UNIVERSITY OF CALGARY

Developmental Changes in Chemical and Physical Properties of Coal Valley Minesoils in the Central Alberta Foothills

by

Hollis Joyce McGrath

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

CALGARY, ALBERTA

FEBRUARY, 2001

0-612-64970-9

ABSTRACT

An analysis of the chemical and physical changes in minesoils within a 20 year period of soil development was conducted on the Coal Valley Mine in the central Alberta foothills. The analysis was based on comparisons between three age classes (5-8, 12-14, and 17-20 years), and undisturbed soils from the surrounding area for a total of 32 profiles. The dominant processes for early soil development within the minesoils were weathering, leaching, and organic matter accumulation. Sodium and magnesium concentrations, sodium adsorption ratios, electrical conductivity, bulk density, pH, and sand content decreased significantly with site age. Aluminum and ammonium concentrations; and organic matter, silt, and clay content increased significantly with site age. Little differentiation occurred within the 40 cm sampling depth for all age classes. The data suggests a relatively rapid return (≤ 50 years) of tested soil properties in a minesoil to approximate profile averages in an undisturbed soil.

ACKNOWLEDGMENTS

I would like to thank my supervisor Art Limbird for his guidance and support throughout my thesis. The advice, assistance, and comments of Wayne Strong were also invaluable. I would like to thank Dane McCoy and Rick Ferster of Luscar Ltd. for access to the Coal Valley Mine. I couldn't have done it without the field assistance and support of Greg Seale. Many thanks also to Brenda Mottle and Richard Rogalski for their help with my lab analysis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF PLATES

1.0 INTRODUCTION

The government requires the development and implementation of a reclamation plan for large land disturbances such as a coal mine. Reclamation can be defined as "the construction of topographic, soil, and plant conditions after disturbance, which may not be identical to the predisturbance site, but which permits the degraded land mass to function adequately in the ecosystem of which it was and is a part" (Munshower, 1994). This definition is reflected in the guiding principles of Alberta Environmental Protection (1997), which promote the return of a disturbed site to a land capability equivalent to the pre-disturbance land capability. This capability must be sustainable under normal land management.

The short-term goal of reclamation is to stabilize the new landscape and prevent erosion. The long-term goal of reclamation is to establish the approved end land use. Reclamation can be used to accelerate the accomplishment of this goal. The end land use can vary from agricultural, forage, or commercial timber production, to recreation or the creation of wildlife habitat. However, pre-development soil, landscape, and vegetation conditions are accepted as the usual target for the post-development environment (Alberta Environmental Protection, 1997).

Coal mine reclamation follows a series of steps, to produce a landscape that will meet the long-term reclamation goal over time. The process of reclamation generally involves construction of the landscape, implementation of drainage patterns, minesoil construction and placement, site preparation, revegetation, erosion control, and the addition of soil amendments. The first step in landscape construction is to refill the mining pits to the upper limit of the highwall, after which surface topography can be created (Munshower, 1994). Alternatives to refilling the mining pits can be made by the creation of a lake in the mined area as part of the reclamation plan. The constructed topography needs to provide adequate slope stability and surfaces suitable for plant growth. Recontouring, which is also part of the reclamation process should allow the disturbed site to blend into the surrounding undisturbed area. This is especially important regarding the hydrology of the site because drainage patterns of the reclaimed mine must tie into the existing natural drainage basin.

The construction of a minesoil is an important step in the process of reclamation. Minesoil is the term used to refer to a reconstructed soil on a reclaimed mine that generally consists of overburden material with an overlying layer of coversoil (Lyle, 1987). Overburden is defined as the geologic material that is removed to access the coal seams. Coversoil provides the suitable medium for vegetation development and can be derived from former soil profile material along with unconsolidated "soil" material such as clay, sand, peat, or soft bedrock (Knapik and Rosentreter, 1999). After minesoil construction, surface crusts and weeds must be eliminated before seeding. This is accomplished using methods such as plowing, chiselling, disking, or harrowing (Munshower, 1994). Revegetation then can proceed by the application of a chosen reclamation seed mixture using either broadcast or direct seeding. Erosion control measures such as mulches may then be used to protect these seeds and aid their establishment. The vegetation and minesoils benefit from additions of organic amendments or fertilizer to stimulate plant growth and soil nutrient cycles (Munshower, 1994). Once these initial steps are performed reclamation proceeds by mainly natural processes such as vegetation development and pedogenesis.

1.1 Research Rationale and Objectives

The reclaimed areas on the Coal Valley Mine provided an excellent opportunity to study the physical and chemical changes occurring in a minesoil over a 20 year time period. The mine contains a continuum of ages with respect to reclaimed sites that allows comparisons between minesoils of different ages. The validity of the comparison is further enhanced by the use of similar construction practices and seed mixtures on these sites over the studied time period. Multiple reclaimed sites of different ages and undisturbed sites could be located within a relatively small area, serving to minimize differences in climate and site characteristics such as elevation.

To analyze the temporal changes occurring in the minesoils on the Coal Valley Mine, four specific objectives were identified:

1) Quantify the changes in chemical and physical properties in the minesoils over a 20 year time period.
2) Compare these properties to undisturbed soils to determine changes due to minesoil construction.

3) Relate chemical and physical properties of the minesoils to vegetation development.
4) Determine the dominant pedogenic processes and their contribution to minesoil development trends within the depth of a profile and over the 20 year time period.

The investigation of these research objectives provided the opportunity to interpret reclamation success and the direction of soil development.

2.0 LITERATURE REVIEW

2.1 Soil Development

Once a minesoil is constructed it undergoes the same processes of soil development that occur in an undisturbed soil. However, differences in the physical and chemical characteristics of a soil can change the emphasis or direction of some soil processes. Soil formation can be broken down into two main processes, which are *i)* the accumulation of parent material and *ii)* horizon differentiation in the soil profile (Simonson, 1967). Horizon differentiation can be attributed to additions, removals, transfers, and transformations within the soil system. Some of the most common processes that occur to create horizons are additions of organic matter, removals of soluble salts and carbonates, transfers of humus and sesquioxides, and transformations of primary minerals into secondary minerals (Simonson, 1967). Soil classification often is based on distinguishing between different horizons present in a soil, usually by a colour or structure difference. Therefore, changes in horizon presence or order will affect what type of soil is present in a disturbed area.

Pedogenic processes such as illuviation, eluviation, and transformations can be affected in a reconstructed soil. Eluviation of soil constituents is due to three different processes (Ross, 1989). The first process is leaching, defined as the translocation of soluble salts either from the upper to the lower portion of the profile where they are precipitated, or out of the profile entirely. The second process is cheluviation, which is the translocation of organometallic complexes or chelates (Atkinson et al., 1967; Ross, 1989). The third process for translocation is lessivage, or the translocation of colloidal clay particles.

In much of the literature on soil formation the five main influential factors mentioned are climate, vegetation, parent material, relief, and time (Allen et al., 1983; Jenny, 1941; Simonson, 1967). Of these five factors, vegetation and climate are considered active factors, and parent material and relief are considered passive factors, while time is needed for any changes to occur (Howitt, 1981). Changes in emphasis of soil processes are directly dependent on hydration, oxidation, solution, leaching, precipitation, and mixing. Climate, organisms, parent material, and topography control these processes and therefore control soil formation.

2.1.1 Role of Climate

Climate is often divided into two primary factors, which are precipitation and temperature. Precipitation is especially important in soil development because water is involved in numerous reactions. Water content in the soil is necessary for rock weathering and mineral transformation, as well as plant growth (Yaalon, 1983). Water is also fundamental in the translocation and leaching of soil constituents, which control the horizons that develop in a soil. In fact, the availability of water and its location within the profile determines the rate of most soil formation processes. The solubility of minerals determines where they will accumulate within a soil profile. For example, chlorides, sulfates, and carbonates usually occur from top to bottom, respectively, in a profile due to their solubility differences (Yaalon, 1983).

Temperature affects the water content of the soil and the type of vegetation that develops in an area. Temperature also has an effect on the viscosity of the soil moisture, therefore, infiltration rates and water movement in the profile will increase with increasing temperatures (Yaalon, 1983). The rate of chemical reactions increases with increased temperature, so a higher rate of soil development occurs during warmer periods. The rate of a reaction will approximately double for each 10°C rise in temperature. Cool temperatures are a limiting factor for soil reactions and water movement, but will restrict evaporation.

2.1.2 Role of Organisms

It has been shown that the process of soil development occurs at a faster rate when biota are present (Ugolini and Edmonds, 1983). Microorganisms play an important role in the process by providing available nitrogen for plant life. Nitrogen from the atmosphere is fixed by microorganisms and changed to a form that can be absorbed by plants. The C:N ratio of a soil is an important measure of the availability of nitrogen to vegetation. When plant residue in the form of litter or amendments with a high C:N ratio is added to the soil there is microorganism competition for available nitrogen (Brady and Weil, 1999). If there is an inadequate supply of nitrogen in the organic matter, microorganisms will be forced to use nitrogen from the soil solution resulting in less for vegetation. With insufficient nitrogen to support microorganisms, the decomposition of organic matter will be much slower resulting in a reduced rate of soil development.

Factors such as aeration, moisture and temperature can also affect the rate of mineral nitrogen formation in soil and the rate of organic matter decomposition. A temperature of approximately 25°C provides an environment for optimum activity for many soil bacteria and fungi (Ugolini and Edmonds, 1983). Additionally, microorganism population size or diversity can be reduced by the construction of a minesoil with material that has been stockpiled for several years (Thurber Consultants Ltd. et al., 1990). This decrease is related to the loss of organic matter that occurs in a stockpiled soil, which is an important energy source for microorganisms. Although, microorganism populations are generally able to return to acceptable levels a few years after spreading of the stockpiled material.

In a forest ecosystem, the amount of fungal biomass is usually greater than the amount of bacterial biomass. The reason fungi tend to dominate in a forest ecosystem is because these organisms function better at an acid pH than bacteria, although both organisms achieve optimum growth near neutral pH (Ugolini and Edmonds, 1983). The reestablishment of a healthy microorganism population is an important step to aiding pedogenesis in a minesoil. Without microorganisms, a functioning nitrogen cycle is not possible.

2.1.3 Role of Vegetation

Vegetation has a strong influence on soil formation because of the changes that occur in chemical concentrations due to nutrient uptake by plants (Simonson, 1967). The location of certain chemicals in a soil profile will depend on which nutrients are preferred by plants for absorption, because these nutrients will tend to accumulate in the upper part of the profile (Crompton, 1967).

Vegetation is the source of the majority of organic matter in a developing soil. Organic matter is important because it promotes granulation and aggregate stability, increases the cation exchange capacity, and provides the majority of the pH buffering capacity in soils (Brady and Weil, 1999). Organic matter also has an important role in increasing infiltration and lowering bulk density. The presence of organic matter reduces the thermal conductivity or transmissibility, so that the water holding capacity of a soil is increased. When a soil does not have the ability to hold moisture, the moderating effects of the moisture on surface temperature fluctuations are lost (Headdon, 1980).

Organic matter additions to the surface are usually one of the first changes to a material undergoing soil formation (Simonson, 1967). At the onset of soil development, organic matter additions in the form of litter are usually greater than the rate of decay. The rate of decay and transfers of the organic matter tend to increase until they are equal to the gains from animal and plant residues. The end result is an organic matter level that changes little over time after the steady state is reached (Simonson, 1967).

Generally, in boreal forest conditions, organic matter additions to the soil are low. Added organic matter often is rapidly mineralized to small molecular weight organic acids (Howitt, 1981). However, organic matter accumulation may be aided by low temperatures, and acid rich and nutrient poor litter of coniferous needles and ericaceous shrubs causing slow decomposition (Crompton, 1967). In areas of forest vegetation, leaching is usually more intense than under grasslands. Therefore, in grassland areas the dominant soil process is usually movement of carbonates, while under forest vegetation other minerals such as iron can be mobilized (Ehrlich et al., 1967).

Factors that influence the amount of organic matter in the soil are climate, flora, fauna, and the age of the soil (Simonson, 1967). Organic matter transfers within a soil profile may be due to water percolating through the profile, or by mixing of the soil by fauna. Soil properties that aid in rapid decomposition and mineralization of organic matter are a pH that is near neutral, adequate soil moisture, sufficient aeration (≤60% pores filled with water), and temperatures between 25°C to 35°C (Brady and Weil, 1999). These conditions are also optimal for heterotrophic microorganisms, which use organic matter as an energy source.

Vegetation can influence soil formation because of its role in nitrogen and carbon fixation from the atmosphere (Cady, 1967). Bulk density and pH of the soil are also affected by vegetation and both properties can influence pedogenic factors. The texture of a soil can be changed by vegetation growth because plants may aid in the breakdown of larger particles into clay or silt sized particles (Naeth et al., 1991).

2.1.4 Role of Parent Material

The parent material in which a soil develops directly affects the rate and direction of changes (Simonson, 1967). The pH of the parent material can affect which direction chemical reactions in the soil will proceed, causing either an acceleration or deceleration of soil development. However, one of the first occurrences in soil development is the leaching of carbonates from the soil, which causes a subsequent decrease in pH (Wright et al., 1967).

The minerals that are present in a soil profile are derived mainly from the parent material, but also can be formed *in situ* by weathering, or translocated into their current position (Cady, 1967). Minerals formed *in situ* have been subjected to weathering processes such as freeze/thaw cycles, wet/dry cycles, and physical breakdown by plant roots (Crompton, 1967); or decomposition by organic acids that are produced by bacteria or fungi (Ugolini and Edmonds, 1983). The effectiveness of these weathering processes is dependent upon parent material properties such as rock porosity, texture, temperature, and acidity of the soil solution (Crompton, 1967). As part of the process of soil development, cations that are absorbed by plants from the soil solution are replaced by cations that have dissociated from clay surfaces; these then are replaced by cations provided by weathering of the parent material.

2.1.5 Role of Topography

The topography of an area affects the formation of soil due to its influence on runoff, soil erosion, water infiltration, groundwater flow (Dumanski et al., 1972), and soil temperature regimes. Relief also affects the development of soil by creating microsites of a different character within a landscape. A microsite such as a depression will tend to accumulate weathered material from higher areas, and then undergo a more rapid rate of soil development due to an enrichment of minerals and moisture (Crompton, 1967). These same processes tend to occur in a lower slope position, in contrast to an upper slope location where soil may be quite thin and develop slowly.

2.1.6 Role of Time

The soil system is generally in a state of dynamic equilibrium where input equals output (Yaalon, 1983). When change occurs within a soil system, a new equilibrium will become established while allowing for a lag in adjustment. Most soil properties can be divided into those that achieve a steady state fairly quickly (i.e. <1000 years), and those that reach the steady state slowly (i.e. >1000 years) (Yaalon, 1983). The soil properties that are considered to approach a steady state fairly rapidly are usually associated with biotic factors, such as organic matter, nitrogen, pH, and structure (Crocker, 1967; Ugolini and Edmonds, 1983). The development of a Bt horizon, which is the diagnostic horizon for a Luvisolic soil and a common soil type in the study area, is an example of the latter group (Agriculture Canada Expert Committee on Soil Survey, 1987). Soil development may undergo some rapid initial changes, but these changes are short-lived, because the rate of change decreases with time (Yaalon, 1983).

2.2 Physical Problems Associated with Reconstructed Minesoils

Soil physical properties often present the main limitations to the reclamation of disturbed lands (Albrecht and Thompson, 1982; King and Evans, 1989; McSweeney and Jansen, 1984). Physical properties such as texture, bulk density, porosity, water holding capacity, and structure can influence the establishment of vegetation, which is necessary for proper reclamation of a site. Texture, porosity, water holding capacity, infiltration, and hydraulic conductivity are also important for the hydrologic characteristics of a reclaimed site. Establishment and maintenance of microbial activities on a reclaimed site can be dependent on texture, porosity, water holding capacity, and structure. These physical soil properties must each be within an acceptable range for the creation of a self-sustaining ecosystem.

2.2.1 Texture

Surface mining results in changes to the texture of a soil because of the mixing of horizons during soil salvage operations and reconstruction. The texture of a soil is important because it affects the soil water and nutrient content, water and nutrient availability, soil aeration, and plant root systems (Naeth et al., 1991). When horizons are mixed to form a minesoil, one should ensure that fine-textured impermeable materials are not placed below coarser textured materials or a perched water table may result. A perched water table can cause waterlogging of the upper profile and the activation of anaerobic soil microorganisms (Omodt et al., 1975). However, a perched water table may be desirable in some coarse textured soils to improve water retention.

The mixing of soil horizons in a reconstructed minesoil tends to bring coarse particles to the surface, which were formerly at depth, causing an increase in coarse particle content. If a two-lift procedure is used in reclamation, topsoil and subsoil of a minesoil may have originated in two different locations. This may result in an abrupt textural difference between the coversoil and subsoil (Keck et al., 1993). Such textural differences could be due to variations in parent material or dominant processes that were active in the site where the soil was originally formed.

2.2.2 Weathering

A minesoil represents a type of parent material that contains weatherable minerals throughout the soil column. Due to the loose structure of the overburden, many weatherable facies are exposed. This characteristic allows many distinct reactions to occur at different depths in a profile. Reactions such as weathering, secondary mineral formation, and movement or removal of soil constituents can occur throughout the soil and subsoil (Cady, 1967). In an undisturbed soil, the majority of reactions occur in only the top A and B horizons, therefore soil development proceeds at a more rapid rate in a reconstructed soil.

2.2.3 Variability

According to Macyk (1986) the main influence on reconstructed soil properties is parent material characteristics, but materials handling procedures also influence the soil properties. A stockpiled soil will have more mixing of the horizons than a directly placed soil because of the increase in handling and movement of the soil. Minesoils are generally quite homogeneous, with less variability than undisturbed soils on a landscape scale. However, more variability is present on a local scale (Schafer, 1979). The increased local variability of a minesoil occurs because of the mixing of a number of soil series or associations to create the new soil (Macyk, 1986). This local variability when combined with the increased coarse fragment content can result in a minesoil profile having large stones beside masses of clay. These extremes within a small area can cause problems with root development and hydraulic conductivity.

2.2.4 Bulk Density

When a soil is reconstructed after surface mining, the bulk density is often much higher than the original soil material (Bussler et al., 1984; Davies et al., 1992; Naeth et al., 1991; Potter et al., 1988). The change in texture of the soil is one of the causes of the increase in bulk density (Manrique and Jones, 1991). A reconstructed soil often has low levels of organic matter, which contributes to an increase in soil bulk density (Davies et al., 1992). Other characteristics that influence bulk density are soil shrinking and swelling, water content, structure, and mineralogy (Naeth et al., 1991). Plant growth, water infiltration, and the amount of traffic on a soil can also affect its bulk density.

Bulk density has a tendency in a natural soil to increase with depth due to decreases in porosity and structure changes (Manrique and Jones, 1991; Naeth et al., 1991). The bulk density of a soil can be lowered by natural processes such as freeze-thaw cycles, wet-dry cycles, earthworms, other burrowing animals, and plant roots; however, these processes work very slowly (Naeth et al., 1991).

When a soil is severely compacted it can affect the growth of vegetation. Bulk density limitations for root growth change with the texture of a soil. Bulk density that results in zero root growth varies from 1.85 g/cm^3 to 1.80 g/cm^3 for the textural classes of sand to sandy clay loam, respectively (Bussler et al., 1984; Vepraskas, 1988). The recommended bulk density limits are 1.60 g/cm^3 within 50 cm of the surface and 1.80 g/cm^3 within 100 cm of the surface to allow successful reclamation (Haigh, 1995).

2.2.5 Porosity

The porosity of a soil is dependent on texture and structure, which often are changed or destroyed by salvage and reconstruction procedures (Bussler et al., 1984; Davies et al., 1992). Porosity is important to soil development because microorganisms and soil animals need pores in which to live and move. Changes in pore size distribution often create problems for soil reactions and vegetation growth. A reconstructed soil experiences an increase in micropore and mesopore space, and a significant decrease in macropore space as a percentage of the total pore space in the soil. For example, macropores may not be present in a one or two year old minesoil, while micropores make up 80% of the total porosity (Varela et al., 1993). Soils with a macropore volume less than 0.10 m^3/m^3 tend to have aeration problems (Vomocil and Flocker, 1961). The optimal porosity for plant growth is 50% (Glinski and Lipiec, 1990), but roots generally only propagate freely in continuous pores of greater than 60 μm in diameter. The proportion of pores between 0.2 μm and 60 μm is also important because these pores hold water against gravity that is also available to plants (Naeth et al., 1991). Improvements in porosity to undisturbed levels may take decades. One study found that the macropore volume on a reclaimed site was significantly less than that of an undisturbed site and was still at a level considered to be limiting to soil processes and plant growth after 11 years of development (Potter et al., 1988).

2.2.6 Water Holding Capacity, Infiltration, and Hydraulic Conductivity

A reconstructed soil generally has a lower water holding capacity than an undisturbed soil, which can be attributed to decreases in porosity and hydraulic conductivity (Bussler et al., 1984; Potter et al., 1988). Other soil properties that affect the water holding capacity of a soil are particle size distribution, bulk density, and organic matter content (Davies et al., 1992). With an increase in bulk density and decreased organic matter content, infiltration into the soil can be inhibited to the degree that winter precipitation cannot recharge subsoil water reserves. The inability to recharge subsoil water reserves can cause a reconstructed soil to reach the permanent wilting point earlier in the growing season than an undisturbed site. Although an undisturbed site may have more productive vegetation, and therefore, experience a greater degree of evapotranspiration, it still contains more available water than a reclaimed site (Davies et al., 1992). Reclaimed mine sites have a tendency to form surface crusts (Macyk and Steward, 1977), which can create an impermeable layer that may prevent seedling emergence and water infiltration. Hydraulic conductivity is adversely affected in a reconstructed minesoil (Varela et al., 1993), due to decreases in porosity, increases in bulk density, and texture changes.

2.2.7 Structure

Soil reclamation techniques can result in the loss of favorable soil structure. Movement of the soil and stockpiling causes soil aggregates to break down. When soil is reconstructed, scrapers generally are used to position and level the soil resulting in compaction and massive structure. Some methods of soil movement can result in the formation of a new structure type referred to as fritted (McSweeny and Jansen, 1984). Fritted structure consists of rounded aggregates loosely compressed together within the size classes for block-like and polyhedral aggregates. This type of structure is much more favorable to plant rooting than a massive structure. Profiles with fritted structure do not have problems associated with lateral growth of roots at the base of the topsoil, or vertical and flattened root growth in desiccation cracks associated with soils with a massive structure (McSweeny and Jansen, 1984).

2.2.8 Erosion

Erosion can be a problem after reclamation and prevent the formation of a self-sustaining landscape (Nicolau, 1996). When a post-mining landscape is created, the slopes may be greater than those originally present on the site. The increased slopes combined with a new landscape that does not contain dense vegetation to provide cover and stabilization of the ground surface can result in increased erosion. Immediate seeding of a reclaimed site with fast growing species that will provide good ground cover can mitigate erosion rates because of the associated increase in infiltration. A site with 100% plant coverage experiences one-third the runoff of a site with 50% coverage (Nicolau, 1996).

Erosion does not always increase with reclamation, in some reconstructed minesoils the erosion rates may be comparable to those of an undisturbed site. This accomplishment is dependent upon adequate topsoil to protect subsoil, which can experience erosion rates greater than that of unreclaimed mine spoil (McIntosh and Barnhisel, 1993). The high rate of erosion on subsoil compared to mine spoil can be attributed to the larger particle size in mine spoil. However, over time, weathering would produce abundant erodible particles that would increase erosion rates on mine spoil.

It has been suggested that topsoil should be spread differently depending on the landscape. The sides and bottoms of slopes should receive a thinner layer of topsoil, and the upper and summit parts of the slopes should receive a thicker layer (Merrill et al., 1998). This procedure would serve as a preventative action for long-term slope denudation from erosion. Erosion that does occur would then transfer excess soil from top slopes to bottom slopes.

2.3 Chemical Problems Associated with Reconstructed Minesoils

Generally, a newly constructed minesoil is deficient in nitrogen (Fedkenheuer et al., 1987; Li and Daniels, 1994; Mays and Bengtson, 1978), and phosphorus (Chen et al., 1998; Fedkenheuer et al., 1987; Kost et al., 1998). Nitrogen and phosphorus are also deficient in coal spoil heaps (Headdon, 1980), which can be part of the parent material of a minesoil. A minesoil also can tend to experience low levels of potassium, decreases in pH and organic matter, and increases in electrical conductivity and metal concentrations.

2.3.1 Nitrogen

The input of nitrogen to a newly constructed soil usually is accomplished by the seeding of nitrogen-fixing legumes and grass species, as well as fertilization. The nitrogen-fixing legumes release nitrogen directly into the soil system with the help of microorganisms. Grasses and other plants contribute organic matter to the soil, which then will encourage a healthy microorganism population to supply nitrogen to the soil system. The development of an available organic nitrogen pool can occur in five to nine years on a reclaimed soil (Fyles, 1984), or show no signs of development after seven years (Takyi and Islam, 1985). Nitrogen fertilizers may be needed to initiate the establishment of the nitrogen cycle.

2.3.2 Phosphorus

Phosphorus may often be fixed into an unavailable form in a minesoil and therefore, be deficient (Monterroso Martinez et al., 1996). Many soil properties influence the adsorption or desorption of phosphorus such as clay, organic matter, iron, aluminum, manganese, calcium, and pH. Clay and organic matter affect phosphorus levels by the exchange sites they contain to which phosphorus may adsorb. At low pH, metals are at a higher concentration due to their increased solubility. Therefore, phosphorus can be complexed easily with metals when they are in an available form. A low pH can be caused by sulfur content, which is a common contaminant in mine spoils (Monterroso Martinez et al., 1996). Calcium would affect phosphorus availability at a high pH where it can bond with phosphorus to form calcium phosphate precipitate.

Phosphorus deficiency on minesoils must often be mitigated by the addition of phosphorus fertilizers or organic amendments (Monterroso Martinez et al., 1996). Phosphorus availability to plants can be increased by the presence of mycorrhizal fungi. The fungi function as a filamentous extension to plant roots aiding nutrient uptake, especially phosphorus (Osborne, 1996). A minesoil affected by severe acidity may benefit from liming to increase the availability of phosphorus (Monterroso Martinez et al., 1996).

2.3.3 Organic Matter

Reconstructed minesoils may experience a decrease in organic matter content when compared to undisturbed soils (Bussler et al., 1984). Decreased organic matter levels have wide ranging effects on many other soil properties. Properties such as aggregate stability, infiltration, water holding capacity, porosity, cation exchange capacity, nitrogen cycling, and vegetation growth will all be adversely affected by low organic matter levels. However, organic matter accumulation can occur fairly quickly within the surface layers of a disturbed soil (Varela et al., 1993).

