Reclamation of abandoned bentonite mine spoils with phosphogypsum and magnesium chloride amendments
by Steven Carl Smith

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University
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Abstract:
Abandoned bentonite mine spoils are scattered over southeast and north central Montana. The clayey, saline-sodic nature of these spoils creates adverse physicochemical properties. Invasion of native plant species is precluded and revegetation is difficult. Infiltration of surface water is severely limited due to surface crusting and shrink-swell processes.

Chemical amendments have recently been shown to be effective in ameliorating adverse physical and chemical spoil properties. Chemical amendment use increases reclamation costs significantly, therefore effective, low cost amendments are needed. Phosphpgypsum and magnesium chloride brine are low cost industrial wastes that have not been tested for use in land reclamation. Experimental field plots were implemented to evaluate the effects of phosphogypsum (40.4 mt/ha) and magnesium chloride brine (36.2 mt/ha) incorporated to a 35 cm depth. Effects of nitrogen fertilizer (0, 67 kg/ha, and 134 kg/ha) on seedling emergence were also tested.

Representative unamended spoil at the site had a sodium adsorption ratio (SAR) of 33.8 and an electrical conductivity (EC) of 8.0 mmhos/cm. Over a 14 month sampling period, SAR (0-5 cm) declined to 24.5 on phosphogypsum treated plots, and to 21.3 on magnesium chloride brine treated plots. Electrical conductivity (0-5 cm) increased to 10.1 mmhos/cm on phosphogypsum treated plots, and to 15.9 mmhos/cm on magnesium chloride brine treated plots.

Following 30 minutes of simulated rainfall, minesoil infiltration rates were 2.8 cm/hr on phosphogypsum treated plots and 3.8 cm/hr on magnesium chloride brine treated plots, compared to .1 cm/hr on unamended spoil.

Nitrogen fertilizer at 67 kg/ha resulted in significantly greater seedling density among fertilizer treatments, at 192 seedlings/m^2. Plant canopy cover of 39% estimated on magnesium chloride brine treated plots was significantly greater than 28% on phosphogypsum treated plots. Above ground plant production was 1753 kg/ha on phosphogypsum treated plots and 2717 kg/ha on magnesium chloride brine treated plots. Production of pioneering (non-seeded) annual forbs comprised 60% of total production on phosphogypsum treated plots and 83% on magnesium chloride brine treated plots.

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ABSTRACT

Abandoned bentonite mine spoils are scattered over southeast and north central Montana. The clayey, saline-sodic nature of these spoils creates adverse physicochemical properties. Invasion of native plant species is precluded and revegetation is difficult. Infiltration of surface water is severely limited due to surface crusting and shrink-swell processes.

Chemical amendments have recently been shown to be effective in ameliorating adverse physical and chemical spoil properties. Chemical amendment use increases reclamation costs significantly, therefore effective, low cost amendments are needed. Phosphogypsum and magnesium chloride brine are low cost industrial wastes that have not been tested for use in land reclamation. Experimental field plots were implemented to evaluate the effects of phosphogypsum (40.4 mt/ha) and magnesium chloride brine (36.2 mt/ha) incorporated to a 35 cm depth. Effects of nitrogen fertilizer (0, 67 kg/ha, and 134 kg/ha) on seedling emergence were also tested.

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Nitrogen fertilizer at 67 kg/ha resulted in significantly greater seedling density among fertilizer treatments, at 192 seedlings/m^2. Plant canopy cover of 39% estimated on magnesium chloride brine treated plots was significantly greater than 28% on phosphogypsum treated plots. Above ground plant production was 1753 kg/ha on phosphogypsum treated plots and 2717 kg/ha on magnesium chloride brine treated plots. Production of pioneering (non-seeded) annual forbs comprised 60% of total production on phosphogypsum treated plots and 83% on magnesium chloride brine treated plots.

