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PROPERTIES OF SOIL PROFILES OVER SODIC MINE SPOIL 16 YEARS AFTER CONSTRUCTION

By

Danielle L. H. Bailey ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Land Reclamation and Remediation

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ABSTRACT

Physical, chemical and root mass differences between two constructed profiles were examined after 16 years. Silty clay subsoil of 0.55 m or 0.95 m thickness was placed over a sodic sandy clay mine spoil topped by 15 cm of clay loam. At common depths below 65 cm, significantly greater 0.55 m spoil Db (ca 1.7 Mg m^{-3}) occurred compared to subsoil Db (ca 1.6 Mg m^{-3}) of the 0.95 m profile. Soluble Ca, Mg, and Na, SAR, EC and pH did not differ ($P<0.05$) between profiles at common distances from spoil interface. A notable increase of soluble Na to (ca 11 mmol L^{-1}) and SAR (10) occurred in the 15 cm directly above both spoil interfaces. Root mass, predominantly alfalfa (*Medicago sativa*) and bromegrass (*Bromus inermis*) did not differ between profiles. Still, the 0.55 m and 0.95 m profiles differed in agricultural capability, rated at class 4 and class 3, respectively.

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TABLE OF CONTENTS

CHAPTER 3 - CHEMICAL PROPERTIES OF SOIL PROFILES OVER SODIC MINE SPOIL 16 YEARS AFTER CONSTRUCTION.

3.3 Materials and Methods

CHAPTER 4 - ROOTING PROPERTIES OF SOIL PROFILES OVER SODIC MINE SPOIL 16 YEARS AFTER CONSTRUCTION.

4.3 Materials and Methods

CHAPTER 5 - LAND CAPABILITY CLASSIFICATION

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 BACKGROUND

1.1.1 Coal Demand

Coal is one of Alberta's most lucrative natural resources. Not only is Alberta one of the largest coal producing provinces, but it also consumes the largest amount of coal in Canada (Shapiro 1997). The Alberta government recognizes this in the coal Development Policy which states, " An energy source of this magnitude cannot be ignored or remain undeveloped indefinitely, especially in view of the fact that Alberta's supplies of relatively low cost energy sources- conventional crude oil and natural gas - are being steadily depleted" (Patching et al.1980).

1.1.2 Strip Mining and Government Environmental Implications

Strip mining, the most common method of coal mining in the Alberta plains, creates a potential threat of extensive degradation to the environment. The very nature of surface mining alters the topography, destroys vegetation and disrupts unique soil horizons. The extent of disruption depends on the geological placement of the coal-bearing strata and their characteristics. Open cast mining can operate up to 40 years. Surface disruption would be at a maximum during this period, but may continue after conclusion and reclamation, in the form of subsidence (Kourotchkine 1991). The Alberta government's main objective towards land reclamation is to "ensure that the mined or disturbed land will be returned to a state which will support plant and animal life or be otherwise productive or useful to man at least to the degree it was before it was disturbed" (Patching et al. 1980). In terms of remedial measures for land use, preference is towards agriculture restoration (Kourotchkine 1991). Many environmental engineers in the plains region face the challenge of restoring the land to cereal crop production, the most stringent level of reclamation for agricultural land (Patching 1980). In such cases, it is necessary to mine selectively to separate overburden material from the topsoil material. In some cases, such as a bentonitic mine spoil, it is extremely difficult to revegetate due to high sodicity, clay content, low permeability and semiarid climate (Schuman et al.

1994). In some cases, a layer of selected material is placed between the overburden and topsoil to facilitate a less compacted, deeper root zone and to mitigate the potential upward movement of unfavorable ions in climates where evaporation exceeds precipitation. However, Day et al. (1979) found that approximately the same yields of alfalfa, barley and wheat could be produced utilizing coal mine spoil from the Black Mesa Coal Mine in northeastern Arizona, when supported with optimum soil moisture and plant nutrients. Their study was laboratory and greenhouse based, so it lacked the compounding affects of compaction from mining equipment, which can result in increased bulk density and decreased percolation.

1.1.3 Highvale Soil Reconstruction Project History and Capability

In 1982, the Highvale Soil Reconstruction Project was initiated and continued during the following five years (1983-1987). The focus of the research was to identify the physical and chemical limitations in coal strip mine soil reclamation from which guidelines and a reclamation protocol would be established. This study's objective was also to minimize soil disturbance and ensure the return of soil capability equal to that which existed prior to disturbance. Another objective was to discern a suitable thickness of subsoil for forage and cereal crop production. Due to climate, topography, soil structure and drainage limitations, the soil capability for agriculture of the project area was not rated above Class 3 (Graveland et al. 1988). Approximately 20% of the mining permit area met the requirements of a class 3 capability while 37% and 35% were rated 4 and 5, respectively. The remaining 8% of the area was rated as class 6, suitable for rough grazing only.

1.2 LITERATURE REVIEW

1.2.1 Subsoil Thickness

Since the 1970s, research in the Northern Great Plains of North America has demonstrated that subsoil thickness which maximizes agricultural crop production varies widely depending on the demands of the soil environment. Hargis and Redente (1984) think three ecological factors determine soil replacement thickness; they are (in increasing order of importance): quality of overburden to be covered, annual average effective precipitation, and soil quality. In the case of sodic overburden that has potentially toxic concentrations of sodium for plant roots, subsoil should be placed to a depth such that the diffusion of sodium into the root layer is minimized or prevented completely. Failure to place sufficient subsoil over the spoil may cause deleterious effects on vegetation productivity for several years after replacement, due to upward sodium diffusion (Hargis and Redente 1984). Barth and Martin (1984) determined from their studies in Montana, Wyoming and North Dakota, that maximum production could be obtained with 71 cm of loam subsoil, over spoil with a pH of 8.2 and a SAR of 28. However, this was based on a relatively short, 6-year study of cool season perennial grasses, known to be easily established and maintained (compared to most other plants) in reclaimed soil due to their relatively low water requirements and drought tolerance (Day et al. 1979). Schuman and Power (1981) from research in North Dakota also suggested that a subsoil thickness exceeding 75 - 100 cm had little benefit. Power et al. (1981), also in North Dakota, had a similar sentiment from a constructed subsoil wedge experiment, that a total soil thickness exceeding 150 cm was unwarranted. However, they also concluded that the subsoil thickness should be no less than 90 cm over spoil with a SAR of 25, and 38% clay. Hargis and Redente (1984) deemed it important that the replacement material be thick enough to store spring runoff precipitation at field capacity to support plant requirements during the dry summer months of the semiarid western United States. The Halvorson et al. (1986) North Dakota study concluded that a loamy sand spoil texture required a thicker layer of replacement subsoil compared to finer textured spoils such as clay loam and silty clay loam, to produce comparable yields. This finding was based on the greater ability of the finer textured material to supply water to the growing crop throughout the growing season. However, this finding was also based on non-sodic, non-saline spoil, and therefore is likely an underestimation of the required subsoil thickness for sodic spoil where upward sodium migration into the subsoil can decrease subsoil capability and agricultural crop yields.

Replacing subsoil is the single most costly item in land reclamation of drastically disturbed land (Barth and Martin 1984). Thus, it is important to understand what thickness of subsoil is required for certain soil factors to sustain maximum crop production. Likewise, for economic reasons, the thickness of subsoil should not be excessive, such that the length of the growing season or precipitation are not sufficient to permit vegetation from deriving maximum benefit from the total soil thickness (Hargis and Redente 1984). Only then, can guidelines be established with confidence that the soil will be restored to equal capability, avoiding excessive costs.

1.2.2 Soil Physical Properties Associated with Sodic Mine Spoils

The physical characteristics of a reclaimed soil will change as a result of mining practices, particularly if the soil overlies sodic spoil. These physical characteristics include an increase in bulk density and a change in drainage properties. Potter et al. (1988) indicated the important potential for using soil physical and chemical properties as a quick and less costly index to measure reclamation success after soil construction.

Reclamation success can be evaluated by direct measurement of soil physical properties such as bulk density. Soil structure and the related inter-aggregate pore spaces are among the most important soil properties disrupted from mining and reclamation practices (McSweeney and Jansen 1984). Bell et al. (1994) observed massive subsoil properties of constructed profiles after mining and replacement. This contributed to the high subsoil bulk densities that ranged 1.79 - 1.89 Mg m^{-3}. The high bulk density values are at least partly related to the specific mining equipment used during soil replacement operations (wheeled scrappers having a more detrimental effect than tracked vehicles). The method used to determine bulk density is also important. Bell et al. (1994) utilized the clod method to determine bulk density, which can have a bias towards more compact intact clods. Potter et al. (1988) found that constructed profile subsoil had greater bulk densities that increased with time compared to undisturbed soils. Despite the greater bulk density and the associated lower total pore volume, their 11-year site had a greater proportion of macropore volume compared to the 4-year site. However, differences in topsoil and subsoil replacement for each site (0.40 m and 0.33 m, respectively in the 4-yr site; and 0.19 m and 0.22 m, respectively in the 11-yr site) made it difficult to attribute the differences in bulk density and pore size distribution, to time alone.

Mine spoils are also characterized by high bulk density values with low porosity resulting from the lack of structure and a compacted state (Thurman and Sencindiver 1986); whereas, natural soils are more porous with an elaborate system of cracks and fissures (Pedersen et al. 1980). Mine spoil bulk densities can span anywhere from 1.55 to 1.86 Mg m^{-3} (Thurman and Sencindiver 1986). Pedersen et al. (1980) found a spoil bulk density resulting from surface-coal mining in Pennsylvania to be 1.76 Mg m^{-3}. However, Pedersen et al. (1980) also described spoil with large spaces and cavities, to have a bulk density as low as 1.00 Mg m^{-3}. It was expected, though, that the higher bulk densities are associated with shallow spoils that have a larger degree of equipment compaction and include consolidated solid sandstone or shale fragments.

High-density and lower porosity diminish the water holding capacity of a soil, which increases the likelihood of a saturated soil (Bell et al. 1994). Pedersen et al. (1980) and Ward et al. (1983) resolved that mine spoils had lower percolation values compared to natural soils. Ward et al. (1983) attributed low spoil water percolation to high spoil bulk densities; however, measurements were based on a lab experimental design and may not have reflected field conditions. The study also noted reduced water flow through 15 cm of a silt loam topsoil (above the spoil) due to a surface sealing phenomenon where the cracks swelled and then were further sealed with sediment-laden flow. Bunting (1978) and Scullion and Mohammed (1986) found that initially, the subsoil was effective at facilitating field drainage. However, this deteriorated after 2 to 4 years. These results may be unique to the climate of the study sites in the East Midlands and South Wales, respectively, (which averages more than three times the annual precipitation compared to the subhumid climate in parts of Alberta). However, El-Mowelhi et al. (1976) also found that the ameliorative effects of subsoiling, over sodic spoil lasted only 18 -24 months in their study of Egyptian soils. This result may also have been due to the sealing phenomenon mentioned above, since montmorillonite was the dominant clay mineral. Stewart and Scullion (1989) described the inevitable destruction of soil structure from excavation, storage and replacement practices of mining that contributed to the close packing of particles and excess soil water. This was further validated when Merrill et al. (1985) attributed the accumulated soil water above the subsoil/ mine spoil contact, to the reduced percolation rate of the mine spoil. Highly saline or alkaline soils became poorly aerated and impermeable, and in the presence of a high water table, accelerated upward movement of salts toward the soil surface occurred (Ansari et al. 1979). For this reason, it is crucial that there is adequate profile drainage to leach the dissolved sodium downward. This was a concern in the 1982 Highvale study. It was noted that soil water accumulating above the subsoil/ mine spoil contact could facilitate an upward movement of soluble sodium from the sodic mine spoil (Oddie and Bailey 1988). However, Power et al. (1981) observed no evidence of soil water accumulation above the subsoil / spoil interface in their North Dakota study of subsoil over spoil high in clay and sodium (SAR about 25). As well, Schuman and Power (1981) in North Dakota did not observe water accumulating above the soil / spoil interface that would enhance upward salt migration.

1.2.3 Soil Chemical Properties Associated with Sodic Mine Spoils

Sodic mine spoils, such as those originating from the Edmonton Formation from upper Cretaceous strata (Lindsay 1968), create the potential for adverse chemical properties that need to be monitored. Salinity refers to the total soluble salt content in soil solution. Electrical conductivity is the standard measurement for salinity. Sodicity, on the other hand, is a ratio of sodium ions occupying the soil exchange sites compared to the preferred calcium and magnesium ions (Bauder 1998a). Chemical properties such as pH, electrical conductivity, exchangeable and soluble cations provide a good measure of the health of the soil. These properties offer a baseline from which to monitor change since these chemical properties change slowly and only if there are dramatic changes in the soil environment, such as a change in drainage (Bauder 1998b).

Deterioration of subsoil quality resulting from the upward migration of sodium from spoil may contribute to a decline in soil productivity, defined as the 'capacity of a soil to produce a certain yield of crops or other plants with a specified system of management' (SSSA 1999). It is important to characterize the soluble and exchangeable cations in the soil profile since studies of constructed soils (less than two years old) showed increased concentrations of exchangeable calcium and sodium, reflecting overburden characteristics, compared to the natural soils (Indorante et al. 1981). Accumulated water above the mine spoil due to reduced permeability increases the efficiency of sodium migration upward via chemical diffusion or convection (Merrill et al. 1985, Oddie and Bailey 1988). Barth and Martin (1984) observed sodium migration from the spoil (SAR of 28) upward into 14 cm of the lower subsoil material, during a 5-year study. Within this zone, soluble sodium increased from 2.9 to 11.7 mmol L^{-1}. High concentrations of the sodium cation compared to the other cations present, pose a threat to soil quality, which may limit crop productivity.

Sodic soils are described to have an exchangeable sodium percent (ESP) greater than 15 (Hall and Berg 1983, Pessarakli 1991) and a sodium adsorption ratio (SAR) of 13 or more (Sommerfeld and Rapp 1982). The ion exchange phenomenon describes the status of the soil colloid with respect to the exchanging cations and anions between the clay surface and soil water. Cation exchange equilibrium occurs under nonsymmetrical exchange, which depends on the valence of the adsorbed and counter ions and the total ionic concentration of the soil solution. In dilute soil solution, cations with higher valences are preferred over lower valence cations to balance the clay's negative charge. Hence, for soil solutions containing cations with different valences, greater adsorption of higher valence cations would occur (i.e., calcium cation favored over sodium). However, under increasing ionic concentration of the soil solution, cations with lower valences are preferred for replacement to the colloidal exchange sites (sodium cation favored over calcium). These changes in colloidal status of cation replacement affect physical, chemical and biological properties of the soil (Szabolcs 1989).

Sodic soils have the adverse consistency of hard when dry and plastic and sticky when wet (Tanji 1990). High sodium concentration associated with the clay exchange complex will lead to the physical breakdown of soil structure and reduced soil permeability (Goldberg and Glaubig 1987). Clay dispersion, caused by the repulsion of the individual colloidal particles, fosters the migration of clay to plug soil pores, restricting the movement of air and water, which is the dominant cause of reduced permeability in sodic soils (Fairbridge and Finkl 1979, Goldberg et al. 1991).

Another hazard of sodic soils is the osmotic stress endured by the plant roots due to high concentrations of soluble cations (such as sodium) in the soil water. This sodic hazard is compounded by the low level of available water from restricted water infiltration into the root zone (Tanji 1990), since hydraulic conductivity is inversely related to increases in ESP values of sodic soils (Szabolcs 1989).

Goldberg et al. (1991) not only found that critical coagulation concentration (CCC) values increased with increasing SAR and ESP for reference montmorillonite clays, but the greatest incremental change in CCC occurred in the increase of SAR from 0 to 20, compared to larger values of SAR. However, due to the asymmetrical exchange of sodium and calcium ions, adsorption shifts to favor one cation over the other depending on the ionic concentration, as described by the ion exchange phenomenon (Szabolcs 1989).

Bauder (1997) describes a healthy soil to have a pH between 6.5 and 8.2 and an EC less than 1.0 dS m^{-1}. Conversely non-saline sodic soils are alkaline. The pH of the saturated paste is high, often surpassing 8.5 (Sommerfeldt and Rapp 1982), while the electrical conductivity is less than 4 dS m^{-1} at 25°C (Fairbridge and Finkl 1979). Indorante et al. (1981) in Illinois studied the changes in constructed soils over bentonitic mine spoil. After two years, the pH in the subsoil increased to reflect the pre-mining overburden character compared to the natural soil.

Alkaline sodic soils are commonly associated with poorly drained sites (Bauder 1998a). In extreme cases, the soil can be impervious to water (Fairbridge and Finkl 1979). Alkaline conditions cause aggregates to disintegrate and disperse soil particles that reduce the large pore space in soils (Pessarakli 1991). Goldberg and Glaubig (1987) and Goldberg et al. (1991) found that pH affected the flocculation - dispersion behavior of reference montmorillonitic clays such that the critical coagulation concentration of the sodium-affected clays increased with increasing pH. However, this pH effect was more pronounced with sodium kaolinite than sodium montmorillonite, which was attributed to the greater proportion of pH dependent charge associated with kaolinite mineralogy compared to montmorillonite. The Goldberg and Foster (1990) study also validated the detrimental effect of increasing pH's encouraging dispersion in reference montmorillonite soil, noting that extrapolation from reference clay results (based on mineralogy) should be done with caution. However, other factors such as iron and aluminum oxides and organic material should be considered since they influence the dispersion behavior of clays.

It is accepted that no crop plant will suffer detrimental effects from salt injury when the electrical conductivity of a saturation paste extract (EC) is less than 4 dS m^{-1}. However, if the EC exceeds 8 dS m^{-1}, only salt tolerant crops will produce satisfactory yields (Fairbridge and Finkl 1979). Despite the relationship of increased soil water salinity with decreased water availability and reduced crop growth and yields (Tanji 1990), high levels of electrolyte concentration can significantly improve the physical characteristic of water infiltration through sodic soils (Schuman and Meining 1993). The structural integrity of sodic soil may be lost to clay dispersion and thus, aggregate breakdown, if the electrical conductivity of the soil water is less than the clay's critical coagulation concentration for a particular soil (Goldberg and Glaubig 1987). The flocculation value of a soil is unique depending on the presence of binding material such as organic material and oxides. However, as the percent of exchangeable sodium increases, so does the electrical conductivity for the clay to remain flocculated (Tanji 1990).

1.2.4 Root Development

Mining practices that disrupt important soil properties such structure and increase bulk density may affect root proliferation. Consequently, the interaggregate pore spaces necessary for macropores and aeration, that provide areas of low mechanical impedance to root growth, are reduced due to compaction from the mining equipment (Potter et al. 1988). Some extreme reconstruction cases, associated with scraper equipment, have reported massive subsoil properties, that restrict vertical and encourage lateral proliferation of roots (McSweeney and Jansen 1984, Bell et al. 1994). Thus, rooting depth can elucidate a limiting layer within the reconstructed profile. As well, analyzing root mass from revegetation experiments, gives insight to the biological success of the complex recovery process (Hargis and Redente 1984).

The 1982 Highvale study (Oddie and Bailey 1988) concluded that forage root depth increased with increasing total soil thickness. Without the restriction imposed by spoil material, the effective root zone of the alfalfa - smooth bromegrass mix extended to 185 cm based on root depth and soil moisture measurements. Generally, the effective root zone accounts for ≥ 80% of the total water removed from the soil via evaporation and transpiration (Graveland et al. 1988). Schuman and Power (1981) in North Dakota observed water extraction by alfalfa to a depth of 135 cm, if the roots did not encounter spoil material. However, root water uptake is affected by gradients in soil water potential, soil hydraulic conductivity and root density, so caution should be exercised in interpreting water extraction as a result of root penetration (Merrill et al. 1985).

Root penetration into the mine spoil would likely reduce bulk density and improve percolation of soil water. The Highvale study noted that in 1987 the alfalfa - smooth bromegrass roots penetrated the mine spoil in the 0.55 m and 0.95 m treatments to an average depth of 17 and 26 cm respectively (Oddie and Bailey 1988). The Power et al. (1981) North Dakota 4-year study assumed soil water withdrawal to be an indicator of root penetration, and found greater depths of root activity to 30 -90 cm into sodic mine spoil when the upper boundary of the spoil was within 90 cm from the surface. As well, Merrill et al. (1985) in North Dakota observed herbaceous crop species roots penetrating to a depth of 25 cm into spoil (SAR of 29) with comparable root weights to what was found in the subsoil. In a 0.50 m subsoil thickness treatment, the root weights in the mine spoil between the depth of 50 - 75 cm were not significantly different from the root weights in subsoil at the same depth for either the 0.75 or 1.0 m subsoil treatment. However this spoil had a lower bulk density (1.45 Mg m^{-3}) compared to the subsoil (1.64 Mg m^{-3}). Thus, root growth into the mine spoil was not limited by the constraints of compaction that characterize other spoils. However, Barth and Martin (1984) in the Northern Great Plains, reported root penetration only 10 cm into spoil with similar characteristics. Depuit et al. (1982) also noticed a drastic decline in 2-year-old root biomass across the contact zone into the sodic spoil material with an SAR of 23, so that only 6% to 12% of total root material occurred within the spoil material.

Schroeder and Halvorson (1988) noted that growing season precipitation and the ability of the crop's rooting system to deplete stored soil water during the off season, as key factors, limiting crop growth in the Northern Great Plains. During periods of inadequate or poorly distributed precipitation, they linked lower yields from reclaimed sites to the shallower root growth and the associated lesser depletion of soil water, compared to undisturbed soil. They noted that if not for differences in soil water depletion between the reclaimed and undisturbed soils, the reclaimed soil would most likely have met the "equal or better than" reclamation law requirement.

1.2.5 Soil Capability Classification

The Land Capability Classification of Arable Agriculture in Alberta (ASAC 1987) recognizes three major components that influence soil capability independently. Capability is defined by 'the nature and degree of limitations imposed by the physical characteristics of a land unit for a certain use' (ASAC 1987). The three components rated separately are; climate (moisture and energy), soils (surface and subsurface) and landscape. The final, lowest numerical rating (based on accumulated points of deduction) decides the class rating. There are seven classes, class 1 -having the least amounts of deducted points (index span of 80 - 100), described to have no significant limitation to crop productivity. Class 7 has the greatest amount of point deductions (index span of 0 - 9). This class is described as incapable to support arable agriculture. Class 3 (45 - 59 index points) describes land with moderate limitations restricting the range of crops and/or requires modified management practices. Class 3 is the lowest class of land that is considered acceptable for agricultural production without requiring severe and special management practices, and classes numerically higher than class 4 are not recommended for crop cultivation at all.

Capability class denotes land that is similar in the degree of limitation; however, it is the subclass that portrays the kind of limitation for a certain capability class. In total there are twenty-one different subclasses recognized in this system. These subclasses highlight soil and land characteristics that should be considered when deciding management practices.

The system's applicability to disturbed or reclaimed land suggests that since the system is based on quantitative and measurable factors of climate, soil or landscape, the integrity of the system is not compromised if it were to be applied to a reclaimed soil. Assessment of land pre-and post-disturbance may differ in limited soil and/or landscape characteristics; however, the reliability of agriculture capability assessment of features that affect plant growth would not be reduced.

The Agricultural Capability Classification for Reclamation (RRTAC 1993) is a system, specifically intended for Alberta's agricultural zone where land is disturbed by the oil and gas industry and by coal mining. This classification system is primarily based on the soil and landscape component. It is assumed that climate remains unchanged regardless of pre or post disturbance, so it is optional. Soil capability for agriculture is defined here as the 'nature and degree of limitations imposed by the physical, chemical and biological characteristics of a soil unit for crop production' (RRTAC 1993). The system is like the other in the description of classes that are also based on points deducted based on criteria stated in the different subclasses. There is agreement between both systems, only classes 1 - 3 can support sustained production of cultivated crops, while class 4 is marginal. Classes are based on similar index point ranges, however some of the criteria for deductions within certain subclasses may vary.

The Agricultural Capability Classification of Reclamation system differs from the other in that it evaluates the upper one meter of soil, emphasizing the upper 50 cm to relate to root zone quality. The capability survey of undisturbed land assesses the 1 m soil profile in two sections: surface (0-20 cm) and subsurface (20-100 cm). However the reclamation system considers the soil profile to consist of the three principal layers of profile and geologic materials: topsoil (0 up to 30 cm), upper subsoil (lower boundary of topsoil to 50 cm) and lower subsoil (50-100 cm). Also, the threshold value used to denote differences in the seven classes is a 15% reduction in soil productivity potential from one class to the next, such that on average, class 2 land would have 15% greater yields than class 3 land. It has been suggested that one method to evaluate reclamation success would be to compare the agricultural soil capability before and after disturbance. It is important to compare the two rating systems; Land Capability Classification for Arable Agriculture in Alberta and Agricultural Capability Classification for Reclamation to acknowledge any discrepancies between the two systems resulting in a different capability rating for soil quality.

1.3 RESEARCH OBJECTIVES

This study examines the success of a previous subsoil thickness reclamation project at the Highvale Experimental Plots, established in 1982. It is of interest to elucidate the type and direction of processes that are occurring within the two profile treatments constructed of 0.55 m and 0.95 m of subsoil, and to gain an understanding of what can be expected from reclamation projects similar to this. Ultimately, the purpose of this study is to describe how different treatments of subsoil replacement thickness affect the capability classification of reclaimed soil profiles overlying sodic mine spoil, after 16 years of soil development.

The objectives of this study are:

1. Determine if the physical properties of bulk density and volumetric soil water are different between the two subsoil profiles (0.55 m and 0.95 m), after 16 years of soil development, and how these properties affect soil capability.
2. Determine if the chemical properties of soluble cations, SAR, exchangeable cations, EC and pH are different between the two subsoil profiles (0.55 m and 0.95 m). Also, to consider the direction of soil development with respect to these chemical properties, particularly sodium migration, in the last 16 years and the associated implications to soil capability.

3. To assess if there are differences in root mass density between the two subsoil profiles (0.55 m and 0.95 m), and if so, to attribute the difference to specific limiting soil properties.

The synthesis chapter (chapter 6) evaluates and compares the two subsoil profile class ratings via the Agricultural Capability Classification for Reclamation, according to chemical soil profile properties, both in 1982 and currently. Also, trends of what may occur in the future will be suggested based on the findings of the past 1982 Highvale study and our current 1998 study. Finally, the specific property of sodium migration in our study is analyzed for differences or similarities compared to the other North American findings of constructed soils over sodic material with a common climate.

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CHAPTER 2

PHYSICAL PROPERTIES OF SOIL PROFILES OVER SODIC MINE SPOIL 16 YEARS AFTER CONSTRUCTION.

2.1 INTRODUCTION

In Alberta, the coal industry is currently faced with needs for greater amounts of coal resources, resulting in the expansion of surface mines, which in many instances incorporate and disturb large areas of agricultural land. Surface mining operations typically create mine spoils with physical and chemical properties that limit capability, especially if the spoil is sodic. It is important for reclamation protocol to provide an environment that will restore the soil's properties to obtain an equal capability rating.

Replacing subsoil and reconstructing soil horizons that existed prior to disturbance is the preferred method of reclamation for sodic mine spoils (Sandoval and Gould 1978). However, there is little consensus on the required thickness of subsoil to be replaced over mine spoil to alleviate the physical deterioration of structure and compaction resulting from mining operations. Barth and Martin (1984) in Wyoming, Montana and North Dakota determined that maximum production of perennial grasses could be obtained with 71 cm of loam subsoil, over spoil with a pH of 8.2, and a SAR of 28. As well, Schuman and Power (1981) suggested that a subsoil thickness exceeding 30 - 40 inches (75 - 100 cm) had little benefit to forage and crop yields. However, Power et al. (1981) concluded that the subsoil thickness should be no less than 90 cm over spoil with a SAR of 25 and 38% clay texture. Despite the discrepancy for the required thickness of subsoil replacement necessary for successful reclamation, it is understood that failure to replace sufficient subsoil over spoil may cause deleterious effects on vegetation production years after replacement. These deleterious effects could result from sodium diffusion (Hargis and Redente 1984), and the compounding effects of compaction from mining equipment during placement, causing increased bulk density and low infiltration.

Soil structure and the related inter-aggregate pore spaces are among the most important soil properties disrupted from mining and reclamation practices (McSweeney and Jansen

1984). Mine spoils have been characterized with high bulk densities and low porosity resulting from the lack of structure and the compacted state (Thurman and Sencindiver 1986); whereas, natural soils are more porous with an elaborate system of cracks and fissures (Pedersen et al. 1980). Bell et al. (1994) observed that reconstructed subsoil became massive as a result of mining. This contributed to the high subsoil bulk densities, which ranged from 1.79 to 1.89 Mg m^{-3}. The Highvale Reconstruction Project (Graveland et al. 1988), which studied the bulk density of constructed profiles varying in subsoil thickness ranging from 0.0 to 3.45 m, during 1983-1987, found no difference between the 0.55 and 0.95 m subsoil thickness profiles. However, a significant decrease in the profile bulk density occurred with time for the 0.55 m thick subsoil profile.

High-density soils with lower proportions of porosity diminish the water-holding capacity of a soil, increasing the likelihood of a saturated soil (Bell et al. 1994). Ward et al. (1983) attributed low spoil water percolation to high spoil bulk densities; however, measurements were based on a lab experimental design and may not reflect field conditions. Bunting (1978) and Scullion and Mohammed (1986) found that initially, subsoiling was an effective method to aid field drainage, however this deteriorated after 2 - 4 years. Stewart and Scullion (1989) describe the inevitable destruction of soil structure from excavation, storage and replacement practices of mining as contributing to the close packing of particles and excess soil water. This was further validated when Merrill et al. (1985) attributed the accumulated soil water above the subsoil / mine spoil contact, to the reduced infiltration capacity of the mine spoil. It has also been noted that highly saline or alkaline soils become poorly aerated and impermeable, and in the presence of a high water table, salt movement accelerates upward toward the soil surface (Ansari et al. 1979). For this reason, it is crucial that there is adequate drainage to leach the dissolved sodium downward away from the surface. This was a concern in the previous Highvale Plains Reclamation Research Project (1983-1987). It was noted that if soil water were to accumulate above the subsoil / mine spoil contact, an upward movement of soluble sodium from the sodic mine spoil, could result (Oddie and Bailey 1988). However, Power et al. (1981) observed no evidence of soil water accumulation above the soil / spoil interface in their study of subsoil over spoil high in clay and sodium (SAR about 25) in semiarid North Dakota.

To quantify and understand the specific soil properties of varying subsoil thickness to mitigate limitation associated with constructed soils over sodic mine spoils, this study analyzed two treatments of subsoil replacement varying in thickness from 0.55 m and 0.95 m, after 16 years of development. It was of interest to compare the two subsoil thickness profiles in their ability to restore physical properties such as bulk density and water storage from the deleterious effects of mining.

2.2 OBJECTIVES

The Highvale Plains Reclamation Research Project determined that a constructed soil profile with 0.95 m of subsoil was sufficient and necessary to produce regionally optimum yields of 4780 kg ha^{-1} yr^{-1} of alfalfa-smooth bromegrass hay based on a 5-year mean between 1983-1987 (AE 1989). However, the study also showed that yield difference between the 0.55 m and 0.95 m subsoil profile was not significant (Oddie and Bailey 1988). Thus, the purpose of this study was to elucidate the differences in physical properties, if any, between the two constructed profiles established over a sodic mine spoil, 16 years after placement. The specific objectives were to determine if the physical properties of bulk density and volumetric soil water content differed between the two subsoil profiles (0.55 m and 0.95 m), and to consider the direction and possible limitations they may pose to current soil genesis. The null hypotheses tested were:

1. There is no difference in bulk density with depth between and within the 0.55 m and 0.95 m subsoil profile.

2. There is no difference in volumetric soil water with depth between and within the 0.55 m and 0.95 m subsoil profile, measured October 18, 1999.

2.3 MATERIALS AND METHODS

2.3.1 Experimental Site

The experimental plots were located within the Highvale Mine Permit Area, 65 km west of Edmonton, (Sec. 7, Twp 52, Rge 4-W5) (53°29'N Lat., 114°34'W Long.) (Graveland et al. 1988, Oddie and Bailey 1988). The site was dominated with Gray Solodized Solonetz and Solonetzic Dark Gray Luvisolic soils with weathered residual bedrock and glacial till parent geological materials. Unconsolidated material overlaying a sodic bedrock ranged from 1 - 7 m thickness in the northern half of the Highvale mine Permit Area and up to 50 m in the southern half. This unconsolidated material consisted of lacustrine and till materials from the Tertiary Period Scollard Member of the Edmonton Formation (Graveland et al 1988). The bedrock coal-field consists of sandstone, shale and siltstone.

2.3.2 Background on Experimental Plots

The objective of the initial 1982 study was to determine a suitable thickness of subsoil for forage and cereal crop production. The experimental plots of constructed soil profiles were established in 1982 and monitored for the following 5 years (1983-1987). The Highvale study experimental design and layout (Figure 2-1) consisted of two factors in a randomized complete block design with 3 replicates. Six subsoil thicknesses (0.00, 0.55, 0.95, 0.1.35, 1.85, and 3.45 m) were randomized within main blocks with two seeded crop species: alfalfa (*Medicago sativa* L.) (cv. Rambler) / smooth bromegrass (*Bromus inermis* Leyss.)(cv. Carlton) forage mix, and barley (*Hordeum vulgare*) (cv. Klondike), randomized as split plots. Each main plot measured 16 m wide and 20 m long, and each subplot measured 8 m wide and 20 m long.

The experimental site was situated on the leveled peak of a spoil pile. The elevation of this berm-like landscape was approximately 746 m, 10 m above a hauling road (R. Lyle personal communication, Transalta Utilities), oriented parallel to the northern side of the experimental site and curving around the west side. On the south side of the experimental site, laid an active excavation pit that extended to a depth of approximately 25 m from the surface of the plots. The east side of the experimental site was flanked by an abandoned slope experiment, which rose above the experimental site by 4 m. The west side of the experimental site gently graded down towards the hauling road.

Plot construction included excavation of spoil material by a caterpillar tractor into post mine landscape and leveling to the required depth. The sides of the pits were lined in plastic to prevent possible lateral water and sodium movement. Subsoil, consisting of B and C horizon material was scraped from a borrow site using a bulldozer and packed to be level with the surrounding surface by truck. Topsoil consisting of predominantly Ah horizon material was added to a 15 cm thickness (Figure 2-2). The borrow site was located adjacent to the mined plot site and consisted of the soils from the Dark Gray Luvisol and Orthic Humic Regosol subgroups, underlain by till and weathered residual bedrock parent materials. The experimental site was graded to facilitate drainage away from the plots. The water table in the area was approximately at an elevation of 727 m.

2.3.3 Sampling Design

A total of seventy-two soil cores (12 per subplot, Figure 2-3), 6 cm in diameter and 1m to 1.25 m in length, were drilled by Terra Test Drilling Services Inc. Cochran AB, in October 1998 using a hydraulic drilling system. The cores contained in PVC pipes with the ends covered in resinite packaging film were stored at -10°C. The drill holes were back-filled prior to any precipitation with topsoil and subsoil material taken from the adjacent barley subplots. The following October (1999), 12 Uhland cores were manually extracted within 0.5 m of TDR probes (Figure 2-3) to augment bulk density data and calibrate TDR results for volumetric water content.

2.3.4 Soil Site Descriptions

In late October 1998, soil morphology was described for each subplot between the first and second most easterly northern cores. The pits were 1 m x 1 m to 15 cm below the subsoil / mine-spoil interface. Descriptions of color, mottles, structure, texture, consistency, coarse fragments, effervescence, roots and horizon boundary followed ACECSS (1987) (Figure A-1).

2.3.5 Physical Properties

A total of 12 drilled cores of 6 cm inside diameter were used for bulk density testing. Two cores per subplot were thawed and cut into approximately 7-15 cm length sections in each of the constructed layers, topsoil (TS), subsoil (SS) and spoil (Sp). Parts of the core that were fragmented with rocks, disturbed or broken were omitted from analysis. The samples were oven dried at 105°C to a constant weight.

In October 1999, Uhland core samples of 7.5 cm inner diameter and 331.2 cm^3 volume were also obtained to determine bulk density and field water content for calibration of the TDR probes. Two cores were drilled within half a meter of each of the two TDR probes in each subplot (Figure 2-3). Samples were taken at the depths: 0-10 cm, 15-25 cm, 25-40 cm, 40-50 cm, 50-60 cm, 65-75 cm, 75-85 cm, 95-105 cm, and 105-115 cm. Soil bulk density was determined using the method of Kalra and Maynard (1991).

Volumetric soil water was measured in situ with a type A, Moisture Point probe, developed by the Environmental Sensors Incorporation using Time Domain Reflectometry (TDR) technology. Prior to manual installation in the first week of November 1998, Environmental Sensors Inc. updated the data reader control box and calibrated the twelve probes. The probes have an active length of 120 cm divided into five segments of 0-15, 15-30, 30-60, 60-90, 90-120 cm (Figure 2-2). The volumetric soil water was expressed for the average depths of 7.5 cm, 22.5 cm, 45 cm, 75 cm, and 105 cm. Volumetric soil water content was measured twice in November 1998, and periodically from May through October 1999.

2.3.6 Statistical Procedures

Bulk density and volumetric soil water content results were analyzed with depth between the two subsoil profiles of 0.55 m and 0.95 m. The statistical model consisted of a split-plot analysis of variance (SAS Institute Inc., 1987). The current 1998 experimental design's main plots consisted exclusively of the forage profiles with the two subsoil thicknesses (0.55 m and 0.95 m) that occurred within the pre-existing randomized complete block experimental design (section 2.3.2), that were further split into depth increments. The general linear model procedure (GLM) was used to test the independent and fixed factor of subsoil thickness treatment with depth, with significant F values based on $P \leq 0.05$. A comparison of means from the interaction between depths within a common treatment was analyzed using the PDIFF option of the least significant means (LSMEANS) statement in the model. To compare similar depths between the two profiles, hand calculated least significant difference t-tests were used (Steel and Torrie, 1980)

2.4 RESULTS

2.4.1 Bulk Density

The significant treatment x depth interaction, determined from ANOVA (Table 2-1), showed greater measured bulk density (Db) in the 0.55 m subsoil profile ($P<0.05$) compared to the 0.95 m subsoil profile at depths below 0.65 m, which was the spoil material for the 0.55 m profile. As well, the significant depth effect portrayed a trend of increasing Db with depth, particularly in the 0.55 m subsoil where Db increased from topsoil to subsoil to spoil, compared to the 0.95 m subsoil, that only increased from topsoil to shallow subsoil.

The interaction effect of subsoil thickness and depth resulted from the greater spoil Db of the 0.55 m subsoil profile (about 1.75 Mg m^{-3}) compared to the lesser Db of the subsoil material of the 0.95 m profile (about 1.55 Mg m^{-3}) at a common depth (Figure 2-4). Bulk density above the depth of 0.65 m, of common profile material did not differ between the 0.55 m and 0.95 m subsoil profiles.

The significant depth effect portrayed a trend of increasing Db, particularly in the 0.55 m subsoil, where Db increased significantly from the topsoil layer (1.15 Mg m^{-3}) to the subsoil (about 1.55 Mg m^{-3}) to the spoil material (about 1.75 Mg m^{-3}). Other than the initial increase in Db from topsoil (1.1 Mg m^{-3}) to shallow subsoil (1.4 Mg m^{-3}), the Db of the 0.95 subsoil did not differ below the depth of 0.25 m (ca 1.55 Mg m^{-3}) (Figure 2-4).

2.4.2 Volumetric Water Content

Due to inaccurate volumetric water content readings from the TDR probes, discussed below, only the values determined from the Uhland cores taken on October 18, 1999 were used for statistical analysis. ANOVA determined no significant subsoil thickness treatment x depth interaction, or treatment effect (Table 2-2). However, the significant depth effect indicated a general increase in volumetric water content with depth below the topsoil layer. In both subsoil profiles, volumetric water content increased from about 0.17 $m^3 m^{-3}$ in the clay loam topsoil to about 0.23 $m^3 m^{-3}$ in the silty clay subsoil (Figure 2-5).

Unfortunately, the volumetric water content readings from the TDR probes taken during the 1999-growing season proved to be unreliable. The Uhland core calibration results indicated a general overestimation of water content by the TDR probes for all depths measured, particularly in the lower depths 60-90 cm and especially at 90-120 cm (Figure B-1). Also, consecutive readings for a depth segment of any particular probe were associated with high coefficient of variance (above 0.1), primarily for the depth segments 0-15 cm, 15-30 cm and 90-120 cm (Table B-1). Finally, porosity calculations based on the Uhland core Db indicated overestimation of TDR determined volumetric water content, typically in the 90-120 cm depth segment of both the 0.55 m and 0.95 m subsoil profile (Table B-2).

2.5 DISCUSSION

2.5.1 Bulk Density

It was anticipated that the spoil Db of the 0.55 m subsoil would be greater than the subsoil Db of the 0.95 m subsoil. Differences in Db between the subsoil profiles in the 0.6 to 1.2 m depth most likely reflected the inherent Db differences between the subsoil and spoil material. The spoil excavation by caterpillar tractor likely contributed greater spoil bulk density compared to the lighter truck used to deposit the subsoil and topsoil. Physical properties of spoil material generally include increased Db values compared to subsoil values unless the spoil contains large spaces and cavities often associated with high rock fragments such as solid shale or sandstone (Pederson et al. 1980). However in the absence of high rock fragments, spoil material can have Db as high as 1.8 Mg m^{-3} (Pedersen et al. 1980). Mechanical compaction of spoil, resulting from scrapers excavating and leveling spoil during soil profile construction, contributes to an undesirable massive physical condition (McSweeny and Jansen 1984). The massive structure of the spoil would add to increased Db. Lack of root penetration and freeze thaw cycles responsible for structure formation, at the depth of the spoil contact and below, would also have contributed to spoil Db being greater than subsoil Db.

The trend of increasing Db with depth from topsoil to subsoil in both profiles was also expected. In natural soils, topsoil Db values are normally between 1.1 to 1.3 Mg m^{-3} while subsoil Db is generally greater, at values of 1.3 to 1.7 Mg m^{-3} (Fairbridge and Finkl 1979). The topsoil and subsoil Db of both subsoil profiles were within these ranges. Furthermore, the Land Capability Classification for Arable Agriculture in Alberta (ASAC 1987) relates the physical properties of the constructed profile's Ah horizon (Figure A-2) of clay loam texture, granular structure and friable to slightly hard consistency, with a Db of 1.1 Mg m^{-3}. The topsoil Db in both profiles were near or equal to this agricultural value. Thus, topsoil Db of both subsoil profiles did not indicate deleterious effects from compaction during soil profile construction.

However, subsoil Db in both the 0.55 m and 0.95 m profiles increased with depth despite the effect of stockpiling replacing B and C horizon material as a relatively uniform subsoil (compared to natural soils that may vary in soil properties affecting Db). Reconstructed soils are more homogeneous for certain soil properties than native soils (Keck et al. 1993). Subsoil homogenized from the mining practices to create a medium uniform in texture would be expected to have similar Db values throughout the subsoil medium. Generally, Db values of constructed soils are greater compared to undisturbed soils (Potter et al. 1988). In fact, Potter et al. (1988) found the subsoil Db of an older 11-year old reclaimed soil profile to be greater than that of the younger 4-year old reclaimed site. Subsoil Db in both profiles did not increase ($P<0.05$) with depth between 25-65 cm depth, however subsoil showed signs of physical properties implying a slightly compacted state based on soil structure and consistence at lower depths, particularly in the 0.95 m subsoil profile. Comparison of the structure and consistence of the 0.55 m and 0.95 m subsoil profiles (Figure A-2) generally showed a structure change with increasing depth from granular to subangular blocky along with a consistence grading from friable and slightly hard to hard and very hard. Although the structure in the 0.55 m subsoil was never a strong grade, the structure was present over the entire subsoil thickness. On the other hand, structure in the 0.95 m subsoil (also not strong in grade) did not extend the entire thickness of subsoil material. Structure in the 0.95 m profile graded to massive conditions below a depth of 70 cm (Figure A-2). Compaction and a weakening grade of structure related to increased Db can restrict root penetration. Management practices that cause compaction are related to decreased pore space thereby decreasing water movement and gas diffusion in the soil (Fairbridge and Finkl 1979). Soil structure disrupted from the mining and reclamation process diminishes the associated interaggregate pore spaces (McSweeny and Jansen 1984, Keck et al. 1993). Moderately fine textured constructed soils high in Db and lacking structure may make the constructed profiles unfavorable for crop growth (Indorante et al. 1981).

