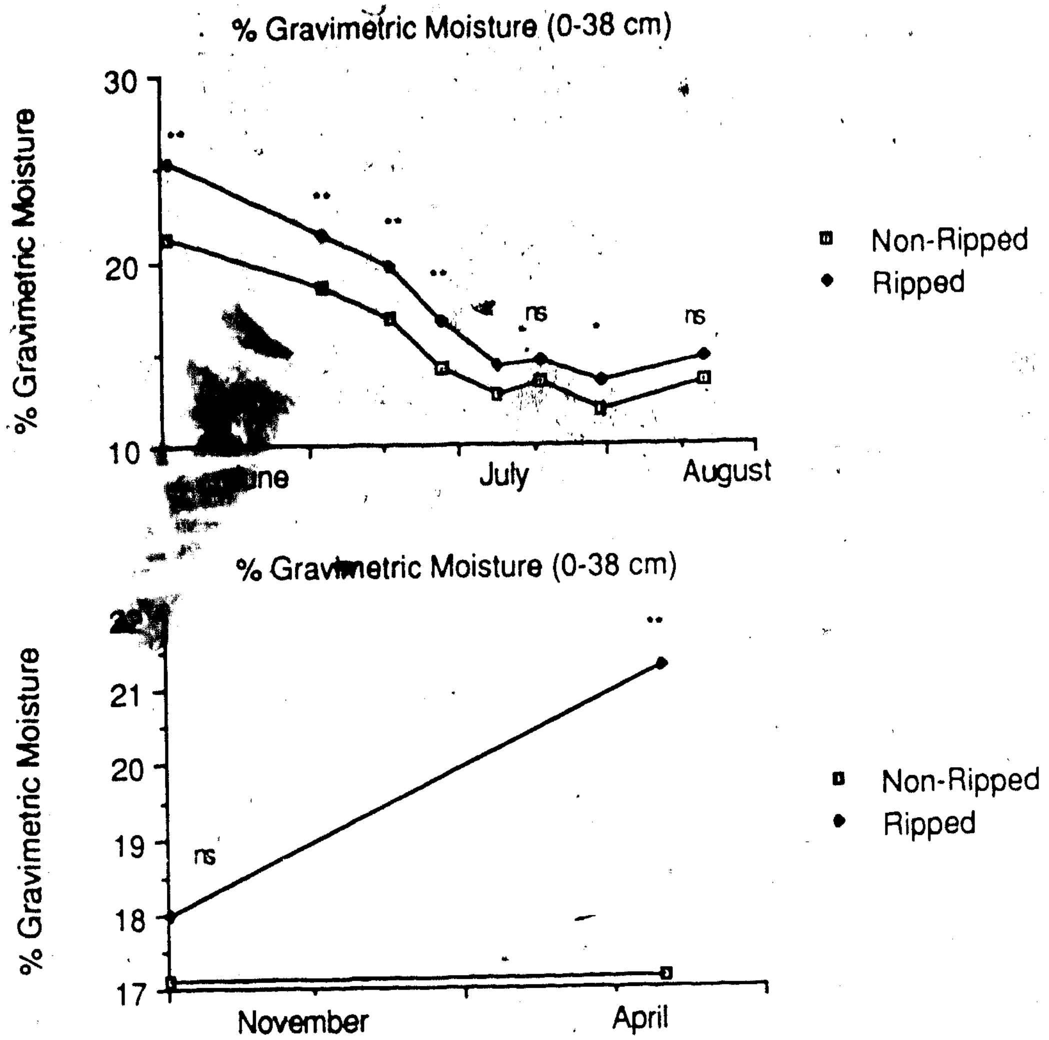

Figure 9. Percent Gravimetric Moisture, Ripped[1] versus Non-Ripped[2] treatments, 0-38 cm depth, for Spring - Summer 1985, and Fall - Spring 1985-1986.

[1] Ripped = A composite of Ripped on shank, Ripped intershank, Ripped+Lime on shank and Ripped+Lime intershank treatments.

[2] Non-Ripped = A composite of Control and Limed treatments.

** f value for differences between treatments is highly significant, $p \leq 1$ %.

* f value for differences between treatments is significant, $p \leq 5$ %.

ns f value for differences between treatments is not significant.

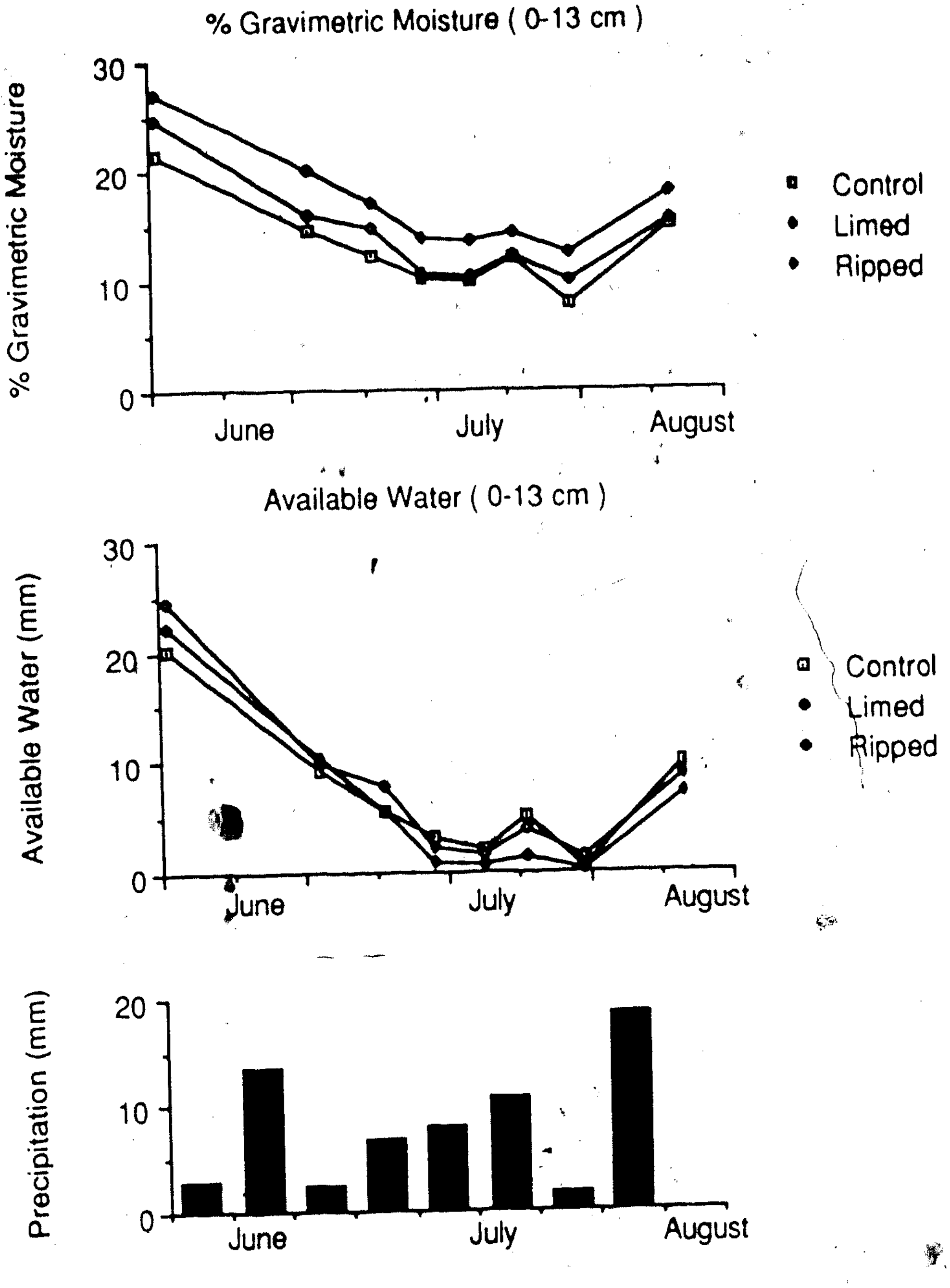

Figure 10. Moisture Time Analyses, Spring - Summer 1986, 0-13 cm depth, for Control Limed and Ripped[1] treatments with daily precipitation data

[1] Ripped = A composite of Ripped on shank, Ripped intershank, Ripped+Lime on shank and Ripped+Lime intershank treatments.

showed little overall difference between "Ripped" and non-ripped treatments over the spring-summer of 1985. Available water was lower in the "Ripped treatment" in mid summer due to improved crop growth and the resulting increase in moisture demand.

The reasons for the difference between L and C treatments are not as clear. The L treatment had a higher clay content and a higher wilting point than the C treatment although they were not significantly different. These differences were included in the calculation for the determination of available water. The time moisture graph for available water showed higher values in the L treatment early in the growing season but lower values in mid summer. The addition of lime may have improved soil structure and thus slightly increased moisture penetration in the top 13 cm. Enhanced crop growth, due to improved pH conditions, may have increased the demand for this water later in the growing season.

Precipitation was extremely sparse throughout the growing season. Total precipitation from May 30 to August 11 was 67.5 mm; approximately one third of that amount came in one precipitation event on August 8. The influence of precipitation on soil moisture was more noticeable in the non-ripped treatments because the heavier crop growth in the "Ripped treatment" utilized precipitation more quickly.

Spring-summer moisture time analysis for the 13-26 cm and 26-38 cm depth increments are presented in Figure 11. No significant differences between treatments for bulk densities, clay content or wilting point values were found below the Ap horizon. For this reason only data pertaining to available water are presented, as available water is directly related to percent gravimetric moisture in this case.