2.3.4 Potassium

Potassium levels also can be deficient in a minesoil (Bussler et al., 1984), since their monovalent nature results in a high leaching tendency (Headdon, 1980). The increase in weatherable surfaces in a minesoil releases potassium into the soil solution, which is then rapidly removed by dissolution.

2.3.5 Electrical Conductivity

Electrical conductivity has a tendency to be higher in reconstructed soils than in undisturbed soils. Edwards and Schumacher (1989) found a correlation between reclaimed sites with poor vegetation growth and high levels of electrical conductivity, soluble boron, magnesium, sodium, and potassium. Over time electrical conductivity at the surface may decrease; causing a corresponding increase with depth due to the leaching of soluble salts (Chichester and Hauser, 1991).

2.3.6 pH

Minesoils may experience a decrease in pH due to acid leaching from material brought to the surface that was formerly at depth (Haigh, 1995). However, acid leaching is not encountered at the Coal Valley Mine because the parent material generally does not contain the metals that cause acid formation. Researchers have recommended a soil pH between 3.5 to 8.5 within 150 cm of the soil surface for successful reclamation (Haigh, 1995). However, a soil with a pH of 5.0 or less can cause phosphates to become fixed and unavailable to plants. Additionally, oxidation or fixation of nitrogen is slowed at a pH of 5.5 or less due to a lower volume of soil bacteria and actinomycetes in the soil.

2.3.7 Metals

The action of metals in a reconstructed minesoil will be dependent on the conditions at the site. If problems with acid drainage are experienced, metals may increase in concentration due to their increased solubility at a low pH. Metal concentration may also be decreased in comparison to undisturbed soils because of the soil mixing that has occurred which results in a higher salt concentration at the surface (Varela et al., 1993). Site conditions and parent material also may cause local toxic conditions in a minesoil due to high concentrations of zinc, cadmium, lead, or copper (Gentcheva-Kostadinova and Zheleva, 1994).

2.4 Vegetation Problems Associated with Reclaimed Sites

Vegetation on a reclaimed minesoil often has to survive in substandard conditions and overcome the chemical and physical soil problems that may be present. The harshest conditions are often encountered directly after reclamation. Vegetation may experience a lack of moisture, extreme temperature fluctuations, and rooting impedance (Headdon, 1980; Naeth et al., 1991). Soil nutrients also may be in short supply or certain elements may be present in high concentrations that are detrimental to plant growth (Gentcheva-Kostadinova and Zheleva, 1994).

2.4.1 Moisture Stress

Vegetation often suffers from moisture stress because spoil heaps or reconstructed soils may not hold adequate soil moisture (Headdon, 1980). The inability of the soil to hold moisture is related to the decreases in infiltration and water holding capacity. Vegetation establishment will be more successful in depressional microsites and less successful on sloping areas (Lesko et al., 1975). The success of vegetation in depressional microsites may be due to the accumulation of fine particles in these sites which increases the water holding capacity of the site, plus the depression is less exposed, and therefore less prone to evaporation of water than a flat area (Baker, 1973). Temperature can affect the water content of the soil and the vegetation present in an area. Once vegetation is established on a minesoil, it will serve to regulate the microclimate and reduce the effects of severe temperature changes.

2.4.2 Plant Establishment and Native Species Invasion

The establishment of vegetation on a minesoil is affected by soil physical properties such as bulk density. Bulk density can affect seedling emergence, total plant biomass, plant growth patterns, and plant physiologic functions (Edwards and Schumacher, 1989). The effects of bulk density on plants are often indirect due to its affect on other soil qualities such as pore space, and soil water and air movement.

Before certain volunteer species will inhabit a disturbed area, the soil must have the appropriate physical structure that will hold the necessary moisture content and temperature conditions needed for establishment. As a reclaimed site ages, an increase in both seeded cover and dry weight of species occurs. Over time, a site also will experience an increase in the cover and number of volunteer species (Edwards and Schumacher, 1989). The density of volunteer species is also somewhat dependent on the distance from a seed source (Kost et al., 1998) or the quantity of viable plant propagules in the coversoil. Improvements in vegetation growth and native species establishment can be attributed partially to improved soil properties that occur in a reconstructed soil over time.

An increase in the bulk density of a minesoil, can affect the length, spatial arrangement, and total biomass of plant roots (Naeth et al., 1991). Root growth may tend to follow wet/dry cracks or other paths of least resistance when growing in a compacted soil. Root growth may also progress downwards until it reaches a layer of compaction, where it will then proceed to grow laterally. The maximum bulk density that a root can penetrate is dependent on soil texture and water content (Jones, 1983). An optimal bulk density range for plant growth is usually less than 1.3 g/cm^3 (Haigh, 1995).

3.0 STUDY AREA

The Coal Valley Mine is located approximately 80 km southwest of Edson, Alberta in Townships 47 and 48, Ranges 19 and 20, west of the 5th meridian (Figure 3.1). The Coal Valley Mine is located in a region of Alberta referred to as the Coal Branch, which was originally developed to supply coal for the railroad. The operation of the Coal Valley Mine began in 1978 by Luscar Sterco (1977) Ltd. and covers an area approximately 19 km long and up to 2.5 km wide (Strong, 2000).

3.1 Geology and Geomorphology

The study site is located in the physiographic region of the Rocky Mountain Foothills. The foothills are described as northwest-southeast trending ridges located between the Rocky Mountains and the Interior Plains (Dumanski et al., 1972). The local relief is generally less than 33 m, but can reach over 100 m. The elevation range of the foothills is from approximately 1267 m to 1833 m above sea level.

The bedrock in the study area generally consists of sandstones, conglomerates, siltstones, and mudstones of the Brazeau and Paskapoo formations. The source of the coal that is mined at the Coal Valley mine, are the Coalspur beds between the Brazeau and Paskapoo formations. The coal seams are interbedded with carbonaceous shale, claystone/mudstone, siltstone, and medium grained sandstone units (Fedkenheuer et al., 1987).

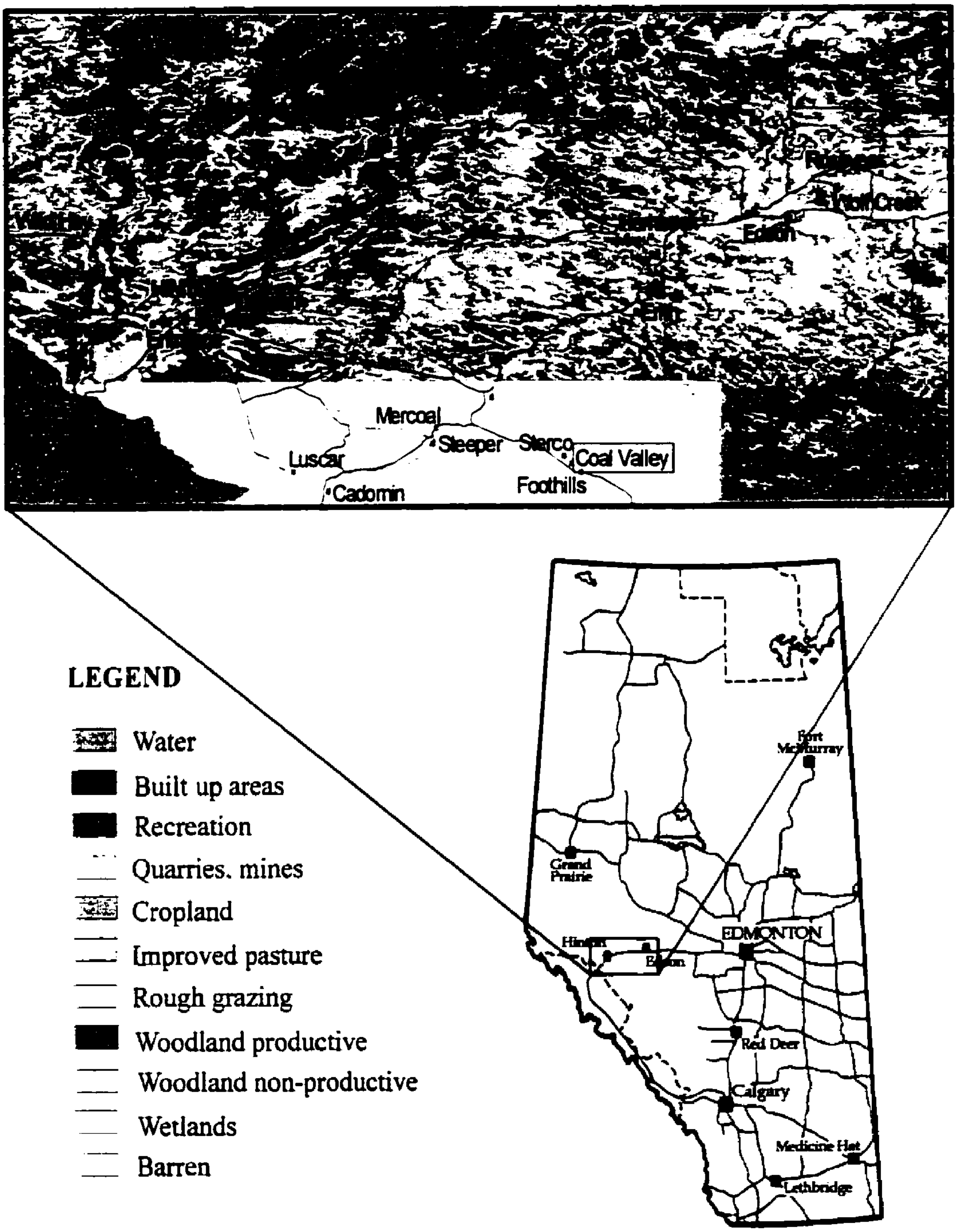

Figure 3.1. Study area location – Coal Valley Mine in the central Alberta Foothills (adapted from Government of Canada, 2000).

The surficial geology within the vicinity of the study area consists of till, glaciolacustrine, and glaciofluvial deposits. The thickness of the till overlying the bedrock is quite variable with an average depth of about 70 cm (Dumanski et al., 1972). The principal glacial till located in the study area is referred to as the Robb till. The Robb till has a medium texture, is of Cordilleran origin, and generally has a low but variable lime content. The glaciolacustrine and glaciofluvial deposits have an average depth of 3 m and are generally found in locations of lower elevation.

The landscape of the reclaimed mine was constructed to mimic naturally occurring landforms. A series of ridges were created with a northwest/southeast orientation. Equipment such as draglines, scraper, and shovel-trucks were used in the construction of the landscape from the overburden. The ridges are created with a maximum angle of 27° (60%) before topsoil is added (Knapik and Rosentreter, 1999). However, most of the reclaimed topography has slopes ranging from 5% to 30% (Strong, 2000). Additions of microtopographic features such as terraces and surface roughness further shape the ridged topography.

3.2 Climate

The study area is located in a region of subhumid continental climate (Dumanski et al., 1972) with a summer maximum of precipitation. The potential evapotranspiration in the study area is approximately equal to the expected precipitation. The nearest permanent recording station is in Robb, Alberta at an elevation of 1130 m. The mean precipitation is 109.4 mm and 38.4 mm for July and January, respectively (Environment Canada, 2000). The mean annual daily temperature is 2.2°C. The warmest month of the year is July with a mean daily temperature of 14.1°C. January is the coldest month of the year with a mean daily temperature of –10.9°C. The frost-free period in the region lasts about 72 days. The Lovett Lookout summer recording station is closer to the study site and located at an elevation of 1445 m. The mean daily temperature in July is 12.9°C and the mean precipitation for July is 119.7 mm, which results in a somewhat wetter and colder environment than that present at the Robb station (Environment Canada, 2000). The study site is within the Upper Foothills Subregion (Government of Alberta, 2000). The climate for this subregion includes a mean annual precipitation of 540 mm and a mean May to September temperature of about 10°C to 12°C.

3.3 Vegetation

Well drained soils in the study area support lodgepole pine (*Pinus contorta* Loudon) with a smaller component of aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), white spruce (*Picea glauca* (Moench) Voss), and black spruce (*Picea mariana*) (Knapik and Rosentreter, 1999). Shrub species within pine stands are typically Labrador tea (*Ledum groenlandicum* Oeder), low bush cranberry (*Viburnum edule Michx.*), Canada buffaloberry (*Shepherdia canadensis L.*), bearberry (*Arctostaphylos uva-ursi* (L.) Spreng.), and common blueberry (*Vaccinium myrtilloides* Michx.). Ground cover species often include creeping raspberry (*Rubus pedatus Sm.*), bunchberry (*Cornus *canadensis* L.), twinflower (*Linnea borealis L.*), and various feathermosses. Valleys between the ridges that are not well drained may be vegetated with birch (*Betula spp.*), willow (*Salix spp.*), sedges (*Carex spp.*), and mosses (Knapik and Rosentreter, 1999).

Most of the rooting for the majority of forest types in the area occurs in the 30 to 50 cm soil depth, with the fine roots concentrated in the upper 5 to 10 cm (Fedkenheuer et al., 1987). The top 15 to 20 cm of a soil profile is where plants germinate and most soil biological activities take place. Lodgepole pine has an average rooting depth of 36 cm with a maximum of 62 cm for trees between five and 15 years of age (Fedkenheuer. 1987).

All of the reclaimed sites on the Coal Valley Mine have been seeded with a similar mixture of grasses and forbs (Table 3.1). The mixture contains 30% legumes by weight with the remainder consisting of grass species. The seed mixture was applied at a rate of 25 to 50 kg/ha (Strong, 2000). Short-awned foxtail (*Alopecurus aequalis* Sobol.) was included in the seed mixture for four years, from 1982 to 1986. All reclaimed areas were fertilized with 16-20-0 at the time of seeding at a rate of 80 to 120 kg/ha. If problems were encountered with vegetation growth on a reclaimed site a second application of the same fertilizer, at a rate of 150 to 200 kg/ha was applied. A second fertilizer application was seldom needed and was not performed after the fifth year of growth (Strong, 2000).

The sampled reclaimed sites on the Coal Valley Mine had been planted with either lodgepole pine or white spruce seedlings a few years after initial seeding. The seedlings were container grown with a median height of approximately 22 cm (Strong, 2000). The delay after seeding allows time for organic matter to accumulate which will help ensure seedling success (Knapik and Rosentreter, 1999). A few sites also were planted with deciduous trees and shrubs from 1981 to 1996 (Strong, 2000). Species such as willow (*Salix spp.*), green alder (*Alnus crispa*), and aspen (*Populus tremuloides*) were used on a limited basis.

Table 3.1. Reclamation seed mixture composition on the Coal Valley Mine (adapted from Strong, 2000).

Species	Common Name	Percent Composition by Weight
Lolium perenne L.	Ryegrass	20
Festuca rubra L.	Red fescue	15
Trifolium repens L.	Dutch clover	15
Bromus inermis Leyss.	Smooth brome	10
Phleum pratense L.	Timothy	10
Agrostis stolonifera L.	Redtop	10
Onobrychis viciifolia Scop.	Sainfoin	10
Festuca ovina L.	Sheep fescue	5
Melilotus officinalis (L.) Lam.	Yellow sweet clover	5

3.4 Soil

The pre-development soils within the study area were mainly Luvisols and Brunisols (Dumanski et al., 1972). The Luvisols occur on moderately sloping to flat terrain, while

Brunisols tend to occur on steeply sloping and ridge crest locations. On poorly drained sites between ridges, Gleysolic or Organic soils may be present. The majority of soils in this area were formed from glacial materials (till or glaciolacustrine), and lesser amounts were formed from loess, alluvium, colluvium, or organic materials. The depth of soil development on bedrock in the foothills on crests is often only 25 to 30 cm, and increases to 30 to 70 cm to the bottom of the B or BC horizon in other areas (Knapik and Rosentreter, 1999).

The two soil associations present in the study area are the Robb and the Maskuta (Dumanski et al., 1972). The Robb till is the parent material of the Robb Association while soils within the Maskuta Association develop on weathered bedrock. The three main soil series of the Robb Association are the Mercoal, Coalspur, and Felton series. Podzolic Gray Luvisols, Orthic Gray Luvisols, and Eluviated Eutric Brunisols represent the Mercoal, Coalspur, and Felton series, respectively. The main soil series of the Maskuta Association in the study area are the Sterco and Levi. The Sterco series consists of Orthic Gray Luvisols and the Levi series are Eluviated Eutric Brunisols (Knapik and Rosentreter, 1999). Any occurrences of organic soil would be part of the Fickle soil complex. This complex is dominantly Mesisols with significant to minor inclusions of Humisols, Fibrisols and Gleysols (Dumanski et al., 1972)

A more detailed soil inventory performed on the Coal Valley Mine documented the presence of predominantly Brunisolic Gray Luvisols on sandy clay loam to clay loam veneers over soft sandstone bedrock (Knapik and Rosentreter, 1999). Eluviated Dystric

Brunisols on morainal veneers over sandstone bedrock and Podzolic Gray Luvisols were also present. Soils within the study area have a pH range of 3.8 to 4.0 in the L-F and Ae horizons, which increases to 4.5 to 5.0 in the B and C horizons (Knapik and Rosentreter, 1999). The cation exchange sites tend to be dominated by calcium, magnesium, and hydrogen, with sodium and potassium in very low concentrations. The acidity of the soils causes aluminum to occupy a portion of the exchange sites, excluding these sites from participation in most soil reactions. Soils in the study area tend to be @9Xdeficient in nitrogen, phosphorus, and sulfur (Dumanski et al., 1972).

Soil salvage at the Coal Valley Mine is done in one lift to a maximum depth of 1.2 m (Knapik and Rosentreter, 1999). One lift is used in soil reconstruction when the soil has either a shallow depth or insignificant quality differences with depth (Fedkenheuer et al., 1987). One lift was used at the Coal Valley Mine in an attempt to improve the characteristics of the minesoil by mixing the acidic and less stable Ae and upper Bm horizons with the lower Bt, BC, and C horizons. The soil material at the mine usually is stockpiled for several months to a few years before it is used in reclamation. Direct placement is not used substantially at the Coal Valley Mine due to the sequencing of mining operations and hauling distance from soil salvage sites (Knapik and Rosentreter, 1999). Minesoils at the Coal Valley Mine are constructed using various materials that have been salvaged from the mine. Materials such as soil profile material, overburden, subsoil, and peat are used to form a minesoil (Knapik and Rosentreter, 1999).

4.0 METHODOLOGY

4.1 Site Selection

The Coal Valley mine consists of four mine zones: Mynheer A, Mynheer B, Silkstone, and Val D'Or (Figure 4.1). Of these zones, the majority of the sampling was performed within Mynheer B, Silkstone, and Val D'Or due to the age of the reclaimed land and their status as having non-sodium affected parent material (Strong, 1999). The reclaimed land on the Coal Valley Mine had an age span of three to 20 years from the time that the land was first seeded (as of 1999). The age of the reclaimed sites is based on records provided by mine personnel. Within this age span three age categories of 5-8 years, 12-14 years, and 17-20 years were chosen to examine the changes in minesoils over time. Five sites were chosen from each age category with a slope <25%. It was anticipated that aspect would be constrained to southwest or southerly aspects to maintain fairly uniform conditions within each minesoil. However, if an adequate sample size could not be obtained within this range, other aspects were considered for sampling although an attempt was made to use sites with low slopes to minimize aspect-related influences. Two undisturbed sites were also sampled to represent the dominant plant community types within the area of Lodgepole Pine–Aspen/Bog Cranberry (*Pinus contorta-Populus tremuloides/Vaccinium vitis-idaea*) and Lodgepole Pine/Labrador Tea (*Pinus contorta/Ledum groenlandicum*).

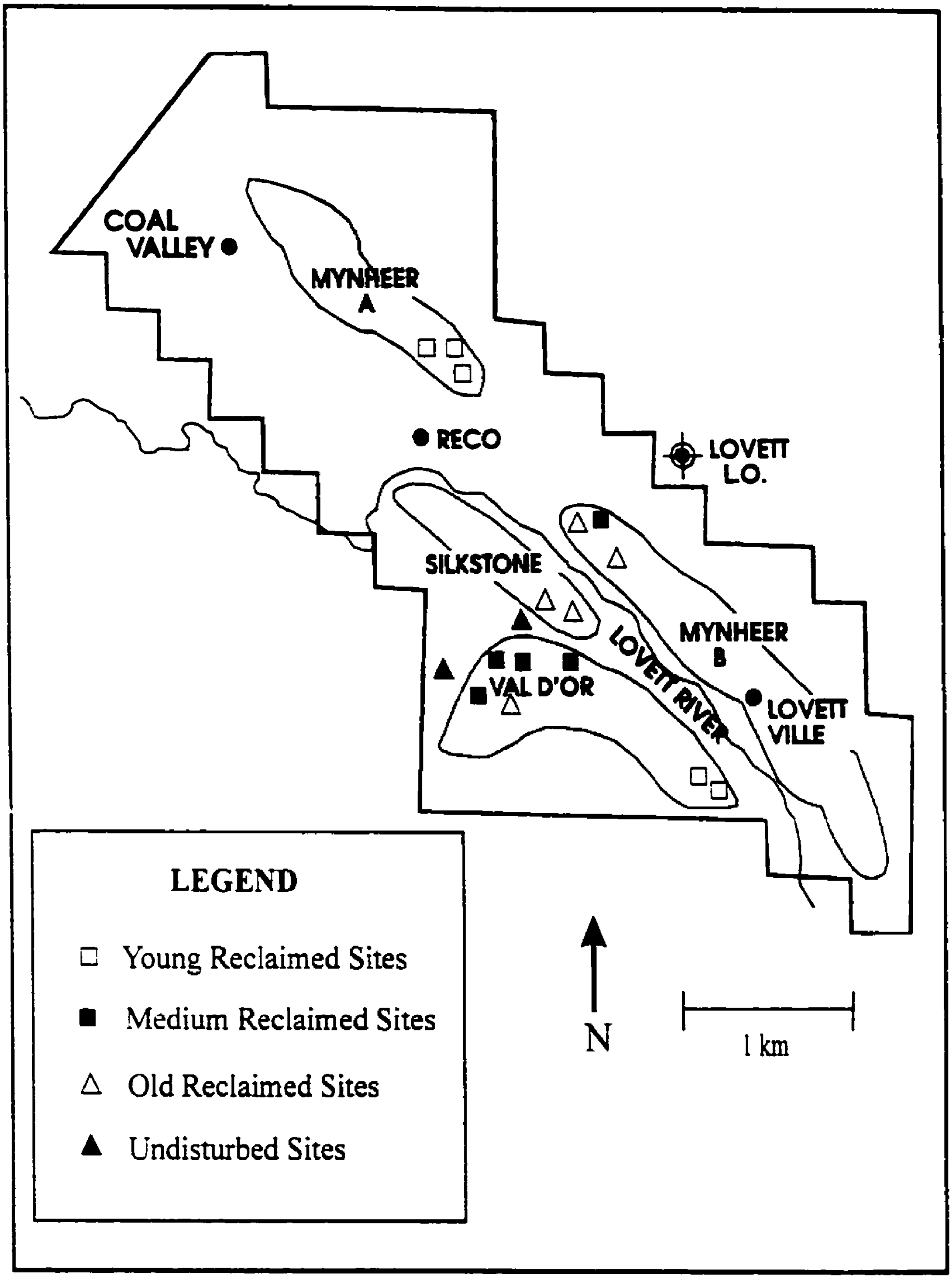

Figure 4.1. Mine zones and sample site locations within the Coal Valley Mine (adapted from Knapik and Rosentreter, 1999).

4.2 Data Collection

Data collection was performed during July of 1999. Once the reclaimed sites were located, two soil sampling locations were arbitrarily chosen within each site (Figure 4.1). One soil pit was sampled for each undisturbed site. Visual site characteristics such as erosion or deposition and other site-specific characteristics of importance were recorded for all sample sites. Individual soil samples were taken from 0-5, 5-10, 10-15, 15-20, and 35-40 cm depths. Soil samples were collected from the bottom of the profile to the surface using a trowel. Approximately 500 g was collected from each depth to provide enough soil for all tests. Bulk density rings with a volume of 58.9 cm^3 were used to sample at 0-5, 10-15, and 35-40 cm depths for each profile. A soil field description sheet was completed for each sampling site to describe the visual profile characteristics such as effective rooting depth, rooting orientation, stoniness, depth to coal spoil, and depth to the water table. The effective rooting depth of a plant was measured from the ground surface to the depth at which root abundance declined to few. Few roots was defined as an average of 10 roots/dm^2 (Agriculture Canada Expert Committee on Soil Survey, 1982).

Stoniness was assessed on a qualitative scale of the percent space occupied by stones (Table 4.1). Stones were defined as any particles greater than 2 mm in size, and abundance was measured at the 0 to 15 cm depth and 15 to 30 cm depth.

Table 4.1. Qualitative assessment scale for stoniness (adapted from Limbird, 1997).

Stoniness Level	**Space Occupied by Stones**
Free of rock fragments	0%
Few pebbles	Trace – 2%
Common stones	2-5%
Many stones	5-15%
Gravelly	15-50%
Very gravelly	50-90%
Gravel	>90%

The species of tree planted on each site was recorded, along with its vigor and height. The presence of shrubs and their species were recorded based on nomenclature by Moss (1983). The composition of a 1x1 m vegetation quadrat at the location of every profile was summarized based on the percent cover of grass, forbs, exposed mineral matter, and "other". "Other" refers to the coverage of litter, moss, wood, or other miscellaneous fragments. This same quadrat was used to estimate percent cover of all ground cover species within the plot.

4.3 Laboratory Analysis

All soil samples were analyzed for chemical and physical properties at the University of Calgary Soil Geomorphology lab. Soil samples were air-dried, ground, and put through a 2 mm sieve. Samples to be used at field moist conditions were frozen until the day of testing. Once samples were prepared they were tested for particle size proportions, organic matter content, exchangeable cations, extractable nitrates and ammonium, pH, electrical conductivity, bulk density, and available phosphorus. Samples from the 35 cm depth were excluded for organic matter, exchangeable cations, extractable nitrates and ammonium, and available phosphorus analysis.

4.3.1 Particle Size

Particle size proportions were determined using a Malvern Instruments Mastersizer 2000. The laser particle size analyzer was used to determine the percent weight in particle size classes from 2000 µm to 0.020 µm for each soil sample by following the method specified by Mottle and Moorman (1999). The method required riffling of the soil sample to obtain a representative sample. The riffled samples were then treated with 2 mL of 30% hydrogen peroxide and left to dry. Subsequently, 5 mL Calgon solution and 5 mL of distilled water were added to the sample and left overnight before the sample was analyzed. A texture class was then assigned to the soil samples based on the Canadian textural triangle (Agriculture Canada Expert Committee on Soil Survey, 1987).

