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IN SITU AMELIORATION OF SODIC MINESPOIL USING SULFUR, GYPSUM AND CROP MANAGEMENT

by

JEFF JACK SANSOM

A thes ted to the Faculty of Graduate Studies and Research in partial fulfillment of the req nts for the degree of Master of Science

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Jeff Sansom

Jeff Jack S nsom
63 Collin ood Ave.
Spruce Grove, Alberta
T7X 2B7

Oct. 2/1996

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled IN SITU AMELIORATION OF MINESPOIL USING SULFUR, GYPSUM AND CROP MANAGEMENT submitted by JEFF JACK SANSOM in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in SOIL SCIENCE.

M.A. Naeth
Co-Supervisor

D.S. Chanasyk
Co-Supervisor

R.C. Izaurralde

J.C. Bateman

I. A. Campbell

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ABSTRACT

The objective of this study was to determine the effectiveness of sulfur and gypsum amendments in conjunction with crop management (summerfallow and forage) in reducing the sodicity of a sandy loam textured, calcareous minespoil at Highvale coal mine, west of Edmonton, Alberta. Sodium adsorption ratio (SAR) and numerous other chemical, hydrologic, physical and vegetation parameters were measured.

Gypsum showed an immediate ameliorative effect on SAR, while sulfur was slower at reducing SAR. Sulfur and gypsum elevated concentrations of Na^+, Ca^{2+}, Mg^{2+}, K^+ and SO_4^{2-} in the amended minespoil layer. Crop management treatments did not significantly lower SAR; however, fallow/barley facilitated leaching more due to higher soil moisture.

The amendment and crop management treatments had no significant effect on organic carbon, bulk density, species composition, canopy or ground cover. Crop management significantly affected penetration resistance (it was generally higher under forage), while amendment treatments did not.

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1.0 INTRODUCTION

1.1 Background

Salvaging and respreading topsoil and subsoil on recontoured minespoils is the dominant practice when reclaiming surface-mined land. Minespoils that are poor media for plant growth require a considerable thickness of suitable quality soil materials covering them to ensure adequate plant productivity. With sodic minespoils under semiarid conditions, 90 to 120 cm of cover soil is recommended by Power et al. (1981). Oddie and Bailey (1988) recommended 15 cm of topsoil and 55 to 95 cm of suitable subsoil over sodic minespoil to restore land to post-mine productivity. Such amounts of suitable quality soil material are often lacking in areas where sodic minespoils are found (Merrill et al., 1982). In addition, there are lands disturbed for reasons other than coal mining, neither generally nor necessarily covered by soil replacement requirements, that need to be reclaimed (abandoned spoils, road cuts, water catchments, etc.). Thus the study of alternative reclamation techniques to subsoil salvaging and respreading for sodic minespoils are required. The application of calcium-supplying amendments to sodic minespoils is one such alternative. Another alternative is partial leaching of salts from sodic minespoils by increased soil water accumulation within the soil profile. In both techniques, an attempt is made to lower the elevated levels of exchangeable sodium in the minespoils, thus improving the chemical and physical properties of the minespoils necessary for successful revegetation.

1.2 Sodic Spoils

Sodic minespoils, those which contain excessive amounts of sodium, are frequently unearthed by surface coal mining in the western Great Plains. In minespoils, sodium ions are found either in solution or adsorbed to the clay fraction with the sodic minespoil exchangeable-sodium percentage (ESP) 15 or greater. ESP can be explained in the following manner. Soil particles, mainly clays, are negatively charged and can attract positively charged ions such as sodium, calcium and magnesium. If 15% or more of the ions adsorbed to the clays are sodium, the minespoils are considered sodic. Sodium adsorption ratio (SAR) is another means of classifying sodic minespoils; here the relative activity of sodium ions to that of calcium and magnesium in exchange reactions with spoil material is expressed. The mathematical equation for SAR is $Na^+/[(Ca^{2+}+Mg^{2+}/2)]^{1/2}$, where Na^+ (sodium), Ca^{2+} (calcium) and Mg^{2+} (magnesium) are the concentrations of the designated soluble cations expressed in milliequivalents per liter. When SAR is greater than 13, the minespoils are classified as sodic (U.S. Salinity Laboratory Staff, 1954). A relationship between ESP and SAR was developed by Richards from 59 soil samples from 9 Western States (U.S. Salinity Laboratory Staff, 1954). This relationship is defined by the equation: $ESP = 100(-0.0126 + 0.01475\ SAR)/[1 + (-0.0126 + 0.01475\ SAR)]$.

1.3 Sodic Soils and Plant Growth

Sodic minespoils limit revegetation success on surface coal mine lands. The primary effect of excess sodium is to impart undesirable physical properties to the soil material (Barth, 1976). Such inferior physical characteristics inhibit plant growth and development. For instance, the dispersed nature of sodic minespoils decreases the rate of water infiltration into and percolation within the spoils; with less water entering sodic minespoils, plants may suffer drought stress. Furthermore, dispersed soil materials may physically restrict root growth (Pearson, 1960). Plants with poorly developed root systems are vulnerable to drought and to nutritional deficiencies. Even when water does enter sodic minespoils, the air within pore spaces may be completely displaced. Water does not readily move out of sodic minespoils which may result in persistent anaerobic conditions. This is unfavorable for revegetation since both normal plant germination and root development require sufficient air. This was reported by Pearson (1960) who found plants frequently died on sodic soils that became saturated with water. High soluble sodium concentration also reduces water availability to plants due to osmotic effects as plant roots are unable to obtain water in soil solutions with low osmotic potential. Gauch and Wadleigh (1944) demonstrated the progressive reduction of growth of beans (*Phaeseolus sp.* L.) in solution cultures with increasing salinity. Except for sodium carbonate (Na_2CO_3), salts of different ionic composition have about the same influence on water availability at comparable osmotic concentrations. Thorup (1969) reported that plants growing in Na_2CO_3 solutions wilted rapidly, while plants growing in sodium chloride (NaCl) solutions of equal Na^+ ion concentration and equal or greater osmotic pressure grew well.

In sodic minespoils, poor plant growth may result from the toxic effect of a specific ion in the soil. Certain elements common to minespoils can be toxic to some plants; however, sodium (Na^+) and chloride (Cl^-) are toxic most often. Sodium effects on plants seem due to the highly caustic effects of the carbonate (CO_3^{2-}) ion and direct and indirect effects of exchangeable sodium. High alkalinity (high pH) damage is due to the dissolving effect of the CO_3^{2-} ions on organic matter with the formation of soluble Na-humates (Sandoval and Gould, 1978).

In contrast to toxicity, adverse nutritional deficiencies associated with high levels of sodium occur in sodic minespoils. One cause of poor plant growth on sodic minespoils is the inability of plants to obtain an adequate supply of calcium. This condition has been termed sodium-induced calcium deficiency. Chang and Dregne (1955) studied the effect of adsorbed Na on soil physical properties and mineral uptake in alfalfa (*Medicago sativa* L.) and noted the decreased yield was associated with an increase in sodium and a corresponding decrease in calcium of plant tissue. Bower and Turk (1945) reported that Ca and Mg deficiencies may occur in sodic calcareous soils of high pH. Greenway (1963) reported that NaCl reduces potassium (K) uptake in barley (*Hordeum vulgare* L.) under salt stress. Moreover, in greenhouse studies, high levels of exchangeable Na generally caused an increase in the absorption of Na, nitrogen (N) and molybdenum (Mo) and a decrease in the absorption of Ca, K, Mg, sulfur (S), copper (Cu), zinc (Zn), boron (B) and Cl by five different crops. Effects of elevated sodium are most dominant in the alkaline pH range. Under these conditions, phosphorus (P) solubility increases rapidly because of the formation of soluble Na-phosphate compounds. In calcareous spoils with high exchangeable Na, P solubility is usually high because Ca solubility is depressed and Na-phosphates are formed (Barth, 1976).

Nitrogen cycling is also affected by elevated levels of sodium: there is evidence that nitrate (NO_3^-) formation is reduced in sodic soil. Breazeale and McGeorge (1931) found that a solution with high sodium concentration and pH greater than 7.6 impeded NO_3^- absorption by plant roots even though the pH itself was not high enough to be toxic to plants. Mineralization of N was insufficient in sodic soil due to the lack of decomposable organic N-compounds (Cairns, 1963). Sandoval et al (1973) found that although appreciable quantities of exchangeable ammonium (NH_4^+) were present in minespoils of coal lands, mineralizable organic N forms were lacking.

1.4 Amelioration of Sodic Soils

With such physical and chemical limitations to healthy plant growth and development, amelioration of sodic soils (minespoils) has been given substantial attention by many researchers. Most of the principles accepted today come from early work done by Kelley (1951). His principles in improving sodic soils include (1) establishment of drainage to lower water tables; (2) the leaching of excess soluble salts; (3) the replacement of exchangeable Na directly or indirectly; and (4) the rearrangement and aggregation of soil particles to improve structure.

Studies to date focused on the second and third principles of improving sodic soil material. In these studies, chemical amendments (gypsum, lime, $CaCl_2$, sulfur, H_2SO_4) and/or hydrologic regimes (fallow, irrigation) were used to lower the concentration of sodium in the soils. Although numerous types of amendments were used, all have one thing in common: they supplied water-soluble calcium, directly or indirectly, to sodic minespoils. Calcium displaced sodium on exchange sites of clay particles, consequently improving chemical and physical properties of the spoils. For example, gypsum addition to sodic soils improved flocculation and macroporosity (Chartres et al., 1985), reduced surface crusting (Gal et al., 1984), decreased bulk density (Southard et al., 1988) and increased permeability (Frenkel et al., 1989). The incorporation of gypsum into sodic soils also resulted in higher infiltration rates and hydraulic conductivities after only one year (Ilyas et al., 1993). With a vast improvement in physical and chemical properties, amending sodic spoils may be equivalent to spreading salvaged subsoil in reclaiming surface mined land.

The hydrologic regime of the reconstructed profile and climate of the area are important factors in ameliorating sodic minespoils. Adequate soil moisture is required to solublize certain amendments (salts) into their constituent ions. For example, gypsum, a relatively insoluble compound (0.25 % at normal temperatures), requires sufficient soil moisture to make it an effective amendment. Without sufficient soil moisture in the amended spoil layer, gypsum remains as a salt and is ineffective in sodium exchange reactions. Similarly, effective sulfur amelioration requires sufficient soil moisture to provide a suitable environment for soil microorganisms. Oxidation of sulfur by soil microorganisms is necessary for sulfur to be an effective amendment of sodic minespoils.

Soil moisture is also important in the subsequent downward transport of soluble Na produced by the exchange reactions in the amended spoil layer. The effectiveness of leaching under nonirrigated conditions is dependent upon the amount and intensity of precipitation, evapotranspiration, infiltration and soil moisture retention properties. Effective leaching of salts means their removal from the plant root zone deep enough into the profile to prevent damage from upward return. Water movement below the rooting zone can occur only when there is a net excess of precipitation over evapotranspiration. Even in the semiarid climate of North Dakota, Merrill et al. (1983a) reported decreases of average sodicity levels in the uppermost 30 cm of topsoiled and non-topsoiled minespoils as a result of gypsum application. Although the amount of soil moisture available for salt leaching in semiarid climates is constraining, Merrill et al. (1980) concluded that the hydraulic conductivity of spoils is the critical factor in effective salt leaching.

1.5 Chemical Amendments

The use of chemical amendments to improve sodic minespoil is based on ion exchange phenomena. Ion exchange is a reversible process by which cations and anions are exchanged between solid and liquid phases, and between solid phases in close contact (Sandoval and Gould, 1978). Adsorption implies the increase of an ion species on a solid, whereas, desorption refers to the replacement of adsorbed ions.

Adsorbed cations are combined chemically with the soil particles but they may be replaced by other cations occurring in the soil solution. Because adsorbed cations can interchange freely with adjacent cations in the soil solution, the proportion of the various cations on the exchange complex will be related to their concentration in the soil solution. Sodic minespoils have high concentrations of exchangeable and soluble Na. Adding sulfur or gypsum as chemical amendments increases the amount of soluble Ca in solution to displace adsorbed Na on the clay fraction of sodic spoil. This improves the chemical and physical properties of minespoil necessary for good plant development and growth.

1.5.1 Sulfur Amendment

Elemental sulfur is a common chemical amendment used in ameliorating calcareous sodic soils. For sulfur to be beneficial as an amendment, soil microorganisms must first convert the elemental sulfur to sulfuric acid. Minespoils, as contrasted with soils, are unlikely to contain sufficient microorganisms to oxidize sulfur. Thus this amendment is not recommended for use on spoils (Barth, 1976). However, amending spoils with sulfur and covering them with sufficient topsoil may constitute a feasible method of amelioration.

Adding sulfur to calcareous sodic spoils indirectly adds Ca^{2+} ions to the soil solution through several chemical reactions (Kelley, 1951): (1) $2\ S + 3\ O_2 \leftrightarrow 2\ SO_3$ (microbial activity), (2) $2\ SO_3 + 2\ H_2O \leftrightarrow 2\ H_2SO_4$, (3) $2\ H_2SO_4 + 2\ CaCO_3 \leftrightarrow 2\ CaSO_4 + CO_2 + 2\ H_2O$ and (4) $4\ NaX + 2\ CaSO_4 \leftrightarrow 2\ CaX_2 + 2\ Na_2SO_4$. Overstreet et al. (1951) found adding sulfur to an alkali soil of the Fresno series to be beneficial. However, sulfur was inferior to sulfuric acid or gypsum for improving yield of seeded pastures.

1.5.2 Gypsum Amendment

Gypsum ($CaSO_4$) is the most common and cheapest amendment for sodic soils. However, gypsum is not very soluble and disassociates rather slowly into its constituent ions, Ca^{2+} and SO_4^{2-}. Divalent Ca^{2+} ions are important in displacing exchangeable monovalent Na^+ ions. The addition of gypsum is a direct addition of Ca^{2+} ions to the soil solution: $2\ NaX + CaSO_4 \leftrightarrow CaX_2 + Na_2SO_4$.

Several researchers have documented the results of gypsum application to sodic soils. Boawn et al. (1952) obtained increased productivity with gypsum treatment on a saline-sodic soil in the Yakima Valley of Washington. Chang and Dregne (1955) found gypsum effective in reclaiming saline-sodic soils in southern New Mexico. Arbol et al. (1975) found surface application of gypsum more effective in increasing exchangeable Ca^{2+} and hydraulic conductivity than mixing the gypsum in a saline-sodic soil. They found soluble carbonate precipitated when gypsum was mixed with the soil but only a small portion precipitated from surface application. Merrill et al. (1980) found gypsum application to topsoiled and non-topsoiled sodic minespoils reduced sodicity, increased hydraulic conductivity and increased yield of crested wheatgrass (*Agropyron desertorum* (Fisch.) Schult.).