INTRODUCTION

Bentonite is a highly colloidal mineral consisting predominantly of smectite clays (Berg 1969). High swelling capacity and thixotropic properties make bentonite a valued industrial mineral. These characteristics are enhanced when sodium is the dominant adsorbed cation. Commercial uses of sodium bentonite are various, ranging from well drilling mud to toothpaste. Because it is used in a wide variety of industrial processes and commercial products, bentonite has been referred to as the clay of 1000 uses (Romo 1981).

The tri-state region of Montana, South Dakota, and Wyoming contains approximately 90 to 95 percent of the world's commercially minable deposits of high-grade sodium bentonite (Romo 1981). Montana possesses the greatest reserves with 270 million metric tons (Ampian 1985). Mining was widespread during the mid 1900's before reclamation laws were enacted. As a result, thousands of acres of bentonite disturbances were abandoned on the Northern Great Plains. Adverse physicochemical conditions which occur on bentonite spoils result in reclamation difficulties. Factors which typically inhibit revegetation are saline-sodic conditions, high smectite clay content, and impermeable surface crusts.

Chemical amendments can be effective in reclaiming bentonite spoils by improving the physicochemical properties. However, many of these chemicals are not cost effective for large scale use. The identification of low cost chemical amendments is an important step in the advancement of bentonite reclamation technology. Through funds made available by the Surface Mining Control and Reclamation Act of 1977 (Public Law 96-87), the Montana Abandoned Mined Lands Program staff is planning field reclamation of abandoned bentonite sites. Advancements in reclamation technology are needed to assist the state in meeting this reclamation challenge.

Objectives

The Belle Fourche, South Dakota research site was selected for continued bentonite reclamation research. The objectives of this study were to:

1) investigate the effectiveness of phosphogypsum and magnesium chloride brine as minesoil amendments;

2) evaluate the effects of nitrogen fertilizer on seedling emergence;

3) investigate improvements in rainfall infiltration on chemically amended test plots;

4) evaluate plant performance characteristics on chemically amended test plots.

LITERATURE REVIEW

Montana's Open Cut Act of 1971 set guidelines for bentonite mining and reclamation. Until this time, spoils were left randomly piled adjacent to mined out pits. Significant acreages were disturbed by bentonite mining prior to enactment of controlling legislation.

The discontinuous nature of bentonite deposits resulted in numerous pits scattered over localized areas. When overburden stripping ratios became uneconomical, pits were abandoned only to be re-opened a short distance away where the ratio was again acceptable. Pit size ranged from 3 to 10 acres with depths of less than 50 feet (Hemmer et al. 1977). The pit mining method greatly increased the total area affected by mining, but left undisturbed "islands" among the spoils. Researchers at the National Academy of Science (1973) reported that as of the early 1970's, more spoils had accumulated in Montana from bentonite mining than from coal mining.

Commercial mining of sodium bentonite, often referred to as "Wyoming bentonite" began in the Northern Great Plains in the late 1800's. At that time, bentonite was used primarily in cosmetics (Wolfbauer 1976). During the mid

1900's, bentonite production reached a peak due to demand for oil well drilling fluids and taconite binding agents.

In Montana, the majority of bentonite mining occurred during the mid-1900's near Vananda, Glasgow, and Alzada. These areas were mined prior to regulations implemented under the Open Cut Act and remain totally unreclaimed.

Adverse conditions on bentonite spoils inhibit natural vegetative invasion from adjacent rangeland. These spoils remain barren for many years. Factors limiting plant growth often include high clay content comprised mainly of smectite mineralogy, elevated salinity and sodicity, extremes in pH, and surface crusting (Dollhopf and Bauman 1981, Sieg et al. 1983). Mixtures of overburden and bentonite, referred to as "cleanings" usually remained on the spoil surface magnifying plant growth problems (Hemmer et al. 1977, Bjugstad 1979). Sieg et al. (1982) found 25 fewer plant species and a large standing crop deficit on bentonite spoils as compared to adjacent undisturbed rangeland. Spoil materials are impermeable to water increasing runoff and accelerating erosion processes (Dollhopf and Bauman 1981). Mine pits fill with sediment laden runoff creating boggy conditions that are hazardous to livestock and wildlife.