4.3.2 Organic Matter

The organic matter content of each soil sample was determined by the Modified Walkley-Black method (McKeague, 1978). This method provides an estimate of 77% of the organic matter present in a soil. The Modified Walkley-Black procedure was chosen to allow the most accurate determination of organic matter in a soil that contains coal. The procedure uses concentrated sulfuric acid and potassium dichromate to oxidize the organic matter without an external heat source. This level of oxidization does not permit elemental sources of carbon such as coal or charcoal to be broken down and included in the determination of organic matter (Page, 1982). This aids interpretation of the results because the coal fragments do not provide available nutrients to vegetation. The extract was filtered and then analyzed colorimetrically with a Perkin-Elmer Lambda 3B UV/VIS Spectrophotometer to determine the percent transmittance of the solution. The resulting values were then converted into percent organic matter (McKeague, 1978).

4.3.3 Exchangeable Cations and Total Exchangeable Bases

The concentration of exchangeable cations for the soil samples was determined using atomic absorption spectrometry. This method was used to determine the quantities of Ca, Mg, Na, K, Fe, and Al cations. These ions were extracted using 0.025 M barium chloride, shaken mechanically for two hours, then filtered (Hendershot and Duquette, 1986). The resulting extracts were analyzed with a Unicam 939 AA Spectrometer at a 1:1 ratio for Fe and Al, and a 10:1 ratio for Ca, Mg, Na, and K.

The total exchangeable bases values were calculated by summing all exchangeable bases (Ca, Mg, Na, K) in meq/100g. The sodium adsorption ratio (SAR) was calculated based on the equation: $SAR = [\,Na+\,] / (([\,Ca^{2+}\,] + [\,Mg^{2+}\,]) / 2)^{0.5}$

4.3.4 Extractable Ammonium and Nitrates

A Technicon Autoanalyzer was used to measure the levels of extractable ammonium and nitrates. The methods used were the Technicon Industrial Method # 98-70 W/A and # 100-70 W/B for ammonium and nitrates, respectively. Both methods used KCl as the extracting solution.

4.3.5 pH

The pH of all soil samples was calculated using a 1:2 ratio of soil to distilled water (Kalra and Maynard, 1991). The analysis used 10 g of the air-dried soil and 20 ml of distilled water in a centrifuge tube. The solution then was stirred with a glass rod and centrifuged for 30 minutes. The pH was measured in the resulting supernatant with a Fisher Scientific Accumet 50 digital pH/conductivity meter. The pH meter was calibrated with buffer solutions of 4.0 and 7.0 pH throughout the measurement process.

4.3.6 Electrical Conductivity

Electrical conductivity of soil samples also was calculated using a 1:2 ratio of soil and distilled water (Kalra and Maynard, 1991). The same procedure was followed as that used to measure pH. The electrical conductivity was measured in the supernatant with a digital pH/EC meter.

4.3.7 Bulk Density

Bulk density cores were weighed at field moist conditions. The cores were then oven dried at 105°C for two days and reweighed (Kalra and Maynard, 1991). Bulk density then was calculated by dividing the oven-dried sample weight by the volume of the core.

4.3.8 Available Phosphorus

Available phosphorus (PO_4-P) was measured using the Bray 1 procedure because of the acidic and non-calcareous nature of the soils under analysis (Kalra and Maynard, 1991). This procedure uses ammonium fluoride and dilute sulfuric acid as the extracting agents. The concentration of phosphates in the resulting extracts were determined colorimetrically using a Perkin-Elmer Lambda 3B UV/VIS Spectrophotometer.

4.4 Statistical Analysis

4.4.1 Descriptive Statistics

The profile data at each site were averaged by depth and subjected to a set of descriptive statistical analyses. These included calculations of the mean, standard deviation, skewness, and kurtosis for each test within an age category (Appendix A). Skewness can be defined as a measure of the degree of asymmetry in a distribution around its mean (Burt and Barber, 1996). A positive skew indicates a distribution with its tails towards the positive values. A negative skew indicates a distribution with its tails towards the negative values. Kurtosis is a measure of the relative peakedness or flatness of a distribution compared with the normal distribution (Burt and Barber, 1996). A positive kurtosis indicates a peaked distribution, while a negative value indicates a flat distribution. Skewness and kurtosis values were used to determine if the data was normally distributed. The data was considered normally distributed if the skewness value was within the range of –0.90 to +0.90, and the kurtosis value was within the range of -0.40 to +1.80 (Wetherill, 1981).

The data were determined to have dominantly non-normal distributions. This indicated that non-parametric statistics must be used in the analysis of the data. Non-parametric statistics also are considered more effective with a small sample size. When the sample size is less than 10 to 15, it is generally advisable to use non-parametric tests (Burt and Barber, 1996).

4.4.2 Kruskal-Wallis Test

The Kruskal-Wallis test is the non-parametric equivalent of the analysis of variance (Burt and Barber, 1996). This test is used when more than two samples are being compared. If the average ranks of the tested samples differ, it indicates that at least one of the samples comes from a different population (Burt and Barber, 1996). The test statistic for the Kruskal-Wallis test is the H value. If the H value is greater than the critical value, two samples are considered statistically different ($P \leq 0.05$).

If a significant result is obtained from the Kruskal-Wallis test a pairwise multiple comparison must be performed to show where the difference occurs. The Scheffé range test is used to determine which populations are different when comparing more than two populations (Miller, 1966). The equation used to derive the critical value for the Scheffé range test is:

$$|R_i - R_{i'}| \leq (h^{\alpha}{}_{k-1})^{1/2} [N(N+1)/12]^{1/2} (1/n_i + 1/n_{i'})^{1/2}$$

Three different critical values were used because sample sizes differed between tests. Some soil tests were performed on all five depths, while others were performed on four or three depths. The calculated critical values for the Scheffé range test were 25.77, 23.17 and 20.07 for five, four, and three depths, respectively. The difference in mean rank between the two samples must be greater than the critical value. Letters are assigned to demonstrate where the differences occur. When values are followed by the same letter they are not considered statistically different ($P>0.05$). Letters were systematically assigned beginning with the young age category.

4.4.3 Correlation and Linear Regression Analysis

Correlation analysis measures the strength of association between two variables (Burt and Barber, 1996). Linear regression is used to derive the mathematical function that links variable X to variable Y. The regression equation is $Y = a + bX$, where "a" is the y-intercept and "b" is the slope of the line. The coefficient of determination (r^2) is used to indicate the proportion of the total variation in variable Y that is explained by the regression of variable X. Various transformations such as logarithmic and log-normal were applied to the data to attempt to improve the goodness of fit of the regression line.

5.0 RESULTS

5.1 Site Characteristics

The sites in the youngest age category (Y) ranged from five to eight years old based on the elapsed time since seeding. The topography in this age category varied from 1% to 18% slope (Table 5.1 and Plate 5.1). The most common aspect was southwest. Signs of past and present erosion such as rills and small gullies formed from the runoff of precipitation were evident on two sites. Three sites had signs of poor drainage demonstrated by ponded surface water.

The medium aged category (M) sites ranged in age from 12 to 14 years. These sites covered a range of slopes from 8% to 17% and had southerly aspects (Table 5.1 and Plate 5.2). The medium age class had a greater incidence of past or present erosion than the young class with four sites displaying signs such as rills, small gullies, and exposed ground. Four sites had topographic contouring features such as terracing or hummocky terrain, which was implemented during initial landscape construction.

The sites in the old age category (O) were within 17 to 20 years of age. These sites had slopes of 1% to 22% and were associated with a range of aspects (Table 5.1 and Plate 5.3). Two sites had past or present erosional features such as rills or exposed ground. However, none had small gullies, which were present on both the young and medium aged sites.

Table 5.1. Site characteristics for young (Y), medium (M), and old (O) reclaimed sites, and undisturbed (UN) sites. Differences between classes were evaluated using Kruskal-Wallis and the Scheffé non-parametric range tests. Means followed by the same letter are not significantly different (P < 0.05).

Site	Site Characteristics				
	Age (yrs)	**% Slope**	**Aspect**	**Erosion/Deposition**	**Other**
Y 01	6	15	SE	rills, small gullies	pond on site
Y 02	7	10	SW	--	--
Y 03	5	18	SW	rills, small gullies	--
Y 04	8	6	SW	--	ponding
Y 05	8	1	NE	--	ponding
Mean	6.8*a*	10*a*			
M 01	14	17	SW	rills, small gullies	--
M 02	13	8	SW	--	hummocky terrain
M 03	13	15	S	rills, small gullies	hummocky, terraced terrain
M 04	12	13	SW	rills, small gullies, eroded hummocks	hummocky terrain
M 05	13	15	SSW	exposed ground	--
Mean	13.0*b*	13.6*a*			
O 01	18	22	SW	--	--
O 02	20	1	NW	--	--
O 03	17	18	SW	rills	terraced terrain
O 04	19	9	SSE	--	--
O 05	17	13	ENE	rills, exposed ground	hummocky terrain
Mean	18.2*c*	12.6*a*			
UN 01	--	11	NW	--	--
UN 02	--	18	NE	--	--
Mean	--	14.5*a*			
H	12.60	0.97			
P	0.002	0.808			

Plate 5.1. Reclaimed site within the young age category (eight years since initial seeding).

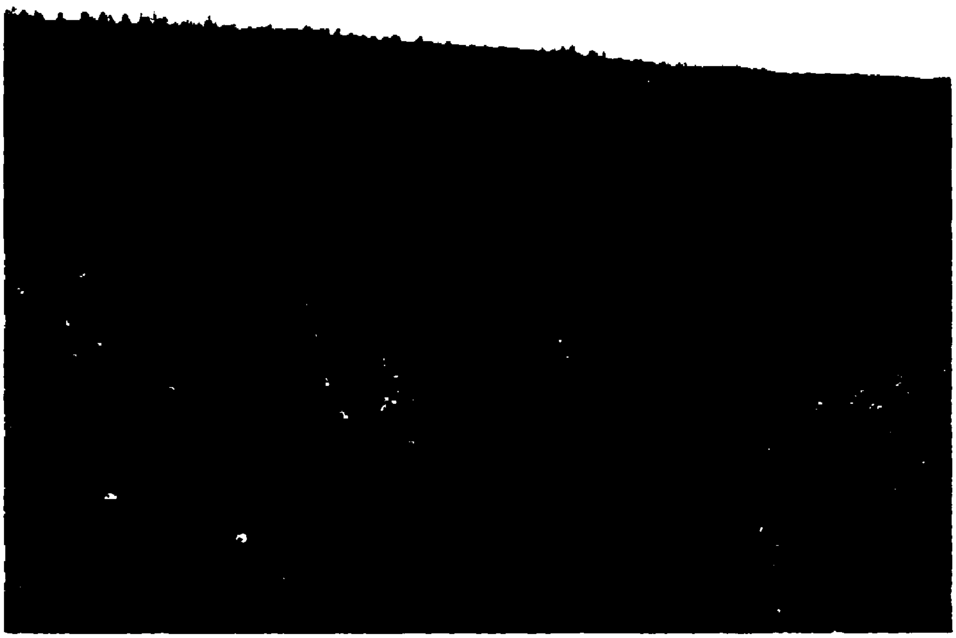

Plate 5.2. Reclaimed site within the medium age category (13 years since initial seeding).

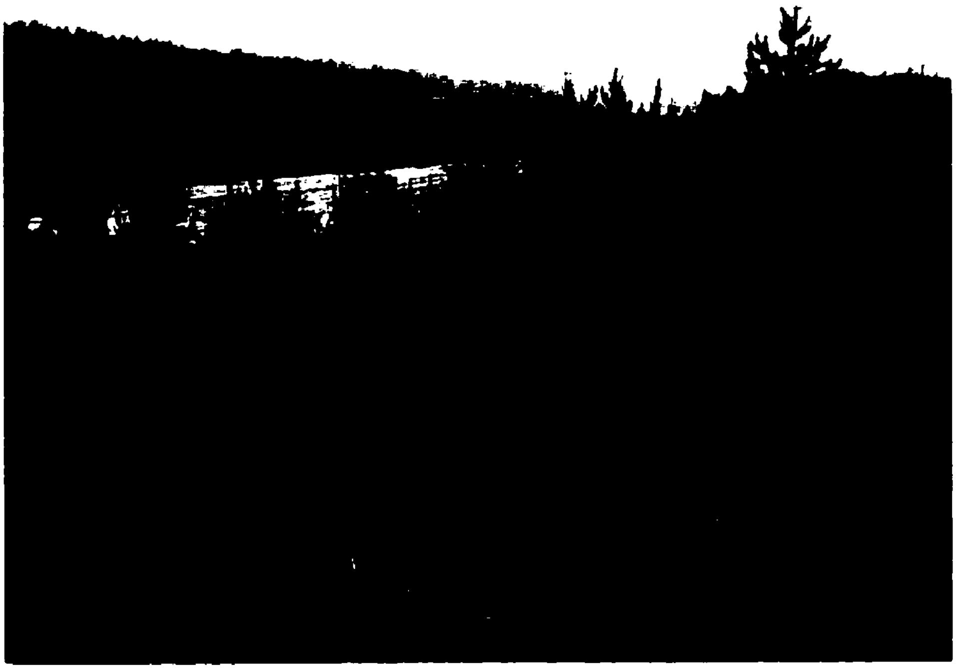

Plate 5.3. Reclaimed site within the old age category (18 years since initial seeding).

Plate 5.4. Undisturbed site from a Lodgepole Pine–Aspen/Bog Cranberry (*Pinus contorta-Populus tremuloides/Vaccinium vitis-idaea*) stand

The undisturbed sites (UN) had slopes of 11% and 18% with aspects of northwest and northeast, respectively (Table 5.1 and Plate 5.4). The undisturbed sites showed no evidence of erosion. The three reclaimed age classes were statistically different in age but no significant difference occurred in slope values.

5.2 Visual Soil Characteristics

The youngest minesoils had effective rooting depths that ranged from 5 to 15 cm with a mean of 8.5 cm (Table 5.2 and Plate 5.5). A profile can show a clear pattern of either dominantly vertical or horizontal rooting, or a combination of the two rooting types. Three of the youngest aged minesoils had vertical rooting while the remaining seven contained a mixture of horizontally and vertically oriented rooting. The degree of stoniness for the youngest minesoils was most often classified as "many", with two profiles that had a stoniness of "common" at the 0 to 15 cm depth. The 15 to 30 cm depth of the youngest minesoils had a stoniness level of "many" for most profiles, while "gravelly" material occurred in four profiles. Coal spoil was not encountered in any of the young profiles. A perched water table was found at a depth of 40 cm in two profiles on sites with ponded surface water.

Table 5.2. Visual soil characteristics for young (Y), medium (M), and old (O) minesoils, and undisturbed (UN) soils. Differences between classes were evaluated using Kruskal-Wallis and the Scheffé non-parametric tests. Means followed by the same letter are not significantly different (P < 0.05).

Site	Effective Rooting Depth (cm)	Rooting Orientation	Stoniness		Depth to Coal Spoil (cm)	Depth to Water Table (cm)
			0-15 cm	15-30 cm		
Y 01A	10	vertical	many	gravelly	>SD	>SD
Y 01B	10	V/H	many	many	>SD	>SD
Y 02A	5	V/H	many	gravelly	>SD	>SD
Y 02B	5	vertical	many	gravelly	>SD	>SD
Y 03A	15	V/H	many	gravelly	>SD	>SD
Y 03B	10	V/H	many	many	>SD	>SD
Y 04A	10	vertical	common	many	>SD	>SD
Y 04B	5	V/H	common	common	>SD	40
Y 05A	10	V/H	many	many	>SD	40
Y 05B	5	V/H	many	many	>SD	>SD
Mean	8.5*a*					
M 01A	20	V/H	common	many	>SD	>SD
M 01B	10	V/H	common	many	>SD	>SD
M 02A	10	V/H	many	many	>SD	>SD
M 02B	10	V/H	many	many	35	>SD
M 03A	15	vertical	common	common	>SD	>SD
M 03B	15	vertical	many	many	>SD	>SD
M 04A	20	V/H	common	common	>SD	>SD
M 04B	10	V/H	common	common	>SD	>SD
M 05A	20	V/H	common	common	>SD	>SD
M 05B	10	V/H	common	common	>SD	>SD
Mean	14*a*					
O 01A	10	V/H	common	common	>SD	35
O 01B	10	V/H	common	many	35	40
O 02A	15	V/H	common	common	35	40
O 02B	15	V/H	common	common	32	>SD
O 03A	10	V/H	common	common	35	35
O 03B	10	V/H	common	common	20	>SD
O 04A	5	vertical	common	common	30	>SD
O 04B	10	V/H	common	common	>SD	>SD
O 05A	10	vertical	common	common	>SD	>SD
O 05B	20	V/H	common	common	>SD	>SD
Mean	11.5*a*					
UN 01	6	horizontal	few	few	>SD	>SD
UN 02	0	horizontal	common	many	>SD	>SD
Mean	3*a*					
H	11.21					
P	0.011					

*>SD = found at a depth greater than the sampling depth of 40 cm.

** V/H = profile contains both vertical and horizontal rooting orientations.

Plate 5.5. Minesoil profile within the young age category (six years since initial seeding).

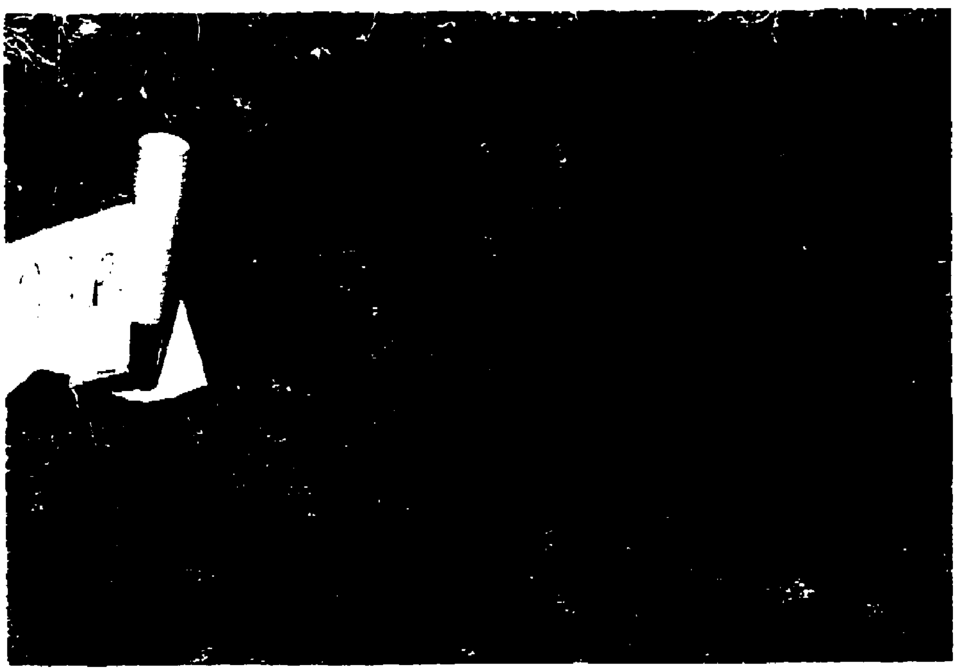

Plate 5.6. Minesoil profile within the medium age category (13 years since initial seeding).

The medium aged minesoils had an average effective rooting depth of 14 cm, calculated from values that ranged from 10 to 20 cm (Table 5.2 and Plate 5.6). The roots within this category had both vertical and horizontal orientations in eight of the ten sampled profiles. Stoniness levels for the 0 to 15 cm and 15 to 30 cm depths were classified most often as "common" and "many", respectively. None of the medium aged profiles were classified as "gravelly", although this stoniness level was found in the young profiles. Coal spoil was encountered in one profile at 35 cm and a perched water table was not found within the sampling depth in any of the medium age class profiles.

The old minesoils contained a wide range of effective rooting depths (5 to 20 cm), with an average of 11.5 cm (Table 5.2 and Plate 5.7). Eight of the ten profiles were found to have a combination of vertical and horizontal rooting. All of the profiles had a stoniness level of "common" for both measurement depths, except for one occurrence of "many" at the 15 to 30 cm depth. Coal spoil and perched water tables were encountered frequently at depths greater than 20 cm and 35 cm, respectively.

The visual soil characteristics of the undisturbed soil profiles were considerably different from those of the minesoils. The undisturbed soils had the shallowest effective rooting depth of all profiles that were sampled, with an average depth of 3 cm (Table 5.2 and Plate 5.8). The effective rooting depths were significantly different using the Kruskal-Wallis test ($P = 0.011$), but the Scheffé test did not differentiate between the age classes.

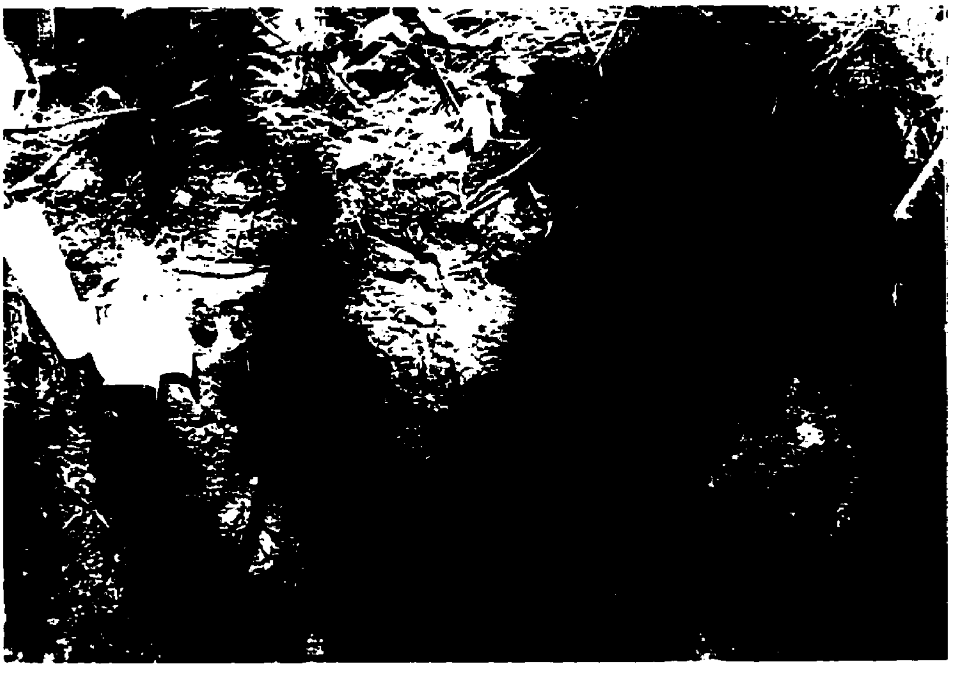

Plate 5.7. Minesoil profile within the old age category (20 years since initial seeding).

Plate 5.8. Undisturbed soil profile from a Lodgepole Pine–Aspen/Bog Cranberry (*Pinus contorta-Populus tremuloides/Vaccinium vitis-idaea*) stand.

Both undisturbed soils had a dominantly horizontal rooting orientation, which was not present in any of the disturbed soils. One undisturbed soil profile (UN 01) had "few" stones at both depths, which was less than any amount found in the minesoils. The second undisturbed soil (UN 02) had a stoniness of "common" at the 0 to 15 cm depth and "many" at the 15 to 30 cm depth, which duplicated that found in several of the minesoils. The amount of space occupied by stones generally decreased from the young minesoils to the undisturbed soils. Neither coal spoil nor a perched water table were encountered within the sampling depth of the undisturbed soils. The undisturbed sites had the greatest litter accumulation with an average depth of 8.5 cm. The litter was much thinner in the minesoils, which had average depths of 3, 3, and 4 cm for the young, medium, and old age categories, respectively.

5.3 Vegetation Characteristics

5.3.1 Tree and Shrub Characteristics

All reclaimed sites were planted with either lodgepole pine (*Pinus contorta* Loudon) or white spruce (*Picea glauca* (Moench) Voss) seedlings. However, white spruce seedlings were only found on the reclaimed sites in the youngest age category (Table 5.3). The trees on the undisturbed sites were predominantly lodgepole pine with either white spruce or aspen (*Populus tremuloides* Michx.) as secondary tree species. The lodgepole pine trees were approximately 20 m tall, the aspen were 15 m tall, and the white spruce were between 4.0 to 4.5 m in height.

Table 5.3. Summary of tree and shrub characteristics for young (Y), medium (M), and old (O) reclaimed sites, and undisturbed (UN) sites. Differences in tree height were evaluated using Kruskal-Wallis and the Scheffé non-parametric range tests. Means followed by the same letter are not significantly different ($P < 0.05$).

Site	Trees			Shrubs
	Species	**Vigor**	**Average Height (m)**	**Species**
Y 01	*Pinus contorta*	Poor	0.45	--
Y 02	*Pinus contorta* *Picea glauca*	Fair	0.40 0.40	--
Y 03	*Pinus contorta*	Poor	0.20	--
Y 04	*Picea glauca*	Poor	0.35	*Salix spp.*
Y 05	*Pinus contorta* *Picea glauca*	Poor	0.40 0.40	*Salix spp.*
Mean			0.33*a*	
M 01	*Pinus contorta*	Good	1.50	--
M 02	*Pinus contorta*	Good	1.50	*Salix spp.*
M 03	*Pinus contorta*	Good	1.00	*Salix spp.*
M 04	*Pinus contorta*	Good	2.50	--
M 05	*Pinus contorta*	Good	2.00	*Salix spp.* *Betula glandulosa*
Mean			1.70*ab*	
O 01	*Pinus contorta*	Good	2.00	*Salix spp.* *Betula glandulosa*
O 02	*Pinus contorta*	Good	5.00	*Salix spp.*
O 03	*Pinus contorta*	Good	3.00	--
O 04	*Pinus contorta*	Good	3.50	--
O 05	*Pinus contorta*	Good	2.50	*Salix spp.* *Betula glandulosa*
Mean			3.20*b*	
UN 01	*Pinus contorta* *Populus tremuloides* *Picea glauca*	Good	20 15 4	*Salix spp.*
UN 02	*Pinus contorta* *Picea glauca*	Good	20 4.5	*Salix spp.*
H			9.41	
P			<0.001	

The vigor of the tree seedlings was generally poor on the young reclaimed sites. Tree vigor improved dramatically on all other sites beginning at 12 years of age. Tree height also changed substantially between the young and medium age categories. The average tree height for the reclaimed sites was 0.33 m (Y), 1.70 m (M), and 3.20 m (O). The Kruskal-Wallis test determined that the old sites had significantly taller ($P<0.001$) trees than the young sites (Table 5.3). The undisturbed sites were not included in this test. The dominant shrub species on the reclaimed sites were willow (*Salix spp.*) and bog birch (*Betula glandulosa* Michx.). Willows occurred on sites within all of the age categories, while birch grew only on the medium and old reclaimed sites.