1.6 Crop Management

Crop management practices can affect sodic spoil amelioration by influencing the amount of soil water available for leaching excess Na^+ in solution. Furthermore, adequate soil water is required for effective amendment dissolution. Thus, it is important to consider what crop management would optimize soil water available for effective amendment use and optimal downward salt leaching. For example, sufficient soil water is necessary for microorganisms to oxidize elemental sulfur. Likewise, gypsum requires adequate water to solubilize and release Ca^{2+} ions. Gypsum is not highly soluble so cropping practices that promote adequate soil water are important, particularly in semiarid and arid regions. Crop management can also affect spoil physical properties due to root 'biological tillage' (Materchera et al. 1991).

1.6.1 Forages

Part of developing a sodic minespoil amelioration plan involves the use of plants in improving the permeability of the spoil layer. Poor drainage can be improved by using crops with deep rooting systems and having the ability to tolerate both concentrations of high soluble salts and water-logged conditions. For instance, deep rooted perennials, such as alfalfa, may improve percolation in soils with poor physical properties (Meek et al., 1989). Furthermore, plant species with extensive root systems (high root:shoot ratios) may improve the physical structure of minespoil material by increasing soil aggregation and root channeling. Roots increase soil permeability by increasing soil microporosity and macroaggregation as they decay (Meek et al., 1989). Root decay during the growing season leaves vertical channels in the reconstructed soil profile for enhanced water movement. The extent to which vegetation can modify minespoil physical properties depends partially on plant root pattern and biomass, the rate of root decomposition and rooting depth. With improved percolation, the downward movement of water into the amended minespoil layer and subsequent downward movement of soluble Na could be expected. Plants also increase soil water by reducing evaporation from the soil surface through shading (Luken, 1962). However, forage plants consume large volumes of water during the growing season. In semiarid or arid regions where precipitation is limited, there is a concern that soil water may not be sufficient to render amendments effective and leach soluble Na ions downward out of the amended zone. Contrary to this, removal of water throughout the rooting zone by plants may be beneficial by reducing the upward movement of salts into respread topsoil by diffusive forces (White and de Jong, 1975; Merrill et al., 1983b).

1.6.2 Summerfallowing

Summerfallow may be used to increase soil water for more effective amelioration by the amendments and deeper salt leaching within the profile. Soil water is increased due to the elimination of evapotranspiration by plants. Merrill et al. (1983a) found that summerfallowing at four strip-mine sites in west-central North Dakota increased soil water with depth but had no significant effect on reducing sodicity of topsoiled and non-topsoiled minespoils amended with gypsum as compared to seeding with crested wheatgrass.

1.7 Research Objectives and Hypotheses

Research is required on the suitability of coarse-textured minespoil as a suitable subsoil source. Due to inherent physical and chemical properties, plant growth and performance may be limited. Although research on ameliorating sodic spoils on reclaimed surface-mined lands has been conducted (Dollhopf et al., 1980; Merrill et al., 1983a; Fullerton and Regier, 1987), few long-term studies focusing on chemical amendments and crop management effects on chemical, hydrologic and physical properties of the sodic minespoils have been reported in the literature. In this study, all these parameters were integrated to understand the effects of amendment use and crop management on sodic minespoil amelioration along with their implications for successful reclamation of sodic strip-mined soils.

Specific research objectives were: (1) to quantify the effectiveness of sulfur and gypsum treatments in reducing the sodicity (SAR) of a sandy loam minespoil and (2) to quantify the effectiveness of these amendments in reducing the sodicity (SAR) of minespoil under both barley/fallow and continuous perennial forage crop management.

It was hypothesized that both sulfur and gypsum addition to sodic minespoil will lower SAR by adding soluble Ca^{2+} to displace exchangeable Na^{+} adsorbed onto the minespoil. It was anticipated that the direct addition of Ca^{2+} by gypsum would immediately reduce the SAR of the amended spoil, whereas the increased availability of Ca^{2+} by sulfur would require a longer period of time to reduce SAR. However, the effectiveness of each amendment in reducing SAR of sodic minespoil in a semiarid climate is unknown. In this study, the effective depth of amelioration for each amendment under different crop management will also be determined.

Like amendments, the effect of crop management on lowering SAR of sodic minespoil is unclear. The fallow/barley rotation was hypothesized to lower SAR more than forage. It was expected that the elevated soil water within the fallow/barley soil profiles will enhance amendment effectiveness, as well as the subsequent leaching of displaced Na ions out of the amended spoil layer. Although it was hypothesized that the barley/fallow treatment would reduce SAR in the amended spoil layer due to higher soil water, the effect of roots in the forage treatment on soil water movement are not clear. Perhaps, deep rooting plants such as alfalfa will create continuous channels within the minespoil, resulting in higher infiltration rates and greater infiltration depths, thus enhancing the effectiveness of either amendment in lowering SAR.

Information on the effects of amendment and crop management on ameliorating sodic minespoils is important where shortages of suitable quality subsoil occur (road cuts, water catchments, etc.) or where salvaging suitable quality subsoil was not previously a legal requirement (abandoned mines and spoils before 1963).

At the TransAlta Utilities Highvale Mine, information on ameliorating sodic minespoil is needed to evaluate an alternative technique to salvaging and respreading subsoil in reclaiming areas of land. At Highvale, some of the minespoil is classified as unsuitable for subsoil (Alberta Agriculture, 1987). Although the spoil is sandy loam or coarser, SAR in the material is >20 and thus it is classified as inappropriate as subsoil. Without amelioration, the spoil must be covered with an appropriate amount of suitable subsoil to obtain reclamation certification by Alberta Environmental Protection (AEP). However this practice is an expensive operation. Hence, the Amended Plot Study was developed to evaluate the potential of chemically amending unweathered spoil with either sulfur or gypsum under different crop management. If the proposed amelioration of minespoil is deemed feasible, a cost effective alternative (saving approximately $7000/ha) to subsoil salvaging and respreading becomes available to coal mine operators when reclaiming areas of the mine with sodic minespoils.

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2.0 IN SITU AMELIORATION OF SODIC MINESPOIL USING SULFUR, GYPSUM AND CROP MANAGEMENT

2.1 Introduction

Salvaging and respreading topsoil and subsoil on recontoured minespoils is the dominant practice in the reclamation of surface-mined land. Minespoils that are unsuitable media for plant growth require a considerable thickness of suitable quality soil materials covering them for adequate plant productivity. Sodic minespoils, spoils with high amounts of exchangeable sodium (Na), are particularly limiting to revegetation success on surface-mine lands. The primary effect of excess Na is to impart undesirable physical properties to the soil material that inhibit plant growth and development (Barth, 1976). For example, dispersed soils physically restrict plant root growth (Pearson, 1960). Plants with poorly developed root systems are susceptible to drought and nutritional deficiencies. In addition, the dispersion of sodic minespoils decreases the rate of water infiltration into and percolation through the minespoil; with less water entering sodic minespoils, plants may suffer drought stress. Even when water does enter sodic spoils, it does not readily move out which may result in persistent anaerobic conditions. This is unfavorable for revegetation since both normal plant germination and root development require sufficient air. Pearson (1960) found plants growing on sodic soils that became saturated frequently died. High soluble Na concentrations also reduce water availability to plants due to osmotic effects as plant roots are unable to obtain water in soil solutions with low osmotic potential.

High levels of soluble Na in sodic minespoils also influence plant nutrition. High levels of Na^+ and Cl^- have toxic effects on plants. High levels of Na^+ also result in nutritional deficiencies involving other essential elements. For instance, Greenway (1963) reported that NaCl reduces potassium (K) uptake in barley (*Hordeum vulgare* L.) under salt stress. Moreover, in greenhouse studies, high levels of exchangeable Na generally caused an increase in the absorption of Na, nitrogen (N) and molybdenum (Mo) and a decrease in the absorption of Ca, K, Mg, sulfur (S), copper (Cu), zinc (Zn), boron (B) and chloride (Cl) by five different crops.

With such limitations to plant growth and development, amelioration of sodic soils (minespoils) has been given substantial attention by many researchers. Many of the principles for improving sodic soils accepted today came from early work done by Kelley (1951): (1) establishment of drainage to lower water tables; (2) leaching of excess soluble salts; (3) replacement of exchangeable Na directly or indirectly; and (4) rearrangement and aggregation of soil particles to improve structure. Other research has since been conducted on the effectiveness of using chemical amendments (Overstreet et al., 1951; Miyamoto et al., 1975; Dollhopf et al., 1980; Merrill et al. 1983a) to ameliorate sodic soils or minespoils by replacing the exchangeable Na with Ca ions. Chemical amendments in these studies included sulfur, sulfuric acid and gypsum. Research has also been conducted on the importance of soil hydrologic regime in ameliorating sodic minespoils with different amendments (Dollhopf et al., 1980; Merrill et al., 1983a). Hypothetically, management practices which increase soil moisture within the profile assist amendments in lowering Na levels by increasing solubility of the amendments and increasing subsequent leaching of the displaced exchangeable Na. By reducing Na levels in the amended spoil, many beneficial changes in chemical and physical properties occur which provide a suitable subsoil root zone for plants.

This research was designed to evaluate the suitability of unweathered sandstone minespoil as subsoil at the Highvale Mine, approximately 90 km west of Edmonton. Two types of overburden overly the coal seam: weathered and unweathered sandstone overburdens from the Paskapoo Formation. Both materials are suitable for subsoil according to accepted criteria if their SAR is < 20; however, the weathered minespoil appears better for subsoil replacement than the unweathered minespoil due to lower SAR and higher hydraulic conductivity (Alberta Agriculture, 1987). Although both minespoils may meet existing criteria, concerns about other characteristics of the minespoils have been expressed including: poor water retention, low fertility, low nutrient status and restricted root growth. This research was developed to examine amelioration of the unweathered coarse textured sodic minespoil with SAR > 20 into suitable subsoil using sulfur, gypsum and crop management. If SAR could be reduced to < 20 through these methods, amending highly sodic minespoils may be a cost effective alternative to salvaging and respreading subsoil when reclaiming these difficult areas.

2.2 Materials and Methods

2.2.1 Site Location

This study was conducted on surface coal-mined land at the Highvale Mine owned and operated by TransAlta Utilities Corporation. The mine is located at 53.5 °N, 114.6 °W, in the Mid Boreal Mixedwood Ecoregion (Strong, 1992).

Soils at the mine developed under a forested environment and are low in organic matter. Solonetzic and Luvisolic soils are common with Gleysols in depressional areas and Organic soils in bogs and fens (Table 2). The native vegetation in the area represents a transition of the Aspen-Grove and Mixedwood section of the Boreal Forest Region. The Upland Poplar is the most common community comprising 95% of the non-agricultural lands surrounding the mine. Dominant species are aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), willow (*Salix sp.*), dogwood (*Cornus stolonifera* Michx.), roses (*Rosa acicularis* Lindl.) and saskatoon (*Amelanchier alnifolia* Nutt.). The topography of the area is gently to undulating with slopes in the range of 0 to 9%. Other slopes are more complex and vary between 16 and 30%. Long term average annual precipitation and temperature for the region are 534 mm and 3.3 °C, respectively. Highest precipitation occurs in June (91 mm) and July (105 mm). Mean annual temperature ranges from a low of -12 °C in January to a high of 16.4 °C in July (Table 3).

2.2.2 Strip Mining Operations

Strip mining is the most effective method of extracting coal deposits situated near the surface under flat landscapes in Alberta. Reclamation of all lands disturbed by mining is now mandatory as outlined in Alberta's Environmental Protection and Enhancement Act (AEPEA). Under this act, all available topsoil and suitable subsoil must be salvaged and stockpiled for replacement as cover soil upon reconstruction of soil profiles after mining. These salvage operations are usually accomplished by large scrapers which remove both horizons at a prescribed depth, after which overburden overlying the coal seam is removed and furrowed adjacent to the strip-mine using a dragline.

After all usable coal has been extracted, the minespoil is contoured. Then, subsoil and topsoil are spread over the minespoil at an appropriate depth and contoured to blend with adjacent area topography. The more often materials need to be handled or the greater the quantities of material to be moved, the greater the cost of mining. Reclamation cost in 1981 were estimated to range from $400 to $9000 per hectare (Webb, 1982). If ameliorating sodic minespoil with chemical amendments and crop management is deemed feasible in this study, coal mine operators have a cost effective alternative (saving approximately $7000/ha) to subsoil salvaging and respreading when reclaiming sodic minespoils.

2.2.3 Experimental Design and Site Establishment

In summer 1991, experimental field plots, each 40 × 25 m were constructed on leveled unweathered sandstone minespoil from Pit 04 of the Highvale Mine. These plots were in a 'split-block' with three chemical amendment treatments (control, sulfur and gypsum) representing the whole plot and two crop management treatments (fallow/barley and forage) representing the subplot components (Steel and Torrie, 1980). In each of three such experimental blocks, treatments were randomized using a subroutine in a statistics program (SAS Institute, 1988).

Prior to plot construction, chemical and physical properties of the minespoil were determined. The minespoil was sandy loam textured, calcareous, non-saline and sodic (Table 4). As a result of the high sodicity, the minespoil was classified as unsuitable as subsoil in post-mining reclamation and thus, chemical amendments were added to ameliorate it. The spoil was amended with gypsum and sulfur at rates of application (18.25 tonnes ha^{-1} gypsum and 3.25 tonnes ha^{-1} sulfur) calculated to exchange 4 (Na) cmol kg^{-1} soil to a 35-cm depth below the topsoil. A bulk density of 1.40 Mg m^{-3} was approximated for the minespoil. Amendment application was considered appropriate because cation exchange capacity of the spoil was low (Table 4). Both the gypsum and sulfur were incorporated into the spoil with three passes of a heavy duty disk. Following this, 20 cm of clay loam topsoil were applied uniformly over the amended spoil with a D11 crawler tractor.

In spring 1992, the forage subplots were seeded at 25 kg ha^{-1} with rye (*Secale cereale* L.) as a cover crop seeded at 126 kg ha^{-1}. The seed mix consisted of six forages varying in proportion by seed weight: alfalfa (*Medicago sativa* L.) (37%), smooth brome (*Bromus inermis* Leyss.) (37%), creeping red fescue (*Festuca rubra* L.) (11%), reed canary grass (*Phalaris arundinacea* L.) (9%), timothy (*Phleum pratense* L.) (3%) and Canada bluegrass (*Poa compressa* L.) (3%). At the same time, the fallow/barley subplots were seeded with fall rye. During mid-summer 1992, the forage subplots were mowed and forage removed to simulate haying practices of the area; the fallow/barley subplots were sprayed with glyphosate at manufacturer's recommended rates and cultivated in the fall. For the remainder of the study (1993 to 1995), the forage subplots were mowed in mid-summer. The fallow/barley subplots were cultivated to remove weeds each year except in 1994 when they were seeded to barley (*Hordeum vulgare* L.). Barley was included in the rotation to simulate practices of the local farmers. The forage and fallow/barley treatments were imposed to provide contrasting soil water regimes.