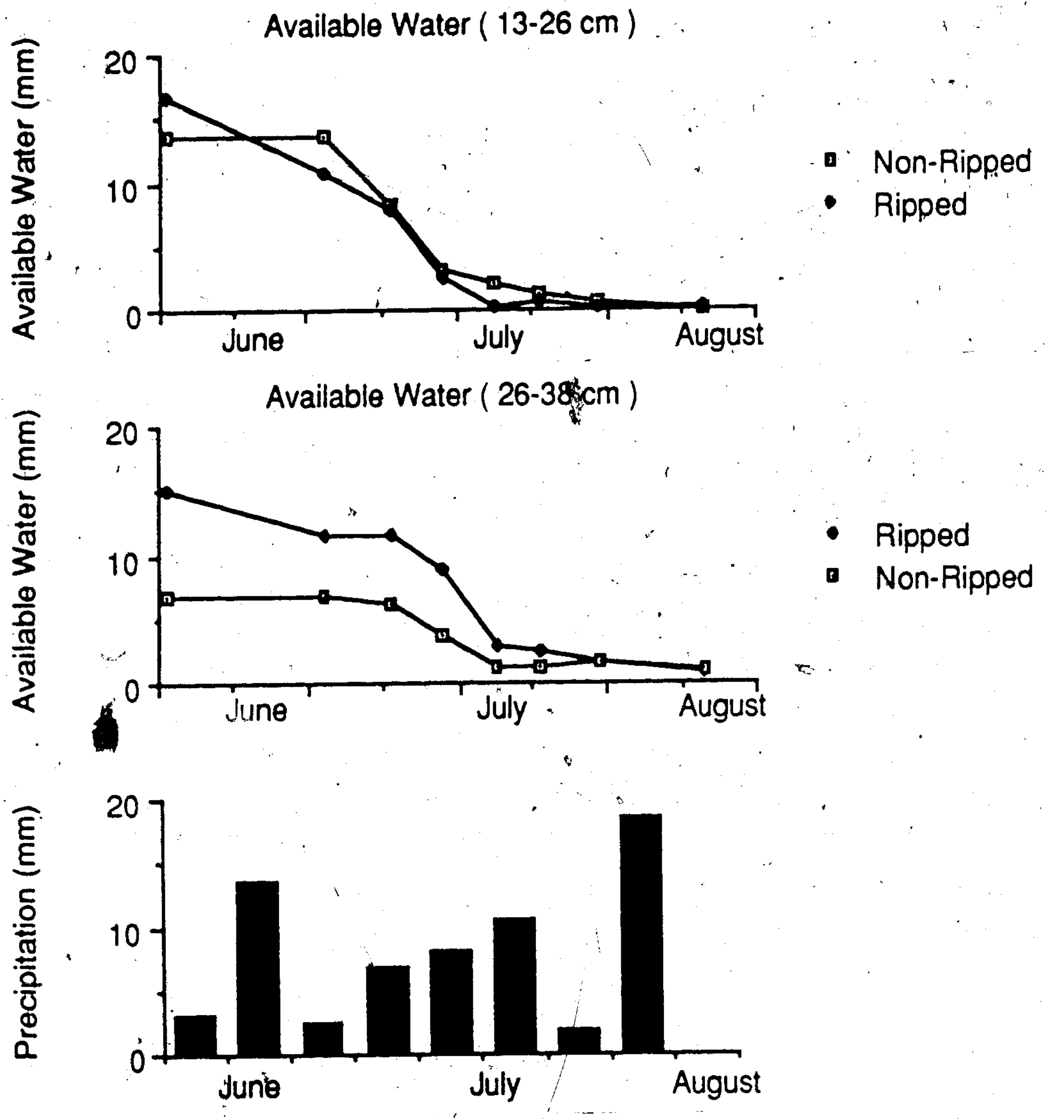

Figure 11. Moisture time Analyses, Spring - Summer 1985 , for two depth increments, Ripped[1] versus Non-Ripped[2] treatments.

[1] Ripped = A composite of Ripped on shank, Ripped intershank, Ripped+Lime on shank and Ripped+Lime intershank treatments.

[2] Non-Ripped = A composite of Control and Limed treatments.

The 13-26 cm depth roughly corresponds to the Bnt and upper BC horizons. Differences in percent gravimetric moisture were non-significant, between treatments, in this depth increment as reflected in the graph of available water. The "Ripped treatment" had slightly higher available water in the early spring and this water appears to be released more rapidly than in the "Non-Ripped treatment". Ripping has shattered the dense Bnt horizon and improved structure through the elevation of Ca salts and the downward leaching of Na. This may encourage quick root penetration and increased moisture utilization in the early growing season.

The 26-38 cm depth roughly corresponds to the lower BC and upper Cca horizons. There was substantially more available water in the "Ripped treatment" at the start of the growing season but by late July there was no difference between treatments. The "Ripped treatment" showed an earlier, quicker release of available water. The shattering of the slowly permeable Bnt horizon through ripping has improved infiltration of fall and winter precipitation and increased stored moisture at depth. Moisture removal by the crop was more rapid in the "Ripped treatment" presumably due to faster root penetration at depth. There was no noticeable effect of precipitation on either treatment in the 13-26 cm, or 26-38 cm depth increments.

Fall(1985) - Spring(1986) time moisture analysis for the three depth increments are presented in Figure 12. In the "Ripped treatment" there was an increase in available water at all depths from the fall to spring sampling dates but there was no such increase in the "Non-Ripped treatment". In the spring of 1986 as in the spring of 1985 the 26-38 cm depth increment showed the greatest difference in available water between "Ripped" and "Non-Ripped"

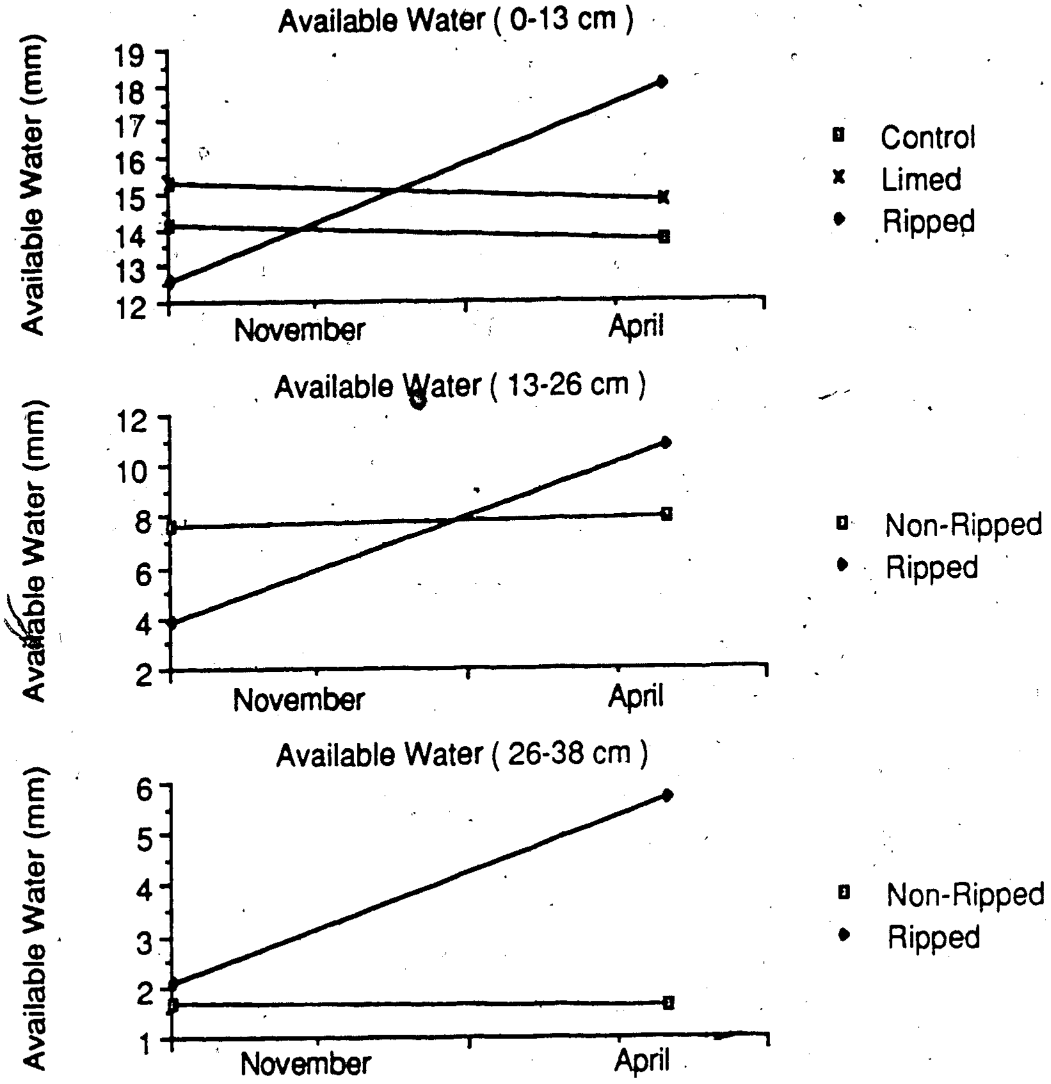

Figure 12. Moisture time Analyses, Fall (1985) - Spring (1986), for three depth increments, Ripped[1] Versus Non-Ripped[2] treatments.

[1] Ripped = A composite of Ripped on shank, Ripped intershank, Ripped+Lime on shank and Ripped+Lime intershank treatments.

[2] Non-Ripped = A composite of Control and Limed treatments.

treatments.

The reason for the difference in available water between "Ripped" and non-ripped treatments in the 0-13 cm depth increment in the spring of 1986 is unknown. It may be due to thicker higher stubble in the "Ripped treatment" as a result of improved crop growth in 1985. Snow entrapment may have been increased, thus increasing stored moisture. Sampling in 1986 was done before spring planting operations had disturbed and dried the soil surface, whereas sampling in the spring of 1985 was done after seeding operations. This may account for the differences observed in the amount of available water in the 0-13 cm depth increment between the two years.

4.2.1 Summary

Riddell (1986) found significant moisture differences between on shank and intershank positions when wide (122 cm) shank spacings were used. Significant moisture differences did not occur between on shank and intershank locations in this study where narrow (61 cm) shank spacings were used. Ripping on a 61 cm shank spacing appears to have effectively shattered the Bnt in the intershank as well as the on shank zone.

The differences detected in percent gravimetric moisture between "Ripped" and "Non-Ripped" treatments were due to two factors. In the 0-13 cm depth increment, increased gravimetric moisture in the "Ripped treatment" was the result of increased moisture retention due to the elevation of clay during the ripping operation. In the 26-38 cm deoth the increased moisture in the "Ripped treatment" was due to enhanced moisture infiltration as a result of the disruption of the slowly permeable Bnt horizon. Ripping has increased the depth of potential moisture storage.

Moisture samples were taken to the approximate depth of ripping (40 cm); roots penetrated to at least twice that depth as will be discussed in a later section. It is probable that the trend toward increased moisture storage in the 26-38 cm depth of the "Ripped treatment" extended into the lower depths (>38 cm depth). In years of drought, such as 1985, the observed improved crop growth on ripped plots in comparison to non-ripped plots, may be primarily due to increased penetration and storage, at depth, of fall and winter precipitation.

4.3 Crop, Root, Tissue Analyses

4.3.1 Crop Yields

Alberta Agriculture has monitored crop yields, in the Ripped, Ripped+Lime, Limed and Control plots, since 1981. The plots have been continually cropped to wheat. Grain and straw yields were compared, for each year, through a one way analysis of variance. The f values for treatment effects were significant in all years monitored, multiple means comparisons are presented in Table 12. A two way analysis of variance (treatments X years) also showed significant differences between treatments for both grain and straw yields; a bar graph showing multiple means comparisons, between treatments, for the 1982-1985 period is presented in Figure 13.

Since 1982 the two ripped treatments have continually exceeded the two non-ripped treatments in both grain and straw yields. In 1983 the Ripped+Lime treatment had significantly higher grain yields than the Ripped treatment, this trend was reversed in 1985; the reasons for this are unknown.

Table 12 Multiple Means Comparisons[1] of Grain and Straw Yields, for Four Treatments and Four Years.

Grain Yields t ha^{-1}

	Year			
Treatment	1982	1983	1984	1985
Control	2.1a	0.9a	0.9a	1.1a
Limed	2.4b	1.1a	1.1ab	1.4a
Ripped	3.0c	1.4b	1.7c	2.7c
Ripped+Lime	3.0c	1.8c	1.4bc	2.1b

Straw Yields t ha^{-1}

	Year			
Treatment	1982	1983	1984	1985
Control	2.8a	2.3a	1.2a	1.2a
Limed	2.9a	2.8ab	1.9b	1.7a
Ripped	3.9b	3.2bc	2.1bc	2.6b
Ripped+Lime	3.9b	3.7c	2.3c	2.2b

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[1] Means within columns not followed by the same letter(s) are significantly different according to the least significant difference test at $p \leq 5\%$.