The spoil was even more limiting compared to the subsoil based on increased Db and the morphological properties of structure and consistence. In both subsoil profiles the spoil was generally of extremely hard consistence and was always massive (Figure A-2). During mining and reclamation, the degree of compaction can vary depending on the equipment used, such as type of vehicle and pattern of traffic, and soil factors such as soil moisture content, soil texture and rock fragment (Bell et al. 1994). The greater Db observed in the Highvale sandy clay spoil compared to the silty clay subsoil cannot be explained by texture. In this case the coarser textured sandy clay material was associated with the greater Db. As well, since both the subsoil and spoil material had little rock fragment content, both soil materials were equally susceptible to the effects of compaction (Bell et al. 1994). However, perhaps the soil moisture content or equipment traffic (differing between spoil excavation to subsoil replacement) was responsible for the difference between subsoil and spoil compaction during soil profile construction. One implication of compaction in the lower subsoil and spoil would be limited available water. Water availability for plant growth depends on the capillary force to retain water in the pores and secondly on the hydraulic conductivity of soil adjacent to absorbing roots (Fairbridge and Finkl 1979). Both decreased porosity and lack of structure resulting from compaction may limit the soil to supply water as well deter root penetration. It has been suggested that a Db of 1.8 Mg m^{-3} will restrict root penetration of agricultural crops (ASAC 1987). Another soil hazard related to high soil bulk density and compaction, is the increased sensitivity to the detrimental affects of high sodium and low electrolyte concentrations from the resultant decreased inter-connected macropores restricting downward water percolation through the profile. The smaller pores contribute to potential swelling and dispersion that further restrict and cut off pores in sodic soils (Williams and Schuman, 1987).

2.5.2 Volumetric Water Content

Based on the volumetric water data measured October 18, 1999, greater amounts of water occurred in the subsoil and spoil compared to the topsoil. The greater topsoil root mass and resulting water uptake may be partly accountable for the lower level of soil water content. As well, downward water percolation through the subsoil profile past the spoil interface could be in part limited by the weak to moderate grade of subsoil structure (Figure A-2), particularly in the 0.95 m subsoil profile due to the massive conditions at lower subsoil depths. However, volumetric water content did not differ between subsoil or spoil in either the 0.55 m or 0.95 m subsoil. Also, none of the three materials were saturated (Table B-2), based on porosity values determined from the Uhland cores. It should also be noted that this one-time measurement indicated that water was not pooling in a localized area directly above the spoil interface. Volumetric water content in the spoil of the 0.55 m subsoil profile did not differ from that in subsoil of the 0.95 m profile at the same depth. However, the lack of structure (Figure A-2), and decreased porosity (Table B-2) resulting from the increased Db, likely limit saturated hydraulic conductivity of the spoil material.

2.6 CONCLUSION

Soil physical limitations imposed from surface mining practices such as structure loss and increased bulk density have long been documented. However, more information is needed to determine the specific ameliorative subsoil thickness affects on soil profile Db over sodic mine spoil with time. This study measured Db with depth for 0.55 m and 0.95 m subsoil profiles. With regard to the first hypothesis, our study found Db to increase with depth from topsoil to subsoil for both profiles, and to further increase in spoil Db in the 0.55 m profile. Also, significantly greater spoil Db occurred in the 0.55 m profile below a depth of 0.65 m compared to the Db of the subsoil in the 0.95 m subsoil profile at common depths. Topsoil Db occurred within values for an Ap (Ah) horizon with clay loam texture, showing no signs of compaction. However, the spoil in the 0.55 m subsoil and the lower subsoil in the 0.95 m profile showed signs of compaction of lack of structure and hard to extremely hard consistency combined with high bulk density values. Subsoil compaction most likely resulted from equipment traffic over the material. The spoil would have been similarly compacted, including additional effects from spoil excavation under possibly moist spoil conditions during construction. The massive state of the lower subsoil in the 0.95 m profile and the spoil material in the 0.55 m profile would likely decrease water percolation through the material and limit soil water availability to roots for plant growth, due to lack of cracks and fissures allowing for water drainage. Also, root penetration could be deterred by the hard to extremely hard consistence of the materials. Likewise, root growth could potentially be limited due to potential air / water imbalances resulting from the limited pore space in the spoil material. The lower subsoil in the 0.95 m subsoil profile does not provide an optimal environment to support plant productivity and should be considered a limited growing medium. Compared to the 0.55 m subsoil profile, the greater thickness of subsoil in the 0.95 m profile was not more effective in ameliorating the physical limitations imposed on constructed soils over surface mined sodic spoil.

Drainage that allows downward percolation of soil water is essential to mitigate the upward migration of sodium from sodic spoil. Based on a one-time measurement in the fall of 1999, greater water content was observed in the subsoil and spoil, compared to the topsoil material. Root uptake or evaporation may have been partly responsible for lowered topsoil water contents. Subsoil and spoil volumetric water content did not differ and were not at saturated conditions. This fall measurement detected no pooling of soil water above the spoil interface. The lack of difference between volumetric water measured in the spoil of the 0.55 m subsoil profile and the subsoil of the 0.95 m profile suggests that the lower subsoil of the 0.95 m profile has similar drainage properties as the spoil. Compaction and the massive state of the 0.95 m lower subsoil would likely limit water percolation similar to that of the spoil material. As well, if decreased pore volume resulting from the increased Db exists with slow hydraulic conductivity limiting the drainage of water through the soil profile, the lower subsoil and spoil risk prolonged saturation during times of heavy precipitation, further limiting these media to support crop productivity.

The spoil material of the 0.55 m subsoil profile and the lower subsoil of the 0.95 m subsoil profile are physically limited as a growing medium to some degree by the massive state of the materials, high Db and hard to extremely hard consistence. Also, the potential for saturated conditions from decreased porosity and slow drainage resulting from probable low hydraulic conductivity would also deter root proliferation. Below a depth of approximately 70 cm, neither profile was superior to the other in mitigating the physical limitations imposed on constructed profiles over surfaced mined sodic spoils after 16 years.

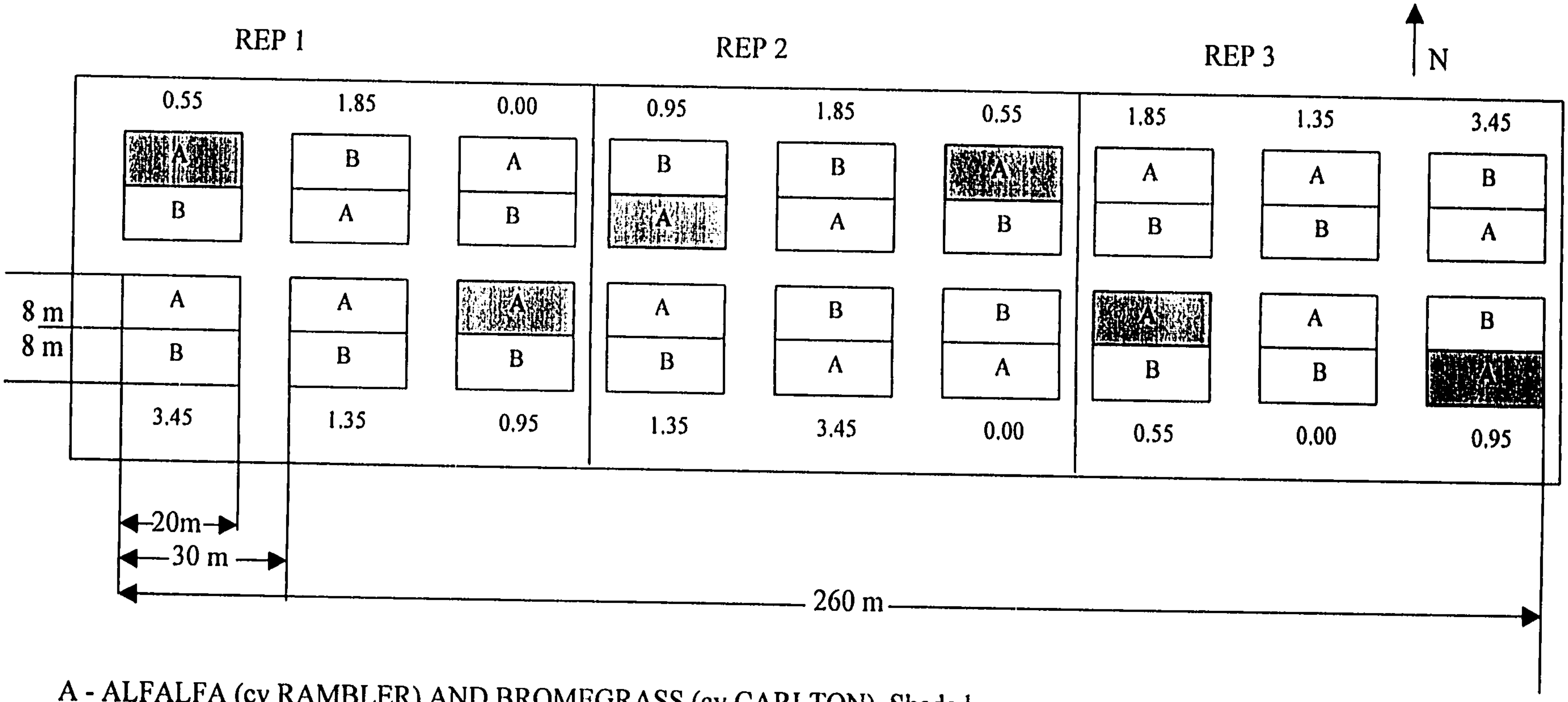
Table 2-1. ANOVA summary for bulk density with depth in the 0.55 m and 0.95 m subsoil profiles.

Source	df	F value	P > F
Treatment	1	3.97	0.185
Depth	8	63.06	<0.001
Treatment x Depth	8	3.85	0.003

Table 2-2. ANOVA summary for volumetric water determined with depth from Uhland cores on October 18, 1999 in the 0.55 m and 0.95 m subsoil profiles.

Source	**df**	**F value**	**P > F**
Treatment	1	0.41	0.586
Depth	8	3.98	0.002
Treatment x Depth	8	0.78	0.621

Figure 2-1 Layout of plots in the original 1982 Highvale experiment.



A - ALFALFA (cv RAMBLER) AND BROMEGRASS (cv CARLTON) Shaded
B - BARLEY (cv KLONDIKE)

Subsoil Thickness (m): 0.00, 0.55, 0.95, 1.35, 1.85, and 3.45

Figure 2-2. Schematic diagram of the TDR probe segments and the 0.55 m and 0.95 m subsoil profiles.

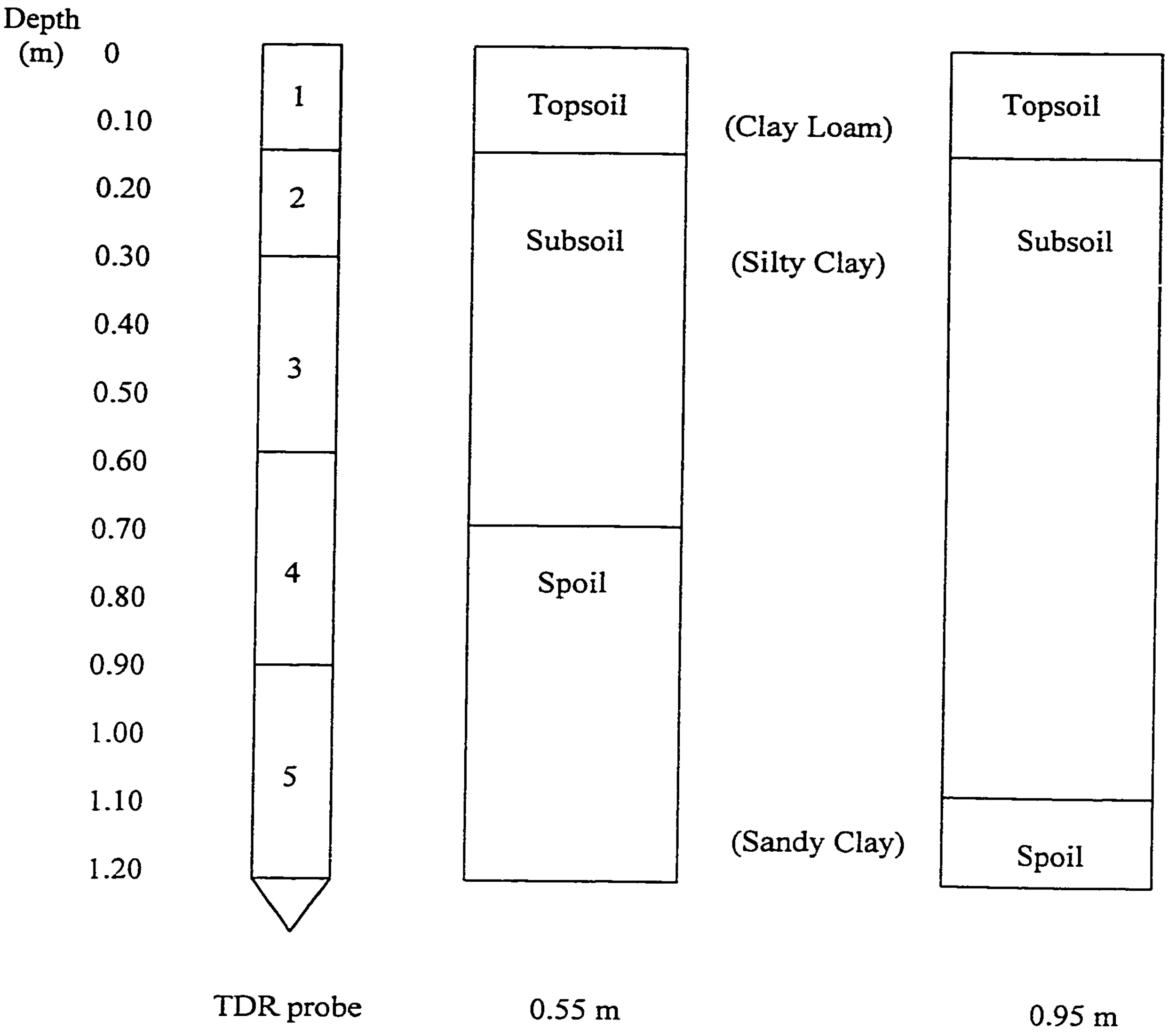


Figure 2-3. Plot layout of drilled cores, 1982 neutron probes, Uhland cores and TDR probes within a plot.

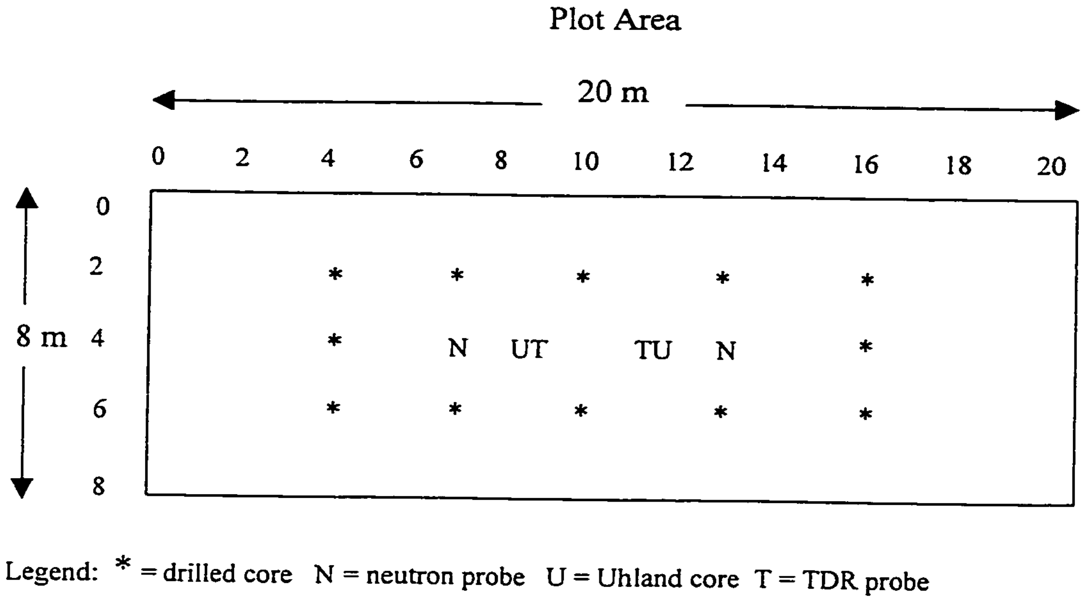
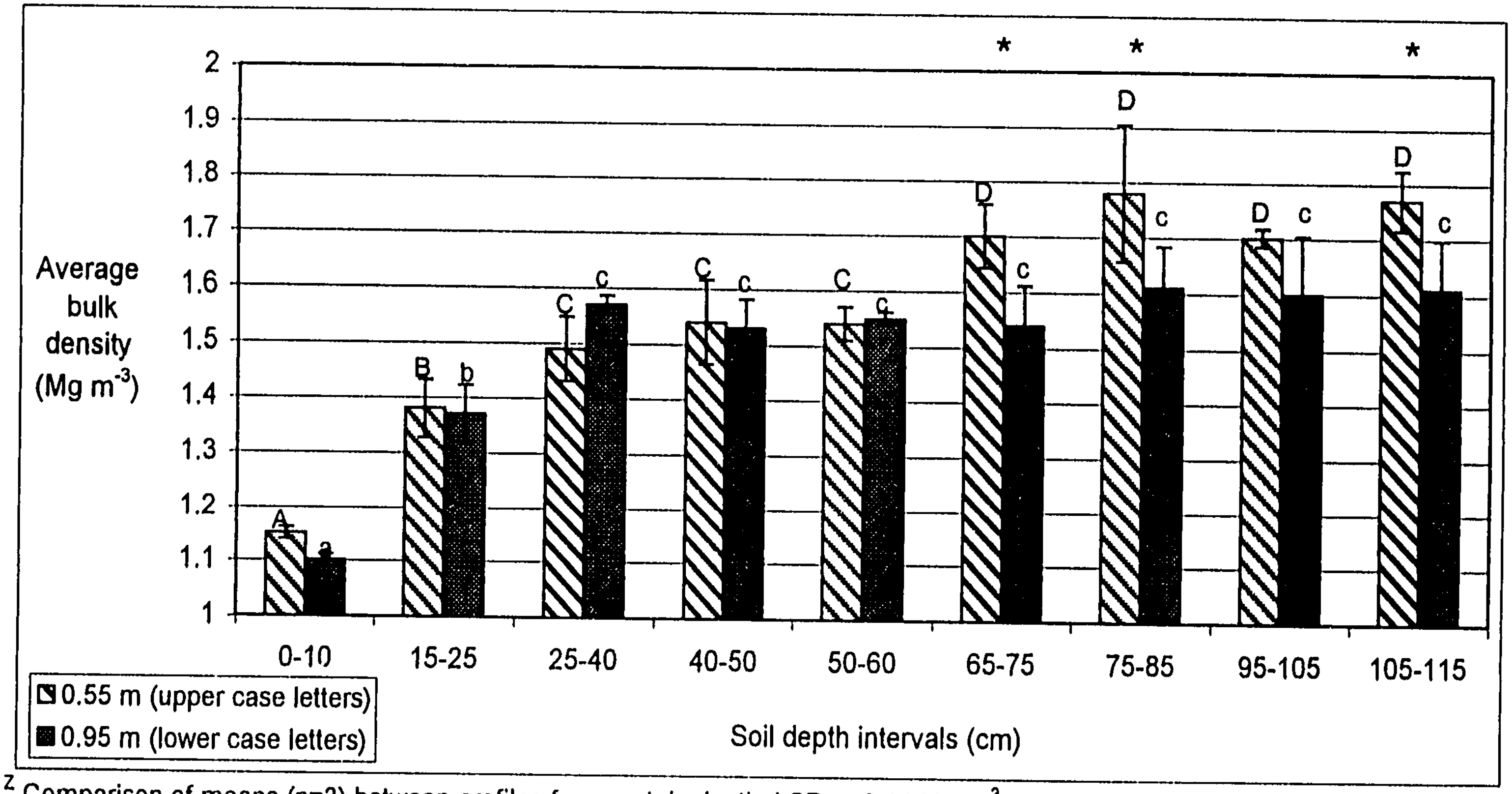
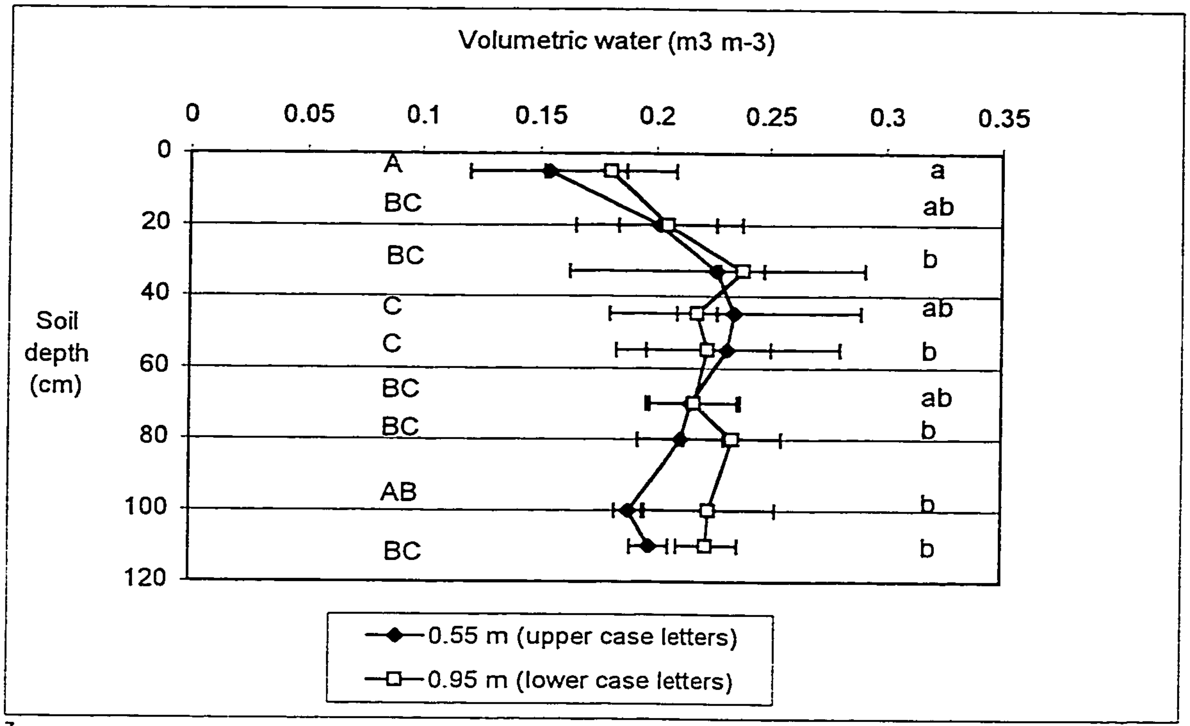


Figure 2-4. Comparison of average bulk density with depth between and within the 0.55 m and 0.95 m subsoil profiles^{ZYX}.



^{Z} Comparison of means (n=3) between profiles for a certain depth, LSD = 0.14 Mg m^{-3}, different means ($P<0.05$) denoted with an (*).
^{Y} Within profile, comparison of depth means (n=3) with the same letter do not differ at $P<0.05$, LSD = 0.09 Mg m^{-3}.
^{X} Error bars = +/- 1 st. deviation.

Figure 2-5. Comparison of average volumetric soil water content with depth between and within the 0.55 m and 0.95 m subsoil profiles on October 18, 1999[ZYX].



[Z] Means (n=3) between profiles, at any depth, do not differ at P<0.05, LSD =7.00 m^3 m^{-3}.

[Y] For comparison of depth increments within subsoil profile, means (n=3) with the same letter do not differ P<0.05, LSD = 4.04 m^3 m^{-3}.

[X] Error bars = +/- 1 st. deviation.

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CHAPTER 3

CHEMICAL PROPERTIES OF SOIL PROFILES OVER SODIC MINE SPOIL 16 YEARS AFTER CONSTRUCTION.

3.1 INTRODUCTION

In Alberta, the current coal industry is faced with needs for greater amounts of coal resources, resulting in the expansion of surface mines, which incorporate and disturb greater areas of agricultural land. Surface mining operations typically create mine spoils with limited agricultural land capability, especially if the spoil is sodic, such that the soil is adversely effected by physical characteristics that limit the unit of soil for a certain use. Since high concentrations of sodium (Na) in the spoil affects plant productivity negatively through its effect on chemical and physical properties, it is important that reclamation protocol provides an environment that will restore the soil's properties to obtain an equal capability rating to that which existed prior to disturbance. Replacing subsoil to reconstruct soil horizons that existed prior to disturbance, is the preferred method of reclamation for sodic mine spoils (Sandoval and Gould 1978). However, there is little consensus on the required thickness of subsoil to be replaced over the mine spoil to alleviate the chemical properties altered from mining operations.

Initially, after soil profile construction that placed non-sodic material above sodic spoil, the two horizons would not be in equilibrium with each other with respect to chemical properties. Chemical properties such as soluble and exchangeable cations, SAR, electrical conductivity and pH are dynamic, and thus may change with time depending on other properties in the soil environment. If changes in physical properties such as structure deterioration and increased bulk density result from mining operations, soil water drainage will be reduced and water may accumulate above the subsoil / spoil contact. This reduced soil permeability increases the efficiency of Na migration upward via chemical diffusion or convection (Merrill et al. 1983, Oddie and Bailey 1988). High Na concentration associated with the clay exchange complex in the subsoil may further the physical breakdown of soil structure and soil permeability (Goldberg and Glaubig 1987). Another aspect of sodic soils is the osmotic stress endured by the plant roots due to high concentrations of soluble cations (such as Na) in the soil water, compounded by the limited available water resulting from restricted water infiltration into the root zone (Tanji 1990). Thus, deterioration of subsoil quality resulting from the upward migration of Na may contribute to a decline in crop productivity.

Studies of constructed soils less than 2 years old have reported increased concentrations of exchangeable calcium (Ca) and Na reflecting overburden characteristics compared to the natural soils (Indorante et al. 1981). Thus, it is of interest to observe these chemical changes after a longer period of time. With time and a consistent environment, fluctuations in chemical properties become less as these chemical properties move towards attaining equilibrium with its environment.

The focus of this study is to analyze the chemical properties of two constructed profiles that vary in subsoil thickness (0.55 m and 0.95 m), and to determine the direction and extent of Na migration after sixteen years. It was noted that water accumulating above the contact of the two materials would increase the opportunity for upward movement of soluble Na from sodic spoils into the subsoil (Oddie and Bailey 1988). The Highvale study (1983-87) from which this study is based, had described water accumulating immediately above the subsoil / spoil contact. However, this condition was an infrequent occurrence and did not pose much of a concern for the subsoil thickness treatments due to the consumptive use of available soil water by the perennial forages (Oddie and Bailey 1988). The intent of this current study, is to gain an understanding on the long term fate of Na in constructed profiles, to quantify the changes, if any, in soil chemical properties after sixteen years of development and to project future trends of the chemical soil properties.

3.2 OBJECTIVES

The purpose of this study was to determine differences, if any, between two treatments of subsoil replacement thickness (0.55 m and 0. 95 m) developing over a sodic mine spoil, after 16 years. If there were differences, it would be of interest to assess how these differences affect the capability classification rating for agricultural crops. The specific objectives were to determine if the chemical properties of, soluble cations (Na, Mg and Ca), exchangeable cations (Na, Mg, Ca, and K), sodium absorption ratio (SAR), electrical conductivity (EC) and pH differed between the two subsoil thickness treatments. As well, we aim to project future trends and possible limitations these chemical properties may pose to current soil genesis and capability classification. The null hypotheses tested were:

1. There is no difference in soluble cations (Na, Mg and Ca), SAR, EC or pH with distance from the spoil interface between and within the 0.55 m and 0.95 m subsoil profiles.

2. There is no difference in exchangeable cations (Ca, Mg, K, and Na) in the topsoil, between the 0.55 m and 0.95 m subsoil profiles.

3.3 MATERIALS AND METHODS

3.3.1 Experimental Site

Refer to chapter 2, section 2.3.1.

3.3.2 Background on Experimental Plots

Refer to chapter 2, section 2.3.2 and Figure 3-1.

3.3.3 Sampling Design

Refer to chapter 2, section 2.3.3.

3.3.4 Chemical Properties

Twenty-four of the drilled cores were used to determine the chemical properties for the two treatments. Four cores from each of the three plots per treatment were chosen (two from the north side of the plot, two from the south side of the plot). Each core was partitioned into 5 or 3-cm sections. At the interface between subsoil and spoil material, each core was sectioned into five 3-cm length segments above, (defined as the upper critical zone), and five 3 cm length segments below the interface (defined as the lower critical zone) (Figure 3-2). These segments collectively spanned a total of 15 cm of soil directly above and below the contact. The remainder of a core was divided into 5-cm segments starting directly above the upper critical zone to the top of the core (soil surface), as well as the area directly below the lower critical zone for the remainder of the core. Statistical analysis of the upper profile represented soil intervals at 20-25, 30-35, and 40-45 cm height above the spoil interface, and included one topsoil section (Figure 3-1).

The individual soil sections of each core were air dried and ground to pass a 2 mm sieve. Soluble cation analysis, SAR, EC and pH were conducted on all of the upper and lower critical zone segments. As well, subsoil samples included every second segment for a distance of 30 cm beginning at the upper boundary of the upper critical zone towards the soil surface (top of the core). Above that, every third segment was selected, to the lower boundary of the topsoil, including one topsoil segment selected at approximately half the depth of the total topsoil layer.

Soluble cations, SAR, EC and pH were determined from aqueous extracts of saturated soil pastes (Yash 1994). Soluble cations and SAR were determined by atomic absorption spectrometry (Analytical Methods for Atomic Adsorption Spectrophotometer, 1982). Electrical conductivity was determined using a model 31 conductivity bridge (Instructions for Model 31 Conductivity Bridge, 1967) and soil pH was determined using a combination pH glass electrode and pH meter (Fisher Accumet Model 630 pH meter Instructions Manual, 1980). Sodium adsorption ratio (SAR) was calculated from the formula:

$$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{[\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]}}$$

where [Na], [Ca] and [Mg] represent the soluble ion concentrations in mmol L^{-1}.

Exchangeable cations were determined according to Chapman (1965). Extractable cations (Na, Ca, Mg and K) were determined by atomic adsorption spectrometry. Per core, exchangeable cations were determined in one-topsoil section.

3.3.5 Statistical Procedures

The chemical properties of soluble cations, SAR, exchangeable cations, EC and pH were compared between the two subsoil thickness treatments of 0.55 m and 0.95 m. The statistical model consisted of a split plot analysis of variance (SAS Institute Inc., 1987). The 1982 Highvale study experimental design consisted of two factors in a randomized complete block design with 3 replicates. Main plots of the six subsoil thicknesses (0.00, 0.55, 0.95, 1.35, 1.85, 3.45 m) were randomized within blocks with two seeded crop species (alfalfa / bromegrass forage mix and barley) randomized as split plot. The current 1998 experimental design's main plots consisted exclusively of the forage profiles with the two subsoil thicknesses: 0.55 m and 0.95 m, that occurred within the pre-existing randomized complete block experimental design. The constructed soil properties were further split into depth increments. The data were transformed to the square root of the chemical values measured, to better meet the assumptions of the ANOVA model of normal distribution and homogeneous variance. In all of the dependent chemical properties analyzed, the transformation lowered the model's coefficient of variance and produced a more normal distribution based on a visual comparison of the box plot of the individual observations. The general linear model procedure (GLM) was used to test the independent and fixed factor of subsoil thickness treatment with depth, with significant F values based on $P \leq 0.05$. A comparison of means from the interaction between different depths within a common treatment was analyzed using the PDIFF option of the least significant means (LSMEANS) statement in the model. To compare similar depths between the two profiles, hand calculated least significant difference t-tests were used (Steel and Torrie 1980).

3.4 RESULTS

For determination of chemical properties in the constructed soil profiles, sampling by depth intervals was at a finer spatial resolution within 15 cm above and below the subsoil / spoil interface (3 cm intervals) compared to the upper subsoil and topsoil layer (5 cm intervals). Due to these varying depth intervals, ANOVA was conducted separately for 1) the upper profile (topsoil and subsoil) and 2) for the combined two critical zones, (the upper immediately above, and the lower immediately below the subsoil / spoil interface).

Statistical comparisons of chemical properties of materials used in profile construction with those of current profile layers was not possible due to lack of replication in the former measurements at a treatment (subsoil thickness) level.

3.4.1 Soluble Calcium and Magnesium

For both the upper profile and critical zone, no significant interaction was found between subsoil thickness x distance from spoil interface for soluble calcium (Ca) and soluble magnesium (Mg) concentrations, as determined by ANOVA (Table 3-2). As well, the main effect of subsoil thickness was not significant, nor did weighted average of soluble Ca or soluble Mg for the entire subsoil differ ($P<0.05$) between subsoil profiles. However, a gradient of increasing soluble Ca and Mg towards the soil surface was a significant main effect of distance from spoil interface (Figure 3-2 and 3-3). Soluble Ca concentration generally decreased with depth from the topsoil value of about 2.7 mmol L^{-1} into upper subsoil (ca 1.9 mmol L^{-1}) and from lower subsoil value of about 1.2 mmol L^{-1} into upper spoil ca 0.7 mmol L^{-1} (Figure 3-2). Soluble Mg concentration generally decreased with depth from the topsoil of about 0.8 mmol L^{-1} into upper subsoil (ca 0.5 mmol L^{-1}). Soluble Mg in the critical zones of about 0.3 mmol L^{-1} in the 0.55 m subsoil profile did not differ. However, soluble Mg of 0.4 mmol L^{-1} in the lower subsoil in the 0.95 m profile decreased to 0.2 mmol L^{-1} in the spoil material (Figure 3-3).

The current (1998) topsoil and upper subsoil results also show increased soluble Ca and Mg concentrations compared to 1982 stockpiled values of the materials used to construct the soil profiles (Table 3-1). Current topsoil soluble Ca and Mg concentrations were larger, compared to the stockpiled values of 2.3 mmol L^{-1} and 0.6 mmol L^{-1}, respectively. Likewise, Ca and Mg concentrations in the upper subsoil were currently larger, compared to the stockpiled subsoil value of 1.7 mmol L^{-1}, and 0.5 mmol L^{-1} respectively, measured in 1982. However, within 30 and 20 cm distance from the spoil interface for the 0.55 m and 0.95 m subsoil profiles respectively, the subsoil concentrations of the two cations were smaller than the initial stockpiled-subsoil concentrations. Soluble Ca and Mg measured in the lower critical zone was slightly larger compared to the 1982 spoil concentrations of 0.6 mmol L^{-1}, and 0.2 mmol L^{-1} respectively.

3.4.2 Soluble Sodium

For both the upper profile and critical zone, no significant interaction between subsoil thickness x distance from spoil interface was found for soluble sodium (Na) concentration, as determined by ANOVA (Table 3-2). As well, the main effect of subsoil thickness was not significant, nor did the weighted average of soluble Na concentration for the entire subsoil, differ ($P<0.05$) between subsoil profiles. However, a gradient of decreasing soluble Na with height above the spoil interface was a significant main effect of distance from spoil interface (Figure 3-4). Soluble Na concentration increased exponentially with depth from the topsoil at approximately 0.4 mmol L^{-1} into upper subsoil (ca 3.5 mmol L^{-1}) and from lower subsoil at approximately 8.0 mmol L^{-1} into upper spoil at ca 17.0 mmol L^{-1} (Figure 3-4). Within the upper critical zone there was a gradient of increasing soluble Na towards the spoil interface. Below the spoil interface soluble Na did not differ with distance in either subsoil profile.

Unlike soluble Ca or Mg, current (1998) soluble Na concentrations of topsoil and uppermost subsoil remained unchanged from 1982 values of the stockpiled topsoil of 0.6 mmol L^{-1} and subsoil material of 0.9 mmol L^{-1} used for plot construction (Table 3-1). However, with depth in the subsoil, soluble Na was larger than the 1982 stockpiled-subsoil concentration (Table 3-1). In fact, soluble Na showed larger subsoil concentrations to a maximum height above the spoil interface of 30-35 cm. Soluble Na measured in the lower critical zone value was also greater compared to the 1982 spoil concentration of 14.4 mmol L^{-1}.

3.4.3 Sodium Adsorption Ratio

For both the upper profile and critical zones, no significant interaction between subsoil thickness x distance from spoil interface for SAR was found, as determined by ANOVA (Table 3-2). As well, the main effect of subsoil thickness was not significant, nor did the weighted average of SAR for the entire subsoil, differ ($P<0.05$) between subsoil profiles. However, a gradient of decreasing SAR with height above the spoil interface occurred, indicated by the significant main effect of distance from spoil interface (Figure 3-5). SAR gradient resembled soluble Na by increasing exponentially with depth from the topsoil at approximately 0.3 to ca 2.3 in upper subsoil and from lower subsoil of about 6.7 to ca21.7 in upper spoil. However, subsoil SAR increased over a greater gradient compared to soluble Na. As well, SAR increased with depth in both critical zones.

Compared to the 1982 stockpiled topsoil SAR of 0.4, the current (1998) topsoil SAR is slightly less. Similarly the upper subsoil SAR was slightly less or slightly greater than the SAR value of the stockpiled subsoil in 1982 of 0.7. However, larger subsoil SAR values (not statistically compared to the 1982 stockpiled value of subsoil) began at 20-25 cm height above spoil interface and continued to increase towards the spoil interface. In 1982, the spoil was characterized with an SAR of 20.1. With exception of the greater depths in the lower critical zone, the 1998 SAR value of the spoil directly below the interface was smaller than 20.1.

3.4.4 Electrical Conductivity

For both the upper profile and critical zones, no significant interaction between subsoil thickness x distance from the spoil interface for EC was found, as determined by ANOVA (Table 3-2). As well, the main effect of subsoil thickness was not significant, nor did the weighted average of EC for the entire subsoil differ ($P<0.05$) between subsoil profiles. However, a gradient of decreasing EC with height above the spoil interface occurred as indicated by the significant main effect of distance from spoil (Figure 3-6). Topsoil and upper subsoil EC of about 0.4 dS m^{-1} generally did not differ with depth. However, upper critical zone EC significantly increased towards the spoil interface to about 1.3 dS m^{-1}. The spoil EC of ~ 1.5 dS m^{-1} did not differ with distance in the lower critical zone. Compared to the 1982 EC values of the three stockpiled materials (Table 3-1); topsoil (0.6 dS m^{-1}), subsoil (0.5 dS m^{-1}) and spoil (1.9 dS m^{-1}), current (1998) EC values of the topsoil and spoil material in both profiles (Figure 3-6) were smaller. Subsoil EC values were larger in the upper critical zone only.

3.4.5 pH

For both, the upper profile and critical zones, no significant interaction between subsoil thickness x distance from the spoil interface for pH was found, as determined by

ANOVA (Table 3-2). As well, the main effect of subsoil thickness was not significant, nor did the weighted average of pH for the entire subsoil, differ ($P<0.05$) between subsoil profiles. However, a gradient of decreasing pH with height above the spoil interface was apparent from the significant main effect of distance from spoil interface (Figure 3-7). pH increased with depth from a slightly alkaline topsoil (~ 7.3) to a strongly alkaline upper subsoil (~ 8.9) above the upper critical zone. pH in the critical zones followed no identifiable trend and generally did not differ with depth. The pHs in these zones ranged between 8.4 to 8.8.

Compared to the pHs of the stockpiled materials used for profile construction (Table 3-1), current topsoil and spoil pHs have remained the same, 7.2 and 8.5 respectively. However the current subsoil pH was larger (≥8.6) compared (not statistically) to the stockpile measurement of 7.7.

3.4.6 Exchangeable Topsoil Cations

In the topsoil, no significant subsoil thickness effect occurred for any of the exchangeable cations (Ca, Mg, K and Na) measured, as determined by ANOVA (Table 3-3). The order of concentrations of exchangeable cations was Ca> Mg> K> Na, with ~ 27.0 cmol(+) kg^{-1} of exchangeable Ca and about 0.1 cmol(+) kg^{-1} soil of exchangeable Na (Table 3-3).

3.5 DISCUSSION

The following sections discuss how the 1998 soil chemical properties may have evolved based on the properties described in the 1982 constructed soil profiles, and how these current properties influence constructed profiles as rooting media.

3.5.1 Vertical Ionic Gradients

Compared to the soluble cation concentrations of the stockpiled materials used in profile construction, both soluble Ca and Mg have increased in the topsoil and upper subsoil during the past 16 years. The topsoil exchangeable cation concentrations confirmed that Ca followed by Mg cations occurred on the exchange complex in the greatest proportions. Most likely the increase in soluble Ca and Mg cation concentration in topsoil and upper subsoil could be attributed to litterfall accumulation and decomposition after the 5 year harvesting of alfalfa-bromegrass (1983-1987) including the associated biological cycling of cations by roots. Mineral weathering and dissolved soluble sulfate salts could also have been a source of soluble Ca and Mg that could have potentially translocated from topsoil material to upper subsoil. The divalent cation concentrations were smaller compared to the initial 1982 values within 25 cm and 15 cm height above the spoil interface for the 0.55 m and 0.95 m subsoil profile, respectively. It is speculated that the lower concentration of the soluble Ca and Mg in the1982 spoil material, compared to the 1982 subsoil concentration, created a downward concentration gradient. As a result, soluble Ca and Mg from the subsoil would have migrated downward into the spoil material, increasing the spoil divalent cation concentrations but decreasing lower subsoil concentrations from the initial values measured in 1982. In addition, upward soluble sodium migration caused concentrations to increase within the subsoil in 35 cm height from the spoil interface, compared to the soluble Na concentration of the subsoil material used in profile construction. The decline of soluble Ca and Mg co-occurring with increasing soluble Na nearing the spoil interface resulted in an increased SAR within a 25 cm height of the spoil interface for both subsoil profiles, compared to 1982 values. Yet, the exponentially increasing SAR towards the spoil interface could potentially pose a concern, as depicted by certain environmental agencies, at the lower subsoil depths within the upper critical zone, more specifically, the 9 cm directly above the spoil interface with SAR ≥10. Environmental agencies such as the North Dakota Public Service Commission and the Wyoming Department of Environmental Quality set the guideline for suitable soil for farming and ranching purposes at SAR ≤10 (Williams and Schuman 1987). However, depending on the specific sodicity tolerances of the crop species to be grown, this SAR criterion may or may not be appropriate. For example, moderately tolerant crops such as alfalfa usually become nutritionally affected only at SAR's of 23.5 or greater (Bernstein 1975).

However, for appreciable amounts of sodium cations to adsorb to the exchange complex, sodium must comprise at least half or more of the soluble cation concentration (Sandoval and Gould 1978). In the topsoil of both subsoil profiles, there was only a minor presence of Na on the exchange complex, while exchangeable Ca dominated in concentration followed by exchangeable Mg, resulting in very low topsoil SAR values. However, with depth in the subsoil towards the spoil interface, there was a transition in the proportions of soluble cations towards soluble Na dominance. Compared to the combined concentrations of soluble Ca and Mg, soluble Na occurred at double or greater concentrations in the critical zones (15 cm height above and below the spoil), in both subsoil profiles. Thus, despite the varying subsoil thickness between the two soil profiles, soluble cation concentrations were similar at common heights above the spoil. In particular, between subsoil profiles, soluble Ca and Mg have similarly accumulated in the topsoil and upper subsoil while having decreased in the lower subsoil above the spoil interface. On the other hand, soluble Na accumulated at similar concentrations at common heights above the spoil interface. Similar vertical ionic gradients of soluble Ca, Mg and Na concentrations between the 0.55 m and 0.95 m subsoil, occurring at common heights above the reference point of the spoil interface, suggest that the two subsoil profiles have developed as a result of similar processes in common environments.

Both subsoil profiles similarly had low EC values (EC < 2 dS m^{-1}) throughout the topsoil, subsoil and spoil material. Their values were only slightly lower compared to 1982 stockpiled values. Bernstein (1975) found crop response to salinity mostly negligible between 0-2 dS m^{-1}. Despite overall low EC values, greater subsoil salinity occurred within 15 cm (0.55 m) and 25 cm height (0.95 m) above spoil interface compared to the upper subsoil and topsoil. Dollhopf et al. (1980) found similar results in their two-year study of 70 cm topsoil (EC= 0.5 dS m^{-1}) over spoil overburden (SAR = 23, EC= 2.8 dS m^{-1}) in which significantly greater subsoil EC concentrations occurred within the 23 cm above spoil material compared to the topsoil above.

3.5.2 Nutrient Imbalance

In both subsoil profiles, topsoil pH has remained neutral and relatively unaltered since 1982. As well, in both profiles, the current larger subsoil and spoil pH values (with reference to the stockpiled values), were similarly strongly alkaline at levels which could potentially limit subsoil quality.