2.3 Field Sampling

2.3.1 Soil Chemical Measurements

In spring 1991, four samples of recontoured minespoil were obtained to locate an appropriate study site (SAR needed to exceed 20). The samples were analyzed for percent saturation (Sat%), pH, electrical conductivity (EC), soluble ions (Na^+, Ca^{2+}, Mg^{2+}, K^+), sodium adsorption ratio (SAR), calcium carbonate equivalent and particle size distribution (Table 4). Following plot construction in October 1991 and again in 1995, subplots were sampled with a coring unit for soil chemical characterization. Three samples, each comprised of three subsamples, were taken from each subplot. Samples were taken from the topsoil (TS) (0-20 cm), upper amended minespoil (UAM) (20-35 cm), lower amended minespoil (LAM) (40-55 cm) and unamended minespoil (UNAM) (55-70 cm) layers. All samples were analyzed for Sat%, pH, EC, soluble ions (Na^+, Ca^{2+},

Mg^{2+}, K^+, SO_4^{2-} and Cl^-) and SAR. Organic carbon (OC) was determined for the TS and UAM layers. All methods of chemical analyses were as described in McKeague (1978).

2.3.2 Soil Hydrologic Measurements

Within each subplot, three aluminum access tubes were randomly installed in spring 1992 to a depth of approximately 100 cm. Volumetric moisture content (VMC) was measured monthly throughout each field season (1992 to 1995), starting at a 15-cm depth, in each access tube using a Campbell Pacific Nuclear 503 Hydroprobe at 10-cm depth increments until the bottom of the access tube was reached. Volumetric moisture content (VMC) at a given depth was determined from the count at that depth divided by the standard count at the site (determined at the start of a set of readings and another at the end) with locally derived curves. Surface soil moisture (0-7.5 cm) was measured using a locally calibrated Campbell Pacific Nuclear 503 Hydroprobe placed in a polyethylene shield (Chanasyk and Naeth, 1988). Two measurements were taken on the soil surface adjacent to each access tube. Total accumulated water (TAW) was determined by multiplying VMC at a given depth by each respective depth increment and summing to the desired depth. Both VMC and TAW were averaged across treatments each time measured. To compare treatment effects, VMC at the surface (VMC0) and at depths of 45 (VMC45) and 75 cm (VMC75) were chosen as representative of the topsoil, amended minespoil and unamended minespoil layers, respectively. TAW to depths of 25, 55 and 75 cm were chosen as representative of depths slightly below the topsoil (TAW25), amended minespoil layer (TAW55) and unamended minespoil layer (TAW75).

2.3.3 Soil Physical Measurements

Within each access tube, starting at a 15-cm depth, bulk density (D_b) was measured using a locally calibrated Campbell Pacific Nuclear 501 Depth Moisture/Density Probe at 10-cm depth increments until the bottom of the access tube was reached. Bulk density was measured at the start (May) and end (October) of each field season (1992 to 1995).

Surface D_b and soil moisture (0 to 10 cm) were measured using a Campbell Pacific Nuclear MC1 or MC3 Surface Moisture/Density Gauge at 10 random locations within each subplot. Two readings were taken at each location and averaged. Measurements were taken two or three times throughout each field season.

All bulk density measurements were averaged across treatments each time sampled. To compare treatment effects, bulk densities at depths of 45 cm and 75 cm represented the amended minespoil layer and unamended minespoil layer, respectively.

At the time of surface D_b measurements, penetration resistance (PR) was measured adjacent to the same 10 locations in each subplot using a dial penetrometer (1.27 cm 30° cone). PR was recorded at depths of 0, 2.5, 5.1, 10.2, 15.2, 22.9, 30.5 and 45.7 cm. Two measurements were taken at each location and averaged at a given depth.

2.3.4 Vegetation Measurements

Vegetation measurements were initiated in summer 1992 in the forage subplots. Within each subplot, ten quadrats (0.1 m^2) randomly located 2 m apart were assessed to determine plant species composition and total plant biomass. Plant biomass was determined from samples cut with electric hand clippers near ground level (2 cm). These samples were sorted into grasses, forbs and legumes, oven dried at 65 °C and weighed. All plant biomass measurements were averaged across treatments each time sampled.

Plant community development and structure within each quadrat were determined through canopy and ground cover (live vegetation, litter and bare ground) assessments in mid summer (August) every year of the study. These vegetation measurements of the fallow/barley subplots were only taken in 1994 when barley was seeded. However, for biomass the barley crop samples were air dried, weighed, threshed and seed and straw weight determined separately.

2.4 Statistical Analyses

The General Linear Model Procedure (GLM) in the SAS statistical program was used to determine variability among treatments at a 5% probability (SAS Institute, 1988). Error terms were adjusted for a 'split-block' design (Steel and Torrie, 1980). If significant treatment differences were found, two multiple comparison procedures were used. With the exception of chemical properties, the Least Significant Difference (LSD) option in SAS was used to rank the treatments at both 5 and 10% probabilities. For chemical properties, significant differences were determined using the Least Square Means (LSM) option in SAS at a 5% probability because of the accuracy of measurement provided in the laboratory for these variables. Hydrologic, physical and vegetation variables were measured with field instruments resulting in higher variability among measurements, consequently, analyses were determined at a lower confidence interval (90%).

2.5 Results

2.5.1 Soil Chemical Properties

2.5.1.1 Percent Saturation

Immediately after plot construction (1991), there were no significant differences in Sat% between the amendment treatments at any depth; however, in 1995, the addition of gypsum significantly lowered Sat% only in the UAM layer (Tables 5 and 6). Although no significant differences were found at other depths, Sat% was lowest in the gypsum amended plots. Sulfur addition had no significant effect on Sat% at any depth in either 1991 or 1995, but Sat% of sulfur amended plots was consistently lower than in the control. No significant differences in Sat% due to crop management treatments were evident in either 1991 or 1995 (Tables 7 and 8). Yet, Sat% in the forage subplots in the minespoil layers was consistently lower than that in the fallow/barley subplots.

2.5.1.2 Soil pH

In 1991 and 1995, pH for both sulfur and gypsum amended plots was significantly lower than for control plots in the UAM although the maximum differences in pH among the three treatments was only 0.6 (Tables 5 and 6). At other depths, there were no significant differences between amended and control plots. For no year or depth did crop management have a significant effect on pH.

2.5.1.3 Electrical Conductivity

In 1991 and 1995, there were significant differences in EC in the UAM layer (Tables 5, 6, 7 and 8). EC in this layer was significantly higher due to sulfur and gypsum addition. In either year, EC was highest in gypsum amended plots (maximum 4.8 dS m^{-1}). In 1995, EC in the LAM layer for sulfur and gypsum amended plots was also significantly different from the control. Significant differences in EC between crop management treatments occurred only in 1995 (Table 8). In the UAM, LAM and UNAM layers, EC was significantly higher in forage subplots than fallow/barley subplots with the average difference between treatments approximately 0.7 dS m^{-1}, regardless of layer considered.

2.5.1.4 Soluble Ions

In both 1991 and 1995, there were no significant differences in soluble salt concentrations in the TS between amendment treatments. In 1991 and 1995, the concentrations of Na^+, Ca^{2+}, Mg^{2+}, K^+ and SO_4^{2-} in the UAM layer were significantly higher in the sulfur and gypsum amended plots than in the control plots (Tables 5 and 6). Moreover, the concentration of each element was highest in gypsum amended plots. In 1991, only in the UAM was Cl^- concentration not significantly different among amendment treatments; however, in 1995, Cl^- concentration was significantly higher in sulfur amended plots than in gypsum amended or control plots. In 1991, K^+ concentration in the LAM was significantly higher in gypsum amended plots than in control plots. Later in the study (1995), the concentrations of Ca^{2+}, Mg^{2+}, K^+ and SO_4^{2-} in the LAM were significantly higher in gypsum amended plots than in control plots. In 1991, Na^+ and SO_4^{2-} concentrations in the UNAM layer of gypsum amended and control plots were significantly higher than in sulfur amended plots; however, in 1995, no significant differences in soluble salt concentrations in the UNAM layer occurred between amendment treatments.

In 1991, no significant differences in soluble salt concentrations between crop management treatments occurred at any depth interval sampled; however, several significant differences occurred in 1995 (Tables 7 and 8). No significant difference in soluble salt concentrations occurred in 1995 within the TS due to crop management treatments. However, in 1995, in fallow/barley subplots significantly lower concentrations of Na^+, Ca^{2+}, K^+ and SO_4^{2-} were found than in forage subplots in the UAM, LAM and UNAM layers. In 1995, only Cl^- concentration was not significantly different at any depth interval between crop management treatments.

2.5.1.5 Sodium Adsorption Ratio

In 1991 and 1995, the SAR of plots amended with sulfur and gypsum was significantly lower than that of the control in the UAM layer (Tables 5 and 6). In 1995, only gypsum addition significantly reduced SAR in the LAM layer compared to the control. In 1991, crop management significantly lowered SAR in the LAM layer. At this depth, SAR of forage subplots was lower than that of fallow/barley subplots. In both 1991 and 1995, crop management significantly lowered SAR in the UNAM layer. Again, SAR was lower in forage subplots than in fallow/barley subplots at this depth (Tables 7 and 8).

2.5.1.6 Organic Carbon

In 1991 and 1995, no significant differences in OC due to amendment or crop management treatments occurred in the TS or UAM layer.

2.5.2 Meteorological Data

Precipitation and temperature data for the study period and long term normal (LTN) are presented in Table 3. During plot establishment year (1991), the growing season began with above LTN precipitation followed by a warm, dry July and very warm August; precipitation in October was much higher than the LTN. Both 1992 and 1993 growing seasons were warm and dry with air temperature > 0.7 °C higher than the LTN and total annual precipitation more than 100 mm below LTN. Growing season (May 1 - September 30) precipitation was near normal in 1991, 1993 and 1994, but only 63% of the LTN in 1992 and exceedingly high for 1995. Precipitation in July was consistently below normal in 1991 to 1994, inclusive, especially in 1991 with only 23% of the LTN; however, slightly above normal for 1995. Overwinter (October 1-March 31) precipitation was above normal in 1991-1992 and 1992-1993 and below normal in 1993-1994, 1994-1995 and 1995-1996. Precipitation for 1993-94 in this period was only 63% of LTN.

2.5.3 Soil Hydrologic Properties

2.5.3.1 Volumetric Moisture Content

At the soil surface, there were generally no significant differences in VMC0 due to amendments (20 out of 23 measurement dates) (Table 11). Although not statistically significant, VMC0 consistently was lowest in gypsum amended plots. Significant differences in volumetric surface moisture occurred between forage and fallow/barley treatments (10 out of 23 measurements dates), although there was no consistent trend (Table 11).

At a depth of 45 cm, amendment additions had no significant effect on VMC (Table 12). Similar to VMC0, VMC45 was consistently lower in gypsum amended plots than in sulfur amended and control plots. Conversely, crop management had at times a significant effect on VMC45 (13 of 28 measurement dates). VMC45 was substantially lower in forage subplots than in fallow/barley subplots on 26 of 28 measurement dates (Table 12).

At a 75-cm depth, VMC was lower in gypsum amended plots than in sulfur amended and control plots on all dates except one (Table 13). Again, crop management had significant effects on VMC75 with forage subplots significantly lower in VMC75 on all but the first two measurement dates (Table 13).

2.5.3.2 Total Accumulated Water

TAW25 was significantly affected by the addition of gypsum, being lowest for this treatment on all dates, significantly on 17 of 28 measurement dates (Table 14). Furthermore, TAW25 was highest in sulfur amended plots on 11 dates; whereas, on the significant dates, TAW25 was always lowest in gypsum amended plots but sulfur amended and control plots tended to alternate. Crop management significantly affected TAW25 (18 of 28 dates). TAW25 was lower in forage subplots than in fallow/barley subplots on all but 5 measurement dates (Table 14). The trends in TAW25 described above were also evident in TAW55 and TAW75 (Tables 15 and 16).

2.5.4 Soil Physical Properties

2.5.4.1 Bulk Density

Significant differences in surface D_b between amendment and crop management treatments were not consistent throughout the duration of the project nor were they large (< 0.07 Mg m^{-3}) (Table 17). Nevertheless, the highest surface D_b throughout the study was in gypsum amended plots, although generally not significant. Crop management occasionally (3 of 8 measurement dates) had significant effects on surface D_b with significantly higher surface D_b in forage treatments on all three dates (Table 17).

Significant differences in D_b at a 45-cm depth were found between gypsum amended plots and either sulfur amended or control plots only in 1992 and 1993, one and two years after amendment addition (Table 18). Early in the study, gypsum addition lowered D_b within the amended minespoil layer. Yet, later on in the study, no significant differences in D_b within this layer were found between amendment treatments. Crop management had no significant effect on D_b in the amended minespoil layer at any time (Table 18).

Below the amended minespoil layer at 75 cm, no significant differences in D_b were attributed to either amendment or crop management treatments (Table 19). There was no clear trend in either increasing or decreasing D_b at either 45 or 75 cm for any treatment over time.

2.5.4.2 Penetration Resistance

Throughout the study, significant differences in PR due to amendments were often found only at the lower topsoil and amended minespoil layer interface (between 10.2 and 22.9-cm depths) (Tables 20 to 28). PR was consistently higher in gypsum amended plots at this interface than in either sulfur amended or control plots. Deeper within the amended spoil layer, there was no significant effect on PR due to amendment treatments. With only one exception, PR increased with depth for all treatments on all dates.

2.5.5 Vegetation

2.5.5.1 Plant Species Composition

No significant differences in plant species composition occurred between amendment treatments within an individual field season (1992-1995); however, plant species composition changed dramatically between each successive field season. In 1992, rye (*Secale cereale* L.) was the dominant plant species comprising 49% to 56% cover. Other grasses such as timothy (*Phleum pratense* L.), creeping red fescue (*Festuca rubra* L.) and quack grass (*Agropyron repens* (L.) Beauv.) were common (Table 30). Legume and forb species cover percentages were quite low although numerous species were identified. In 1993, creeping red fescue, timothy and fall rye continued to dominate and smooth brome (*Bromus inermis* Leyess.) began to appear. Legume and forb species cover percentages remained small (Table 31). In 1994, timothy, creeping red fescue and smooth brome remained dominant and alfalfa (*Medicago sativa* L.) began to appear in appreciable quantities. Other legume species also increased in cover percentage. Forb species cover percent remained relatively unchanged (Table 32). In 1995, smooth brome, creeping red fescue and timothy continued to be high; however, alfalfa became the dominant plant species. Forbs cover percentage remained unchanged (Table 33). During the study, the number of species in the plots fluctuated only slightly each field season.

In 1994, when barley/fallow subplots were seeded to barley, cover percentages of barley ranged from 66% to 86%. Canada thistle (*Cirsium arvense* (L.) Scop.) was also quite successful in establishing (Table 34).