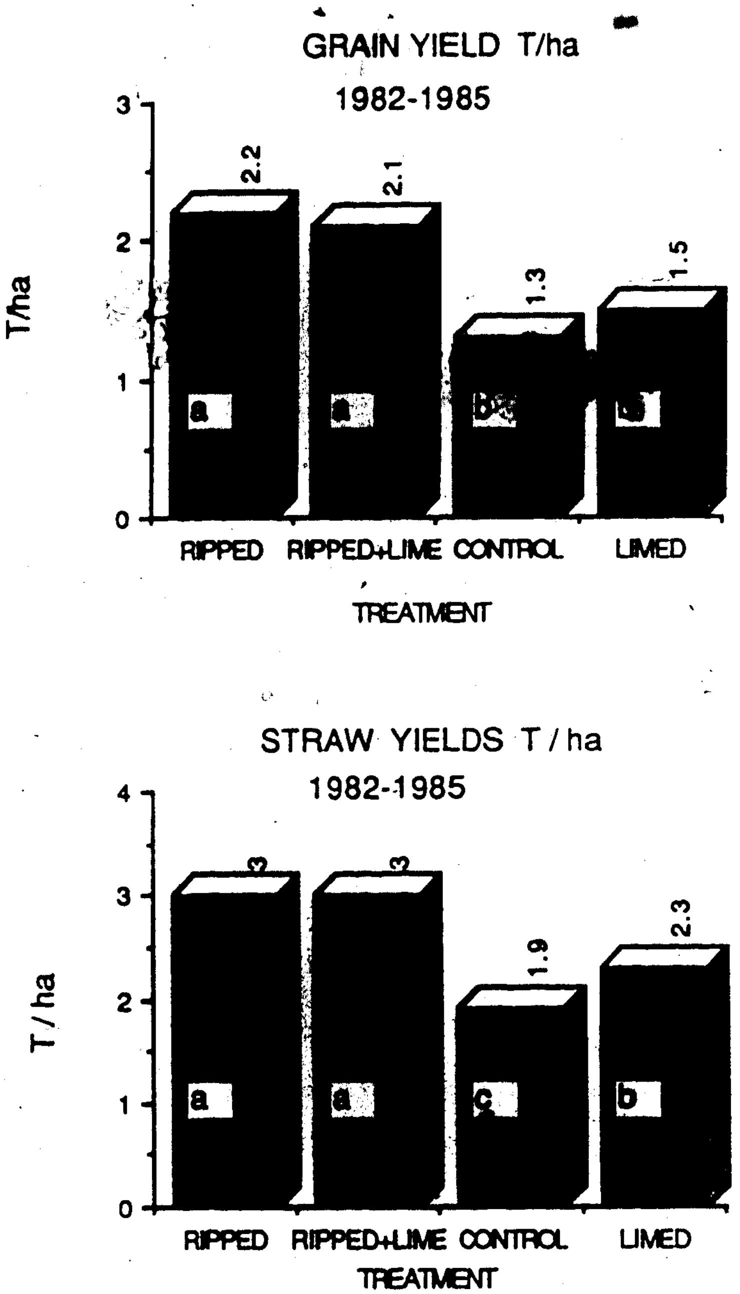

Figure 13 Grain and Straw Yields[1] for Four Treatments, 1981-1985.

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[1] Treatment means not containing the same letter(s) are significantly different according to the least significant difference test at $p \leq 5\%$.

Differences in straw yields between Ripped and Ripped+Lime treatments were not significant at any time. In 1982 grain yields were significantly higher in the Limed treatment than in the Control; this trend was also observed in straw yields for 1984.

The overall yield analysis (Figure 13) showed no significant differences between Ripped and Ripped+Lime treatments, for grain or straw yields. The two ripped treatments were significantly higher in both grain and straw yields than the two non-ripped treatments. There was no significant difference in grain yield between Control and Limed treatments, but the Limed treatment had significantly higher straw yields. The addition of lime appears to have improved crop growth marginally. For the total four year period liming increased grain yields by 0.2 t ha^{-1}, ripping+liming by 0.8 t ha^{-1} and ripping alone by 0.9 t ha^{-1}. Ripping was responsible for the largest increase in yields, the addition of lime in combination with ripping had no additional beneficial influence on crop growth for the years monitored.

4.3.2 Root Yields

Root as well as water penetration are restricted by the dense slowly permeable Bnt horizon (Cairns 1978). In this study paired soil cores were taken from a "Ripped" (Ripped+Lime) and a "Non-Ripped" (Limed) treatment. Cores were taken to a total 76 cm depth and then split into six equal segments. Paired T-tests were used to compare total root mass and root mass in each depth segment.

Differences between treatments for the total 0-76 cm depth were non-significant. There were significant differences between treatments in the 13-25, 25-38 and 38-51 cm depth increments. A plot of root mass versus depth is presented in Figure 14. In the 13-25 and 25-38 cm increments, corresponding to the Bnt, BC and upper Cca the rootmass in the "Non-Ripped" treatment was significantly higher than the root mass in the "Ripped" treatment. In the 38-51 cm depth increment the root mass of the "Ripped" treatment was significantly higher than the "Non-Ripped" treatment. This trend continued below the 51 cm depth although differences between treatments were not significant. If root mass was combined in the three depth increments below 38 cm differences between treatments were highly significant.

Sampling was done at the end of the growing season when further root growth would not be expected. Root mass was higher in the Bnt and BC of the "Non-Ripped" treatment as the downward movement of roots was restricted by the hard uniform subsurface. Root growth through the Bnt horizon occurs mostly along the edges of the columns where resistance to penetration is least (Holmes and Stace 1967). In the unaltered Bnt, upper columns of small diameter merge at depth into larger columns creating "dead ends" within the horizon. If ripping is successful the large columns will be shattered and continuous fractures which contain less sodic material will be found throughout the Bnt and BC (White and Gartner 1981). In the "Ripped" treatment roots penetrated the Bnt and BC with greater ease and total root mass at depth was increased. The combination of increased root proliferation and moisture status at depth contributed to the higher yields observed in the ripped treatments as compared to the non-ripped.

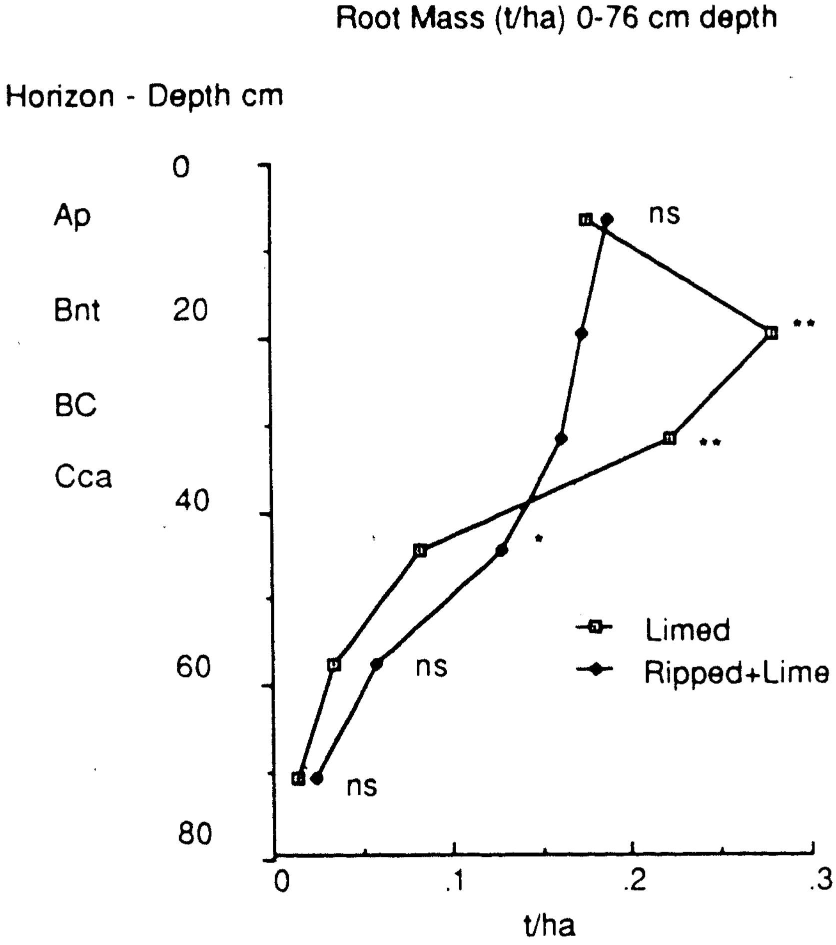

Figure 14 Root Mass versus Depth, 0-76 cm, for Ripped+Lime and Limed Treatments.

**differences between treatments are highly significant at depth indicated, $p \leq 1$ %.
*differences between treatments are significant at depth indicated, $p \leq 5$ %.
nsdifferences between treatments are not significant at depth indicated.

4.3.3 Crop Tissue Analysis

Chemical soil analysis revealed the possibility of Ca and K deficiencies due to high Mg/Ca and low Ca/TC ratios in the Bnt of the non-ripped treatments. A tissue analysis was performed on crop samples gathered at the five leaf stages from Ripped, Ripped+Lime, Control and Limed treatments. Data from the analysis are presented in Appendix 3.

All values measured were statistically analyzed through a one way analysis of variance. Differences between treatments for % protein, % Ca, % Mg, or % K were non-significant. Significant differences in % P were found and multiple means comparisons for treatments are presented in Table 13. All nutrient concentrations measured were within the "sufficient" range according to published values for small grains (Ward *et al* 1973). There does not appear to have been Ca or K deficiencies in the crop.

Percent P was significantly higher in tissue samples obtained from the two ripped treatments as compared to the non-ripped treatments. The availability and uptake of phosphate ions should be decreased by the higher pH values found in the Ap of the ripped treatments (Tisdale and Nelson 1975; Bohn *et al* 1979). It would appear that the observed trend was due to the uptake of phosphate ions from depth, and not from the surface horizon. In the ripped treatments it appears that increased root proliferation enabled plants to extract nutrients from a larger volume of soil, thus accounting for the increased amount of P in plant tissue. An additional factor may have been the increased moisture status in the ripped treatments. The amount of total dissolved phosphate ion will increase under higher moisture conditions and these ions will diffuse more readily to the root surfaces, thus enhancing potential uptake.

Table 13. **Multiple Means Comparisons[1] of Percent Plant Phosphorus (dry wt. basis) for Four Treatments.**

Treatment	Percent Plant Phosphorus (dry wt. basis)
Control	0.20a
Limed	0.23a
Ripped	0.29b
Ripped+Lime	0.29b

[1] Means not followed by the same letter(s) are significantly different according to the least significant difference test, $p \leq 5\%$.

5. Conclusions

The main differences observed between treatments were due to the effects of ripping. For the period from 1982 to 1985 liming increased grain yields by 0.2 t ha^{-1}, ripping+liming by 0.8 t ha^{-1} and ripping alone by 0.9 t ha^{-1}. Ripping elevated material from depth into the Ap and Bnt horizon with both positive and negative agronomic results.

The elevation of salts, containing carbonate and bicarbonate, into the Ap horizon substantially increased the pH and E.C. The increase in pH was higher than that achieved through the application of lime. Ripping in combination with lime did not increase the pH of the Ap over ripping alone. The increase in pH through ripping was higher than desired for agronomic production. There has been speculation that ripping may result in the resalinization of the soil surface. Although E.C. in the Ap was increased through ripping the increase appeared to be due to the mechanical elevation of salts and not resalinization through upward capillary water movement. The electrolyte concentration was not increased to the degree that even very sensitive crop plants would be harmed.

The elevation of sodic clay into the Ap, through ripping, and the subsequent increase in breaking strength may result in crop emergence problems. This tendency has been noted following deep plowing and questions have been raised on the degree to which this will be found after ripping. In this study soil strength was not increased to the point that has been reported for similar soils following deep plowing. The germination of cereal crops should not be affected by the measured increase in breaking strength, but the decline in surface tilth could be a concern if more sensitive crops are grown.

Changes in bulk densities were not observed at depth following ripping. It is not surprising that the bulk density of the soil material is unaltered, but bulk density may also reflect increased pore volume. The increase in water infiltration following ripping may be partially due to the creation of large fractures within the soil profile. The existence of these macropores could not be documented through bulk density measurements, although they were visually observed during sampling operations.