The negative chemical effects associated with pH in alkaline sodic soil results from the hydrolysis of exchangeable sodium or sodium carbonate (Fairbridge and Finkl 1979). Consequently the sodium hydroxide produced from this hydrolysis solubolizes and depletes organic matter. Thus, subsoil organic matter deposited from possible root decomposition could be lost indirectly from the high pH. Furthermore, crop productivity may be limited by the nutrient imbalance associated with pH above 8.5 by the appreciable amounts of the CO_3^{-2} anion precipitating Ca and Mg, such that only small amounts of these cations occur in soil solution, risking Ca deficiency. As well, the solubility of $CaCO_3$ already existing in the calcareous subsoil and spoil, decrease as pH increase, further limiting available calcium (Sandoval and Gould 1978). Phosphorous element solubility and thus availability is also affected by pH. At pH > 6 phosphorous become increasingly insoluble and eventually precipitates with calcium as apatite (Fairbridge and Finkl 1979).

3.5.3 Sodium Migration and Ion Transport

In the situation of low soil hydraulic conductivity and moist subsoil, accumulation of Na by diffusion would dominate in the lower subsoil (Dollhopf et al. 1980, Merrill et al. 1980). However, the chemical gradient of Na must be sufficiently great between the spoil and subsoil to maintain transport by diffusion (Merrill et al. 1983). By the very nature of this process, driven by a concentration gradient, it is slow and self-limiting (Merrill et al. 1980). We think that Na migration from Highvale spoil into the upper critical zone in the subsoil profiles was in part, a result of diffusive transport. Upon soil profile construction at the Highvale mine, the subsoil and spoil interface had an abrupt soluble Na gradient from 0.9 mmol L^{-1} to 14.4 mmol L^{-1}, respectively. The potential for water retention in the finer textured silty clay subsoil along with an assumed current low hydraulic conductivity would create an environment conducive for Na accumulation via diffusion. In addition, it is also possible that Na migration from the spoil upward into the lower subsoil of both subsoil profiles, could have been facilitated by convective water movement as a result of evapotranspiration. Dollhopf et al. (1980) described salt movement by convective flow in response to a hydraulic gradient created by plant transpiration where the majority of the plant root mass, occurring above the spoil, drew the soil water upwards (gradient in water potential), supplying a conducting medium for salt migration into the topsoil. The mottled profiles observed in both subsoil thickness treatments indicated limited downward drainage (Figure A-1). It seemed probable that the hydraulic wetting front of the water retained in the spoil and subsoil could be drawn upwards by the root mass which occurred entirely in the subsoil and topsoil. This would have assisted upward Na migration via an upward evapotranspiration hydraulic pull. Bresler (1973) confirmed that a solute's dispersion is attributed, in general, to both diffusion and convective transport occurring together. A concern associated with the dual convective and diffusive salt transport is the theoretical distribution potential for salts. Sodium that has accumulated in the lower 15-20 cm of the subsoil by diffusion could be transported by convective flow towards the soil surface and ultimately taint an entire 1.0 m thick topsoil zone (Dollhoph et al. 1980). This situation would most likely be a concern for mine spoil reclamation in arid climates, where the evaporation greatly exceeds precipitation.

Merrill et al. (1983) concluded that significant Na accumulation would diffuse from 10 to 15 cm upward in mine spoil (SAR $\geq$10) covered with 30 cm of non-sodic soil material. However, it was also noted that if more than 30 cm of soil overlies a mine spoil where diffusive transport dominated, both the amount of Na accumulation and thickness of subsoil in which Na accumulated would be greater. Our study indicated Na migration from the sodic spoil up into the upper critical zone (15 cm), and to a lesser extent up to 35 cm above the spoil interface. Barth (1984) found similar results after a 4-year study of constructed soil profiles over a spoil (SAR $\geq$25) in the Northern Great Plains where Na migrated from 7 to 14 cm into the overlying soil. He also noted that despite the Na increase from 2.9 mmol L^{-1} to an average of 11.7 mmol L^{-1} in this zone, the SAR remained low due to increasing Ca concentrations. Equally, in this current study, soluble Na over the upper critical zone in both 0.55 m and 0.95 m subsoil profile averaged 10.8 mmol L^{-1} and 11.8 mmol L^{-1} respectively, which match Barth's results. The few differences between the two studies include the low SAR resulting from increased Ca in the earlier 4-yr study, while our study observed decreasing soluble Ca and Mg concentrations with depth, which caused the SAR to increase. It should also be noted the similar Na concentrations between the two studies despite the difference in elapsed time of 4 yr and 16 yr, (our study), since time of profile construction, potentially indicating a decline in rate of net Na movement with time.

3.5.4 Water Retention and Movement Through the Profiles

The hydraulic conductivity within a soil profile can dictate the upward or downward fate of Na originating from soil material. Dollhoph et al. (1980) reported that the successful downward percolation of soil water through the reconstructed mine spoil profile, with 70 cm of non-saline subsoil was responsible for mitigating significant Na accumulation in the subsoil during the 2-year period. Studies have noted aggregate dispersion and partial to complete plugging of pores are often associated with impermeable hardpan qualities (Sommerfeldt and Rapp 1982), that act to reduce hydraulic conductivity and permeability of the soil profile (Fairbridge and Finkl 1979). Without sufficient drainage to leach Na downward out of the subsoil, further upward cation diffusion can be facilitated, over a greater thickness of subsoil. The assumed limited percolation resulting from sodium affected structure and massive conditions in the lower subsoil of the 0.95 m soil profile, was speculated to cause the profile to be similar to the spoil in the 0.55 m subsoil profile, at similar depths.

Soil sensitivity to excessive Na also increases with clay content and bulk density (Frenkel et al. 1978). They reported appreciable decreases in hydraulic conductivity in soils with only 8% montmorillinite clay, when leached with distilled water at ESP of 10. Fine-textured sodic spoils are often associated with slow water infiltration and high water-holding capacity. Merrill et al. (1983) supported the idea that both soil texture and water content determine the amount of Na migration, such that, finer textured soils with greater water contents promote greater Na movement compared to coarser, dryer soils. Thus, in our study, the assumed decreased hydraulic conductivity particularly in the silty clay subsoil material of the profiles, was also based on the mottles observed throughout the soil profiles (Figure A-1) indicating imperfect to poor drainage. As well, Dollhopf et al. (1980) noted that mine spoil compaction from heavy equipment inhibited water transmission through the soil profile. Thus, the soil physical properties of the subsoil profiles, such as increased bulk density and compaction with depth to spoil (Chapter 2-Physical properties) also supported the assumption of limited drainage. Clay mineralogy, particularly montmorillonitic mine spoils - as in our study, also affects the soil's hydraulic properties, due to the sensitivity of the swelling clay to Na accumulation (Dollhopf et al. 1980).

Furthermore, the physical reduction in soil aggregate stability causing soil to have lower permeability is also correlated with sodic soils, high in pH (Fairbridge and Finkl 1979). Suarez et al. (1984) noted the significant adverse effect on relative hydraulic conductivity in montmorillinitic soil with increased pH from 6 to 9. Goldberg and Glaubig (1987) also supported this idea with the observed increase in dispersion with increases in pH for predominantly montmorillinitic soil. They found the critical coagulation concentration (CCC) of the clay to be pH dependent such that a pH = 6.4 required a CCC of 14 mmol L^{-1} of NaCl while a pH = 9.4 required a CCC of 28 mmol L^{-1} to maintain flocculation. However, this pH effect results from the edge charges on clays and the surface charge of variable-charged minerals such as iron and aluminum oxides. The CCCs for kaolinites are more pH dependent compared to montmorillonite due to the type of ion associated with the kaolinite clay mineral. Thus the sensitivity of a soil to this pH effect is dependent on the type and amount of clay, as well on the quantity of variable charge minerals and soil organic matter present (Suarez et al. 1984).

Clay dispersion and hydraulic conductivity are also sensitive to electrolyte concentration. Montmorillonitic clay is more prone to dispersion in weak EC solutions at low SAR values compared to kaolinitic-halloysitic clay high in iron oxide (Velasco-Molina et al. 1971). Their work characterized 10 to 20% montmorillinitic clay dispersions associated with SAR values of 3 to 12 in weak electrolyte solution. Similar SAR values in our study occurred in the upper critical zone. Finally, Shainberg et al. (1980) also demonstrated that soil solution low in EC, similar to rain water, could be detrimental to soil physical properties with exchangeable sodium percentages (ESP) of only 5%. With the low EC values measured in the silty clay subsoil in our study, it is not surprising that the subsoil in the 15 cm to 34 cm directly above the spoil interface of the 0.95 m subsoil treatment was massive. Likely the lack of structure resulted from aggregate instability from Na dispersion (Figure A-2). However subsoil directly above the spoil in 0.55 m subsoil, albeit at a shallower depth, did maintain structure.

3.5.5 Subsoil as a Rooting Medium

Sandoval and Gould (1978) consider the increase in osmotic pressure of the soil solution and the subsequent indirect effect on plant water uptake as the main salinity effect. However sodic soils usually do not contain substantial neutral soluble salts, with EC measuring less than 4 dS m^{-1} at 25°C (Fairbrige and Finkl 1979). Thus, in either profile, the low electrolyte subsoil would not contribute to increased osmotic pressure in the root zone.

Nevertheless, the subsoil properties of increased bulk density of a fine textured soil with a high expanding clay content, along with low electrolyte concentration increase the soil's sensitivity to conditions of high exchangeable Na, resulting in clay swelling, restriction of pores and possible dispersion (Williams and Schuman 1987). The massive and hard to extremely hard consistence observed within the subsoil layer 15 to 34 cm directly above the spoil in the 0.95 m soil profile (Figure A-2) was potentially caused by Na dispersion of aggregates. In contrast, the lower subsoil including the 15 cm of subsoil directly above the spoil interface of the 0.55 m soil profile, was both prismatic and sub-angular blocky in structure with a slightly hard to very hard consistence (Figure A-2). The breakdown of soil structure from excess Na, indirectly affects plant growth by restricting root elongation, aeration and water movement through the profile (Williams and Schuman 1987). The two subsoil profiles showed comparable depths of aggregation, with massive conditions occurring about 70 - 75 cm depth. However, the 0.55 m subsoil profile differed, expressing both macro and meso structure compared to only the meso structure of the 0.95 m profile. The lower subsoil of the thicker 0.95 m subsoil (below 75 cm) probably is not structurally suitable to be considered a high quality rooting medium for root growth.

3.6 CONCLUSION

Surface mining and profile reconstruction disrupts established chemical gradients occurring in natural soil systems. The placement of topsoil and subsoil over sodic spoil can create a strong potential for the migration of cations upward or downward from the spoil resulting from the newly established chemical gradients. In the case of excess Na, permeability, particularly for montmorillinitic soils with low salinity, and chemical toxicity can be limiting factors to crop productivity. With respect to the first hypothesis, no difference was observed between the 0.55 m and 0.95 m subsoil profiles, with any of the soil chemical properties ([soluble cations], SAR, EC and pH), measured with distance from the spoil interface. Likewise for the second hypothesis, topsoil exchangeable cations (Ca, Mg, K, and Na) did not differ between the two profiles. More specifically, soluble Ca and Mg in topsoil and upper subsoil have increased since profile construction, most likely due to the residual aboveground accumulation of litter matter after the 5 yrs of harvested alfalfa (1983-1987). However, soluble Ca and Mg decreased from the initial 1982 values within 25 cm and 15 cm of the spoil interface, most likely from downward diffusive migration of the divalent cations in response to the concentration gradient between the subsoil and spoil material. On the other hand, compared to stockpile concentrations measured in 1982, Na migrated upward to a maximum height of 35 cm above the spoil interface. However, in either subsoil profile only the 15 cm directly above the spoil (upper critical zone) had appreciable amounts of soluble Na accumulation ranging from about 6.5 to 15.0 mmol L^{-1}. As a result of increased soluble divalent cations since profile construction, topsoil and upper subsoil SAR values have decreased to ~ 0.2 and 0.5 for the 0.55 m and 0.95 m subsoils respectively. Yet, the lower subsoil SAR has increased exponentially with depth to a maximum of about 13, due to both decreasing soluble Ca and Mg concentration and increasing soluble Na concentration. Finally, the high pH of about 8.6 and low EC (maximum of about 1.6 dS m^{-1}) of the upper critical zone and spoil, may potentially contribute to changes of physical properties such as decreased hydraulic conductivity.

A similar concentration of Na (ca 11 mmol L^{-1}) accumulated over a height of 15 cm above spoil, between a 4-yr-old study (Barth 1984) and our 16-yr-old study suggests that the rate of upward Na migration may be decreasing with time. Currently in both subsoil profiles, only 9 cm of subsoil directly above spoil interface exceeds an SAR $\geq$10. However, the concern still exists that Na transport from the combined mechanisms of convective flow and diffusion will result in further upward Na migration, occurring any time when evaporation exceeds precipitation. The 0.55 m subsoil currently provides ~ 45 cm of subsoil with SAR <10, while the 0.95 m subsoil profile provides ~ 85 cm of subsoil with SAR values <10. For the properties examined, both profiles show little chemical limitation as a rooting medium in the upper subsoil according to capability criteria. However the Northern Great Plains climate of the Highvale experimental site of semi-arid to sub-humid denotes slight to significant water deficit during the growing season (ACECSS 1987). The evapotranspiration exceeding precipitation could limit downward rain water percolation, and in fact, promote upward soil water movement in response to evaporation of soil water near the surface. In this climate, Na may continue to migrate and accumulate in the subsoil to greater heights and at increasing concentrations, thus, decreasing the thickness of the subsoil available as a chemically suitable rooting medium. However, the greater thickness of the subsoil for a growing medium devoid of significant Na accumulation provided by the 0.95 m subsoil profile, can only be considered as a future benefit. Currently, the whole subsoil of the two profiles did not differ in the chemical properties assessed.

Table 3-1. Soil chemical properties of the stockpiled topsoil, subsoil and spoil material used for plot construction in 1982[z]

Soil Property	Topsoil	Subsoil	Spoil
Texture	Clay Loam	Silty Clay	Sandy Clay
pH $_{H20}$	7.2	7.7	8.5
Saturation %	57	57	95
	Water soluble ions (mmol L^{-1})		
Na	0.6	0.9	14.4
K	0.9	0.3	0.3
Ca	2.6	1.7	0.6
Mg	0.6	0.5	0.2
Cl	0.5	0.3	0.2
SO_4	0.4	0.4	5.4
SAR	0.4	0.7	20.1
EC (dS m^{-1})	0.6	0.5	1.9

[z] Properties from Graveland et al. (1988)

Table 3-2. ANOVA summary for water soluble cations , SAR, EC and pH for square root - transformed data

		Calcium		Magnesium		Sodium		SAR		EC		pH	
Source	df	F ratio	P>F	F ratio	P>F	F ratio	P>F	F ratio	P>F	F ratio	P>F	F ratio	P>F
Upper profile:Topsoil and 15-25, 25-35, 35-45 cm above spoil interface													
Trt	1	0.86	0.453	2.85	0.234	0.04	0.859	0.43	0.580	0.99	0.425	1.54	0.340
Dpth	3	4.04	0.034	6.67	0.007	62.23	<0.001	63.25	<0.001	2.75	0.089	300.06	<0.001
TxD	3	2.62	0.099	0.43	0.736	0.83	0.505	0.32	0.812	0.70	0.572	7.54	0.004
Critical zone: +/- 15 cm from the spoil interface													
Trt	1	0.01	0.921	0.70	0.490	0.13	0.751	0.12	0.763	0.02	0.900	1.58	0.336
Dpth	9	4.37	<0.001	2.86	0.012	17.28	<0.001	57.71	<0.001	13.21	<0.001	1.73	0.118
TxD	9	0.24	0.985	0.82	0.599	0.65	0.744	0.39	0.935	0.46	0.892	0.59	0.799
Weighted averages for the total subsoil													
Trt	1	1.30	0.373	2.55	0.251	2.86	0.233	4.23	0.176	0.14	0.748	4.56	0.166

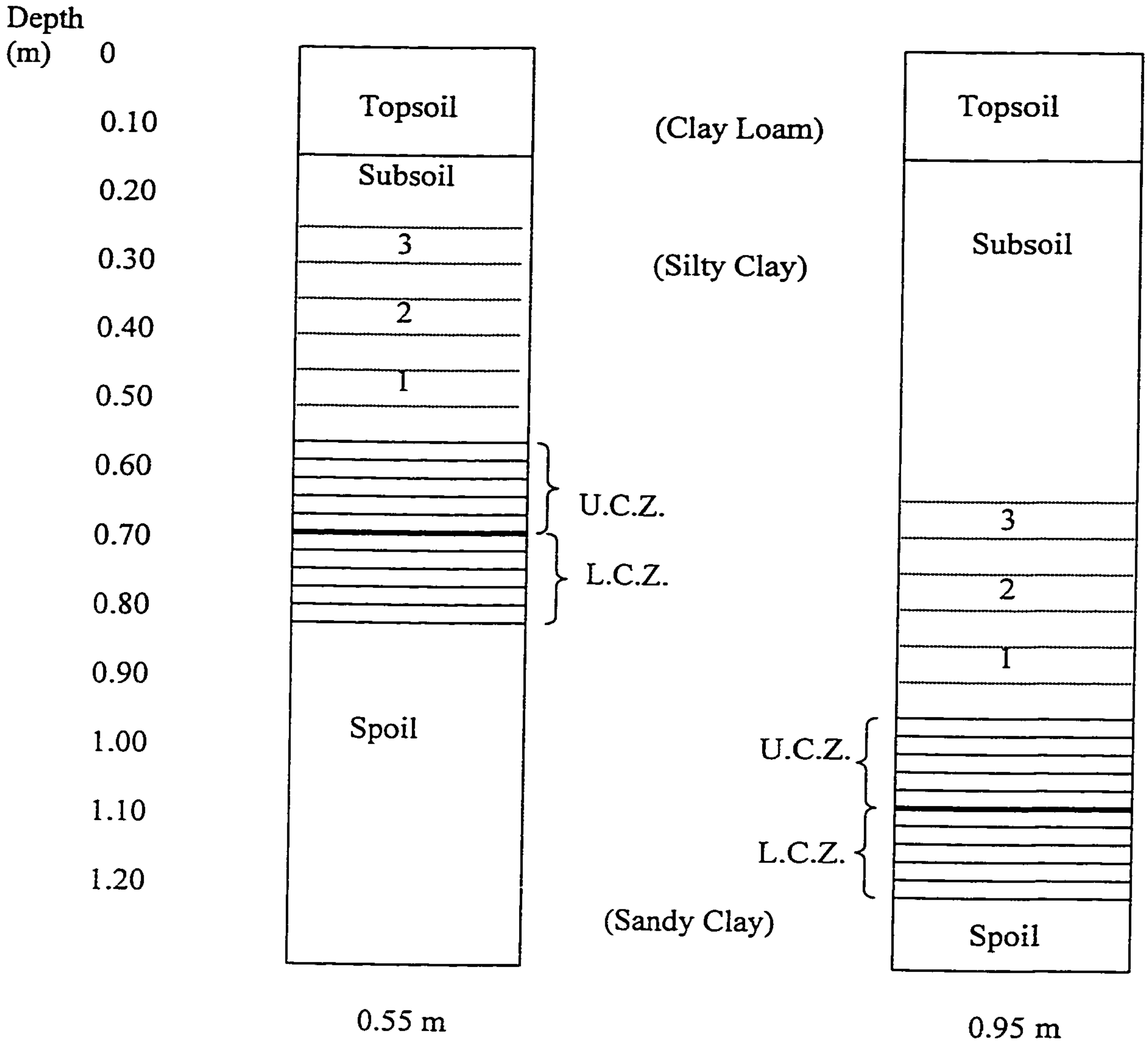
Table 3-3. ANOVA summary for concentrations of exchangeable cations (cmol(+) kg^{-1}) in the topsoil of the 0.55 m and 0.95 m subsoil profiles[Z]

Exchangeable Cations	Subsoil Profile[Y] 0.55 m	0.95 m	F ratio	P>F
Ca	25.79 +/- 2.58	28.05 +/- 3.79	10.48	0.084
Mg	4.90 +/- 0.21	4.82 +/- 0.23	1.16	0.394
K	1.03 +/- 0.32	1.03 +/- 0.28	0.00	0.988
Na	0.15 +/- 0.04	0.11 +/- 0.02	1.40	0.358

[Z] df =1

[Y] Concentration = mean (n=3) +/- 1st. deviation

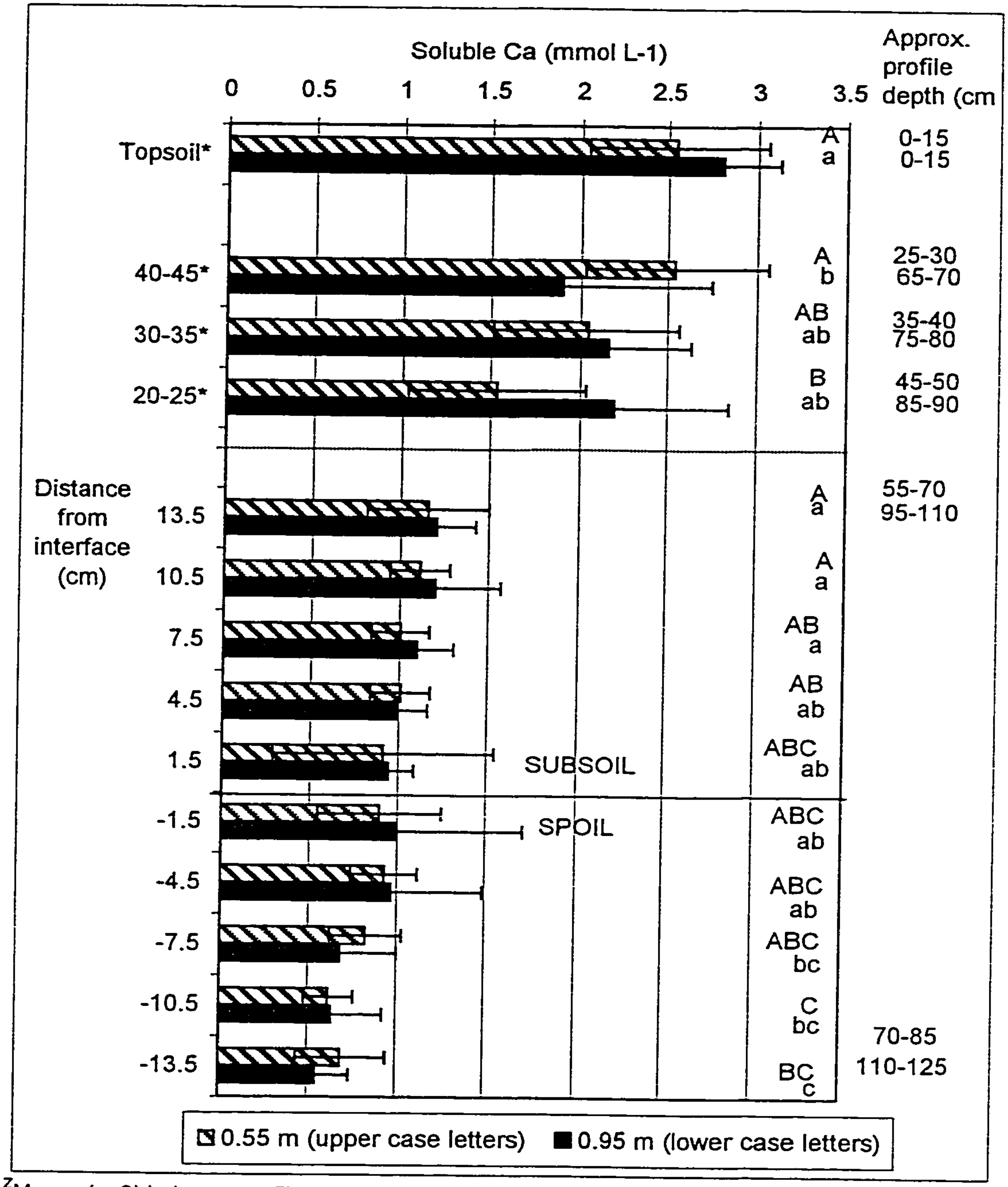
Figure 3-1. Schematic diagram of the 0.55 m and 0.95 m subsoil profiles and general placement of the sampling intervals with reference to the spoil interface.



Sampling intervals in height above spoil interface:

1 = 20-25 cm, 2 = 30-35 cm, and 3 = 40-45 cm (5 cm-thick samples)
U.C.Z. = Upper critical zone (3 cm-thick samples)
L.C. Z. = Lower critical zone (3 cm-thick samples)

Figure 3-2. Comparison of soluble calcium concentration in the upper profile and critical zones between and within the 0.55 m and 0.95 m subsoil profiles^{ZYXW}.



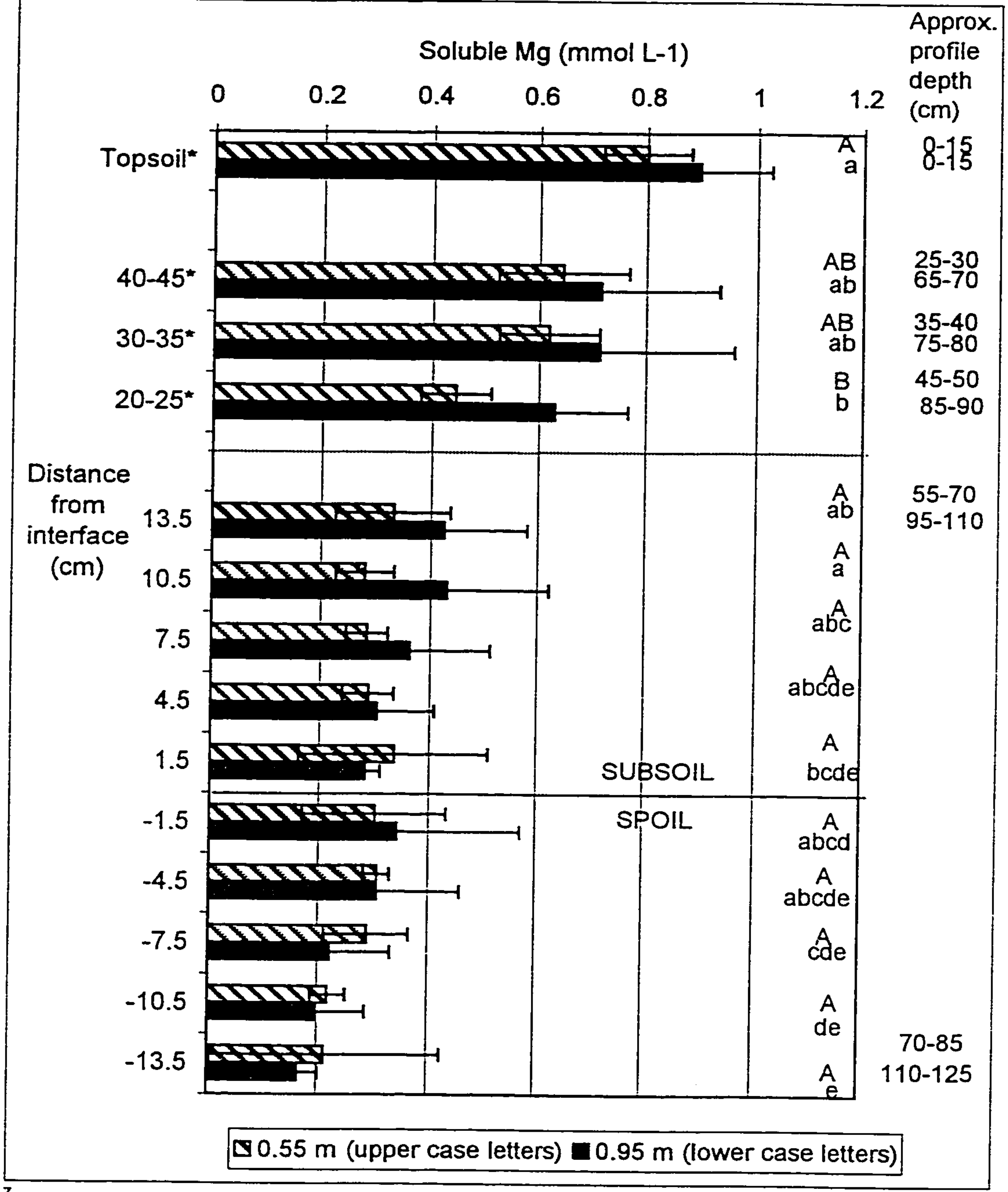
^{Z}Means (n=3) between profiles, at any depth do not differ at $P<0.05$ and error bars = +/- 1 st. deviation.

^{Y}Depth means within profile with the same letter do not differ at $P<0.05$.

^{X}Soil distances with (*) were tested in separate ANOVA from distances +/- 15 cm from spoil, upper profile LSD = 0.77 mmol L^{-1} and critical zones LSD = 0.38 mmol L^{-1}.

^{W}Soluble Ca of 1982 stockpiled material in TS, SS and Sp = 2.3, 1.7 and 0.6 mmol L^{-1}.

Figure 3-3. Comparison of soluble magnesium concentration in the upper profile and critical zones between and within the 0.55 m and 0.95 m subsoil profiles[ZYXW].



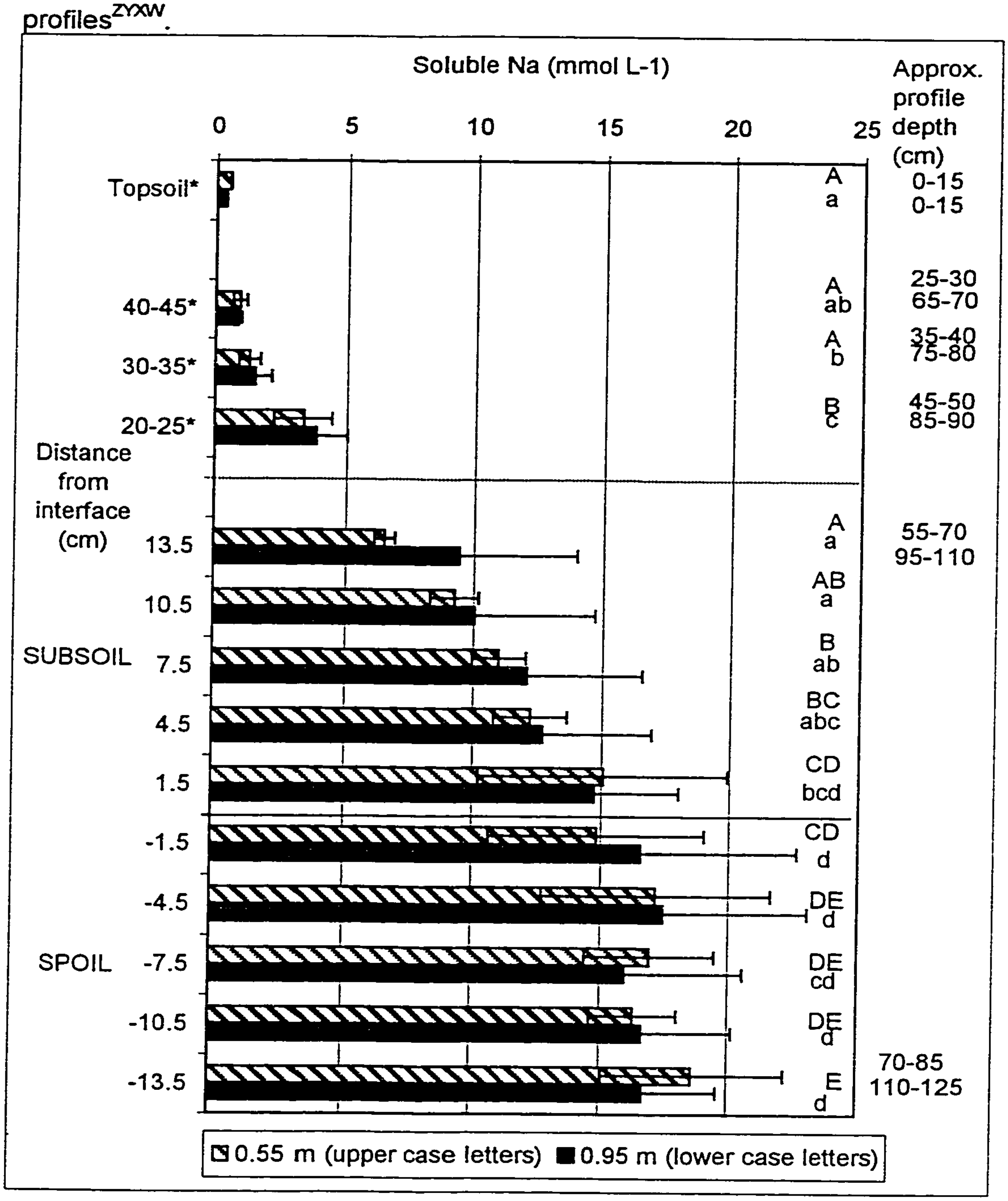
[Z] Means (n=3) between profiles, at any depth do not differ at $P<0.05$ and error bars = +/- 1 st. deviation.

[Y] Depth means within profile with the same letter do not differ at $P<0.05$.

[X] Soil distances with (*) were tested in separate ANOVA from distances +/- 15 cm from spoil, upper profile LSD = 0.22 mmol L^{-1} and critical zones LSD = 0.15 mmol L^{-1}.

[W] Soluble Mg of 1982 stockpiled material in TS, SS and Sp = 0.6, 0.5 and 0.2 mmol L^{-1}.

Figure 3-4. Comparison of soluble sodium concentrations in the upper profile and critical zones between and within the 0.55 m and 0.95 m subsoil profiles[ZYXW].



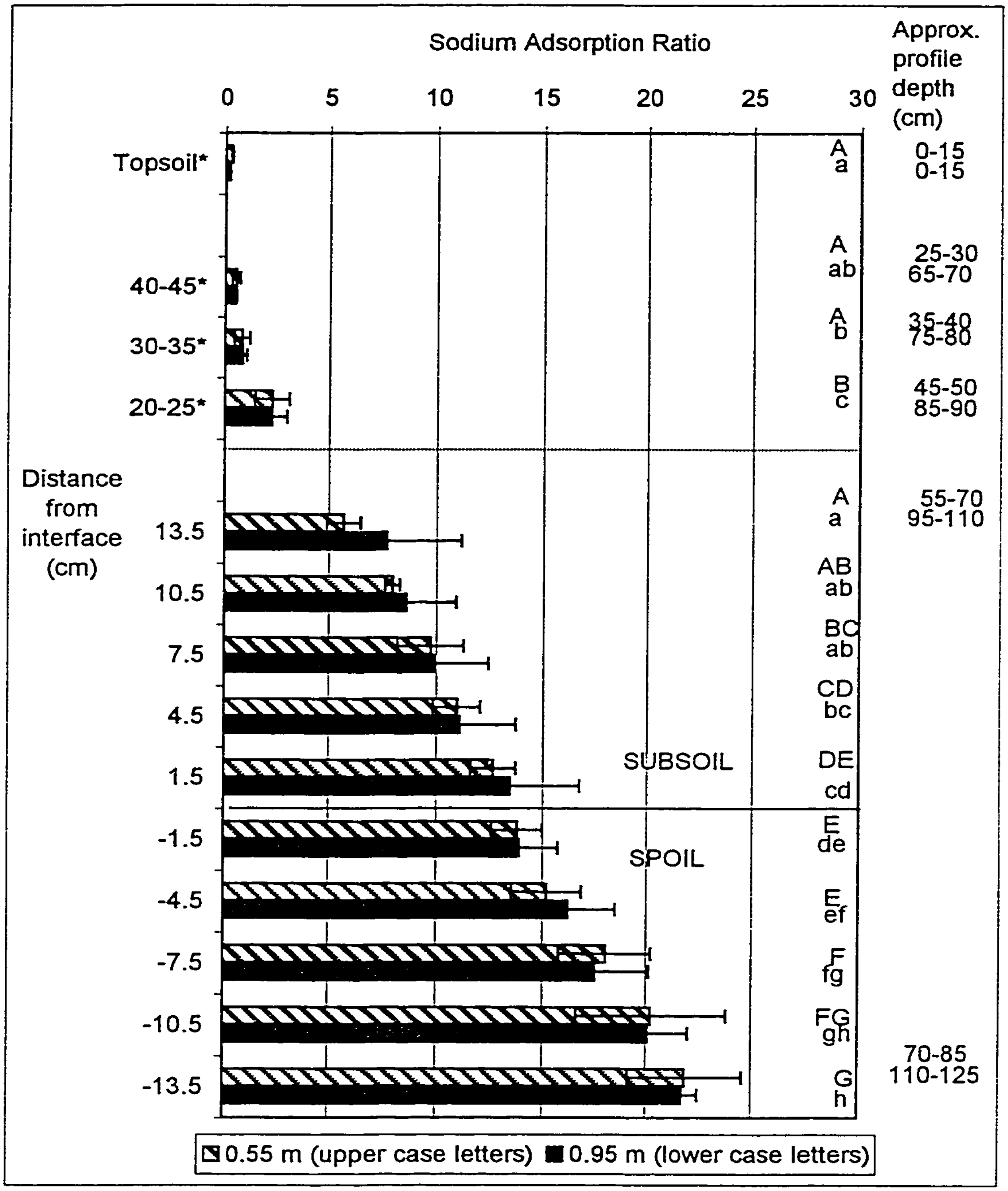
[Z] Means (n=3) between profiles, at any depth do not differ at $P<0.05$ and error bars = +/- 1 st. deviation.

[Y] Depth means within profile with the same letter do not differ at $P<0.05$.

[X] Soil distances with (*) were tested in separate ANOVA from distances +/- 15 cm from spoil, upper profile LSD = 0.99 mmol L^{-1} and critical zones LSD = 3.44 mmol L^{-1}.

[W] Soluble Na of 1982 stockpiled material in TS, SS and Sp = 0.6, 0.9 and 14.4 mmol L^{-1}.

Figure 3-5. Comparison of SAR in the upper profile and critical zones between and within the 0.55 m and 0.95 m subsoil profiles[ZYXW].



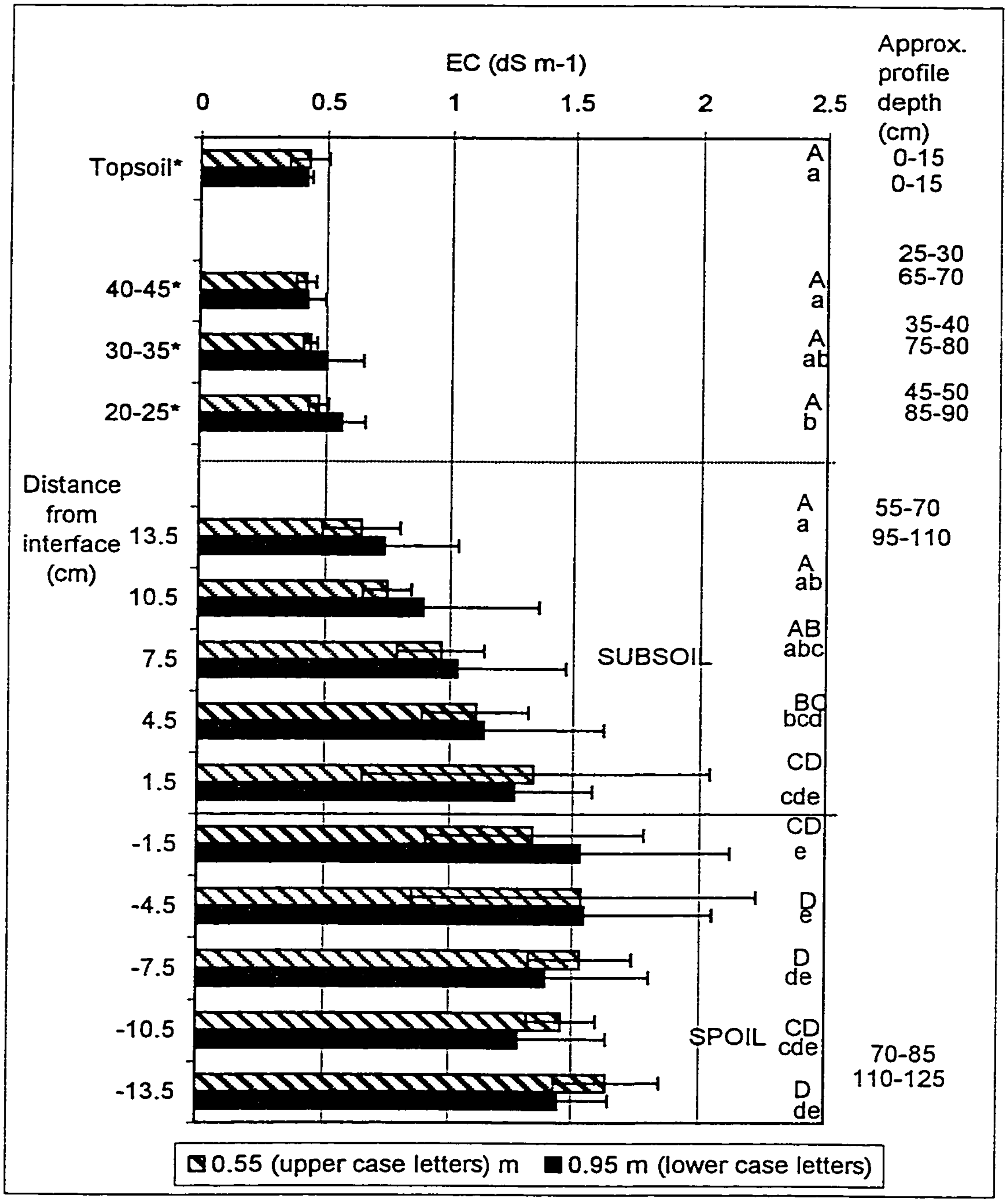
[Z] Means (n=3) between profiles, at any depth do not differ at $P<0.05$ and error bars = +/- 1 st. deviation.

[Y] Depth means within profile with the same letter do not differ at $P<0.05$.

[X] Soil distances with (*) were tested in separate ANOVA from distances +/- 15 cm from spoil, upper profile LSD = 0.66 mmol L^{-1} and critical zones LSD = 2.70 mmol L^{-1}.

[W] SAR values of stockpiled material in 1982, topsoil =0.4, subsoil = 0.7 and spoil = 20.1.

Figure 3-6. Comparison of EC in the upper profile and critical zones between and within the 0.55 m and 0.95 m subsoil profiles^{ZYXW}.



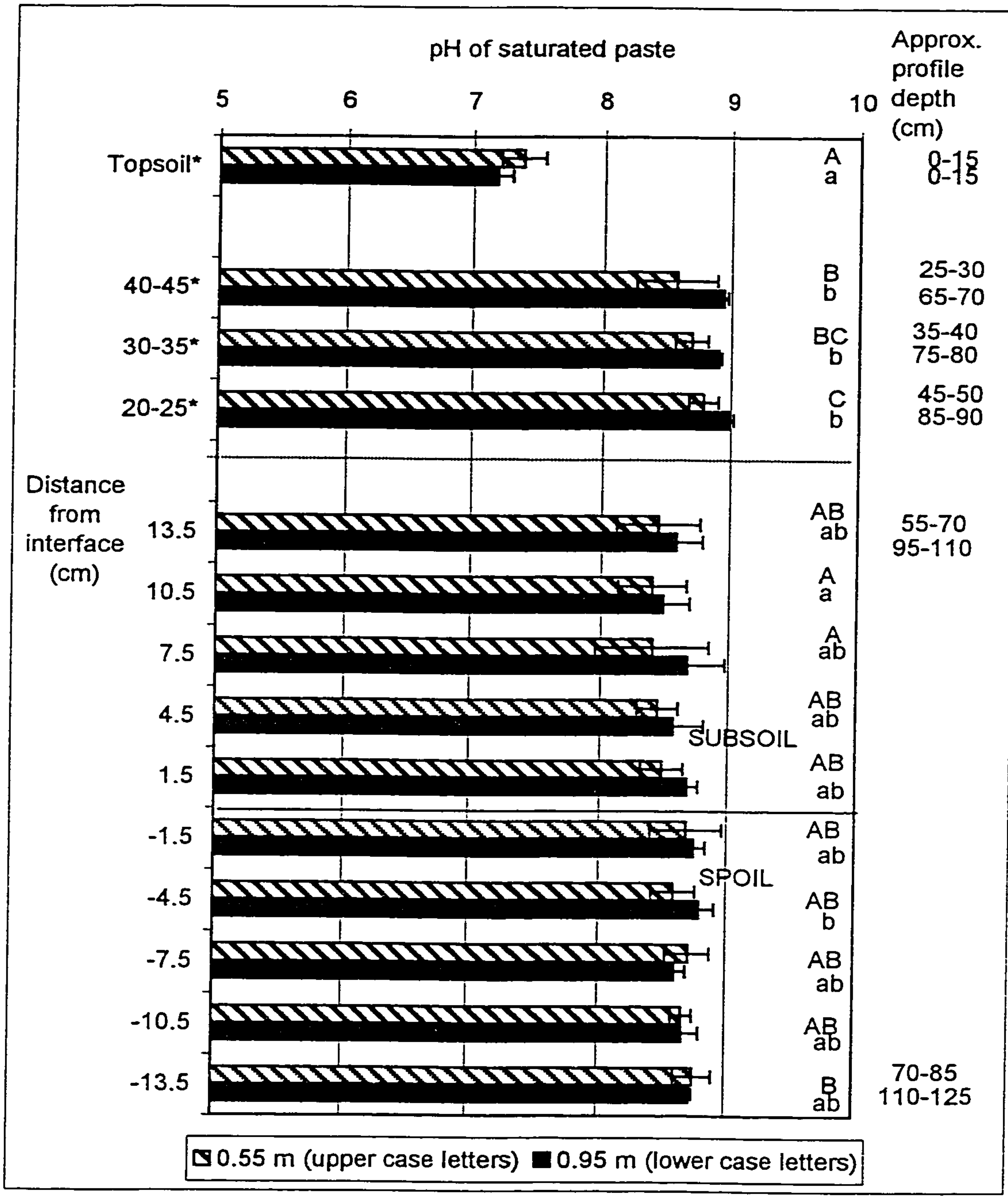
^{Z}Means (n=3) between profiles, at any depth do not differ at $P<0.05$ and error bars = +/- 1 st. deviation.