2.5.5.2 Plant Cover Percentage and Canopy Development

Significant differences in canopy cover percentages were found between amended plots in 1992, 1993 and 1995 (Table 35). In 1992 and 1993, live canopy cover was significantly higher in sulfur amended plots than in gypsum amended plots. In 1995, live canopy cover was significantly higher in control plots than in either sulfur or gypsum amended plots. Significant differences in litter canopy cover between amendment treatments were also found. In 1992, litter canopy cover was higher in sulfur amended plots than in gypsum amended and control plots. In 1995, litter canopy cover was significantly higher in both sulfur and gypsum amended plots than in control plots. Within individual field seasons, no significant differences in bareground canopy cover between amendment treatments were found. However, a reduction of bareground canopy cover percentage occurred in each successive field season.

Significant differences in ground cover percentages only existed for litter and bare ground for 1992 (Table 35). In 1992, litter ground cover was much higher in sulfur amended plots than in either gypsum amended or control plots, as well, bare ground cover in sulfur amended plots was less than the other amendment treatments.

As the study progressed, the percentage of litter ground cover continued to increase as plants would die and leave their residues. Consequently, the percentage of bare ground cover also decreased as the study progressed.

2.5.5.3 Plant Productivity

No significant differences in total annual plant biomass between amendment treatments were found within an individual field season (Table 36). As well, no amendment treatment showed a consistently higher productivity. For instance in 1992, highest annual biomass was in sulfur amended plots, whereas, in 1993, highest total annual biomass was in gypsum amended plots. However, in 1994 and 1995, highest total annual biomass was in control plots. Total annual biomass varied between field seasons. In 1992, total annual biomass exceeded 3000 kg ha^{-1} for all amendment treatments. In 1993, total annual biomass was considerable lower, averaging only 1745 kg ha^{-1} for all treatments. In 1994 and 1995, total annual biomass increased slightly from 1993, averaging 1938 kg ha^{-1} and 1968 kg ha^{-1}, respectively.

Similar to total annual biomass, no significant differences in annual grass, legume and forb biomass between amendment treatments were measured within a field season; however, annual grass, legume and forb biomasses differed between field seasons. In 1993 and 1994, annual grass biomass was high with yields averaging 1603 kg ha^{-1} and 1326 kg ha^{-1}, respectively. In 1995, annual grass biomass was lower, averaging 957 kg ha^{-1}. As the study progressed, annual grass biomass became lower while annual legume and forb biomass increased. In 1993, annual legume biomass was quite low. In the next two years, annual legume biomass increased dramatically from 88 kg ha^{-1} in 1993 to 729 kg ha^{-1} in 1995. Likewise, annual forb biomass also increased as the study progressed. in 1993, annual forb biomass averaged 54 kg ha^{-1}; whereas in 1995, it averaged 281 kg ha^{-1}.

In 1994, no significant differences in total annual barley biomass between amendment treatments were found (Table 37). In addition, no significant difference between amendment treatments were found for biomass of annual grain, straw and 100-seed weight.

2.6 Discussion

2.6.1 Soil Chemical Properties

2.6.1.1 Percent Saturation

In 1991, immediately after the plots were constructed, amendment treatment effects were not expected since insufficient time had passed for the expected ameliorative effects to occur. By 1995, the addition of Ca^{2+} ions by gypsum and sulfur addition resulted in lower Sat% due to the displacement of exchangeable Na causing flocculation of clay minerals. The slower reduction by sulfur addition is explained by the indirect addition of Ca ions. In the LAM layer, in the gypsum and sulfur amended plots, higher Sat% was likely due to the leaching of Na^{+} ions from the UAM layer.

The lower Sat% in fallow/barley subplots in 1995 than in forage plots at all depths except the UNAM layer is in agreement with the initial hypothesis that increased leaching in the fallow/barley subplots would reduce soluble salts within the profile, particularly Na.

2.6.1.2 Soil pH

In 1991 and 1995, in the UAM layer of the sulfur and gypsum amended plots, pH was lowered by the displacement and leaching of exchangeable Na from the amended minespoil. A few studies on alkaline (sodic) soils support an slight acidic shift in pH with the addition of calcium-supplying amendments (Dollhopf et al., 1980; Merrill et al., 1983a). The reduction of pH in the amended plots was quite fast since significant differences among the amendment treatments were measured in 1991.

2.6.1.3 Electrical Conductivity

In both 1991 and 1995, higher EC was expected in the UAM layer. The addition of calcium-supplying amendments raised the concentration of dissolved ions in solution. In addition to raising the concentration of Ca^{2+} ions, amendment addition also raised the concentration of Na^{+} ions in solution. In 1995, significantly higher EC in the LAM layer was the result of direct additions of Ca^{2+} ions from the amendment or indirectly from leaching of dissolved ions from the UAM layer above.

2.6.1.4 Soluble Salts

In both 1991 and 1995, significantly higher concentrations of Na^{+}, Ca^{2+}, Mg^{2+}, K^{+} and SO_4^{2-} ions were measured in the UAM layer of gypsum and sulfur amended plots than in the control, as hypothesized. Concentration of soluble Na^{+} was highest in gypsum amended plots due to the relatively rapid and direct addition of Ca^{2+} ions which quickly displaced exchangeable Na^{+} into solution. Meanwhile, chemical reactions with sulfur to produce Ca^{2+} ions took longer and consequently, sulfur was not as effective in displacing exchangeable Na^{+}, particularly early in the study (1991). However by 1995, sulfur reactions were beginning to produce sufficient quantities of Ca^{2+} ions to displace exchangeable Na^{+}. As expected, the concentrations of Ca^{2+} and SO_4^{2-} ions both increased in the UAM due to the addition of both gypsum and sulfur with concentrations in UAM layer higher in gypsum amended subplots versus sulfur amended subplots due to the immediate addition of Ca^{2+} and SO_4^{2-} ions in gypsum amended plots. In 1995, higher concentrations of Ca^{2+} and SO_4^{2-} were still found in gypsum amended plots than in sulfur amended plots; however, the differences became smaller than in 1991. In 1995, significant increases in Ca^{2+} and SO_4^{2-} concentrations were also noticeable in the LAM layer due to gypsum and sulfur addition indicating the amendments were supplying Ca^{2+} and SO_4^{2-} ions to the LAM layer. In 1991 and 1995, concentrations of Mg^{2+} and K^{+} increased with the addition of sulfur and gypsum to the minespoil. In 1991, significantly higher concentrations of both Mg and K in the amended plots could only be seen in the UAM layer; however in 1995, Mg and K concentrations were significantly higher in both the UAM and LAM layer. Elevated concentrations of both Mg and K due to calcium-supplying amendments are well documented in the literature (Miyamoto and Stroehlein, 1973, Merrill et al., 1983a). The increase in concentration of both Mg and K was due to the lowering of pH of the sodic minespoil since both elements are more soluble under acidic conditions. The significant differences in Mg and K concentrations in the LAM layer of the amended plots versus the control plots in 1995 reflected the effectiveness of the amendments in the LAM layer later in the study. The only element whose concentration remained unaffected by amendment addition was Cl. This was expected since Cl^- ions are not involved in either gypsum and sulfur amendment reactions.

In 1991, as expected, the concentrations of all soluble salts at depth were not significantly affected by crop management because sufficient time had not passed to see differences in leaching between crop management treatments. However, in 1995, significantly lower concentrations of Na^+, Ca^{2+}, Mg^{2+}, K^+ and SO_4^{-2} in the fallow/barley treatment versus the forage treatment occurred at all three depth intervals. This was attributed to the additional soil water in the fallow/barley subplots which increased leaching of salts. Crop management had no affect on Cl^- ion concentration. This was surprising since it was expected that negatively charged Cl^- ions would be leached deeper in fallow/barley subplots versus forage subplots due to the repulsion by clays and an increase in soil water which would lower Cl^- concentration.

2.6.1.5 Sodium Adsorption Ratio

As hypothesized, the addition of sulfur and gypsum significantly reduced SAR in both 1991 and 1995. In 1991, both sulfur and gypsum significantly reduced SAR in the UAM layer. As expected, gypsum immediately reduced SAR since it directly supplied Ca^{2+} ions that displaced exchangeable Na on the clay minerals. Although sulfur addition significantly reduced SAR, SAR remained higher than under gypsum addition since the chemical reactions involved in sulfur amelioration took longer to indirectly produce gypsum. In 1995, both sulfur and gypsum amendments significantly reduced SAR versus the control in the UAM layer. The reduction of SAR in the sulfur amended plots by 1995 indicated that chemical reactions involved with sulfur amelioration needed more time to supply Ca^{2+} ions. The reduction of SAR in the LAM layer due to sulfur and gypsum addition showed that the chemical amendments were effective at this depth. Although sulfur and gypsum lowered SAR versus that in the control in the LAM layer, elevated

SAR of all amendment treatments in 1995 as opposed to 1991 at this depth were due to Na^+ ions from the UAM layer being leached in the soil profile (Tables 5 and 6).

As hypothesized, crop management had significant effects on SAR in the plots. In 1991, significantly higher SARs in the LAM and UNAM layers of the fallow/barley subplots gave some early indication of the increased leaching of Na^+ ions within fallow/barley subplots versus forage subplots. In 1995, the increase in leaching in the fallow/barley subplots resulted in higher SAR in both the LAM and UNAM layers, than the forage subplots with the latter being significant, concurring with the study hypothesis.

2.6.1.6 Organic Carbon

Amendment treatments had no effect on OC in the TS or UAM layer due to insufficient time for root decomposition. That crop management treatments had no effect on OC in the TS or UAM layer was unexpected since higher OC in the forage subplots than in fallow/barley subplots in the TS layer and perhaps even the UAM layer would be anticipated. Again, insufficient time for root decomposition may explain the lack of a treatment effect at both depths.

2.6.2 Soil Hydrologic Properties

2.6.2.1 Volumetric Moisture Content

One of the primary effects of excess Na^+ is to cause dispersion of clays in sodic soils resulting in poor water percolation within the soil profile. It was hypothesized that the addition of calcium-supply amendments to the minespoil would displace Na^+ on the exchange sites on clay minerals causing their flocculation and better water movement within the soil profile. Throughout the study, volumetric surface moisture, VMC45 and VMC75 was lower in gypsum amended plots than in sulfur amended and control plots, supporting this hypothesis. With higher percolation, it was expected that VMC would be lower in amended plots which was the case for gypsum. However, our initial hypothesis did not explain the VMC at depth of sulfur amended plots, which remained similar to that of the control plots. VMC of sulfur amended plots should have been lower than that of control plots due to improved physical properties (flocculation) of the minespoil resulting in higher percolation rates. Even though sulfur took longer than gypsum to displace changeable Na on the clays with Ca^{2+} ions, the expected improvement in physical properties of the minespoil (flocculation) from the addition of sulfur resulting in lower VMC likely did not occur even later in the study (1995), as evidenced by the VMC.

As hypothesized, VMC was higher in fallow/barley subplots than in forage subplots at surface, 45 and 75 cm depths due to water which was not evapotranspired by plants in the fallow/barley subplots. As hypothesized, the additional soil water available to percolate in fallow/barley subplots accelerated the leaching of salts present in soil pore water thus improving the ameliorative effects of the chemical amendments. The increase in leaching of salts due to higher VMC was most noticeable in gypsum amended plots where salt concentrations in the UAM layer in gypsum × fallow/barley subplots were lower than in gypsum × forage subplots. Similar reductions in salt concentrations in the UAM layer among fallow/barley treatments versus forage treatments were observed in the sulfur plots.

2.6.2.2 Total Accumulated Water

Like VMC, the reduction of exchangeable Na^+ by the addition of calcium-supplying amendments had a significant effect on TAW. Throughout the study, TAW was lower in gypsum amended plots than in sulfur amended and control plots to depths of 25, 55 and 75 cm, likely due to flocculation of clay minerals by Ca^{2+} ions supplied by gypsum which displaces exchangeable Na. Flocculation of clays resulted in an increase in macroporosity and consequently improved percolation which was reflected by lower TAW at all depths in gypsum amended plots. Although it was hypothesized that lower TAW at depth would be measured in sulfur amended plots versus the control, this was not the case. Throughout the study, TAW in the sulfur amended plots was similar to that of the control. This was unexpected since sulfur supplied soluble Ca^{2+} ions which were expected to flocculate the clays and increase percolation and lower TAW.

The larger difference in TAW between the crop management treatments at greater depths was the result of the summation of smaller differences in TAW which existed throughout the soil profile. As hypothesized, higher TAW in fallow/barley subplots was due to less evapotranspiration by plants. Differences in TAW between crop management likely had significant effects on leaching of salts. Fallow/barley subplots with higher TAW had increased salt leaching as reflected in the lower soluble salt concentrations in the UAM layer of both sulfur and gypsum amended plots under a fallow/barley crop rotation versus a forage crop.

2.6.3 Soil Physical Properties

2.6.3.1 Bulk Density

Early in the study, the higher surface D_b in gypsum amended plots than either sulfur amended and control plots was not expected since the TS layers of all plots were not amended with gypsum or sulfur. Although statistically significant, the differences in surface D_b between amendment treatments were considered small and not physically significant. Although no significant differences in surface D_b between the amendment treatments were found during the remainder of the study, gypsum amended plots continued to have slightly higher surface D_b. D_b in the amended (D_b45) and unamended (D_b75) minespoil layers was affected by the addition of chemical amendments. Throughout the study, gypsum amended plots had lower D_b45 and D_b75 than sulfur amended or control plots. This was anticipated because the addition of gypsum should have decreased bulk density due to an increase in soil aggregation (Gal et al., 1984). Theoretically, Ca^{2+} ions displace exchangeable Na^+ and result in the flocculation of the clay minerals in the minespoil. Flocculation increases soil aggregation between soil particles resulting in larger pore spaces and lower bulk density. Besides the gypsum treatment effects, D_b remained relatively unchanged in all treatments throughout the study as was expected since wetting and drying cycles have their weakest effects on lowering D_b in sandy soils (Heinonen, 1986).

Throughout the study, the lack of significant effect of crop management on surface D_b, D_b45, and D_b75 was not surprising since changes in soil moisture would not be expected to affect D_b of the minespoil because of its low clay content.

2.6.3.2 Penetration Resistance

The slightly higher PR in gypsum than the sulfur amended or control plots, particularly near the TS/UAM layer interface (10.2 - 22.9 cm) was not surprising since soil strength increases as soil moisture decreases (Camp and Gill, 1969). Soil moisture in sulfur amended plots remained higher than in gypsum amended plots and similar to control plots. Consequently, the PRs of the sulfur and control treatments were similar.

Since soil moisture affects PR, it is not surprising that PR was lower in fallow/barley subplots where soil moisture throughout the profile was higher than in the forage subplots.

PR magnitudes in the UAM layer (20-35 cm) fluctuated above and below the critical rooting strength of 2 MPa in coarse textured soils suggested by Naeth et al. (1991). The variation in PR was caused by differences in soil moisture on the date the measurements were taken. In the LAM layer (40-55 cm), PR values were generally well above 2 MPa, indicating a potential problem for root penetration deeper into the reconstructed profile.