Ripping improved the physical structure of the Bnt through an elevation of Ca salts and a subsequent leaching of Na; SAR values in the Bnt were significantly lower in the ripped treatments as compared to the non-ripped treatments. Improved soil structure in the Bnt allowed increased infiltration of fall and winter precipitation and hence an increase in stored soil moisture at depth. Ripping also increased root growth below 38 cm; the more substantial root growth at depth was better able to exploit the subsurface for water as well as for plant nutrients. As a result of increased available moisture and root mass at depth, crop yields were substantially higher in the ripped treatments as compared to the non-ripped treatments.

There were no clear differences between Ripped and Ripped+Lime treatments. The Ripped+Lime treatment had slightly lower SAR and E.C. values throughout the soil profile than the Ripped treatment but differences were largely non-significant and could not be attributed to the application of lime. At the pH values measured in the Ap of the ripped treatments (>8.2) lime would be very sparingly soluble. This may account for the lack of difference in physicochemical properties between Ripped and Ripped+Lime treatments. Ripping in conjunction with lime was similar to ripping alone. In this study ripping alone was the most economically justifiable treatment. Given an average price of wheat of $180^{.00}$ t $^{-1}$ and an average yearly yield increase of 0.9 t ha^{-1}, ripping costs of approximately $74^{.00}$ ha^{-1} would be more than reimbursed within the first crop year at this site.

The initial ripping operation was done under ideal conditions. The subsurface was dry and maximum shattering was achieved with a 61 cm shank spacing; consequently no major differences were detected between on shank or intershank positions in either the Ripped or Ripped+Lime treatments. The soil profile at this site was shallow, the lime salt layer was above the maximum depth of ripping. The Bnt was moderately sodic, average SAR values for the unaltered Bnt were less than fifteen. The solodization process appeared advanced and there was no evidence of resalinization. Under conditions where a deeper more highly sodic Bnt is present, and the solodization process is not as advanced, ripping may not have the positive results observed in this study.

Little evidence exists that the soil is reverting to its unaltered condition. Chemical changes in the Bnt may be permanent and crop yields do not appear to be diminishing over time. Under certain conditions ripping may provide a more permanent solution than originally believed for these problem soils.

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APPENDICES

Appendix 1

Chemical Water Analysis

for well site on N.W. 30 36 15 W4

	(me L^{-1})		(me L^{-1})
Calcium	.90	Sulfate	.40
Potassium	.26	Chloride	.17
Magnesium	.16	Bicarbonate	36.6
Sodium	35.0		

SAR	48
pH	8.2
T.D.S	1966 p.p.m
Conductivity	3.2 millisiemens/cm
Na^+/Total Cations	.96
HCO_3^-/Total Anions	.98

Appendix 2

Preliminary chemical analysis prior to treatment application.

Location N.E. 25-36-16-W4

Sampling date Sept 10 1981.

Analysis date Dec 31 1981 A.S.F.T.L

				(Soluble Cations(me L^{-1}))				
Sample	Hor.	pH	E.C*.	Ca	Mg	Na	K	S.A.R
	Ap			no data				
1	Bnt	7.9	1.8	2.1	1.2	17.6	.2	13.7
1	Ccsa	7.8	7.2	18.0	14.0	61.0	1	15.2
1	Csak	8.0	3.9	4.7	3.5	33.0	.6	16.4
	Ap		no data					
2	Bnt	7.1	.7	2.9	1.0	5	.1	3.6
2	BC	7.4	1.0	3.9	1.1	7	.1	4.4
2	Csak	7.3	3.8	22.0	6.0	20	.4	5.2
2	Csak2	7.5	4.8	13.0	6.0	36	.5	11.4
	Ap			no data				
3	Bnt	7.8	1.4	2.5	1.1	13.6	.1	10.1
3	Cca	8.0	1.7	2.5	1.0	16.1	.1	12.2
3	Csak	7.7	6.1	23.6	12.1	44.0	.4	10.4

* E.C. millisiemens/cm

Appendix 2 continued

Lime Requirement

Sample	Hor.	pH	T/ha (CaCO3) to raise pH to 6.5
1	Ap	5.5	4.49
2	Ap	5.8	3.14
3	Ap	5.6	4.26

Appendix 3

Tissue analysis on wheat. Sampled June 30, 1985.

Analysis by A.S.F.T.L

Treatment	% Protein	% Ca	% P (Dry wt. basis)	% Mg	% K
Ripped					
1	22.2	0.33	0.27	0.23	1.85
2	25.7	0.30	0.29	0.22	1.64
3	29.2	0.26	0.32	0.24	1.62
mean	25.7	0.30	0.29	0.23	1.70
Ripped+Lime					
1	22.0	0.41	0.31	0.23	1.80
2	22.7	0.41	0.27	0.21	1.59
3	24.9	0.36	0.30	0.22	1.61
mean	23.2	0.39	0.29	0.22	1.67
Control					
1	21.7	0.34	0.18	0.25	1.56
2	25.3	0.35	0.21	0.26	1.62
3	26.0	0.28	0.20	0.25	1.60
mean	24.3	0.32	0.20	0.25	1.59
Limed					
1	27.4	0.29	0.24	0.24	1.72
2	26.3	0.34	0.22	0.22	1.57
3	25.6	0.53	0.24	0.24	1.60
mean	26.4	0.39	0.23	0.23	1.63

Appendix 4. Chemical Analysis

Treatments
Ripped on shank (Plt Number) = ROS#
Ripped intershank (Plt Number) = RIS#
Ripped + Lime on shank (Plt Number) = RLOS#
Ripped + Lime intershank (Plt Number) = RLIS#
Control (Plt Number) = C#
Limed (Plt Number) = L#

Treatment+Plt	Horizon	Sodium meq/L	Potassium meq/L	Calcium meq/L	Magnesium meq/L	Sulfate meq/L	Carbonate meq/L	Bicarbonate meq/L	Chloride meq/L	Nitrate meq/L	SAR	E.C mS/cm	pH
ROS1	Ap	7.07	0.18	5.96	1.75	6.17	1.28	4.09	0.36	0.00	3.6	1.18	8.24
RIS1	Ap	6.00	0.16	4.60	1.33	4.92	1.07	4.69	0.61	0.00	3.5	0.92	8.20
ROS2	Ap	4.37	0.11	2.34	0.71	1.08	0.94	4.98	0.23	0.00	3.5	0.80	8.54
RIS2	Ap	4.91	0.11	2.69	0.87	1.76	1.20	4.88	0.37	0.00	3.7	0.88	8.44
ROS3	Ap	5.67	0.13	2.68	1.08	1.31	1.41	6.01	0.44	0.00	4.1	0.78	8.40
RIS3	Ap	6.00	0.14	2.61	1.04	1.33	1.11	6.25	0.40	0.00	4.4	0.75	8.37
ROS4	Ap	9.13	0.11	1.98	0.83	3.08	0.90	8.31	0.68	0.00	7.7	0.89	8.59
RIS4	Ap	11.50	0.11	2.60	1.04	3.66	1.16	7.43	0.74	0.00	8.6	1.07	8.58
ROS5	Ap	10.62	0.16	2.90	1.87	1.94	1.78	8.97	0.70	0.00	6.8	1.19	8.45
RIS5	Ap	8.91	0.12	2.64	1.17	1.71	1.11	8.05	0.88	0.00	6.5	0.90	8.46
ROS6	Ap	14.52	0.11	3.30	1.96	6.00	1.20	8.82	1.83	0.00	9.0	1.48	8.48
RIS66	Ap	11.72	0.12	2.70	1.48	4.86	1.48	8.70	0.88	0.00	8.1	1.23	8.37
ROS7	Ap	6.74	0.18	3.69	1.68	5.54	1.41	8.00	1.02	0.00	4.2	0.92	8.27
RIS7	Ap	6.54	0.18	3.42	1.48	2.77	1.07	8.38	1.34	0.00	4.2	0.89	8.30
ROS8	Ap	6.63	0.23	3.81	2.17	2.19	1.71	6.61	1.08	0.00	3.9	1.01	8.31
RIS8	Ap	8.48	0.20	4.04	2.44	3.42	1.62	7.00	1.68	0.00	4.7	1.21	8.09
ROS9	Ap	8.04	0.18	3.30	1.76	1.44	1.46	8.00	0.44	0.00	5.1	0.98	8.43
RIS9	Ap	8.80	0.14	3.69	1.87	4.62	1.03	7.46	0.70	0.00	5.4	1.07	8.28
ROS10	Ap	5.35	0.18	3.30	1.80	0.92	1.37	8.76	0.39	0.00	3.4	0.81	8.03
RIS10	Ap	5.02	0.14	2.73	1.37	0.98	1.20	6.42	0.26	0.00	3.5	0.75	7.98
RLOS1	Ap	4.28	0.22	3.86	1.80	1.08	1.24	6.12	0.78	0.00	2.6	0.82	8.08
RLIS1	Ap	3.50	0.26	3.85	1.87	0.69	1.60	6.99	0.70	0.00	2.1	0.71	8.08
RLOS2	Ap	5.78	0.22	3.60	1.73	2.44	1.20	8.38	0.44	0.00	3.6	0.85	7.74
RLIS2	Ap	5.48	0.16	2.56	1.38	1.38	1.37	6.67	0.42	0.00	3.9	0.89	8.24
RLOS3	Ap	5.13	0.18	2.86	1.55	0.86	1.11	6.26	0.37	0.00	3.5	0.72	8.28
RLIS3	Ap	5.57	0.20	3.30	1.83	1.10	1.28	6.81	1.04	0.00	3.6	0.84	8.31
RLOS4	Ap	7.07	0.12	1.66	1.01	1.36	1.03	6.68	0.46	0.00	6.2	0.81	8.44
RLIS4	Ap	8.37	0.16	2.20	1.45	1.60	1.54	7.38	0.67	0.00	6.2	0.92	8.44