^{Y}Depth means within profile with the same letter do not differ at $P<0.05$.

^{X}Soil distances with (*) were tested in separate ANOVA from distances +/- 15 cm from spoil, upper profile LSD = 0.12 mmol L^{-1} and critical zones LSD = 0.35 mmol L^{-1}.

^{W}EC values of 1982 stockpiled material TS, SS and Sp =0.6, 0.5, and 1.9 dS m^{-1}.

Figure 3-7. Comparison of pH in the upper profile and critical zones between and within the 0.55 m and 0.95 m subsoil profiles[ZYXW].



[Z] Means (n=3) between profiles, at any depth do not differ at $P<0.05$ and error bars = +/- 1 st. dev.

[Y] Depth means within profile with the same letter do not differ at $P<0.05$.

[X] Soil distances with (*) were tested in separate ANOVA from distances +/- 15 cm from spoil, upper profile LSD = 0.20 mmol L^{-1} and critical zones LSD = 0.31 mmol L^{-1}.

[W] pH values of stockpiled material in 1982, topsoil =7.2, subsoil = 7.7 and spoil = 8.5.

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CHAPTER 4
ROOTING PROPERTIES OF SOIL PROFILES OVER SODIC MINE SPOIL 16 YEARS AFTER CONSTRUCTION.

4.1 INTRODUCTION

In Alberta, the current coal industry is faced with needs for greater amounts of coal resources, resulting in the expansion of surface mines, which incorporate and disturb greater areas of agricultural land. Surface mining operations typically create mine spoils with physical and chemical properties that can limit capability, especially if the spoil is sodic. It is important for reclamation protocol to provide an environment that will restore the soil's properties to obtain an equal capability rating. Replacing subsoil and reconstructing soil horizons that existed prior to disturbance, is the preferred method of reclamation for sodic mine spoils (Sandoval and Gould 1978). However, there is little consensus on the required thickness of subsoil to be replaced over mine spoil to alleviate the physical deterioration of structure and compaction resulting from mining operations. Hargis and Redente (1984) deem it important that the replacement thickness be thick enough to store spring runoff precipitation at field capacity to support plant requirements during the dry summer months. Halvorson et al (1986) study concluded that a loamy sand spoil texture required a thicker layer of replacement subsoil compared to finer textured spoils such as clay loam and silty clay loam, to produce comparable yields. This finding was based on the greater ability of the finer textured material to supply water to the growing crop throughout the growing season. As well, failure to replace sufficient subsoil over the spoil may also cause deleterious effects on vegetation production years after replacement, due to Na diffusion (Hargis and Redente 1984).

Another concern associated with soil properties disrupted from mining practices is the loss of soil structure and increased bulk density, which affect root proliferation. Consequently, the interaggregate pore spaces necessary for aeration, and macropores which provide areas of low mechanical impedance to root growth, are reduced due to compaction from mining equipment (Potter et al. 1988).

Analyzing standing root mass offers insight to the biological success of the complex recovery process (Hargis and Redente 1984). The original Highvale study (1983-1987), concluded that forage root depth increased with increasing total soil thickness to 1.35 m (Graveland et al. 1988). Schuman and Power (1981) observed water extraction from alfalfa to a depth of 1.35 m, contingent that the roots did not encounter spoil material. However, soil water potential, soil hydraulic conductivity and root length density all affect root water uptake, so caution should be exercised in interpreting water extraction as a result of root penetration alone (Merrill et al. 1985).

Root penetration into mine spoil would likely reduce bulk density and improve percolation of soil water. The Highvale study noted that a 3- year average (1985-87) of the alfalfa - smooth bromegrass root penetration into the mine spoil in the 0.55 m and 0.95 m subsoil profiles was an average of 0.09 and 0.00 m, respectively (Graveland et al. 1988). On the other hand, Merrill et al. (1985) observed in his North Dakota study, roots penetrating to a depth of 25 cm into spoil (SAR of 29) that had comparable root weights to those found in the 50 cm-thick subsoil.

Two treatments of subsoil replacement varying in thickness from 0.55 m and 0.95 m, 16 years after development, have been analyzed to quantify and understand the specific soil properties of varying subsoil thickness to mitigate limitation associated with constructed soils over sodic mine spoils,. This study compares the biological success between the two subsoil thickness treatments by analyzing root mass density with depth, total profile root mass and maximum root penetration into spoil material.

4.2 OBJECTIVES

The Highvale Plains Reclamation Research Project determined that a constructed soil profile with 0.95 m of subsoil was sufficient and necessary to produce regionally optimum yields of 4780 kg ha^{-1} yr^{-1} of alfalfa-smooth bromegrass hay based on a 5-year mean between 1983-1987 (AE 1989). However, the study also showed that difference between the 0.55 m and 0.95 m subsoil profile was not significant (Oddie and Bailey 1988). Thus, the purpose of this study was to discern rooting differences, if any, between the two constructed soil profiles of subsoil replacement thickness (0.55 m and 0. 95 m) established over a sodic mine spoil after 16 years. The specific objectives were to determine if root mass density with depth differed between the two subsoil profiles (0.55 m and 0.95 m). The null hypotheses tested were:

1. There is no difference in root mass density with depth between and within the 0.55 m and 0.95 m subsoil profiles.

2. There is no difference in total profile root mass between the 0.55 m and 0.95 m subsoil profiles.

4.3 MATERIALS AND METHODS

4.3.1 Experimental Site

Refer to chapter 2, section 2.3.1.

4.3.2 Background on Experimental Plots

Refer to chapter 2, section 2.3.2.

4.3.3 Sampling Design

Refer to chapter 2, section 2.3.3.

4.3.4 Root Separation

A total of 18 cores were used to determine average root mass density and total profile root mass for the two treatments. From the three cores per subplot allotted for root mass determination, at least one core was chosen from the northern, and one from the southern side of the subplot core layout design (Figure 2-3). The cores were thawed, sectioned and bagged for root analysis. The 0.55 m treatment cores were sectioned into topsoil, lower boundary of topsoil to 30 cm, 30-50 cm, 50 cm to contact of spoil material, 0- 3 cm of spoil material, 3-10 cm of spoil material, 10-20 cm of spoil material. The cores of the 0.95 m treatment were sectioned similarly except due to the greater subsoil thickness, there was an additional segment of 50-70 cm and 70 cm to contact of spoil material. The roots from each core segment were separated from soil in a root washer. The root washer was constructed by the machine shop at the University of Alberta following the design from the Alberta Environmental Center, which is a modification of a design by Cahoon and Morton (1960), Mckell et al. (1961) and Welbank and Williams (1968). Roots were washed under slightly pressurized tap water (50 psi), caught in a mesh sieve and air-dried to constant weight. Detection limit for root mass density was 0.018 kg m^{-3}.

4.3.5 Statistical Procedures

Root mass density was analyzed between the two subsoil thickness treatments of 0.55 m and 0.95 m. The statistical model consisted of a split plot analysis of variance (SAS Institute Inc., 1987). The 1982 Highvale study experimental design consisted of two factors in a randomized complete block design with 3 replicates. Main plots of the six subsoil thicknesses (0.00, 0.55, 0.95, 1.35, 1.85, 3.45 m) were randomized within blocks with two seeded crop species (alfalfa / bromegrass forage mix and barley) randomized as split plot. The current 1998 experimental design's main plots consisted exclusively of the forage profiles with the two subsoil thicknesses (0.55 m and 0.95 m) that occurred within the pre-existing randomized complete block experimental design, that were further split into depth increments. The data were transformed to the square root of the root weight values, to meet the assumptions of the ANOVA model of normal distribution and homogeneous variance. The transformation lowered the model's coefficient of variance and produced a more normal distribution based on a visual comparison of the box plot of the observations. The general linear model procedure (GLM) was used to test the independent and fixed factor of subsoil thickness treatment with depth, with significant F values based on $P \leq 0.05$. A comparison of means from the interaction between different depths within a common treatment was analyzed using the PDIFF option of the least significant means (LSMEANS) statement in the model. To compare similar depths between the two profiles hand-calculated least significant difference (LSD) t-tests were used (Steel and Torrie, 1980).

4.4 RESULTS

Total profile root mass of approximately 4.5 kg m^{-2} did not differ ($P<0.05$) between subsoil profiles; as well, no significant subsoil thickness x depth interaction was found for root mass density, as determined by ANOVA (Table 4-1). Also, there was no significant main effect of subsoil thickness treatment. However root mass density decreased significantly with depth from topsoil to subsoil, within both 0.55 m and 0.95 m subsoil profiles (Figure 4-1). It should be noted that total profile root mass and root mass density values represent live plus dead root material. The values stated are not estimates of current year productivity, as the roots belonged to both alfalfa and herbaceous species that occurred on the plots. Rather, these values are intended more for relative comparisons between subsoil profiles.

In both subsoil profiles, greatest root mass density of about 20 kg m^{-3} occurred in the topsoil (0-10 cm) and decreased with depth into the subsoil (Figure 4-1) . The 10-23 cm depth representing topsoil and subsoil material had about 13 kg m^{-3}. The root mass density measured below 23 cm occurred in subsoil material only, with the exception of the depth increment of 50-70 cm, which included some spoil material for 4/9 cores from the 0.55 m subsoil. The declining root weight measured at these lower subsoil depths of about 1.5 kg m^{-3} did not differ. Generally roots in either the 0.55 m or 0.95 m subsoil profile were not observed below the spoil interface (Figure A-1). It should be noted, that despite the tendency for roots not to penetrate past the spoil interface, and although not detectable by the root washings, maximum root penetration was observed at 20 and 10 cm depth into the spoil interface for the 0.55 m and 0.95 m subsoil profile, respectively. Compared to the 0.55 m subsoil profile, detectable roots in the 0.95 m subsoil did extend to a greater depth into the lower subsoil to a depth of 90 cm. Due to spoil interfaces occurring between 82-107 cm among cores of the 0.95 m profile, the 70-90 cm depth increment included spoil material from 4/9 cores analyzed. However regardless of subsoil or spoil material, measurable roots in the 0.95 m subsoil profile could not be detected beyond 90 cm depth.

4.5 DISCUSSION

Root mass determined by washing soil samples did not occur in the spoil material in either subsoil profile. Even though, root mass density tapered with depth in the subsoil to low values; the spoil did not appear to pose an inherent localized limitation to root penetration. In fact, very few roots were observed below a depth of 90 cm in the 0.95 m subsoil profile, demonstrating either a potential increase in physical or chemical limitation posed by the lower subsoil or a possible plant genetic limit to further vertical root growth.

The earlier 1982 Highvale study defined the effective rooting zone under alfalfa, based on root depth and soil moisture measurements, to be a depth of 185 cm in subsoil material, contingent upon the spoil material not occurring at a shallower depth. Only the thickness of the subsoil to the spoil contact was considered as the effective rooting zone when the spoil interface occurred at depths < 185 cm. On the other hand, Schuman and Power (1981) determined alfalfa to extract water to only 135 cm, conditional that the roots did not encounter sodic spoils in the Northern Great Plains of the USA. Based on our measured root results, the effective rooting zone occurred only to a depth of 70 and 90 cm for the 0.55 m and 0.95 m subsoil profiles, respectively. The shallow spoil interface of some of the cores analyzed may have contributed to lowering root mass densities. Although, very few to no roots were observed in the cores below the depth of 90 cm, when the spoil interface was deeper than 90 cm. Compared to 1987 Highvale results of observed root penetration of 17 and 26 cm into the sodic mine spoil for the 0.55 m and 0.95 m subsoil profiles (Oddie and Bailey 1988), respectively, the current (1998) observed root penetration generally has receded. Despite the shallowness of the overall root penetration, both subsoil profiles showed an invariable progressive reduction in root mass density with increasing depth that follows the general pattern of root depth distribution curves.

Total profile root mass showed no difference between subsoil profiles indicating that the extra roots measured in the subsoil of the 0.95 m profile below 70 cm did not contribute significantly compared to the total root weight in the 0.55 m subsoil profile. The small amounts of roots that occurred from 70-90 cm depth in the 0.95 m subsoil profile occurred in a generally massive subsoil (Figure A-2). Poor physical condition associated with sodic soils, of hard when dry, massive and compact (Fairbridge and Finkl 1979) could in part limit root penetration and proliferation and thus, productivity in soils. Physical properties of the subsoil material may have contributed to a gradual yet consistent limitation to root proliferation and elongation. Physical soil limitations associated with sodic alkaline soils have long been documented as poorly aerated, impermeable, sticky and difficult to till (Ansari et al. 1979). It has been suggested that a bulk density of 1.8 Mg m^{-3} restricts root growth of agricultural crops in fine textured soils (ASAC 1987). Thus, increased subsoil bulk density to about 1.5 Mg m^{-3} and particularly the spoil bulk density of $\geq$1.7 Mg m^{-3} at depths greater than 70 cm in the 0.55 m subsoil profile may have contributed to decrease root elongation. Similarly, the massive lower subsoil in the 0.95 m profile with a Db of about 1.6 Mg m^{-3} at depths greater than 70 cm also could have limited root penetration. McSweeney and Jansen (1984), who documented the compacting effects of mining practices on the rooting behavior in reconstructed non-sodic mine soils in southern Illinois, found massive subsoil to deter root proliferation. They noted extensive lateral rooting at the base of the 40 cm topsoil emphasizing the inability of herbaceous roots to penetrate the massive condition and cited both scrapers and extensive grading of subsoil as causes of massive soil conditions. Barth (1984) also described a severely restricted rooting depth in spoil material (SAR $\geq$25). He found that after 7 years since profile construction, herbaceous roots only penetrated to a maximum of 10 cm into the spoil regardless of topsoil thickness (0-152 cm) based on a wedge design in Wyoming, Montana and North Dakota.

Dollhoph et al. (1980) noted from their 2-year study of 70 cm topsoil over a spoil (SAR=23), that the majority of the root mass from perennial grasses occurred between 0-70 cm, with significantly greater biomass occurring at 45 - 70 cm than at 22.5 - 45 cm. Both physical limitation from increased spoil bulk density, and chemical limitation from excess salt in the form of increased sodium, were reasons cited to explain the sudden inhibition of root elongation at the spoil interface. Depuit et al. (1982) also found a significant drastic decline in root biomass across the topsoil / subsoil (overburden) interface along with relatively high concentration of roots in the topsoil zone immediately above the sodic subsoil (SAR=23), related to increased lateral proliferation of roots. It was suggested that the roots were unable to tolerate the increased sodium concentrations of the material and unable to physically penetrate the more compacted condition of the finer textured subsoil. On the other hand, based on the assumption that depth of water withdrawal indicates depth of root activity, Power et al. (1981) observed water extraction to 135 cm depth by an alfalfa crop. This constructed profile of 20 cm topsoil and 30 cm subsoil over a spoil (SAR= 25) indicated that the rooting medium extended well below the spoil interface during their 4-year study in North Dakota.

Crops vary in salt tolerance, but generally salinity effects of soil water with ECs <2 dS m^{-1} causing osmotic stress is mostly negligible (Bernstein 1975). The EC of both the subsoil and spoil in our study are < 2 dS m^{-1}. However, soil sodicity can induce other associated chemical problems that limit plant growth such as calcium deficiency (Sandoval and Gould 1978). As well, increases in subsoil ESP have been documented to decrease crop production. Bernstein and Pearson (1956) determined that an ESP value of 45 is associated with a 50% decrease in alfalfa yield. They noted that the growth response was a function of ESP (emphasizing calcium and magnesium deficiency) rather than absolute level of exchangeable sodium. However, Bernstein and Hayward (1958) and Bernstein (1975) disagreed, stating that it is ionic concentrations in the soil solution that governs plant response, rather than their proportions on the exchange complex. Still, when the total soluble salt concentrations are low, such as in non-saline soils, increases in exchangeable sodium are balanced by decreases in exchangeable Ca and Mg, leading to deficiencies, which in the case of calcium, impairs root growth more than top growth (Tanji 1990).

Bernstein (1975) noted that plants appear to be more sensitive to changes in salinity in the upper root zone compared to the lower root zone, as a function of the root distribution with depth and the resulting greater amount of water uptake from that upper root zone. If alfalfa is relatively unaffected by salinity in the lower root zone, it is not surprising the similar results of root mass density with depth, and total profile root mass between subsoil profiles particularly when the spoil and lower subsoil ECs are < 2 dS m^{-1}. Also, the significant soluble sodium accumulation in the 15 cm of lower subsoil directly above the spoil interface (SAR ~ 10) for both subsoil profiles, would have affected only a small amount of roots at either 50-70 or 70-90 cm depth in the 0.55 m and 0.95 m subsoil profiles, respectively. Furthermore, the SAR value of either profile's upper critical zone was less than 23.5, the SAR moderately sodic tolerant crops, such as alfalfa, usually become affected nutritionally (Bernstein 1975). The majority of roots occurring between 0-23 cm would have been unaffected by the sodium increase in the subsoil. However, even roots that existed in the lower subsoil above the spoil in the 0.55 m profile, most likely would not have been limited by the chemical properties of SAR or EC.

The current root distribution could also have been a result of a genetically controlled limit in vertical root development resulting from the current (1998) mixed plant community on the experimental plots, rather than physical or chemical limitations imposed by the subsoil of the constructed profiles. The shallower rooting behavior measured in the profiles compared to typical rooting depths of alfalfa of 135 to 185 cm (Schuman and Power 1981, Graveland et al. 1988), may be attributed to the change in plant community. Initially (1983), alfalfa (*Medicago sativa* L.) and bromegrass (*Bromus inermis* Leyss.) was exclusively harvested on the subsoil profile plots. However, the current plant community included residual alfalfa and herbs that have established since abandonment of crop harvesting (1987), such as fescue (*Festuca scabrella* Torr.), red clover (*Trifolium pratense* L.) and wild oat (*Avena fatua* L.). The rooting behaviors of these herbs may have genetically influenced the overall root distribution to a shallower depth than alfalfa.

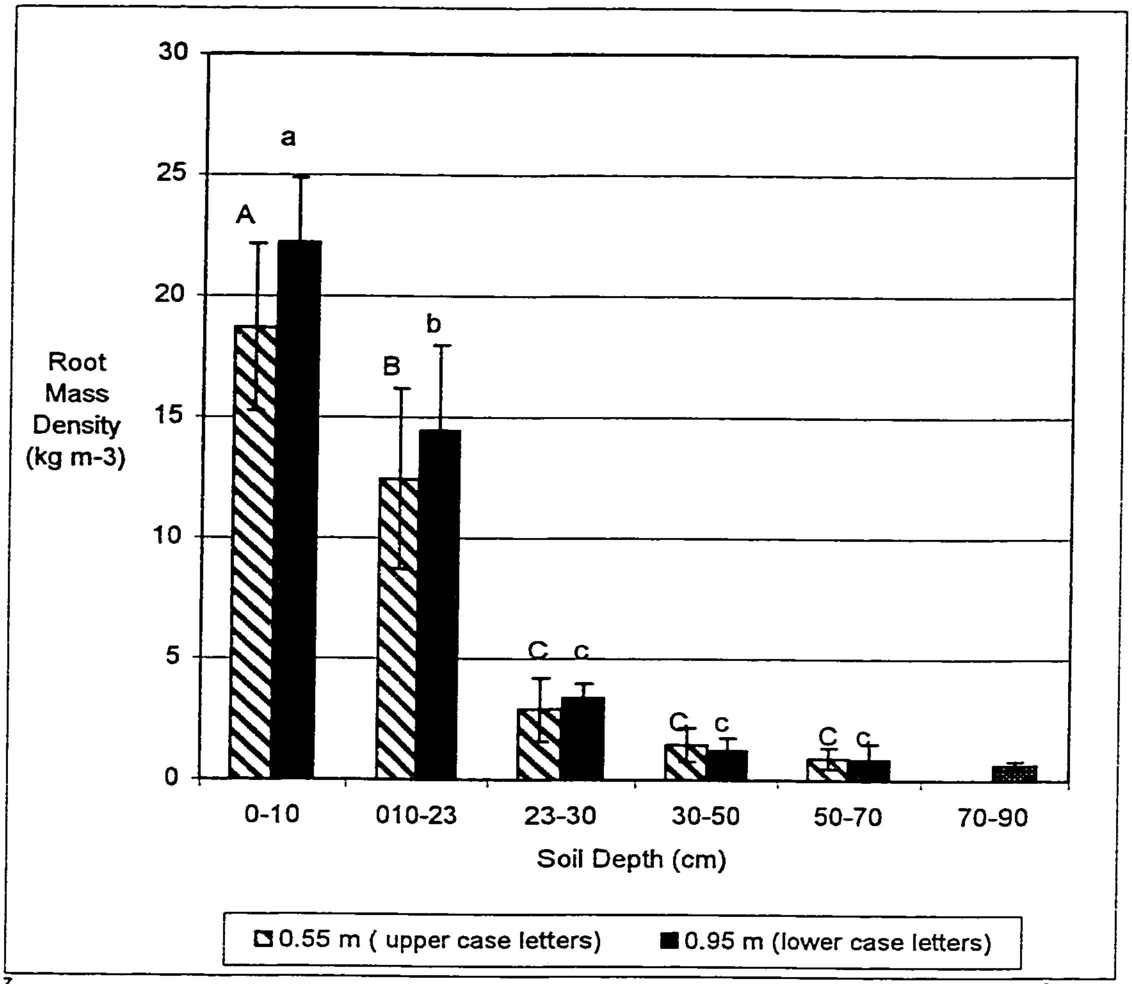
4.6 CONCLUSION

Poor soil physical conditions and high pH causing nutrient imbalances, often associated with surface mined land, are the principal causes of poor soil productivity limiting crop growth (Fairbridge and Finkl 1979). However, it is unknown if varying subsoil thickness in constructed profiles over sodic spoils differ in the ability to mitigate these principal limitations to crop productivity. With regard to the hypotheses, our study found no difference (P<0.05) between the 0.55 m and 0.95 m subsoil profiles in root mass density with depth and total profile root mass. It was observed, in general, that roots in either subsoil profile did not penetrate the spoil, characterized with both high bulk density ($Db \cong 1.7$ Mg m^{-3}) and high SAR values ($SAR \cong 20$). As subsoil Db increases, there is the potential for restricted water transmission, aeration and the physical limitation to root elongation. The increased Db with depth in the subsoil of our study could have influenced a gradual continuum of fewer roots with depth. The chemical effects of sodium accumulation most likely had little influence on root elongation. The SAR value ($SAR \cong 10$) associated with the 15 cm of lower subsoil directly above the spoil interface may have affected roots by potentially risking Ca and Mg deficiency. However, the SAR of this localized area of lower subsoil did not reach the threshold cited in the literature, to affect moderately sodic tolerant crops nutritionally. On the other hand, physical restriction resulting from possible sodic structural deterioration in the lower subsoil in the 0.95 m profile could have deterred root elongation. Another explanation for the current root distribution involves a genetically controlled limit in vertical root development resulting from the current (1998) mixed plant community on the experimental plots. The shallower rooting behavior measured in the profiles compared to typical rooting depths of alfalfa as stated in the literature, could possibly be attributed to the change in plant community from exclusively alfalfa / bromegrass to the current residual alfalfa / bromegrass plus invaded herbs.

Table 4-1. ANOVA summary for root mass density with depth, and total profile root mass for the 0.55 m and 0.95 m subsoil profiles.

Source	df	F ratio	P>F
Root mass density with depth in topsoil and subsoil to 70 cm.			
Treatment	1	0.43	0.579
Depth	4	146	<0.001
Treatment x depth	4	0.63	0.647
Profile root mass per m^2 surface area			
	1	0.34	0.619

Figure 4-1. Average root mass density with depth between and within the 0.55 m and 0.95 m subsoil profiles[ZYX].



[Z] At any depth, subsoil profiles means (n=3) do not differ at $P < 0.05$ and LSD = 5.83 kg m^{-3}.
[Y] Within profile, depth means (n=3) with the same letter do not differ at $P<0.05$, and LSD = 3.41 kg m^{-3}.
[X] Root mass density of 0.95 m subsoil at depth 70-90 cm, not included in Anova model.

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CHAPTER 5
LAND CAPABILITY CLASSIFICATION

5.1 Land Capability Classification for Arable Agriculture in Alberta

The Land Capability Classification for Arable Agriculture in Alberta (ASAC 1987) quantitatively assesses the soil according to prairie agricultural standards (Figure 5-1). The following classification was based on the morphological descriptions and chemical properties determined from the soil profiles found at the Highvale experimental site.

Mineral Soil

Mineral soil rating is broken into three parts: surface features (0-20 cm), subsurface features (20-100 cm) and drainage. Emphasis is placed on the surface features since it is the thickness of soil that is cultivated, seeded and holds the majority of nutrients. Mineral soil rating is primarily based on the surface soil features, with subsurface features and drainage as modifiers. The subclasses in this component are:

1. Texture (M)
2. Structure and Consistence (D)
3. Organic Matter (F)
4. Depth of Ap / Ah (E)
5. Acidity (V)
6. Salinity (N)
7. Sodicity and Saturation Percent (Y)
8. Calcareousness (K)
9. Peaty surface (O)
10. *Depth to Non Conforming Layer (R, D, M)
11. Drainage (W)

*Denotes the subclass that applies only to the subsurface soil rating modification.

SURFACE FEATURES

1. Texture (M)

The texture subclass acts as an index to the amount of water available for plant growth. Unlike the climate moisture factor (A), which does not assume limitation from soil, the texture factor (M) correlates climate with soil factors to quantify the moisture supplying capability of the soil. The rating is based on a combination of precipitation minus potential evaporation (P – PE) index with texture.

Texture Subclass Rating

The deductions for moisture supplying ability, based on surface soil texture and the climate (A) factor indicate a **12.5 point** deduction. The climate index (interpolated from the climate moisture map, included with rating system package) for the Highvale region in Alberta was found to be **P-PE = – 200 mm.** The surface texture was a combination of **clay loam** (topsoil 0-17 cm or 0-15 cm for the 0.55 m and 0.95 m subsoil profiles, respectively) and **silty clay** (subsoil contribution from lower boundary of topsoil to 20 cm depth) (Graveland et al. 1988). Note: Both textures received equal deductions in climates with low negative values of P-PE. The deductions are based on the rationale that a loam soil with P-PE index of –100 should not be limited to supply moisture. However, as the climate becomes drier (with a P-PE index of –500), the moisture supplying ability of a loam texture becomes marginal (class 4) with 60 point deduction.

Note: Adjustment to the texture rating based on the texture of the subsoil, was not necessary since the subsoil was slightly finer within one textural class.

2. Structure and Consistence (D)

Structure depicts the aggregation of the soil particles, which influence soil aeration, water infiltration and workability of the topsoil. Consistence is a measure of the aggregate's resistance to crushing, which is effected by moisture content. This subclass is based on both structure and consistence. There is a maximum of 10 point deduction associated with this subclass since management can modify these surface features in cultivated soils.

Structure and Consistence Rating

Due to the optimum structure and consistence that pose little limitation in resistance to root growth, both subsoil profiles gained **0 point deductions** for surface structure of **granular** with a moist consistence of **friable to very friable** (Figure A-2).

3. Organic Matter (F)

Organic matter contributes to soil structure and the water holding capacity, however more importantly it supplies a valuable nutrient pool. The organic matter subclass correlates the Munsell Soil Color notation of the organic mineral horizon (Ah/Ae or Ap) with percent organic matter. A maximum of 15 points deduction are allotted for this subclass, since organic matter content can be modified by management inputs.

Organic Matter Rating

The color of the surface Ah horizon (which in the site descriptions, extend generally to 20 cm, Figure A-1), were reported as moist values. The Agricultural Capability Rating System gauges the organic matter on a dry value. For the purposes of the rating system then, the values describing the surface soil of the experimental profiles were considered as one less in value (to represent a dry value). The deductions associated with both profiles were **2 point deductions** for an Ah horizon with a dry Munsell value of **4/X (dark gray or dark brown)** which is associated with 4-5% organic matter. Deductions in this subclass are maximized when the Munsell value of the organic horizon is higher than 5 and lighter than brown – gray based on the correlation with less than 2% organic matter, which is thought to cause a sharp deterioration in soil quality.

4. Depth of Topsoil (E)

The topsoil (Ah/Ap horizon) generally has more organic matter and more favorable structure compared to the subsoil. The greater the thickness of the topsoil, the less limiting the soil profile is to plant growth and thus, associated with greater capability. However, this subclass also considers the unfavorable subsoil qualities such as limiting consistence or strongly calcareousness (Bt, Bnt, Ae or Cca horizons). Greater deductions are associated with soils that have unfavorable subsoil compared to favorable subsoil, with equivalent topsoil thickness.

Depth of Topsoil Rating

The average topsoil thickness from the cores drilled was **17 cm** in the 0.55 m subsoil profile and **15 cm** in the 0.95 m profile. Rounding to the nearest category of topsoil thickness (15 cm), **5 points** were deducted based on topsoil thickness overlying subsoil with **firm** to **hard** consistency with **Bk** horizons. The deduction was a result of the unfavorable subsoil qualities of limiting consistence and calcareousness including the Ck or Cca horizon in both profiles.

5. Acidity (V)

The acidity subclass quantifies the pH of the surface soil. Neutral to slightly acidic pHs are ideal for a balanced nutrient supply. Crops vary in their tolerance to acidity; however, as the pH drops below 5, yield is negatively effected. Elements in the soil may become toxic at pHs below 4. Alkaline environments or high pH (which are usually linked to saline or sodic conditions) also cause detrimental affects on plant responses to their environment. If deductions are made in either the salinity or sodicity subclass, the acidity subclass is not included in the overall rating, to mitigate a double penalty for a related soil quality.

Acidity Rating

The average pHs of the topsoil in the 0.55 m and 0.95 m subsoil profiles were **7.6±0.16** and **7.5±0.04**, respectively. Point deductions for surface soil pH as measured in a saturated paste between 6.5 – 7.5 is **0 points**. These pH values (and the following chemical values for the topsoil), have been calculated based on weighted values within 0-20 cm depth per individual core.

6. Salinity (N)

This subclass quantifies the soluble salts found in the surface soil. Since moisture deficit is prevalent in some areas of Alberta farmland, salt content becomes an important consideration. The chemical properties of salt can adversely affect crop development as well salinity can cause osmotic stress to plant water uptake. Crops vary in their salt tolerance; however, salinity effects become noticeable at electrical conductivity of 4 dS m^{-1}. At electrical conductivity (EC) greater than 8 dS m^{-1}, the effects become appreciable to severe, with little to no crop growth at ECs ≥ 16, with the exception of select salt tolerant species such as red samphire (*Salicoria europaea* L.).

Salinity Rating

Point deductions for surface soil salinity, expressed in electrical conductivity (EC) was **0 points** deduction for the average topsoil EC of **0.4±0.03 dS m^{-1}** for the 0.55 m and 0.95 m subsoil profiles. These values are not greater than 2 dS m^{-1} to warrant point deductions.

7. Sodicity and Saturation Percentage (Y)

This subclass is only recommended for reconstructed soils. This subclass depicts the situation where percent sodium increases on the soil exchange complex threatening instability in soil aggregates and dispersion among the soil's clay and colloidal organic factions. Sodium adsorption ratio (SAR) of a saturated paste is one way to quantify the sodium dominance within the soil complex. Sodicity can also be quantified using saturation percentage. The classification system suggests that the most limiting of these two indexes be used. Saturation percentage was not recorded, so this subclass will be based on SAR values.

Sodicity Rating

There are no point deductions for surface soil sodicity that has an SAR value equal to, or less than 4. In both the 0.55 m and 0.95 m profiles, the average topsoil SAR values (**0.3±0.03** and **0.2±0.02** respectively) were less than 4, thus there were **0 points** deduction for both profiles.

8. Calcareousness (K)

This subclass accounts for the calcium carbonate in the soil (CaCO3) which can also cause osmotic stress to plants, limiting water availability. It may also limit nutrient availability such as phosphorus. Calcium carbonate is quantified by the salt's reaction with 10% HCl.

Calcareousness Rating

Based on the morphological descriptions of both subsoil profiles (Figure A-1), there was **no calcium carbonate reaction** with dilute acid in the top 20 cm of the profiles. Thus, there are **0 point deductions** for surface calcareousness in either subsoil profile.

9. Organic (Peaty) Surface (0)

This subclass describes the potential for management problems associated with peaty soil surfaces. Greater point deduction are linked to the fibric organic material which is porous and less compact due to the lesser degree of peat decomposition compared to humic (well decomposed) material. As well, the deeper the depth of peat, the greater amount of points deducted as the soil grades into organic soils.

Organic Rating

There was **no surface peat** on the profiles on the Highvale experimental site, thus **0 points** were deducted for both subsoil profile.

SUBSURFACE FEATURES

The subsurface in this rating system extends from 20-100 cm depth to represent the effective rooting zone for most annual crops. These subsurface factors only act as percent modifiers to the primary point rating of the surface factors. Subsoil modification is made to the five factors of:

1. *Structure and Consistence (D)
2. *Depth to Nonconforming layer (R, D, or M)
3. Acidity (V)
4. Salinity (N)
5. Sodicity and Saturation Percent (Y)

Note: If a paralithic contact is present, the more limiting of either structure and consistence or paralithic contact is considered, but not both parameters.

1. Structure and Consistence (D)

Subsurface structure and consistence will affect root penetration and ultimately the availability of water and nutrients to plants. Points are deducted in association with

Solonetzic soils due to the high densities resulting from hard to compact consistence and possible massive structure. The rating system suggests a bulk density of ≥1.8 Mg m^{-3} would restrict root growth. Also, it suggests that the small pore space and limited aeration related to clay textures restrict root proliferation compared to sandy soils of similar density. Since density is not easily measured in the field, the relationship of structure and consistence is used to estimate resistance to root growth.

Structure and Consistence Rating

Deductions for this subclass were calculated from the sum of weighted deductions incurred from individual horizons that existed within 20 - 100 cm depth of the profiles (Figure A-2). The calculation of deductions from each profile can be found in Appendix E. The average subsoil structure and consistence deduction for the 0.55 m and 0.95 m profiles were **21 percent** and **25 percent** deductions, respectively. The increase in percent deductions associated with the 0.95 m profile was due to the lack of structure in the lower depths of the profile (about 75 cm). Also, the very hard consistence found in the subsoil, compared to the slightly hard or hard consistence found in the 0.55 m subsoil profile added to the profiles' net deductions. As well, the 0.55 m profile showed some advanced prismatic macrostructure, compared to the 0.95 m profile.

2. Depth to Nonconforming Layer (R, D or M)

A nonconforming layer is described as a change in geological material that limits water movement and root penetration within the profile. The layer is a geologic feature rather than a pedologic feature caused by soil forming factors. Layers can be identified based on textural changes associated with increased density or related hardness. However, the rating system bases the deductions in this subclass on depth to contact of either a lithic, paralithic layer or change in texture from loam texture or finer, to gravel or gravel and sand.

Depth to Nonconforming Layer Rating

The spoil used in the experimental soil profiles originated from an overburden pile. Since the spoil was a product of mining, the spoil contact in the subsoil profiles fails to meet the requirements of a lithic contact, because the spoil is not consolidated bedrock nor does the contact prohibit root penetration. The spoil contact between subsoil and spoil material did represent a boundary where the finer textured subsoil (silty clay) abruptly changed to the coarser spoil texture (sandy clay). However, the spoil does not have the coarse fragments that are associated with gravel or sand mixed with gravel, which was the requirement for the textural change. Nevertheless spoil bulk densities associated with the 0.55 m subsoil profile were significantly greater compared to subsoil bulk densities (Chapter 2). However, in the 0.95 m subsoil profile, spoil bulk density was not significantly different from subsoil bulk density values. Based on the significant increase in spoil bulk density values of the 0.55 m treatment, it was assumed that the spoil material represented a paralithic contact of poorly consolidated bedrock which could be dug with a spade when moist and was severely constraining but not impenetrable by roots. The average depth to spoil contact in the 0.55 m subsoil profile was 67 cm; so the deductions associated with a **paralithic contact at 70 cm depth** is **17 percent**. Due to similar subsoil and spoil bulk densities of the 0.95 m subsoil profile (Chapter 2), the spoil contact failed to meet the requirements of a paralithic contact. However, since deductions for the paralithic contact was less than the deductions acquired in the subsoil structure and consistence subclass (21 % deduction), the paralithic parameter was not considered in the overall subsoil rating.

6. Subsoil Acidity (V)

This subclass considers only acidic pH levels, since higher basic pH values that are commonly associated with salinity and sodicity, are accounted for in the next two subclasses. The system assumes that the majority of Alberta soils have developed from calcareous parent geological material; thus, it only considers the depth of 20 - 60 cm as critical to describe subsoil acidity. Within each profile, subsoil acidity mean (n=3) was calculated from weighted pH values determined with depth from 20-60 cm for each core analyzed (4 per plot).

Subsoil Acidity Rating

For each subsoil profile the average subsoil acidity was calculated from weighted values determined at depths within 20-60 cm of each core analyzed. The average pH for the 0.55 and 0.95 m subsoil profiles were **8.7±0.12** and **8.9±0.09** respectively. Due to the alkaline nature of these pHs, **0 percent** deductions were allotted to both profiles in this subclass.

7. Subsoil Salinity (N)

Deductions for subsoil salinity should only be used if the limitation is more limiting than the surface. **Note:** Within each profile, subsoil salinity and subsoil sodicity means (n=3) were calculated from weighted EC and SAR values respectively, determined within the depth of 20-100 cm for each core analyzed (4 per plot).

Subsoil Salinity Rating

Weighted EC averages for the 0.55 and 0.95 m subsoil profiles were **1.0±0.14 dS m^{-1}** and **0.6±0.13 dS m^{-1}**, respectively. These values were slightly higher compared to the topsoil values; however, they were still well below 4 dS m^{-1} which is the lower threshold for subsoil salinity deductions. Thus **0 points** were deducted from either profile.

8. Subsoil Sodicity and Saturation Percentage (Y)

This subclass is referred to only for reconstructed soils. Subsoil sodicity is only considered if it is evaluated as more limiting than the surface sodicity. Similar to surface sodicity, this subclass should only be considered for soil textures of loam or finer.

Subsoil Sodicity and Saturation Percentage Rating

Only SAR values were determined and not saturation percentages. The subsoil SAR averages for the 0.55 and 0.95 m subsoil profiles were **10.7±3.04** and **3.5±1.65** respectively. The percent deductions associated with these SAR values, are **20 percent** deduction for the 0.55 m profile and **0 percent** deduction for the 0.95 m profile since the value is less than 4. The subsoil SAR value in the 0.55 m profile was larger since the spoil contact occurred near 70 cm depth, thus there was a larger contribution of spoil material supplying a source of soluble sodium and causing an increase in the SAR value. The contact of the 0.95 m profile occurred deeper in the profile, so generally there was little spoil material included in the chemical values determined from the control section (0-100 cm).

9. Drainage (W)

This subclass is important both for plant growth aspects, as well as land management considerations. This subclass is based on the depth to the water table over a minimum period of one month during the growing season. In lieu of this, both soil morphology and vegetation features can be used to indicate depth of water table.

Drainage Rating

All three materials in the constructed profiles were mottled (Figure A-1). This indicated imperfect to poor internal drainage. The water table at the Highvale experimental area was well below 1 m (C. Bateman, personal communication, Trans Alta Utilities). Furthermore, the absence of gleyed features in the soil profiles indicated that water was not continuously stagnant at the subsoil spoil interface, nor did a perched aquifer exist. Rather, the compound effects of increased bulk density and grading of structure to massive conditions, with depth, within the subsoil and spoil has presumably decreased water drainage throughout these materials. Also, the increase in swelling montmorillonite clay from the topsoil texture of clay loam to the silty clay subsoil, could also lead to slower drainage throughout the medium, accounting for the mottles noted in the topsoil of some of the soil site descriptions (Figure A-1).

The imperfect drainage moisture regime in the Land Capability Classification for Arable Agriculture in Alberta (ASAC 1987) also describes the depth to the water table within 50 cm for a minimum of one month and gleyed soils with mottling below 50 cm. In lieu of the gleyed conditions depicted in this regime, mottles were observed in both subsoil profiles which indicate drainage limitation, and thus, prevented these subsoil profiles from meeting the requirements of the moderately well drainage class moisture regime.

Unfortunately, this assumption was only precautionary, and due to unreliable soil water measurements, it could not be substantiated.

The moisture regime further distinguishes imperfectly drained soils, which can be cultivated 6 out of the 10 years from soils that can be cultivated 9 out of 10 years. Considering that residual alfalfa-smooth bromegrass still exists since 1988, at the fruition of the Highvale 5-year study in1987, it was expected that the drainage of the profiles could not be too restricted, to sustain alfalfa growth during ten years of abandonment. Thus, it was assumed both soil profiles showed potential for cultivation 9 out of 10 years.

Based on this rationale both subsoil profiles would have **imperfect subsoil drainage,** allowing cultivation 9 out of 10 years, for which they received **10 percent** deductions.

5.2 Agricultural Capability Classification for Reclamation

The Agricultural Capability Classification for Reclamation (RRTAC 1993) was also used to assess soil capability in the 0.55 m and 0.95 m subsoil profiles (Figure 5-2). This reclamation capability document offers a classification system similar to the land capability classification of arable agriculture, however it is oriented to assess soils after reclamation. This system assumes that climate limitations remain the same throughout the disturbance and reclamation process and so offers the climate rating as an option. The document also suggests the potential to evaluate reclamation success by comparing agricultural capability prior to disturbance and after reclamation. It is intended for the Alberta agricultural zone that has been disturbed primarily by mining, the oil and gas industry, utilities, right-of-way construction and transportation. The soils are assumed to be free of anthorpogenically added hydrocarbons, heavy metals, herbicides and sterilants.

The rating system evaluates the soil profile to 1 m depth from the surface.
However, the rating system emphasizes the upper 50 cm of the profile for favorable growing conditions relating to root zone quality. Three principal layers are considered in the reclaimed profile: topsoil, upper subsoil and lower subsoil. Topsoil is defined as the uppermost mineral and organic soil materials, which are valued as a growth medium.

The upper subsoil consists of the soil material from the lower boundary of the topsoil to a depth of 50 cm. The lower subsoil extends from 50 to 100 cm depth in the soil profile, which may include spoil material if the spoil contact occurs at a depth shallower than 100 cm.

Mineral Soil Component (S)

The following subclasses are evaluated in the soil component in the rating system.

1. Moisture Availability (M)
2. Structure and Consistence (D)
3. Organic Carbon Mass (F)
4. Acidity / Alkalinity (V)
5. Salinity (N)
6. Sodicity (Y)
7. Nutrient Balance (K)
8. Peaty Surface (O)
9. Topsoil Loss (G)
10. Moisture Regime Factors (W)
    - wetness
    - climatic doughtiness

SURFACE FACTORS

1. Moisture Availability (Based on texture): Subclass M

The main factors controlling available water are thickness and texture. Available water holding capacity (AWHC) is determined according to a weighted equation (below) that emphasizes the upper root zone (0-50 cm depth) based on the thickness and textures of the soil within the control section (1 m from surface).

AWHC (mm/100 cm) =

[0.7 AWHC in mm (0-50 cm) + 0.3 AWHC in mm (50-100 cm)] x 2

Moisture Availability Rating

In both subsoil profiles, the deduction for soil profile moisture availability was **0 points**. Using the above equation, the 0.55 m profile was calculated to have an available water holding capacity (AWHC) of **197 mm** water per 100 cm soil. The 0.95 m profile was determined to have an AWHC of **212 mm** of water per 100 cm soil. For soils with an AWHC ≥ 150 mm in the control section, there were no deductions made towards the subclass. The AWHC in the 0.95 m profile was larger compared to the 0.55 m profile due to the increased thickness of the silty clay subsoil horizon, the textural class that accounts for the greatest contribution for supplying available water (2.25 mm of H_2O per cm soil) compared to the other textures.