5.3.2 Growth Form Characteristics

Grass cover averaged 55.5%, 66.0%, and 48.5% for the young, medium, and old reclaimed sites, respectively (Table 5.4). These values were similar but undisturbed sites had a much lower cover at 1.8%. However, grass cover values were not significantly different ($P>0.05$) among the age classes using the Kruskal-Wallis test.

The average forb cover of the reclaimed sites was also similar, with values of 34.8%, 30.2%, and 38.5% for the young, medium, and old minesoils, respectively. A greater average forb cover of 65.5% was found on the undisturbed sites. However, no significant difference ($P>0.05$) was found among any of the age classes based on a Kruskal-Wallis test. An undisturbed site in the study area generally had ground cover that was predominantly forbs with a small grass component; a more even representation was present on the disturbed sites.

Table 5.4. Summary of growth form characteristics for young (Y), medium (M), and old (O), and undisturbed (UN) sites. Differences between percent cover were evaluated using Kruskal-Wallis and the Scheffé non-parametric tests. Means followed by the same letter are not significantly different ($P < 0.05$).

Site	% Cover			
	Grasses	**Forbs**	**Exposed Mineral Matter**	**Other**
Y 01A	35	60	2	3
Y 01B	55	20	7	18
Y 02A	70	25	0	5
Y 02B	85	13	0	2
Y 03A	85	10	1	4
Y 03B	55	35	10	0
Y 04A	30	50	0	20
Y 04B	40	45	0	15
Y 05A	35	60	0	5
Y 05B	65	30	0	5
Mean	55.5*a*	34.8*a*	2.0*a*	7.7*a*
M 01A	70	30	0	0
M 01B	80	15	1	4
M 02A	50	35	1	14
M 02B	55	40	0	5
M 03A	50	50	0	0
M 03B	75	25	0	0
M 04A	75	25	0	0
M 04B	85	12	0	3
M 05A	40	55	0	5
M 05B	80	15	1	4
Mean	66.0*a*	30.2*a*	0.3*a*	3.5*a*
O 01A	70	25	0	5
O 01B	65	35	0	0
O 02A	5	60	0	35
O 02B	65	30	0	5
O 03A	80	20	0	0
O 03B	15	75	0	10
O 04A	15	30	0	55
O 04B	40	40	0	20
O 05A	75	25	0	0
O 05B	55	45	0	5
Mean	48.5*a*	38.5*a*	0*a*	13.5*a*
UN 01	0.50	85	0	14.5
UN 02	3	45	0	52
Mean	1.8*a*	65.5*a*	0*a*	33.3*a*

H	7.65	3.90	5.80	6.44
P	0.054	0.272	0.122	0.092

The undisturbed and old sites had no exposed mineral matter, but the young and medium aged sites had bare ground on four and three sites, respectively. The exposed mineral matter on these sites had average cover values of 2.0% for the young and 0.3% for the medium age categories, although there was no significant difference ($P>0.05$) between these age classes.

Miscellaneous components such as moss or litter on the ground surface had an average cover of 7.7% and 3.5% on the young and medium aged reclaimed sites, respectively. The oldest and undisturbed sites tended to have higher values of 13.5% and 33.3%, respectively. However, none of these values were significantly different when tested.

5.3.3 Ground Cover Species Characteristics

A total of 24 plant taxa were found for all site classes (Table 5.5). Six of the 24 taxa present were in the original reclamation seed mixture or were planted on the mine. These six species were short-awned foxtail (*Alopecurus aequalis* Sobol.), red fescue (*Festuca rubra* L.), sainfoin (*Onobrychis viciifolia* Scop.), other grasses, clover (*Trifolium spp.*), and lodgepole pine (*Pinus contorta* Loudon). Twelve of the taxa were considered volunteer species. The volunteer species have seeded themselves from sources such as wind dispersal from undisturbed sites. Volunteer species found on the reclaimed sites that were not present in the sampled undisturbed sites were common yarrow (*Achillea millefolium* L.), pussytoes (*Antennaria spp.*), Lindley's aster (*Aster ciliolatus* Lindl.), marsh reed grass (*Calamagrostis canadensis* (Michx.) Beauv.), lichen (*Peltigera spp.*), and common dandelion (*Taraxacum officinale* Weber).

Table 5.5. Mean plant taxa and species cover for young (Y), medium (M), and old (O) reclaimed sites, and undisturbed (UN) sites. Differences among age classes were evaluated using Kruskal-Wallis and the Scheffé non-parametric range tests. Means followed by the same letter are not significantly different ($P < 0.05$) ($n = 24$).

Species / Taxa	Scientific Name	% Cover				H	P
		Y	M	O	UN		
Trees							
Lodgepole pine*	*Pinus contorta***	0.0	1.5	2.5	0.0	1.24	0.743
Shrubs							
Dwarf bilberry	*Vaccinium caespitosum*	0.0*a*	0.0*a*	0.0*a*	5.0*a*	15.00	0.002
Labrador tea	*Ledum groenlandicum*	0.0*a*	0.0*a*	0.0*a*	5.0*a*	31.00	<0.001
Willow	*Salix spp.*	0.0*a*	0.0*a*	0.1*a*	1.5*a*	8.27	0.041
Herbs							
Bog cranberry	*Vaccinium vitis-idaea*	0.0*a*	0.0*a*	0.0*a*	20.5*a*	31.00	<0.001
Bunchberry	*Cornus canadensis*	0.0*a*	0.0*a*	0.0*a*	13.5*a*	22.00	<0.001
Clover*	*Trifolium spp.***	27.7	26.2	16.0	0.0	7.32	0.062
Common dandelion	*Taraxacum officinale*	0.5*a*	1.5*a*	3.5*a*	0.0*a*	12.30	0.007
Common yarrow	*Achillea millefolium*	0.0	0.0	1.0	0.0	2.20	0.532
Fireweed	*Epilobium angustifolium*	0.0*a*	2.4*a*	3.9*a*	0.5*a*	12.10	0.007
Five-leaf bramble	*Rubus pedatus*	0.0*a*	0.0*a*	0.2*a*	2.0*a*	8.27	0.041
Heart-leaved arnica	*Arnica cordifolia*	0.0*a*	0.0*a*	0.0*a*	15.0*a*	15.00	0.002
Horsetail	*Equisetum spp.*	0.0	0.0	0.3	0.5	7.03	0.071
Lindley's aster	*Aster ciliolatus*	0.0	0.0	2.9	0.0	7.04	0.071
Marsh reed grass	*Calamagrostis canadensis*	0.0	0.0	2.0	0.0	2.20	0.532
Other grasses*	Other grasses*	7.9	3.8	3.0	1.7	4.78	0.189
Palmate-leaved coltsfoot	*Petasites palmatus*	0.0	0.0	3.4	0.5	7.73	0.052
Pussytoes	*Antennaria spp.*	0.0	0.0	0.2	0.0	2.20	0.532
Red fescue*	*Festuca rubra**	59.40	55.80	49.60	0.0	6.75	0.080
Sainfoin*	*Onobrychis viciifolia**	4.9*a*	0.0*a*	0.0*a*	0.0*a*	18.80	<0.001
Short-awned foxtail*	*Alopecurus aequalis**	0.0*a*	13.2*a*	8.8*a*	0.0*a*	9.54	0.023
Stiff club-moss	*Lycopodium annotinum*	0.0*a*	0.0*a*	0.0*a*	5.0*a*	15.00	0.002
Mosses and Lichens							
Lichen	*Peltigera spp.*	0.0	0.0	0.3	0.0	2.20	0.532
Feathermoss	Feathermoss	1.2	0.4	4.0	31.0	7.44	0.059

*•species were present in original seed mixture or planted.

Six of 24 taxa were found only on undisturbed sites; these include heart-leaved arnica (*Arnica cordifolia* Hook), bunchberry (*Cornus canadensis* L.), Labrador tea (*Ledum groenlandicum* Oeder), stiff club-moss (*Lycopodium annotinum* L.), dwarf bilberry (*Vaccinium caespitosum* Michx.), and bog cranberry (*Vaccinium vitis-idaea* L.). The reclaimed sites demonstrated an increase in species richness over time. The young and medium reclaimed sites had a total of six and eight species, respectively. This total increased to 17 species on the old reclaimed sites, which exceeds the 13 species on undisturbed sites.

Half of the taxa that were present on the sampled sites had a significant ($P<0.05$) difference in percent cover over time, but when the Scheffé range test was applied none of the age classes could be differentiated. Six of these taxa were species that occurred only on undisturbed sites. However, the absence of these species on the reclaimed sites was not demonstrated by the use of statistics. The remaining six plants with significant differences among the age classes were willows, dandelion, fireweed, five-leaf bramble, sainfoin, and short-awned foxtail.

5.4 Chemical and Physical Properties of Minesoils and Undisturbed Soils

Representative values are provided for all tests performed on the soil samples (Table 5.6). These values are the mean of all measurements obtained within an age category. The values from all sampling depths (0-5, 5-10, 10-15, 15-20, and 35-40 cm) were averaged because differences in values with depth were negligible. A list of the original values can be found in Appendix A.

5.4.1 Chemical Properties of Minesoils and Undisturbed Soils

All but three chemical soil properties showed a statistically significant difference between at least one of the age categories. Potassium (K), nitrates (NO_3-N), and ammonium (NH_4-N) had no significant difference in the concentrations present in the age groups. Although, ammonium values nearly reached a significant level (P=0.055). Potassium levels ranged from 0.22 (UN) to 0.29 meq/100g (O). Nitrate and ammonium levels were quite low with values that ranged from 0.80 to 2.72 and 1.48 to 6.22 μg/g, respectively. Although the values were not statistically different, both nitrates and ammonium had the smallest concentrations in the young minesoils and the largest concentrations in the undisturbed soils.

Table 5.6. Mean chemical and physical properties of young (Y), medium (M), and old (O) minesoils, and undisturbed (UN) soils. Differences were evaluated using the Kruskal-Wallis and Scheffé non-parametric range tests. Means followed by the same letter are not significantly different (P<0.05). Standard deviations are represented in parentheses.

Soil Characteristics	Y	M	O	UN	H	P
TEB (meq/100g)	33.80*a* (8.80)	30.30*a* (4.10)	31.90*a* (8.84)	14.10*b* (8.50)	19.90	<0.001
Ca (meq/100g)	29.80*a* (8.55)	27.00*a* (3.66)	28.80*a* (8.27)	12.30*b* (7.83)	18.20	<0.001
Na (meq/100g)	0.74*a* (0.63)	0.33*ab* (0.14)	0.29*b* (0.13)	0.32*ab* (0.13)	18.60	<0.001
K (meq/100g)	0.28*a* (0.09)	0.25*a* (0.11)	0.29*a* (0.14)	0.22*a* (0.12)	4.65	0.199
Mg (meq/100g)	3.00*a* (0.37)	2.75*a* (0.76)	2.50*a* (0.77)	1.23*b* (0.74)	21.90	<0.001
Fe (meq/100g)	<DL	<DL	<DL	<DL	--	--
Al (meq/100g)	0.31*a* (0.13)	1.36*b* (0.71)	1.24*b* (1.00)	4.18*b* (2.67)	44.40	<0.001
SAR (meq/100g)	0.19*a* (0.18)	0.09*a* (0.04)	0.08*a* (0.04)	0.14*a* (0.07)	18.10	<0.001
PO_4-P (mg/kg)	0.21*a* (0.17)	0.44*ab* (0.19)	0.29*a* (0.16)	0.70*b* (0.33)	22.20	<0.001
NO_3-N (µg/g)	0.80*a* (0.78)	1.75*a* (1.90)	0.98*a* (1.06)	2.72*a* (4.25)	1.49	0.686
NH_4-N (µg/g)	1.48*a* (2.29)	5.83*a* (7.17)	5.41*a* (8.89)	6.22*a* (3.44)	7.59	0.055
Organic Matter (%)	1.53*a* (0.46)	1.82*ab* (0.51)	2.17*b* (0.44)	1.54*ab* (0.46)	16.00	0.001
pH	7.14*a* (0.67)	5.78*bc* (0.30)	5.85*b* (0.33)	5.33*c* (0.24)	56.40	<0.001
EC (µS/cm)	44.40*a* (32.13)	24.80*a* (8.28)	29.50*a* (12.05)	24.00*a* (9.11)	9.86	0.020
Bulk Density (g/cm^3)	1.55*a* (0.13)	1.40*ab* (0.12)	1.28*b* (0.18)	1.28*ab* (0.27)	17.20	0.001
Sand (% by wt.)	60.29*a* (12.52)	53.43*ab* (9.54)	45.24*bc* (6.22)	41.00*c* (3.65)	29.40	<0.001
Silt (% by wt.)	38.52*a* (11.75)	42.88*a* (9.31)	46.49*a* (5.86)	57.45*b* (4.86)	24.90	<0.001
Clay (% by wt.)	1.02*a* (1.34)	3.69*ab* (4.19)	8.27*b* (6.10)	1.56*ab* (1.54)	28.90	<0.001

* <DL = less than detectable limit of 0.01 meq/100g

Many of the cations that were measured demonstrated similar statistical trends. The concentrations of total exchangeable bases (TEB), calcium (Ca), and magnesium (Mg) in the reclaimed sites were not significantly different from one another but all of the reclaimed sites were significantly different from the undisturbed sites. The amount of total exchangeable bases in the minesoils had little variance with values around 32 meq/100g but these values were much higher than the average of 14.10 meq/100g for undisturbed soils. Calcium values followed a similar pattern since they formed the largest component of the total exchangeable bases. The reclaimed sites had an average calcium concentration of 28.53 meq/100g with a significantly lower value of 12.30 meq/100g in the undisturbed soils. Magnesium concentrations for the minesoils ranged from 2.50 to 3.00 meq/100g, while the undisturbed sites had an average concentration of 1.23 meq/100g.

Sodium (Na) concentrations significantly decreased between the young (0.74 meq/100g) and old (0.29 meq/100g) minesoils. Sodium levels in the undisturbed soils were not significantly different from any of the concentrations present in the minesoils. The sodium adsorption ratio (SAR) covered a range of 0.08 to 0.19 meq/100g and showed a statistical difference among the categories based on a Kruskal-Wallis test. However, when the Scheffé range test was applied no significant difference was identifiable.

Average iron (Fe) concentrations for all of the age classes were below the detection limit of 0.01 meq/100g; therefore, statistics were not performed on the values. Aluminum (Al) concentrations were statistically similar for the medium (1.36 meq/100g), old (1.24 meq/100g), and undisturbed (4.18 meq/100g) soils, yet all of these values were significantly higher than the concentrations present in the youngest minesoils (0.31 meq/100g).

Phosphorus (PO_4-P) levels were significantly greater in the undisturbed (0.70 mg/kg) soils than the young (0.21 mg/kg) and the old (0.29 mg/kg) minesoils. None of the reclaimed soils had statistically different concentrations of phosphorus. The amount of organic matter in the profiles increased significantly between the young (1.53%) and old (2.17%) minesoils. The undisturbed soils (1.54%) had statistically similar amounts of organic matter to that present in all of the reclaimed soils.

The average pH value for the young minesoils was 7.14, which was significantly higher than the average values for all of the other age classes. There was no difference between the average pH for the medium (5.78) and undisturbed (5.33) soils, but the pH of the old minesoils (5.85) and the undisturbed soils were significantly different. The electrical conductivity (EC) in the young minesoils (44.40 µS/cm) was greater than the values for the other soils which only covered a range of 24.00 to 29.50 µS/cm. A significance value (P) of 0.020 resulted from the Kruskal-Wallis test on these values, but no difference was found when the Scheffé range test was applied.

5.4.2 Physical Properties of Minesoils and Undisturbed Soils

Bulk density decreased significantly between the youngest (1.55 g/cm^3) and the oldest (1.28 g/cm^3) minesoils. The bulk density of the undisturbed soils was an average of 1.28 g/cm^3, which was statistically similar to all of the values for the minesoils. The texture of the soils was measured by assessing the quantities of sand, silt, and clay in each sample. The sand component had a tendency to decrease significantly from the young minesoils

(60.29%) to the undisturbed (41.00%) soils (Table 5.6). Silt content was statistically similar for all of the reclaimed sites (38.52%-Y, 42.88%-M, 46.49%-O), but was significantly more abundant in undisturbed soils (57.45%). Clay content increased significantly from the young (1.02%) to the old (8.27%) minesoils, but was lower in the undisturbed soils.

The texture class of the minesoils included sandy loams, silty loams, loams, and loamy sands (Appendices A1 to A4). However, the frequency of these textures differed between the age categories. The youngest age category had 15 of 25 soil samples with a texture of sandy loam. Silty loam and loamy sand samples were each found in five soils. The medium aged minesoils also had sandy loam as the most common texture with occurrences in 16 of 25 soil samples. Silty loam texture was found in seven soil samples, and loamy sand and loam were both found in one soil sample each. The presence of the coarse loamy sand texture decreased from the young to the medium aged minesoils. The oldest minesoils most frequently had a loamy texture. This differs considerably from the young and medium aged minesoils which together only had one in 50 soil samples with a loamy texture. Textures of silty loam and sandy loam were found in eight and seven soil samples, respectively, out of 25 samples for the old minesoils. The undisturbed soil samples had textures of silty loam, except for one sample that had a sandy loam texture. Among the sampled age classes, the coarsest textures were found in the young minesoils, and the finest textured samples were found in the old minesoils.

5.5 Changes in Chemical and Physical Soil Properties with Depth

Soil characteristics were analyzed using regression and correlation analysis to determine if they increased or decreased within the sampling depth of 40 cm (Table 5.7). In general, few of the chemical and physical characteristics of the soils were correlated with depth. Sodium, potassium, phosphorus, nitrates, sodium adsorption ratio, pH, and electrical conductivity were the chemical properties that had a relationship with the depth in the profile. The physical properties of bulk density, and sand, silt, and clay content had at least one age category that displayed a significant correlation with depth (Table 5.7).

Of all tested soil properties, pH had the most consistent correlation with depth among the reclaimed age classes (Table 5.7). These correlations were positively related to depth with explained variances (r^2) of up to 31% (Figure 5.1, Appendices B1, B2). Sodium concentrations had a significant positive correlation for the young minesoils with a r^2 value of 0.26 (Figure 5.2). The sodium adsorption ratio was closely linked with sodium concentration and displayed the same results. A positive relationship occurred between sodium adsorption ratio and depth with a r^2 value of 0.22 in young minesoils (Figure 5.3).

Table 5.7. Summary of regression and correlation analysis with depth as the independent variable for tested chemical and physical soil characteristics of the young (Y), medium (M), and old (O) minesoils, and undisturbed (UN) soils.

Soil Characteristic	Age Group	r	r^2	P	Soil Characteristic	Age Group	r	r^2	P
Total Exchangeable Bases (TEB)	Y	0.01	0.00	0.956	**Ammonium (NH_4-N)**	Y	0.00	0.00	0.976
	M	0.22	0.05	0.361		M	-0.32	0.10	0.165
	O	-0.18	0.03	0.456		O	-0.14	0.02	0.552
	UN	-0.04	0.00	0.925		UN	-0.00	0.00	0.998
Calcium (Ca)	Y	-0.02	0.00	0.932	**Organic Matter**	Y	-0.13	0.02	0.594
	M	0.24	0.06	0.311		M	-0.11	0.01	0.648
	O	-0.16	0.03	0.505		O	-0.03	0.00	0.889
	UN	-0.04	0.00	0.929		UN	-0.69	0.47	0.061
Sodium (Na)	Y	0.51	0.26	0.023*	**pH**	Y	0.45	0.21	0.023*
	M	0.21	0.04	0.378		M	0.54	0.29	0.006*
	O	0.36	0.13	0.116		O	0.56	0.31	0.004*
	UN	-0.12	0.01	0.777		UN	0.60	0.36	0.066
Potassium (K)	Y	-0.39	0.15	0.093	**Electrical Conductivity (EC)**	Y	0.32	0.10	0.119
	M	-0.66	0.43	0.002*		M	-0.18	0.03	0.400
	O	-0.62	0.39	0.004*		O	-0.11	0.01	0.588
	UN	-0.67	0.45	0.070		UN	-0.75	0.56	0.013*
Magnesium (Mg)	Y	0.02	0.00	0.923	**Bulk Density**	Y	0.60	0.36	0.018*
	M	0.07	0.01	0.758		M	0.42	0.18	0.115
	O	-0.28	0.08	0.229		O	-0.00	0.00	0.989
	UN	0.08	0.01	0.858		UN	0.51	0.26	0.307
Aluminum (Al)	Y	0.17	0.03	0.471	**Sand (%)**	Y	0.13	0.02	0.543
	M	0.04	0.00	0.856		M	0.21	0.05	0.303
	O	0.10	0.01	0.685		O	0.01	0.00	0.947
	UN	-0.10	0.01	0.810		UN	0.72	0.52	0.019*
Phosphorus (PO_4-P)	Y	0.08	0.01	0.742	**Silt (%)**	Y	-0.10	0.01	0.645
	M	-0.04	0.00	0.868		M	-0.22	0.05	0.302
	O	-0.44	0.20	0.050*		O	0.16	0.03	0.441
	UN	0.28	0.08	0.502		UN	-0.76	0.58	0.010*
Nitrates (NO_3-N)	Y	-0.09	0.01	0.684	**Clay (%)**	Y	-0.20	0.04	0.339
	M	-0.56	0.32	0.010*		M	-0.01	0.00	0.960
	O	-0.00	0.00	0.997		O	-0.17	0.03	0.419
	UN	-0.29	0.09	0.480		UN	0.71	0.51	0.021*
Sodium Adsorption Ratio (SAR)	Y	0.47	0.22	0.038*					
	M	0.18	0.03	0.456					
	O	0.38	0.15	0.096					
	UN	-0.23	0.05	0.580					

* Correlation significant at the P≤ 0.05 level.

Potassium concentration had a negative correlation with depth for the medium and old minesoils with r^2 values of 0.43 and 0.39, respectively (Figure 5.4 and Appendix B3). The oldest minesoils demonstrated a negative correlation (r^2=0.20) between phosphorus concentration and depth (Appendix B4). A significant negative correlation revealed that depth explained 32% of the variance in nitrate concentration in medium aged minesoils (Appendix B5). Electrical conductivity decreased with depth in undisturbed soils with a r^2 of 0.56 (Appendix B6).

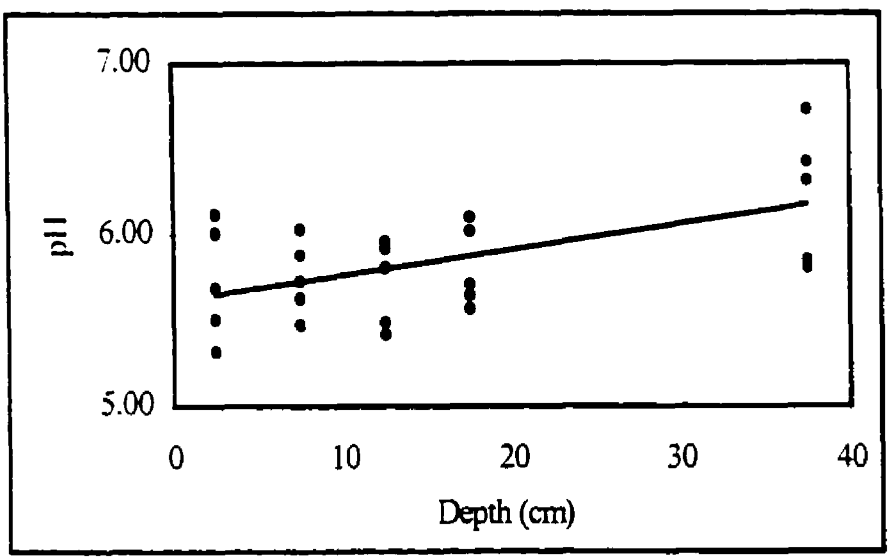

Figure 5.1. Relationship between pH and depth in the profile for the old minesoils. Equation: pH = 5.62 + 0.0149(depth in cm), n=25, r^2=0.31, P=0.004

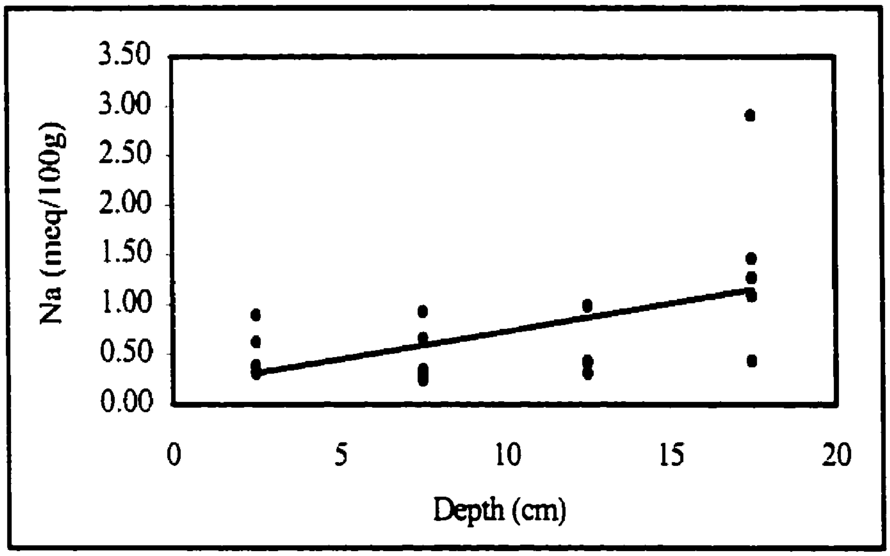

Figure 5.2. Relationship between sodium (Na) concentration and depth in the profile for the young minesoils. Equation: Na = 0.183 + 0.0554(depth in cm), n=20, r^2=0.26, P=0.023.