Appendix 4 Continued

Treatment+Pit	Horizon	Sodium me/L	Potassium me/L	Calcium me/L	Magnesium me/L	Sulfate me/L	Carbonate me/L	Bicarbonate me/L	Chloride me/L	Nitrate me/L	SAR	E.C. mS/cm	pH
RLOS5	Ap	6.00	0.19	4.40	2.17	1.21	1.63	8.13	0.48	0.00	3.3	0.90	8.28
RLIS5	Ap	6.63	0.12	2.85	1.38	1.48	1.88	6.63	0.61	0.00	4.6	0.81	8.41
RLOS6	Ap	6.54	0.16	4.40	2.05	4.67	1.64	5.95	0.56	0.00	3.6	[illegible]	8.27
RLIS6	Ap	5.48	0.16	3.28	1.48	1.19	1.48	6.72	0.61	0.00	3.5	0.81	8.27
RLOS7	Ap	6.74	0.13	3.08	1.40	1.67	1.88	6.63	0.51	0.00	4.5	0.89	8.34
RLIS7	Ap	6.00	0.15	2.93	1.53	1.21	1.33	7.15	0.28	0.00	4.0	0.77	8.39
RLOS8	Ap	7.28	0.14	2.84	1.78	0.94	1.18	8.41	0.44	0.00	4.8	0.89	8.30
RLIS8	Ap	6.74	0.13	2.63	1.26	1.33	1.41	7.17	0.32	0.00	4.8	0.86	8.36
RLOS9	Ap	6.43	0.12	2.54	1.18	1.19	1.24	7.13	0.33	0.00	4.7	0.77	8.37
RLIS9	Ap	5.48	0.12	2.23	1.08	0.88	1.28	6.48	0.28	0.00	4.3	0.72	8.45
RLOS10	Ap	7.81	0.12	2.48	1.18	2.27	0.94	6.98	0.58	0.00	5.8	0.92	8.31
RLIS10	Ap	6.54	0.13	2.58	1.38	1.85	2.14	6.12	0.53	0.00	4.7	0.86	8.24
C1	Ap	3.47	0.17	0.43	0.33	2.73	0.01	0.88	0.82	0.00	5.6	0.51	6.13
C2	Ap	1.39	0.11	0.41	0.29	0.96	0.01	0.51	0.58	0.00	2.3	0.28	5.73
C3	Ap	4.44	0.21	0.68	0.36	2.42	0.01	0.34	1.18	0.42	6.2	0.67	5.51
C4	Ap	2.73	0.15	0.44	0.33	2.58	0.01	0.39	0.82	0.00	4.4	0.43	5.65
C5	Ap	3.67	0.27	0.91	0.49	1.85	0.01	0.32	1.30	0.60	4.4	0.64	5.34
C6	Ap	3.53	0.16	0.61	0.45	2.86	0.01	0.41	1.41	0.00	4.8	0.52	5.62
C7	Ap	2.30	0.23	0.80	0.48	1.29	0.01	0.34	1.15	0.44	2.9	0.47	5.32
C8	Ap	2.97	0.31	0.64	0.58	1.98	0.01	0.47	1.57	0.00	3.8	0.47	5.80
C9	Ap	2.54	0.12	0.53	0.33	1.29	0.01	0.32	1.20	0.00	3.9	0.37	6.08
C10	Ap	4.46	0.18	0.63	0.48	1.88	0.01	1.11	2.41	0.00	6.0	0.60	6.39
L1	Ap	4.83	0.20	2.04	1.43	1.90	0.01	4.56	1.51	0.00	3.7	0.77	7.35
L2	Ap	5.00	0.16	2.63	1.65	1.31	1.07	5.29	1.72	0.00	3.4	0.78	7.79
L3	Ap	3.47	0.17	2.27	1.70	0.90	0.43	4.49	0.74	0.00	2.5	0.82	7.48
L4	Ap	4.18	0.14	1.69	1.33	1.48	0.30	3.49	1.37	0.00	3.4	0.86	7.00
L5	Ap	5.04	0.04	0.36	0.12	2.52	0.01	2.18	0.00	0.00	10.3	0.52	5.94
L6	Ap	4.35	0.17	1.35	0.68	2.92	0.01	1.93	1.37	0.00	4.3	0.63	6.65
L7	Ap	6.17	0.17	1.39	0.76	4.17	0.01	3.51	1.09	0.00	6.0	0.89	6.92
L8	Ap	7.87	0.22	2.14	1.68	4.67	0.01	4.99	1.85	0.00	5.7	1.09	7.29
L9	Ap	5.96	0.21	1.67	0.78	4.58	0.01	3.30	1.32	0.00	5.4	0.89	7.02
L10	Ap	3.38	0.22	2.03	0.86	2.25	0.01	3.17	0.53	0.00	2.8	0.58	6.91
ROS1	Bnt	16.48	0.21	23.60	9.17	39.38	0.01	3.78		0.77	4.1	3.35	7.44
RIS1	Bnt	13.57	0.11	17.40	7.60	33.33	1.13	2.23		0.80	3.8	2.78	7.80
ROS2	Bnt	5.74	0.09	1.99	1.00	2.06	0.92	4.20		0.15	4.7	0.70	7.80
RIS2	Bnt	5.65	0.09	1.65	0.83	1.73	1.18	4.45		0.11	5.1	0.82	8.26
ROS3	Bnt	7.04	0.09	2.21	1.33	1.56	1.34	4.33		0.66	5.3	0.94	8.18
RIS3	Bnt	5.48	0.08	1.22	1.00	2.29	1.01	3.07		0.16	5.2	0.70	8.37
ROS4	Bnt	7.30	0.05	1.14	1.00	4.02	1.05	2.04		0.31	7.1	0.81	8.54
RIS4	Bnt	8.35	0.03	1.34	0.92	2.85	1.39	4.88		0.13	7.9	0.81	8.37
ROS5	Bnt	17.00	0.05	2.30	2.00	1.44	1.01	4.03		0.36	11.6	1.87	8.51
RIS5	Bnt	8.74	0.03	1.50	1.25	3.19	1.78	5.02		0.05	7.5	0.94	8.51
ROS6	Bnt	10.13	0.03	1.66	1.50	8.85	0.88	4.35		0.00	8.1	1.03	8.66
RIS66	Bnt	10.09	0.03	1.20	1.08	8.13	0.88	4.54		0.00	9.5	1.01	8.48
ROS7	Bnt	5.74	0.04	1.30	0.67	2.42	0.84	3.42		0.08	5.8	0.67	8.48

Appendix 4 Continued

Treatment+Pit	Horizon	Sodium me/L	Potassium me/L	Calcium me/L	Magnesium me/L	Sulfate me/L	Carbonate me/L	Bicarbonate me/L	Chloride me/L	Nitrate me/L	SAR	E.C. mS/cm	pH
RIS7	Bnt	7.35	0.08	2.04	1.17	2.17	0.84	6.07		0.29	5.8	0.88	8.28
ROS8	Bnt	6.04	0.07	1.60	1.00	1.33	0.42	4.79		0.26	4.4	0.68	8.37
RIS8	Bnt	5.39	0.09	1.78	1.17	1.21	1.30	4.28		0.24	4.5	0.72	7.79
ROS9	Bnt	7.87	0.08	1.37	1.00	2.16	0.88	4.37		0.48	7.2	0.86	8.03
RIS9	Bnt	9.39	0.12	2.35	1.17	2.90	0.88	4.14		1.29	7.1	1.17	8.24
ROS10	Bnt	7.74	0.07	2.64	1.33	2.17	1.34	4.98		0.94	5.5	.00	7.97
RIS10	Bnt	5.48	0.07	1.95	1.25	1.46	1.39	4.58		0.31	4.3	0.76	8.00
RLOS1	Bnt	6.13	0.07	1.94	1.17	1.38	1.05	4.28		0.19	4.1	0.73	8.07
RLIS1	Bnt	4.30	0.05	1.58	1.17	1.15	0.97	4.28		0.00	3.7	0.57	8.29
RLOS2	Bnt	8.39	0.12	2.06	1.33	3.04	1.13	6.69		0.31	6.5	1.01	7.89
RLIS2	Bnt	7.52	0.08	1.41	1.00	3.54	0.80	3.83		0.18	6.9	0.88	8.37
RLOS3	Bnt	4.67	0.07	2.08	1.17	1.44	0.76	5.08		0.00	3.6	0.62	8.05
RLIS3	Bnt	4.78	0.05	1.55	1.25	1.77	0.97	3.57		0.08	4.0	0.62	8.37
RLOS4	Bnt	8.39	0.07	1.21	0.83	3.13	0.01	4.26		0.32	8.3	0.86	8.54
RLIS4	Bnt	9.65	0.08	1.44	0.92	7.71	0.01	4.87		0.13	8.9	0.94	8.48
RLOS5	Bnt	7.70	0.06	1.90	1.00	2.81	1.22	4.58		0.08	6.4	0.86	8.25
RLIS5	Bnt	6.48	0.05	1.09	0.75	2.13	1.22	4.35		0.00	6.8	0.73	8.32
RLOS6	Bnt	4.83	0.06	1.61	0.83	1.40	1.05	4.47		0.03	4.4	0.64	8.10
RLIS6	Bnt	5.52	0.06	1.90	1.00	1.94	0.92	4.45		0.15	4.6	0.75	8.20
RLOS7	Bnt	7.13	0.10	1.95	1.17	2.48	0.92	5.21		0.23	5.7	0.90	8.19
RLIS7	Bnt	8.91	0.10	2.29	1.33	3.75	1.01	6.28		0.29	6.6	1.06	8.02
RLOS8	Bnt	15.43	0.22	5.16	2.58	2.33	1.22	5.46		3.44	7.8	2.16	7.80
RLIS8	Bnt	7.78	0.05	1.16	0.83	3.48	1.47	4.34		0.00	7.6	0.86	7.84
RLOS9	Bnt	9.09	0.08	1.60	0.92	2.98	1.54	6.23		0.27	8.1	1.00	8.05
RLIS9	Bnt	8.35	0.05	1.38	0.76	2.38	1.19	4.30		0.00	8.2	0.70	8.42
RLOS10	Bnt	11.00	0.07	1.86	1.17	3.42	1.55	6.09		0.63	9.0	1.26	8.05
RLIS10	Bnt	8.43	0.11	0.83	0.67	5.92	0.63	2.94		0.13	9.7	0.86	8.01
C1	Bnt	8.26	0.04	0.49	0.32	2.73	0.67	3.44		0.00	9.8	0.69	7.48
C2	Bnt	8.43	0.06	1.49	0.92	1.27	2.44	6.80		0.00	7.7	0.90	7.90
C3	Bnt	16.39	0.14	0.72	0.76	9.63	0.01	4.31		0.97	19.1	1.72	7.60
C4	Bnt	10.61	0.08	0.64	0.40	8.98	1.18	3.74		0.00	14.7	1.09	7.79
C5	Bnt	18.22	0.08	1.10	1.17	6.92	4.41	8.76		0.31	17.1	1.72	7.91
C6	Bnt	7.62	0.06	0.39	1.17	6.17	0.01	2.60		0.00	8.5	0.84	7.18
C7	Bnt	4.78	0.06	0.34	0.20	2.60	0.01	2.75		0.00	9.2	0.56	7.03
C8	Bnt	14.43	0.17	0.68	0.67	8.27	2.60	8.07		0.32	17.8	1.40	8.34
C9	Bnt	9.87	0.06	0.80	0.87	1.88	2.06	7.14		0.00	11.5	0.93	7.97
C10	Bnt	14.30	1.62	1.80	1.42	4.44	1.56	10.31		0.00	11.3	1.67	7.64
L1	Bnt	10.61	0.27	1.16	1.08	6.54	0.56	6.56		0.08	10.0	1.02	7.49
L2	Bnt	6.04	0.11	1.62	0.83	1.36	0.84	6.13		0.00	5.5	0.69	7.99
L3	Bnt	4.00	0.95	1.21	0.76	1.08	1.06	3.72		0.00	4.0	0.63	7.43
L4	Bnt	9.57	0.13	2.67	1.92	1.67	0.63	11.51		0.00	6.4	1.12	7.16
L5	Bnt	11.65	0.07	0.72	0.67	3.33	0.50	5.94		0.28	14.0	1.10	8.20
L6	Bnt	13.52	0.27	0.59	1.17	13.27	0.01	4.20		0.95	14.4	1.42	8.07
L7	Bnt	19.48	0.06	0.74	0.83	14.92	1.05	3.30		0.26	22.0	1.97	8.23
L8	Bnt	15.78	0.07	1.59	1.17	10.40	1.93	6.53		0.00	13.4	1.57	7.70