2.6.4 Vegetation

The lack of treatment differences in species composition, canopy and ground cover were expected since all the plots had sufficient topsoil depth and were well managed (fertilization and weed control). Although some statistically significant differences were found, the absolute values are not biophysically significant.

Throughout the study, treatment yields (total as well as grasses, legumes and forbs) did not differ although higher yields were expected in the amended plots due to the ameliorative effects in the minespoil layer which would result in a better rooting zone due to chemical, hydrologic and physical improvements. As viewed in soil pits, the majority of plant roots were in the topsoil; consequently, the improvements in the minespoil were not reflected in either forage or barley yield.

2.7 Conclusions

1) Overall, gypsum was more effective (although not statistically significant) than sulfur at reducing sodicity (SAR) of a sandy loam minespoil due to the direct addition of Ca^{2+} ions.
2) Although sulfur was also an effective amendment at reducing sodicity (SAR) of a sandy loam minespoil, it took a longer period of time to be effective since its reactions to produce Ca^{2+} ions were indirect and required microbial oxidation.

3) Besides lowering SAR, both gypsum and sulfur affected other chemical properties in the minespoil. They lowered Sat% and pH, but elevated the concentrations of Na^{+}, Ca^{2+}, Mg^{2+}, K^{+} and SO_4^{2-} in the UAM and LAM layers.

4) Gypsum affected these chemical properties in the manner just described above to a larger degree than sulfur and to greater depths.

5) Crop management had no significant effect on reducing sodicity (SAR) of sandy loam minespoil. However, due to higher soil moisture in fallow/barley plots, soluble salts were leached to greater depths than in forage subplots.

6) Only gypsum addition had an effect on soil moisture within the profile with less soil water at all depths. Although sulfur addition affected the same chemical properties, soil moisture in sulfur amended plots was similar to that in the control.

7) Crop management had a significant effect on the amount of soil moisture within the profile. Soil moisture was higher in fallow/barley subplots than in forage subplots.

8) Crop management had a significant effect on PR. PR was higher in forage subplots than in fallow/barley subplots. However, PR was unaffected by amendment treatments.

9) Amendment and crop management treatments had no significant effect on OC, Db, species composition, ground and canopy cover or annual biomass.

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3.0 SYNTHESIS

3.1 Purpose of the Study

The purpose of the study was to assess the ameliorative effects of sulfur and gypsum addition on a calcareous sandy loam textured sodic minespoil. Although many researchers have determined the ameliorative effects of numerous chemical amendments on sodic soils, in few studies (Dollhopf et al., 1980; Merrill et al., 1983 and Fullerton and Regier, 1987) has there been an attempt to describe the ameliorative chemical effects of amendment addition on minespoil in relation to other parameters (hydrologic, physical and vegetation) over a long period of time. Thus, this study was designed to provide a more complete picture of the feasibility of ameliorating a calcareous, sandy loam textured, sodic minespoil into a suitable subsoil material for reclamation with a characterization of the relationships between changes in soil chemistry due to amendment addition and its effect on other parameters. From the conclusions formulated in this study, informed decisions can be made regarding reclaiming lands in which sodic materials are a problem.

3.2 Impacts on Sodic Minespoil Reclamation

From the data collected, several conclusions were formulated regarding sulfur and gypsum addition effects on chemical, hydrologic, physical and vegetation properties.

Sulfur and gypsum reduced the SAR of the original recontoured minespoil (SAR > 20) to values as low as 3.9 in the UAM layer (20-35 cm) within 4 years. According to the suitability criteria for reclamation (Alberta Agriculture, 1987), this reduction in SAR changed the rating of the minespoil in the UAM layer by the end of the study from unsuitable (SAR >20) to fair (SAR < 8) or good (SAR < 4) depending on the amendment and crop management treatment. Suitability ratings of minespoil in the LAM (40-55 cm) remained poor even with amendment addition according to the suitability criteria for reclamation (Alberta Agriculture, 1987). Although amendment additions slightly reduced SAR in the LAM layer versus the control, the ameliorative effects were masked by the addition of salts (Na) from leachate water from the UAM layer. Thus more time is required for soil water to completely leach the salts out of the LAM layer.

The reduction of SAR was initially quite high after plot construction. In plots initially constructed of minespoils with SAR > 20, SAR ranged from 8.7 (gypsum) to 13.7 (control) after only 5 months, (the time baseline soil chemistry was measured in October 1991). However, after this quick initial reduction in SAR, the reduction in SAR was quite small during the remainder of the study, particularly in the control. The unsuitable rating for the control plots remained relatively unchanged during the study indicating that amendment addition was necessary to reduce SAR beyond the baseline SAR in 1991 and that time itself was not sufficient in reducing SAR after the initial reduction. Therefore, amendment additions are necessary to lower SAR to dramatically improve the suitability of the sodic minespoil for reclamation.

In addition to amendments, soil moisture was important in reducing SAR of minespoil. Throughout the study, the premise that summerfallowing increased soil moisture within the soil profile resulting in elevated leaching and accelerating the reduction of SAR in the amended minespoil layer was supported. Regardless of the amendment treatment, the amount of soil moisture was a significant factor in lowering SAR and soluble salts in the minespoil.

Besides the quantity of soil moisture, the amount of time required for leaching was also important in reducing SAR and salt concentration. After 4 years, the salts were leached sufficiently only from the UAM layer and accumulated in the LAM layer. Perhaps due to the climate, soil moisture was a constraining factor on the depth at which salts were eventually leached; however, another critical factor in salt leaching within the profile may be the hydraulic conductivity of the minespoil. Regardless of the amount of soil moisture, more time to sufficiently leach salts out of the LAM layer will be necessary due to its low hydraulic conductivity.

3.3 Other Reclamation Issues

Besides the effectiveness of the amendment, availability and cost have implications in determining the feasibility of its use. Both gypsum and sulfur are usually available, either as a mineral or as a by-product of industry. Since both amendments are effective at reducing sodicity in minespoil, the selection of either sulfur or gypsum may be determined by availability of source, closeness of source to site and difference in transportation costs. Since the quantity of sulfur required to displace an equivalent amount of Na is 1/6 that of gypsum, dramatic differences in transportation cost may warrant the use of sulfur although gypsum is the more effective amendment at lowering SAR.

Although summerfallowing was more effective than forages in reducing SAR in the UAM layer, there may be situations were its use is inappropriate. In areas of high wind and water erosion, conservation of topsoil may be of greater importance to reclamation success than the need for increased soil moisture to enhance amelioration of the minespoil. As well, summerfallowing may be detrimental in landscapes with very steep slopes due to topsoil losses from water erosion. Strip farming may be a possible method of ameliorating sodic minespoil while protecting the topsoil in these areas. By strip farming, a portion of the reclaimed area would receive the benefits of summerfallowing; however, the cropped area would reduce erosion in the area without vegetation.

3.4 Future Research Recommendations

From this study, several unresolved issues involving sodic minespoil amelioration warrant continued study and new research. Monitoring of salt leaching within the soil profile should be continued to determine the time frame necessary to leach all salts out of the amended minespoil layer.

Research is required on the effect of amendment treatments on vegetation. In this study, sufficient topsoil (20 cm) was placed over the recontoured minespoil; consequently, no treatment effects were seen on vegetation. In soil pits at the study site, the majority of plants rooted in the topsoil horizon, thus any differences in vegetation response on unamended and amended minespoil layers were not seen. Perhaps, new plots could be constructed including variation in topsoil depth (0 to 20 cm) to determine amendment treatment effects on vegetation, particularly effects on rooting depth.

Further work is needed to understand the mechanism involved in the potential of this calcareous minespoil to cement when dried. Although cementing did not appear to be a problem in the topsoiled minespoil plots in this study, from visual observations made adjacent to the study site cementing may be a potential problem when the minespoil is left exposed to dry.

3.5 References

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Table 1: Soil properties of weathered and unweathered sandstone minespoil.

Property	Weathered	Unweathered
Physical		
% Sand	75	76
% Silt	15	12
% Clay	10	12
Texture	Sandy Loam	Sandy Loam
% Montmorillonitic Clay	78	81
% Kaolinitic Clay	12	10
Particle density (Mg m^{-3})	2.65	2.62
Hydrologic		
10 kPa (kg kg^{-1})	0.160	0.165
Field Capacity - 33 kPa (kg kg^{-1})	0.126	0.150
Wilting Point - 1500 kPa (kg kg^{-1})	0.058	0.059
Hydraulic Conductivity (cm s^{-1})	2.5×10^{-3}	6.0×10^{-6}
Chemical		
Saturation Paste pH	7.9	8.1
Percent Saturation	74.9	75.5
Electrical Conductivity (dS m^{-1})	0.4	2.1
SAR	1.8	13.0

Table 2: General soil classification of soil map units at the Highvale Mine.

Soil Classification		Parent Material				
Soil Order	Subgroup	Residual Bedrock	Morainal	Glaciolacustrine	Fluvial	Organic
Solonetz	Dark Gray Solodized	Kavanagh				
	Gleyed Black		Namepi			
	Black Solodized			Wabamun		
	Gleyed Black Solonetz			Wabamun		
	Dark Gray Solod		Thorsby			
	Black Solod		Thorsby			
	Gleyed Black Solod		Thorsby			
Luvisol	Dark Gray	Pegasus	Uncas	Keephills	Fawcett	
	Dark Gray	Modeste			Leith	
	Orthic Gray			Highvale		
	Gleyed Gray			Evansburg		
	Solonetzic Gray		Nakamun			
Gleysol	Humic Luvic		Onoway			
	Orthic Luvic				Raven	
	Orthic				Raven	
Brunisol	Orthic Eutric	Modeste				
Organic						
	Typic Mesisol					Eaglesham
	Terric Mesisol					Eaglesham
	Typic Mesisol					Kenzie
	Terric Mesisol					Kenzie

Table 3: Mean monthly, yearly and long-term normal precipitation and temperature.

Month	Stony Plain 1966-94	Stony Plain 1991	Stony Plain 1992	Stony Plain 1993	Stony Plain 1994	Stony Plain 1995	Highvale 1991	Highvale 1992	Highvale 1993	Highvale 1994	Highvale 1995
Precipitation											
January	25	31	31	3	60	1	-	-	-	-	
February	20	30	42	10	17	10	-	-	-	-	
March	20	17	5	21	1	5	-	-	-	-	
April	25	37	32	22	4	19	-	-	-	-	25
May	50	99	33	50	54	20	111	-	47	4	23
June	91	106	20	103	119	67	72	3	110	118	76
July	105	24	61	80	84		59	33	112	46	113
August	77	79	51	70	85		42	45	36	66	133
September	46	20	69	22	44		5	64	28	29	8
October	24	87	6	13	16		-	-	-	-	
November	21	5	25	24	18		-	-	-	-	
December	26	18	21	12	11		-	-	-	-	
Oct. 1 - Mar. 31	136	125	188	86	127		-	-	-	-	
May 1 - Sept. 30	369	328	234	325	386		-	-	-	-	
Total Annual	534	551	394	430	512		-	-	-	-	
Mean Daily											
January	-12.1	-10.4	-5.1	-12.2	-15.0	-10.1	-	-	-15.1	-15.7	-12.5
February	-8.9	-0.7	-6.4	-8.1	-16.9	-7.9	-	-	-7	-17.6	-8.8
March	-3.2	-4.3	2.6	-1.3	1.3	-3.3	-	-	0.2	0.5	-4.1
April	4.7	7.0	6.0	5.2	6.3	3.5	-	-	6.1	5.7	3.0
May	10.9	10.6	9.7	12.3	11.6	11.3	11.1	-	13.5	11.4	11.2
June	14.6	13.8	16.0	13.8	14.3	15.5	13.7	-	15.4	14.2	16.4
July	16.4	16.9	15.9	15.1	17.4		17.2	11.9	17.2	18.7	12.8
August	15.6	18.5	15.1	14.9	16.0		18.3	20.0	15.3	15.6	10.6
September	10.6	11.7	8.7	11.1	13.4		11.4	16.7	11.9	12.8	
October	5.1	1.6	4.9	5.9	5.3		-	-	6.6	3.8	
November	-4.2	-4.2	-1.5	-3.1	-4.3		-	-	-2.9	-6.1	
December	-10.1	-6.4	-13.6	-4.3	-9.3		-	-	-12.1	-13.7	
Mean Annual	3.3	4.5	4.4	4.1	3.3		-	-	4.1	3.8	

Table 4: Pre-construction baseline chemical data of unweathered sandstone minespoil.

Sample*	Percent Saturation	pH	Electrical Conductivity (dS m^{-1})	Sodium Adsorption Ratio	ESP (%)
1	53	7.9	4.58	20.2	12.3
2	61	8.1	2.96	23.1	11.9
3	60	8.2	1.57	30.5	12.3
4	53	8.1	1.71	21.6	14.0
Mean	57	8.1	2.71	23.9	12.6

Sample	CaCO3 Equivalent (%)	CEC (meq L^{-1})	Sand (%)	Silt (%)	Clay (%)
1	2.2	13.4	75	9	16
2	2.0	12.6	74	9	17
3	2.4	13.1	72	12	16
4	3.1	12.4	73	11	16
Mean	2.4	12.9	74	10	16

	Soluble Cations			
Sample	Sodium (meq L^{-1})	Calcium (meq L^{-1})	Magnesium (meq L^{-1})	Potassium (meq L^{-1})
1	43.7	7.62	1.76	< 0.02
2	29.2	2.82	0.38	< 0.02
3	15.7	0.45	0.08	< 0.02
4	16.2	0.91	0.21	< 0.02
Mean	26.2	2.95	0.61	< 0.02

* Samples were taken randomly on recontoured minespoil prior to construction of amended plots.

Table 5: Summary of soil chemical properties by depth and amendment for 1991.