2. Structure / Consistence: Subclass D

This subclass only considers the topsoil horizon. Surface soil structure which influence aeration and water permeability is associated with texture and organic matter content. Surface soil consistence, which affects soil workability, depends on stability of aggregates, bulk density and compactness.

Structure / Consistence Rating

This subclass rating is based on the most limiting condition in either structure or consistence. The most limiting structure and consistence in the topsoil of both subsoil profiles were **coarse granular** (5-10 mm) structure with a **friable** consistence. These soil surface structure and consistence qualities were given a deduction of **5 points** for both subsoil profiles.

3. Organic Carbon and Topsoil Depth: Subclass F

Organic material (humus) is an integral contributor the nutrient pool, structure, water holding capacity, workability and biological activity of the soil. Either organic carbon can be measured in the laboratory or it can be estimated based on the "value" component of the Munsell topsoil color notation. A calculation is used to determine tonnes of organic carbon per hectare, based on bulk density and thickness of topsoil layer.

$\text{Tonnes OC ha}^{-1} = \text{OC\%} \times \text{depth (m)} \times \text{bulk density (Mg m}^{-3}) \times 10\,000 \text{ m}^2 \text{ ha}^{-1}$

Organic Carbon and Topsoil Depth Rating

Munsell value (moist) in both subsoil profiles was 3. The value is increased by 1 unit to approximate the dry value. The organic carbon content associated with a value of 4 (d) is 3% (equal to an organic matter content of 5.3%). The topsoil bulk densities used in the equations for the 0.55 m and 0.95 m subsoil profiles were 1.2 Mg m^{-3} and 1.1 Mg m^{-3}, respectively. The calculated mass of organic carbon was equal to **58.7 T ha^{-1}** and **49.5 T ha^{-1}** for the respective 0.55 m and 0.95 m subsoil profiles. The deduction attributed to the organic carbon content in the 0.55 m profile with a 1.2 Mg m^{-3} bulk density was **13 points**, while that for the 0.95 m profile with a bulk density of 1.1 Mg m^{-3} was **16 points**. The 0.55 m subsoil profile received less deductions based on the higher bulk density of the topsoil (rounded up to 1.2 Mg m^{-3}) and the slightly thicker topsoil of 17 cm compared to 15 cm topsoil averaged in the 0.95 m profile.

4. Soil Reaction: Subclass V

Generally, crop yields are maximized under a neutral or slightly acidic soil environment. Low pH will offset the balance of the nutrient supply, to a point that some elements may occur in toxic quantities. High pH or alkaline conditions are usually associated with highly saline or sodic conditions, and will also decrease crop yields. If deductions are made in either the salinity (N) or sodicity (Y) subclass, then deductions are omitted in the reaction subclass (V).

Soil Reaction Rating

The pH of the topsoil, measured in saturated paste, of the 0.55 m and 0.95 m subsoil profiles were **7.4±0.16** and **7.2±0.11**, respectively. Since these topsoil pHs occur within the range of 6.5-7.5, considered as neutral, there were **0 point** deductions for both profiles.

5. Salinity: Subclass N

Soluble salts in the soil water can affect crop growth through chemical means or by limiting available water to plants. Crop species vary in salt tolerance; however, at ECs >4 dS m^{-1} crop yield decreases appreciably.

Salinity Rating

The electrical conductivity of the topsoil, measured in saturated paste, of the 0.55 m and 0.95 m subsoil thickness treatments were **0.4±0.08 dS m^{-1}**. Both topsoil EC values were less than 2 dS m^{-1} and thus have **0 point** deduction.

6. Sodicity and Saturation Percentage: Subclass Y

At sodium adsorption ratios above 12 (usually associated with a pH ≥ 8.5) finer particles such as clay and colloidal organic material begin to disperse, which adversely affects soil aggregate stability. This subclass utilizes the more limiting of the two measurements, sodium adsorption ratio or saturation percentage.

Sodicity Rating

Unfortunately, saturation percentage was not measured in this study, so SAR values were used by default. The SAR of the topsoil in the 0.55 m and 0.95 m subsoil profiles were **0.31±0.03** and **0.20±0.02**. There were **0 point** deductions incurred for this subclass since both values were well below 4, the lower SAR limit for deductions.

7. Nutrient Imbalance: Subclass K

Similar to soluble salts, calcium carbonate ($CaCO_3$) can limit plant available water, and the availability of certain nutrients such as phosphorus to ultimately limit plant growth. However, calcium carbonate is less soluble and thus less seasonally variable as well; the effects are not as severe compared to the soluble salts.

Nutrient Imbalance Rating

Topsoil calcareousness was measured in the field with 10% HCl for both subsoil profiles. There was **no reaction** in the topsoil for either profile, indicating very little to no influence of free calcium carbonate in the topsoil. There were **0 point** deductions for either subsoil profile in this subclass.

8. Organic (Peaty) Surface: Subclass O

This subclass considers the management problems associated with organic peaty surfaces, particularly the fibric material. Compacted, well-decomposed mesic and humic material in a granular structure is preferable over the spongy, porous fibric mosses.

Organic (Peaty) Surface Rating

This subclass is intended for soil profiles that have peat surfaces ≥ 10 cm in thickness. Neither subsoil thickness treatment profile had a peaty surface. The litter layer consisted of grasses, contributing to a **LFH layer**, that was about 2-3 cm thick. There were **0 point** deductions for both profiles.

9. Topsoil Loss: Subclass G

This subclass deducts points for loss in topsoil thickness compared to an average control depth (or specified depth) resulting from the reclamation process. This loss may result from the grading process (either stripping or replacing the soil), unleveled replacement or during storage.

Topsoil Loss Rating

Examples of topsoil thickness less than the required 15 cm replacement thickness were noted from cores drilled within both subsoil profile's plots. However, treatment averages of topsoil thickness was at least **15 cm** in the 0.95 m profile and **17 cm** for the 0.55 m profile. These values meet and exceed the soil profile's 15 cm requirement for topsoil layer thickness, constructed sixteen years ago. There are **0 point** deductions for either profile in this surface topsoil loss subclass.

SUBSURFACE FACTORS

The subsoil is sectioned into upper (topsoil to 50 cm) and lower subsoil (50-100 cm). Deductions incurred in the two layers are weighted 2:1 or 67:33%, as a percentage, which act to modify the surface rating. There are four subsurface factors: structure, acidity, salinity and sodicity. Chemical values determined for the upper and lower subsoil thickness are based on weighted values determined from samples taken within these sections.

1. Subsoil Structure: Subclass D

Root penetration and the accessibility of water, air and nutrients are in part controlled by structure. This subclass considers the abundance and size of the dominant soil aggregates, as well as rooting and consistence in the subsoil. Again, the most limiting of structure or consistence within a layer is to be rated.

Subsoil Structure Rating

Since both subsoil profiles had more than one horizon in each of the upper and lower subsoil segment, each horizon was rated for deductions based on the structure and consistence, and weighted over the total subsoil segment thickness. The thickness of the upper subsoil segment was equal to 50 cm minus topsoil thickness, and the thickness of the lower subsoil segment was equal to 50 cm. Upper subsoil structure percent deductions in the 0.55 m and 0.95 m subsoil profiles were **7.4%** and **18.9%,** respectively. The two profiles generally had a similar structure of **subangular blocky**. However, greater amount of deductions associated with the 0.95 m profile was due to the increased consistence from **slightly hard** (as in the 0.55 m profile) to **hard**. As well, the influence of admix in the upper subsoil segment, that contributed to a massive structure and very hard consistence in the 0.95 m profile, also increased deductions. Lower subsoil structure percent deductions in the 0.55 m and 0.95 m subsoil profiles were **41.7%** and **42.5%,** respectively. The two profiles generally Lacked structure and were very hard to extremely hard.

2. Subsoil Reaction: Subclass V

Subsoil reaction only applies to acidic situations, since alkaline pH is usually implicated with saline or sodic conditions and therefore dealt with in those subclasses. Again, acidic conditions would limit plant growth similarly as discussed for topsoil reaction. Note: Within each profile subsoil, subsoil pH, salinity and sodicity means (n=3) were determined from weighted pH, EC or SAR values respectively, within the upper subsoil (lower boundary of topsoil to 50 cm) and lower subsoil (50-100 cm) for each core (4 per plot).

Subsoil Reaction Rating

The upper subsoil pH in the 0.55 m and 0.95 m profiles were **8.7±0.15** and **8.9±0.10,** respectively. The lower subsoil pH in the 0.55 m and 0.95 m subsoil profiles were **8.7±0.16** and **8.8±0.06**, respectively. Since this subclass quantifies an acidic environment, the alkaline values for both subsoil profiles, received **0 percent** deduction.

3. Subsoil Salinity: Subclass N

Subsurface salinity, as a percent modifier is rated regardless of topsoil salinity condition.

Subsoil Salinity Rating

Upper subsoil EC values in the 0.55 m and 0.95 m subsoil profiles were **0.5±0.04** and **0.4±0.06 dS m^{-1}**, respectively. Lower subsoil EC values in the 0.55 m and 0.95 m subsoil profiles were **1.4±0.19** and **0.7±0.20 dS m^{-1}**, respectively. The EC of both profiles, in both the upper and lower subsoil were less than 2 dS m^{-1}, the lower boundary of salinity considered for deductions. Thus, **0 percent** deductions were assigned to either profile in either subsoil section.

4. Subsoil Sodicity and Saturation Percentage: Subclass Y

Again, only the more limiting of SAR or saturation percentage is considered for deductions.

Subsoil Sodicity Rating

Only SAR was determined, so these values were used by default. Upper subsoil SARs in the 0.55 m and 0.95 m subsoil profiles were **1.5±0.57** and **0.4±0.02**. These treatment values are less than the minimum for sodicity deduction (SAR = 4), so there was **0 percent** deduction for the upper subsoil. However lower subsoil SARs of the 0.55 m and 0.95 m subsoil profiles were **16.1±4.43** and **5.4±2.65**. These higher values corresponded to **70** and **13%** deduction. The higher sodic conditions associated with the 0.55 m profile was a result of the shallower spoil contact, compared to the 0.95 m profile. The sodic spoil material contributed to increasing the SAR of the overall lower subsoil section.

IV Moisture Regime Factor: Subclass W

This subclass evaluates the water supply to the root zone. The subclass considers the more limiting situation of either excessive wetness resulting from a shallow water table and/or poor drainage, or water deficiency arising from a climate that has higher potential evaporation compared to precipitation. The soil moisture regime is rated as a percent modifier to the entire soil rating. Deductions for excessive wetness are based on the uppermost level of the water table for a minimum of one month, during the growing season. Deductions for drought conditions are based on climatic precipitation minus potential evaporation index. The smaller percent modifier of either adjustment is used. Present drainage conditions should be assessed. This subclass is complicated to rate, since soil features respond slowly to soil moisture conditions. Since soil morphology does not always represent the current environmental conditions, especially in newly constructed soils, it is important to discern only present moisture limitations.

Moisture Regime Rating

The precipitation minus potential evaporation extrapolated from the climate index map for the area of the experimental site indicated the area was not subject to drought conditions with a P-PE of -200 mm and thus, no adjustment was necessary. However, an adjustment for limited drainage resulting in excessive wetness, was necessary. Profile morphological descriptions indicated mottling throughout both of the soil profiles (Figure A-1). In all cases the spoil material was not gleyed, suggesting that water was not pooling near the spoil contact. However, the compounded effects of increasing bulk density, structure grading to massive conditions with depth in the subsoil and spoil, and the increase of montmorillonite clay content from the topsoil texture of clay loam to subsoil texture of silty clay, infer an imperfectly drained soil. Both subsoil profiles would similarly be effected by these properties restricting downward saturated flow through the subsoil that occurred within 1 m of the surface. The wetness category associated with these properties was a **W2** wetness category; which describes a water table depth of < 1 m and imperfectly drained, allowing cultivation 8/10 years. This drainage category is associated with an **80% adjustment** factor. Occurrence of mottles in the topsoil, (which may be a result of slower drainage into the finer texture of the subsoil material) and subsoil properties mentioned above, prevented the subsoil profiles from a rating of a W1 wetness category. This category is described to be moderately well drained soil limited in drainage between 1 to 2 meters from the surface.

5.3 Comparison of Rating Systems

The systems are alike in the boundary of index points categorized for each capability class. The systems are also generally alike in the soil properties and the rating structure of these properties, assessed to determine soil capability. However there were some differences between the two rating systems: Land capability classification for arable agriculture in Alberta (ASAC 1987) and Agricultural capability classification for reclamation (RRTAC 1993), that lead to different class ratings for the 0.55 m subsoil profile (Table 5-1).

The weighting of soil properties differ between the two systems. Both share a common 1 m control section, however the classification for arable agriculture in Alberta stresses a surface section of 0-20 cm and to a lesser degree the remaining 20-100 cm of subsurface. The classification for reclamation emphasizes the topsoil as a whole (which can vary in thickness from 10-35 cm) which allows the topsoil properties to be analyzed exclusively from subsoil properties. As well the subsoil is divided into upper subsoil (lower boundary of topsoil to 50 cm) and lower subsoil (50-100 cm), with greater emphasis on the upper subsoil section (2/3) compared to the lower section (1/3). This allows better resolution within the soil profile to the kinds and extent of limitations. As well, the classification for reclamation offered more detailed limits and associated deductions to rate a certain soil property within a certain subclass.

A distinct difference between the structure of the two rating systems was that the classification for arable agriculture in Alberta rating was generally based on an accumulation of percent deductions acquired in the subsoil subclasses. However, the classification for reclamation considered only the most limiting factor based on the highest percent deduction attributed to a subclass, for each of the upper and lower subsoil sections. Similarly, with the exception of the organic carbon determination, the overall surface factor point deduction was also based on the most limiting of the remaining surface subclasses analyzed. This kind of rating system structure, where less limiting factors are omitted from the overall rating, masks the potential of compounded limiting effects of the soil properties. As well, if a soil property (determined in a subclass) was only slightly less limiting compared to the most limiting soil property, the soil subclass would not be documented. Thus, the subclass would not be considered for the soil property's potential to become more limiting and decrease the soil capability with time.

The difference in the class rating of the 0.55 m subsoil profile from a class 4 (agricultural capability rating) to class 3 (reclamation capability rating) was partly a result of the difference in the separation of the control section and the weighting associated with these separations. More specifically, the subsurface structure and consistence parameter of the agricultural rating system acquired greater deductions for the overall subsoil structure to 100 cm depth. However, the reclamation rating system put greater emphasis on the upper subsoil (above 50 cm depth) compared to the lower subsoil (below 50 cm) that encompassed the spoil interface and massive properties. The separation of the subsoil allowed for less deduction in the upper subsoil that had greater weighting compared to the lower subsoil that acquired greater deductions, but was weighted less.

An important discrepancy between the two rating systems that resulted in a difference of class rating was the point deduction incurred in the surface factor for the subclass of moisture supplying ability or available water holding capacity (AWHC) based on texture. The classification for arable agriculture in Alberta only considers the surface (0-20 cm) for this subclass, but does adjust for surface soils overlying coarse subsoil textures. Points were deducted for the climate index interpolated from climate moisture index map (included in rating package) and the combination of a clay loam and silty clay surface texture. However, the classification for reclamation assessed the AWHC based on a calculation that weighted the texture and the associated water holding capacity of the soil horizons throughout the 1 m control section. It was determined from the calculation that the texture was not limiting moisture availability to plants and thus, no points were deducted. If the previous classification for arable agriculture in Alberta did not deduct points for surface moisture supplying ability, then the classification would rate the 0.55 m subsoil profile a class 3 based on 50 index points.

Despite the difference in class rating for the 0.55 m subsoil profile, the two rating systems similarly recognized subsurface sodicity as a limiting subclass. The classification for arable agriculture in Alberta also recognized subsurface structure and consistence as a limiting subclass responsible for the class 4 soil rating. The classification for reclamation only acknowledged subsurface sodicity as limiting. However it allowed for further detail to acknowledge the limitation to the lower subsoil section only (Figure 5-2).

Classification of the 0.95 m subsoil profile was similar between the two rating systems. Both systems rated the subsoil profile a class 3 based on limited subsoil structure and consistence (Table 5-1). The classification for arable agriculture in Alberta rating was based on 54 index points, while the classification for reclamation rating was based on 47 index points. The lower index points acquired from the classification for reclamation system was a result of the limited structure emphasized particularly in the lower subsoil section which was not equally weighted between 20-100 cm as in the arable agriculture in Alberta classification.

Table 5-1. Summarized comparison of capability rating systems

Agricultural Capability Classification	**0.55 m**	**0.95 m**
Numerical value	42.6	54.4
Class	4	3
Subclass	Y and D	D
Reclamation Capability Classification		
Numerical value	47.2	46.5
Class	3	3
Subclass	Y	D

Figure 5-1. The Land Capability Classification for Arable Agriculture: Rating of the soil component.

Location Highvale Experimental Plots

Date: Oct, 1998

I. Surface Factors (point deductions)

	value			point deduction	
	0.55 m	**0.95 m**		**0.55 m**	**0.95 m**
texture (M)	CL / SiC	CL / SiC			
subsoil texture	SiC	SiC		12.5	12.5
structure and consistence (D)	gran/frib	gran/frib		0	0
organic matter (F)	4-5%OM	4-5% OM		2	2
depth of Ah or Ap (E)	17 cm	15 cm		5	5
acidity (V)	7.6	7.5		0	0
salinity (N) (dS/m)	0.4	0.4		0	0
sodicity / saturation % (Y) (SAR)	0.3	0.2		0	0
calcareous (K)	no rxn	no rxn		0	0
peaty surface (O)	n/a	n/a		0	0
			TOTAL =	19.5	19.5
Basic Soil Rating			100 -	19.5	= a) 80.5

II. Subsoil Factors (percent deduction)

	value			percent deduction	
	0.55 m	**0.95 m**		**0.55 m**	**0.95 m**
structure and consistence (D)	sl.-ext.hard SAB-mass	sl.-ext.hard SAB-mass		21.3	24.8
depth to nonconforming layer (R, D, or M)	paralithic at 70 cm	n/a		17*	0
acidity (V)	8.7	8.9		0	0
salinity (N) (dS/m)	1	0.6		0	0
sodicity / saturation % (Y) (SAR)	10.7	3.5		20	0
			TOTAL =	41.3	24.8

* not considered since structure more limiting

Subsoil deduction	**0.55 m**	=	41.3	% of a) =	b) 33.2
	0.95 m	=	24.8	% of a) =	b) 20.0

0.55 m Interim Soil Rating = a) 80.5 - b) 33.2 = c) **47.3**
0.95 m Interim Soil Rating = a) 80.5 - b) 20.0 = c) **60.5**

III. Drainage Factor (percent deductions)

	value		percent deduction	
	0.55 m	**0.95 m**	**0.55 m**	**0.95 m**
Drainage (W)	imperfect	imperfect	10	10

Drainage deduction	**0.55 m**	=	10	% of c) =	d) 4.7
	0.95 m	=	10	% of c) =	d) 6.1

FINAL SOIL RATING (S) 0.55 m = a) 80.5 - [b) 33.2 + d) 4.7] = **42.6** Class **4**, subsclasses **Y** & **D**
FINAL SOIL RATING (S) 0.95 m = a) 80.5 - [b) 20.0 + d) 6.1] = **54.4** Class **3**, subclass **D**

Figure 5-2. The Agricultural Capability Classification for Reclamation: Rating of the soil component.

Location: Highvale Experimental Plots

Date: Oct 98

I. Surface Factors

	value		point deduction	
	0.55 m	**0.95 m**	**0.55 m**	**0.95 m**
AWHC to 100 cm (M)	197 mm	212 mm	0	0
structure and consistence (D) *	gran/friab.	gran/friab.	5	5
organic carbon %	3%	3%		
and depth (F)	17 cm	15 cm	13	16
acidity (V) *	7.38	7.19	0	0
salinity (N) * (dS/m)	0.4	0.4	0	0
sodicity / saturation % (Y) * (SAR)	0.3	0.2	0	0
nutrient imbalance (K) *	no rxn	no rxn	0	0
peaty surface (O) **	n/a	n/a	0	0
topsoil loss (G)	n/a	n/a	0	0
		TOTAL	18	21

* (deduct most limiting D, V, N, Y, or K)

** (when deducting O, also deduct *)

Basic Soil Rating =

0.55 m 100 - = 18 a) 82

0.95 m 100 - = 21 a) 79

II. Upper Subsoil Factors

	value		percent deduction	
	0.55 m	**0.95 m**	**0.55 m**	**0.95 m**
structure (D) *	SAB /sl.hard	SAB/v.hard	7.4	18.9
acidity (V) *	8.7	8.9	0	0
salinity (N) * (dS/m)	0.5	0.4	0	0
sodicity / saturation% (Y) * (SAR)	1.5	0.4	0	0
		TOTAL	7.4	18.9

* (deduct one only, most limiting)

0.55 m Upper subsoil deduction = 7.4 % of (a) x 0.67 = b) 4.1

0.95 m Upper subsoil deduction = 18.9 % of (a) x 0.67 = b) 10

III. Lower Subsoil Factors

	0.55 m	0.95 m	0.55 m	0.95 m
structure (D) *	amorp/ex.hard	amorp/ex. hard	41.7	42.5
acidity (V) *	8.7	8.8	0	0
salinity (N) * (dS/m)	1.4	0.7	0	0
sodicity / saturation% (Y) * (SAR)	16.1	5.42	70	13
		TOTAL	70	42.5

* (deduct one only, most limiting)

0.55 m Upper subsoil deduction = 70 % of (a) x 0.33 = c) 18.9

0.95 m Lower subsoil deduction = 42.5 % of (a) x 0.33 = c) 10.9

0.55 m Interim Soil Rating = (a) 82 - (b) 4.1 - (c) 18.9 = (d) 59

0.95 m Interim Soil Rating = (a) 79 - (b) 10.0 - (c) 10.9 = (d) 58.1

IV. Moisture Regime Factor (W)

	0.55 m	0.95 m	Adjustment	
wetness *	W2	W2	80%	80%
climatic factor *	-200	-200	100%	100%

* (deduct one only, smaller percentage)

e) 80%

0.55 m Final Soil Rating (S) = (d) 59 x (e) 80% = **47.2** Class **3**, subclass **Y**

0.95 m Final Soil Rating (S) = (d) 58.1 x (e) 80% = **46.5** Class **3**, subclass **D**

5.4 REFERENCES

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CHAPTER 6

VARIABLE SUBSOIL THICKNESS OVER SODIC MINE SPOIL AND AGRICULTURAL SOIL CAPABILITY: A SYNTHESIS

A significant challenge of mine companies and of regulatory agencies is mitigating the upward migration of sodium from sodic minespoil into the subsoil (Dollhopf et al. 1980). Reclamation of mined land can be expensive but more importantly it needs to be effective over long term. Therefore, it is crucial to quantify the soil benefits of varying subsoil thickness in constructed soil profiles over sodic spoil towards a goal favoring downward sodium translocation from the subsoil-spoil interface. Ward et al. (1983) suggested that the ability of water to infiltrate and move through reconstructed profiles be of fundamental importance in determining the success of reclamation efforts. Both physical and chemical properties affect hydraulic conductivity, which in turn affects sodium migration in sodium-affected soils. Physical, chemical and root analyses of this study have been compiled to decipher differences, if any, between two profiles varying in subsoil thickness (0.55 m and 0.95 m) to mitigate limitations imposed to constructed soil profiles over sodic minespoil. Results from the Highvale study in 1982-1987 lend useful information to elucidate the soil processes that have occurred within the profiles during the past 16 years. As well, it allows for projection of trends of soil properties. Two soil rating systems, Land Capability Classification for Arable Agriculture in Alberta (ASAC 1987) and Agricultural Capability Classification for Reclamation (RRTAC 1993), have been used to evaluate the current agricultural capabilities of the two soil profiles, to highlight and prioritize the most limiting aspects of each profile to soil productivity. This is important for future reclamation considerations to ensure the minimization of long term effects limiting soil productivity.

The Highvale Plains Reclamation Research Project (1982-1987) determined that a constructed soil profile with 0.95 m of subsoil was sufficient and necessary to produce regionally optimum yields of 4780 kg ha^{-1} yr^{-1} of alfalfa-smooth bromegrass hay based on a 5-year mean between 1983-1987 (AE 1989). However, the study also showed that the 0.55m subsoil profile yield of 4220 kg ha^{-1} yr^{-1} did not differ significantly from the 0.95 m subsoil profile (Oddie and Bailey 1988). The specific objectives of our current study were to analyze the differences in soil properties between the two subsoil profiles, sixteen years after profile construction. The physical properties analyzed were bulk density (Db) and volumetric water content during the growing season, and the chemical properties analyzed were water soluble cations (Ca, Mg and Na), SAR, exchangeable cations (Ca, Mg, K and Na), EC and pH. Root mass distribution was also measured.

The experimental site consisted of two profiles of constructed soil varying in subsoil thickness replacement, over sodic mine spoil located in the northern great-plains area with a humid to sub-humid climate (Oddie and Bailey 1987). The sodic characteristic of the mine spoil in the Highvale mine originated from the Tertiary Period Scollard Member of the Edmonton Formation (Graveland et al. 1988), accounting for the Dark Gray Solodized Solonetz and Solonetzic Dark Gray Luvisols soils that developed above glacial till (Oddie and Bailey 1988). The 1982 Highvale study experimental design (Figure 2-1) consisted of two factors in a randomized complete block design with 3 replicates. Main plots of six subsoil thicknesses (0.00, 0.55, 0.95, 0.1.35, 1.85, and 3.45 m) were randomized within blocks with two seeded crop species (alfalfa /bromegrass forage mix and barley) randomized as split plot. The current 1998 experimental design was also a split plot, however, the main plots consisted exclusively of alfalfa / bromegrass profiles with the two subsoil thicknesses (0.55 m and 0.95 m) that occurred within the pre-existing randomized complete block experimental design. The two constructed soil profiles were further split into depth increments (Figure 3-1). The plots were situated on a leveled peak of a spoil pile. The elevation of this berm-like landscape was approximately 746 m, 10 m above a hauling road (R. Lyle personal communication, Transalta Utilities). Other than a slope experiment at 4 m height above the plots' surface to the east, the experimental plots were elevated from the surrounding landscape. This includes an excavation pit, 25 m below and to the south side of the plots' surface. Thus, results of this study apply to constructed soils over sodic mine spoil that occur at elevated landscape positions under a mix of residual alfalfa (*Medicago sativa* L.) bromegrass (*Bromus inermis* Leyss.) and herbs such as fescue (*Festuca scabrella* Torr.), clover (*Trifolium pratense* L.) and wild oat (*Avena fatua* L.). Also, this study occurred in a climate with slight to significant water deficits during the growing season (ACECSS 1987).

6.1 Changes in Reclamation Capability, During 16 Years

The reclamation capability classification (RRTAC 1993) is a document used by the environmental industry to evaluate soil capability in Alberta's agricultural zone that has been disturbed by coal mining or the oil and gas industry. Soil condition can be used in part to indicate soil productivity (RRTAC 1993). To elucidate the direction of change that has occurred during the past 16 years, the current reclamation capability ratings, based on the two subsoil profiles' chemical properties, were compared to the initial 1982 properties of the constructed profiles (Table 3-1). Subclasses in the reclamation capability classification, affected by the chemical properties analyzed in this study, (Figure 5-2) include both surface and subsurface: soil reaction, salinity, and sodicity.

The current 1998 topsoil pH of about 7.3 in both subsoil profiles, compared to the 1982 topsoil value of 7.2 does not change the capability of the constructed soils, since surface soil pH can vary between 6.5-7.5 without deduction, as outlined in the classification system. As well, the reclamation capability subsoil reaction subclass, only deducts for acidic reactions and thus does not affect the capability between 1982 and 1998 since both the initial subsoil pH of 7.7 and the current subsoil pH which varies between 8.4 and 9.0 in either profile, are both alkaline. In the case of the 0.55 m subsoil profile, where the spoil interface occurs within the 1 m control section, both the initial spoil pH of 8.5 and the current spoil pH of 8.7 also do not affect capability in this subclass. Regardless of capability indifference with time, subsoil pH particularly, has become increasingly alkaline during the past 16 years.

Similar to soil pH, both the soil salinity of the materials used in the 1982 constructed profiles and the salinity of the current subsoil profiles have not influenced a change in capability, in either a surface or subsurface level during the past 16 years. The reclamation classification system does not deduct points for ECs ≤ 2 dS m^{-1}, measured in saturated paste. This EC value is considered the lower threshold of soil salinity that will generally not affect vegetation response appreciably. The initial 1982 EC values of the topsoil, subsoil and spoil material of 0.6, 0.5 and 1.9 dS m^{-1} are below the threshold value. Likewise, the current 1998 topsoil, subsoil and spoil EC values of 0.4, 1.0 and about 1.5 dS m^{-1} also were below the threshold. The ECs of the constructed soil profiles have remained low throughout the 16 years.

However, the capabilities of the initial constructed soil profiles in 1982 have been adversely affected by the net result of upward soluble Na and downward soluble Ca and Mg migration above and below the subsoil / spoil interface during the past 16 years. More specifically, the SAR values of the topsoil, subsoil and spoil material in 1982 of 0.4, 0.7 and 20.1 would have caused the 0.55 m subsoil profile to receive a 50 percent deduction. This deduction occurs in the lower subsoil section (50-100 cm), as a result of the spoil interface occurring at about 70 cm, contributing 30 cm of spoil with elevated SAR values. The weighted average for the SAR value in the lower subsoil would have been equal to 12.3. However, in 1998, the lower subsoil section of the 0.55 m subsoil profile received 70 percent deduction from the greater thickness of soil (spoil plus some subsoil material), measuring elevated SAR values (weighted average SAR = 16.1) due to the upward Na migration from the spoil into the subsoil (Figure 5-2). On the other hand, the 0.95 m subsoil profile initially from 1982, would not have incurred a deduction for the topsoil or subsoil SAR values (since the subsoil extended the entire lower subsoil section to 1 m depth). Currently, the 0.95 m subsoil profile received a 13 percent deduction for the elevated SAR values of the subsoil directly above the spoil interface, again, resulting from upward Na migration occurring within the lower end of the control section (Figure 5-2).

6.2 Future Predictions Based on Past Trends

It is beneficial to compare results from the 1983-87 Highvale study such as Db, soluble Na concentration, SAR, EC and root penetration with current 1998 results to decipher the direction of change and to predict future developments (Figure 6-1). Of the properties analyzed, the current (1998) values did not differ significantly between subsoil profiles, as determined by ANOVA (Table 6-1).

In 1986, the average Db of the subsoil (referred to then as the effective root zone Db), of 1.3 and 1.2 Mg m^{-3} for the 0.55 m and 0.95 m profile respectively, did not significantly differ (Table 6-2). However, the effective root zone Db of the 0.55 m subsoil profile did differ ($P<0.05$) during the 5-year study, but no unidirectional increase in Db occurred (Graveland et al. 1988). The effective root zone Db of the 0.95 m subsoil did not differ within the first 5 years. However, the current 1998 weighted average of the subsoil Db in the 0.55 m and 0.95 m subsoil was 1.5 and 1.6 Mg m^{-3}, respectively (Table 6-2). The increase in subsoil Db during the past 16 years may have contributed to reducing water flow through the subsoil. Also, as a soil Db nears 1.8 Mg m^{-3}, a fine textured subsoil becomes restrictive to root growth of agricultural crops (ASAC 1987). Then again, the current subsoil Db is most likely near a maximum value since the cause of soil compaction, from machinery traffic during profile construction, occurred at the onset of the initial study (1982). Other than soil settling within the constructed profile, there has been little to no anthropogenic traffic on the experimental sites since 1987, to contribute to further increases in subsoil Db. Perhaps the Db of a dense, loam glacial till of about 1.77 Mg m^{-3} (Miller et al. 1993) could be used as a general upper threshold for maximum subsoil Db increase possible for our study's constructed-profile subsoil material that also originates from glacial till parent geological material. Finally, the resulting decrease in pore space and connected pores, from the increase in subsoil Db during the past 16 years, may have contributed to upward Na diffusion by limiting downward convective flow of percolating soil water.

Similar to the physical property of effective root zone Db, the current (1998) chemical properties of the upper critical zone, as determined by the earlier Highvale study (Table 6-2) of soluble Na, SAR and EC also did not differ between subsoil profiles. Neither subsoil profile significantly differed with time during the first 5 years (1983-1987), either. In 1986 the average soluble Na concentration in the upper critical zone for the 0.55 m and 0.95 m subsoil profiles was 4.5 and 5.6 mmol L^{-1}, respectively. In 1998, the soluble Na concentrations for the same critical zones were 10.8 and 11.8 mmol L^{-1} respectively. Although not statistically compared, there has been a notable increase in soluble Na in the past 16 years. Likewise, the SAR has increased in the upper critical zone from 1986 values of 4.5 and 7.5 to the current 1998 values of 9.4 and 10.2, for the respective subsoil profiles. Finally, EC has increased slightly from the 1986 concentration of 0.6 and 0.7 dS m^{-1} to still a current low value of 1 dS m^{-1} for both the 0.55 m and 0.95 m subsoil profile in the upper critical zone.

Upward Na migration can be dependent on many aspects of the soil profile including the magnitude of the concentration gradient, moist soil for the diffusive mechanism and the magnitude and direction of gradients in soil water potential for convective flow (Dollhopf et al.1980). Soils with high montmorillonite clay content, associated with soluble Na concentrations two times or more the combined divalent cation concentrations will result in elevated SAR values and may potentially risk dispersion. This is a potential risk for the 9 cm directly above the spoil interface in our constructed profiles. The mottles observed in both subsoil profiles indicate imperfect drainage and wet conditions for periods of time (Figure A-1). Also, increased subsoil bulk density during the past 16 years and the potential for swelling and restriction of transmitting pores in Na affected montmorillonite clay also may lend to decreased water flow through the subsoil profiles. Moist soil environments with little to no downward convective flow of water through the subsoil and spoil provide a corridor to facilitate further upward Na diffusion into the subsoil.

Finally, the earlier Highvale study observed significantly different average rooting depths of forage roots during a 3-year period (1985-1987). Roots extended 0.09 and 0.00 m into the spoil material for the 0.55 m and 0.95 m subsoil profile, respectively (Graveland et al. 1988). However, throughout the 3-year study period, the rooting depths consistently increased in both subsoil profiles so that in 1987 the approximate root penetration was approximately 17 and 26 cm depth into the spoil material for the 0.55 m and 0.95 m subsoil profiles (Oddie and Bailey 1988). However, subsoil profile root depth with time was not statistically evaluated. From the current (1998) rooting pattern, observed during morphological descriptions (Figure A-1) of the 0.55 m and 0.95 m subsoil profiles, roots generally penetrated the subsoil material with a vertical or random orientation. In most cases roots did not penetrate past the spoil interface; however, a maximum root penetration was about 20 cm (0.55 m) and 10 cm (0.95 m) into the spoil material. There is some indication that current roots may not be penetrating as deep as they once did, 11 years ago. It is important to note that unlike the Depuit et al. (1982) and McSweeny and Jansen (1984) studies, horizontal root orientation or accumulation of root mass was not observed directly above the spoil interface, suggesting that the spoil interface did not completely retard deeper root penetration. In fact, the current root distribution of exponential decrease in root mass density with depth (Figures 4-1 and 6-1) indicated that very few roots occurred at the lower subsoil depths above the spoil interface. Moreover, unlike the Depuit et al (1982) results in Montana, our root distributions did not reveal a localized decrease in root mass as a result of the sodic spoil interface. Additionally, the current total profile root masses of the two subsoil profiles (4.2 kg m^{-2} for the 0.55 m, and 4.8 kg m^{-2} for the 0.95 m) did not differ ($P<0.05$) (Figure 6-1). This result indicated that the few roots measured in the lower subsoil of the 0.95 m profile below 70 cm did not contribute significantly, compared to the 0.55 m subsoil profile. It is important to keep in mind that the roots depths observed in the earlier Highvale study were exclusively of the harvested forage crop. However, the current species at the experimental plots also include fescue (*Festuca scabrella* Torr.), red clover (*Trifolium pratense* L.) and wild oat (*Avena fatua* L.), which may have affected the current rooting behavior. Certainly, if soluble Na concentrations were to increase to levels toxic to the plant species, or if soil aggregate dispersion occurred in the subsoil decreasing aeration to roots, the roots would likely recede to shallower depths of penetration. Nevertheless, there is still evidence of root penetration past the spoil interface, albeit, it is suggested that the roots have receded slightly since the Highvale study.

6.3 Sodium Ion Movement In Constructed Profiles: State Of Knowledge

Reclamation research in the Northern Great Plains of North America (Table 6-3) has demonstrated that the subsoil thickness requirement to maximize agricultural crop production depends on the specific properties of the soil environment. Hargis and Redente (1984) think one of the most important ecological factors include the quality of overburden/ spoil being covered. Certainly when non-sodic, non-saline topsoil is placed over a medium to fine textured sodic spoil consisting of a predominantly smectitic clay mineralogy in a semiarid climate, the potential is present for upward Na migration. The rate of upward salt migration is dependent on; 1) the magnitude of the concentration gradient between the spoil and subsoil materials, 2) the soil water content, and 3) the amount and direction of convective flow (Dollhopf et al. 1980). Dollhopf et al. (1980) 2-year North Dakota study of 70 cm of sandy loam topsoil (SAR=2, EC=0.5 dS m^{-1}) over a sodic loam spoil (SAR=23, EC=2.8 dS m^{-1}) found no net upward Na migration. They suggested the predominantly kaolinitic clay mineralogy of the spoil material as responsible for allowing soil water to percolate downward past the topsoil / spoil interface, thereby leaching down any salt that may have migrated into the topsoil from short term upward diffusion or convective flow events. However, unlike Dollhopf et al. (1980) study, there have been many studies on the fate of sodium migration in constructed soils over a spoil where the combination of swelling (smectite) clays and sodic conditions resulted in decreased soil profile hydraulic conductivity. As a result of the decreased drainage and moist soil, Na migrated upward via diffusion particularly in the 15 cm directly above the spoil interface. The Sandoval and Gould (1978) study in North Dakota of 30 cm of loam topsoil (SAR=2) above a sodic silty clay loam spoil (SAR=25) reported upward Na migration. The 15 cm of topsoil directly above the spoil interface increased in SAR from 2 to 17 during a period of 3 years (Merrill et al. 1983). As well, the Merrill et al. (1980) North Dakota study, of 30 cm of topsoil (SAR=2, EC= 0.9 dS m^{-1} and 20% clay) over a sodic spoil (SAR=25, EC=3.3 dS m^{-1} and 30% clay) observed similar results. Considerable soluble Na accumulation within the 15 cm zone directly above the spoil interface was characterized by the SAR increase from 2 to 18 during the 4-year study. They attributed the low unsaturated hydraulic conductivity of 6 inches per year or less, conducive to Na transport via a predominantly diffusive mechanism. They also projected from their calculations, that a greater thickness of cover soil over the spoil would promote further upward Na accumulation over a greater thickness of cover soil with time. However, they also noted that the greatest increases in sodicity in the 15 cm zone occurred during the first and second year of their study. Furthermore, the Merrill et al. (1983) 4-year study in North Dakota of 30 cm of silty clay topsoil (SAR=2.5) over a sodic sandy clay loam spoil (SAR=26) also noted localized Na accumulation in the 15 cm above the spoil interface. Again, low saturated hydraulic conductivity values of 0.2 to 0.01 cm d^{-1} were thought to allow upward diffusion of Na from the mine spoil into the topsoil that accounted for a topsoil increase in SAR of 2.5 to 11.7. The study also noted a slight increase in SAR from 2.5 to 3.4 in the shallower remaining topsoil (depth interval of 0-15 cm). Finally, the Barth and Martin (1984) Northern Great Plains study utilized wedge plots in Wyoming, Montana and North Dakota with 0-152 cm of topsoil (SAR= 1.4, EC=1.9 dS m^{-1}) over a spoil (SAR=28, EC=2.9 dS m^{-1}). After 5 years, Na had migrated from 7 to 14 cm into the overlying topsoil with an increase in concentration of 2.9 to 11.7 mmol L^{-1}.

Our study's soluble Na results seem consistent with previous studies of sodic spoils containing smectitic clays. The average soluble Na concentration of about 11.0 mmol L^{-1} and SAR of 10 (Table 6-2), for both subsoil profiles in the upper critical zone occurs within the values of the previous studies mentioned, but reflects the environment of the soil profile 16 years after profile construction. Our study's concentrations of soluble Na accumulation in the 15 cm directly above the spoil interface are very similar to those of Barth and Martin (1984). As well, the elevated SAR in the upper critical zone, although lower in our study compared to the others, also agrees with the literature. From the similarity of our findings to the studies mentioned above one could infer that our soil profiles' unsaturated hydraulic conductivity is low enough to prevent downward leaching of salts, and as a consequence diffusion becomes the predominant mechanism of upward Na ion transport. Interestingly, our SAR value of approximately 0.8 in the subsoil 15-20 cm directly above the upper critical zone (30-35 cm above the spoil interface) is slightly larger but comparable to the initial subsoil value determined prior to profile construction (SAR=0.7). Similarly, the Merrill et al. (1983) included the SAR value of 3.4 in the 15 to 30 cm of topsoil above the spoil interface. This value was also slightly elevated from the initial soil value (SAR=2.5); however, the this study occurred 4 years after profile construction, while our study occurred 16 years after profile construction. Despite the difference in time, from profile construction to time of analysis (3 yr versus 16 yr), there is still agreement with values measuring soluble Na (sodicity) within the common zone of 15 cm above the spoil interface. It is speculated for our constructed profiles, that the process of Na migration is slowing in rate of transport as the soil environment reaches an equilibrium state.

6.4 Field Considerations for Reclamation

The 0.55 m and 0.95 m subsoil profiles had similar morphological properties: i) structure graded to a massive state at about 70 cm, ii) consistence of hard to very hard in subsoil and iii) faint to distinct mottling throughout the profile. Also, bulk density in both profiles similarly increased with depth. However, the spoil material in the 0.55 m profile below a depth of 65 cm was significantly greater than that of the subsoil material of the 0.95 m profile, from 65 to 120 cm.

Despite the lack of difference in chemical properties between the two profiles, at common distances from the spoil interface, there was less influence from the upward sodium migration into the 1 m control section in the 0.95 m profile, due to the lower subsoil/spoil interface. The greater thickness of the 0.95 m subsoil profile rated higher in soil capability (class 3) compared to the 0.55 m profile (class 4). This was based on the arable agriculture capability (ASAC 1987), which was the system utilized initially to rate the Highvale mine permit area as class 3, prior to mining activity (Cam Bateman personal communication, Transalta Utilities). Soil capability rating can be used in part to measure the success of the reclamation; however, it is important to be consistent with the rating system used. Considering the equal capability of the 0.95 m profile prior to and after mining disturbance and reclamation, compared to the lowered capability of the 0.55 m profile, we think the 0.95 m profile is superior.

Slope position, soil site drainage and climate need to be considered when selecting potential topographic field sites suitable for this reclamation protocol of 0.95 m of subsoil thickness over sodic mine spoil. Sites that occur at middle to upper slope positions are necessary, along with well drained soil profiles having low water tables throughout the year in humid climates or drier.

We speculate that if this 0.95 m profile is used as a reclamation protocol in the sites depicted above, with time a balance will be reached between downward percolation of water with upward sodium migration from the spoil material so that there is no net sodium movement. General theory of soil development in a salt influenced material (i.e. ACECSS 1987) suggests the soil will slowly develop to have characteristics of a Solonetzic soil. With continued replacement on the colloidal exchange site of subsoil sodium with divalent cations from mineral weathering, downward translocation from topsoil pools or from root cycling, sodium will slowly be leached. Disintegration of the massive and hard lower subsoil will follow resulting in initial stages of aggregation necessary for structure development via wet/ dry and freeze thaw cycles. The soil capability may even improve if soil structure develops deeper in the profile than what exists currently. Another consideration includes a potential to decrease the thickness of subsoil in the constructed profile necessary for the reclamation of sodic spoil in this topographic and climatic environment described above, if the clay mineralogy of the subsoil material were dominantly non-swelling such as kaolinite or hydrous mica.

Table 6-1. ANOVA summary of 1998 properties of Db for the effective root zone, and of soluble Na concentration, SAR and EC for the upper critical zone

Source	df	Bulk Density		Soluble Na		SAR		EC	
		F ratio	P>F	F ratio	P>F	F ratio	P>F	F ratio	P>F
Treatment	1	0.30	0.641	0.41	0.588	0.34	0.618	0.13	0.750

Table 6-2. Comparison of treatment means from the 1982 Highvale study results and the current 1998 study, of Db for the effective root zone and of soluble Na concentration, SAR and EC averaged for the upper critical zone[Z]

Parameter	Bulk Density ($Mg\ m^{-3}$)			Soluble Na ($mmol\ L^{-1}$)				SAR				EC ($dS\ m^{-1}$)			
Year	84	86	1998	82	84	86	1998	82	84	86	1998	82	84	86	1998
Treatment															
0.55 m	1.3	1.3	1.5±0.07[Y]	0.9	3.0	4.5	10.8±1.31	0.6	2.8	4.5	9.4±0.66	0.4	0.5	0.6	1.0±0.23
0.95 m	1.2	1.2	1.6±0.03	6.3	3.7	5.6	11.8±4.21	9.1	3.0	7.5	10.2±2.74	1.0	0.7	0.7	1.0±0.40

[Z] n=3 for treatment means

[Y] mean ± 1 st. deviation

Table 6-3. Summarized results from published research on sodium movement in constructed profiles subsoil / spoil material in the Northern Great Plains.