Origin and Location of Bentonite

Bentonite deposits in the Western U.S. are of two distinct types; Tertiary age bentonites found in Oregon,

California and Nevada; and Cretaceous bentonites located in Montana, Wyoming and South Dakota (Regis 1978). Tertiary bentonites are generally of lower quality and often dominated by calcium. Limited swelling capacity and a lower commercial value result. Cretaceous bentonite is characteristically a relatively pure, sodium saturated mineral with high swelling capacity and high commercial value.

During the Cretaceous period (75 million years ago), volcanic activity occurred in Western Wyoming and Idaho. Volcanic ash was wind deposited in shallow seas to the east in what is now the Northern Great Plains. Being unstable in a marine environment, this ash was altered in situ to clay minerals of the smectite group, or bentonite (Hewett 1917, Dengo 1946, Berg 1969). Evidence of volcanic ash parent material is demonstrated by the large lateral distribution of bentonite beds. In addition, the presence of glass shards and a suite of silicate minerals within the structure represent unaltered phenocrystic material of the volcanic ash (Berg 1969). While western bentonite is generally thought to be formed in marine environments, Byrne and Farvolden (1959) reported the occurrence of beds in non-marine sediments.

Distribution of Cretaceous bentonite is complex due to the variability and vertical extent of the ash falls. Sea level fluctuation provided additional complexity to the depositional environment. Prolonged ash fall events

produced minable bentonite deposits while minor ash fall events resulted in numerous thinner "chalk lines" (Thorson 1976).

Bentonite bearing formations in the region have a total aggregate thickness of about 4,400 feet. Individual beds are located from the Newcastle sandstone of the Early Cretaceous through the Pierre shale of the Late Cretaceous (Knechtel and Patterson 1956). Of particular commercial importance has been the Clay Spur bed near the top of the Mowry shale which occurs throughout much of the region (Knechtel and Patterson 1962).

Physicochemical Properties of Bentonite Spoil

Bentonite mine spoils are dominated by weathered shales rich in 2:1 swelling clay minerals of the smectite group. Montmorillonite, a member of the smectite group, is the most abundant clay species in bentonite (Berg 1969); and is the dominant clay in bentonite spoils.

Smectite crystal units consist of an octahedral sheet sandwiched between two tetrahedral sheets. Tetrahedra are formed by a silica ion surrounded by four oxygen ions. The central octahedra is formed by an aluminum ion surrounded by six hydroxyl ions. Sharing of oxygen and hydroxyl ions produce the sheetlike 2:1 lattice structure (Grim 1968, Buckman and Brady 1969). Individual clay units stack one upon another to infinite thicknesses. Weak "Van der Waal"

forces hold the crystal units loosely together forming clay particles. The weak bonds between crystal units are of key importance. Upon hydration, osmotic potential attracts water to interlayer areas producing the swelling characteristics of smectite.

Isomorphic substitution of lower valence cations within the smectite lattice structure creates excess negative charge on clay surfaces. Aluminum (Al^{3+}) commonly replaces silica (Si^{4+}) in tetrahedral layers; and either magnesium (Mg^{2+}), iron (Fe^{2+}), or lithium (Li^{+}) replace aluminum (Al^{3+}) in the octahedral layer (Regis 1978). Excess negative charge results in adsorption of positively charged soil solution cations, referred to as cation exchange capacity (CEC) (Hillel 1980, Bohn et al. 1985).

Hydrated clays form a colloidal micelle. Together, the micelle and adsorbed cations produce a diffuse electrostatic double layer between clay particles (Hillel 1980). Valence and ion size of adsorbed cations regulate double layer thickness, which markedly influences the magnitude of clay dispersion. Cations of particular importance are sodium (Na^{+}), calcium (Ca^{2+}) and magnesium (Mg^{2+}) because they are adsorbed in the largest quantities. Sodium dominance among adsorbed cations produced a relatively thick double layer because of large size and low valence. The thick double layer allows more water molecules between clay units enhancing swelling processes.