Appendix 4 Continued

Treatment+Pit	Horizon	Sodium me/L	Potassium me/L	Calcium me/L	Magnesium me/L	Sulfate me/L	Carbonate me/L	Bicarbonate me/L	Chloride me/L	Nitrate me/L	SAR	E.C. mS/cm	pH
L9	Bnt	18.91	0.08	1.34	1.42	13.90	0.92	8.78		0.00	16.1	1.89	7.90
L10	Bnt	22.57	0.14	0.73	1.83	21.87	0.76	3.23		0.00	19.9	2.38	8.35
ROS1	BC	25.09	0.21	24.50	10.00	52.77	0.50	3.09		0.42	6.0	4.32	7.53
RIS1	BC	23.74	0.12	23.26	10.00	50.48	0.34	2.90		0.21	5.8	4.00	7.93
ROS2	BC	9.78	0.04	1.95	1.08	9.13	1.01	4.85		0.18	7.9	1.10	8.60
RIS2	BC	10.87	0.05	1.70	0.92	3.52	1.43	7.31		0.27	9.5	1.18	8.70
ROS3	BC	12.70	0.08	2.31	1.42	5.87	1.18	6.97		0.35	9.3	1.33	8.47
RIS3	BC	13.74	0.08	2.71	1.76	11.00	1.34	8.11		0.23	9.2	1.44	8.51
ROS4	BC	22.87	0.09	3.35	2.33	16.38	0.84	7.66		0.23	13.6	2.38	8.73
RIS4	BC	32.17	0.10	4.00	3.17	31.44	1.34	6.43		0.11	17.0	3.46	8.81
ROS5	BC	16.78	0.05	2.50	1.50	11.40	1.26	6.85		0.37	11.9	1.23	8.79
RIS5	BC	23.09	0.06	3.95	2.50	17.29	1.64	6.95		0.36	12.9	2.43	8.82
ROS6	BC	25.04	0.05	3.50	2.92	20.27	0.97	7.08		0.00	14.0	2.59	8.53
RIS66	BC	18.28	0.06	2.43	2.08	13.63	1.13	4.98		0.00	12.2	1.88	8.79
ROS7	BC	8.74	0.04	1.68	0.83	4.16	0.63	4.03		0.00	7.8	0.93	8.72
RIS7	BC	9.00	0.05	1.51	0.92	2.31	1.06	6.03		0.08	8.2	0.89	8.47
ROS8	BC	5.00	0.07	1.48	0.83	1.15	0.92	4.33		0.13	4.7	0.61	8.70
RIS8	BC	5.78	0.05	1.50	1.00	1.23	1.18	4.33		0.10	5.2	0.71	8.59
ROS9	BC	11.91	0.05	1.72	1.17	4.42	0.84	6.05		0.40	9.9	1.32	8.42
RIS9	BC	11.09	0.07	1.91	1.67	2.38	1.68	6.72		0.44	8.3	1.21	8.40
ROS10	BC	8.13	0.04	1.98	1.42	1.71	0.97	5.19		0.68	6.2	1.02	8.19
RIS10	BC	6.57	0.04	1.56	0.92	1.83	0.88	4.22		0.32	5.9	0.82	8.60
RLOS1	BC	6.61	0.04	1.53	0.75	1.83	1.09	4.88		0.00	6.2	0.76	8.43
RLIS1	BC	5.17	0.05	1.45	0.67	1.10	1.18	3.38		0.21	5.0	0.68	8.51
RLOS2	BC	8.65	0.06	1.63	0.83	4.48	1.22	3.82		0.03	7.8	0.94	8.49
RLIS2	BC	12.61	0.10	2.38	1.33	8.79	0.87	5.76		0.21	9.3	1.49	8.42
HLOS3	BC	5.13	0.05	1.98	1.00	1.46	0.50	4.68		0.23	4.2	0.76	8.33
RLIS3	BC	4.78	0.04	1.39	0.76	2.17	0.63	3.57		0.03	4.6	0.66	8.53
RLOS4	BC	10.91	0.08	1.86	1.17	6.27	0.01	4.87		0.27	8.9	1.13	8.68
RLIS4	BC	13.52	0.07	2.13	1.26	12.66	0.01	5.31		0.08	10.4	1.41	8.53
RLOS5	BC	9.74	0.05	1.77	1.00	4.21	1.47	4.72		0.29	8.3	1.07	8.35
RLIS5	BC	7.57	0.04	1.22	0.67	3.31	0.92	4.03		0.03	7.8	0.86	8.49
RLOS6	BC	4.74	0.04	1.30	0.58	1.60	1.18	2.52		0.13	4.9	0.58	8.30
RLIS6	BC	6.83	0.05	1.47	0.76	2.10	1.06	5.10		0.08	6.5	0.79	8.26
RLOS7	BC	6.13	0.04	1.77	0.83	2.08	1.13	4.14		0.31	5.4	0.77	8.23
RLIS7	BC	9.57	0.06	1.86	1.08	5.77	1.09	3.23		0.56	7.9	1.18	8.29
RLOS8	BC	10.52	0.05	1.58	0.92	3.40	0.71	6.65		0.56	9.4	1.21	8.36
RLIS8	BC	9.48	0.02	1.10	0.76	3.46	0.84	5.88		0.00	9.8	0.94	8.53
RLOS9	BC	10.13	0.04	1.53	0.83	5.96	1.13	4.35		0.19	9.3	1.13	8.46
RLIS9	BC	11.52	0.08	2.25	1.25	6.46	1.18	7.14		0.00	8.7	1.29	8.20
RLOS10	BC	10.39	0.05	1.16	0.67	6.19	0.59	5.00		0.03	10.9	1.08	8.52
RLIS10	BC	11.61	0.04	1.35	0.83	6.60	0.88	5.12		0.13	11.1	1.26	8.64
C1	BC	12.30	0.04	2.11	1.17	6.81	1.30	5.38		0.00	9.6	1.18	8.44
C2	BC	11.61	0.05	1.99	1.08	3.98	1.22	8.42		0.00	9.4	1.21	8.01
C3	BC	25.00	0.11	1.52	1.25	19.50	0.01	4.12		0.84	21.2	2.59	8.44

Appendix 4 Continued

Treatment + Pit	Horizon	Sodium meq/L	Potassium meq/L	Calcium meq/L	Magnesium meq/L	Sulfate meq/L	Carbonate meq/L	Bicarbonate meq/L	Chloride meq/L	Nitrate meq/L	SAR	E.C. mS/cm	pH
C4	BC	14.96	0.03	1.47	0.83	12.48	1.28	5.61		0.00	14.0	1.49	8.44
C5	BC	14.52	0.05	1.12	0.75	9.98	0.84	6.72		0.45	15.0	1.49	8.59
C6	BC	10.04	0.03	0.97	0.50	8.31	0.80	4.35		0.00	11.7	1.02	8.15
C7	BC	9.83	0.02	1.18	0.58	3.00	1.05	6.49		0.00	10.5	0.94	8.05
C8	BC	11.74	0.10	0.72	0.50	6.58	0.78	4.41		0.39	15.0	1.18	8.64
C9	BC	10.04	0.04	1.13	0.67	2.79	1.28	6.82		0.00	10.6	0.94	8.60
C10	BC	14.30	0.05	2.03	1.17	8.75	1.47	6.68		0.34	11.3	1.49	8.38
L1	BC	10.91	0.05	1.75	0.83	7.02	0.80	4.39		0.00	9.8	1.10	8.48
L2	BC	7.43	0.08	1.51	0.83	1.90	0.84	6.38		0.00	8.9	0.79	8.30
L3	BC	8.09	0.05	2.24	1.17	1.17	1.01	6.59		0.00	3.9	0.69	7.84
L4	BC	9.70	0.04	1.38	0.83	2.42	1.78	6.95		0.00	9.2	0.97	8.06
L5	BC	9.52	0.08	0.82	0.42	5.68	0.01	2.75		0.47	12.1	1.06	8.50
L6	BC	18.70	0.09	1.07	1.42	14.04	1.01	4.98		0.13	16.0	1.87	8.43
L7	BC	17.83	0.05	0.97	0.76	14.35	0.78	3.82		0.32	19.2	1.81	8.39
L8	BC	13.09	0.03	1.54	0.82	10.96	1.28	5.14		0.00	11.8	1.33	8.38
L9	BC	18.52	0.07	1.48	1.17	13.80	1.28	4.88		0.00	14.4	1.67	8.38
L10	BC	25.04	0.15	1.09	1.92	24.90	0.97	2.88		0.00	20.4	2.59	8.59
ROS1	Cca	43.48	0.38	18.56	10.00	68.63	0.01	3.07		0.03	11.5	5.34	7.91
RIS1	Cca	44.78	0.36	18.20	10.00	65.63	0.01	3.40		0.00	11.9	5.50	7.98
ROS2	Cca	43.04	0.30	18.50	13.33	67.96	0.01	3.40		0.13	10.8	5.50	7.58
RIS2	Cca	27.39	0.16	16.40	9.17	46.58	0.01	3.57		0.13	7.7	4.08	8.18
ROS3	Cca	50.87	0.43	21.55	18.33	78.75	0.01	5.59		0.03	11.4	6.44	7.80
RIS3	Cca	52.17	0.34	14.15	14.17	65.88	0.01	7.12		0.13	13.9	5.89	8.27
ROS4	Cca	63.48	0.44	23.55	17.50	77.60	0.01	8.84		0.08	14.0	7.07	7.81
RIS4	Cca	63.04	0.49	24.35	17.50	75.44	0.01	8.02		0.05	13.8	7.38	7.85
ROS5	Cca	54.35	0.27	21.56	16.83	77.98	0.01	5.71		0.08	12.8	6.44	8.09
RIS5	Cca	48.70	0.30	20.55	15.00	73.50	0.01	6.29		0.08	11.6	6.44	8.35
ROS6	Cca	31.74	0.14	4.95	5.00	31.67	0.01	6.43		0.18	14.2	3.38	8.62
RIS66	Cca	71.30	0.37	23.00	20.83	84.83	0.01	8.69		0.08	15.2	8.09	8.10
ROS7	Cca	38.96	0.31	7.75	6.67	39.88	0.01	4.18		0.03	13.8	4.24	8.36
RIS7	Cca	56.96	0.41	15.95	14.17	78.13	0.01	4.20		0.03	14.7	6.28	8.31
ROS8	Cca	6.78	0.08	1.20	0.67	2.31	1.13	3.99		0.08	7.0	0.71	8.78
RIS8	Cca	6.22	0.10	1.36	0.87	3.19	0.84	3.07		0.03	6.2	0.68	8.75
ROS9	Cca	14.57	0.18	2.18	1.60	15.46	0.42	3.23		0.08	10.7	1.57	8.59
RIS9	Cca	38.70	0.48	19.80	13.33	63.71	0.01	2.90		0.08	9.5	5.26	7.99
ROS10	Cca	6.22	0.06	1.08	0.58	1.98	1.06	3.61		0.13	6.9	0.88	8.59
RIS10	Cca	5.30	0.06	0.96	0.50	1.71	0.92	3.59		0.13	6.2	0.55	8.58
RLOS1	Cca	6.83	0.08	1.34	0.83	6.67	0.67	3.09		0.03	8.5	1.02	8.77
RLIS1	Cca	5.65	0.07	0.85	0.50	3.02	0.71	2.73		0.08	6.9	0.68	8.83
RLOS2	Cca	34.35	0.37	20.20	11.67	61.54	0.01	2.39		0.13	8.8	2.51	7.78
RLIS2	Cca	36.52	0.47	20.20	12.50	58.77	0.01	2.90		0.13	9.0	0.49	7.75
RLOS3	Cca	4.83	0.11	2.35	1.00	4.77	1.05	2.82		0.18	3.7	0.78	8.39
RLIS3	Cca	9.70	0.25	21.30	7.50	34.17	0.01	2.48		0.03	2.6	2.94	8.15
RLOS4	Cca	14.28	0.12	1.93	1.08	16.88	0.01	4.14		0.08	11.6	1.59	8.59
RLIS4	Cca	15.65	0.13	1.80	1.17	18.27	0.01	3.57		0.05	12.8	1.83	8.60