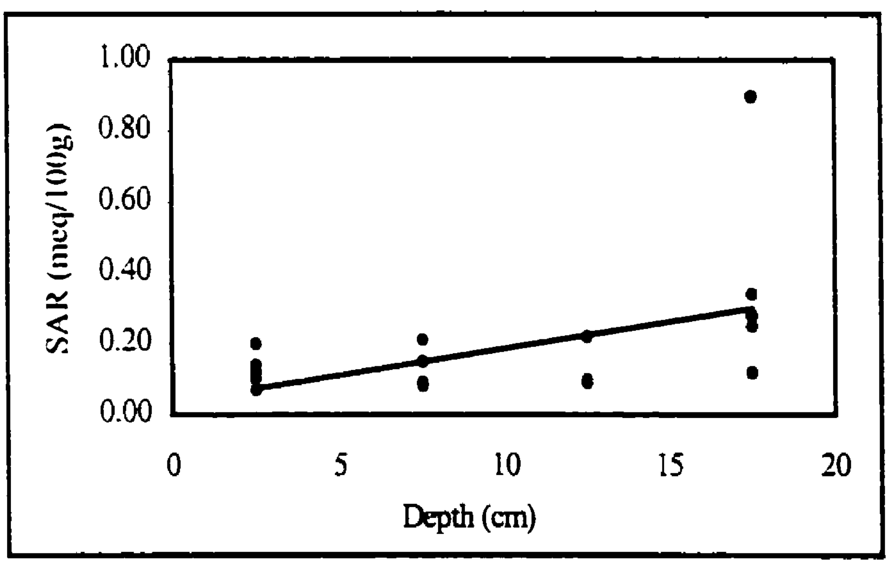

Figure 5.3. Relationship between sodium adsorption ratio (SAR) and depth in the profile for the young minesoils. Equation: SAR = 0.0356 + 0.0150(depth in cm), n=20, r^2=0.22, P=0.038.

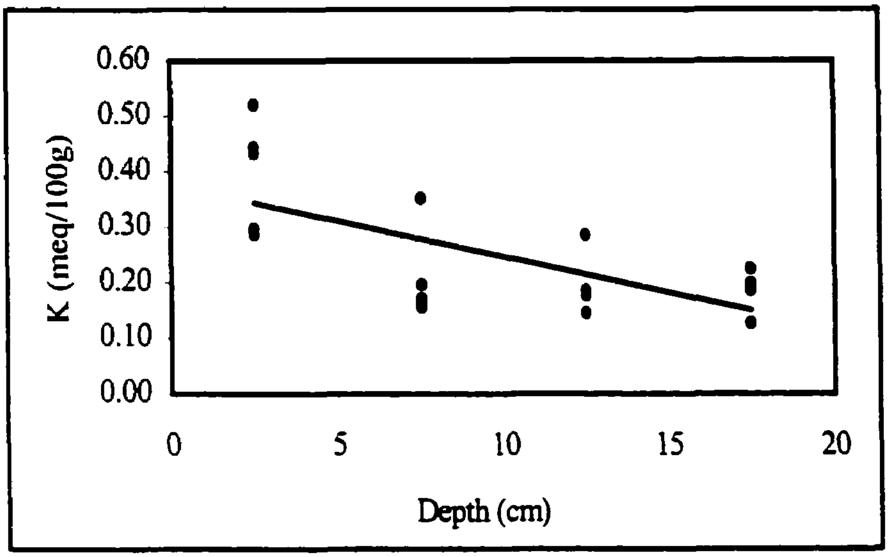

Figure 5.4. Relationship between potassium (K) concentration and depth in the profile for the medium aged minesoils. Equation: K = 0.374 - 0.0125(depth in cm), n=20, r^2=0.43, P=0.002

The depth at which a soil sample was collected explained 36% of the variance in bulk density in the youngest minesoils (Appendix B7). Bulk density values increased with increasing depth below the ground surface. The undisturbed soils demonstrated significant correlations between sand, silt, and clay content with depth. Sand and clay content tended to increase with depth, while silt content decreased with the depth in the profile (Table 5.7). Depth explained 52%, 58%, and 51% of the variance in sand, silt, and clay content, respectively (Appendices B8 to B10).

5.6 Changes in Chemical and Physical Soil Properties with Time

The majority of soil properties were correlated with the age of the site (Table 5.8). Although, the levels for total exchangeable bases, calcium, potassium, phosphorus, and nitrates had no correlation with the age of the minesoil. Regressions were performed exclusively on the soil measurements from reclaimed sites because the age of the undisturbed sites was not determined. Additionally, more realistic trends in soil development can be inferred from regression performed on values from exclusively developing reclaimed sites. These analyses were performed using the values from all depths for each age category, since there is little change with depth (0 to 40 cm) for most minesoil characteristics.

Table 5.8. Regression models for chemical and physical soil properties against reclamation site age (years).

Soil Characteristic	r	r^2	P	Regression Model
TEB (meq/100g)	-0.17	0.03	0.194	TEB= 35.4 - 0.268(age)
Ca (meq/100g)	-0.13	0.02	0.329	Ca= 30.9 - 0.191(age)
Na (meq/100g)	-0.44	0.19	<0.001*	Na= 0.943 - 0.0388(age)
K (meq/100g)	0.07	0.00	0.599	K= 0.253 + 0.00161(age)
Mg (meq/100g)	-0.29	0.08	0.027*	Mg= 3.26 - 0.0405(age)
Al (meq/100g)	0.45	0.20	<0.001*	Al= -0.032 + 0.0790(age)
SAR (meq/100g)	-0.36	0.13	0.004*	SAR= 0.231 - 0.00905(age)
PO_4-P (mg/kg)	0.25	0.06	0.059	PO_4-P= 0.188 + 0.00992(age)
NO_3-N (µg/g)	0.12	0.02	0.351	NO_3-N= 0.733 + 0.0350(age)
NH_4-N (µg/g)	0.28	0.08	0.029*	NH_4-N= -0.888 + 0.405(age)
Organic Matter (%)	0.44	0.20	<0.001*	O.M.= 1.22 + 0.0490(age)
pH	-0.80	0.65	<0.001*	pH= 9.81 – 3.33($\log_{10}$ age)
EC (µS/cm)	-0.46	0.21	<0.001*	EC= 89.6 – 53.2($\log_{10}$ age)
Bulk Density (g/cm^3)	-0.56	0.31	<0.001*	D_b= 1.67 - 0.0207(age)
Sand (% by wt.)	-0.48	0.23	<0.001*	% sand= 67.4 - 1.14(age)
Silt (% by wt.)	0.28	0.08	0.016*	% silt= 35.5 + 0.562(age)
Clay (% by wt.)	0.54	0.29	<0.001*	% clay= -3.15 + 0.590(age)

* Regression significant at the P≤0.05 level.

Sodium concentration and sodium adsorption ratio tended to decrease significantly ($P<0.05$) with increasing site age but only had r^2 values of 0.19 and 0.13, respectively (Figures 5.5 and 5.6). The outliers with distinctly higher concentrations were removed and reanalyzed, but the strength of the correlation was not substantially affected. Magnesium also decreased with site age but the correlation explained only 8% of the variance (Appendix C1). The age of the site explained 20% of the variation in aluminum concentration, which tended to increase with the age of the minesoil (Figure 5.7). Ammonium values were positively, but weakly correlated with age (r^2=0.08) (Appendix C2). The percent organic matter within the soil profiles followed a trend of increasing with site age. Organic matter composition had a significant positive regression with a r^2 value of 0.20 (Figure 5.8). The strongest correlation (r^2= 0.65) with age was related to pH levels which experienced a significant logarithmic decrease over time (Figure 5.9). Electrical conductivity also decreased logarithmically over time with a r^2 value of 0.21 (Appendix C3).

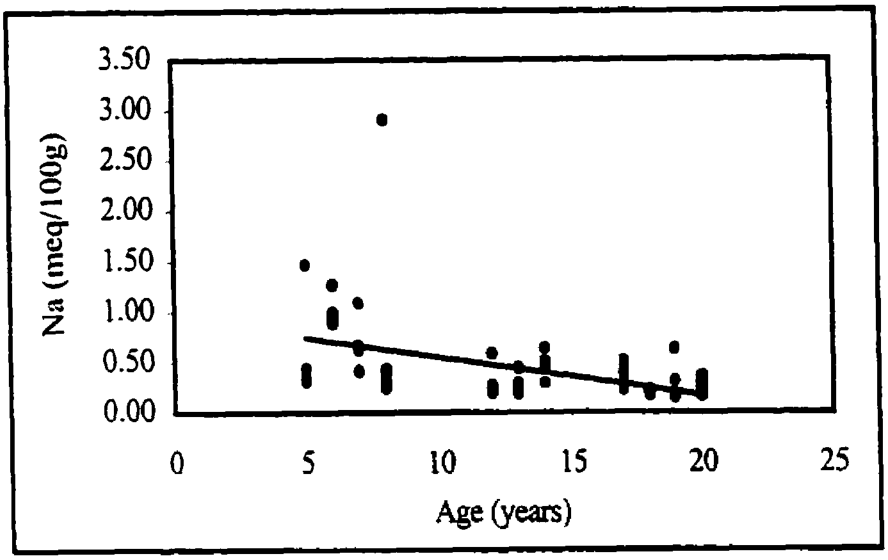

Figure 5.5. Relationship between sodium (Na) concentration and site age.
Equation: Na = 0.943 – 0.0388(age), n=60, r^2=0.19, P<0.001.

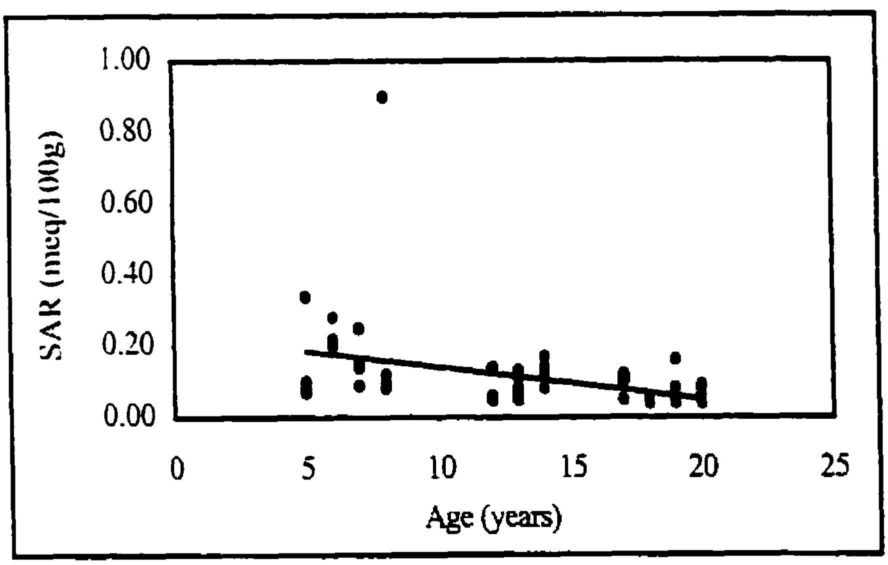

Figure 5.6 Relationship between sodium adsorption ratio (SAR) and site age.
Equation: SAR = 0.231 – 0.00905(age), n=60, r^2=0.13, P=0.004.

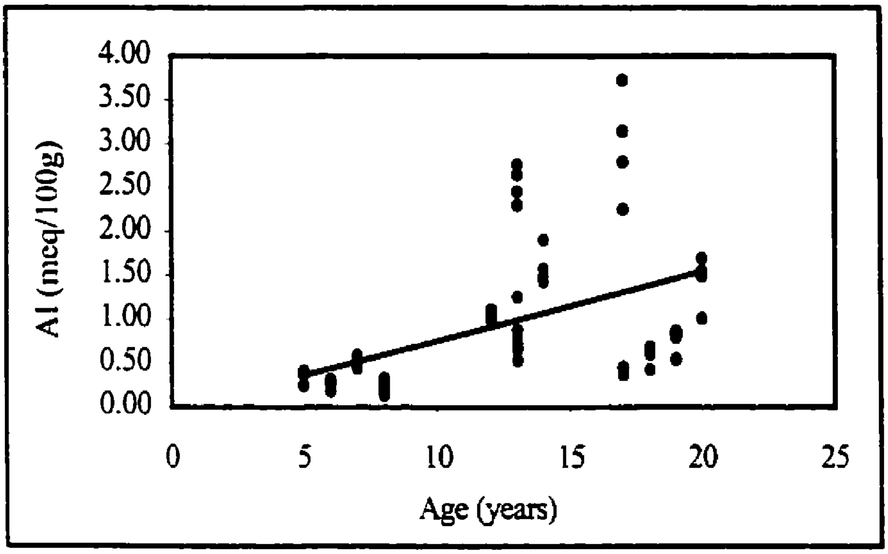

Figure 5.7. Relationship between aluminum (Al) concentration and site age.
Equation: Al = 0.032 – 0.0790(age), n=60, r^2=0.20, P<0.001.

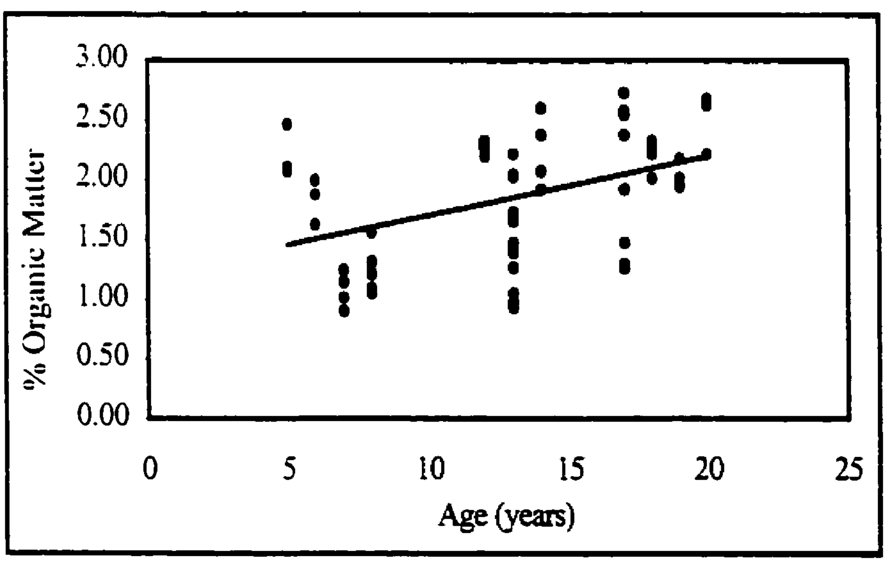

Figure 5.8. Relationship between organic matter content and site age.
Equation: % Organic matter = 1.22 + 0.490(age), n=60, r^2=0.20, P<0.001.

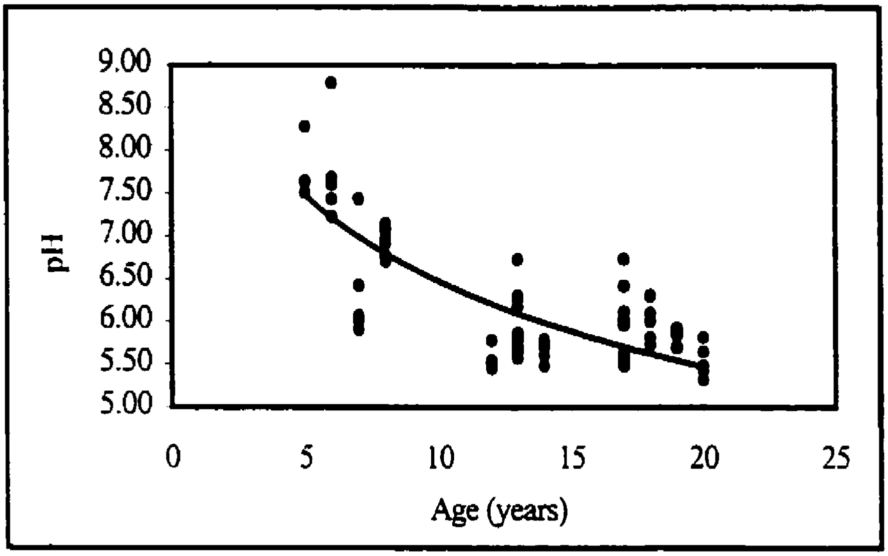

Figure 5.9. Relationship between pH and site age.
Equation: pH = 9.81 – 3.33($\log_{10}$ age), n=75, r^2=0.65, P<0.001.

Bulk density had a negative relationship with age, which explained 31% of the variation in values (Figure 5.10). The minesoils experienced a gradual decrease in overall particle size over time. The coarse (sand) component decreased over time with a r^2 value of 0.23, while the finer components of silt and clay increased over time with r^2 values of 0.08 and 0.29, respectively (Appendices C4 to C6).

Figure 5.10. Relationship between bulk density (D_b) and site age.
Equation: $D_b = 1.67 - 0.0207(\text{age})$, n=45, r^2=0.31, P<0.001.

6.0 DISCUSSION

6.1 Vegetation Composition Changes on Reclaimed Sites

The vegetation present on the reclaimed sites is generally a reflection of the species included in the original seed mixture. However, the composition did show a gradual change over time due to the invasion of volunteer species that was not statistically significant. The higher coverage of grass on the reclaimed sites compared to that on the undisturbed sites was due to the seed mixture that was used for reclamation. This seed mixture contained 70% grass species and 30% forb species. The large grass component is important for the initial coverage of a reclaimed landscape because of its ease of establishment and contribution to soil organic matter. The seed mixture is distinctly different from the composition of undisturbed sites in the area which are vegetated with dominantly ericaceous shrubs and feathermoss with little grass coverage (Strong, 2000).

The young and medium (five to 14 years old) aged sites did not have a large component of volunteer species with only five taxa between the two categories. Those that did occur on these sites are considered weedy species such as common dandelion (*Taraxacum officinale*) and fireweed (*Epilobium angustifolium*), that establish easily on disturbed sites (Strong, 2000). The old reclaimed sites had a total of 12 volunteer species, but some still can be considered indicative of a disturbed environment due to their affinity for hot, dry conditions, such as common yarrow (*Achillea millefolium*). However, other volunteer species on the old reclaimed sites such as Lindley's aster (*Aster ciliolatus*), horsetail (*Equisetum spp.*), palmate-leaved coltsfoot (*Petasites palmatus*) are found also on natural sites in the area. The presence of these taxa may suggest the return of suitable conditions for their growth, such as a lower pH and higher organic matter content in the minesoils.

6.2 Visual Minesoil and Undisturbed Soil Characteristics

The effective rooting depth defines the soil expanse which provides the major part of a plant's water supply (Hausenbuiller, 1978). The difference between the effective rooting depth of the reclaimed and undisturbed soils is associated with litter development. The predominant native soil in the study area is a Brunisolic Gray Luvisol with a customary profile sequence of LFH, Bm, Ae, Bt, BC, C (Agriculture Canada Expert Committee on Soil Survey, 1987). The majority of plant available nutrients are located in the thick LFH horizon, which causes plant roots to concentrate in this zone and limit their growth into the mineral horizons. The reclaimed soils had a thin, poorly developed LFH horizon, consequently most roots were located in the mineral soil.

The litter layer also influences rooting orientation. Since most of the water and nutrients of native soils are located in this layer, roots will have a tendency to grow horizontally near or in this layer. Strong and La Roi (1983) found that most boreal forest trees have mainly horizontally spreading roots that absorb water and nutrients from the top three to 15 cm of the ground surface. When rooting orientation is predominantly vertical in a reclaimed soil this may indicate root growth that is inhibited by soil compaction. Roots that cannot penetrate most of the soil will be more likely to grow in vertical freeze-thaw or wet-dry cracks (Naeth et al., 1991).

The decreased abundance of coarse fragments in the minesoils over time demonstrates the importance of weathering as a soil development process. Large stones brought to the surface during soil salvage and minesoil construction were broken down to the point where stoniness levels resembled the content of undisturbed soils. The greater abundance of stones at a lower depth may be related to the decreased strength of weathering with increased depth. However, this difference in weathering rates did not occur in the analysis of the <2 mm particle size fraction over time. A decrease in the stoniness of minesoils is an important soil development process that aids root penetration and increases the nutrient holding capacity of the soil.

6.3 Chemical and Physical Properties of Minesoils and Undisturbed Soils

The levels of most soil properties significantly differed between the undisturbed and newly reconstructed soils. Some of these changes may be beneficial to the growth of vegetation but others may inhibit growth. The initial goal of reclamation is to develop a quick vegetation cover to reduce erosion. The soil properties that are favorable for grasses and legumes that are used for slope stabilization, often differ from those that support coniferous tree growth, which is the end goal for revegetation on most of the study site.

Many interrelationships exist between pH and other soil properties, which is why pH is often one of the first properties examined in many soil studies. Extremely acidic or basic conditions can be the first indication of restrictions for vegetation growth. The significantly higher pH of the young minesoils in comparison to the undisturbed soils was related to the material that has been brought to the surface from depth during minesoil construction. This material has not undergone extensive weathering and has abundant cations to be released into the soil solution and as a result raises pH levels. A rating system has been developed by The Alberta Soils Advisory Committee (1987) of the ability of disturbed soils to provide a rooting medium suitable for vegetation with reference to soil properties (Appendix D1). The best classification is "good", which then decreases to fair, poor, and unsuitable. The pH of the young minesoils provided a "fair" rooting medium in the Eastern Slopes Region of Alberta (Alberta Soils Advisory Committee, 1987). The initial basic pH decreased after the young age class to classify the minesoils as "good" rooting mediums.

The pH of the young minesoils was within the preferred range of 5.5 to 7.5 for the predominantly grass and legume vegetation present on the sites (Fedkenheuer et al., 1987) (Appendix D2). The young minesoils also supported coniferous tree seedlings that were planted a few years after initial seeding. The tree seedlings prefer a lower pH range of 4.8 to 5.5 than was present in the young minesoils. Therefore, pH may be a contributing factor to the poor vigor and growth rates of tree seedlings during the first few years after planting that was reported by Strong (2000) on the Coal Valley Mine. The pH in the young minesoils may be especially limiting to the growth of white spruce seedlings. Lodgepole pine have a greater tolerance of pH (3.9 to 7.5), than the range of 4.7 to 6.5 recommended for white spruce (Fedkenheuer et al., 1987). However, the preferred pH ranges of both species were met after at least 12 years of soil development, and their heights were predicted to exceed year 14 standards of the Alberta Forest Service (Strong, 2000).

Electrical conductivity in minesoils is often elevated in comparison to undisturbed soils (Edwards and Schumacher, 1989). The soils on the studied sites were no exception, although the increase was not statistically significant due to the high variability of the values, especially in the young minesoils. The concern for a minesoil is that levels will exceed the recommended limit of <2000 μS/cm for good rooting material (Alberta Soils Advisory Committee, 1987), but all minesoils in this study were well below this upper limit. If electrical conductivity levels are high, excess quantities of soluble salts are in the soil solution and can suppress plant growth.

The increased concentrations of total exchangeable bases, calcium, and magnesium in the minesoils when compared to the undisturbed soils, is related to the weathering of material that has been brought to the surface during reclamation. Cations are released from this material to become part of the exchangeable nutrient pool. Calcium levels in the minesoils met and exceeded the requirements for grasses and legumes (0.20 meq/100g) and conifer seedlings (3 to 8 meq/100g) (Fedkenheuer et al., 1987). Magnesium concentrations in the minesoils also exceeded the requirements for the planted vegetation. Conifer seedlings require 0.4 to 2.0 meq/100g of magnesium for proper growth, while grasses and legumes only require 0.30 meq/100g (Fedkenheuer et al., 1987). An excessive increase in the concentration of calcium and magnesium is not reflected in electrical conductivity values. Additionally, toxic levels of macronutrients rarely occur because plants can tolerate excesses of these nutrients (Brady and Weil, 1999).

A study by Bussler et al. (1984) found potassium levels to be deficient in minesoils. The minesoils on the Coal Valley Mine provided the recommended potassium for both conifer tree seedlings (0.2 to 0.3 meq/100g), and grasses and legumes (0.25 meq/100g) (Fedkenheuer et al., 1987). Mine personnel had concerns about the sodicity of the minesoils, due to inclusions of bentonite layers within the overburden. However, all of the soil samples had sodium adsorption ratio values that easily met the recommendations for good root zone material (Alberta Soils Advisory Committee, 1987).

Phosphorus levels are often inadequate in a minesoil (Monterroso Martinez et al., 1996). The phosphorus concentrations in the minesoils and undisturbed soils on the Coal Valley Mine were considered deficient for the growth of conifer seedlings, which require a range of 1.00 to 1.50 mg/kg (Fedkenheuer et al., 1987). However, all minesoils and undisturbed soils had acceptable levels for the maintenance of lodgepole pine growth once past the seedling stage. The slightly higher phosphorus needs of white spruce trees, and grasses and legumes were provided by the medium aged minesoils and undisturbed soils.

Exchangeable aluminum is closely associated with the pH of the soil solution; low pH results in higher solubility of aluminum. The highest aluminum concentrations were found in the undisturbed soils, which also had the lowest pH. The largest change in pH occurred between the young and medium aged minesoils, which is where the jump in aluminum levels also occurred.

Low organic matter content was present in the mineral portion of the undisturbed soils within the study area before mining commenced. Grasses and forbs were seeded on the reclaimed sites to ameliorate this low content by providing litter that is available for accumulation of organic matter. Despite low organic matter content being a "normal" condition in the study area, the levels in the minesoils were still considered deficient for the growth of most reclamation species. Organic matter content should be between 3% and 5% to provide sufficient nutrients for conifer seedlings and greater than 5% for proper growth of grasses and legumes (Fedkenheuer et al., 1987). None of the minesoils or the undisturbed soils met this requirement, and therefore, poor seedling growth on the young minesoils may occur. The continued growth of white spruce and lodgepole pine trees require organic matter contents of 3% to 5%, and 0.7%, respectively. Sufficient levels were provided for lodgepole pine, but insufficient organic matter content was available for white spruce in the minesoils and undisturbed soils.

The minesoils experienced a bulk density increase of 0.27 g/cm^3 from the undisturbed soils to the young minesoils. This increase resulted in a rooting medium slightly more compacted than the 1.5 g/cm^3 limit for reconstructed soils suggested by Fedkenheuer et al. (1987) in the young minesoils. However, bulk density had decreased to acceptable levels after at least 12 years of soil development.

The greater sand component of the minesoils in comparison to the undisturbed soils was related to coarse particles brought to the surface from mixing. The mixing that occurs during minesoil construction changes the proportions of sand, silt, and clay that would be present in the A and B horizons of a native soil. Despite this mixing, the sandy loam and loam textures that occurred most often in the minesoils provide no limitations as root zone material (Alberta Soils Advisory Committee, 1987). These textures also are classified as favorable for the growth of both conifers and herbs (Knapik and Rosentreter, 1999).

Large changes in soil properties can occur due to soil salvage operations and minesoil construction. However, the nutrient and rooting medium needs of the vegetation on reclaimed sites are met for the most part by these minesoils. Bulk density and pH were out of the desirable range for either vegetation or a rooting medium in the early years after reclamation. However, levels were within these desirable ranges by the medium age category or at least 12 years of soil development. Phosphorus and organic matter were considered deficient for most of the revegetation types throughout the studied time period, but these nutrients are generally not statistically different from undisturbed soils. Additionally, organic matter and phosphorus are also usually deficient in natural soils from the study area (Dumanski et al., 1972).