Flocculation is a term used to denote aggregation and structure in soil materials, while dispersion indicates a breakdown of soil structure. Flocculation/dispersion processes in smectite clay minerals are regulated by interrelationships between diffuse double layer activity, soil solution salt concentration, and the "zeta potential" developed. Zeta potential refers to strength of repulsion between clay particles. Positively charged cations act as a bridge between negatively charged clay particles decreasing the strength of repulsion.

When small sized, divalent cations such as calcium or magnesium dominate the double layer, zeta potential is reduced allowing flocculation (Buckman and Brady 1969). In a flocculated condition, the basal spacing between clay units is 9.6 angstroms (Berg 1969). A high zeta potential is promoted by sodium interlayer dominance. In this condition, multiple water molecule layers encroach interlayer areas when excess water is in the system. White and Pilcher (1959) found that sodium montmorillonite could take up in excess of 50 water molecule layers between clay units. The resultant dispersion between clay crystal units is up to 125 angstroms.

The combination of smectite clay mineralogy and high exchangeable sodium percentage (ESP) result in excessive spoil swell from clay dispersion when the system receives moisture. Swelling processes in soil materials greatly

reduce hydraulic conductivity and permeability (Richards 1969, Bohn et al. 1985). Dollhopf and Bauman (1981) found that spoil from the Belle Fourche research site had extremely low hydraulic conductivity and very slow permeability.

Surface crusting caused by clay dispersion is common on bentonite minespoils. Crusting of the spoil surface adversely impacts seedling emergence and rainfall infiltration. Modulus of rupture is an index of crust strength. When modulus of rupture values exceed 1 bar, seedling emergence is often inhibited (Richards 1953). Dollhopf and Bauman (1981) reported modulus of rupture values at the Belle Fourche research site to be greater than 5.7 bars.

Hillel (1980) stated that surface crusts greatly impede water intake by a soil and have a strong effect on infiltration. Rainfall which does penetrate the surface crust infiltrates very slowly due to clay dispersion beneath the surface. The infiltration rate of water into plant growth media is critical to plant survival (Voorhees 1986). In addition, poor infiltration increases surface runoff and accelerates erosion processes.

Abandoned Bentonite Spoil Reclamation

Prior to legislation mandating reclamation of bentonite mined lands, virtually no reclamation was performed. Abandoned spoil piles had accumulated from many decades of

mining. As bentonite reclamation research began in the 1970's, it was soon evident that these lands would be very difficult to reclaim. Bentonite reclamation technology was limited even into the 1980's. Hemmer et al. (1977) and Bjugstad (1979) both had difficulty establishing vegetation on unamended spoil throughout the region. Sieg et al. (1983) found that topsoiling alone was not adequate for successful reclamation of abandoned bentonite spoils.

Encouraging results have been reported using organic amendments. Wood residue amendment is known to improve vegetative production on bentonite spoils (Smith 1984, Schuman and Sedbrook 1984, Uresk and Yamamoto 1986). Dollhopf et al. (1988) reported significant increases in long-term forage production using manure as an amendment. While some successes have been demonstrated with organic amendments, they may not be the complete answer. The ability of these amendments to ameliorate long-term spoil physicochemical problems is questionable. Availability of sufficient quantities for large scale reclamation projects may also be a problem.

Chemical amendments which supply calcium ions have been used for many years in reclamation of sodic soils (Richards 1969), and have been utilized in reclaiming sodic minesoils (Sandoval and Gould 1978, Dollhopf et al. 1980). Calcium ions are strongly adsorbed and replace sodium ions on cation exchange sites (Bohn et al. 1985). As calcium becomes the

more dominant cation, spoils begin to flocculate, enabling water to infiltrate into the spoil profile. Improved infiltration enhances leaching of replaced sodium and results in amelioration of minesoil physicochemical problems.