Appendix 4 Continued

Treatment+Pit	Horizon	Sodium me/L	Potasium me/L	Calcium me/L	Magnesium me/L	Sulfate me/L	Carbonate me/L	Bicarbonate me/L	Chloride me/L	Nitrate me/L	SAR	E.C. mS/cm	pH
RLOS5	Cca	14.74	0.09	3.40	1.92	18.21	0.76	3.30		0.06	9.0	1.83	8.47
RLIS5	Cca	22.04	0.13	6.50	3.83	29.21	0.80	2.86		0.00	9.7	3.09	8.63
RLOS6	Cca	7.61	0.05	1.11	0.50	3.83	0.76	3.49		0.32	8.5	0.87	8.90
RLIS6	Cca	7.35	0.05	1.41	0.58	3.52	1.13	2.92		0.23	7.4	0.80	8.65
RLOS7	Cca	7.04	0.07	1.39	0.67	2.69	0.97	3.86		0.18	6.9	0.80	8.54
RLIS7	Cca	20.22	0.18	7.65	4.08	25.33	0.01	3.36		0.34	8.3	2.70	8.31
RLOS8	Cca	43.46	0.42	20.30	14.17	69.85	0.01	3.02		0.08	10.5	5.88	8.05
RLIS8	Cca	43.48	0.25	11.25	8.33	51.31	0.01	5.48		0.06	13.9	4.77	8.65
RLOS9	Cca	48.26	0.32	22.45	14.17	75.75	0.01	4.77		0.35	11.3	6.20	7.95
RLIS9	Cca	28.43	0.29	22.90	10.00	53.33	0.80	3.13		0.06	7.0	4.61	7.82
RLOS10	Cca	45.22	0.30	19.80	13.33	69.23	0.01	3.28		0.00	11.1	5.80	8.04
RLIS10	Cca	30.87	0.16	8.55	5.00	32.40	0.78	3.82		0.08	12.8	3.58	8.64
C1	Cca	24.91	0.13	6.30	3.83	24.94	0.01	5.88		0.08	11.1	2.83	8.44
C2	Cca	8.00	0.03	1.28	0.58	4.23	0.97	3.57		0.00	8.3	0.80	8.75
C3	Cca	132.17	0.27	22.20	24.17	128.88	0.01	11.21		0.77	27.4	11.45	8.40
C4	Cca	53.48	0.22	22.05	12.50	71.48	0.01	6.78		0.00	12.9	6.12	7.92
C5	Cca	35.70	0.18	6.60	5.00	33.31	1.68	7.77		0.40	14.7	4.05	8.20
C6	Cca	36.65	0.15	11.15	7.50	46.90	0.01	5.88		0.00	12.0	4.53	8.36
C7	Cca	11.04	0.07	1.52	0.83	4.73	1.05	5.35		0.00	10.2	0.60	8.41
C8	Cca	30.57	0.43	3.85	3.42	26.10	0.63	5.29		0.40	16.0	3.34	8.43
C9	Cca	12.36	0.05	1.45	0.92	10.27	1.18	4.05		0.00	11.3	1.27	8.66
C10	Cca	38.57	0.21	19.05	12.50	62.94	0.01	6.24		0.00	9.7	5.41	8.07
L1	Cca	48.26	0.29	21.50	12.50	74.19	0.01	6.72		0.08	11.7	6.04	7.74
L2	Cca	9.91	0.04	1.65	0.92	8.17	1.13	4.26		0.00	8.7	1.03	8.65
L3	Cca	6.35	0.03	1.36	0.58	1.83	1.05	4.14		0.00	6.5	0.68	8.46
L4	Cca	14.39	0.06	1.91	1.33	11.90	0.84	5.10		0.00	11.3	1.69	8.61
L5	Cca	34.78	0.17	3.60	2.33	26.58	0.71	5.17		1.05	20.2	3.50	8.78
L6	Cca	62.61	0.45	19.25	25.00	80.98	0.34	4.87		0.08	13.3	7.79	8.31
L7	Cca	38.26	0.15	4.72	3.83	31.92	0.84	9.09		0.08	18.5	3.90	8.76
L8	Cca	21.22	0.08	3.71	2.33	21.38	1.34	4.79		0.00	12.2	2.31	8.48
L9	Cca	27.35	0.11	3.41	3.08	24.88	1.51	6.03		0.00	15.2	2.94	8.78
L10	Cca	84.78	0.59	19.05	2.42	102.42	0.71	3.78		0.06	25.9	9.54	8.17

Appendix 5. Physical Analysis

Treatments
Ripped on shank (Pit Number) = ROS#
Ripped Intershank (Pit Number) = RIS#
Ripped + Lime on shank (Pit Number) = RLOS#
Ripped + Lime Intershank (Pit Number) = RLIS#
Control (Pit Number) = C#
Limed (Pit Number) = L#

Treatment+Pit	Horizon	% Sand	% Clay	% Moisture 33 kPa	% Moisture 1500 kPa	Bulk Density gms/cubic cm	Modulus of Rupture kPa
ROS1	Ap	32	34	30.3	15.7	1.28	59
RIS1	Ap	37	36	30.0	16.0	1.22	
ROS2	Ap	40	35	29.4	15.7	1.30	50
RIS2	Ap	37	34	28.2	15.9	1.34	
ROS3	Ap	40	28	29.3	14.4	1.36	65
RIS3	Ap	43	27	29.1	14.6	1.21	
ROS4	Ap	46	24	28.3	13.9	1.37	75
RIS4	Ap	46	23	28.1	13.6	1.44	
ROS5	Ap	46	24	24.8	12.4	1.42	25
RIS5	Ap	43	26	25.2	13.1	1.37	
ROS6	Ap	37	28	28.0	14.9	1.23	80
RIS66	Ap	42	28	28.5	14.7	1.18	
ROS7	Ap	42	24	24.9	13.4	1.47	37
RIS7	Ap	44	24	26.1	13.2	1.33	
ROS8	Ap	45	23	24.7	12.6	1.42	38
RIS8	Ap	44	23	24.9	12.7	1.24	
ROS9	Ap	43	23	26.1	13.6	1.40	27
RIS9	Ap	42	24	25.7	13.7	1.18	
ROS10	Ap	46	22	24.9	13.1	1.35	26
RIS10	Ap	48	24	25.1	13.0	1.23	
RLOS1	Ap	40	27	26.3	12.8	1.50	39
RLIS1	Ap	43	29	27.3	13.3	1.42	
RLOS2	Ap	40	31	28.7	13.7	1.37	93
RLIS2	Ap	43	30	29.2	14.6	1.38	
RLOS3	Ap	36	31	29.8	14.6	1.43	53
RLIS3	Ap	37	30	30.3	14.9	1.41	
RLOS4	Ap	37	32	32.9	15.7	1.40	157
RLIS4	Ap	36	31	32.2	15.4	1.40	
RLOS5	Ap	46	24	27.1	12.1	1.47	94
RLIS5	Ap	47	25	26.5	13.1	1.36	
RLOS6	Ap	43	26	27.2	12.5	1.37	66
RLIS6	Ap	44	27	27.0	12.8	1.33	
RLOS7	Ap	40	28	29.9	14.9	1.30	112
RLIS7	Ap	39	28	30.1	14.6	1.34	
RLOS8	Ap	40	27	29.4	14.1	1.27	~~88~~
RLIS8	Ap	40	26	28.0	14.0	1.25	
RLOS9	Ap	36	27	28.4	14.3	1.26	49
RLIS9	Ap	39	28	29.4	14.8	1.32	
RLOS10	Ap	36	27	30.4	14.5	1.28	74
RLIS10	Ap	36	26	29.7	13.5	1.34	
C1	Ap	49	18	23.6	9.7	1.28	23
C2	Ap	46	22	23.1	9.7	1.16	
C3	Ap	47	13	23.2	8.2	1.24	13
C4	Ap	48	16	24.8	8.3	1.28	17
C5	Ap	47	13	23.5	8.0	1.27	16
C6	Ap	49	15	25.2	9.0	1.21	16
C7	Ap	52	13	22.5	7.8	1.27	14
C8	Ap	53	11	21.8	7.3	1.46	14
C9	Ap	46	18	23.6	9.9	1.31	25
C10	Ap	43	20	24.8	11.4	1.23	48
L1	Ap	49	22	23.7	9.8	1.29	19
L2	Ap	43	27	24.4	12.1	1.21	20
L3	Ap	41	24	25.4	12.0	1.31	19
L4	Ap	37	24	27.4	12.9	1.29	18
L5	Ap	49	12	23.5	7.9	1.13	15
L6	Ap	45	16	25.4	9.5	1.33	17
L7	Ap	47	14	22.7	8.6	1.36	41
L8	Ap	47	16	23.9	9.7	1.39	35
L9	Ap	50	15	24.0	9.4	1.35	33
L10	Ap	50	13	22.2	8.3	1.42	14
ROS1	Bnt	36	32	31.3	15.9	1.50	
RIS1	Bnt	37	31	31.6	16.3	1.52	
ROS2	Bnt	37	34	32.1	16.9	1.20	
RIS2	Bnt	40	27	31.7	14.6	1.48	

Appendix 5 Continued

Treatment+Pit	Horizon	% Sand	% Clay	% Moisture 33 kPa	% Moisture 1500 kPa	Bulk Density gms/cubic cm	Modulus of Rupture kPa
ROS3	Bnt	40	28	30.2	14.7	1.56	
RIS3	Bnt	38	32	35.8	18.3	1.49	
ROS4	Bnt	31	35	40.9	21.2	1.22	
RIS4	Bnt	40	25	32.0	16.1	1.10	
ROS5	Bnt	34	37	38.7	20.7	1.43	
RIS5	Bnt	34	31	33.2	16.4	1.39	
ROS6	Bnt	34	33			1.32	
RIS66	Bnt	31	36			1.40	
ROS7	Bnt	43	30			1.42	
RIS7	Bnt	41	26			1.61	
ROS8	Bnt	45	28			1.52	
RIS8	Bnt	45	25			1.49	
ROS9	Bnt	38	24			1.53	
RIS9	Bnt	41	26			1.50	
ROS10	Bnt	43	26			1.52	
RIS10	Bnt	39	26			1.67	
RLOS1	Bnt			29.2	14.4	1.66	
RLIS1	Bnt			30.3	14.3	1.53	
RLOS2	Bnt			32.5	16.8	1.38	
RLIS2	Bnt			37.6	17.8	1.47	
RLOS3	Bnt			30.4	14.8	1.29	
RLIS3	Bnt			36.0	16.2	1.56	
RLOS4	Bnt			44.7	20.1	1.39	
RLIS4	Bnt			42.2	18.1	1.52	
RLOS5	Bnt			30.5	14.7	1.62	
RLIS5	Bnt			34.9	16.9	1.61	
RLOS6	Bnt					1.61	
RLIS6	Bnt					1.59	
RLOS7	Bnt					1.51	
RLIS7	Bnt					1.51	
RLOS8	Bnt					1.47	
RLIS8	Bnt					1.45	
RLOS9	Bnt					1.25	
RLIS9	Bnt					1.23	
RLOS10	Bnt					1.34	
RLIS10	Bnt					1.50	
C1	Bnt	32	34	36.7	19.3	1.58	
C2	Bnt	35	30	30.8	15.6	1.49	
C3	Bnt	43	16	23.7	9.0	1.53	
C4	Bnt	29	47	40.6	19.3	1.44	
C5	Bnt	38	28	32.0	16.5	1.54	
C6	Bnt	36	33			1.38	
C7	Bnt	32	35			1.52	
C8	Bnt	35	31			1.40	
C9	Bnt	35	36			1.55	
C10	Bnt	42	27			1.49	
L1	Bnt			38.8	20.3	1.64	
L2	Bnt			27.4	12.9	1.76	
L3	Bnt			29.0	13.9	1.45	
L4	Bnt			30.8	14.2	1.51	
L5	Bnt			27.1	12.9	1.60	
L6	Bnt					1.36	
L7	Bnt					1.46	
L8	Bnt					1.54	
L9	Bnt					1.41	
L10	Bnt					1.64	
ROS1	BC	36	32	32.5	17.0		
RIS1	BC	37	32	32.4	17.5		
ROS2	BC	35	35	34.4	16.9		
RIS2	BC	44	24	29.5	12.8		
ROS3	BC	33	30	34.2	17.0		
RIS3	BC	28	38	40.3	16.9		
ROS4	BC	28	38	40.8	18.6		
RIS4	BC	17	43	48.0	23.9		
ROS5	BC	31	34	38.0	18.9		
RIS5	BC	30	29	35.0	16.6		
ROS6	BC	39	24				
RIS66	BC	12	44				
ROS7	BC	45	30				
RIS7	BC	42	25				
ROS8	BC	44	29				
RIS8	BC	44	27				
ROS9	BC	37	29				
RIS9	BC	40	28				
ROS10	BC	38	31				
RIS10	BC	33	31				
RLOS1	BC			31.9	16.0		
RLIS1	BC			31.1	15.8		
RLOS2	BC			39.1	19.7		