6.4 Minesoil Development

The exchangeable cations (Al^{3+}, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) in a soil are derived mainly from mineral weathering. Each of these cations has a different adsorption affinity to exchange sites on clay or organic matter (Hausenbuiller, 1978). The main factor that determines the strength of adsorption is the valence of the cation. The higher the valence, the stronger the adsorption to an exchange site. Therefore, in order of decreasing adsorption affinity the cations are: $Al^{3+} > Ca^{2+} = Mg^{2+} > K^{+} = NH_4^{+} > Na^{+}$ (Hausenbuiller, 1978).

The lack of a significant correlation between total exchangeable bases and either profile depth or site age was hindered by an inconsistent trend among the four bases (Ca^{2+}, Na^{+}, K^{+}, Mg^{2+}) that make up the total. The high adsorption affinity of calcium prevents it from being leached easily and is associated with its stability in the profile over the studied time period. The undisturbed soil has been developing since glacial times; therefore, calcium has been leached to about half of the concentration present in the minesoils. The tendency of magnesium to form secondary minerals in weathering environments may be related to decreased magnesium concentration over time (Hausenbuiller, 1978). As magnesium becomes part of a secondary mineral it is no longer in an exchangeable form. Leaching of magnesium may be slowed by the formation of secondary minerals perhaps preventing detection of differences within the sampling depth of a profile.

The low adsorption affinity of sodium (Na^+) is attributed to the hydration and small atomic size of the ion. The sodium ion retains a thick water shell which inhibits tight adsorption to clay surfaces (Hausenbuiller, 1978). The ease with which sodium is leached could explain the increased sodium levels and sodium adsorption ratios with increasing depth in the profile that occurred in the youngest minesoils. The other age classes had no correlation between sodium and profile depth because the majority of the sodium has most likely leached out of the sampling depth or dispersed itself throughout the profile. The solubility properties of sodium also support the trend of decreased sodium concentration and sodium adsorption ratio with the age of the site. As the sites age, more sodium will be leached out of the sampling depth.

Potassium is a small ion with high mobility due to its low bonding capabilities (Hausenbuiller, 1978). The small size of the potassium (K^+) ion is useful between clay layers and it becomes a common component in clay structure. The study area contains smectite clays, which have the ability to fix large quantities of potassium (Brady and Weil, 1999). If potassium is immobilized in clay structures it can be released slowly over time which is associated with the lack of correlation between potassium and site age.

Metals generally increase in solubility with a decrease in the pH of the soil solution. The near neutral pH of the young minesoils was associated with low concentrations of aluminum. As the pH decreased with site age a corresponding increase in aluminum concentration occurred. Higher levels of exchangeable aluminum over time also may be related to an increase in the availability of exchange sites. As the minesoils develop, the concentration of other cations that may occupy exchange sites such as sodium and magnesium decrease due to leaching. With aging, more exchange sites would be available due to organic matter accumulation and increased clay content. The high adsorption affinity of aluminum and its incorporation into clay structures results in a slow release from exchange sites and this may be why changes in concentration are undetectable throughout the depth (40 cm) of the sampled profiles.

Nitrogen and phosphorus are the most commonly deficient nutrients in any soil (Hausenbuiller, 1978). The reason for common phosphorus deficiencies is because it easily forms insoluble precipitates with many other elements. When the pH is neutral or basic this precipitate would commonly be calcium phosphate. Acidic conditions result in the instability of this compound and the formation of complexes between phosphorus and iron or aluminum (Hausenbuiller, 1978). The small amounts of phosphorus present in the minesoils would be very susceptible to fixation with other elements. Complexed phosphorus is less available for soil reactions and uptake by plants, which helps to explain the lack of variation in phosphorus concentration with site age.

The larger quantity of phosphorus at the surface in the old minesoils is associated with increased organic matter content, which is an important source of phosphorus (Brady and Weil, 1999). The shallow effective rooting depth may also help concentrate phosphorus near the soil surface. In an investigation of minesoils, Chichester and Hauser (1991) found little phosphorus below the zone of active rooting.

Soil temperature can have an effect on the amount of extractable nitrogen in a soil. Nitrate (NO_3^-) formation is especially sensitive to temperature, which could explain its correlation with depth and the lack of a correlation with depth for ammonium (NH_4^+). Nitrification proceeds very slowly between freezing and 5°C, and has a maximum rate between 25°C and 40°C (Hausenbuiller, 1978). The warmest month in the study area has a mean daily temperature of 12.9°C therefore; favorable temperature conditions for nitrification are minimal. Additionally, soil temperatures are generally lower than ambient air temperature. Warmer temperatures at the soil surface may be related to the increased level of nitrates seen near the surface in the medium minesoils.

Extractable ammonium showed an increase with site age which may be associated with a build up of nitrogen from N-fixing legumes and increased nitrogen formation by microorganisms due to the increased organic matter content. Furthermore, increased organic matter content would lead to healthier plants that can adequately provide the nutritional needs of N-fixing bacteria leading to an increase in population size. The increased levels of ammonium and lack of change in nitrates as a site ages may be due to leaching or to plant preferences. Ammonium ions can be adsorbed onto exchange sites and held within the soil profile, while nitrate ions do not adsorb to clay or organic matter and are easily lost by leaching (Hausenbuiller, 1978). Plants generally prefer the NO_3^- form of nitrogen because it is easily absorbed, which helps to explain the low levels of NO_3^- throughout the age classes that were studied. However, some plants prefer NH_4^+ ions during the early stages of their growth. Available NH_4^+ may be used more readily by young plants and then experience decreased uptake by roots over time. This preference is associated with low initial levels of NH_4^+ in the young minesoils that increase over time. Chichester and Hauser (1991) also found this trend of a widening gap between NH_4^+ and NO_3^- concentrations over time in minesoils.

The time required for grass and forb litter to decompose and become part of the minesoil is reflected in increased organic matter content with site age. The accumulation of organic matter is important to soil development because of its impact on many other soil properties. Organic matter provides valuable exchange sites necessary for vegetation growth. Organic matter is also important for the development of soil structure, which creates pore space and decreases bulk density. The accumulation of organic matter is not forming a measurable surface organic layer which would be a logical step in the soil development of a site that is vegetated with grasses and forbs. The lack of differentiation with depth in the undisturbed soils is expected because the litter layer was not sampled, which holds the majority of the organic matter in a natural soil from this region.

The increased pH with increasing soil depth and decreased pH over time reflects the occurrence of leaching in all of the minesoils. As bases are leached further down in the profile they would contribute to a higher pH at depth. As the bases are removed from the top of the profile or from the profile entirely, they may be replaced on exchange sites by Al^{3+} or H^+ ions, serving to exacerbate the pH change with depth. A positive reinforcement cycle then forms because once a soil solution is acidic, the organic matter loses its ability to hold cations, which are then lost to the system serving to further reduce the pH (Hausenbuiller, 1978).

The leaching discussed above also influences the electrical conductivity of the minesoils. As soluble salts were leached from the profile, the electrical conductivity decreased over time. The logarithmic relationship between electrical conductivity and site age indicates that the rate of removal was initially rapid and then leveled out. More time for soil development is needed to establish the pattern of differentiation in electrical conductivity values with depth that occurred in the undisturbed soils. A natural soil from this region will have the majority of its organic matter near the surface in the litter layers. Consequently, the soluble salts are located in the upper part of the profile for exchange with plant roots, resulting in higher electrical conductivity near the surface. Additionally, the soluble salts are derived in a large part from the litter on the site rather than from weathering processes. The majority of salts from the parent material have been removed from the profile by leaching early in soil development.

The overall decrease in bulk density over time in the minesoils is associated with increased organic matter content, plant root growth, and structure development. These processes increase pore space, and therefore, decrease soil bulk density. Most soil will demonstrate an increase in bulk density with increasing depth in the profile (Manrique and Jones, 1991). This trend was present in the young minesoils but was not evident in any of the other soil classes. Minesoil construction often produces a medium that has been highly compacted by machinery. The break up of this compacted soil will begin at the surface because soil processes proceed at a higher rate near the surface due to higher temperatures and water availability. Plant roots also can have a significant impact on soil bulk density and would be most active in the upper part of the profile in a young minesoil. A deeper sampling depth would most likely show a greater bulk density in the subsoil for the medium and old minesoils and the undisturbed soils when compared to the surface.

The trends observed in particle size over time highlights the importance of weathering for minesoil development. An overall decrease in particle size was ascertained by the increase in silt and clay content and the corresponding decrease in sand content. The sand particles are breaking down to reduce their contribution to soil texture, and increase the silt and clay components over time. Intense weathering processes are in place to result in a finer texture in the old minesoils than that of the undisturbed soils. However, the depth of sampling may have contributed to findings of low clay levels in the undisturbed soils. The majority of clay has been translocated deeper than the sampling depth over the extensive period of development that the undisturbed soils have undergone.

Weathering processes are said to occur throughout a constructed soil profile (Varela et al., 1993), which was supported by insignificant differences in particle size with depth in the soil. However, the undisturbed soils show differential weathering with depth. There is a larger sand component at depth in the undisturbed soils because the parent material is of a sandy nature and less weathering has occurred at depth. Soil development processes have resulted in translocation of clay deeper into the profile. Silt particles are not as easily translocated due to their size, and tend to accumulate at the top of a profile in a native soil, contributing to the development of an Ae horizon. This differentiation in particle size within the profile has not occurred in the minesoils due to the relatively short development time.

An analysis of the trends in soil chemical and physical properties in the minesoils indicates that weathering, leaching, and organic matter development are the dominant soil forming processes. These processes had the greatest influence on the concentrations or levels of minesoil properties within a profile, and over the 20 year time period. The data also suggests that these processes cause a relatively rapid return of most soil properties to resemble levels in undisturbed soils over the studied time period. Trends indicating either increases or decreases towards undisturbed conditions were observed in 10 of 17 soil properties. However, some properties such as potassium, did not have a relationship with site age but were also not statistically different from undisturbed soils, even in the young minesoils. Therefore, 11 of 17 soil properties either have reached, or are trending towards undisturbed values. Organic matter and clay content were increasing over time, which is the opposite direction from values present in undisturbed soils. Additionally, four properties (TEB, Ca, P, and NO_3-N) had no indication of changes toward or away from the values of undisturbed soils. These soil properties may need a longer period of soil development to approximate undisturbed levels.

However, similarity of nutrient values is one aspect of the comparison between minesoils and undisturbed soils. It should be emphasized that these values were an average of the entire sampling depth of 40 cm. The long-term aspect of soil development may be the differentiation of properties within a profile. Therefore, the minesoils and the undisturbed soils in the study area are still considered quite different. The only soil property that displayed a consistent trend within the profile that matched the trend in an undisturbed soil was pH. A native soil in the area would have the lowest pH at the surface and then demonstrate an increase toward the C horizon (Knapik and Rosentreter, 1999). The lack of trends within the undisturbed profiles in this study was most likely due to the sampling methodology, which was based on distinct depths, rather than horizons. A soil horizon is relatively homogeneous and differences generally are found between horizons.

Soil classification is based mainly on horizon differentiation. The first step in horizon differentiation is the formation of an A horizon. The rapid development of a surface organic or A horizon in minesoils has been observed within a three year period by Varela et al. (1993). Knapik and Rosentreter (1999) documented Ah horizons with a thickness of four to 12 cm on the Coal Valley Mine after less than 15 years of soil development. Observations of surface darkening in the minesoils of up to six cm thickness were noted in the current study, however a greater surface accumulation of organic matter was not demonstrated by the chemical analysis. Increased organic matter at the surface may lead to the development of an Ah, Bm, C horizon sequence, resulting in classification within the Brunisolic order of the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey, 1987). Anderson (1977) found the development of a cambic B horizon (Bm) in less than 50 years. Significant time would most likely be required to develop past the Bm stage of classification. A study of secondary soil development of windthrow mounds reported Ae and Bh horizon development in 50 to

250 years (Bormann et al., 1995). The development of a Bt horizon is estimated to take greater than 1000 years (Yaalon, 1983). Clay was increasing in the minesoil profile, but translocation downward over time is needed for the return of a Luvisolic soil.

7.0 CONCLUSIONS AND FUTURE RESEARCH

The data analysis and interpretation resulted in the conclusion that soil development processes are active within the minesoils, and these processes have impacted the concentration or levels of chemical and physical properties over a 20 year time period. The direction of changes observed in these properties suggests a relatively rapid return (≤50 years) of profile averages to levels in undisturbed soils for Na, SAR, EC, bulk density (D_b), Mg, pH, Al, NH_4-N, K, and sand and silt content. Important steps for reclamation success were occurring in the minesoils, such as increased organic matter content, and increased phosphorus (PO_4-P) and ammonium (NH_4-N) concentrations. However, little horizon differentiation, physical or chemical differences within a profile depth were observed in the 20 year time period. The principal changes and trends in the chemical and physical properties of the minesoils are summarized below.

- Total exchangeable bases, calcium, magnesium, pH, and sand content increased significantly between undisturbed soils and new reconstructed minesoils.
- Aluminum, phosphorus, and silt content decreased significantly between undisturbed soils and new reconstructed minesoils.
- Sodium, potassium, sodium adsorption ratio, nitrates, ammonium, electrical conductivity, bulk density, and organic matter and clay content were not significantly different between undisturbed soils and new reconstructed minesoils.

- The concentrations or levels of most soil properties examined generally provided no limitations as a rooting medium or for the nutrition of revegetation species.
- Bulk density and pH were higher than the desired range for vegetation or a rooting medium in the youngest minesoils, but decreased to favorable levels by the medium age category.
- Organic matter and phosphorus levels were considered deficient for the needs of the revegetation species, but also were deficient in the undisturbed soils.
- The dominant soil development processes in the minesoils over the 20 year time period studied were weathering, leaching, and organic matter accumulation.
- All minesoil age categories had increased pH with increasing profile depth.
- Sodium, sodium adsorption ratio, electrical conductivity, bulk density, magnesium, pH, and sand content all decreased with site age toward levels observed in undisturbed soils.
- Aluminum, ammonium, and silt content increased with site age toward levels observed in undisturbed soils.
- Organic matter and clay content increased with site age past levels observed in undisturbed soils.
- Total exchangeable bases, calcium, potassium, phosphorus, and nitrate concentration had no relationship with site age.

The Coal Valley Mine is an example of successful reclamation, causing an acceleration of minesoil properties toward values present in undisturbed soils. Future research would benefit by a long-term study using the same sites to verify the changes that occur in chemical and physical soil properties within a 50 year time span. It is possible that the regression models will change over time to reveal more logarithmic relationships between soil properties and time. Confirmation of the rate of change in these minesoils would be advantageous for reclamation professionals. Minesoil research with a focus on horizon development could help elucidate rates for differentiation within a profile.

REFERENCES

Agriculture Canada Expert Committee on Soil Survey. 1982. The Canada soil information system (CanSIS) manual for describing soils in the field. Agriculture Canada, Ottawa, ON. 97 pp.

Agriculture Canada Expert Committee on Soil Survey. 1987. The Canadian system of soil classification. 2nd ed. Agriculture Canada Publication 1646, Ottawa, ON. 164 pp.

Alberta Environmental Protection. 1997. Conservation and reclamation guidelines for Alberta. Conservation and Reclamation Information Letter 97-1. Edmonton, AB. 2 pp.

Alberta Soils Advisory Committee. 1993. Soil quality criteria relative to disturbance and reclamation (Revised). Prepared for Alberta Agriculture by the Soil Quality Criteria Working Group. Edmonton, AB. 56 pp.

Albrecht, S.C. and Thompson, E.R. 1982. Impact of surface mining on soil compaction in the mid-western U.S.A. Prepared for Bureau of Mines by Hittman Associates Inc., Lexington Kentucky. U.S. Department of the Interior Open File Report. 319 pp.

Allen, B.L. and Fanning, D.S. 1983. Composition and soil genesis. Pages 141-192 *in* L.P. Wilding, N.E. Smeck, and G.F. Hall, eds. Pedogenesis and soil taxonomy I. Concepts and interactions. Elsevier, New York, NY, USA.

Anderson, D.W. 1977. Early stages of soil formation on glacial till mine spoils in a semi-arid climate. Geoderma. 19: 11-19

Atkinson, H.J. and Wright, J.R. 1967. Chelation and the vertical movement of soil constituents. Pages 366-386. *in* J.V. Drew, ed. Selected papers in soil formation and classification. Soil Science Society of America Inc., Special Publication #1, Madison, WI, USA.

Baker, J. 1973. Nitrogen fractionation of two forest soils in Alberta. Environment Canada. Forestry Service, Northern Forest Research Centre, Edmonton, AB. Information Report NOR-X-63.

Bormann, B.T., Spaltenstein, H., McClellan, M.H., Ugolini, F.C., Cromack, K. Jr., and Nay, S.M. 1995. Rapid soil development after windthrow disturbance in pristine forests. Journal of Ecology. 83: 747-757.

Brady, N.C. and Weil, R.R. 1999. The nature and properties of soil. 12th ed. Prentice Hall, Upper Saddle River, NJ, USA. 881 pp.

Burt, J.E. and Barber, G.M. 1996. Elementary statistics for geographers. 2nd ed. The Guilford Press, New York, NY, USA. 640 pp.

Bussler, B.H., Byrnes, W.R., Pope, P.E. and Chaney, W.R. 1984. Properties of minesoil reclaimed for forest land use. Soil Science Society America Journal. 48: 178-184.

Cady, J.G. 1967. Mineral occurrence in relation to soil profile differentiation. Pages 336-341 *in* J.V. Drew, ed. Selected papers in soil formation and classification. Soil Science Society of America Inc., Special Publication #1, Madison, WI, USA.

Chen, H., Zheng, C., and Zhu, Y. 1998. Phosphorus: A limiting factor for restoration of soil fertility in a newly reclaimed coal mined site in Xuzhou, China. Land Degradation and Development. 9: 115-121.

Chichester, F.W. and Hauser, V.L. 1991. Change in chemical properties of constructed minesoils developing under forage grass management. Soil Science Society of America Journal. 55: 451-459.

Crocker, R.L. 1967. The plant factor in soil formation. Pages 179-190 *in* J.V. Drew, ed. Selected papers in soil formation and classification. Soil Science Society of America Inc., Special Publication #1, Madison, WI, USA.

Crompton, E. 1967. Soil formation. Pages 3-15 *in* J.V. Drew, ed. Selected papers in soil formation and classification. Soil Science Society of America Inc., Special Publication #1, Madison, WI, USA.

Davies, R., Younger, A. and Chapman, R. 1992. Water availability in a restored soil. Soil Use and Management. 8(2): 67-73.

Dumanski, J., Macyk, T.M., Veauvy, C.F. and Lindsay, J.D. 1972. Soil survey and land evaluation of the Hinton-Edson area. Research Council of Alberta, Report No. 93, Alberta Soil Survey Report No. 31, Edmonton, AB. 119 pp.

Edwards, L.M. and Schumacher, A.E. 1989. Soil and vegetation inter-relationships on reclaimed coal mine sites. Soil Use and Management. 5(2): 58-62.

Ehrlich, W.A., Rice, H.M. and Ellis, J.H. 1967. Influence of the composition of parent materials on soil formation in Manitoba. Pages 228-244 *in* J.V. Drew, ed. Selected papers in soil formation and classification. Soil Science Society of America Inc., Special Publication #1, Madison, WI, USA.

Environment Canada. 2000. National Climate Data Archive. Ottawa, ON. www.cmc.ec.gc.ca/climate_archive.htm.

Fedkenheuer, A.W., Knapik, L,J. and Walker, D.G. 1987. Minesoil and landscape reclamation of the coal mines in Alberta's mountains and foothills. Alberta Land Conservation and Reclamation Council. Report No. RRTAC 87-2, Edmonton, AB. 174 pp.

Fyles, H. 1984. Nitrogen cycling through soil-plant systems on high elevation reclaimed minesites. M.Sc. Thesis, University of Alberta, Edmonton, AB.

Gentcheva-Kostadinova, S. and Zheleva, E. 1994. Soil constraints affecting the forest-biological recultivation of coal-mine spoil banks in Bulgaria. International Journal of Surface Mining, Reclamation and Environment. 8: 47-53.

Glinski, J. and Lipiec, J. 1990. Soil physical conditions and plant roots. CRC Press Inc., Boca Raton, FL. USA. 250pp.

Government of Alberta. 2000. Alberta natural regions land classification system. Edmonton, AB. www.gov.ab.ca/env/parks/anhic/landclas.html.

Government of Canada. 2000. Canada land use inventory maps. Ottawa, ON. geogratis.icdg.gc.ca/CLI/frames.html.

Haigh, M.J. 1995. Soil quality standards for reclaimed coal-mine disturbed lands: A discussion paper. International Journal of Surface Mining, Reclamation and Environment. 9: 187-202.

Hausenbuiller, R.L. 1978. Soil science. 2nd ed. Wm. C. Brown Company, Dubuque, Iowa. 611 pp.

Headdon, D. 1980. Physical site characteristics of abandoned coal mine spoil heaps: York Creek Mine, Coleman, Alberta. M.Sc. Thesis. University of Calgary, Calgary, AB. 182 pp.

Hendershot, W.H. and Duquette, M. 1986. A simple barium chloride method for determining cation exchange capacity and exchangeable cations. Soil Science Society of America Journal. 50: 605-608.

Howitt, R.W. 1981. Dynamics of a Gray Luvisol. M.Sc. Thesis. University of Alberta, Edmonton, AB.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill, New York, NY, USA.

Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil Science Society of America Journal. 47: 1208-1211.

Kalra, Y.P. and Maynard, D.G. 1991. Methods manual for forest soil and plant analysis. Foresty Canada, Northwest Region, Northern Forest Research Centre, Information Report NOR-X-319. Edmonton, AB. 116 pp.

Keck, T.J., Quimby, W.F., and Nielsen, G.A. 1993. Spatial distribution of soil attributes on reconstructed minesoils. Soil Science Society of America Journal. 57: 782-786.

King, J.A. and Evans, E.J. 1989. The growth of spring barley related to soil tilth produced on restored open cast and unmined land. Soil Tillage Research. 14: 115-130.

Knapik, L.J. and Rosentreter, R.L. 1999. Characteristics and quality of minesoil profiles and minesoil landscapes at the Coal Valley Mine. *in* Coal Valley Mine Extension Project. Luscar Ltd., Edson, AB. 62pp.

Kost, D.A., Vimmerstedt, J.P. and Brown, J.H. 1998. Site factor effects on establishment of planted and volunteer trees and shrubs on graded cast overburden and replaced topsoil in Southeastern Ohio. International Journal of Surface Mining, Reclamation and Environment. 12: 79-86.

Lesko, G.L., Etter, H.M. and Dillon, T.M. 1975. Species selection, seedling establishment and early growth on coal mine spoils at Luscar, Alberta. Environment Canada. Forestry Service. Northern Forest Research Centre. Information Report NOR-X-117, Edmonton, AB.

Li, R.S. and Daniels, W.L. 1994. Nitrogen accumulation and form over time in young mine soils. Journal of Environmental Quality. 23: 166-172.

Limbird, A.G. 1997. Soil characteristics and formation manual. University of Calgary, Calgary, AB. 42 pp.

Lyle, E.S. Jr. 1987. Surface mine reclamation manual. Elsevier, New York, NY, USA. 260 pp.

Macyk, T.M. 1986. Characterization and variability of soils reconstructed after surface mining in central, Alberta. Alberta Land Conservation and Reclamation Council. Report No. RRTAC 86-2. Edmonton, AB.

Macyk, T.M. and Steward, J. 1977. Reclamation at McIntyre No. 8 Mine. *in* Coal Industry Reclamation Symposium, Banff, AB. 13pp.

Manrique, L.A. and Jones, C.A. 1991. Bulk density of soils in relation to soil physical and chemical properties. Soil Science Society of America Journal. 55: 476-481.

Mays, D.A. and Bengtson, G.W. 1978. Lime and fertilizer use in land reclamation in humid regions. Pages 307-328 *in* F.W. Schaller and P. Sutton, eds. Reclamation of drastically disturbed lands. American Society of Agronomy, Madison, WI, USA.

McIntosh, J.E. and Barnhisel, R.I. 1993. Erodibility and sediment yield by natural rainfall from reconstructed mine soils. Soil Science. 156(2): 118-126.

McKeague, J.A. 1978. Manual of soil sampling and methods of analysis. 2nd ed. Canadian Society of Soil Science, Ottawa, ON.

McSweeney, K. and Jansen, I.J. 1984. Soil structure and associated rooting behavior in minesoils. Soil Science Society of America Journal. 48: 607-612.

Merrill, S.D., Ries, R.E., and Power, J.F. 1998. Subsoil characteristics and landscape position affect productivity of reconstructed mine soils. Soil Science Society of America Journal. 62: 263-271.

Miller, R.G., Jr. (Ed.) 1966. Simultaneous statistical inferences. 2nd. Springer-Verlag, New York, NY, USA. 272 pp.

Monterroso Martinez, C., Fernandez Marcos, M.L., and Alvarez Rodriguez, E. 1996. Factors influencing phosphorus adsorption in mine soils in Galicia, Spain. Science of the Total Environment. 180: 137-145.

Moss, E.H. 1983. Flora of Alberta. 2nd ed. University of Toronto Press, Toronto, ON. 687 pp.

Mottle, B.J. and Moorman, B.J. 1999. Maximizing soil textural data quality from automated particle size analyzers. Proceedings CANQUA-CGRC Conference. August 23-27. University of Calgary, Calgary, AB.

Munshower, F.F. 1994. Practical handbook of disturbed land revegetation. Lewis Publishers, Boca Raton, FL, USA. 265 pp.

Naeth, M.A., White, D.J., Chanasyk, D.S., Macyk, T.M., Powter, C.B., and Thacker, D.J. 1991. Soil physical properties in reclamation. Alberta Land Conservation and Reclamation Council. Report No. RRTAC 91-4. ISBN 0-7732-0880-1, Edmonton, AB. 216 pp.

Nicolau, J.M. 1996. Effects of topsoiling on rates of erosion and erosion processes in coal mine spoil banks in Utrillas, Teruel, Spain. International Journal of Surface Mining, Reclamation and Environment. 10: 73-78.

Omodt, H.W., Schroer, F.W., and Patterson, D.B. 1975. The properties of important agricultural soils as criteria for mined land reclamation. North Dakota State University, Agricultural Experiment Station, Fargo, ND. Bulletin No. 492. 52pp.