Highly soluble calcium amendments can be effective in expediting reclamation. Dollhopf et al. (1988) reported excellent plant establishment on bentonite minesoils amended with soluble calcium amendments, including calcium chloride ($CaCl_2$) and a gypsum/sulfuric acid ($CaSO_4 \cdot 2H_2O/H_2SO_4$) combination. Sparingly soluble calcium amendments, such as agricultural gypsum and lime, have limited effectiveness in arid-alkaline environments. Richards (1969) stated that as the soil solution is concentrated by evaporation, the solubility limits of gypsum and lime are exceeded, in which case they are precipitated with a corresponding increase in the relative proportion of sodium. Under these conditions, a part of the original exchangeable calcium and magnesium is replaced by sodium.

Phosphogypsum and Magnesium Chloride as Amendments

Chemical amendments for use in bentonite reclamation must be both effective and cost feasible. Reduction of ESP is necessary for reclamation success and lower amendment cost promotes utilization. Both phosphogypsum and magnesium chloride ($MgCl_2$) brine are produced as industrial by-

products and create disposal problems at processing facilities. The use of these wastes to reclaim other disturbed sites produces a two-fold reclamation success.

Phosphogypsum and magnesium chloride brine are relatively untested as chemical amendments for use in reclamation. Recently, phosphogypsum was utilized as a bentonite spoil amendment in Wyoming (Anselmi 1986). Initial results appear promising, but long-term effectiveness is unknown. The only known field test of magnesium chloride for sodic soil reclamation occurred in the Soviet Union, again with promising results (Papinyan 1980). As spoil amendments, both materials contain divalent cations which should replace exchangeable sodium. Test plot evaluation in the Northern Great Plains is essential to document effectiveness in this environment. Potential adverse effects, should be identified before these amendments are included in a reclamation plan.

Phosphogypsum

Phosphogypsum is a by-product of the phosphate fertilizer industry. Phosphate ore containing calcium is processed with sulfuric acid (H_2SO_4). Gypsum ($CaSO_4 \cdot 2H_2O$) is precipitated as a silt sized (.002-.05mm) waste product. Phosphogypsum consists of the gypsum waste (tailings) material (80-99% $CaSO_4 \cdot 2H_2O$), mineral impurities, and less than 1% phosphate (P_2O_5) (Keren and Shainberg 1981).

Thousands of tons are produced annually in the United States with no apparent market.

In semi-arid environments, dissolution of gypsum is slow when applied to non-irrigated sodic minesoils (Dollhopf 1986). Because of the silt particle size, phosphogypsum has much more surface area than agricultural gypsum at a given fragment size (Keren and Shainberg 1981). These researchers found that due to the increased surface area, phosphogypsum has approximately ten times the dissolution rate as agricultural gypsum. Increased dissolution enables phosphogypsum to supply exchangeable calcium at a much faster rate.

Surface crusting from clay mineral dispersion often requires an amendment to reduce detrimental effects on seedling emergence and rainfall infiltration. Gal et al. (1984) reported that phosphogypsum application reduced clay dispersion at the soil surface helping to prevent crust formation.

The absence of severe surface crusts allows rainfall to infiltrate into the spoil. However, high sodium levels throughout the spoil profile restrict water movement following surface penetration. Upon initial wetting, the infiltration rate (IR) may appear normal but drop rapidly within minutes due to swelling processes. Kazman et al. (1983) reported that an incorporated phosphogypsum amendment prevented the sharp infiltration rate reduction at all

tested levels of ESP. Incorporation of phosphogypsum into soils improves physical properties and promotes water infiltration (Keren and Shainberg 1981, Kazman et al. 1983, Gal et al. 1984).

Magnesium Chloride

Magnesium is the second most abundant exchangeable cation in soils but has received relatively little study compared to other cations (Bohn et al. 1985). As divalent alkaline earth metals, magnesium and calcium possess similar properties. Richards (1969) classified calcium and magnesium as similar ions important in the development of soil structure.