Depth (cm)	Treatment	Percent Saturation	pH	Electrical Conductivity (dS/m)	Soluble Ions: Sodium (meq/L)	Calcium (meq/L)	Magnesium (meq/L)	Potassium (meq/L)	Chloride (meq/L)	Sulfate (meq/L)	SAR	Organic Carbon (%)
0-20	Control	59.5	5.4	0.53	3.1	1.4	0.7	0.11	0.21	2.4	3.2	2.7
	Sulfur	56.0	5.3	0.52	3.4	1.3	0.6	0.11	0.26	2.3	3.5	3.1
	Gypsum	57.7	5.3	0.54	3.3	1.5	0.7	0.10	0.24	2.6	3.1	2.8
20-35	Control	57.3	7.6 a	1.76 c	16.2 c	2.3 c	0.9 c	0.26 c	0.10	12.9 c	13.7 a	1.5
	Sulfur	56.1	7.3 b	2.78 b	22.3 b	7.3 b	2.4 b	0.43 b	0.09	26.5 b	11.9 b	1.4
	Gypsum	52.6	7.0 c	4.80 a	33.1 a	23.4 a	5.6 a	0.72 a	0.10	59.1 a	8.7 c	1.5
40-55	Control	53.2	7.8	1.87	17.3	2.6	0.9	0.33 ab	0.16	14.1	13.9	-
	Sulfur	53.9	7.7	1.68	15.2	2.2	0.9	0.26 b	0.11	11.8	13.4	-
	Gypsum	51.9	7.7	1.93	17.1	3.0	1.2	0.38 a	0.13	15.1	12.6	-
55-70	Control	51.6	7.7	1.78 ab	16.4 a	2.5	0.9	0.25	0.09	12.5 ab	13.2	-
	Sulfur	53.0	7.5	1.49 b	13.0 b	2.2	0.8	0.24	0.11	8.9 b	12.1	-
	Gypsum	50.7	7.8	1.97 a	17.1 a	3.3	1.2	0.35	0.16	14.7 a	13.4	-

Treatment means for a given depth interval followed by the same letter are not significantly different ($p \leq 0.05$).

Table 6: Summary of soil chemical properties by depth and amendment for 1995.

Depth (cm)	Treatment	Percent Saturation	pH	Electrical Conductivity (dS/m)	Soluble Ions: Sodium (meq/L)	Calcium (meq/L)	Magnesium (meq/L)	Potassium (meq/L)	Chloride (meq/L)	Sulfate (meq/L)	SAR	Organic Carbon (%)
0-20	Control	53.2	5.4	0.45	3.4	1.1	0.5	0.06	0.26	2.1	4.0	2.9
	Sulfur	54.5	5.3	0.82	5.1	2.7	1.2	0.10	0.25	6.3	3.8	3.0
	Gypsum	50.5	5.3	0.69	4.1	2.2	0.9	0.07	0.23	4.6	3.4	2.6
20-35	Control	58.9 a	7.8 a	1.05 c	10.3 b	1.1 c	0.4 b	0.17 b	0.10 b	5.9 c	12.1 a	1.1
	Sulfur	53.3 ab	7.3 b	3.00 b	18.3 a	16.5 b	5.1 a	0.52 a	0.16 a	37.4 b	6.6 b	1.2
	Gypsum	47.3 b	7.3 b	3.51 a	20.6 a	22.8 a	5.5 a	0.50 a	0.08 b	46.3 a	5.3 b	1.3
40-55	Control	60.3	7.9	1.83 b	17.6	2.1 b	0.8 b	0.29 b	0.10	15.8 b	15.8 a	-
	Sulfur	65.2	7.7	2.30 a	20.3	4.4 ab	1.5 ab	0.38 a	0.09	22.9 a	14.2 ab	-
	Gypsum	59.1	7.7	2.43 a	20.4	6.0 a	2.1 a	0.41 a	0.10	25.4 a	12.8 b	-
55-70	Control	59.8	7.8	2.04	18.3	2.9	1.0	0.33	0.10	17.9	15.2	-
	Sulfur	60.0	7.7	2.21	18.5	4.5	1.9	0.39	0.09	21.2	14.4	-
	Gypsum	58.2	7.7	2.29	19.0	5.2	1.5	0.38	0.10	22.8	13.5	-

Treatment means for a given depth interval followed by the same letter are not significantly different ($p \leq 0.05$).

Table 7: Summary of soil chemical properties by depth and crop management for 1991.

Depth (cm)	Treatment	Percent Saturation	pH	Electrical Conductivity (dS/m)	Soluble Ions: Sodium (meq/L)	Calcium (meq/L)	Magnesium (meq/L)	Potassium (meq/L)	Chloride (meq/L)	Sulfate (meq/L)	SAR	Organic Carbon (%)
0-20	Forage	58.1	5.3	0.54	3.2	1.4	0.7	0.10	0.24	2.4	3.2	3.0
	Fallow/Barley	57.4	5.3	0.53	3.3	1.4	0.6	0.11	0.23	2.4	3.3	2.7
20-35	Forage	55.0	7.3	3.14	24.1	11.0	3.0	0.48	0.10	33.1	11.4	1.6
	Fallow/Barley	55.7	7.3	3.09	23.6	11.1	3.0	0.46	0.09	32.6	11.5	1.4
40-55	Forage	52.3	7.8	1.79	15.8	2.7	1.1	0.29	0.11	13.0	12.5 b	-
	Fallow/Barley	53.8	7.7	1.87	17.2	2.6	0.9	0.36	0.16	14.2	14.1 a	-
55-70	Forage	51.1	7.7	1.71	14.9	2.8	1.1	0.30	0.14	11.7	12.0 b	-
	Fallow/Barley	52.4	7.7	1.78	16.2	2.4	0.9	0.27	0.09	12.4	13.8 a	-

Treatment means for a given depth interval followed by the same letter are not significantly different ($p \leq 0.05$).

Table 8: Summary of soil chemical properties by depth and crop management for 1995.

Depth (cm)	Treatment	Percent Saturation	pH	Electrical Conductivity (dS/m)	Soluble Ions Sodium (meq/L)	Calcium (meq/L)	Magnesium (meq/L)	Potassium (meq/L)	Chloride (meq/L)	Sulfate (meq/L)	SAR	Organic Carbon (%)
0-20	Forage	54.3	5.3	0.69	4.5	2.3	0.9	0.08	0.23	4.6	3.7	2.9
	Fallow/Barley	51.2	5.4	0.61	3.9	1.7	0.7	0.07	0.26	4.1	3.7	2.7
20-35	Forage	54.9	7.4	2.86 a	19.4 a	15.1 a	4.1	0.43 a	0.13	34.8 a	8.7	1.3
	Fallow/Barley	51.4	7.5	2.18 b	13.4 b	11.8 b	3.2	0.36 b	0.11	24.9 b	7.3	1.2
40-55	Forage	63.7	7.7	2.53 a	21.9 a	5.7 a	2.0 a	0.41 a	0.09	26.5 a	13.9	-
	Fallow/Barley	59.3	7.8	1.85 b	17.0 b	2.6 b	0.9 b	0.30 b	0.10	16.3 b	14.6	-
55-70	Forage	59.3	7.7	2.51 a	20.4 a	6.0 a	2.1 a	0.43 a	0.09	25.5 a	13.3 b	-
	Fallow/Barley	59.4	7.8	1.86 b	16.9 b	2.5 b	0.9 b	0.30 b	0.10	15.8 b	15.5 a	-

Treatment means for a given depth interval followed by the same letter are not significantly different ($p \leq 0.05$).

Table 9: Summary of soil chemical properties by depth and amendment/crop management interaction for 1991.

Depth (cm)	Treatment	Percent Saturation	pH	Electrical Conductivity (dS/m)	Soluble Ions Sodium (meq/L)	Calcium (meq/L)	Magnesium (meq/L)	Potassium (meq/L)	Chloride (meq/L)	Sulfate (meq/L)	SAR	Organic Carbon (%)
0-20	C/FO	61.6	5.2	0.51	2.9	1.2	0.6	0.10	0.21	2.1	3.2	2.9
	C/FB	57.4	5.5	0.56	3.3	1.5	0.8	0.12	0.21	2.7	3.2	2.5
	S/FO	57.2	5.3	0.57	3.5	1.5	0.8	0.11	0.27	2.7	3.4	3.4
	S/FB	54.8	5.2	0.47	3.2	1.1	0.5	0.10	0.24	1.9	3.6	2.9
	G/FC	55.4	5.3	0.53	3.3	1.5	0.8	0.10	0.24	2.6	3.1	2.7
	G/FB	59.9	5.3	0.56	3.3	1.5	0.7	0.10	0.23	2.6	3.2	2.8
20-35	C/FO	56.6	7.6 ab	1.71 c	15.5 c	2.0 c	0.8 c	0.26 c	0.10	12.0 c	13.3 a	1.5
	C/FB	58.1	7.6 ab	1.81 c	16.9 c	2.5 c	1.0 c	0.26 c	0.10	13.7 c	14.1 a	1.5
	S/FO	55.0	7.3 abcd	2.87 b	22.8 b	7.4 b	2.6 b	0.43 b	0.11	27.5 b	11.8 a	1.5
	S/FB	57.1	7.3 bcd	2.68 b	21.8 b	7.3 b	2.2 b	0.42 b	0.08	25.6 b	11.9 a	1.4
	G/FO	53.4	7.1 bcde	4.83 a	34.1 a	23.5 a	5.5 a	0.76 a	0.10	59.8 a	9.0 b	1.8
	G/FB	51.8	6.9 de	4.76 a	32.2 a	23.4 a	5.7 a	0.69 a	0.10	58.4 a	8.5 b	1.2
40-55	C/FO	54.8	7.9	1.80	16.4 ab	2.2	0.8	0.24 b	0.10 b	12.8	13.8 ab	-
	C/FB	51.6	7.6	1.94	18.3 a	3.0	1.1	0.42 a	0.22 a	15.4	13.9 ab	-
	S/FO	51.0	7.8	1.62	14.0 b	2.4	1.0	0.29 ab	0.13 ab	11.1	11.9 b	-
	S/FB	56.9	7.7	1.74	16.3 ab	2.0	0.8	0.23 b	0.09 b	12.4	14.9 a	-
	G/FO	51.0	7.6	1.93	17.0 ab	3.3	1.4	0.32 ab	0.11 b	15.2	11.7 b	-
	G/FB	52.9	7.7	1.93	17.2 ab	2.7	1.0	0.45 a	0.16 ab	14.9	13.5 ab	-
55-70	C/FO	49.7	7.8 a	1.82 ab	16.5 abc	2.3	0.9	0.24	0.10	12.2 ab	13.5 a	-
	C/FB	54.4	7.6 ab	1.71 ab	16.0 abc	2.4	0.9	0.26	0.10	12.9 ab	13.2 a	-
	S/FO	52.1	7.5 b	1.50 b	12.7 cd	2.4	1.0	0.24	0.11	9.7 b	10.0 b	-
	S/FB	53.9	7.6 ab	1.48 b	13.4 bcd	1.9	0.7	0.24	0.10	8.1 b	14.3 a	-
	G/FO	51.6	7.7 ab	1.82 ab	15.4 abcd	3.8	1.4	0.40	0.22	13.3 ab	12.5 a	-
	G/FB	49.9	7.9 a	2.11 a	18.7 ab	2.7	1.0	0.33	0.10	16.1 a	14.2 a	-

Treatment means for a given depth interval followed by the same letter are not significantly different ($p \leq 0.05$). C = control, S = sulfur, G = gypsum, FO = forage and FB = fallow/barley.

Table 10: Summary of soil chemical properties by depth and amendment/crop management interaction for 1995.

Depth (cm)	Treatment	Percent Saturation	pH	Electrical Conductivity (dS/m)	Soluble Ions Sodium (meq/L)	Calcium (meq/L)	Magnesium (meq/L)	Potassium (meq/L)	Chloride (meq/L)	Sulfate (meq/L)	SAR	Organic Carbon (%)
0-20	C/FO	53.9	5.4	0.48	3.5	1.5	0.6	0.07	0.24	1.9	3.8	3.0
	C/FB	52.6	5.4	0.43	3.2	0.7	0.4	0.06	0.27	2.3	4.3	2.9
	S/FO	55.6	5.3	0.74	4.5	2.6	1.1	0.10	0.24	5.3	3.5	3.1
	S/FB	53.4	5.4	0.90	5.6	2.8	1.2	0.09	0.26	7.3	4.0	2.8
	G/FO	53.4	5.3	0.86	5.4	2.8	1.2	0.08	0.21	6.5	3.9	2.7
	G/FB	47.6	5.3	0.51	2.9	1.6	0.7	0.06	0.25	2.7	2.8	2.5
20-35	C/FO	60.8 ab	7.8 a	1.10 c	10.7 de	1.1 c	0.4 d	0.17 d	0.10 b	5.7 c	12.6 a	1.1
	C/FB	57.0 abc	7.8 a	1.02 c	9.8 de	1.1 c	0.4 d	0.17 d	0.10 b	6.1 c	11.6 a	1.2
	S/FO	54.9 abcd	7.3 b	3.22 b	19.7 bc	17.5 b	5.3 abc	0.54 abc	0.20 a	40.1 b	6.6 b	1.2
	S/FB	51.7 abcd	7.4 b	2.78 b	16.9 bcd	15.4 b	4.8 bc	0.49 abc	0.13 ab	34.6 b	6.6 b	1.3
	G/FO	49.0 bcd	7.3 b	4.27 a	27.6 a	26.7 a	6.5 ab	0.58 ab	0.07 b	58.6 a	6.8 b	1.6
	G/FB	45.6 cd	7.2 b	2.74 a	13.6 cde	19.0 b	4.5 bc	0.42 bc	0.09 b	34.1 b	3.9 b	1.1
40-55	C/FO	64.0	7.8	2.10 bc	20.1 abcde	2.7 bcd	1.0 bcd	0.32 bcd	0.10	19.2 bcd	16.5 ab	-
	C/FB	56.6	7.9	1.56 c	15.1 def	1.4 cd	0.5 cd	0.25 cd	0.10	12.4 cd	15.0 abcd	-
	S/FO	67.3	7.7	2.65 abc	22.5 abcd	6.5 ab	2.2 abc	0.47 ab	0.08	28.8 abc	12.3 cd	-
	S/FB	63.0	7.8	1.94 c	18.2 bcdef	2.3 bcd	0.9 bcd	0.28 bcd	0.09	17.0 bcd	16.0 abc	-
	G/FO	59.7	7.7	2.[illegible]3 a	23.2 abc	8.0 ab	2.9 ab	0.44 ab	0.09	31.5 ab	12.9 bcd	-
	G/FB	58.4	7.7	2.04 c	17.7 cdef	4.0 abcd	1.3 bcd	0.38 abc	0.10	19.4 bcd	12.7 bcd	-
55-70	C/FO	62.8	7.7	2.46 abc	21.8 abc	4.0 ab	1.3 bc	0.38 abcd	0.10	23.4 abc	15.1 ab	-
	C/FB	56.9	7.8	1.61 cd	14.8 cd	1.8 b	0.6 bc	0.27 cde	0.10	12.4 cd	15.4 ab	-
	S/FO	58.7	7.6	2.52 ab	20.4 abc	6.1 ab	2.0 abc	0.47 abc	0.08	25.8 abc	12.3 b	-
	S/FB	61.3	7.8	1.91 bcd	16.6 bcd	3.0 ab	1.1 bc	0.32 bcde	0.09	16.5 bcd	16.4 a	-
	G/FO	56.3	7.7	2.54 ab	18.9 abcd	7.8 a	2.9 ab	0.43 abcd	0.08	27.3 ab	12.3 b	-
	G/FB	60.0	7.8	2.04 abcd	19.1 abcd	2.6 b	0.9 bc	0.32 bcde	0.12	18.4 abcd	14.6 ab	-

Treatment means for a given depth interval followed by the same letter are not significantly different ($p \leq 0.05$). C = control, S = sulfur, G = gypsum, FO = forage and FB = fallow/barley.