Osborne, J.M. 1996. Self-sustainable reclamation: Shrub and tree establishment on saline mine wastes. International Journal of Surface Mining, Reclamation and Environment. 10: 91-95.

Page, A.L. ed. 1982. Methods of soil analysis, Part 2: Chemical and microbiological properties. 2nd ed. American Society of Agronomy Inc., Soil Science Society of America Inc., Madison, WI, USA.

Potter, K.N., Carter, F.S. and Doll, E.C. 1988. Physical properties of constructed and undisturbed soils. Soil Science Society of America Journal. 52: 1435-1438.

Ross, S. 1989. Soil Processes. Routledge, New York, NY, USA. 611 pp.

Schafer, W.M. 1979. Variability of minesoils and natural soils in Southeastern Montana. Soil Science Society of America Journal. 43: 1207-1212.

Simonson, R.W. 1967. Outline of a generalized theory of soil genesis. Pages 301-310 *in* J.V. Drew, ed. Selected papers in soil formation and classification. Soil Science Society of America Inc., Special Publication #1, Madison, WI, USA.

Strong, W.L. 1999. Reclamation vegetation development on the Coal Valley Mine in western Alberta, Canada. *in* Coal Valley Mine Extension Project, Luscar Ltd., Edson, AB.

Strong, W.L. 2000. Vegetation development on reclaimed lands in the Coal Valley Mine of western Alberta, Canada. Canadian Journal of Botany. 78: 110-118.

Strong, W.L. and LaRoi, G.H. 1983. Rooting depths and successional development of selected boreal forest communities. Canadian Journal of Forest Research. 13: 577-588.

Takyi, S.K. and Islam, R.M. 1985. Maintenance fertilization of a revegetated subalpine coal mine spoil. Proceedings 21st Alberta Soil Science Workshop, Lethbridge, AB.

Thurber Consultants Ltd., Land Resource Network Ltd., and Norwest Soil Research Ltd. 1990. Review of the effects of storage on topsoil quality. Alberta Land Conservation and Reclamation Concil Report No. RRTAC 90-5, Edmonton, AB. 116 pp.

Ugolini, F.C. and Edmonds, R. L. 1983. Soil biology. Pages 193-231. *in* L.P. Wilding, N.E. Smeck and G.F. Hall, eds. Pedogenesis and soil taxonomy I. Concepts and interactions. Elsevier, New York, NY, USA.

Varela, C., Vazquez, C., Gonzalez-Sangregorio, M.V., Leiros, M.C., and Gil-Sotres, F. 1993. Chemical and physical properties of opencast lignite minesoils. Soil Science. 156(3): 193-204.

Vepraskas, M.J. 1988. Bulk density values diagnostic of restricted root growth in coarse-textured soils. Soil Science Society of America Journal. 52: 1117-1121.

Vomocil, J.A. and Flocker, W.J. 1961. Effect of soil compaction on storage and movement of soil air and water. Trans. ASAE. 4: 242-246.

Wetherill, G.B. 1981. Intermediate statistical methods. Chapman and Hall, London, UK.

Wright, J.R., Leahey, A. and Rice, H.M. 1967. Chemical, morphological, and mineralogical characteristics of a chronosequence of soils on alluvial deposits in the Northwest Territories. Pages 257-269 *in* J.V. Drew, ed. Selected papers in soil formation and classification. Soil Science Society of America Inc., Special Publication #1, Madison, WI, USA.

Yaalon, D. H. 1983. Climate, Time, and Soil Development. Pages 233-251. *in* L.P. Wilding, N.E. Smeck and G.F. Hall, eds. Pedogenesis and soil taxonomy I. Concepts and interactions. Elsevier, New York, NY, USA.

APPENDIX A

Data and Descriptive Statistics for Chemical and Physical Tests Performed on Minesoils and Undisturbed Soils

Table A1. Soil data and descriptive statistics for chemical and physical tests performed on the young minesoils.

Profile I.D.	Depth (cm)	Exchangeable Cations (meq/100g)								Extractable N (µg/g)		Available P (mg/kg)
		TEB	Ca	Na	K	Mg	Fe	Al	SAR	NO_3-N	NH_4-N	PO_4-P
Y 01	0-5	42.36	38.02	0.90	0.44	3.00	<DL	0.32	0.20	1.10	0.00	0.06
	5-10	42.35	38.11	0.94	0.32	2.98	<DL	0.18	0.21	0.66	0.00	0.11
	10-15	42.59	38.47	1.00	0.29	2.84	<DL	0.30	0.22	0.63	0.00	0.04
	15-20	41.62	37.08	1.27	0.31	2.96	<DL	0.26	0.28	0.27	0.00	0.12
	35-40	--	--	--	--	--	--	--	--	--	--	--
Y 02	0-5	41.35	36.56	0.63	0.42	3.74	<DL	0.44	0.14	1.01	0.46	0.24
	5-10	41.00	36.42	0.67	0.29	3.63	<DL	0.59	0.15	0.30	4.79	0.26
	10-15	40.87	36.39	0.42	0.28	3.78	<DL	0.51	0.09	0.17	0.00	0.33
	15-20	39.76	35.19	1.09	0.27	3.20	<DL	0.49	0.25	1.96	3.55	0.53
	35-40	--	--	--	--	--	--	--	--	--	--	--
Y 03	0-5	41.29	37.86	0.31	0.45	2.67	<DL	0.26	0.07	0.70	0.00	0.12
	5-10	39.51	36.08	0.35	0.30	2.77	<DL	0.38	0.08	0.23	0.00	0.00
	10-15	36.29	33.00	0.44	0.26	2.60	<DL	0.25	0.10	0.24	0.00	0.11
	15-20	38.89	34.32	1.47	0.33	2.77	<DL	0.42	0.34	0.22	2.45	0.00
	35-40	--	--	--	--	--	--	--	--	--	--	--
Y 04	0-5	21.20	17.79	0.32	0.22	2.87	<DL	0.17	0.10	1.01	0.00	0.28
	5-10	22.02	18.69	0.25	0.18	2.90	<DL	0.27	0.08	0.12	0.00	0.29
	10-15	22.87	19.46	0.31	0.20	2.90	<DL	0.33	0.09	0.55	0.00	0.37
	15-20	24.05	18.08	2.91	0.21	2.85	<DL	0.33	0.90	0.16	0.00	0.39
	35-40	--	--	--	--	--	--	--	--	--	--	--
Y 05	0-5	22.38	18.99	0.40	0.24	2.75	<DL	0.15	0.12	2.52	7.71	0.14
	5-10	23.91	20.79	0.30	0.17	2.65	<DL	0.14	0.09	1.03	2.46	0.57
	10-15	25.16	22.04	0.32	0.16	2.64	<DL	0.21	0.09	0.38	5.15	0.11
	15-20	26.30	22.24	0.44	0.19	3.43	<DL	0.15	0.12	2.76	3.11	0.08
	35-40	--	--	--	--	--	--	--	--	--	--	--
Mean		33.79	29.78	0.74	0.28	3.00	--	0.31	0.19	0.80	1.48	0.21
Skewness		-0.41	-0.42	2.41	0.72	1.19	--	0.61	3.34	1.56	1.47	0.81
Kurtosis		-1.88	-1.86	7.14	-0.14	0.29	--	-0.39	12.69	1.70	1.45	-0.13
Standard Deviation		8.80	8.55	0.63	0.09	0.37	--	0.13	0.18	0.78	2.29	0.17

*<DL = less than detectable limit of 0.01 meq/100g.

Table A1. Concluded.

Profile I.D.	Depth (cm)	Organic Matter (%)	pH (H_2O)	EC (µS/cm)	Bulk Density (g/cm^3)	% Sand (by wt.)	% Silt (by wt.)	% Clay (by wt.)	Textural Class
Y 01	0-5	1.88	7.23	50.10	1.50	54.65	40.55	4.81	SL
	5-10	2.00	7.44	45.90	--	55.52	43.66	0.83	SL
	10-15	2.00	7.69	51.45	1.50	51.84	42.28	5.89	SL
	15-20	1.63	7.61	56.75	--	53.22	45.92	0.86	SL
	35-40	--	8.79	153.90	1.52	47.16	52.00	0.85	SiL
Y 02	0-5	1.25	6.01	25.15	1.31	34.16	60.15	1.25	SiL
	5-10	1.15	6.07	17.30	--	37.23	61.60	1.18	SiL
	10-15	1.02	5.91	21.35	1.59	39.91	59.01	1.08	SiL
	15-20	0.91	6.43	16.45	--	45.57	53.37	1.08	SiL
	35-40	--	7.44	32.65	1.71	66.69	32.50	0.81	SL
Y 03	0-5	2.11	7.65	75.60	1.38	58.77	40.60	0.64	SL
	5-10	2.08	7.51	76.95	--	61.55	37.93	0.52	SL
	10-15	2.47	7.63	74.10	1.32	62.24	37.32	0.45	SL
	15-20	2.07	7.64	73.45	--	62.72	36.84	0.45	SL
	35-40	--	8.28	91.50	1.64	56.86	42.69	0.46	SL
Y 04	0-5	1.31	6.92	20.55	1.52	68.78	30.77	0.46	SL
	5-10	1.32	7.07	20.35	--	67.10	32.39	0.52	SL
	10-15	1.57	7.09	26.95	1.70	68.05	31.33	0.63	SL
	15-20	1.23	6.76	21.30	--	67.76	31.70	0.54	SL
	35-40	--	7.07	21.05	1.66	69.05	30.39	0.56	SL
Y 05	0-5	1.32	6.75	28.20	1.59	77.22	22.37	0.41	LS
	5-10	1.21	6.70	24.35	--	75.90	23.74	0.37	LS
	10-15	1.10	6.78	23.35	1.55	75.18	24.51	0.32	LS
	15-20	1.05	6.97	28.10	--	73.80	25.86	0.35	LS
	35-40	--	7.15	33.55	1.70	76.32	23.40	0.28	LS
Mean		1.53	7.14	44.41	1.55	60.29	38.52	1.02	--
Skewness		0.49	0.22	1.89	-0.56	-0.55	0.55	3.14	--
Kurtosis		-1.07	0.58	4.40	-0.56	-0.54	-0.57	9.33	--
Standard Deviation		0.46	0.67	32.13	0.13	12.52	11.75	1.34	--

Table A2. Soil data and descriptive statistics for chemical and physical tests performed on the medium aged minesoils.

Profile I.D.	Depth (cm)	Exchangeable Cations (meq/100g)								Extractable N (µg/g)		Available P (mg/kg)
		TEB	Ca	Na	K	Mg	Fe	Al	SAR	NO_3-N	NH_4-N	PO_4-P
M 01	0-5	29.28	26.39	0.30	0.44	2.14	<DL	1.50	0.08	6.65	21.39	0.64
	5-10	29.20	26.43	0.45	0.35	1.96	<DL	1.44	0.12	4.19	0.00	0.62
	10-15	27.08	24.40	0.51	0.29	1.88	<DL	1.58	0.14	3.25	3.52	0.65
	15-20	27.70	24.78	0.64	0.23	2.06	<DL	1.91	0.17	0.25	0.00	0.60
	35-40	--	--	--	--	--	--	--	--	--	--	--
M 02	0-5	29.00	26.20	0.20	0.29	2.31	<DL	0.74	0.05	3.77	0.00	0.11
	5-10	23.28	20.76	0.44	0.16	1.92	<DL	1.26	0.13	0.18	8.85	0.12
	10-15	32.38	28.07	0.45	0.19	3.67	<DL	0.88	0.11	1.32	0.00	0.31
	15-20	38.29	34.94	0.28	0.20	2.87	<DL	0.74	0.06	0.13	7.95	0.21
	35-40	--	--	--	--	--	--	--	--	--	--	--
M 03	0-5	26.72	23.23	0.24	0.52	2.74	<DL	2.77	0.07	4.14	20.13	0.63
	5-10	24.72	21.77	0.29	0.17	2.49	<DL	2.31	0.08	0.19	0.00	0.44
	10-15	27.44	24.29	0.21	0.18	2.77	<DL	2.66	0.06	3.01	16.66	0.69
	15-20	30.45	27.01	0.23	0.20	3.00	<DL	2.46	0.06	0.11	0.00	0.52
	35-40	--	--	--	--	--	--	--	--	--	--	--
M 04	0-5	32.37	29.15	0.20	0.43	2.59	<DL	1.02	0.05	0.80	4.89	0.71
	5-10	36.27	30.92	0.59	0.20	4.57	<DL	1.08	0.14	0.21	0.00	0.44
	10-15	39.18	34.44	0.27	0.19	4.30	<DL	1.00	0.06	1.61	13.93	0.45
	15-20	32.42	29.69	0.23	0.13	2.37	<DL	1.11	0.06	0.64	2.70	0.44
	35-40	--	--	--	--	--	--	--	--	--	--	--
M 05	0-5	32.08	29.04	0.23	0.30	2.52	<DL	0.54	0.06	3.19	8.85	0.23
	5-10	29.29	25.69	0.18	0.16	3.27	<DL	0.68	0.05	0.20	0.00	0.36
	10-15	29.65	25.88	0.26	0.15	3.37	<DL	0.67	0.07	0.81	7.63	0.30
	15-20	29.14	26.45	0.29	0.19	2.22	<DL	0.79	0.08	0.28	0.00	0.30
	35-40	--	--	--	--	--	--	--	--	--	--	--
Mean		30.30	26.97	0.32	0.25	2.75	--	1.36	0.09	1.75	5.83	0.44
Skewness		0.69	0.64	1.11	1.28	1.11	--	0.89	1.09	1.11	1.07	-0.21
Kurtosis		0.39	0.47	0.08	0.71	0.71	--	-0.47	0.04	0.52	-0.01	-1.14
Standard Deviation		4.10	3.66	0.14	0.11	0.76	--	0.71	0.04	1.90	7.17	0.19

*<DL = less than detectable limit of 0.01 meq/100g.

Table A2. Concluded.

Profile I.D.	Depth (cm)	Organic Matter (%)	pH (H_2O)	EC (µS/cm)	Bulk Density (g/cm^3)	% Sand (by wt.)	% Silt (by wt.)	% Clay (by wt.)	Textural Class
M 01	0-5	2.60	5.48	39.45	1.32	45.27	51.72	3.01	SiL
	5-10	2.38	5.60	31.45	--	40.27	56.27	3.46	SiL
	10-15	2.08	5.70	33.25	1.35	43.25	55.30	1.45	SiL
	15-20	1.92	5.79	21.95	--	55.30	43.69	1.02	SL
	35-40	--	5.74	21.95	1.57	52.96	45.97	1.07	SL
M 02	0-5	2.03	5.69	21.90	1.51	59.33	30.76	9.91	SL
	5-10	1.73	5.57	18.25	--	60.74	34.88	4.39	SL
	10-15	2.05	5.71	16.45	1.55	58.26	32.73	9.02	SL
	15-20	2.22	5.74	20.90	--	53.99	32.82	13.19	SL
	35-40	--	6.31	23.10	1.55	50.95	34.73	14.32	L
M 03	0-5	1.27	5.87	19.60	1.33	42.35	50.89	6.77	SiL
	5-10	0.94	5.82	18.50	--	52.35	46.70	0.95	SL
	10-15	0.98	6.18	19.30	1.44	36.41	58.17	5.42	SiL
	15-20	1.05	6.28	22.85	--	36.94	55.11	7.95	SiL
	35-40	--	6.73	22.20	1.53	70.95	28.60	0.46	LS
M 04	0-5	2.30	5.45	27.85	1.32	50.80	45.63	3.58	SL
	5-10	2.27	5.52	25.20	--	44.27	54.64	1.10	SiL
	10-15	2.33	5.54	39.30	1.36	51.54	47.60	0.87	SL
	15-20	2.20	5.54	30.60	--	53.07	45.94	1.00	SL
	35-40	--	5.78	30.25	1.22	57.17	42.10	0.73	SL
M 05	0-5	1.43	5.62	47.10	1.18	63.61	36.08	0.31	SL
	5-10	1.66	5.62	17.45	--	68.54	30.99	0.47	SL
	10-15	1.40	5.79	13.80	1.3	65.47	34.04	0.50	SL
	15-20	1.48	5.67	15.35	--	64.59	34.91	0.50	SL
	35-40	--	5.74	21.80	1.44	57.49	41.78	0.73	SL
Mean		1.82	5.78	24.79	1.40	53.43	42.88	3.69	--
Skewness		-0.39	1.80	1.15	-0.10	-0.09	0.10	1.37	--
Kurtosis		-1.10	3.40	0.94	-1.13	-0.67	-1.36	0.89	--
Standard Deviation		0.51	0.30	8.28	0.12	9.54	9.31	4.19	--

Table A3. Soil data and descriptive statistics for chemical and physical tests performed on the old minesoils.

Profile I.D.	Depth (cm)	Exchangeable Cations (meq/100g)								Extractable N (μg/g)		Available P (mg/kg)
		TEB	Ca	Na	K	Mg	Fe	Al	SAR	NO_3-N	NH_4-N	PO_4-P
O 01	0-5	34.31	32.04	0.22	0.38	1.67	<DL	0.61	0.05	0.31	1.00	0.32
	5-10	31.30	29.31	0.17	0.19	1.62	<DL	0.68	0.04	0.30	2.03	0.23
	10-15	33.91	31.83	0.18	0.18	1.72	<DL	0.69	0.04	0.29	0.04	0.19
	15-20	36.02	33.82	0.20	0.20	1.79	<DL	0.43	0.05	0.93	1.56	0.18
	35-40	--	--	--	--	--	--	--	--	--	--	--
O 02	0-5	38.63	34.40	0.16	0.71	3.36	0.01	1.01	0.04	2.61	24.17	0.54
	5-10	30.20	26.00	0.29	0.33	3.59	0.01	1.55	0.08	0.23	0.00	0.17
	10-15	34.16	30.67	0.24	0.32	2.93	0.01	1.69	0.06	2.81	21.96	0.06
	15-20	34.45	31.03	0.36	0.28	2.78	0.01	1.50	0.09	0.20	0.00	0.24
	35-40	--	--	--	--	--	--	--	--	--	--	--
O 03	0-5	44.45	40.26	0.22	0.42	3.54	<DL	0.37	0.05	0.67	0.00	0.14
	5-10	41.45	37.57	0.25	0.30	3.33	<DL	0.44	0.05	0.14	0.00	0.23
	10-15	39.66	35.74	0.45	0.26	3.21	<DL	0.46	0.10	0.85	25.02	0.20
	15-20	38.19	34.40	0.51	0.23	3.04	<DL	0.44	0.12	0.09	0.00	0.15
	35-40	--	--	--	--	--	--	--	--	--	--	--
O 04	0-5	34.69	31.25	0.15	0.53	2.75	<DL	0.55	0.04	1.14	16.58	0.41
	5-10	33.52	30.41	0.18	0.32	2.61	<DL	0.87	0.05	0.17	0.00	0.37
	10-15	33.17	29.76	0.63	0.24	2.54	<DL	0.80	0.16	2.79	9.95	0.28
	15-20	33.29	30.17	0.31	0.23	2.58	<DL	0.81	0.08	0.10	0.00	0.36
	35-40	--	--	--	--	--	--	--	--	--	--	--
O 05	0-5	22.17	19.09	0.40	0.26	2.43	<DL	2.26	0.12	1.93	0.00	0.61
	5-10	20.79	18.06	0.38	0.17	2.18	<DL	3.15	0.12	0.11	0.78	0.65
	10-15	12.57	10.83	0.27	0.14	1.33	<DL	3.73	0.11	0.80	1.97	0.24
	15-20	10.86	9.46	0.28	0.19	0.93	<DL	2.80	0.12	3.13	3.22	0.30
	35-40	--	--	--	--	--	--	--	--	--	--	--
Mean		31.89	28.80	0.29	0.29	2.50	0.01	1.24	0.08	0.98	5.41	0.29
Skewness		-1.25	-1.26	1.21	1.80	-0.41	--	1.37	0.60	1.10	1.53	1.02
Kurtosis		1 20	1.02	1.15	3.75	-0.79	--	0.88	-0.87	-0.34	0.75	0.52
Standard Deviation		8.84	8.27	0.13	0.14	0.77	0.00	1.00	0.04	1.06	8.89	0.16

* <DL = less than detectable limit of 0.01 meq/100g.

Table A3. Concluded.

Profile I.D.	Depth (cm)	Organic Matter (%)	pH (H_2O)	EC (µS/cm)	Bulk Density (g/cm^3)	% Sand (by wt.)	% Silt (by wt.)	% Clay (by wt.)	Textural Class
O 01	0-5	2.33	6.01	31.30	1.37	38.42	48.51	13.07	SiL
	5-10	2.22	5.73	20.00	--	38.71	48.40	12.89	SiL
	10-15	2.28	5.81	19.95	1.49	36.51	51.15	12.35	SiL
	15-20	2.02	6.10	22.15	--	31.82	54.74	13.46	SiL
	35-40	--	6.31	38.60	1.5	39.54	40.97	19.49	L
O 02	0-5	2.63	5.32	79.80	1.15	52.41	41.02	6.58	SL
	5-10	2.22	5.48	25.50	--	52.86	46.18	0.96	SL
	10-15	2.67	5.42	28.40	1.41	52.89	43.35	3.77	SL
	15-20	2.68	5.65	22.10	--	54.34	40.60	5.07	SL
	35-40	--	5.81	25.15	0.98	44.95	54.31	0.75	SL
O 03	0-5	2.73	6.12	32.50	1.18	44.45	41.29	14.27	L
	5-10	2.55	6.03	28.35	--	42.98	44.60	12.42	L
	10-15	2.58	5.96	27.55	1.27	40.85	44.94	14.22	L
	15-20	2.38	6.02	22.35	--	44.17	41.00	14.83	L
	35-40	--	6.73	40.40	1.35	56.01	43.16	0.83	SL
O 04	0-5	2.18	5.69	37.50	1.27	46.31	39.40	14.29	L
	5-10	2.02	5.88	26.65	--	47.87	42.35	9.78	L
	10-15	1.97	5.92	26.50	1.45	46.53	42.35	11.12	L
	15-20	1.95	5.71	26.70	--	44.79	41.18	14.04	L
	35-40	--	5.85	22.30	1.29	46.03	46.02	7.96	L
O 05	0-5	1.48	5.51	34.30	1.38	54.72	44.57	0.72	SL
	5-10	1.26	5.63	20.20	--	45.71	53.24	1.06	SiL
	10-15	1.30	5.49	19.55	0.88	38.09	60.73	1.19	SiL
	15-20	1.93	5.57	27.80	--	43.42	55.84	0.74	SiL
	35-40	--	6.42	31.90	1.26	46.67	52.41	0.93	SiL
Mean		2.17	5.85	29.50	1.28	45.24	46.49	8.27	--
Skewness		-0.75	0.78	3.23	-1.01	-0.04	0.85	-0.06	--
Kurtosis		-0.07	0.79	13.02	0.73	-0.40	-0.26	-1.51	--
Standard Deviation		0.44	0.33	12.05	0.18	6.22	5.86	6.10	--

Table A4. Soil data and descriptive statistics for chemical and physical tests performed on undisturbed soils.

Profile I.D.	Depth (cm)	Exchangeable Cations (meq/100g)								Extractable N (μg/g)		Available P (mg/kg)
		TEB	Ca	Na	K	Mg	Fe	Al	SAR	NO_3-N	NH_4-N	PO_4-P
UN 01	0-5	9.88	8.01	0.53	0.47	0.87	0.03	6.74	0.25	10.12	0.00	1.06
	5-10	3.22	2.44	0.25	0.26	0.26	0.01	6.68	0.21	0.59	6.52	0.76
	10-15	5.04	4.10	0.25	0.25	0.45	<DL	6.96	0.16	9.03	10.33	1.12
	15-20	7.52	6.39	0.22	0.18	0.74	<DL	6.24	0.11	0.21	6.17	0.73
	35-40	--	--	--	--	--	--	--	--	--	--	--
UN 02	0-5	23.47	21.23	0.18	0.27	1.79	<DL	2.35	0.05	0.33	9.86	0.24
	5-10	19.50	17.10	0.41	0.12	1.87	<DL	1.70	0.13	0.22	7.67	0.30
	10-15	21.44	19.48	0.24	0.12	1.60	<DL	1.47	0.07	1.06	6.42	0.46
	15-20	22.68	19.85	0.46	0.12	2.26	<DL	1.31	0.14	0.18	2.82	0.92
	35-40	--	--	--	--	--	--	--	--	--	--	--
Mean		14.09	12.32	0.31	0.22	1.23	0.02	4.18	0.14	2.72	6.22	0.70
Skewness		-0.12	-0.08	0.76	1.30	0.01	--	-0.03	0.37	1.44	-0.75	-0.20
Kurtosis		-2.29	-2.31	-1.22	1.92	-1.79	--	-2.66	-0.42	0.10	0.26	-1.54
Standard Deviation		8.50	7.83	0.13	0.12	0.74	0.01	2.67	0.07	4.25	3.44	0.33

* <DL = less than detectable limit of 0.01 meq/100g

Table A4. Concluded.

Profile I.D.	Depth (cm)	Organic Matter (%)	pH (H_2O)	EC (µS/cm)	Bulk Density (g/cm^3)	% Sand (by wt.)	% Silt (by wt.)	% Clay (by wt.)	Textural Class
UN 01	0-5	2.10	4.90	44.70	1.07	39.22	60.15	0.63	SiL
	5-10	1.37	5.18	23.30	--	41.13	57.93	0.93	SiL
	10-15	1.00	5.19	18.70	0.86	41.91	56.97	1.11	SiL
	15-20	1.00	5.24	17.80	--	41.71	57.34	0.95	SiL
	35-40	--	5.33	13.00	1.35	48.10	46.04	5.86	SL
UN 02	0-5	2.23	5.26	30.70	1.33	41.19	57.93	0.89	SiL
	5-10	1.43	5.46	25.00	--	37.26	61.54	1.20	SiL
	10-15	1.48	5.45	24.10	1.48	37.72	61.06	1.22	SiL
	15-20	1.70	5.57	27.20	--	36.39	62.48	1.13	SiL
	35-40	--	5.76	15.40	1.58	45.36	53.01	1.63	SiL

Mean	1.54	5.33	23.99	1.28	41.00	57.45	1.56	--
Skewness	0.41	0.04	1.26	-0.72	0.72	-1.58	2.99	--
Kurtosis	-0.88	0.56	2.27	-0.45	0.18	2.85	9.21	--
Standard Deviation	0.46	0.24	9.11	0.27	3.65	4.86	1.54	--

APPENDIX B

Scatterplots of Significant Relationships between Soil Chemical and Physical Properties and Depth in the Profile

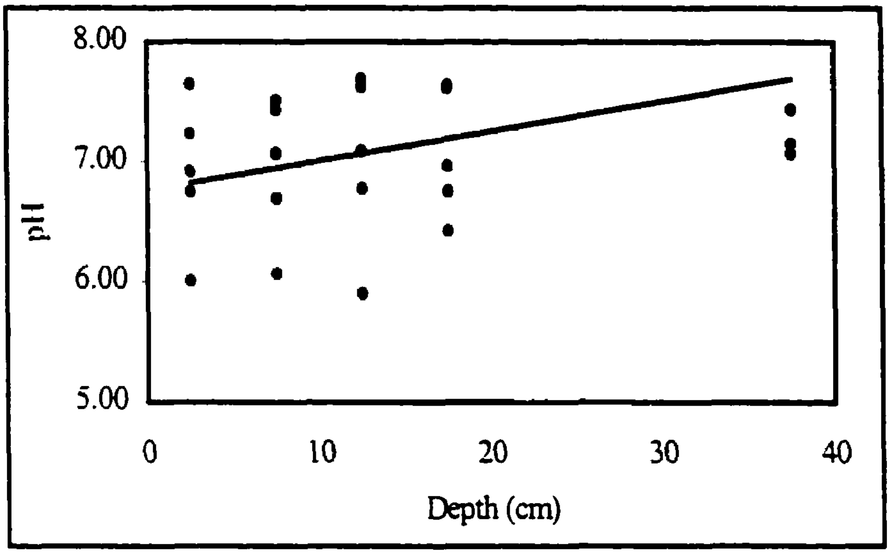

Figure B1. Relationship between pH and depth in the profile for the young minesoils. Equation: pH = 6.76 + 0.0247(depth in cm), n=25, r^2=0.21, P=0.023.