Profile properties

State[Z]	Soil cover		Spoil			
	Thickness (cm)	Texture[Y]	EC (dS m^{-1})	SAR	Texture[Y]	Clay mineralogy
1. ND	70	Sandy Loam	2.8	23	SiCL to Loam	kaolinite
2. ND	30	Loam	3	25	SiCL	montmorillonite
3. ND	30	N/A	3.3	25	N/A	montmorillonite
4. ND	30	SCL	N/A	26	Silty Clay	montmorillonite
5. WY, ND and MT	0-152	N/A	N/A	25-81	N/A	montmorillonite

Changes with time above spoil interface

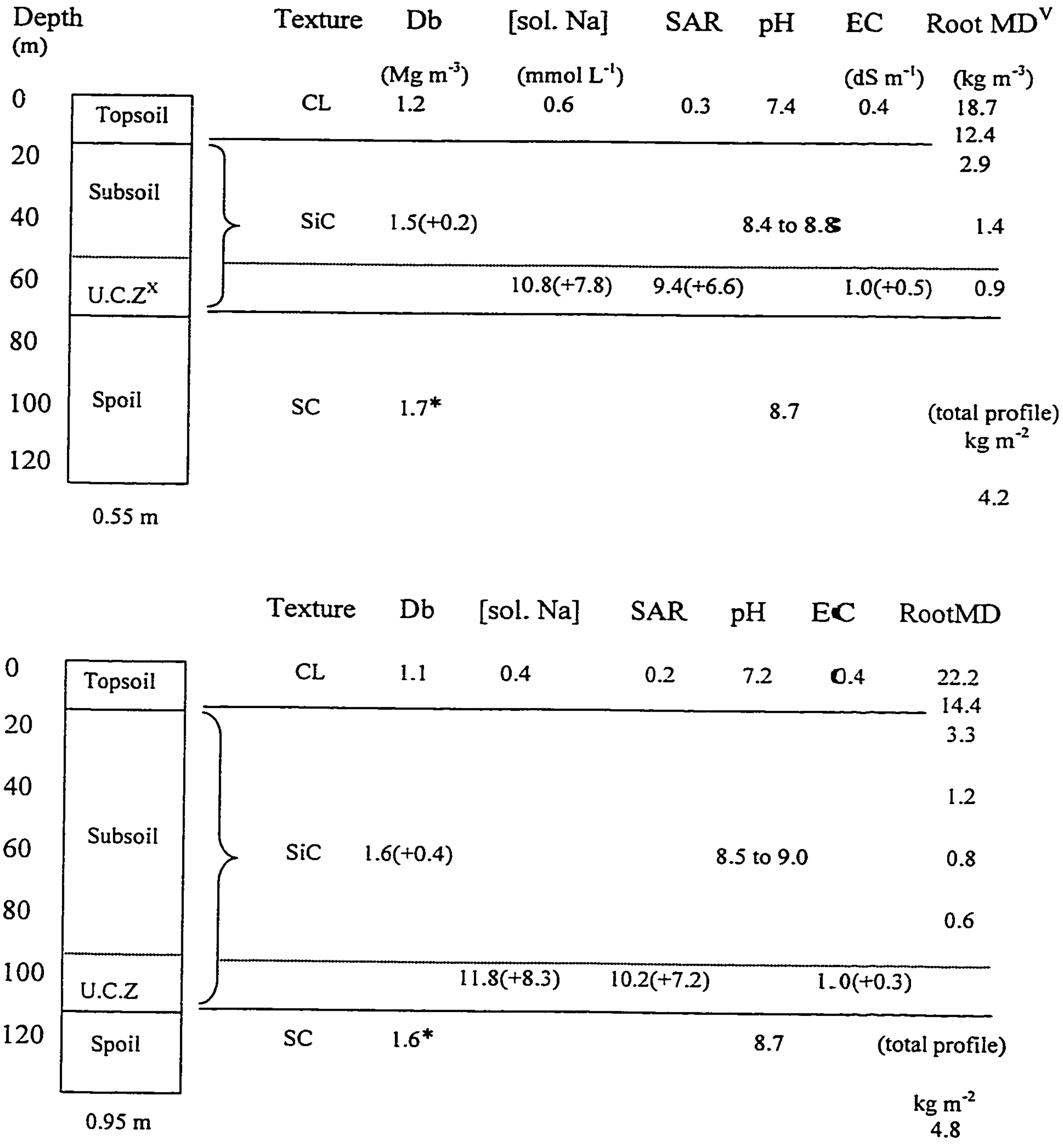
	Lapsed time (yr)	Height above spoil (cm)	Δ SAR	Reference
1.	2	No net upward Na	N/A	Dollhopf et al. 1980
2.	3	15	2 to 17	Sandoval and Gould 1978
3.	4	15	2 to 18	Merrill et al. 1980
4.	4.3	15	2.5 to 11.7	Merrill et al. 1983
		15-30	2.5 to 3.4	
5.	5	7-14	2.9 to 11.7[X]	Barth and Martin 1984

[Z] States: WY = Wyoming, ND = North Dakota and MT = Montana.

[Y] Texture: SCL = sandy clay loam, SiCL = silty clay loam and N/A = not available.

[X] Denotes soluble Na concentration in mmol L^{-1}.

Figure. 6-1. Summary of changes in physical and chemical properties of the 0.55 m and 0.95 m subsoil profiles from 1984 to 1998^{ZYW}.



[Z] 1998 values stated with (+/- change) only for properties that were available for comparison from the Highvale study in1984

[Y] Significantly different values between current properties of the two subsoil profiles are denoted with *

[X] U.C.Z = Upper Critical Zone (15 cm directly above the spoil interface)

[W] Chemical properties have been determined from saturated paste extracts.

[V] Root MD = root mass density

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APPENDIX A - SOIL AND LANDSCAPE DESCRIPTIONS

Figure A-1 Morphological descriptions.

Landscape and Site Description

Date of Description: October 22, 1998
Pit Location: Rep. #1 (.55 cm) treatment. Pit taken between core samples, N1 and N2. (South side of experimental area)
Landform: Berm on what is probably disturbed hummocky disintigration. Pits and overburden stockpiles surround site.
Pgm: glacial lacustrine and residual bedrock material consists of till and weathered shale, coal and sandstone.

A. Landscape Topography

Relief: large local relief
Frequency: 3 per kilometer
Slope Range: 16-30 degrees
Topograhic Class: class 6

B. Site Topography

Elevation: 740 m
Slope Gradient (%): 1-3 degrees (class3) very gentle slope
Slope Aspect: (Road cut to north) Generally, southward aspect

C. Site Specifics

Surface Drainage: poorly drained
Depth to Water Table: 30 m (C. Bateman)
Vegetation: Fescue, clover, wild oat and alfalfa
Aspen in the background (off mine site)

Additional Notes: Northern side of pit had the thickest Bg1 horizon, with it's thinnest part on the south side.
There was no positive test for calcium carbonates, at any depth. The 10% HCl was checked on another pit to make sure it was good.
Drainage class is classified as poor since the site description fails to meet the imperfectly drained definition of distinctly mottled above 50 cm and prominently mottled between 50-100 cm. Soil moisture remains in excess of field capacity in the surface horizons rather than the subsurface horizons.

Horizon	Depth (cm)	Description
Ahg	0-20	Very dark grayish brown (10YR 3/2 m); silt loam; few, fine, distinct, reddish yellow (7.5YR 7/8) mottles; weak, coarse, granular; very friable; abundant, very fine, random, inped and exped, and few, fine, oblique, inped and exped, and few, medium, horizontal, exped, and very few, coarse, vertical, exped roots; abrupt, wavy boundary; 19-21 cm thick.
BgI	20-32	Light brownish gray (10YR 6/2 d); silty clay loam; common, fine, distinct, reddish yellow (7.5 YR 6/8) mottles; weak, very coarse, subangular blocky and strong, medium granular; slightly hard; 5% coal chips and iron stone; plentiful, very fine, vertical, exped roots; clear, wavy boundary; 11-27 cm thick.
BgII	32-70	Light brownish gray (10YR 6/2 d); silty clay; common, fine, distinct, reddish yellow (7.5YR 6/8) mottles; medium prismatic macrostructure and moderate, coarse, subangular blocky; slightly hard to hard; 5% coal chips and iron stone; plentiful, very fine, vertical, inped and exped roots; abrupt, smooth boundary; 14-30 cm thick.
Ckspoil	70+	Light brownish gray (10YR 6/2 d); coal rock (shale) and sandy clay; extremely hard; amorphous

Landscape and Site Description

Date of Description: October 23,1998
Pit Location: Rep #2 (.55 cm) treatment. Pit taken between core samples, N1 and N2. (Northern side of experimental area).
Landform: Berm on what is probably disturbed hummocky disintigration. Pits and overburden stockpiles surround site.
Pgm: glacial lacustrine and residual bedrock material consists of till and weathered shale, coal and sandstone.

A. Landscape Topography

Relief: large local relief
Frequency: 3 per kilometer
Slope Range: 16-30 degrees
Topograhic Class: class 6

B. Site Topography

Elevation: 740 m
Slope Gradient (%): 3.5- 5 degrees (class 4) gentle slopes
Slope Aspect: crest position of northward slope

C. Site Specifics

Surface Drainage: poorly drained
Depth to Water Table: 30 m (C. Batemen)
Vegetation: fescue, clover, wild oat and alfalfa
aspen in the background (off site)

Additional Notes: Slight foaming at 18 cm- HCl test.
Drainage class is classified as poor since the site description fails to meet the imperfectly drained definition of distinctly mottled above 50 cm and prominently mottled between 50-100 cm. Soil moisture remains in excess of field capacity in the surface horizons rather than the subsurface horizons.

Horizon	Depth (cm)	Description
Ahg	0-18	Very dark gray (10YR 3/1 m); loam; common, fine, faint, light yellowish brown (10YR 6/4) mottles; weak, medium, granular; friable; abundant, very fine, random, exped and inped, and few, fine, vertical, exped, and very few, medium, vertical, exped, and very few, coarse, vertical and horizontal, exped roots; clear, wavy boundary; 18-21 cm thick.
BkgI	18-40	Light brownish gray (10YR 6/2 d); clay loam; common, medium, faint, yellowish brown (10YR 5/8) and many, fine, distinct, reddish yellow (7.5YR 6/8) and few, fine, prominent, dark red (2.5YR 4/6) mottles; moderate, fine, granular; slightly hard; 2% angular cobboly; abundant, very fine, random, exped, and very few, fine, horizontal, exped roots; clear, wavy boundary;42-48 cm thick.
BkgII	40-70	Light brownish gray (10YR 6/2 d); clay loam; many, fine, distinct, yellow (10YR 7/8) mottles; weak, medium, prismatic, and weak to moderate, coarse, subangular blocky and moderate, medium, sububangular blocky; hard; 1% angular cobboly; abundant, very fine, vertical, inped and exped roots; abrupt, smooth boundary; 31-34 cm thick.
Ckgspoil	70+	Gray (10YR 6/1 d); sandy loam; common, fine, distinct, yellow (10YR 7/8) and strong brown (7.5YR 5/8) mottles; amorphous; extremely hard; 40% coal chips.

Landscape and Site Description

Date of Description: October 29th, 1998
Pit Location: Rep. #3 (.55 cm) treatment. Pit taken between core samples N1 and N2. (Northern side of experimental site).
Landform: : Berm on what is probably disturbed hummocky disintigration. Pits and overburden stockpiles surround site.
Pgm: glacial lacustrine and residual bedrock material consists of till and weathered shale, coal and sandstone.

A. Landscape Topography

Relief: large local relief
Frequency: 3 per kilometer
Slope Range: 16-30 degrees
Topograhic Class: class 6

B. Site Topography

Elevation: 740 m
Slope Gradient (%): 1-3 degrees (class3) very gentle slope
Slope Aspect: crest position of north facing slope

C. Site Specifics

Surface Drainage: poorly drained
Depth to Water Table: 30 m (C. Bateman)
Vegetation: fescue, clover, wild oat and alfalfa
aspen in the background (Off site)

Additional Notes: Slightly foaming at 21 cm-for the HCl test (interpreted as "k"). Drainage class is classified as poor since the site description fails to meet the imperfectly drained definition of distinctly mottled above 50 cm and prominently mottled between 50-100 cm. Soil moisture remains in excess of field capacity in the surface horizons rather than the subsurface horizons.

Horizon	**Depth (cm)**	**Description**
Ahg	0-21	Very dark grayish brown (10YR 3/2 m); loam; common, medium, and coarse, prominent, olive (5Y 5/3) and few, fine, distinct, strong brown (7.5YR 5/8) mottles; amorphous grading to weak, coarse, granular; friable; abundant, very fine, random, inped and exped, and few, medium, oblique, exped, and very few, coarse, horizontal and vertical, exped roots; clear, wavy boundary; 18-22 cm thick.
BkgI	21-38	Very pale brown (10YR 7/4 d); clay loam; many, fine to medium, prominent, olive yellow (2.5Y 6/6) and common, fine to medium, distinct, (10YR 6/8) mottles; weak, coarse, subangular blocky and moderate, fine, subangular blocky to granular; slightly hard to hard; 10% coarse, yellowish (10YR 5/6) iron stone; abundant, very fine, random, exped and plentiful, fine, random and vertical, exped roots; clear, wavy boundary; 15-24 cm thick.
BkgII	38-76	Very pale brown (10YR 7/4 d); clay loam; common, fine, faint, yellow (10YR 7/8) and few, fine, distinct, brown (7.5YR 4/4) mottles; moderate, fine to medium, subangular to angular blocky grading to weak, fine subangular blocky and granular; slightly hard; at lower 20 cm, 5% coal chips (3-4 cm in diameter); abundant, very fine, random, inped and exped, and plentiful, fine, random and vertical, exped roots; abrupt, wavy boundary; 36-43 cm thick.
Ckgspoil	76+	Dark gray (10YR 4/1 d); sandy loam; common, fine, faint, very pale brown (10YR 7/4) and few, medium, faint, very pale brown (10YR 7/4) and few, fine, distinct, reddish yellow (7.5YR 6/8) mottles; amorphous; very hard; plentiful, very fine, random, exped roots.

Landscape and Site Description

Date of Description: October 22, 1998
Pit Location: Rep #1 (.95 cm) treatment. Pit taken between core samples, N1 and N2. (South side of experimental area)
Landform: Berm on what is probably disturbed hummocky disintigration. Pits and overburden stockpiles surround site.
Pgm: glacial lacustrine and residual bedrock material consists of till and weathered shale, coal and sandstone.

A. Landscape Topography

Relief: large local relief
Frequency: 3 per kilometer
Slope Range: 16-30 degrees
Topograhic Class: class 6

B. Site Topography

Elevation: 740 m
Slope Gradient (%): 1-3 degrees (class3) very gentle slope
Slope Aspect: (Road cut to north) Generally, southward aspect

C. Site Specifics

Surface Drainage: poorly drained
Depth to Water Table: 30 m (C. Bateman)
Vegetation: fescue, clover, wild oat and alfalfa
aspen in the background (off site)

Additional Notes: Positive test for calcium carbonates at 19cm. However, effervescent activity increased at 50 cm.
Drainage class is classified as poor since the site description fails to meet the imperfectly drained definition of distinctly mottled above 50 cm and prominently mottled between 50-100 cm. Soil moisture remains in excess of field capacity in the surface horizons rather than the subsurface horizons.

Horizon	Depth (cm)	Description
Ah	0-19	Very dark gray (10YR 3/1 m); silt loam to loam; moderate, medium, granular; friable; abundant, very fine, random, inped and exped, and few, fine, vertical, exped, and very few, medium, vertical, exped, and very few, coarse, oblique, exped roots; abrupt, wavy boundary; 19-28 cm thick.
BkgI	19-35	Light brownish gray (10YR 6/2 d); silty clay loam; common, fine, distinct, strong brown (7.5YR 5/8) mottles; weak, coarse, granular and moderate, coarse, subangular blocky; slightly hard; 2% angular gravelly and 1% angular cobboly; plentiful, very fine, random, exped, and few, fine, vertical, exped, and very few, medium, vertical, exped roots; clear, wavy boundary; 29-34 cm thick.
BkgII	35-76	Light brownish gray (10YR 6/2 d); silty clay; few, fine, prominent, yellow (2.5Y 7/8) mottles; weak, coarse, subangular blocky and moderate, fine to medium, subangular blocky; very hard; abundant, very fine, random, exped, and few, fine, vertical, exped roots; clear, wavy boundary; 24-29 cm thick.
BCkg	76-96	Very pale brown (10YR 7/4 d); clay loam; few, fine, distinct, reddish yellow (7.5YR 7/6) mottles; amorphous; hard; few, fine, vertical, exped roots; abrupt, smooth boundary; 20-22 cm thick.
Cspoil	96+	Black (10YR 2/1 d); coal (slate) rock; extremely hard.

Landscape and Site Description

Date of Description: October 25, 1998
Pit Location: Rep #2 (.95 cm) treatment. Pit taken between core samples N1 and N2. (Northern side of experimental area).
Landform: Berm on what is probably disturbed hummocky disintigration. Pits and overburden stockpiles surround site.
Pgm: glacial lacustrine and residual bedrock material consists of till and weathered shale, coal and sandstone.

A. Landscape Topography

Relief: large local relief
Frequency: 3 per kilometer
Slope Range: 16-30 degrees
Topograhic Class: class 6

B. Site Topography

Elevation: 740 m
Slope Gradient (%): 3.5-5 degrees (class 4) gentle slopes
Slope Aspect: crest position of south facing slope

C. Site Specifics

Surface Drainage: poorly drained
Depth to Water Table: 30 m (C. Bateman)
Vegetation: fescue, clover, wild oat and alfalfa
aspen in the background (off site)

Additional Notes: Bubbling at 20 cm- for the HCl test (interpreted as "k")
Drainage class is classified as poor since the site description fails to meet the imperfectly drained definition of distinctly mottled above 50 cm and prominently mottled between 50-100 cm. Soil moisture remains in excess of field capacity in the surface horizons rather than the subsurface horizons.

Horizon	Depth (cm)	Description
Ah	0-15	Very dark gray (10YR 3/1 m); loam; moderate, coarse, granular; friable; 10% coal chips (1-3 cm diameter); abundant, very fine, random, inped and exped, and very few, medium, horizontal, exped, and very few, coarse, vertical and oblique, exped roots; clear, wavy boundary; 11-16 cm thick.
AB	15-20	Very dark greyish brown (10YR 3/2 m); loam; many, fine, faint, yellowish brown (10YR 5/4) mottles; moderate, medium, granular; friable to slightly hard; abundant, very fine, random, inped and exped, and very few, medium, horizontal, exped, and very few, coarse, vertical and oblique, exped roots; clear, wavy boundary; 5-6 cm thick.
BkgI	20-40	Yellowish brown (10YR 5/6 d); clay loam; common, fine, faint, brownish yellow (10YR 6/8) mottles; weak, coarse, subangular blocky; slightly hard to hard; 5% coal bits (3-5 cm diameter); abundant, very fine, random, exped roots; clear, wavy boundary;18-22 cm thick.
BkgII	40-72	Yellowish brown (10YR 5/6 d); clay loam; common, fine, distinct, strong brown (7.5YR 5/8) mottles; moderate, medium, subangular blocky; hard to very hard; 30% dark gray (10YR 4/1 d) amorphous clay (28 cm and smaller, diameter); plentiful, very fine, random, inped and exped, and few, medium, vertical, exped roots; clear, wavy boundary;29-34 cm thick.
BkgIII	72-92	Yellowish brown (10YR 5/6 d); clay loam; common, fine, faint, brownish yellow (10YR 6/8) mottles; weak, medium, subangular blocky; very hard; plentiful, very fine, random, inped and exped roots; clear, wavy boundary; 19-22 cm thick.
BCkg	92-107	Light yellowish brown (10YR 6/4 d); clay loam; few, fine, faint, yellowish brown (10YR 5/8) mottles; amorphous; very hard to extremely hard; 60% dark gray (10YR 4/1 d) amorphous clay; few, very fine, random, exped roots; abrupt, smooth boundary; 15-16 cm thick.
Ckgspoil	107+	Dark gray (10YR 4/2 d); sandy loam; few, fine, prominent, yellowish red (5YR 5/8) mottles; amorphous; extremely hard; 40% coal and sandstone bits.

Landscape and Site Description

Date of Description: October 21, 1998
Pit Location: Rep #3 (.95 cm)treatment. Pit taken between core samples,N1 and N2. (South side of experimental area)
Landform: Berm on what is probably disturbed hummocky disintigration. Pits and overburden stockpiles surround site.
Pgm: glacial lacustrine and residual bedrock material consists of till and weathered shale, coal and sandstone.

A. Landscape Topography

Relief: large local relief.
Frequency: 3 per kilometer
Slope Range: 16-30 degrees
Topograhic Class: class 6

B. Site Topography

Elevation: 740m
Slope Gradient (%): 3.5-5 degrees (class 4) gentle slopes
Slope Aspect: northward

C. Site Specifics

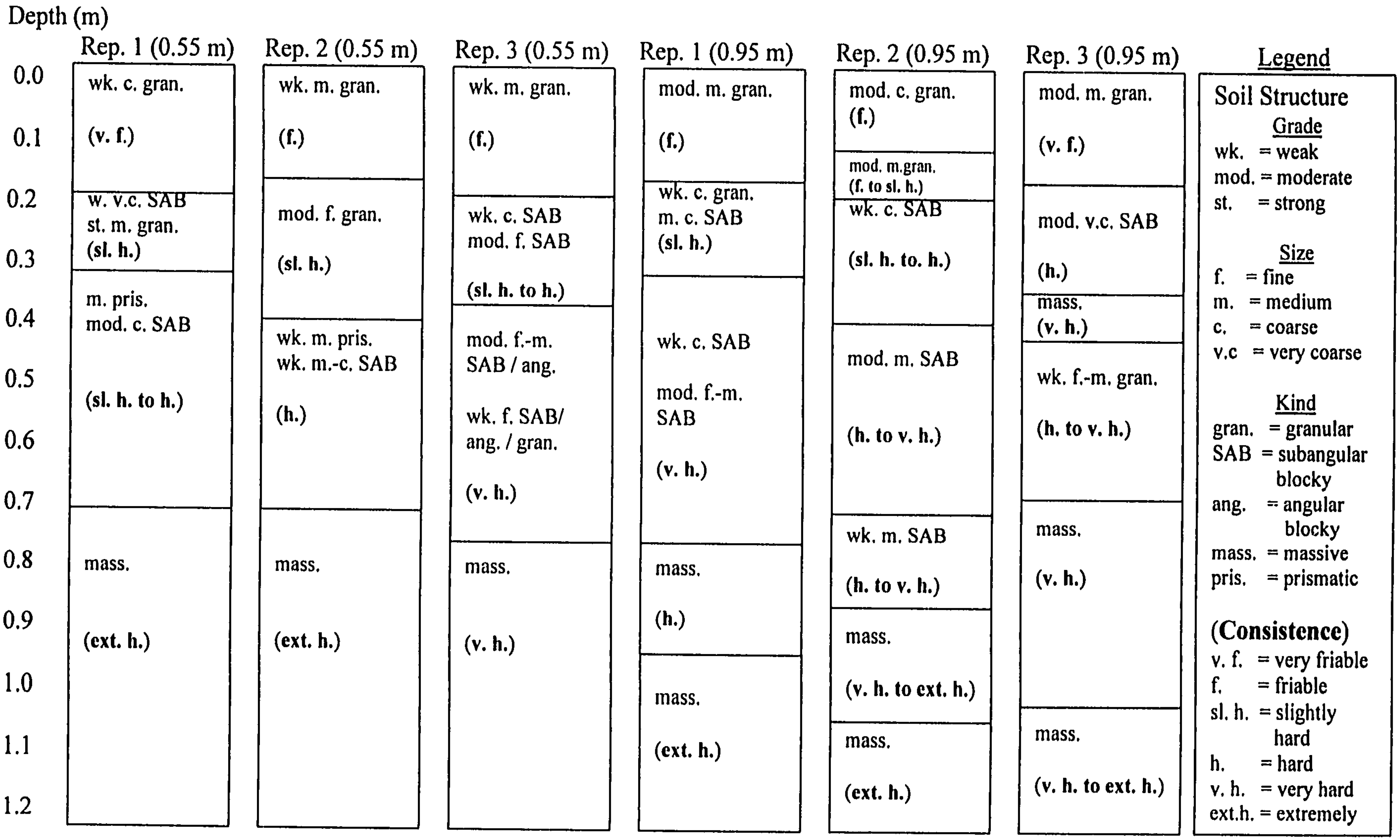
Surface Drainage: poorly drained
Depth to Water Table: 30m (C. Bateman)
Vegetation: fescue, clover, wild oat and alfalfa
aspen in the background (off mine site)

Additional Notes:

Drainage class is classified as poor since the site description fails to meet the imperfectly drained definition of distinctly mottled above 50 cm and prominently mottled between 50-100 cm. Soil moisture remains in excess of field capacity in the surface horizons rather than the subsurface horizons.

Horizon	Depth (cm)	Description
Ahg	0-19	Very dark greyish brown (10YR 3/2 m); loam; few, fine, faint, yellowish brown (10YR 5/6) and few, medium, distinct, dark yellowish brown (10YR 4/6) mottles; moderate, medium, granular; very friable; 1% gravelly; abundant, very fine and fine, random and vertical inped and exped, and plentiful, medium, horizontal and vertical, exped and very few, coarse, vertical, exped roots; clear, smooth boundary; 15-19 cm thick.
BkgI	19-38	Pale brown (10YR 6/3 d); silty clay loam; common, fine and medium, prominent olive yellow (2.5Y 6/6) and distinct reddish yellow (7.5YR 6/8) mottles; moderate, very coarse, subangular blocky; hard; iron stone (2cm diameter) and 10% coal chips (1-1.5 cm diameter) in the top 10 cm of horizon; abundant, very fine, random, exped and plentiful, medium, random, exped and very few, coarse, vertical, exped roots; abrupt, wavey boundary; 19-23 cm thick.
Btg	38-42	Very dark greyish brown (10YR 3/2 d); clay; many, medium, distinct, reddish yellow (7.5YR 6/8) mottles; amorphous; very hard; plentiful, very fine, random, exped roots; abrupt, broken boundary; 0-5 cm thick.
Bcag II	42-70	Pale brown (10YR 6/3 d); silt loam; few, fine, faint, brownish yellow (10YR 6/8) and distinct, strong brown (7.5YR 5/6) mottles; weak, fine to medium granular; hard to very hard; 5% iron stone and 5% coal chips; abundant, very fine, random, inped and exped, and few, medium, vertical, exped, roots; clear, wavey boundary; 29-31 cm thick.
BCcag	70-104	Pale brown (10YR 6/3 d); sandy loam; few, fine and medium, faint, brownish yellow (10YR 6/8) mottles; amorphous; very hard; plentiful, very fine, random, exped roots; abrupt, smooth boundary; 32-34 cm thick.
Ccaspoil	104+	Dark gray (10YR 4/1 d); sandy loam; amorphous; very hard to extremely hard; few, very fine, random, exped roots.

Figure A-2. Schematic outline of soil structure and consistence with depth for one profile in each of the three main plots for the 0.55 m and 0.95 m subsoil profiles.



APPENDIX B - PHYSICAL PROPERTIES, DATA AND DISCUSSION

Legend to be used with appendix B, C, D, and E.

Nomenclature used to describe cores, please refer to figure2-1 and 2-3 for general plot layout.

R_x = Repetition (Block) that core was drilled, where x = 1, 2, 3
S_x = Core taken from south side of plot, where x = 1- 5 from east to west
N_x = Core taken from north side of plot, where x = 1- 5 from east to west
0.55 = Core taken from 0.55 m subsoil thickness treatment plot
0.95 = Core taken from 0.95 m subsoil thickness treatment plot

Example: $R_2S_5$0.55
This represents a core taken from the 0.55 m subsoil thickness plot, rep/block 2 on the south side of the plot at the west edge.

Appendix B
Db = bulk density (Mg m^{-3})
θ = soil water content (m^3 m^{-3})
CV = coefficient of variance (%)

TDR
Segments 1, 2, 3, 4 and 5
represents respective soil depths 0-15, 15-30, 30-60, 60-90, 90-120 cm.

Appendix C
Soluble cations (mmol L^{-1})
Exchangeable cations (cmol (+) kg $^{-1}$)

Ca = calcium
Mg = magnesium
K = potassium
Na = sodium
SAR = sodium adsorption ratio
EC = electrical conductivity (dS m^{-1})
pH = percent hydrogen

Critical zone sections
$$\left.\begin{array}{l}1 = 15\text{-}12\\ 2 = 12\text{-}9\\ 3 = 9\text{-}6\\ 4 = 6\text{-}3\end{array}\right\}\text{ cm above (subsoil)}$$
5 = 3-0 spoil interface
6 = 0-3
$$\left.\begin{array}{l}7 = 3\text{-}6\\ 8 = 6\text{-}9\\ 9 = 9\text{-}12\\ 10 = 12\text{-}15\end{array}\right\}\text{ cm below (spoil)}$$

Appendix D
Root mass density (kg m^{-3})
Total profile root mass (kg m^{-2})

Appendix E
TS = topsoil
SS = subsoil
Sp = spoil

Table B-1 Coefficient of varience of consecutive TDR readings.
Coefficient of varience (CV) > 10% = **underlined**
Oversaturation b/o porosity determined from Uhland core = **boxed**

					seg 1	seg 2	seg 3	seg 4	seg 5
10-Nov 1998	0.55	rep 1	east	vol water	16.3	19.1	28.3	23.7	40.5
				cv	4%	2%	1%	2%	16%
			west	vol water	13.7	30.6	37.6	26.1	51.9
				cv	13%	4%	1%	1%	10%
		rep 2	east	vol water	20.5	30.1	27.2	19.3	45.4
				cv	9%	1%	1%	4%	5%
			west	vol water	22.6	26.8	20.7	27.4	35.6
				cv	2%	1%	1%	6%	13%
		rep 3	east	vol water	21.2	31.4	21.5	11.9	25.2
				cv	5%	3%	2%	6%	2%
			west	vol water	23.2	25.2	23.6	19.4	41.2
				cv	4%	9%	2%	2%	7%
	0.95	rep 1	east	vol water	20.1	27.3	15.6	11.8	20.9
				cv	2%	1%	3%	3%	6%
			west	vol water	14.7	22.5	24.4	18.0	25.7
				cv	4%	6%	3%	2%	2%
		rep 2	east	vol water	19.1	32.4	23.8	15.0	21.0
				cv	4%	3%	3%	8%	6%
			west	vol water	19.8	20.1	31.0	18.0	30.3
				cv	5%	5%	1%	1%	5%
		rep 3	east	vol water	13.1	26.8	30.2	20.7	37.9
				cv	6%	2%	1%	1%	12%
			west	vol water	16.3	24.7	20.9	17.1	36.7
				cv	4%	3%	1%	2%	10%
24-Nov	0.55	rep 1	east	vol water	16.1	16.5	28.2	23.1	39.1
				cv	4%	7%	5%	5%	14%
			west	vol water	14.8	28.0	37.9	25.6	48.7
				cv	14%	4%	2%	2%	15%
		rep 2	east	vol water	20.0	28.7	27.3	18.1	45.3
				cv	3%	4%	2%	6%	8%
			west	vol water	21.1	27.3	20.4	26.0	36.0
				cv	3%	3%	4%	5%	12%
		rep 3	east	vol water	21.0	29.5	21.7	13.4	25.5
				cv	5%	3%	3%	3%	7%
			west	vol water	25.3	23.5	24.0	19.5	38.9
				cv	2%	3%	1%	3%	6%
	0.95	rep 1	east	vol water	20.3	26.1	16.8	9.7	20.8
				cv	3%	2%	2%	9%	2%
			west	vol water	15.3	20.6	25.2	17.3	25.1
				cv	12%	5%	1%	3%	8%
		rep 2	east	vol water	19.2	30.8	23.8	15.9	20.1
				cv	4%	2%	2%	2%	6%
			west	vol water	20.4	18.0	30.8	20.6	28.8
				cv	12%	3%	2%	2%	9%
		rep 3	east	vol water	17.3	24.1	21.8	16.8	36.7
				cv	4%	2%	2%	2%	7%
			west	vol water	14.3	25.0	29.7	21.1	34.4
				cv	11%	2%	2%	1%	8%

					seg 1	seg 2	seg 3	seg 4	seg 5
03-May 1999	0.55	rep 1	east	vol water	21.2	29.8	46.7	30.3	38.6
				cv	23%	11%	1%	4%	15%
			west	vol water	24.4	53.6	49.1	30.7	44.9
				cv	40%	12%	3%	4%	6%
		rep 2	east	vol water	29.2	37.0	40.8	20.0	46.7
				cv	6%	3%	1%	1%	6%
			west	vol water	36.1	34.0	38.3	30.0	38.8
				cv	8%	4%	1%	1%	13%
		rep 3	east	vol water	32.6	38.7	33.5	12.9	24.1
				cv	12%	8%	3%	5%	3%
			west	vol water	34.5	30.4	41.0	21.2	38.6
				cv	4%	17%	1%	3%	12%
	0.95	rep 1	east	vol water	31.1	35.3	34.7	9.8	20.2
				cv	8%	9%	1%	7%	3%
			west	vol water	23.3	29.6	34.0	15.0	23.3
				cv	17%	17%	5%	3%	4%
		rep 2	east	vol water	32.6	44.1	33.5	14.2	20.3
				cv	19%	13%	2%	2%	3%
			west	vol water	25.8	26.0	39.3	22.9	26.3
				cv	13%	11%	1%	3%	13%
		rep 3	east	vol water	27.9	32.8	41.5	30.1	38.7
				cv	8%	5%	1%	4%	8%
			west	vol water	14.2	35.2	41.5	31.9	33.7
				cv	n/a	n/a	n/a	n/a	n/a
10-May	0.55	rep 1	east	vol water	21.5	26.5	45.2	35.2	36.9
				cv	16%	7%	1%	9%	14%
			west	vol water	19.4	43.2	46.7	33.1	52.0
				cv	26%	19%	1%	4%	7%
		rep 2	east	vol water	26.3	39.2	42.0	27.6	49.3
				cv	13%	8%	1%	2%	10%
			west	vol water	32.9	32.5	36.4	35.6	41.3
				cv	9%	7%	2%	2%	19%
		rep 3	east	vol water	28.2	33.3	38.3	14.1	25.8
				cv	24%	6%	2%	2%	4%
			west	vol water	28.4	29.3	40.6	30.3	45.0
				cv	9%	6%	1%	2%	14%
	0.95	rep 1	east	vol water	27.0	36.8	35.5	14.0	21.1
				cv	15%	10%	1%	4%	4%
			west	vol water	20.9	29.7	38.6	15.9	23.9
				cv	41%	20%	2%	6%	3%
		rep 2	east	vol water	23.9	46.1	39.8	19.9	21.5
				cv	18%	9%	4%	3%	2%
			west	vol water	24.6	21.9	38.5	33.0	27.6
				cv	7%	14%	2%	1%	9%
		rep 3	east	vol water	24.3	30.6	40.7	33.8	42.9
				cv	10%	5%	1%	3%	10%
			west	vol water	17.5	32.3	39.2	36.5	39.9
				cv	10%	9%	2%	3%	10%

					seg 1	**seg 2**	**seg 3**	**seg 4**	**seg 5**
17-May	0.55	rep 1	east	vol water	21.7	24.8	44.8	35.7	39.3
				cv	28%	12%	1%	5%	19%
			west	vol water	24.5	48.0	46.4	33.9	48.6
				cv	32%	21%	1%	2%	9%
		rep 2	east	vol water	24.2	36.6	41.4	28.7	46.4
				cv	13%	9%	2%	3%	5%
			west	vol water	26.7	34.6	35.4	36.1	40.6
				cv	24%	7%	2%	2%	17%
		rep 3	east	vol water	27.1	32.6	37.2	15.5	26.5
				cv	17%	9%	0%	1%	5%
			west	vol water	27.9	27.5	39.6	31.7	50.1
				cv	7%	9%	1%	1%	14%
	0.95	rep 1	east	vol water	26.2	37.3	35.2	15.2	21.5
				cv	23%	11%	1%	2%	2%
			west	vol water	16.6	29.0	38.5	17.2	24.0
				cv	15%	16%	2%	1%	5%
		rep 2	east	vol water	21.1	37.9	38.9	21.5	22.3
				cv	27%	9%	3%	2%	3%
			west	vol water	21.9	24.7	38.3	34.3	30.2
				cv	14%	14%	3%	3%	10%
		rep 3	east	vol water	23.4	29.2	39.3	35.9	45.6
				cv	4%	5%	1%	4%	6%
			west	vol water	18.0	32.0	38.8	38.1	42.2
				cv	20%	3%	1%	1%	10%
25-May	0.55	rep 1	east	vol water	19.9	27.6	46.4	36.2	41.0
				cv	27%	20%	1%	1%	20%
			west	vol water	26.0	43.3	48.5	35.2	50.3
				cv	26%	21%	6%	2%	7%
		rep 2	east	vol water	24.2	39.4	41.2	30.2	47.0
				cv	24%	9%	2%	2%	8%
			west	vol water	33.4	33.8	36.2	37.7	39.0
				cv	11%	7%	1%	8%	18%
		rep 3	east	vol water	22.0	38.2	36.8	16.7	28.0
				cv	22%	12%	2%	2%	11%
			west	vol water	25.7	30.1	39.6	33.0	53.1
				cv	14%	22%	2%	1%	8%
	0.95	rep 1	east	vol water	25.2	35.6	35.0	16.3	21.6
				cv	14%	13%	3%	3%	1%
			west	vol water	10.8	26.9	39.1	17.9	25.1
				cv	55%	15%	4%	2%	4%
		rep 2	east	vol water	26.6	44.5	42.0	23.2	24.0
				cv	35%	21%	6%	2%	8%
			west	vol water	25.1	26.1	38.3	34.8	31.3
				cv	7%	10%	1%	1%	10%
		rep 3	east	vol water	22.3	31.2	39.6	39.0	43.2
				cv	32%	3%	1%	2%	16%
			west	vol water	16.0	33.9	39.5	39.0	38.9
				cv	39%	5%	1%	1%	17%

					seg 1	seg 2	seg 3	seg 4	seg 5
31-May	0.55	rep 1	east	vol water	19.8	26.9	45.3	36.2	45.8
				cv	48%	21%	1%	8%	14%
			west	vol water	22.3	46.4	47.6	35.6	51.5
				cv	43%	22%	5%	4%	10%
		rep 2	east	vol water	19.3	31.5	39.9	30.4	49.5
				cv	32%	6%	1%	2%	21%
			west	vol water	24.0	30.5	34.8	36.9	43.2
				cv	20%	5%	3%	2%	15%
		rep 3	east	vol water	20.4	26.5	35.4	15.8	29.0
				cv	29%	16%	1%	11%	5%
			west	vol water	18.8	20.8	38.1	33.6	53.4
				cv	15%	20%	1%	3%	6%
	0.95	rep 1	east	vol water	17.8	29.7	34.3	16.3	22.6
				cv	41%	8%	2%	2%	1%
			west	vol water	12.2	23.4	38.3	18.7	26.5
				cv	31%	18%	2%	2%	9%
		rep 2	east	vol water	18.7	31.8	35.9	22.4	23.7
				cv	34%	18%	3%	1%	6%
			west	vol water	18.2	22.5	37.5	34.5	31.1
				cv	12%	10%	1%	2%	14%
		rep 3	east	vol water	15.4	25.8	37.9	38.9	47.4
				cv	12%	4%	1%	2%	9%
			west	vol water	12.8	27.3	38.8	38.4	43.3
				cv	21%	8%	2%	3%	10%
7-Jun	0.55	rep 1	east	vol water	21.8	27.4	44.5	36.8	42.4
				cv	19%	23%	1%	2%	11%
			west	vol water	21.7	44.3	47.8	36.9	53.6
				cv	14%	15%	4%	5%	11%
		rep 2	east	vol water	20.3	27.0	38.8	31.2	53.0
				cv	14%	9%	1%	2%	15%
			west	vol water	24.2	27.2	34.0	37.2	43.2
				cv	8%	6%	1%	3%	17%
		rep 3	east	vol water	19.2	24.3	33.1	17.2	28.9
				cv	33%	27%	2%	5%	4%
			west	vol water	16.2	18.7	36.0	33.7	47.9
				cv	19%	6%	2%	2%	21%
	0.95	rep 1	east	vol water	18.7	27.3	32.9	17.0	22.7
				cv	20%	18%	2%	1%	3%
			west	vol water	13.7	27.2	36.1	19.3	26.3
				cv	39%	22%	1%	1%	6%
		rep 2	east	vol water	15.5	37.6	35.2	22.7	24.4
				cv	46%	17%	5%	3%	8%
			west	vol water	19.7	20.3	36.2	34.6	31.7
				cv	11%	7%	3%	2%	20%
		rep 3	east	vol water	18.8	27.0	36.1	39.0	51.8
				cv	9%	8%	2%	2%	12%
			west	vol water	12.8	24.8	37.8	39.4	41.4
				cv	16%	6%	2%	1%	13%

					seg 1	seg 2	seg 3	seg 4	seg 5
7-Jul	0.55	rep 1	east	vol water	21.5	32.3	47.6	43.4	46.0
				cv	22%	25%	3%	6%	6%
			west	vol water	21.8	46.3	49.2	42.0	70.3
				cv	36%	11%	4%	2%	11%
		rep 2	east	vol water	20.6	32.8	32.2	30.6	61.3
				cv	10%	3%	1%	1%	10%
			west	vol water	25.0	35.2	27.9	37.4	45.5
				cv	16%	3%	1%	3%	9%
		rep 3	east	vol water	22.0	37.6	28.5	18.0	31.4
				cv	19%	13%	3%	1%	4%
			west	vol water	25.1	28.0	31.2	33.1	51.7
				cv	11%	9%	1%	2%	10%
	0.95	rep 1	east	vol water	21.9	35.4	24.0	17.5	25.2
				cv	13%	6%	1%	1%	8%
			west	vol water	20.2	34.1	35.0	21.5	29.1
				cv	17%	15%	5%	1%	4%
		rep 2	east	vol water	23.9	46.7	32.5	22.9	26.2
				cv	46%	6%	7%	1%	9%
			west	vol water	24.9	26.9	33.8	33.0	36.5
				cv	18%	5%	1%	2%	7%
		rep 3	east	vol water	23.4	38.4	36.1	33.3	48.2
				cv	8%	6%	1%	1%	6%
			west	vol water	17.8	35.0	35.5	35.5	43.6
				cv	9%	6%	2%	1%	15%
16-Jul	0.55	rep 1	east	vol water	28.4	38.0	48.7	42.8	47.1
				cv	20%	21%	2%	8%	11%
			west	vol water	23.2	45.5	50.5	43.2	72.3
				cv	39%	12%	4%	3%	6%
		rep 2	east	vol water	23.7	35.7	31.4	30.6	51.8
				cv	5%	7%	2%	2%	5%
			west	vol water	30.0	38.9	27.7	37.2	44.4
				cv	14%	5%	1%	1%	6%
		rep 3	east	vol water	31.5	41.9	28.0	18.0	31.5
				cv	8%	11%	2%	4%	5%
			west	vol water	29.3	30.5	30.7	33.4	50.5
				cv	25%	6%	2%	5%	11%
	0.95	rep 1	east	vol water	27.9	42.0	24.8	17.5	24.5
				cv	21%	10%	3%	5%	2%
			west	vol water	24.2	45.9	35.5	21.9	29.0
				cv	18%	9%	1%	1%	6%
		rep 2	east	vol water	37.0	50.9	34.4	23.0	25.8
				cv	27%	9%	1%	1%	3%
			west	vol water	28.2	29.5	34.4	33.2	33.7
				cv	6%	3%	3%	1%	7%
		rep 3	east	vol water	26.8	41.8	38.8	32.9	50.6
				cv	7%	10%	2%	3%	17%
			west	vol water	29.1	39.8	38.4	35.6	42.1
				cv	22%	6%	2%	2%	9%