Table 11: Average surface moisture content (0-7.5 cm, vol %) by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	21.4	19.0	19.5	19.7	20.2
	Jul-22	16.7 A	13.2 B	16.9 A	15.9	15.3
	Aug-17	9.0	9.7	8.2	7.7 B	10.1 A
	Sep-23	22.9	21.2	23.4	21.1	24.0
	Oct-16	21.2	19.4	19.5	18.8 b	21.2 a
1993						
	May-05	12.6	10.5	12.8	14.3 A	9.7 B
	May-29	24.9	22.7	23.4	23.5	23.9
	Jun-08	18.0	16.7	17.3	13.3 B	21.3 A
	Jul-13	18.7	20.8	18.8	23.5 A	15.4 B
	Aug-09	34.3	32.2	34.4	32.1	35.2
	Oct-12	11.6	11.4	11.6	12.4	10.6
1994						
	May-05	11.1	10.1	12.4	10.7	11.7
	Jun-03	14.1	12.6	13.3	11.4 B	15.2 A
	Jun-23	19.1	17.2	18.0	17.9	18.3
	Jul-20	22.2	21.2	24.7	22.6	22.7
	Aug-08	22.4	21.2	21.2	20.2 b	23.0 a
	Sep-20	15.4 A	12.6 B	14.4 AB	15.0	13.3
	Oct-18	15.8	15.0	14.7	14.7	15.6
1995						
	May-24	10.2	8.9	9.6	9.6	9.6
	Jun-22	18.8	17.4	18.2	19.1 a	17.2 b
	Jul-24	22.7	19.8	21.7	19.4 B	23.7 A
	Aug-16	27.2 A	23.2 B	24.5 C	23.9 B	26.1 A
	Sep-21	17.5	15.9	17.4	17.7	16.2

Treatment means within a row on a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 12: Volumetric moisture content (%) at 45 cm by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	36.9	36.3	37.5	37.5	36.3
	Jul-22	29.3	28.6	29.4	28.7	29.5
	Aug-17	29.6	27.7	30.4	27.5 b	31.1 a
	Sep-23	34.2	33.2	34.8	32.8 b	35.4 a
	Oct-16	32.4	31.1	33.7	30.6 B	34.3 A
	Nov-18	31.0	29.6	31.6	29.3 b	32.2 a
1993						
	Apr-21	33.1	32.3	34.9	31.9 b	34.9 a
	May-05	31.4	29.8	31.7	30.1	31.9
	May-29	30.6	30.5	31.2	29.6 B	32.0 A
	Jun-08	29.2	27.6	30.1	26.5 B	31.4 A
	Jun-30	36.0	35.3	36.7	35.2	36.8
	Jul-13	36.0	34.0	36.4	33.8 B	37.1 A
	Aug-09	37.6	36.7	37.4	35.8	38.6
	Oct-12	29.8	28.1	30.8	27.0	32.1
1994						
	May-05	32.6	30.9	33.1	30.7 b	33.7 a
	Jun-03	30.4	28.9	31.1	26.3 B	33.9 A
	Jun-23	32.4	30.3	32.6	27.7 B	35.9 A
	Jul-20	33.8	31.0	34.0	30.9 b	35.0 a
	Aug-08	30.6	27.8	30.7	29.8	29.6
	Sep-20	24.2	22.2	24.4	22.8	24.5
	Oct-18	27.4	25.4	27.4	25.6	27.8
1995						
	May-02	28.9	27.2	28.4	26.8	29.5
	May-24	26.1	23.8	26.3	24.1	26.7
	Jun-22	26.1	24.1	25.6	23.7 b	27.0 a
	Jul-24	21.6	20.7	22.3	20.0 b	23.3 a
	Aug-16	34.4	34.1	35.4	34.4	34.9
	Sep-21	33.0	31.7	32.9	32.0	33.0
	Oct-04	46.4	44.3	46.0	44.4	46.8

Treatment means within a row on a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively. Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 13: Volumetric moisture content (%) at 75 cm by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	36.4 a	33.9 b	35.9 a	35.8	35.0
	Jul-22	30.5 a	28.2 b	30.6 a	29.8	29.7
	Aug-17	31.7	30.1	31.4	31.0	31.2
	Sep-23	33.5	32.6	35.2	32.2	35.4
	Oct-16	32.4	31.3	34.0	30.4 B	34.5 A
	Nov-18	31.2 ab	30.2 b	32.5 a	29.7	33.0
1993						
	Apr-21	33.2 AB	32.5 B	34.9 A	32.1	34.8
	May-05	31.5	30.0	32.5	30.5	32.2
	May-29	30.7	29.5	30.7	29.3	31.2
	Jun-08	30.7 AB	28.9 B	31.7 A	29.1	31.7
	Jun-30	34.7	33.0	33.6	31.7 B	35.8 A
	Jul-13	35.4	35.0	35.9	32.6 b	38.1 a
	Aug-09	36.5	35.8	37.0	34.7 b	38.2 a
	Oct-12	33.1	32.0	34.1	31.6	34.6
1994						
	May-05	33.3 ab	32.0 b	34.4 a	31.7	34.8
	Jun-03	32.9	31.3	34.0	30.7 b	34.8 a
	Jun-23	33.9	32.7	34.1	30.6 B	36.4 A
	Jul-20	34.1	32.1	34.0	30.9 B	36.0 A
	Aug-08	33.2	30.8	32.9	30.5	34.2
	Sep-20	29.7 AB	27.3 B	30.5 A	27.1	31.3
	Oct-18	30.3	29.1	31.1	28.6	31.8
1995						
	May-02	31.9 a	29.0 b	31.7 ab	29.2	32.6
	May-24	29.4 AB	26.8 B	30.1 A	26.8 b	30.7 a
	Jun-22	29.3	27.2	29.6	26.6 b	30.9 a
	Jul-24	26.1 a	23.9 b	26.4 a	23.0 B	28.3 A
	Aug-16	33.3	33.2	34.2	32.0	35.1
	Sep-21	32.2	32.6	31.9	30.7	33.9
	Oct-04	46.0	46.8	45.4	48.2 a	43.9 b

Treatment means within a row on a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 14: Total accumulated water (mm) to a 25-cm depth by amendment and crop management.

		Amendment			Crop Management	
Year	Date	Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	107	104	106	107	105
	Jul-22	70	68	73	64 B	76 A
	Aug-17	63	61	65	50 B	77 A
	Sep-23	100 AB	95 B	101 A	93 B	105 A
	Oct-16	91 AB	84 B	92 A	80 B	97 A
	Nov-18	95 A b	89 B c	98 A a	89 B	99 A
1993						
	Apr-21	110 B	108 B	112 A	106 B	114 A
	May-05	83 AB	78 B	85 A	81 B	83 A
	May-29	94	91	94	89 B	98 A
	Jun-08	76 A	71 B	76 A	56	93
	Jun-30	127 ab	118 b	128 a	126	123
	Jul-13	101	97	101	99	101
	Aug-09	121	115	120	115 B	122 A
	Oct-12	65	62	65	59 B	69 A
1994						
	May-05	85	81	86	79 B	90 A
	Jun-03	82	79	80	66 B	94 A
	Jun-23	94	89	89	81 B	100 A
	Jul-20	102 AB	95 B	105 A	98 B	104 A
	Aug-08	84 a	80 b	81 b	78	86
	Sep-20	62 A	55 C	59 B	59	59
	Oct-18	76 a	72 b	75 ab	71 b	77 a
1995						
	May-02	91 A	85 B	89 AB	88	88
	May-24	75 a	69 b	75 a	73	73
	Jun-22	75 A	70 B	73 AB	71	75
	Jul-24	61 AB	60 B	63 A	58 b	65 a
	Aug-16	116 A	105 B	112 A	112	111
	Sep-21	92 a	85 b	90 ab	85 B	93 A
	Oct-04	144	136	141	128 B	154 A

Treatment means within a row on a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 15: Total accumulated water (mm) to a 55-cm depth by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	217 A	211 B	219 A	218	214
	Jul-22	158	152	161	149 B	165 A
	Aug-17	150 B	143 C	154 A	129 B	170 A
	Sep-23	203 AB	194 B	207 A	191 B	212 A
	Oct-16	187 AB	177 B	194 A	172 B	200 A
	Nov-18	188 AB	178 B	194 A	176 B	197 A
1993						
	Apr-21	208 B	205 B	218 A	202 B	219 A
	May-05	177 A	167 B	181 A	171 B	179 A
	May-29	186	182	188	177 B	194 A
	Jun-08	163 A	152 B	167 A	134 B	188 A
	Jun-30	236	224	239	232 B	234 A
	Jul-13	210	200	212	204	212
	Aug-09	233	222	234	222	238
	Oct-12	152	145	157	139 B	164 A
1994						
	May-05	183	176	186	172 B	192 A
	Jun-03	173	166	174	145 B	197 A
	Jun-23	191	180	193	168 B	207 A
	Jul-20	202 AB	188 B	208 A	191 B	208 A
	Aug-08	174 a	163 b	172 ab	164 b	175 a
	Sep-20	134	122	133	127	133
	Oct-18	157 A	148 B	159 A	148 B	162 A
1995						
	May-02	178	166	175	169	178
	May-24	153 AB	141 B	155 A	145	154
	Jun-22	153 A	142 B	151 A	142 B	156 A
	Jul-24	125 ab	121 b	130 a	117 B	135 A
	Aug-16	219	208	219	215	217
	Sep-21	191	179	189	181 b	192 a
	Oct-04	284	269	278	260 B	295 A

Treatment means within a row on a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 16: Total accumulated water (mm) to a 75-cm depth by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	290 A	280 B	291 A	289	284
	Jul-22	218	210	222	210	224
	Aug-17	213 A	203 B	220 A	191 B	233 A
	Sep-23	270 AB	259 B	277 A	255 B	283 A
	Oct-16	255 A	239 B	263 A	232 B	271 A
	Nov-18	250 AB	238 B	259 A	235 B	263 A
1993						
	Apr-21	275 B	270 B	287 A	266 b	288 a
	May-05	240 A	227 B	247 A	231 b	244 a
	May-29	247	241	250	235 B	256 A
	Jun-08	224 AB	211 B	231 A	192 B	252 A
	Jun-30	306 A	289 B	304 AB	294 b	305 a
	Jul-13	281	270	284	269 B	287 A
	Aug-09	307	293	308	292 B	314 A
	Oct-12	218 ab	208 b	226 a	201 B	233 A
1994						
	May-05	249	239	255	235 B	260 A
	Jun-03	238	227	242	206 B	265 A
	Jun-23	258	243	261	228 B	280 A
	Jul-20	270 ab	251 b	276 a	252	280
	Aug-08	240 a	222 b	238 a	232	235
	Sep-20	192 A	174 B	193 A	179	194
	Oct-18	217	205	220	204 b	224 a
1995						
	May-02	241	224	238	225	244
	May-24	213 A	193 B	215 A	199	215
	Jun-22	210 A	196 B	210 A	194 B	217 A
	Jul-24	176 ab	167 b	183 a	162 B	191 A
	Aug-16	286	275	288	280	287
	Sep-21	253	242	254	242 b	258 a
	Oct-04	375	360	370	346 B	391 A

Treatment means within a row on a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.

Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 17: Surface bulk density (0-7.5 cm) (Mg m^{-3}) by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	1.02 B	1.09 A	1.04 AB	1.04	1.06
	Jul-22	1.03 ab	1.06 a	0.99 b	1.03	1.02
1993						
	May-05	1.02 B	1.06 A	1.05 AB	1.03	1.05
	Jun-07	1.01	1.05	1.03	1.04	1.02
	Jul-13	1.01	1.01	0.99	1.07 A	0.94 B
1994						
	May-10	0.98	1.03	1.02	1.02 a	1.00 b
1995						
	May-29	0.68	0.71	0.68	0.70	0.68
	Aug-18	1.09	1.11	1.09	1.14 A	1.05 B

Treatment means within a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 18: Bulk density (Mg m^{-3}) at 45 cm by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	1.50 A	1.41 B	1.46 AB	1.48	1.44
1993						
	May-29	1.56 a	1.44 b	1.53 a	1.52	1.50
1994						
	Oct-18	1.44	1.38	1.43	1.40	1.42
1995						
	May-02	1.46	1.41	1.45	1.42	1.46
	Oct-04	1.42	1.38	1.49	1.41	1.45

Treatment means within a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 19: Bulk density (Mg m^{-3}) at 75 cm by amendment and crop management.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	1.44	1.39	1.46	1.45	1.40
1993						
	May-29	1.57	1.49	1.52	1.57	1.48
1994						
	Oct-18	1.47	1.41	1.53	1.49	1.45
1995						
	May-02	1.47	1.41	1.53	1.48	1.46
	Oct-04	1.43	1.47	1.51	1.46	1.48

Treatment means within a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 20: Penetration resistance (MPa) for June 16, 1992 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.19	0.20	0.21	0.19	0.21
2.5	0.56	0.58	0.59	0.58	0.58
5.1	0.80	0.84	0.78	0.79	0.82
10.2	1.12	1.13	1.01	1.08	1.09
15.2	1.24 AB	1.42 A	1.12 B	1.30	1.22
22.9	1.21	1.27	1.25	1.22	1.26
30.5	1.57	1.31	1.50	1.48	1.44
45.7	3.23 a	2.49 b	2.59 b	2.80	2.73

Treatment means within a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 21: Penetration resistance (MPa) for July 22, 1992 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.40	0.41	0.55	0.50	0.40
2.5	0.88	1.15	1.14	1.18	0.93
5.1	1.44	1.55	1.48	1.73 a	1.25 b
10.2	2.18	2.09	2.19	2.63 A	1.68 B
15.2	2.56	2.76	2.54	2.99 a	2.25 b
22.9	2.78	2.95	2.67	3.22 A	2.37 B
30.5	3.48	3.02	3.12	3.89 A	2.53 B
45.7	4.31	4.09	4.44	4.53	4.06

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 22: Penetration resistance (MPa) for Aug. 18, 1992 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.30	0.34	0.39	0.39	0.30
2.5	0.78	0.99	1.02	1.05 A	0.81 B
5.1	1.23	1.55	1.44	1.61 A	1.20 B
10.2	1.98	2.68	2.18	2.87 A	1.69 B
15.2	2.46	2.81	2.54	3.28 A	1.93 B
22.9	2.79	2.83	2.46	3.45 A	1.94 B
30.5	3.36	2.77	3.30	3.76 A	2.52 B
45.7	4.49 A	4.04 B	4.47 A	4.94 A	3.73 B