Appendix 5 Continued

Treatment+Pit	Horizon	% Sand	% Clay	% Moisture 33 kPa	% Moisture 1500 kPa	Bulk Density gms/cubic cm	Modulus of Rupture kPa
RLIS2	BC			37.9	19.7		
RLOS3	BC			33.9	17.3		
RLIS3	BC			37.6	19.4		
RLOS4	BC			47.0	18.7		
RLIS4	BC			46.5	19.9		
RLOS5	BC			31.6	14.9		
RLIS5	BC			34.2	13.6		
RLOS6	BC						
RLIS6	BC						
RLOS7	BC						
RLIS7	BC						
RLOS8	BC						
RLIS8	BC						
RLOS9	BC						
RLIS9	BC						
RLOS10	BC						
RLIS10	BC						
C1	BC	25	41	42.8	20.5		
C2	BC	39	26	32.5	14.7		
C3	BC	43	20	28.7	11.5		
C4	BC	23	36	39.0	19.9		
C5	BC	35	31	37.4	18.2		
C6	BC	27	36				
C7	BC	29	32				
C8	BC	23	39				
C9	BC	35	34				
C10	BC	36	33				
L1	BC			44.0	18.1		
L2	BC			30.2	13.6		
L3	BC			30.6	13.0		
L4	BC			33.0	16.1		
L5	BC			28.5	11.8		
L6	BC						
L7	BC						
L8	BC						
L9	BC						
L10	BC						
ROS1	Cca			29.4	15.5		
RIS1	Cca			36.8	18.3		
ROS2	Cca			35.6	19.3		
RIS2	Cca			26.6	12.4		
ROS3	Cca			26.4	14.2		
RIS3	Cca			24.3	11.6		
ROS4	Cca			37.4	23.5		
RIS4	Cca			31.7	18.8		
ROS5	Cca			29.6	16.3		
RIS5	Cca			30.5	15.5		
ROS6	Cca						
RIS66	Cca						
ROS7	Cca						
RIS7	Cca						
ROS8	Cca						
RIS8	Cca						
ROS9	Cca						
RIS9	Cca						
ROS10	Cca						
RIS10	Cca						
RLOS1	Cca			31.1	11.6		
RLIS1	Cca			31.1	12.8		
RLOS2	Cca			28.9	15.1		
RLIS2	Cca			26.8	13.8		
RLOS3	Cca			29.0	15.0		
RLIS3	Cca			29.1	14.6		
RLOS4	Cca			46.5	16.8		
RLIS4	Cca			43.9	19.0		
RLOS5	Cca			31.2	13.8		
RLIS5	Cca			27.0	10.6		
RLOS6	Cca						
RLIS6	Cca						
RLOS7	Cca						
RLIS7	Cca						
RLOS8	Cca						
RLIS8	Cca						
RLOS9	Cca						
RLIS9	Cca						
RLOS10	Cca						
RLIS10	Cca						
C1	Cca			28.4	12.5		
C2	Cca			36.4	14.2		

Appendix 5 Continued

Treatment+Pit	Horizon	% Sand	% Clay	% Moisture 33 kPa	% Moisture 1500 kPa	Bulk Density gms/cubic cm	Modulus of Rupture kPa
C3	Cca			28.0	12.0		
C4	Cca			30.2	15.3		
C5	Cca			29.7	11.6		
C6	Cca						
C7	Cca						
C8	Cca						
C9	Cca						
C10	Cca						
L1	Cca			31.9	17.2		
L2	Cca			29.7	13.2		
L3	Cca			30.9	14.4		
L4	Cca			35.8	14.6		
L5	Cca			25.0	9.4		
L6	Cca						
L7	Cca						
L8	Cca						
L9	Cca						
L10	Cca						

Appendix 6. Wheat and Straw Yields

Wheat Yields 1982
gms/ sq. yd.

Sample	Check	Ripped	Limed	Ripped+Lime
1	184	265	148	212
2	94	287	174	261
3	108	228	194	203
4	188	291	212	201
5	178	197	234	237
6	200	200	243	252
7	232	250	195	291
8	147	220	216	266
9	165	257	224	238
10	145	299	174	203
11	223	284	181	238
12	261	208	193	280
13	183	230	246	235
14	214	209	229	305
15	154	238	180	248
16	170	335	213	296
17	207	238	187	279
18	147	184	207	262
19	163	315	174	280
20	147	305	221	311

Straw Yields 1982
gms/ sq. yd.

Check	Ripped	Limed	Ripped+Lime
252	353	198	200
131	360	202	309
138	295	218	212
185	349	237	233
231	249	264	267
220	272	269	306
246	324	260	363
289	347	296	344
219	322	300	297
233	357	221	311
186	321	243	380
270	272	242	406
335	321	267	320
242	268	242	480
277	327	225	304
217	451	270	415
249	332	124	387
263	273	226	387
211	381	266	297
207	405	287	383

Appendix 6 Continued

	Wheat Yields 1983 gms/ sq. yd.				Straw Yields 1983 gms/ sq. yd.			
Sample	Check	Ripped	Limed	Ripped+Lime	Check	Ripped	Limed	Ripped+Lime
1	71	122	127	122	262	295	310	226
2	71	116	75	187	165	415	178	473
3	54	133	77	151	180	273	214	392
4	69	153	114	156	150	339	290	304
5	93	130	97	186	196	354	314	290
6	77	146	139	135	176	339	288	214
7	41	129	135	129	104	262	236	236
8	55	130	114	216	131	258	384	375
9	68	106	160	151	174	225	257	318
10	73	151	48	185	171	324	180	309
11	62	114	46	136	166	213	103	215
12	75	109	79	134	162	214	199	235
13	108	124	52	130	239	232	154	265
14	70	98	56	116	175	237	181	203
15	43	101	69	143	101	235	141	253
16	117	72	69	192	261	210	170	399
17	91	140	173	135	149	261	402	303
18	48	90	62	126	214	212	201	402
19	133	101	85	156	403	257	218	368
20	116	121	100	146	268	242	268	366

Appendix 6 Continued

	Wheat Yields 1984 gms/ sq. yd.				Straw Yields 1984 gms/ sq. yd.			
Sample	Check	Ripped	Limed	Ripped+Lime	Check	Ripped	Limed	Ripped+Lime
1	74	66	89	77	100	112	127	111
2	98	110	72	113	134	145	109	185
3	109	99	189	92	141	139	233	145
4	93	74	51	129	114	111	74	191
5	56	73	94	84	73	121	134	134
6	71	183	56	211	95	217	86	300
7	69	179	74	71	89	203	134	176
8	117	181	143	75	131	232	244	165
9	60	152	77	171	73	174	152	249
10	47	111	73	114	64	144	182	231
11	43	129	55	90	49	172	119	166
12	52	208	53	73	70	256	130	170
13	63	165	35	99	90	217	79	174
14	65	149	52	106	97	174	107	208
15	114	182	96	114	57	212	165	182
16	107	218	165	131	145	258	312	227
17	32	192	172	138	67	205	248	218
18	82	109	88	194	121	167	156	286
19	112	70	89	98	161	124	195	167
20	108	128	83	88	127	169	136	113

Appendix 6 Continued

	Wheat Yields 1985 gms/ sq. yd.				Straw Yields 1985 gms/ sq. yd.			
Sample	Check	Ripped	Limed	Ripped+Lime	Check	Ripped	Limed	Ripped+Lime
1	117	133	108	144	115	137	112	163
2	78	166	83	265	67	179	91	296
3	200	168	196	195	178	188	211	213
4	110	310	104	135	101	327	116	138
5	57	258	192	104	66	234	242	114
6	66	269	71	142	72	239	124	149
7	126	235	172	179	118	219	190	182
8	56	302	154	181	58	281	148	178
9	27	201	110	151	40	201	152	160
10	62	239	58	223	76	226	76	208
11	142	233	29	217	142	244	54	192
12	63	225	51	184	71	227	86	164
13	113	200	213	235	116	188	276	214
14	40	206	157	172	52	189	171	164
15	149	202	58	113	185	208	77	136
16	75	318	50	180	77	355	54	223
17	180	233	76	109	205	183	74	64
18	27	165	175	225	56	150	212	237
19	123	215	74	182	152	197	87	193
20	116	199	165	249	120	169	203	286

Appendix 7 Root Mass Data

Root mass values are expressed in gm dry wt. of roots per sampling core.
Sampling core volume was 443.4 cubic cm.

Ripped+Lime Treatment or "Ripped"

Core #	0-13 cm Depth	13-26 cm Depth	26-38 cm Depth	38-51 cm Depth	51-64 cm Depth	64-76 cm Depth
1.	0.0640	0.0746	0.0787	0.0708	0.0150	0.0122
2.	0.0470	0.0468	0.0526	0.0290	0.0109	0.0055
3.	0.0676	0.0463	0.0501	0.0272	0.0057	0.0020
4.	0.0653	0.0542	0.0420	0.0290	0.0146	0.0095
5.	0.0962	0.0685	0.0675	0.0697	0.0521	0.0253
6.	0.0448	0.0525	0.0717	0.0495	0.0205	0.0033
7.	0.0654	0.0154	0.0379	0.0397	0.0240	0.0083
8.	0.0577	0.0566	0.0425	0.0416	0.0136	0.0043
9.	0.0972	0.0588	0.0570	0.0512	0.0310	0.0077
10.	0.0561	0.0767	0.0703	0.0461	0.0101	0.0032

Limed Treatment or "Non-Ripped"

Pit	0-13 cm Depth	13-26 cm Depth	26-38 cm Depth	38-51 cm Depth	51-64 cm Depth	64-76 cm Depth
1.	0.0538	0.0616	0.0629	0.0662	0.0203	0.0072
2.	0.0354	0.0835	0.0965	0.0154	0.0026	0.0007
3.	0.1135	0.1024	0.0525	0.0088	0.0044	0.0038
4.	0.0701	0.0755	0.1138	0.0653	0.0332	0.0124
5.	0.0534	0.0859	0.1168	0.0522	0.0287	0.0097
6.	0.0824	0.1702	0.0716	0.0167	0.0066	0.0072
7.	0.0956	0.0968	0.0484	0.0059	0.0028	0.0018
8.	0.0538	0.1089	0.0482	0.0099	0.0041	0.0016
9.	0.0304	0.1035	0.0795	0.0304	0.0031	0.0007
10.	0.0338	0.0934	0.0912	0.0183	0.0166	0.0023