					seg 1	seg 2	seg 3	seg 4	seg 5
23-Jul	0.55	rep 1	east	vol water	21.5	32.6	47.0	45.7	45.0
				cv	34%	33%	2%	7%	11%
			west	vol water	18.7	41.3	49.9	44.4	67.3
				cv	37%	7%	4%	3%	12%
		rep 2	east	vol water	12.8	25.9	32.4	30.5	60.4
				cv	19%	9%	1%	2%	11%
			west	vol water	14.1	25.2	27.2	37.2	49.9
				cv	12%	3%	1%	3%	7%
		rep 3	east	vol water	15.5	28.6	29.6	18.6	31.9
				cv	25%	12%	1%	4%	4%
			west	vol water	14.5	20.8	31.4	32.8	60.0
				cv	6%	9%	1%	4%	7%
	0.95	rep 1	east	vol water	16.4	30.9	24.0	17.7	25.9
				cv	15%	12%	3%	2%	8%
			west	vol water	12.9	31.8	34.5	21.3	28.4
				cv	57%	9%	5%	1%	9%
		rep 2	east	vol water	18.5	41.2	30.0	22.0	27.7
				cv	47%	5%	2%	2%	8%
			west	vol water	17.1	22.4	33.9	32.5	35.2
				cv	10%	10%	4%	2%	8%
		rep 3	east	vol water	17.9	34.7	35.3	33.5	49.8
				cv	13%	5%	2%	2%	10%
			west	vol water	13.0	32.1	36.5	36.1	46.1
				cv	20%	3%	2%	1%	11%
13-Aug	0.55	rep 1	east	vol water	26.6	23.6	41.0	47.9	49.0
				cv	25%	14%	2%	7%	12%
			west	vol water	21.8	33.3	44.1	44.8	70.6
				cv	21%	11%	4%	4%	8%
		rep 2	east	vol water	19.8	23.1	29.4	28.9	56.5
				cv	8%	3%	1%	2%	12%
			west	vol water	24.6	19.0	24.4	33.4	45.3
				cv	5%	4%	2%	2%	7%
		rep 3	east	vol water	24.0	19.6	25.7	17.3	34.5
				cv	15%	18%	2%	2%	11%
			west	vol water	22.0	16.9	27.2	28.9	55.7
				cv	8%	7%	1%	3%	8%
	0.95	rep 1	east	vol water	20.0	21.8	19.9	16.5	25.1
				cv	11%	11%	3%	1%	5%
			west	vol water	19.0	40.5	29.8	21.2	31.3
				cv	48%	16%	3%	3%	9%
		rep 2	east	vol water	22.7	36.2	27.4	21.3	27.2
				cv	29%	9%	1%	2%	7%
			west	vol water	20.8	17.1	28.5	29.8	34.6
				cv	15%	14%	3%	4%	9%
		rep 3	east	vol water	27.0	29.0	27.0	30.8	60.5
				cv	5%	11%	1%	1%	10%
			west	vol water	16.3	21.3	31.1	34.0	52.7
				cv	7%	4%	1%	1%	7%

					seg 1	**seg 2**	**seg 3**	**seg 4**	**seg 5**
27-Aug	0.55	rep 1	east	vol water	15.3	18.5	37.0	45.7	47.9
				cv	10%	11%	1%	6%	23%
			west	vol water	17.4	28.5	41.8	45.9	75.6
				cv	20%	16%	2%	2%	13%
		rep 2	east	vol water	9.3	20.8	26.9	27.4	59.1
				cv	15%	4%	3%	1%	9%
			west	vol water	5.8	16.3	21.0	32.1	44.8
				cv	26%	3%	3%	6%	12%
		rep 3	east	vol water	10.5	15.8	23.5	16.1	37.7
				cv	17%	12%	1%	1%	7%
			west	vol water	7.8	14.3	24.5	25.9	62.5
				cv	22%	6%	2%	4%	8%
	0.95	rep 1	east	vol water	9.9	20.2	17.6	14.9	25.9
				cv	8%	2%	1%	1%	5%
			west	vol water	8.5	21.0	29.0	21.7	30.3
				cv	88%	20%	9%	2%	3%
		rep 2	east	vol water	15.0	31.6	23.7	19.5	27.0
				cv	20%	16%	3%	2%	5%
			west	vol water	8.8	15.7	26.3	26.7	34.6
				cv	26%	16%	2%	4%	15%
		rep 3	east	vol water	10.1	23.9	24.0	27.4	53.9
				cv	11%	6%	1%	2%	7%
			west	vol water	9.6	15.8	27.4	30.6	55.4
				cv	10%	7%	3%	2%	9%
9-Sep	0.55	rep 1	east	vol water	20.8	23.8	35.0	43.7	49.0
				cv	7%	6%	1%	6%	10%
			west	vol water	22.1	40.1	38.2	44.9	69.8
				cv	17%	16%	2%	6%	4%
		rep 2	east	vol water	18.4	29.5	26.1	26.5	56.5
				cv	11%	4%	2%	2%	9%
			west	vol water	17.7	25.5	20.8	31.3	42.6
				cv	8%	3%	2%	4%	18%
		rep 3	east	vol water	23.8	24.4	22.4	15.9	36.7
				cv	8%	5%	2%	5%	15%
			west	vol water	14.1	17.9	24.7	26.3	56.7
				cv	10%	6%	1%	3%	12%
	0.95	rep 1	east	vol water	18.0	29.2	17.3	15.7	26.7
				cv	3%	3%	3%	2%	9%
			west	vol water	16.7	36.0	28.1	21.4	31.2
				cv	21%	22%	6%	4%	4%
		rep 2	east	vol water	24.9	38.9	26.0	19.8	26.0
				cv	12%	14%	2%	5%	2%
			west	vol water	18.4	24.7	26.8	25.5	32.2
				cv	18%	12%	5%	1%	16%
		rep 3	east	vol water	18.2	30.7	22.9	26.2	52.2
				cv	8%	2%	1%	1%	10%
			west	vol water	13.4	24.4	27.5	29.9	54.5
				cv	5%	5%	1%	0%	11%

					seg 1	**seg 2**	**seg 3**	**seg 4**	**seg 5**
23-Sep	0.55	rep 1	east	vol water	14.4	21.5	33.9	41.5	59.5
				cv	23%	5%	1%	5%	17%
			west	vol water	19.4	29.3	37.1	45.9	65.9
				cv	24%	12%	2%	6%	3%
		rep 2	east	vol water	10.2	22.9	26.5	25.9	54.6
				cv	11%	3%	1%	3%	12%
			west	vol water	8.5	17.8	21.1	29.7	44.9
				cv	7%	2%	1%	5%	9%
		rep 3	east	vol water	11.8	18.2	22.9	16.0	32.5
				cv	35%	5%	2%	6%	15%
			west	vol water	9.0	15.7	24.7	25.7	57.7
				cv	22%	5%	1%	7%	9%
	0.95	rep 1	east	vol water	10.8	21.9	17.2	15.2	24.6
				cv	17%	6%	1%	2%	8%
			west	vol water	11.3	23.8	27.9	21.2	31.1
				cv	28%	21%	2%	4%	9%
		rep 2	east	vol water	14.3	31.0	24.9	19.4	28.5
				cv	27%	10%	7%	1%	10%
			west	vol water	10.2	19.8	26.4	26.1	32.8
				cv	27%	21%	2%	5%	12%
		rep 3	east	vol water	9.9	24.5	22.5	25.5	53.2
				cv	6%	3%	1%	1%	11%
			west	vol water	6.7	17.7	27.3	29.3	58.4
				cv	13%	7%	2%	2%	7%
7-Oct	0.55	rep 1	east	vol water	13.9	18.6	32.7	40.1	57.6
				cv	9%	7%	1%	4%	9%
			west	vol water	19.2	24.3	35.4	41.3	62.2
				cv	9%	7%	1%	4%	12%
		rep 2	east	vol water	10.4	21.5	25.5	25.8	53.7
				cv	5%	5%	2%	3%	10%
			west	vol water	8.3	16.4	20.1	29.8	40.2
				cv	13%	4%	2%	4%	17%
		rep 3	east	vol water	11.7	16.6	22.3	15.5	38.3
				cv	31%	8%	1%	1%	10%
			west	vol water	8.2	14.7	23.3	24.8	53.3
				cv	8%	5%	1%	4%	11%
	0.95	rep 1	east	vol water	10.7	18.9	16.5	14.2	24.7
				cv	7%	3%	2%	7%	4%
			west	vol water	11.0	20.9	26.5	21.0	30.3
				cv	43%	11%	2%	2%	7%
		rep 2	east	vol water	17.0	28.0	22.7	18.6	26.6
				cv	26%	3%	2%	3%	13%
			west	vol water	10.9	19.6	25.9	25.3	34.5
				cv	18%	15%	4%	4%	12%
		rep 3	east	vol water	10.3	23.1	22.2	24.7	49.0
				cv	11%	2%	2%	1%	9%
			west	vol water	7.4	15.9	26.2	28.6	55.1
				cv	13%	3%	1%	2%	8%

					seg 1	**seg 2**	**seg 3**	**seg 4**	**seg 5**
18-Oct	0.55	rep 1	east	vol water	14.5	17.1	32.3	38.2	52.0
				cv	13%	9%	1%	4%	7%
			west	vol water	17.1	22.7	33.4	41.0	60.6
				cv	13%	7%	10%	8%	10%
		rep 2	east	vol water	9.8	21.4	25.9	25.8	54.3
				cv	16%	4%	2%	4%	12%
			west	vol water	8.7	16.4	20.0	27.6	42.3
				cv	16%	3%	2%	3%	12%
		rep 3	east	vol water	10.8	15.5	21.6	13.4	32.7
				cv	4%	5%	2%	7%	11%
			west	vol water	7.6	14.3	22.8	24.2	49.8
				cv	10%	9%	2%	5%	13%
	0.95	rep 1	east	vol water	10.5	19.3	16.4	13.3	24.9
				cv	8%	2%	1%	10%	8%
			west	vol water	11.1	19.5	26.5	20.6	30.0
				cv	68%	8%	4%	4%	5%
		rep 2	east	vol water	14.0	28.7	22.4	18.5	25.7
				cv	48%	14%	3%	4%	15%
			west	vol water	10.6	16.2	25.3	25.2	31.6
				cv	31%	10%	2%	4%	11%
		rep 3	east	vol water	9.2	23.3	22.0	24.8	50.6
				cv	7%	2%	1%	4%	10%
			west	vol water	6.2	16.5	25.9	28.0	54.6
				cv	19%	4%	2%	4%	14%

Table B-2 Porosity calculations based on Uhland core samples

Determined from bulk density of subsoil profiles. Particle density assumed to be 2.54 Mg m^{-3} for Ah horizon and 2.65 Mg m^{-3} for subsoil and spoil.

0.55 m Subsoil Thickness Treatment

Depth (cm)	Rep.1 east	Rep. 1 wes	Rep.2 east	Rep. 2 wes	Rep. 3 eas	Rep. 3 west
0-10	63.8	55.6	61.0	59.5	56.7	60.6
15-25	55.1	51.0	44.7	47.1	47.0	58.9
25-40	41.8	47.9	40.1	51.4	49.1	55.2
40-50	44.5	41.5	49.7	38.0	48.6	50.5
50-60	42.6	43.9	43.2	39.9	44.3	45.6
65-75	46.0	45.8	36.2	37.3	37.6	38.5
75-85	41.6	41.1	23.5	27.3	40.7	38.3
95-105	44.7	40.3	38.1	32.5	43.4	42.8
105-115	34.7	40.0	n/a	n/a	43.3	37.5

0.95 m Subsoil Thickness Treatment

Depth (cm)	Rep.1 east	Rep. 1 wes	Rep.2 east	Rep. 2 wes	Rep. 3 eas	Rep. 3 west
0-10	58.6	60.8	58.9	57.8	57.7	61.8
15-25	49.7	50.1	42.4	57.6	45.8	52.8
25-40	42.8	42.2	38.8	35.7	46.0	39.1
40-50	40.3	41.8	43.8	45.7	45.4	37.8
50-60	37.4	46.1	47.4	41.0	40.9	38.3
65-75	38.9	43.2	40.5	49.8	37.9	43.2
75-85	43.5	42.7	35.5	40.8	31.9	38.2
95-105	48.5	48.8	42.9	37.2	32.0	43.8
105-115	37.7	49.2	44.0	46.7	38.7	41.3

Porosity averaged to represent each of the five TDR segment depths, for the 0.55 m and 0.95 subsoil thickness treatment.

TDR section depth(cm)	**0.55 m**	**0.95 m**
0-15	59.5%	59.3%
15-30	50.6%	49.7%
30-60	45.4%	41.7%
60-90	37.8%	40.5%
90-120	39.0%	42.6%

Determination of particle density for Ah horizon.
Org material = Dp=1.4 Mg m-3
Assume Ah with 5% OM
Assume 100g soil (oven dry) with 5% OM gives =5g OM and 95 g of mineral soil
volume of OM = 5g/1.4 Mg m-3 = 3.57m3
volume of mineral =95g/2.65 Mg m-3 =35.85 total volume=39.42
particle density =100/39.42 = 2.54 Mg m-3

Porosity = 1-Db/Dp

Table B-3 Bulk Density results

Both the uhland and drilled cores for the depth increments (4/plot)
Uhland Core results with (*)
E = core taken from east side of subplot
W = core taken from west side of subplot

0.55 m Treatment

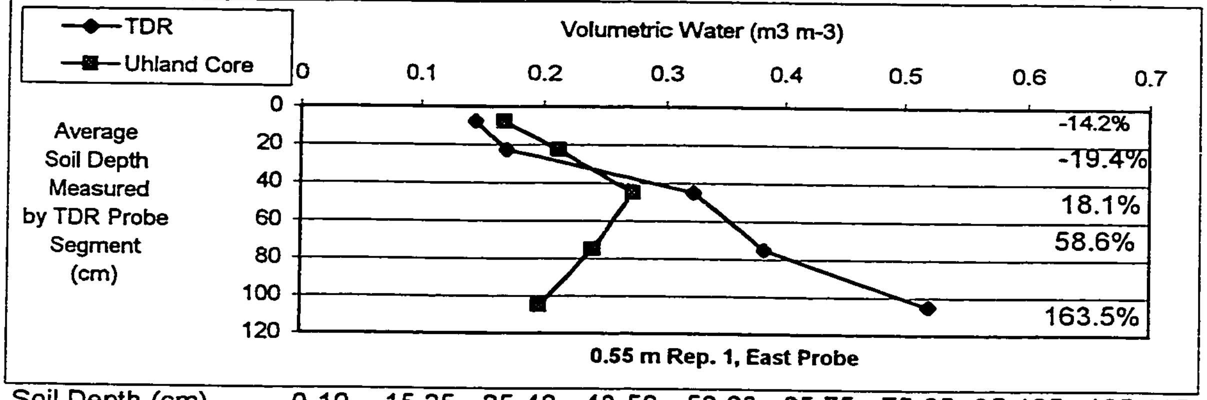
depth	*R1E	*R1W	*R2E	*R2W	*R3E	*R3W	R1E	R1W	R2E	R2W	R3E	R3 W
0-10	0.92	1.13	0.99	1.03	1.10	1.00	1.32	1.28	1.31	1.24	1.20	1.27
15-25	1.19	1.30	1.47	1.40	1.40	1.09	1.56	1.33	1.44	1.43	1.42	1.47
25-40	1.54	1.38	1.59	1.29	1.35	1.19	1.60	1.48	1.57	1.70	1.65	1.51
40-50	1.47	1.55	1.33	1.64	1.36	1.31	2.03	1.42	1.60	1.50	1.70	1.51
50-60	1.52	1.49	1.50	1.59	1.48	1.44	n/a	1.56	1.62	n/a	1.63	1.51
65-75	1.43	1.44	1.69	1.66	1.65	1.63	2.15	1.89	1.75	1.89	1.48	1.79
75-85	1.55	1.56	2.03	1.93	1.57	1.63	1.69	1.74	1.76	1.75	2.33	1.79
95-105	1.47	1.58	1.64	1.79	1.50	1.52	1.94	1.85	1.82	1.62	1.85	1.87
105-115	1.73	1.59	n/a	n/a	1.50	1.66	1.75	1.86	1.86	1.81	2.06	1.80

0.95 m treatment

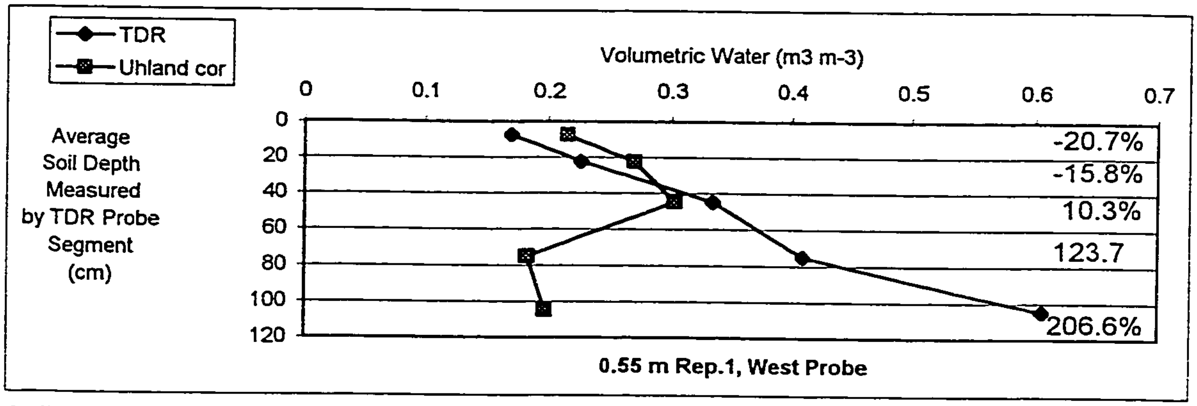
depth	*R1E	*R1W	*R2E	*R2W	*R3E	*R3W	R1E	R1W	R2E	R2W	R3E	R3W
0-10	1.05	0.99	1.04	1.07	1.07	0.97	1.05	1.24	1.08	1.17	1.24	1.14
15-25	1.33	1.32	1.53	1.12	1.44	1.25	1.36	1.48	1.23	1.37	1.52	1.45
25-40	1.51	1.53	1.62	1.70	1.43	1.61	1.56	1.71	1.36	1.60	1.57	1.57
40-50	1.58	1.54	1.49	1.44	1.45	1.65	n/a	1.58	1.39	1.56	1.48	1.63
50-60	1.66	1.43	1.39	1.56	1.57	1.64	1.60	1.53	n/	1.70	1.54	1.40
65-75	1.62	1.51	1.58	1.33	1.65	1.51	1.49	n/	1.47	1.50	1.67	1.63
75-85	1.50	1.52	1.71	1.57	1.81	1.64	1.56	n/	1.68	1.66	1.41	1.72
95-105	1.36	1.36	1.51	1.66	1.80	1.49	1.71	1.50	1.89	1.53	1.62	1.79
105-115	1.65	1.35	1.48	1.41	1.62	1.56	1.53	1.57	1.68	1.83	1.63	1.97

Figure B-1 Uhland core calibration results vs TDR results : Graph of ecah probe.

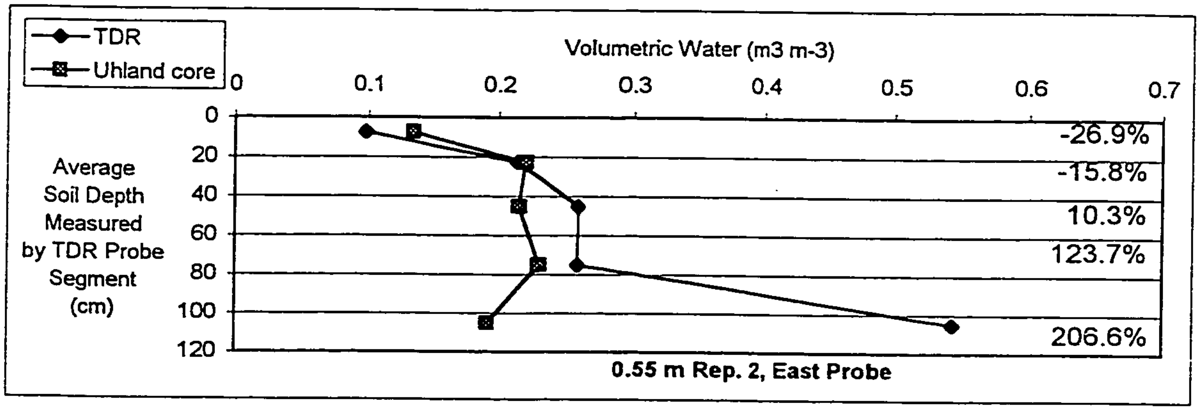
Uhland core for east and west probes in each plot of the 0.55 m and 0.95 m subsoil treatment. Bulk density included, determined from Uhland core samples with depth in soil profile. Overestimation of probes compared to Uhland core calibration included on right of graph.



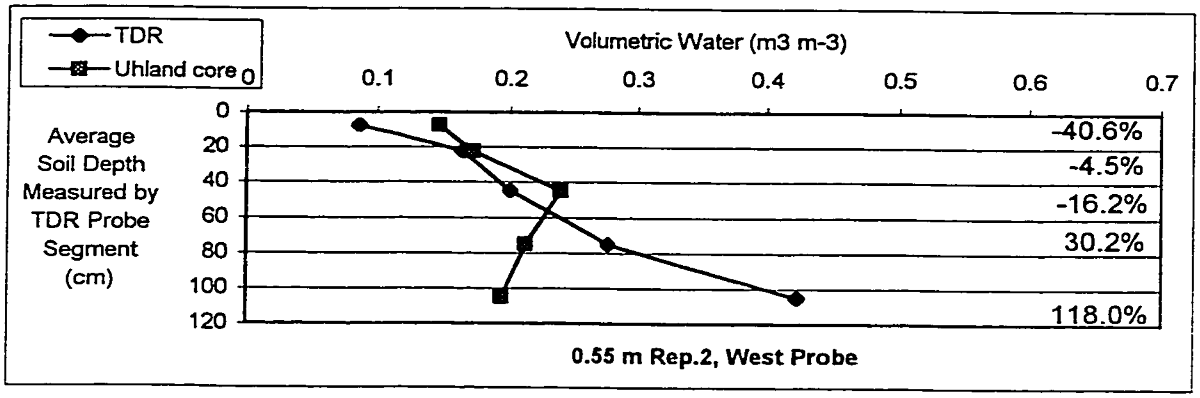
Soil Depth (cm)	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	105-115
Db (mg m-3)	0.92	1.19	1.54	1.47	1.52	1.43	1.55	1.47	1.73



Soil Depth (cm)	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	105-115
Db (mg m-3)	1.13	1.30	1.38	1.55	1.49	1.44	1.56	1.58	1.59

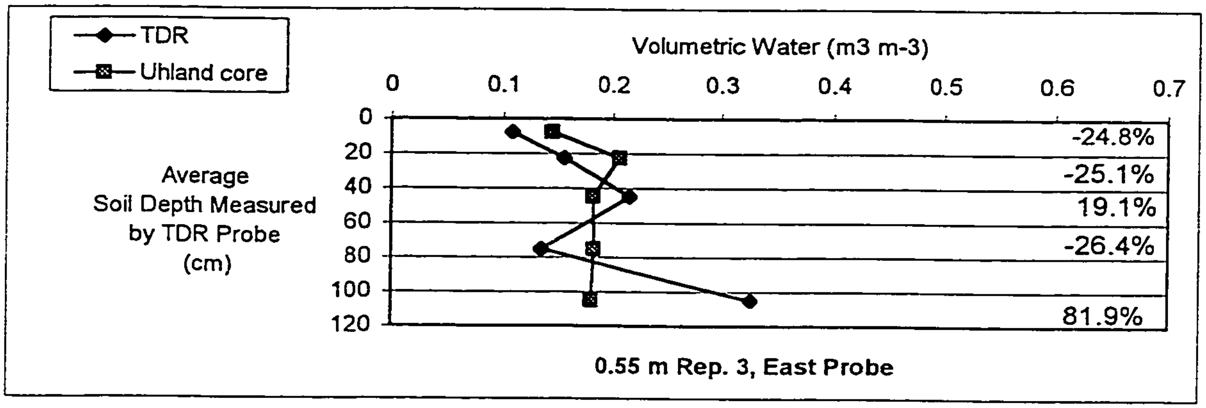


Soil Depth (cm)	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	105-115
Db (mg m-3)	0.99	1.47	1.59	1.33	1.50	1.69	2.03	1.64	n/a



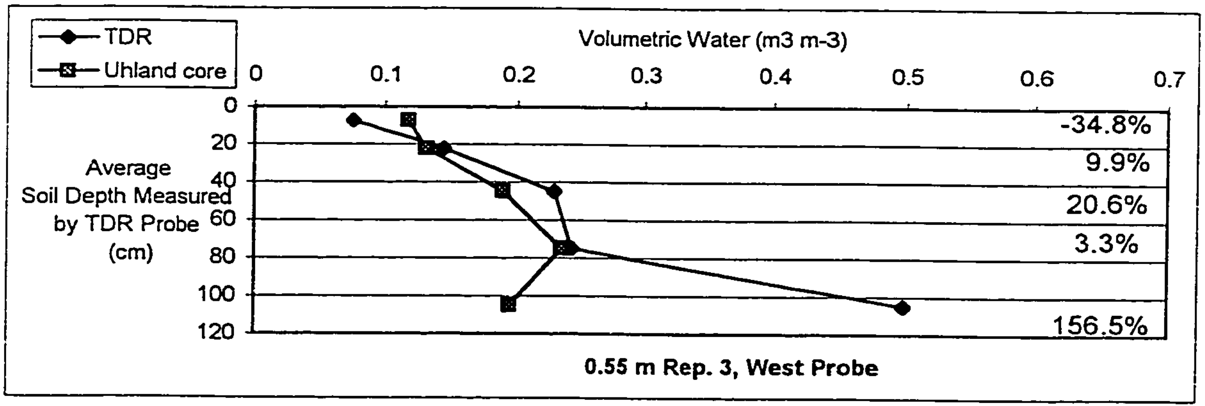
0.55 m Rep.2, West Probe

Soil Depth (cm	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	05-115
Db (mg m-3)	1.03	1.40	1.29	1.64	1.59	1.66	1.93	1.79	n/a



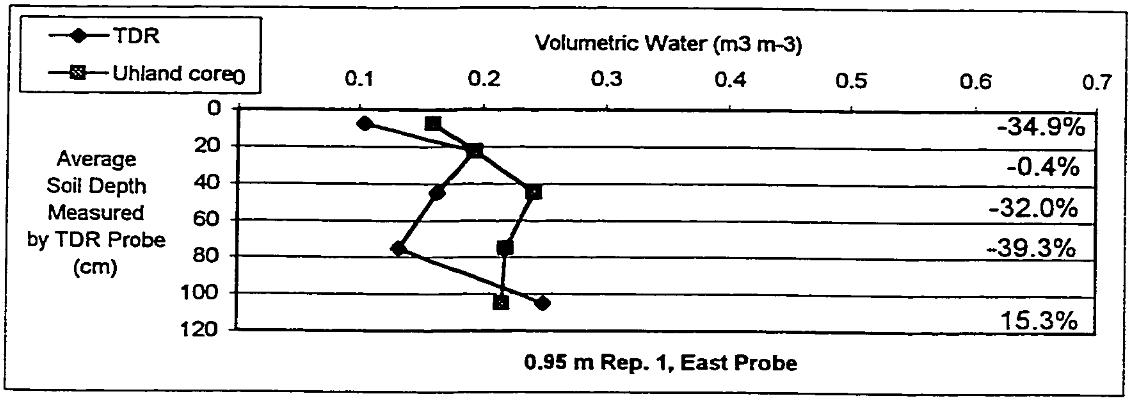
0.55 m Rep. 3, East Probe

Soil Depth (cm	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	05-115
Db (mg m-3)	1.10	1.40	1.35	1.36	1.48	1.65	1.57	1.50	1.50



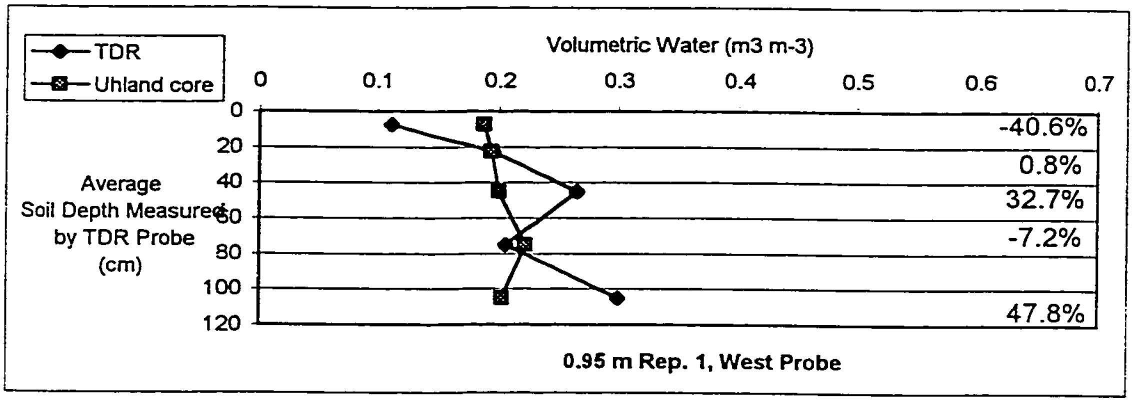
0.55 m Rep. 3, West Probe

Soil Depth (cm	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	05-115
Db (mg m-3)	1.00	1.09	1.19	1.31	1.44	1.63	1.63	1.52	1.66



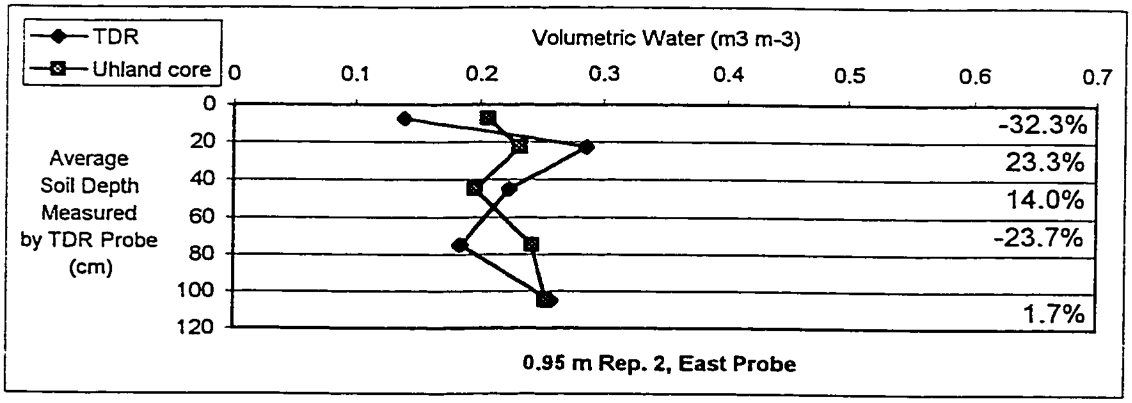
0.95 m Rep. 1, East Probe

Soil Depth (cm	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	105-115
Db (mg m-3)	1.05	1.33	1.51	1.58	1.66	1.62	1.50	1.36	1.65



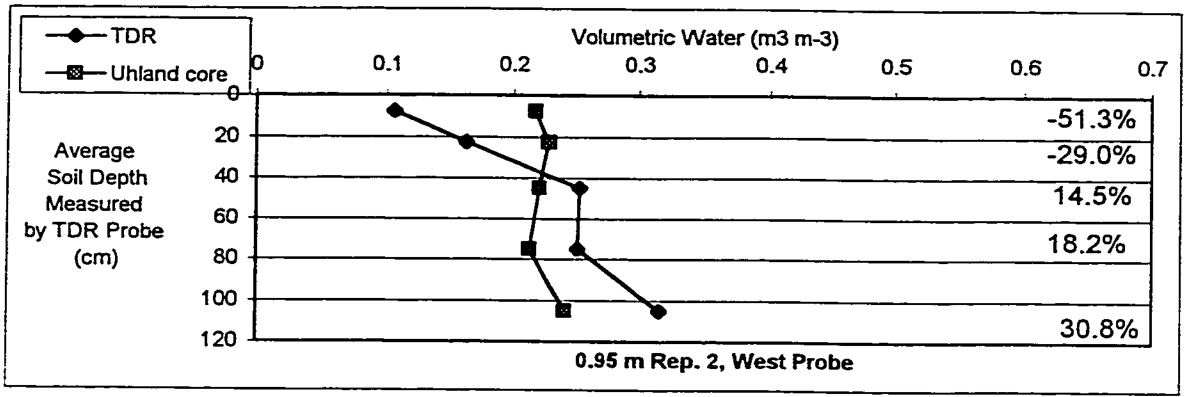
0.95 m Rep. 1, West Probe

Soil Depth (cm	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	105-115
Db (mg m-3)	0.99	1.32	1.53	1.54	1.43	1.51	1.52	1.36	1.35



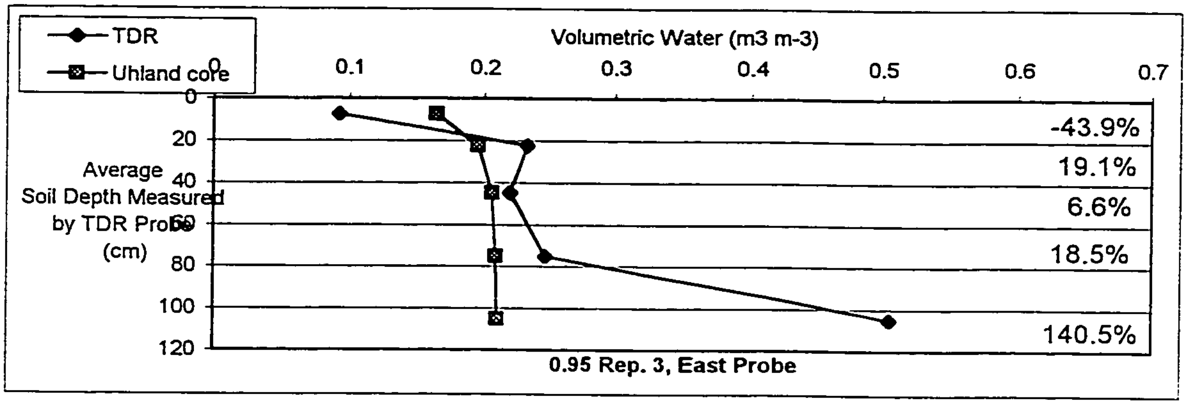
0.95 m Rep. 2, East Probe

Soil Depth (cm	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	105-115
Db (mg m-3)	1.04	1.53	1.62	1.49	1.39	1.58	1.71	1.51	1.48



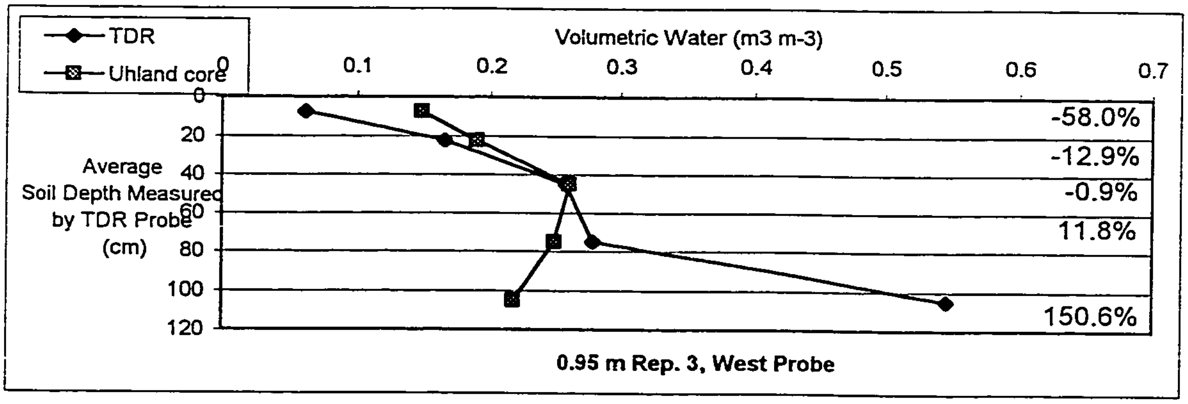
0.95 m Rep. 2, West Probe

Soil Depth (c	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	05-115
Db (mg m-3)	1.07	1.12	1.70	1.44	1.56	1.33	1.57	1.66	1.41



0.95 Rep. 3, East Probe

Soil Depth (c	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	05-115
Db (mg m-3)	1.07	1.44	1.43	1.45	1.57	1.65	1.81	1.80	1.62



0.95 m Rep. 3, West Probe

Soil Depth (c	0-10	15-25	25-40	40-50	50-60	65-75	75-85	95-105	05-115
Db (mg m-3)	0.97	1.25	1.61	1.65	1.64	1.51	1.64	1.49	1.56

APPENDIX B
Figure B-2. DISCUSSION OF TDR RESULTS

INTRODUCTION

Reclamation of surface-mined land often involves constructed soil profiles over mine spoil. Depending on the nature of the material, the depth of the layer and the handling procedure the soil profile may be porous or highly compacted (Ward et al. 1983). As well, deterioration of the soil's natural structure are an inevitable consequence of excavation, storage and replacement (Stewart and Scullion 1989). Further physical limitations can be imposed if the spoil is sodic, from dispersion closing off conducting pores. Since hydrologic balance including infiltration and the ability of water to move through reconstructed profiles is of fundamental importance in determining the success of reclamation efforts (Ward et al. 1983), it is important to ensure that the constructed profiles allow for water percolation rather than pooling above the spoil interface. Clearance of soil water depends on maintained structure and the prevention of close packing of particles (Stewart and Scullion 1989).

OBJECTIVE

The Highvale Plains Reclamation Research Project determined that a constructed soil profile with 0.95 m of subsoil was sufficient and necessary to produce optimum yields. However, the study also showed that difference between the 0.55 m and 0.95 m subsoil profile was not significant (Oddie and Bailey 1988). Thus, the purpose of this study was to decipher differences, if any, between the two constructed soil profiles of subsoil replacement thickness (0.55 m and 0. 95 m) established over a sodic mine spoil after 16 years. The specific objective was to determine if the physical properties of volumetric soil water differed between the two subsoil profiles (0.55 m and 0.95 m), and to consider the direction and possible limitations they may pose to current soil genesis. The null hypothesis tested was:

> There is no difference in volumetric soil water with depth between and within the 0.55 m and 0.95 m subsoil profiles during the growing season.

MATERIALS AND METHODS

Please refer to Chapter 2, section 2.3 for materials and methods. In addition, porosity calculated for the Ah horizon was based on 5% organic matter (Dp = 1.40 Mg m^{-3}) (Juma, Online, 2000), assumed from dark gray brown color outlined in the Land Capability Classification for Arable Agriculture in Alberta (ASAC 1987).

RESULTS

Comparison of volumetric water determined from Uhland cores and TDR probes indicated particular measurement discrepancies in both subsoil profiles. Underestimation of volumetric water by the probes, compared to the Uhland cores (Figure B-1), ranged from 14% to 41% and 32% to 58% in topsoil (0-15 cm) for the 0.55 m and 0.95m subsoil profile respectively. Lower over/under estimations occurred in the two depth measurements of 15 - 30 cm and 30 - 60 cm, compared to other depths measured. However, still the variation in over or under estimation ranged from 2.6% to 25% and 10.3% to 20.6% for the respective depths for the 0.55 m subsoil profile. Likewise, the over or under estimation measured in the 0.95 m subsoil profile ranged from 0% to 29% and 1% to 33%, for the same depths. Even greater overestimation occurred at lower depths measured. The 0.55 m and 0.95 m subsoil profile measured a maximum overestimation of 124% and 40% volumetric water at a depth of 60-90 cm and a 207% and 151% overestimation at the depth of 90-120 cm, for the respective profiles (Figure B-1).

In addition, high coefficient of variance (CV) (CV ≥ 10%) occurred between consecutive depth segment readings, in many of the probes, particularly in the depth increments of 0-15 cm, 15-30 cm and 90-120 cm (Table B-1). The manual accepts a CV of 1% for consecutive readings of a probe emulator. It states that the readings should correspond to the values noted with the accepted variation (CV ≤1%). Without clearly stating an upper threshold limit for acceptable variation in consecutive probe values, our study considered any CV >10% unacceptable. The most extreme CV of 88% was measured in the 0.95 m subsoil profile in the topsoil segment (0-15 cm), compared to the maximum CV of 48% in one of the 0.55 m subsoil profile probes for the same depth. High CV associated with

TDR water content readings were neither probe, nor time specific. During the period of the growing season, each probe, at least once, recorded a measurement associated with a CV above 10% for a certain depth (Table B-1). As a result there was little agreement between the east and west probe measuring soil within plot. The probes have been documented to have an absolute volumetric water measurement error up to 0.03 m^3 m^{-3} (Hook and Livingston 1996). However, our study found a larger discrepancy (>0.03 m^3 m^{-3}) between consecutive readings of a certain probe for a depth, as well between the east and west pair of probes within a plot.

Finally, porosity calculated from the bulk density determined from the Uhland core samples (Table B-2), illustrate the overestimation of the volumetric water values measured by the TDR above 100% possible saturation (Table B-1). Principally, many of the probes in the 0.55 m subsoil profile measured excessive volumetric water (to a maximum value of 0.76 m^3 m^{-3}) compared to the calculated porosity (subsoil profile average for segment #5 = 39%), for the deepest probe segment of 90-120 cm. Likewise probes in the 0.95 m subsoil profile overestimated water content (to a maximum value of 0.65 m^3 m^{-3}) compared to the calculated porosity (subsoil profile average for segment #5 = 43%) indicating greater amounts of soil water beyond soil saturation.

DISCUSSION

TDR probe technology utilizes the propagation time of a dielectric pulse to travel the length of the probe to determine volumetric water, based on the linear relationship of increased propagation velocity related to an increase in soil medium permittivity (Sun et al. 2000). As soil water content increases so does the propagation time of the pulse based on the increased permittivity of water compared to either air or dry soil. However, there are a few soil properties that interfere with this relationship. Soil bulk electrical conductivity includes surface charges of clay particles and the EC of the soluble salts in the soil solution, which is further emphasized under increasing Db, act to decrease the dielectric pulse that is initiated from the middle of the probe (at 60 cm depth). Signal attenuation due to energy dissipation by current flow and signal dispersion have been cited as factors affecting TDR moisture determination (Sun et al. 2000). As a result, signal attenuation is lost and the relationship between electrical current propagation time and soil water ceases to be linear. This phenomenon is particularly prevalent in the longer probes, since the pulse has a longer distance to travel and thus, greater potential for signal loss. Consequently, segments measuring volumetric water at the tips of the probe are more prone to obscured results since the pulse weakens with distance away from point of origin, in the middle of the probe. However, it has been observed that probes with shorter active lengths of 15 cm can endure higher EC's without affecting water measurement because the pulse remains strong over the smaller distance it travels through the probe (J. Sun, personal communication, Environmental Sensors Inc. soil physics technician). It has also been suggested that clay soils behave differently than other soils over the transition from a dry clay soil to saturated states. When water is added to clay soils, it either exists in a bound or free state based according to some fixed ratio. However, the slope that relates propagation time with water content differs between these two states causing discrepancy in readings associated with the change from bound to free water (Hook and Livingston 1996). Thus, increase in clay content, soil EC and bulk density cumulatively affect the ability of the probe to properly measure soil water.

The calibration of the TDR probes which indicated that the shallowest (topsoil segment of 0-10 cm) and the deepest segment (90-120 cm) of the probe produced the most extreme over or under estimation of volumetric water measurements agree with the theory that the tips of the probe are most affected. However, the depth segment of 60-90 cm in the 0.55 m subsoil profile also overestimated soil water, which most likely resulted from the significant increase in spoil bulk density of the 0.55 m subsoil profile at depths greater than 65 cm, compared to the 0.95 m subsoil. The greater bulk density would increase the bulk electrical conductivity in this segment, causing a decrease in probe signal attenuation. As well, increased sodium salt content of the 0.55 m spoil in the depth segments of 60-90 cm and 90-120 cm, compared to the 0.95 m subsoil, would further obscure the water measurements by this theory. The greater overestimation in the 0.55 m subsoil profile compared to the 0.95 m, for both of these segments, supports this theory.

The high coefficient of variance (CV ≥0.1) associated with the consecutive sampled readings for a probe depth occurred throughout the growing season particularly at the end segments of the probe (both the tips and bottom segment). The high CV further support the theory of signal loss as it travels away from point of origin in the middle of the probe, resulting in inconsistent values determining volumetric soil water. Another cause for the faulty readings could be that over the course of the winter, freeze thaw processes disturbed the soil contact from the active face of the probe, causing inaccurate measurements by the probe. High measurement variance occurred in the probes at depths that encompass all three materials used in the profile construction. However, measurement variance occurred more frequently in the topsoil segment. Perhaps the swelling properties of the clay fraction in the subsoil (or even dispersed clay particles) improved the soil contact to the probe during periods of wetness, allowing for, at the very least, consistent results for a particular segment.