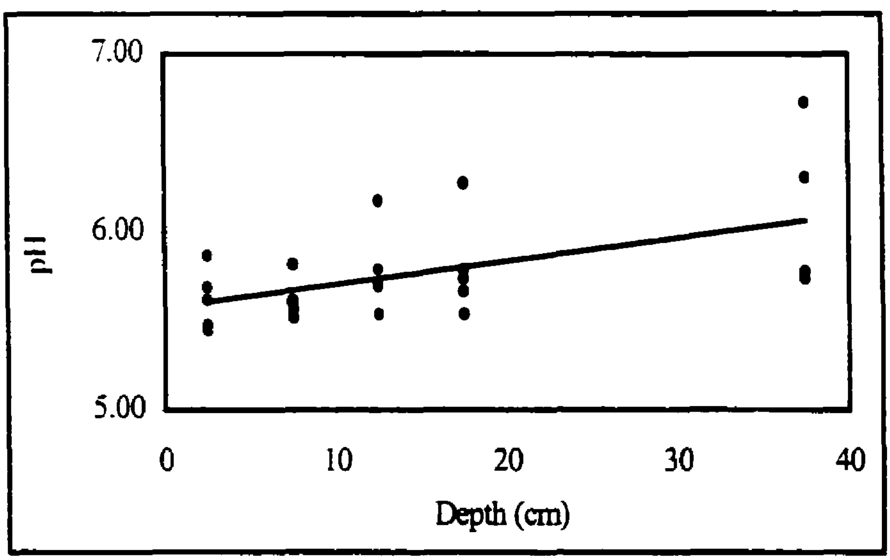

Figure B2. Relationship between pH and depth in the profile for the medium aged minesoils. Equation: pH = 5.58 + 0.0130(depth in cm), n=25, r^2=0.29, P=0.006.

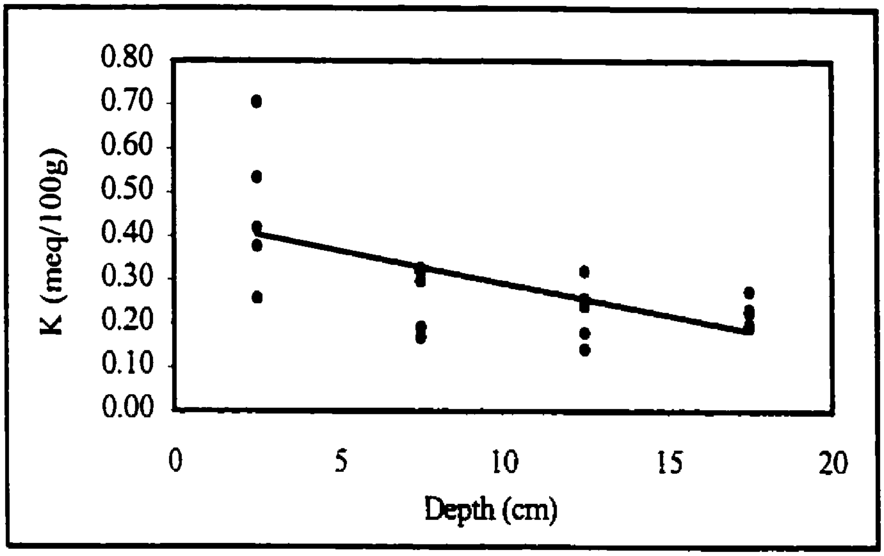

Figure B3. Relationship between potassium (K) and depth in the profile for the old minesoils. Equation: K = 0.441 - 0.0147(depth in cm), n=20, r^2=0.39, P=0.004.

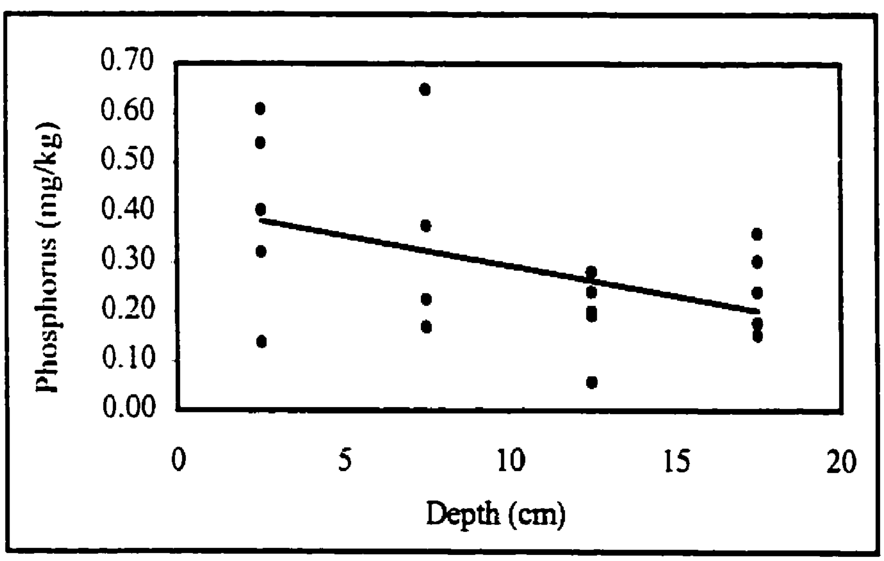

Figure B4. Relationship between phosphorus (PO_4-P) and depth in the profile for the old minesoils. Equation: PO_4-P = 0.416 - 0.0122(depth in cm), n=20, r^2=0.20, P=0.050.

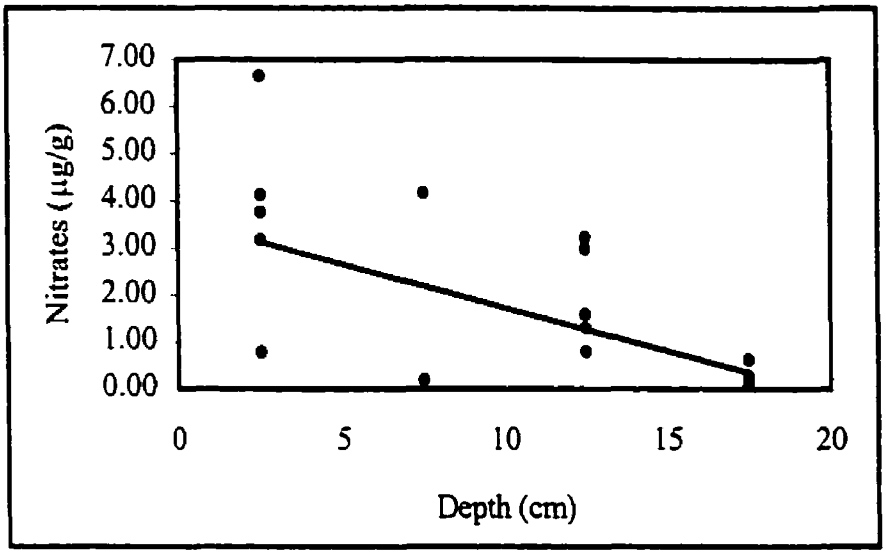

Figure B5. Relationship between nitrates (NO_3-N) and depth in the profile for the medium aged minesoils. Equation: $NO_3\text{-}N = 3.60 - 0.186(\text{depth in cm})$, n=20, r^2=0.32, P=0.010.

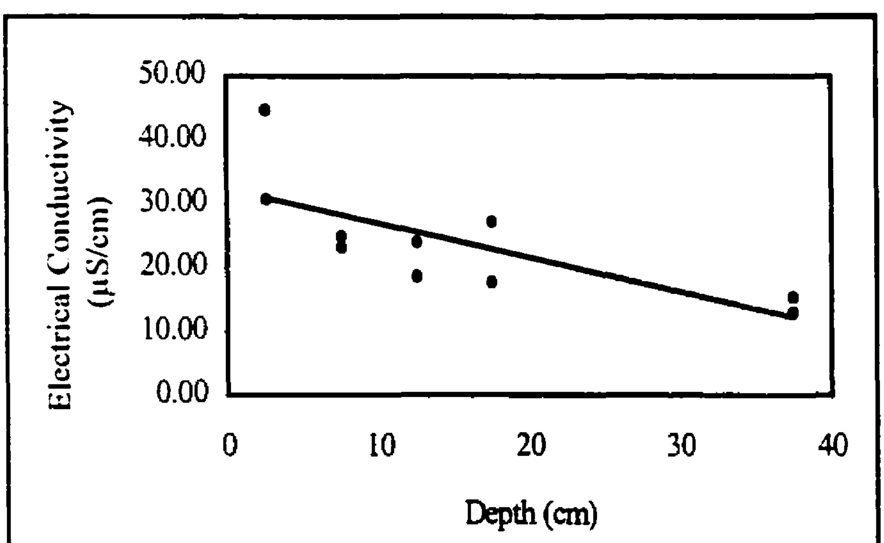

Figure B6. Relationship between electrical conductivity (EC) and depth in the profile for the undisturbed soils. Equation: $EC = 32.3 - 0.534(\text{depth in cm})$, n=20, r^2=0.56, P=0.013.

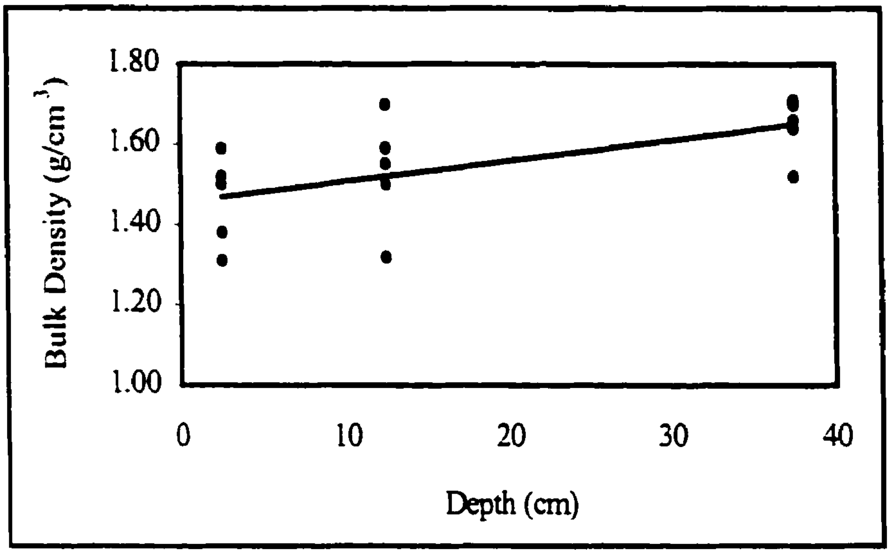

Figure B7. Relationship between bulk density (D_b) and depth in the profile for the young minesoils. Equation: $D_b = 1.46 + 0.00517$(depth in cm), n=15, r^2=0.36, P=0.018.

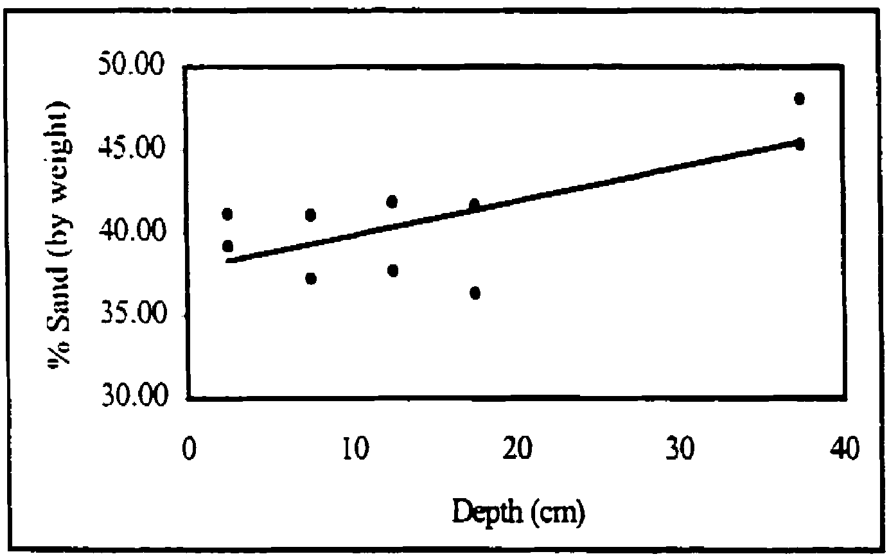

Figure B8. Relationship between sand content and depth in the profile for the undisturbed soils. Equation: % Sand = 37.8 + 0.206(depth in cm), n=10, r^2=0.52, P=0.019.

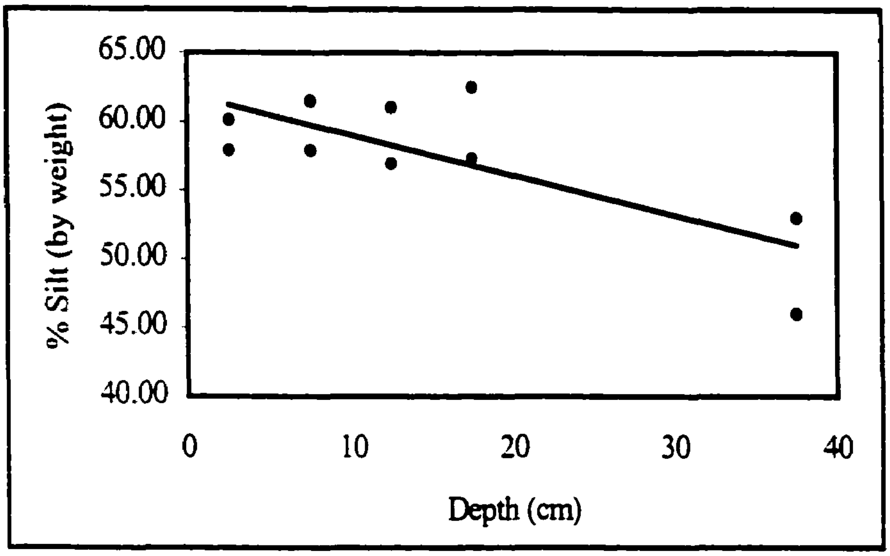

Figure B9. Relationship between silt content and depth in the profile for the undisturbed soils. Equation: % Silt = 62.0 - 0.292(depth in cm), n=10, r^2=0.58, P=0.010.

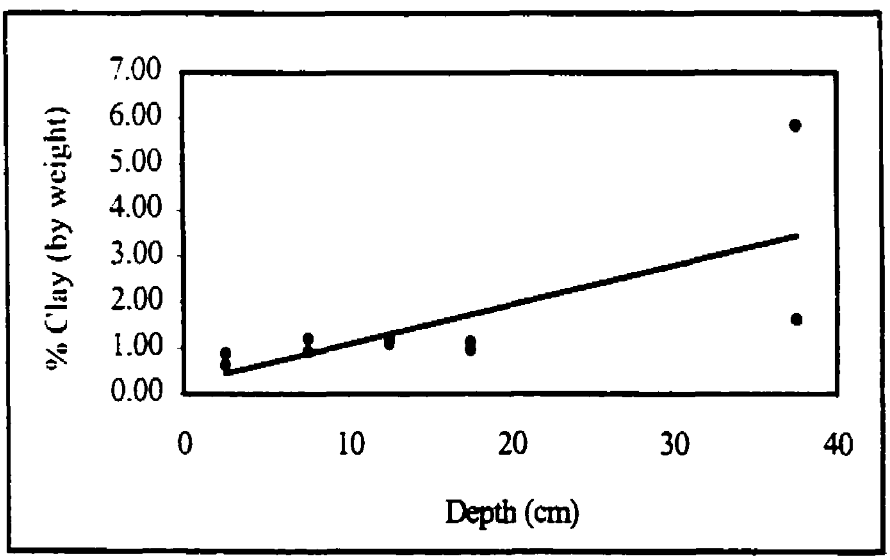

Figure B10. Relationship between clay content and depth in the profile for the undisturbed soils. Equation: % Clay = 0.226 + 0.0857(depth in cm), n=10, r^2=0.51, P=0.021.

APPENDIX C

Scatterplots of Significant Relationships Between Soil Chemical and Physical Properties and Site Age

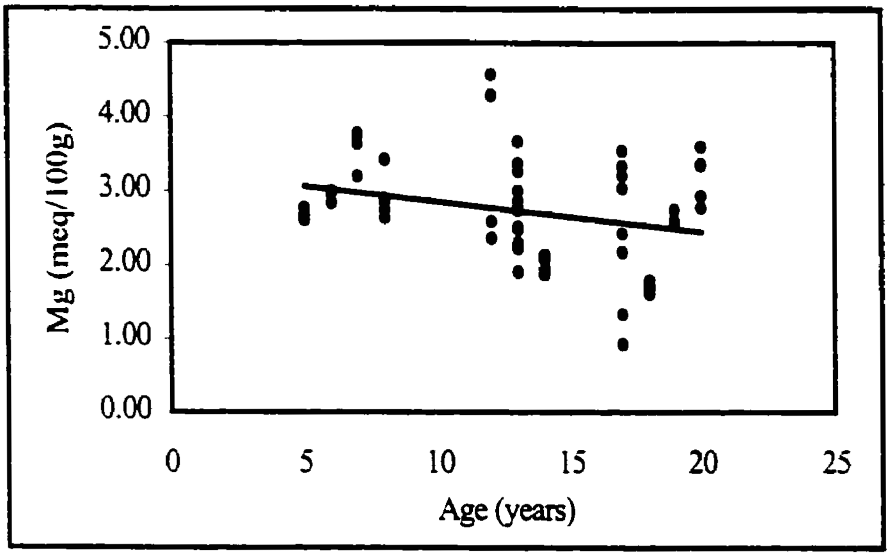

Figure C1. Relationship between magnesium (Mg) concentration and site age.
Equation: $Mg = 3.26 - 0.0405(age)$, $n=60$, $r^2=0.08$, $P=0.027$.

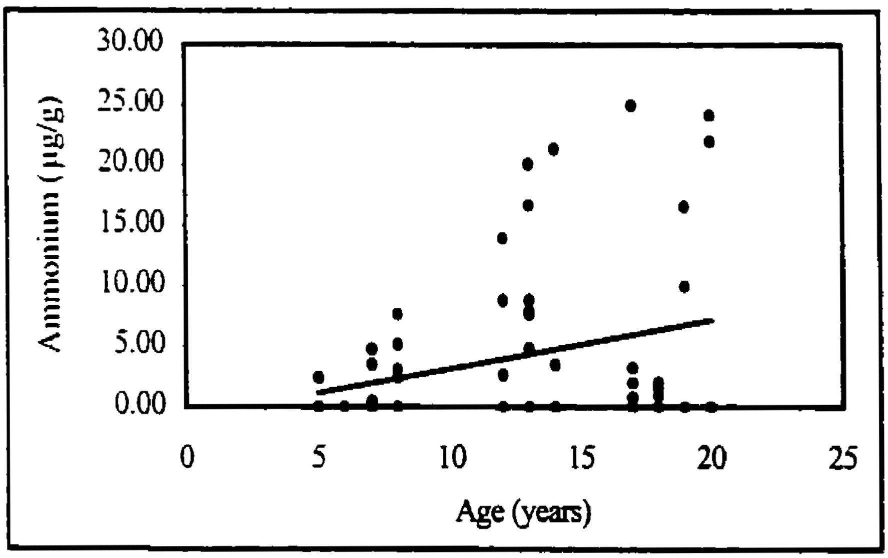

Figure C2. Relationship between ammonium (NH_4-N) concentration and site age.
Equation: $NH_4\text{-}N = -0.888 + 0.405(age)$, $n=60$, $r^2=0.08$, $P=0.029$.

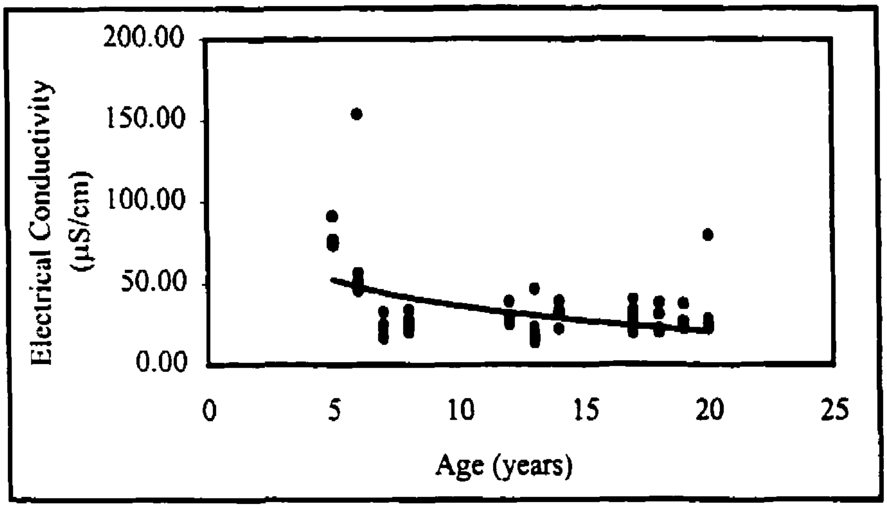

Figure C3. Relationship between electrical conductivity (EC) concentration and site age.
Equation: EC = 89.6 – 53.2($\log_{10}$age), n=75, r^2=0.21, P<0.001.

Figure C4. Relationship between sand content and site age.
Equation: % Sand = 67.4 – 1.14(age), n=75, r^2=0.23, P<0.001.

Figure C5. Relationship between silt content and site age.

Equation: % Silt = 35.5 + 0.562(age), n=75, r^2=0.08, P=0.016.

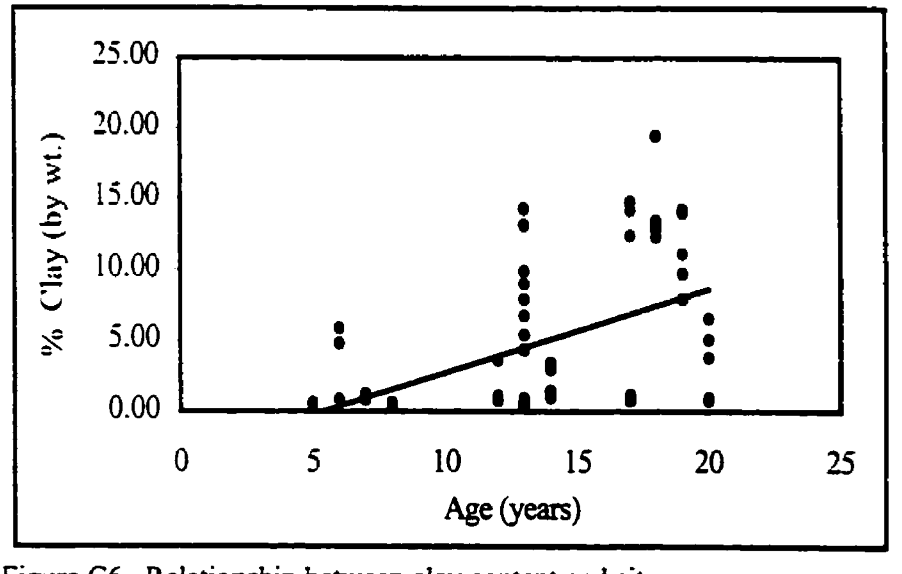

Figure C6. Relationship between clay content and site age.

Equation: % Clay = -3.15 + 0.590(age), n=75, r^2=0.29, P<0.001.

APPENDIX D

Criteria for Suitable Root Zone Material and Nutrition of Revegetation Types

Table D1. Criteria for evaluating the suitability of root zone material in the Eastern Slopes Region of Alberta (adapted from Alberta Soils Advisory Committee, 1987 and Fedkenheuer et al., 1987).

Rating/Property	Good (G)	Fair (F)	Poor (P)	Unsuitable (U)
Reaction (pH)	5.0 to 6.5	4.0 to 5.0 6.5 to 7.5	3.5 to 4.0 7.5 to 9.0	<3.5 and >9.0
Salinity (EC) (μS/cm)	<2000	2000 to 4000	4000 to 8000	>8000
Sodicity (SAR)	<4	4 to 8	8 to 12	>12
Texture	L, SiCL, SCL, SL, FSL	CL,SiL,VFSL, SC, SiC	LS, S, Si, C, HC	Consolidated Bedrock
Bulk Density	Recommended : < 1.5 g/cm^3			

Table D2. Soil property requirements for the nutrition of various revegetation types (adapted from Fedkenheuer et al., 1987).

Revegetation Type	pH	O.M. (wt. %)	Exchangeable (meq/100g)			Available P (mg/kg)
			K	Ca	Mg	
Conifer Seedlings	4.8 – 5.5	3 - 5	0.2 – 0.3	3 - 8	0.4 – 2.0	1 – 1.5
Grass-legume	5.5 – 7.5	5.0	0.25	0.20	0.30	0.30
Mature Lodgepole Pine	3.9 – 7.5	0.7	0.25	0.60	--	0.03 – 3
Mature White Spruce	4.7 – 6.5	3 - 5	0.17	3.00	0.70	0.40
Aspen	4.6 – 5.4	2.7	0.15	0.79	0.40	0.05