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 23: Penetration resistance (MPa) for May 5, 1993 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.43	0.46	0.51	0.57 A	0.36 B
2.5	0.86	0.93	0.96	1.07 A	0.76 B
5.1	1.10	1.17	1.19	1.35 A	0.95 B
10.2	1.43	1.70	1.59	2.04 A	1.11 B
15.2	1.54 B	2.13 A	1.72 B	2.31 A	1.28 B
22.9	1.68 b	2.16 a	1.74 b	2.20 A	1.51 B
30.5	2.00	2.31	2.27	2.66 A	1.73 B
45.7	3.94	3.41	3.81	4.31 A	3.13 B

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 24: Penetration resistance (MPa) for June 7, 1993 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.43	0.41	0.38	0.42	0.39
2.5	0.97	0.84	1.04	1.15 A	0.75 B
5.1	1.21	1.23	1.27	1.56 A	0.91 B
10.2	1.93	1.88	1.65	2.58 A	1.06 B
15.2	2.51	2.49	2.19	3.56 A	1.24 B
22.9	2.56	2.80	2.41	3.83 A	1.34 B
30.5	2.71	2.69	2.53	3.64 A	1.64 B
45.7	3.87	3.67	3.81	4.88 A	2.68 B

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 25: Penetration resistance (MPa) for July 13, 1993 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.31	0.31	0.38	0.58 A	0.09 B
2.5	0.60 B	0.78 A	0.66 AB	1.11 A	0.24 B
5.1	0.68 B	0.86 A	0.78 AB	1.14 A	0.41 B
10.2	0.91 b	1.23 a	0.94 b	1.38 A	0.68 B
15.2	1.06 b	1.49 a	1.11 b	1.58 A	0.86 B
22.9	1.11 b	1.63 a	1.25 ab	1.67 A	0.99 B
30.5	1.40 b	1.73 a	1.69 ab	1.87 A	1.34 B
45.7	3.20	3.13	3.37	3.87 A	2.59 B

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 26: Penetration resistance (MPa) for May 10, 1994 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.48	0.43	0.34	0.62 A	0.21 B
2.5	0.97	1.05	0.90	1.54 A	0.41 B
5.1	1.26	1.44	1.50	2.18 A	0.62 B
10.2	1.89 ab	2.04 a	1.70 b	2.70 A	1.05 B
15.2	2.30	2.51	2.19	3.36 A	1.30 B
22.9	2.31	2.36	2.37	3.31 A	1.38 B
30.5	2.75	2.51	2.66	3.62 A	1.66 B
45.7	3.96 A	3.72 B	3.94 A	4.87 A	2.87 B

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 27: Penetration resistance (MPa) for May 29, 1995 by amendment and crop management.

	Amendment			Crop Management	
Depth (cm)	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.67	0.64	0.62	0.87 A	0.42 B
2.5	1.54	1.61	1.50	2.02 A	1.08 B
5.1	1.77	1.93	1.74	2.14 A	1.49 B
10.2	2.10 B	2.47 A	2.25 AB	2.58 A	1.97 B
15.2	2.38 b	2.87 a	2.42 b	2.97 A	2.14 B
22.9	2.39	2.90	2.64	3.16 A	2.12 B
30.5	2.75	2.64	3.01	3.12	2.48
45.7	3.26	3.02	3.44	2.64 a	3.83 b

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 28: Penetration resistance (MPa) for Aug. 10, 1995 by amendment and crop management.

Depth (cm)	Amendment			Crop Management	
	Control	Gypsum	Sulfur	Forage	Fallow/Barley
0	0.21 ab	0.22 a	0.19 b	0.28 A	0.14 B
2.5	0.27 b	0.34 a	0.29 ab	0.42 A	0.18 B
5.1	0.37 b	0.52 a	0.41 ab	0.58 A	0.29 B
10.2	0.51 B	0.70 A	0.61 AB	0.72 a	0.49 b
15.2	0.62 C	0.95 A	0.75 B	0.86	0.68
22.9	0.75 C	1.07 A	0.91 B	1.03	0.79
30.5	0.97	1.17	1.10	1.21 a	0.94 b
45.7	2.15	1.89	2.11	2.42	1.68

Treatment means within a given depth followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 29: Surface moisture (0-7.5 cm, vol %) by amendment and crop management for 1991-1995.

Year	Date	Amendment			Crop Management	
		Control	Gypsum	Sulfur	Forage	Fallow/Barley
1992						
	Jun-16	20.6	18.9	19.3	19.3 b	20.0 a
	Jul-22	14.4 a	13.4 b	13.7 ab	13.6	14.1
1993						
	May-05	20.7	18.9	20.5	16.2 B	23.9 A
	Jun-07	17.3	15.6	17.5	11.8 B	21.8 A
	Jul-13	24.7	22.1	24.5	23.6	23.9
1994						
	May-10	16.2	14.2	15.2	14.5	15.8
1995						
	May-29	9.7	8.5	9.7	9.1	9.5
	Aug-18	29.9 A	23.8 B	28.3 A	30.1 A	24.6 B

Treatment means within a given date followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
Comparisons are for control, sulfur and gypsum amendment treatments; and forage and fallow/barley crop management treatments; but not their interactions.

Table 30: Species composition (%) of amended plots on July 27, 1992.

Latin Name	Common Name	Control	Sulfur	Gypsum
Grasses and Sedges				
Secale cereale	Rye	49	56	49
Phleum pratense	Timothy	10	5	6
Festuca rubra	Creeping red fescue	7	6	7
Agropyron repens	Quack grass	6	4	4
Bromus inermis	Smooth brome	5	5	5
Danthonia spicatum	Poverty oatgrass	3	2	3
Equisetum arvense	Common horsetail	3	3	4
Legumes				
Medicago sativa	Alfalfa	5	5	6
Trifolium hybridum	Alsike clover	2	2	2
Trifolium pratense	Red clover	1	1	+
Trifolium repens	White clover	1	1	2
Vicia americana	Wild vetch	+	+	1
Forbs				
Ranunculus acris	Tall buttercup	4	4	5
Galeopsis tetrahit	Hemp nettle	2	2	2
Epilobium angustifolium	Fireweed	1	1	1
Polygonum arenastrum	Common knotweed	1	1	1
Artemisia cana	Sagebrush	+	-	-
Cirsium arvense	Canada thistle	+	-	+
Plantago major	Common plantain	+	1	+
Polygonum convolvulus	Wild buckwheat	+	+	+
Tanacetum vulgare	Common tansy	+	+	+
Fragaria virginiana	Wild strawberry	-	-	1
Taraxacum officinale	Common dandelion	-	-	+

(+) - indicates composition less than 1%.
(-) - indicates absence of species in plot.

Table 31: Species composition (%) of amended plots on June 18, 1993.

Latin Name	Common Name	Control	Sulfur	Gypsum
Grasses and Sedges				
Festuca rubra	Creeping red fescue	19	18	21
Bromus inermis	Smooth brome	17	16	19
Phleum pratense	Timothy	16	24	17
Secale cereale	Rye	11	15	16
Agropyron repens	Quack grass	6	3	2
Danthonia spicatum	Poverty oatgrass	2	1	2
Phalaris arundinacea	Reed canary grass	5	2	1
Poa compressa	Canada bluegrass	4	3	1
Poa palustris	Fowl bluegrass	1	1	1
Poa pratensis	Kentucky bluegrass	-	-	+
Legumes				
Medicago sativa	Alfalfa	7	5	8
Trifolium hybridum	Alsike clover	2	1	2
Trifolium pratense	Red clover	1	1	+
Trifolium repens	White clover	1	2	1
Vicia americana	Wild vetch	+	+	+
Forbs				
Ranunculus acris	Tall buttercup	4	1	2
Potentilla norvegica	Rough cinquefoil	4	3	4
Tanacetum vulgare	Common tansy	+	-	1
Plantago major	Common plantain	1	1	+
Crepis tectorum	Annual hawksbeard	-	+	-
Chenopodium album	Lamb's-quarters	-	-	+
Geranium bicknelli	Crane's-bill	-	1	+
Taraxacum officinale	Common dandelion	-	1	-

(+) - indicates composition less than 1%.
(-) - indicates absence of species in plot.

Table 32: Species composition (%) of amended plots on June 28, 1994.

Latin Name	Common Name	Control	Sulfur	Gypsum
Grasses and Sedges				
Phleum pratense	Timothy	21	22	24
Festuca rubra	Creeping red fescue	15	15	18
Bromus inermis	Smooth brome	10	8	6
Poa compressa	Canada bluegrass	4	2	2
Agropyron repens	Quack grass	3	5	6
Poa palustris	Fowl bluegrass	2	2	1
Dactylis glomerata	Orchard grass	1	1	1
Phalaris arundinacea	Reed canary grass	+	-	+
Poa pratensis	Kentucky bluegrass	+	-	+
Danthonia spicatum	Poverty oatgrass	-	+	1
Carex spp.	Sedge	-	+	+
Legumes				
Medicago sativa	Alfalfa	15	15	17
Trifolium hybridum	Alsike clover	7	7	6
Trifolium pratense	Red clover	6	7	2
Trifolium repens	White clover	6	9	10
Vicia americana	Wild vetch	+	+	+
Forbs				
Ranunculus acris	Tall buttercup	7	3	1
Potentilla norvegica	Rough cinquefoil	4	2	2
Taraxacum officinale	Common dandelion	+	+	-
Plantago major	Common plantain	-	+	+
Tanacetum vulgare	Common tansy	-	-	2

(+) - indicates composition less than 1%.
(-) - indicates absence of species in plot.

Table 33: Species composition (%) of amended plots on July 18, 1995.

Latin Name	Common Name	Control	Sulfur	Gypsum
Grasses and Sedges				
Bromus inermis	Smooth brome	19	21	27
Festuca rubra	Creeping red fescue	16	16	16
Phleum pratense	Timothy	10	9	9
Poa compressa	Canada bluegrass	4	4	3
Agropyron repens	Quack grass	3	3	3
Danthonia spicatum	Poverty oatgrass	1	2	1
Phalaris arundinacea	Reed canary grass	1	1	-
Bromus spp.	Meadow brome	+	+	-
Carex spp.	Sedge	+	1	+
Poa palustris	Fowl bluegrass	+	1	+
Sisyrinchium montanum	Blue-eyed grass	+	+	-
Sonchus uliginosus	Perennial sow thistle	-	+	-
Legumes				
Medicago sativa	Alfalfa	26	26	26
Trifolium pratense	Red clover	6	3	3
Trifolium repens	White clover	4	5	3
Trifolium hybridum	Alsike clover	2	3	2
Vicia americana	Wild vetch	-	+	+
Forbs				
Ranunculus acris	Tall buttercup	5	4	4
Tanacetum vulgare	Common tansy	2	+	2
Cirsium arvense	Canada thistle	+	-	-
Fragaria virginiana	Wild strawberry	+	-	-
Potentilla norvegica	Rough cinquefoil	+	+	-
Plantago major	Common plantain	+	+	+
Silene pratensis	White cockle	+	-	-
Taraxacum officinale	Common dandelion	+	+	+
Iris missouriensis	Blue flag	-	-	+
Vaccaria pyramidata	Cow-cockle	-	-	+

(+) - indicates composition less than 1%.
(-) - indicates absence of species in plot.

Table 34: Species composition (%) of fallow/barley subplots on June 28, 1994.

Latin Name	Common Name	Control	Sulfur	Gypsum
Grasses and Sedges				
Hordeum vulgare	Barley	66	66	86
Sonchus uliginosus	Perennial sow thistle	4	3	-
Bromus inermis	Smooth brome	3	-	+
Poa compressa	Canada bluegrass	1	-	+
Poa palustris	Fowl bluegrass	+	+	+
Equisetum arvense	Common horsetail	+	+	+
Agropyron repens	Quack grass	-	2	+
Danthonia spicatum	Poverty oatgrass	-	+	-
Phleum pratense	Timothy	-	-	2
Legumes				
Trifolium hybridum	Alsike clover	1	+	+
Trifolium repens	White clover	1	5	2
Medicago sativa	Alfalfa	+	1	-
Vicia americana	Wild vetch	+	-	-
Trifolium pratense	Red clover	-		+
Forbs				
Cirsium arvense	Canada thistle	10	8	4
Taraxacum officinale	Common dandelion	4	6	2
Plantago major	Common plantain	2	1	-
Potentilla norvegica	Rough cinquefoil	2	+	-
Spergula arvensis	Corn spurry	2	3	2
Brassica spp.	Mustard	1	+	-
Polygonum arenastrum	Common knotweed	1	+	1
Polygonum convolvulus	Wild buckwheat	1	1	+
Tanacetum vulgare	Common tansy	1	-	+
Camelina spp.	False flax	-	-	+
Crepis tectorum	Annual hawksbeard	-	+	-
Galeopsis tetrahit	Hemp nettle	-	+	-
Kochia scoparia	Summer cypress	-	+	-
Silene pratensis	White cockle	-	+	-

(+) - indicates composition less than 1%.
(-) - indicates absence of species in plot.

Table 35: Canopy and ground cover (%) by amendment of forage subplots in 1992-1995.

		Canopy Cover			Ground Cover		
Year	Amendment	Live	Litter	Bare	Live	Litter	Bare
1992							
	Control	43 ab	12 B	46	18	15 B c	67 A a
	Sulfur	48 a	22 A	30	15	38 A a	46 B c
	Gypsum	40 b	12 B	35	17	25 B b	57 AB b
1993							
	Control	54 AB	35	11	22	59	19
	Sulfur	62 A	29	10	21	63	17
	Gypsum	51 B	36	13	18	62	20
1994							
	Control	80	19	1	18	78	3
	Sulfur	80	18	2	16	81	3
	Gypsum	82	17	1	16	81	2
1995							
	Control	74 A	23 B	3	13	86	1
	Sulfur	67 B	32 A	0	12	85	3
	Gypsum	67 B	33 A	1	12	85	2

Means among amendment treatments within a given year followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.
All cover percentages do not add up to 100 %; due to the exclusion of small cover percentages of mosses and rocks.

Table 36: Annual biomass (kg ha^{-1}) by amendment of forage subplots in 1992-1995.

Year	Amendment	Grasses	Legumes	Forbs	Total
1992					
	Control	-	-	-	3220
	Sulfur	-	-	-	3593
	Gypsum	-	-	-	3078
1993					
	Control	1560	88	53	1701
	Sulfur	1586	90	59	1736
	Gypsum	1663	86	49	1798
1994					
	Control	1463	547	99	2109
	Sulfur	1193	539	74	1807
	Gypsum	1323	492	82	1897
1995					
	Control	1125	747	260	2132
	Sulfur	893	716	300	1909
	Gypsum	855	724	283	1862

Means among amendment treatments within a given year followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.

Table 37: Annual biomass (kg ha^{-1}) by amendment of fallow/barley subplots in 1994.

Amendment	Grain	Straw	Weeds	Total	Seed
Control	2422	2083	1028	5532	30.6
Sulfur	2437	2479	305	5221	29.8
Gypsum	2048	1945	947	4940	30.2

Treatment means within a given year followed by different upper or lower case letters are significantly different at ($p \leq 0.05$) and ($p \leq 0.10$), respectively.