Soil water overestimation in the deepest TDR segment of 90-120 cm, confirmed by porosity values determined from Uhland cores, also support the theory that increased bulk electrical conductivity skewed the probe's measurement. Decreased signal attenuation causing an overestimation of soil water should be at a maximum for the lowest segment measured, where both Db and EC are greatest compared to shallower depths.

CONCLUSION

Unfortunately volumetric water reading over the growing season have proved to be inaccurate and unreliable. The bulk electrical conductivity from surface charges of clay minerals, soil solution EC and increased Db interfere with the linear relationship of propagation time versus soil water content that TDR technology is based on. Calibration of the probes with Uhland core samples showed greatest deviation in volumetric water determined at both tips of the probe. The high coefficient of variance associated with consecutive readings of a probe also confirmed the data was unreliable. In addition, porosity calculated from the Uhland cores indicated that the TDR readings described conditions far beyond saturated states, possible for the two subsoil profiles. Thus, the volumetric water readings over the growing season were not analyzed in this study.

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APPENDIX C - CHEMICAL PROPERTIES, DATA

Table C-1 Total profile weighted averages of chemical properties
Refer to legend p146.
For each of the 3 rep values, there were 4 core samples.

0.55 Treatment

				mmol L-1				dS m-1
			SAR	**Ca**	**Mg**	**Na**	**pH**	**EC**
rep 1	R1 S2.55	Sum	5.07	2.23	0.62	6.72	8.68	0.71
	R1 S1.55	Sum	3.18	2.01	0.46	4.62	8.20	0.61
	R1 N4 .55	Sum	3.19	1.80	0.45	4.12	8.64	0.52
	R1 N2 .55	Sum	3.25	1.74	0.46	3.39	8.44	0.54
rep 2	R2 N4 .55	Sum	4.22	2.91	0.66	5.02	8.94	0.66
	R2 S5.55	Sum	3.24	1.33	0.37	3.60	8.71	0.47
	R2 S2 .55	Sum	3.16	1.21	0.37	2.94	8.50	0.41
	R2 N3 .55	Sum	3.86	1.86	0.57	4.48	9.01	0.59
rep 3	R3 S1 .55	Sum	4.46	1.47	0.47	6.70	9.03	0.82
	R3 N3 .55	Sum	3.40	1.15	0.40	3.47	8.49	0.49
	R3 N5.55	Sum	3.02	1.48	0.42	3.55	8.39	0.51
	R3 S4.55	Sum	3.81	2.20	0.67	5.49	8.55	0.80

0.95 Treatment

			SAR	**Ca**	**Mg**	**Na**	**pH**	**EC**
rep 1	R1 S3.95	Sum	2.04	1.94	0.46	2.31	8.81	0.40
	R1 N3 .95	Sum	2.12	1.81	0.46	2.69	8.86	0.46
	R1 N4.95	Sum	2.03	1.93	0.54	2.60	8.99	0.48
	R1 S2.95	Sum	1.81	1.52	0.43	2.12	8.68	0.37
rep 2	R2 N5 .95	Sum	2.83	3.86	1.18	4.11	9.05	0.74
	R2 N4.95	Sum	2.58	2.95	0.74	3.90	8.82	0.75
	R2 S1.95	Sum	2.11	1.88	0.58	2.67	8.64	0.58
	R2 S2.95	Sum	1.79	1.86	0.55	2.31	8.73	0.44
rep 3	R3 S3 .95	Sum	3.88	2.00	0.77	4.46	8.97	0.62
	R3 N1.95	Sum	4.05	1.48	0.62	4.45	8.92	0.57
	R3 S5.95	Sum	3.43	2.13	0.72	5.46	8.89	0.78
	R3 N2.95	Sum	3.07	1.72	0.57	4.04	8.73	0.62

Table C-2. Upper profile chemical properties.

0.55 Treatment (Soluble cations=mmol L-1) (EC=dS m-1)

		SAR				**Sol Ca**			
	Depth	R1 S2.5	R1 S1.5	1 N4 .5	1 N2 .55	R1 S2.5	R1 S1.5	R1 N4 .55	R1 N2 .55
	TS	0.47	0.20	0.22	0.48	1.99	2.09	2.24	1.67
	30	0.55	0.32	n/a	0.44	2.61	2.78	n/a	2.13
rep 1	20	0.57	0.57	0.48	0.6	3.84	2.13	1.83	2.63
	10	2.57	1.42	0.63	0.96	1.86	2.18	2.33	1.98
	Depth	2 N3 .5	2 N4 .5	R2 S5.5	2 S2 .55	R2 N3 .5	2 N4 .5	R2 S5.55	R2 S2 .55
	TS	0.42	0.35	0.18	0.19	2.12	3.54	3.44	2.84
	30	0.52	0.37	0.42	0.44	3.22	5.85	1.49	1.79
rep 2	20	0.89	0.82	0.54	0.64	2.27	2.57	1.69	1.39
	10	3.75	3.41	1.64	1.58	1.12	1.82	1.39	1.29
	Depth	3 S1 .5	3 N3 .5	R3 N5.5	R3 S4.55	R3 S1 .5	3 N3 .5	R3 N5.55	R3 S4.55
	TS	0.21	0.38	0.36	0.24	2.22	2.12	3.89	2.49
	30	0.89	0.74	0.52	0.91	1.27	1.79	1.89	3.27
rep 3	20	1.71	1.23	0.79	1.34	1.17	1.19	1.74	2.12
	10	4.16	2.41	1.63	3.54	0.82	0.89	1.44	1.32

		Sol Mg				**Sol Na**			
	Depth	R1 S2.5	R1 S1.5	1 N4 .5	1 N2 .55	R1 S2.5	R1 S1.5	R1 N4 .55	R1 N2 .55
	TS	0.71	0.70	0.82	0.61	0.77	0.33	0.38	0.73
	30	0.71	0.44	n/a	0.47	1.01	0.58		0.71
rep 1	20	1.21	0.47	0.45	0.74	1.27	0.92	0.73	1.10
	10	0.45	0.52	0.58	0.53	3.90	2.34	1.08	1.51
	Depth	2 N3 .5	2 N4 .5	R2 S5.5	2 S2 .55	R2 N3 .5	2 N4 .5	R2 S5.55	R2 S2 .55
	TS	0.61	0.90	0.92	0.94	0.69	0.73	0.37	0.37
	30	1.09	1.07	0.44	0.54	1.08	0.97	0.58	0.66
rep 2	20	0.69	0.83	0.48	0.49	1.53	1.51	0.79	0.88
	10	0.36	0.52	0.35	0.44	4.55	5.21	2.16	2.08
	Depth	3 S1 .5	3 N3 .5	R3 N5.5	R3 S4.55	R3 S1 .5	3 N3 .5	R3 N5.55	R3 S4.55
	TS	0.67	0.71	1.25	0.80	0.36	0.64	0.82	0.43
	30	0.51	0.51	0.53	0.93	1.18	1.12	0.81	1.86
rep 3	20	0.37	0.51	0.53	0.70	2.12	1.6	1.18	2.25
	10	0.31	0.40	0.40	0.50	7.6	2.73	2.21	4.77

		pH				**EC**			
	Depth	R1 S2.5	R1 S1.5	1 N4 .5	1 N2 .55	R1 S2.5	R1 S1.5	R1 N4 .55	R1 N2 .55
	TS	7.02	7.12	7.57	7.12	0.41	0.28	0.42	0.30
	30	8.56	8.01	n/a	8.04	0.45	0.29	n/a	0.40
rep 1	20	8.85	7.82	8.63	8.91	0.59	0.38	0.32	0.56
	10	9.11	8.33	8.91	8.85	0.53	0.53	0.43	0.54
	Depth	2 N3 .5	2 N4 .5	R2 S5.5	2 S2 .55	R2 N3 .5	2 N4 .5	R2 S5.55	R2 S2 .55
	TS	6.95	7.67	7.79	7.71	0.31	0.48	0.74	0.51
	30	8.93	8.88	8.47	8.6	0.51	0.53	0.34	0.32
rep 2	20	9.07	8.92	8.56	8.69	0.43	0.53	0.34	0.34
	10	9.03	8.98	8.72	8.86	0.45	0.53	0.37	0.37
	Depth	3 S1 .5	3 N3 .5	R3 N5.5	R3 S4.55	R3 S1 .5	3 N3 .5	R3 N5.55	R3 S4.55
	TS	7.19	7.32	7.91	7.24	0.40	0.36	0.54	0.38
	30	9.09	8.75	8.56	8.74	0.32	0.34	0.37	0.80
rep 3	20	8.72	8.6	8.56	8.94	0.40	0.37	0.38	0.59
	10	8.91	8.64	8.53	8.56	0.61	0.38	0.38	0.53

0.95 Treatment

SAR

	Depth	R1 S3.9	1 N3 .9	R1 N4.9	R1 S2.95
	TS	0.23	0.14	0.14	0.24
rep 1	30	0.45	0.63	0.43	0.51
	20	0.61	0.77	0.65	0.81
	10	1.75	1.75	1.5	1.64
	Depth	2 N5 .9	R2 N4.9	R2 S1.9	R2 S2.95
	TS	0.13	0.21	0.12	0.26
rep 2	30	0.57	0.60	0.41	0.47
	20	1.97	1.15	0.73	0.55
	10	3.39	2.37	1.60	1.18
	Depth	3 S3 .9	R3 N1.9	R3 S5.9	R3 N2.95
	TS	0.17	0.22	0.14	0.35
rep 3	30	0.51	0.64	0.55	0.48
	20	0.81	0.92	0.89	0.68
	10	3.80	3.24	3.34	1.93

Sol Ca

	Depth	R1 S3.9	R1 N3 .95	R1 N4.9	R1 S2.95
	TS	6.62	1.99	1.79	2.19
rep 1	30	1.93	1.93	2.28	1.62
	20	1.73	1.98	2.13	1.67
	10	1.93	2.13	1.58	1.57
	Depth	R2 N5 .9	R2 N4.95	R2 S1.9	R2 S2.95
	TS	4.99	2.57	1.72	1.84
rep 2	30	n/a	1.73	2.43	1.89
	20	4.47	2.63	2.08	1.69
	10	2.17	5.98	1.53	2.14
	Depth	R3 S3 .9	R3 N1.95	R3 S5.9	R3 N2.95
	TS	1.49	3.29	2.74	2.54
rep 3	30	2.34	0.96	1.96	1.68
	20	1.71	1.61	2.01	2.28
	10	1.41	1.36	3.21	1.38

Sol Mg

	Depth	R1 S3.9	1 N3 .9	R1 N4.9	R1 S2.95
	TS	2.06	0.65	0.60	0.76
rep 1	30	0.49	0.51	0.66	0.51
	20	0.43	0.50	0.62	0.50
	10	0.43	0.54	0.50	0.45
	Depth	2 N5 .9	R2 N4.9	R2 S1.9	R2 S2.95
	TS	1.17	0.71	1.15	0.65
rep 2	30	2.13	0.47	0.70	0.55
	20	1.94	0.80	0.70	0.53
	10	0.82	1.09	0.54	0.48
	Depth	3 S3 .9	R3 N1.9	R3 S5.9	R3 N2.95
	TS	0.42	0.91	0.95	0.77
rep 3	30	0.94	0.51	0.64	0.53
	20	0.66	0.70	0.60	0.62
	10	0.47	0.62	1.12	0.55

Sol Na

	Depth	R1 S3.9	R1 N3 .95	R1 N4.9	R1 S2.95
	TS	0.69	0.23	0.22	0.41
rep 1	30	0.71	0.99	0.73	0.75
	20	0.90	1.21	1.08	1.18
	10	2.68	2.86	2.17	2.34
	Depth	R2 N5 .9	R2 N4.95	R2 S1.9	R2 S2.95
	TS	0.33	0.38	0.21	0.41
rep 2	30	1.73	0.88	0.73	0.73
	20	4.99	2.12	1.21	0.81
	10	5.86	6.30	2.30	1.90
	Depth	R3 S3 .9	R3 N1.95	R3 S5.9	R3 N2.95
	TS	0.23	0.46	0.26	0.64
rep 3	30	0.92	0.77	0.88	0.71
	20	1.25	1.40	1.45	1.16
	10	5.21	4.55	6.95	2.68

pH

	Depth	R1 S3.9	1 N3 .9	R1 N4.9	R1 S2.95
	TS	7.29	7.23	7.13	7.37
rep 1	30	8.76	8.99	9.18	8.85
	20	8.76	8.93	9.16	8.86
	10	8.98	8.91	9.22	8.96
	Depth	2 N5 .9	R2 N4.9	R2 S1.9	R2 S2.95
	TS	6.49	7.35	7.19	7.19
rep 2	30	8.90	9.07	8.87	8.79
	20	8.99	8.84	8.86	8.83
	10	9.32	9.04	8.74	8.72
	Depth	3 S3 .9	R3 N1.9	R3 S5.9	R3 N2.95
	TS	7.27	7.19	7.35	7.17
rep 3	30	9.16	8.90	8.95	8.90
	20	8.95	9.05	8.89	8.71
	10	9.13	9.13	8.91	8.82

EC

	Depth	R1 S3.9	R1 N3 .95	R1 N4.9	R1 S2.95
	TS	0.71	0.31	0.33	0.40
rep 1	30	0.32	0.40	0.41	0.32
	20	0.33	0.40	0.46	0.35
	10	0.45	0.51	0.46	0.42
	Depth	R2 N5 .9	R2 N4.95	R2 S1.9	R2 S2.95
	TS	0.66	0.35	0.26	0.31
rep 2	30	0.88	0.33	0.46	0.35
	20	0.96	0.64	0.75	0.34
	10	0.74	0.96	0.51	0.38
	Depth	R3 S3 .9	R3 N1.95	R3 S5.9	R3 N2.95
	TS	0.36	0.45	0.52	0.37
rep 3	30	0.51	0.29	0.46	0.33
	20	0.48	0.34	0.53	0.45
	10	0.53	0.45	0.86	0.48

Table C-3. Critical zone chemical properties
0.55 Subsoil treatment

	Rep 1							Rep 2					
	SAR	**Ca**	**Mg**	**Na**	**pH**	**EC**		**SAR**	**Ca**	**Mg**	**Na**	**pH**	**EC**
	R1 S2.55							**R2 N3 .55**					
1	6.97	1.25	0.31	8.68	8.21	0.65	1	7.18	0.77	0.23	7.17	8.88	0.66
2	15.21	1.30	0.32	19.33	8.46	0.98	2	9.43	1.13	0.25	11.08	9.05	0.95
3	11.82	1.44	0.37	15.85	7.78	1.17	3	10.50	0.87	0.25	11.08	9.05	1.04
4	12.09	1.27	0.36	15.42	8.26	1.30	4	11.97	0.93	0.26	13.04	8.79	1.26
5	17.48	1.06	0.31	20.42	8.73	1.30	5	12.46	0.77	0.26	12.60	8.99	1.21
6	16.06	0.72	0.23	15.64	9.09	1.30	6	13.34	0.85	0.31	14.34	9.02	1.47
7	22.61	0.17	0.09	11.29	8.81	0.86	7	13.74	1.77	0.64	21.30	8.86	2.40
8	28.53	0.14	0.08	13.46	8.73	0.89	8	13.74	1.77	0.64	21.30	9.19	2.50
9	27.50	0.11	0.04	10.42	8.64	0.73	9	16.02	1.45	0.55	22.60	9.13	2.57
10	32.16	0.07	0.02	9.77	8.69	0.62	10	17.96	0.85	0.32	19.34	9.06	2.07
	R1 S1.55							**R2 N4 .55**					
1	4.74	1.40	0.37	6.29	8.46	0.63	1	7.13	0.89	0.25	7.60	8.84	0.66
2	6.25	1.58	0.36	8.69	8.29	0.70	2	9.33	0.66	0.17	8.47	8.89	0.69
3	6.74	1.31	0.36	8.69	8.25	0.81	3	13.89	1.35	0.38	18.25	9.21	1.71
4	8.16	1.88	0.51	12.60	8.48	1.19	4	12.37	0.79	0.22	12.38	9.03	1.04
5	10.33	1.60	0.45	14.77	8.49	1.27	5	14.30	0.50	0.15	11.51	8.92	1.02
6	12.09	1.20	0.34	14.99	9.15	1.27	6	15.27	0.37	0.12	10.64	8.77	0.81
7	13.88	0.85	0.36	15.21	8.50	1.54	7	14.50	0.81	0.26	14.99	8.98	1.30
8	13.73	0.93	0.34	15.42	8.81	1.53	8	15.40	1.17	0.41	19.34	9.13	1.95
9	17.87	0.53	0.33	16.51	8.57	1.45	9	17.72	0.74	0.25	17.60	9.07	1.63
10	16.02	2.80	1.46	33.03	8.48	3.38	10	18.62	0.39	0.13	13.25	8.86	1.14
	R1 N4 .55							**R2 S5.55**					
1	3.38	1.70	0.48	4.99	8.49	0.49	1	7.01	0.66	0.20	6.50	9.66	0.44
2	5.56	1.50	0.37	7.60	8.13	0.49	2	7.17	1.09	0.31	8.46	8.64	0.80
3	6.57	1.38	0.38	8.69	8.28	0.73	3	11.72	0.74	0.23	11.50	9.19	0.67
4	7.88	1.01	0.27	8.90	9.00	0.81	4	9.09	1.26	0.35	11.50	8.80	1.03
5	10.03	1.08	0.25	11.51	8.19	0.98	5	10.42	0.71	0.21	9.98	8.86	0.85
6	11.64	1.18	0.30	14.12	9.02	1.22	6	12.74	0.47	0.20	10.42	8.38	0.83
7	14.03	0.94	0.24	15.21	8.73	1.31	7	12.17	0.67	0.16	11.07	8.30	0.89
8	17.40	0.99	0.28	19.55	9.08	1.76	8	16.40	0.41	0.18	12.59	8.28	1.01
9	20.93	1.11	0.34	25.21	9.24	2.20	9	16.52	0.31	0.11	10.63	8.35	0.83
10	19.85	0.98	0.35	22.82	9.17	2.15	10	15.57	0.37	0.08	10.42	8.83	0.81
	R1 N2 .55							**R2 S2 .55**					
1	4.23	1.41	0.37	5.64	8.03	0.52	1	3.70	0.78	0.17	3.59	7.89	0.41
2	5.67	0.79	0.21	5.64	8.23	0.47	2	6.50	0.92	0.16	6.72	8.25	0.50
3	7.36	0.55	0.14	6.07	7.65	0.42	3	8.71	0.42	0.11	6.29	8.04	0.49
4	10.94	0.57	0.16	9.33	7.59	0.64	4	11.17	0.40	0.12	8.03	7.91	0.59
5	11.64	0.65	0.19	10.64	8.19	0.89	5	10.15	0.57	0.13	8.46	7.94	0.81
6	12.65	1.10	0.31	14.99	8.77	1.34	6	11.34	0.30	0.08	6.94	8.02	0.65
7	16.40	1.07	0.32	19.33	9.03	1.71	7	13.32	0.34	0.09	8.68	8.14	0.83
8	19.32	0.34	0.11	12.81	8.85	1.04	8	16.55	0.25	0.08	9.55	8.29	0.89
9	29.73	0.09	0.03	10.20	8.51	0.84	9	17.03	0.25	0.08	9.76	8.05	0.98
10	29.61	0.07	0.04	9.55	8.48	0.76	10	23.78	0.37	0.16	17.16	8.92	1.59

0.55 m subsoil treatment

Rep 3

	SAR	Ca	Mg	Na	pH	EC
R3 S1 .55						
1	14.14	0.88	0.41	16.08	9.08	1.64
2	10.64	0.95	0.32	11.95	9.39	1.21
3	13.12	1.13	0.37	16.08	9.31	1.69
4	15.62	1.23	0.41	19.99	9.40	2.05
5	14.08	4.45	1.21	33.47	8.87	3.80
6	18.10	2.22	0.77	31.30	9.01	3.18
7	19.02	0.63	0.21	17.39	8.72	1.73
8	19.04	0.38	0.09	13.04	8.91	1.21
9	23.53	0.21	0.10	13.04	8.74	1.21
10	21.92	0.11	outlier	21.92	8.78	1.26
R3 N3 .55						
1	4.04	0.61	0.15	3.51	7.99	0.39
2	6.90	0.65	0.19	6.29	7.92	0.60
3	9.46	0.73	0.25	9.33	7.94	0.91
4	10.94	0.66	0.22	10.20	7.94	1.06
5	11.69	0.62	0.15	10.20	8.21	1.11
6	12.09	0.52	0.17	9.99	8.40	1.12
7	15.87	1.30	0.44	20.86	8.56	2.18
8	16.79	0.62	0.16	14.77	8.30	1.28
9	16.85	0.98	0.31	19.12	8.63	1.95
10	20.98	0.72	0.51	23.25	8.92	2.45
R3 N5.55						
1	3.50	0.95	0.27	3.86	7.92	0.46
2	5.66	1.12	0.30	6.73	7.81	0.62
3	7.26	0.82	0.22	7.38	7.98	0.65
4	9.25	0.83	0.24	9.55	8.04	0.93
5	14.80	1.01	0.31	16.94	8.18	1.46
6	14.36	1.07	0.55	18.25	8.33	1.76
7	9.61	1.50	3.71	38.68	8.01	4.47
8	13.79	2.02	0.77	23.03	8.49	2.52
9	17.52	0.52	0.13	14.12	8.54	1.32
10	21.82	0.43	0.13	16.29	8.33	1.50
R3 S4.55						
1	2.45	2.61	0.80	4.51	7.88	0.81
2	7.13	1.71	0.44	10.42	7.75	0.97
3	9.56	1.36	0.39	12.60	8.20	1.28
4	12.18	1.28	0.37	15.64	8.13	1.40
5	14.94	1.43	0.44	20.42	8.27	1.46
6	16.19	0.78	0.27	16.51	8.22	1.18
7	17.46	1.11	0.51	22.16	8.41	1.81
8	25.58	0.91	0.36	28.68	8.37	1.81
9	21.68	1.16	0.39	26.94	8.42	1.81
10	24.19	1.16	0.39	26.94	8.47	1.94

0.95 msubsoil treatment

Rep 1

	SAR	Ca	Mg	Na	pH	EC
R1 S3.95						
1	7.40	0.86	0.20	7.60	8.40	0.39
2	6.73	0.66	0.16	6.08	8.10	0.33
3	7.83	0.66	0.13	6.95	8.36	0.46
4	9.08	0.64	0.11	7.82	8.26	0.46
5	10.77	0.89	0.18	11.08	8.93	0.81
6	15.61	1.17	0.40	19.55	9.08	1.98
7	19.93	1.34	0.44	26.51	9.08	2.28
8	22.28	0.56	0.16	18.90	8.81	1.63
9	20.63	0.64	0.15	18.25	8.85	1.46
10	21.85	0.69	0.19	20.42	9.07	1.63
R1 N3 .95						
1	5.32	0.83	0.22	5.42	8.55	0.37
2	6.85	0.81	0.22	6.95	8.39	0.46
3	7.77	0.88	0.26	8.25	8.88	0.67
4	8.59	0.98	0.27	9.55	8.60	0.81
5	10.17	1.40	0.36	13.47	9.13	1.15
6	11.98	1.75	0.58	18.25	9.02	1.66
7	13.09	1.83	0.51	19.99	9.27	1.79
8	14.58	1.23	0.35	18.25	9.18	1.63
9	17.08	1.01	0.28	19.34	8.89	1.66
10	20.54	0.79	0.27	21.08	8.88	1.71
R1 N4.95						
1	6.22	1.11	0.30	7.38	8.37	0.49
2	5.80	0.92	0.26	6.29	8.22	0.49
3	7.94	1.01	0.25	8.90	8.19	0.66
4	8.83	1.07	0.27	10.20	8.14	0.80
5	12.53	1.30	0.35	16.07	8.43	1.28
6	12.64	1.11	0.30	14.99	8.52	1.23
7	13.85	1.34	0.36	18.03	8.81	1.56
8	15.11	1.09	0.31	17.81	8.63	1.56
9	16.86	0.99	0.25	18.68	8.83	1.49
10	16.76	1.27	0.31	21.07	8.87	1.65
R1 S2.95						
1	3.78	0.98	0.26	4.21	8.12	0.39
2	4.30	0.88	0.27	4.60	8.42	0.38
3	6.06	1.23	0.26	7.38	8.10	0.49
4	8.43	0.63	0.14	7.38	8.26	0.48
5	7.43	0.84	0.15	7.38	8.35	0.58
6	9.63	1.18	0.31	11.73	8.77	1.12
7	12.99	1.23	0.31	16.07	8.73	1.25
8	9.41	0.78	0.45	10.42	7.80	0.90
9	22.07	0.16	0.07	10.42	8.17	0.72
10	24.76	0.10	0.08	10.42	8.25	0.79

0.95 msubsoil treatment

Rep 2

	SAR	Ca	Mg	Na	pH	EC
R2 S2.95						
1	3.08	1.22	0.39	3.89	7.97	0.49
2	5.00	1.02	0.36	5.85	7.89	0.57
3	8.34	1.07	0.37	9.98	8.34	0.78
4	8.28	1.00	0.33	9.55	8.06	0.89
5	11.36	1.03	0.33	13.24	8.19	1.14
6	11.74	0.43	0.15	8.89	8.38	0.98
7	14.15	0.30	0.10	8.89	8.26	0.85
8	15.33	0.24	0.08	8.68	8.21	0.81
9	18.97	0.43	0.15	14.33	8.38	1.28
10	16.99	0.30	0.11	10.85	8.46	1.15
R2 N5 .95						
1	6.43	1.37	0.55	8.90	9.09	0.89
2	17.06	1.32	0.54	outlier	9.07	0.98
3	9.84	0.82	0.30	10.42	9.76	0.93
4	12.16	0.79	0.25	12.38	8.79	1.04
5	14.33	0.61	0.22	13.03	8.92	1.12
6	17.48	0.27	0.12	10.86	8.88	0.89
7	16.55	0.41	0.13	12.16	8.79	1.06
8	19.42	0.31	0.10	12.38	8.77	0.98
9	27.18	0.14	0.07	12.16	8.83	0.98
10	29.08	0.16	0.06	13.68	8.73	0.98
R2 N4.95						
1	7.00	1.69	0.72	10.85	9.03	1.18
2	8.51	1.69	0.66	13.03	8.92	1.34
3	11.16	1.23	0.42	14.33	8.79	1.48
4	11.37	1.14	0.36	13.90	8.60	1.51
5	15.80	0.62	0.26	14.77	8.57	1.51
6	15.32	0.68	0.28	14.98	8.62	1.56
7	18.57	0.43	0.21	14.77	8.71	1.43
8	17.83	0.35	0.10	11.94	8.71	1.04
9	24.49	0.19	0.09	12.81	8.81	1.06
10	24.12	0.17	0.07	11.72	8.93	1.01
R2 S1.95						
1	5.91	0.94	0.36	6.72	8.93	0.64
2	8.07	0.85	0.31	8.68	8.91	0.72
3	9.83	0.99	0.34	11.29	9.03	1.06
4	10.80	1.07	0.34	12.81	9.03	1.23
5	12.01	1.06	0.33	14.11	9.33	1.29
6	13.29	0.44	0.16	10.20	8.71	0.97
7	15.38	0.39	0.12	10.85	8.95	0.95
8	15.84	0.41	0.14	11.72	8.74	1.03
9	18.14	0.56	0.17	15.42	8.75	1.28
10	18.88	0.71	0.25	18.46	8.83	1.80

Rep 3

	SAR	Ca	Mg	Na	pH	EC
R3 S3 .95						
1	15.19	0.74	0.27	15.21	8.60	0.65
2	10.45	1.07	0.33	12.38	8.88	0.98
3	13.26	0.72	0.28	13.25	8.63	1.02
4	14.00	0.72	0.27	13.90	8.88	1.19
5	15.03	0.79	0.27	15.43	8.62	1.30
6	15.37	0.79	0.25	15.64	8.55	1.33
7	20.35	0.70	0.27	19.99	8.74	1.63
8	19.36	0.60	0.19	17.17	8.73	1.46
9	21.71	0.54	0.14	17.82	8.65	1.46
10	21.06	0.59	0.12	17.60	8.66	1.35
R3 N1.95						
1	14.97	0.90	0.35	16.73	8.81	0.81
2	13.10	1.75	0.79	20.86	9.04	1.79
3	12.79	1.47	0.67	18.69	9.05	1.71
4	13.79	0.95	0.34	15.64	8.66	1.30
5	16.51	0.85	0.32	17.82	8.66	1.63
6	16.18	1.72	0.79	25.64	8.91	2.16
7	18.86	0.96	0.37	21.73	8.92	1.87
8	21.07	1.22	0.42	26.95	7.98	2.28
9	19.02	1.82	0.67	29.99	8.76	2.76
10	20.88	1.12	0.34	25.21	8.61	2.19
R3 S5.95						
1	7.66	2.51	0.99	14.33	9.07	1.51
2	8.83	2.19	0.78	15.20	7.82	1.63
3	13.64	2.06	0.74	22.81	8.81	1.84
4	13.89	1.71	0.60	21.07	9.26	2.11
5	19.84	0.85	0.28	21.07	8.82	1.46
6	15.61	1.17	0.40	19.55	9.08	1.98
7	19.93	1.34	0.44	26.51	9.08	2.28
8	22.28	0.56	0.16	18.90	8.81	1.63
9	20.63	0.64	0.15	18.25	8.85	1.46
10	21.85	0.69	0.19	20.42	9.07	1.63
R3 N2.95						
1	9.04	1.32	0.50	12.16	8.11	1.01
2	8.49	1.25	0.52	11.29	8.15	1.06
3	10.39	1.09	0.38	12.59	8.17	1.26
4	14.05	1.28	0.41	18.24	8.33	1.85
5	15.81	1.13	0.37	19.33	8.21	1.93
6	14.43	3.74	1.10	31.72	8.49	3.32
7	14.98	1.67	0.66	22.81	8.37	2.50
8	18.63	0.70	0.24	18.03	8.50	1.76
9	17.57	0.63	0.21	16.07	8.85	1.51
10	19.88	0.42	0.11	14.33	8.42	1.34

Table C-4. Exchangeable cations in topsoil
units = cmol (+) kg-1 soil

	0.55 m subsoil treatment					**0.95 m subsoil treatment**				
	Core	**Ca**	**Mg**	**K**	**Na**	Core	**Ca**	**Mg**	**K**	**Na**
	R1 S2 .55	25.58	4.57	0.48	0.15	R1 S3 .95	23.09	4.05	0.85	0.08
Rep 1	R1 S1 .55	26.21	5.71	0.83	0.08	R1 N3 .95	24.96	4.57	1.35	0.07
	R1 N4 .55	26.84	5.71	1.18	0.09	R1 N4 .95	23.71	4.98	1.29	0.07
	R1 N2 .55	19.33	4.56	0.63	0.11	R1 S2 .95	33.08	6.44	1.5	0.22
	R2 N3 .55	26.21	4.17	0.41	0.14	R2 N5 .95	32.89	4.97	0.91	0.1
Rep 2	R2 N4.55	31.39	4.28	1.18	0.11	R2 N4 .95	31.83	4.46	0.43	0.11
	R2 S5 .55	33.08	5.81	2.84	0.20	R2 S1 .95	33.08	4.98	0.98	0.05
	R2 S2 .55	24.33	5.08	1.11	0.14	R2 S2 .95	31.83	5.19	0.54	0.27
	R3 S1.55	20.96	3.79	1.12	0.10	R3 S5 .95	25.76	4.91	1.48	0.08
Rep 3	R3 S2 .55	26.83	4.98	0.53	0.20	R3 S3.95	23.96	4.61	1.18	0.08
	R3 N3 .55	23.08	4.77	0.84	0.23	R3 N1 .95	24.96	4.36	1.41	0.07
	R3 N5.55	25.58	5.4	1.19	0.21	R3 N2 .95	27.46	4.36	0.49	0.11

APPENDIX D - ROOT MASS DATA

Table D-1 Root mass density with depth
Refer to legend p. 146.
(units = kg m-3)

0.55 m subsoil treatment

	Rep 1		
Depth	R1 N3.55	R1 N1 .5	R1 S4.55
0-10	22.5	26.5	19.0
010-23	17.6	18.2	13.4
23-30	1.1	4.9	4.4
30-50	1.0	0.5	0.4
50-70	1.0	0.2	0.2

	Rep 2		
Depth	R2 N2.55	R2 S3.55	R2 S4.55
0-10	20.4	9.4	19.2
010-23	16.8	6.4	3.8
23-30	4.6	4.4	3.8
30-50	3.5	1.5	0.8
50-70	1.0	1.6	1.3

	Rep 3		
Depth	R3 S5.55	R3 N2.55	R3 S3.55
0-10	22.6	17.4	11.2
010-23	7.9	17.4	10.4
23-30	2.2	1.1	1.7
30-50	1.8	2.2	1.3
50-70	1.5	0.9	0.2

0.95 m subsoil treatment

	Rep 1		
Depth	R1 S1.9	R1 N1.95	R1 S5 .95
0-10	23.1	22.6	11.8
010-23	6.1	12.5	13.5
23-30	6.1	0.6	1.2
30-50	1.3	0.3	0.8
50-70	0.4	0.8	0.5
70-90	0.3	0.8	0.2

	Rep 2		
Depth	R2 S5.9	R2 N2.95	R2 S3 .95
0-10	37.1	18.2	14.2
010-23	19.8	16.9	7.5
23-30	5.0	1.6	4.5
30-50	0.8	1.1	1.0
50-70	0.5	0.4	0.2
70-90	1.1	0.6	0.3

	Rep 3		
Depth	R3 N3.9	R3 N4.95	R3 S2.95
0-10	43.6	12.3	16.9
010-23	35.3	2.3	15.7
23-30	7.6	1.5	2.0
30-50	3.7	1.2	0.5
50-70	2.7	1.1	1.0
70-90	1.0	0.3	1.0

Table D-2 Total profile root mass

Total core root weight (Kg m-2)
Each rep value was determined from 3 core samples

0.55 m subsoil treatment

rep 1	5.0	5.5	4.1
rep 2	5.5	2.7	3.1
rep 3	4.2	4.8	2.9

0.95 m subsoil treatment

rep 1	4.0	4.3	2.6
rep 2	7.2	4.6	3.0
rep 3	10.9	2.2	4.4

APPENDIX E - SOIL CAPABILITY RATING SYSTEM CALCULATIONS

Table E-1 Agricultural Rating System: Determination of values
Refer to legend p.146.

Texture moisture availability (subclass M)

clay loam and silty clay (both) = 20 point deduction at - 260 P-PE and 10 pnt deduction for -180 P - PE. Every 8 unit inc in P-PE there is 1 point deduction 12.5 point deduction

Subsoil Structure and consistence (subclass D)

Consistence and structure subsoil modifier, table outlining the deductions for both treatments
Taken from site descriptions found in Appendix A
Weighted calculation =SUM of [cm of horizon x deductions / 80 cm subsoil layer (20-100 cm

		Consistence	**Structure**	**deduction**	weighted
0.55 m treatment					
rep 1	20-32 cm	sl. Hard	SAB and granular	**0**	
	32-62	sl.hard to hard	SAB / (prismatic 32-5	**10**	3.75
	70+	ext hard	massive	**50**	18.75
				Total	**22.50**
rep 2	18-40	sl. Hard	gran/amor	**0**	
	40-70	hard	SAB/prismatic (40-55)	**10**	3.75
	70+	ext. hard	massive	**50**	18.75
				Total	**22.50**
rep 3.	21-38	sl .hard to hard	SAB/gran	**10**	2.13
	38-76	sl hard	SAB	**10**	4.75
	76+	V. hard	amorphous	**40**	12.00
				Total	**18.88**
0.95 m treatment					
rep 1	19-35	slightly hard	gran/SAB	**0**	
	35-76	v. hard	SAB	**30**	15.38
	76-96	hard	massive	**30**	7.50
	96+	ext. hard	massive	**50**	2.50
				Total	**25.38**
rep 2	20-40	sl.hard to hard	SAB	**10**	2.50
	40-72	hard to v. hard	SAB	**20**	8.00
	72-92	v. hard	SAB	**30**	7.50
	92-107	v.hard to ext. hard	massive	**45**	4.50
				Total	**22.50**
rep 3	19-38	hard	SAB	**10**	2.38
	38-42	V.hard	amorph	**40**	2.00
	42-70	hard to v.hard	granular	**20**	7.00
	70-104	v.hard	massive	**40**	15.00
				Total	**26.38**

Deductions not stated but I implied

**very hard and amorphous = 40 point deduction
** hard and massive = 30 point deduction (average of hard = 10 and massive = 50)
**hard to v. hard and SAB = 20 pnt dedcution

Total Poinst deducted for Subsoil Consistence and Structure subclass

0.55 mTreatment Average	**0.95 mTreatment Average**
21.29	**24.75**

Determination of chemical properties used in agricultural rating system
(Subclasses V, N, and Y)

SURFACE 0-20 cm **SUBSURFACE** 20-60 or 100 cm

Note: pH value = weighted average to 60 cm depth in subsoil, EC and SAR to 100 cm

	SURFACE 0-20 cm			SUBSURFACE 20-60 or 100 cm		
	pH	**EC**	**SAR**	**pH**	**EC**	**SAR**
0.55 m subsoil treatment						
rep 1	7.52	0.42	0.50	8.72	0.73	17.29
	7.57	0.28	0.26	8.33	1.90	10.40
	7.57	0.42	0.22	8.67	1.36	11.98
	7.44	0.33	0.47	8.52	0.74	15.76
	7.52	**0.37**	**0.36**	**8.56**	**1.18**	**13.86**
rep 2	6.95	0.31	0.42	9.01	1.15	8.44
	7.67	0.48	0.35	8.92	0.91	10.06
	8.20	0.50	0.32	8.78	0.68	10.04
	8.09	0.43	0.30	8.47	0.91	12.65
	7.73	**0.43**	**0.35**	**8.79**	**0.91**	**10.30**
rep 3	7.19	0.40	0.21	9.04	0.92	5.77
	7.32	0.36	0.38	8.68	0.95	7.77
	7.91	0.54	0.36	8.47	1.03	8.93
	7.24	0.38	0.24	8.75	1.07	8.75
	7.42	**0.42**	**0.30**	**8.73**	**0.99**	**7.81**
0.95 m subsoil treatment						
rep 1	7.29	0.71	0.23	8.91	0.39	1.88
	7.23	0.31	0.14	8.89	0.54	2.83
	7.13	0.33	0.14	9.13	0.49	2.05
	8.04	0.41	0.27	8.84	0.50	5.50
	7.42	**0.44**	**0.19**	**8.94**	**0.48**	**3.06**
rep 2	7.25	0.59	0.18	9.07	0.74	2.28
	7.70	0.45	0.24	8.69	0.68	1.65
	7.74	0.38	0.23	8.46	0.59	2.31
	7.19	0.31	0.26	8.89	0.46	2.40
	7.47	**0.43**	**0.23**	**8.78**	**0.62**	**2.16**
rep 3	7.27	0.36	0.17	9.01	0.73	5.70
	7.19	0.45	0.22	8.85	0.61	3.97
	8.37	0.44	0.21	8.92	1.06	7.75
	7.17	0.37	0.35	8.92	0.57	4.02
	7.50	**0.40**	**0.24**	**8.92**	**0.74**	**5.36**

Table E-2. Reclamation Rating System: Determination of values

Moisture Availabilty Calculation (Subclass M)

0.55 m treatment	length c	soil text.	mm/cm av. H20
0-17	17	clay loam	1.7
17-50	33	silty clay	2.25
50-67	17	silty clay	2.25
67-100	33	sandy cla	1.5
0.95 m treatment			
0-15	15	clay loam	1.7
15-50	35	silty clay	2.25
50-96	46	silty clay	2.25
96-100	4	sandy cla	1.5

No deductions for either treatment.

AWHC in 0.55 m
197.06 mm

AWHC in 0.95 m
211.65 mm

Subsoil Structure (Subclass D)

		Consistence	**Structure**	weighted deduction	**upper** to 50 cm	**lower** subsoil
0.55 m treatment						
rep 1	20-32 c	sl. Hard	SAB and granular	**0**	0.00	
	32-70	sl.hard to hard	SAB / (prismatic 32-55	**10**	6.00	4.00
	70+	ext hard	massive	**70**		42.00
				Total	**6.00**	**46.00**
rep 2	18-40	sl. Hard	gran/amor	**0**		
	40-70	hard coarse	SAB/prismatic (40-55)	**20**	6.25	8.00
	70+	ext. hard	massive	**70**		42.00
				Total	**6.25**	**50.00**
rep 3.	21-38	sl .hard to hard	SAB/gran	**10**	5.86	
	38-76	sl hard	SAB /ang-blky	**10**	4.14	5.20
	76+	V. hard	amorphous	**50**		24.00
				Total	**10.00**	**29.20**
0.95 m treatment						
rep 1	19-35	slightly hard	gran/SAB	**0**		
	35-76	v. hard	SAB	**30**	14.52	15.60
	76-96	hard	massive	**50**		20.00
	96+	ext. hard	massive	**70**		5.60
				Total	**14.52**	**41.20**
rep 2	20-40	sl.hard to hard	SAB	**10**	6.67	
	40-72	hard to v. hard	SAB	**30**	10.00	13.20
	72-92	v. hard	SAB	**30**		12.00
	92-107	v.hard to ext. hard	massive	**70**		11.20
				Total	**16.67**	**36.40**
rep 3	19-38	hard	SAB	**10**	6.13	
	38-42	V.hard	amorph	**50**	6.45	
	42-70	hard to v.hard	granular	**50**	12.90	20.00
	70-104	v.hard	massive	**50**		30.00
				Total	**25.48**	**50.00**

Total Poinst deducted for Subsoil Consistence and Structure subclass

0.55 m treatment upper SS	**7.42**	**0.95 m treatment upper SS**	**18.89**
0.55 m lower subsoil	**41.73**	**0.95 m lower subsoil**	**42.53**

Determination of chemical values in upper and lower subsoil 50-100 cm.

0.55 m treatment

upper subsoil	(below TS -50 cm)			**lower subsoil**	(50 -100 cm)		
	pH	**EC**	**SAR**		**pH**	**EC**	**SAR**
rep 1	8.80	0.54	2.01	rep 1	8.63	0.83	26.14
	8.15	0.51	2.29		8.55	2.70	14.97
	8.64	0.45	2.15		9.07	1.90	17.86
	8.59	0.51	1.55		8.60	0.87	24.25
ave →	**8.55**	**0.51**	**2.00**		**8.71**	**1.57**	**20.81**
rep 2	9.02	0.43	1.11	rep 2	9.02	1.57	12.78
	8.92	0.53	1.35		8.93	1.15	15.30
	8.66	0.39	1.86		8.72	0.84	14.45
	8.62	0.36	1.57		8.56	1.24	19.09
	8.81	**0.43**	**1.47**		**8.81**	**1.20**	**15.40**
rep 3	9.10	0.38	0.63	rep 3	8.94	1.25	8.93
	8.69	0.35	0.94		8.48	1.31	11.84
	8.55	0.38	0.86		8.19	1.43	13.95
	8.81	0.73	1.06		8.34	1.28	13.39
	8.79	**0.46**	**0.87**		**8.49**	**1.32**	**12.03**

0.95 m treatment

	pH	**EC**	**SAR**		**pH**	**EC**	**SAR**
rep 1	8.96	0.38	0.46	rep 1	8.69	0.38	2.73
	8.83	0.36	0.43		8.89	0.65	4.25
	9.11	0.40	0.31		8.91	0.53	3.09
	8.73	0.33	0.45		8.52	0.62	8.57
	8.91	**0.37**	**0.41**		**8.75**	**0.54**	**4.66**
rep 2	9.00	0.53	0.34	rep 2	9.10	0.87	3.45
	8.68	0.61	0.37		8.99	0.71	2.43
	8.32	0.45	0.41		8.89	0.69	3.45
	8.96	0.36	0.40		8.54	0.53	3.59
	8.74	**0.49**	**0.38**		**8.88**	**0.70**	**3.23**
rep 3	9.01	0.51	0.36	rep 3	8.87	0.85	8.92
	8.84	0.38	0.38		8.97	0.76	6.05
	8.92	0.45	0.47		8.89	1.44	12.30
	8.95	0.37	0.38		8.54	0.70	6.22
	8.93	**0.43**	**0.40**		**8.82**	**0.94**	**8.37**

upper subsoil treatment mean				**lower subsoil** treatment mean			
	pH	**EC**	**SAR**		**pH**	**EC**	**SAR**
0.55	8.71	0.46	1.45	**0.55**	8.67	1.36	16.08
0.95	8.86	0.43	0.40	**0.95**	8.82	0.73	5.42