The effectiveness and unlimited availability of calcium chloride has made it popular as a sodic spoil amendment in recent years. In some instances, the relatively high cost of calcium chloride has been prohibitive. Similar properties give magnesium chloride the potential to be as effective as calcium chloride in reclamation. Industrial processes result in magnesium chloride brine being available in a solution of approximate 32% purity (Redfern 1986).

Magnesium chloride effectively displaces sodium from the cation exchange complex (Petersen and Oad 1974, Arora and Coleman 1979). In field research, Papinyan (1980) reported significant soil ESP reductions using magnesium chloride amendments to reclaim sodic soils.

A "specific effect" of magnesium is the deterioration of structure in some magnesium saturated soils. Quirk and Schofield (1955) found that a magnesium saturated illite soil showed decreases in hydraulic conductivity when leached with distilled water. Further research indicated that the specific effect of magnesium is regulated by the ESP, dominant clay minerals, and electrolyte concentration of the solution. Rowell and Shainberg (1979) found similar hydraulic conductivity in sodium-magnesium and sodium-calcium systems when montmorillonite was the dominant clay. Rahman and Rowell (1979) stated that in a soil dominated by montmorillonite where clay swelling was the main mechanism causing conductivity changes, magnesium had no specific effect; the conductivity being simply controlled by the ESP and electrolyte concentration. Papinyan (1980) reported considerable improvements in soil-water relationships when magnesium chloride was used to amend sodic soils.

Plant growth is thought to be affected by the calcium: magnesium ratio in the soil. Bohn et al. (1985) stated that high magnesium concentration may repress calcium uptake. Application of magnesium chloride brine as an amendment will elevate magnesium levels and reduce the calcium:magnesium ratio. Although there is potential for plant growth problems due to increased magnesium levels, Simson et al. (1979) found that satisfactory plant growth could be maintained between calcium:magnesium ratios of 0.8 to 5.0.

Hunter (1949) reported no yield influence on alfalfa within a calcium:magnesium ratio range of .25 to 32.

MATERIALS AND METHODS

Site Description

The research site is located approximately 7 miles northwest of Belle Fourche, South Dakota. Local precipitation averages 36.7 cm/yr (NOAA 1986). Dominant plant species on native rangeland are big sagebrush (Artemisia tridentata) and western wheatgrass (Agropyron smithii). Bentonite mining in the area began in the early 1900's and is currently active. Abandoned spoils are scattered throughout the area and are concentrated along the east-west haul road. The study site, located adjacent to a 1980 bentonite field study (Dollhopf and Bauman 1981), lies 5 miles northwest of the American Colloid Company processing facility and 500 meters north of the haul road (Figure 1).

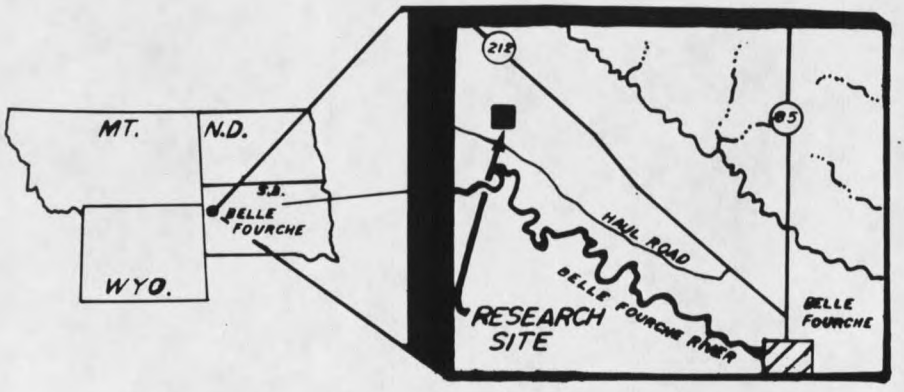


Figure 1. Site location, Belle Fourche, South Dakota.

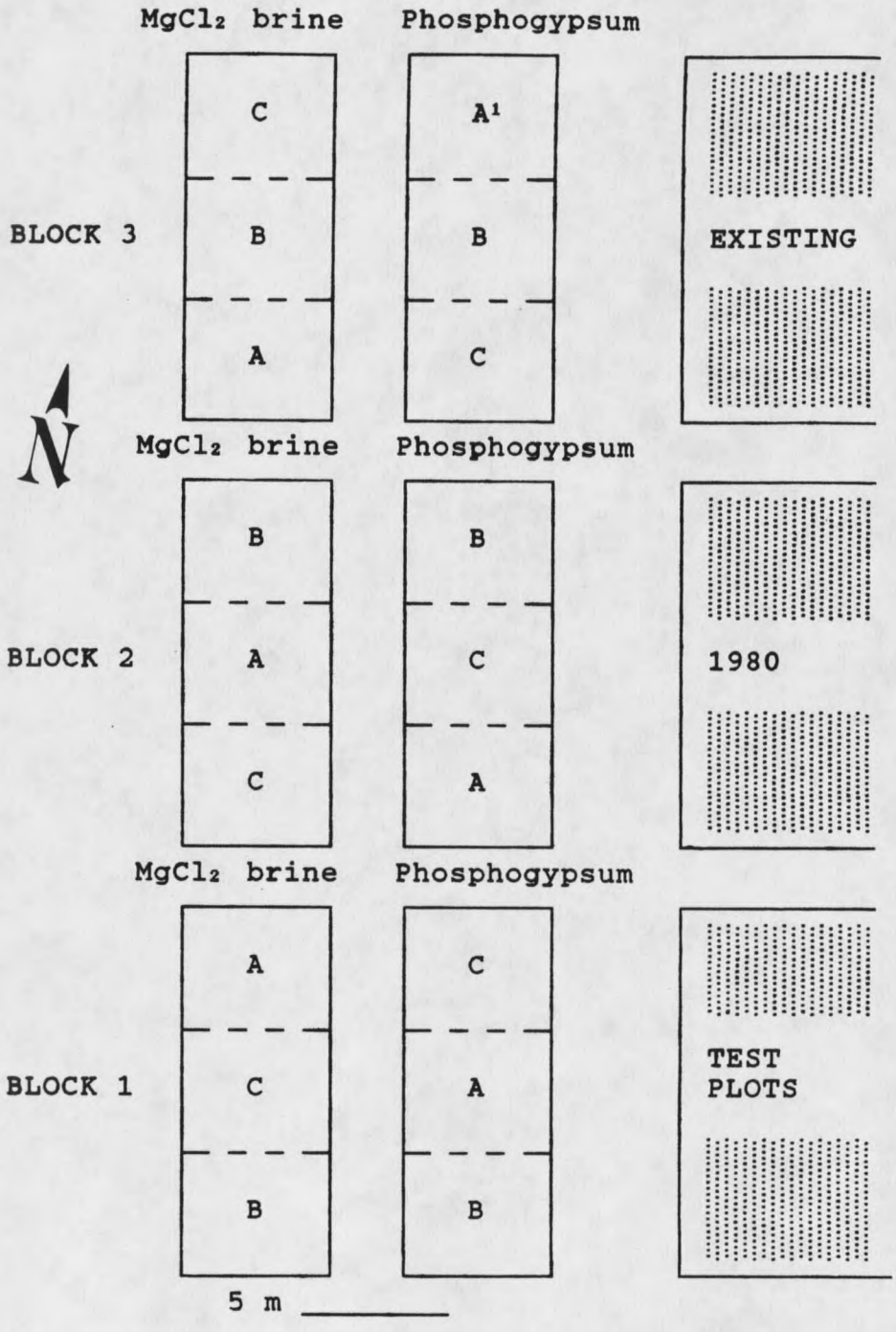
Field Plot Design

During early May, 1986, implementation work began on the nearly level spoils (3% south) at the Belle Fourche study site. Two chemical amendments and 3 nitrogen fertilizer rates were to be tested within 6 test plots and 18 subplots (Table 1). The field plot design implemented was a split-plot in three replications (Figure 2). The ability to make long-term comparisons between newly implemented test plots, and the 1980 test plots (Dollhopf and Bauman 1981), was a key objective of the field plot design. Although control plots for this site were established in 1980, no control plots were implemented for plots established in 1986 due to the lack of space at this location.

Table 1. Chemical amendment and nitrogen fertilizer rate treatments at the Belle Fourche site.

TREATMENT	RATE
Phosphogypsum, 0-35cm	40.4 mt[1]/ha/30cm (17.9 t/ac/ft)
Magnesium chloride brine, 0-35cm	36.2 mt/ha/30cm (16.1 t/ac/ft)
Subplots -- No N applied	0.0
N applied	67.0 kg/ha (60 lbs/ac)
N applied	134.0 kg/ha (120 lbs/ac)

[1] - Metric ton (2205 lbs.)



1 -- Letters denote subplot fertilizer rates. A denotes no N, B denotes 67 kg/ha, C denotes 134 kg/ha.

Figure 2. 1986 Field plot design at the Belle Fourche site.

Test plots, 5 x 15 m were staked with a 2 m alley between replications. Each plot was divided into three, 5 x 5 m subplots for randomized nitrogen fertilizer rate treatments.

Amendments and Application Rate Determinations

Representative unamended spoil at the research site had a sodium adsorption ratio (SAR) of 33.8 (see Table 4). Exchangeable sodium percentage (ESP) and SAR are nearly identical in this range (Richards 1969). Therefore, ESP and SAR were considered equal for amendment rate calculations. Average spoil CEC at the site was 35.4 milliequivalents (meq)/100 g soil (Dollhopf and Bauman 1981).

Soils which have an ESP in excess of 15 are considered to be sodic (Richards 1969). To reduce minesoil sodium to a non-sodic level, a net decrease of 20.0 SAR (ESP) units was set as the reclamation goal on all treated test plots. To reach this goal, removal of 7 meq of exchanged Na/100 g soil was required. Replacement of 7 meq of sodium results in SAR reduction from 33.8 to 13.8 by the equations:

$$1)\quad \text{ESP (SAR)} = 33.8 = \frac{11.9 \text{ (meq Na/100 g soil)}}{35.4 \text{ (CEC)}}$$

$$2)\quad \text{ESP (SAR)} = \frac{11.9 - 7}{35.4} = \frac{4.9 \text{ (meq Na/100 g soil)}}{35.4 \text{ (CEC)}} = 13.8$$

As industrial waste products, purity of the phosphogypsum and magnesium chloride brine was uncertain. In addition, there was the potential of phytotoxically excessive levels of trace elements being present in the amendments. Therefore, representative samples of the phosphogypsum and magnesium chloride brine used on the project were analyzed for chemical constituents by method 3050 (EPA 1982). The analyses included total concentrations of a suite of 20 trace elements.

The phosphogypsum amendment had a $CaSO_4 \cdot 2H_2O$ content of 82.1% as determined by method 3050 (EPA 1982). Amendment texture was relatively fine with 87% passing a .149 mm (100 mesh) sieve. Moisture content of the phosphogypsum was 15% as determined by oven drying (Gardner 1986).

Mined (agricultural) gypsum solubility is 2.4 g/L in cold water (Weast 1986). Phosphogypsum has been reported to have ten times greater solubility compared to agricultural gypsum (Keren and Shainberg 1981). At a ten fold increase, phosphogypsum solubility is approximately 24 g/L in cold water.

In calculating test plot application rates, amendment purity and plot size must be considered. An amendment purity factor of 1.218 was used to compensate for 17.9% impurities in the amendment. The test plot size of 5 x 15 m was equivalent to .0075 hectare. An additional factor of 1.25 was used for the lack of quantitative replacement.

This factor increases the application rate to account for incomplete exchange reactions between the amendment and the spoil.

One meq of exchangeable Na/100 g soil is replaced by 1.7 tons $CaSO_4 \cdot 2H_2O$/acre-foot (Richards 1969). The metric conversion is 3.8 metric tons (mt) $CaSO_4 \cdot 2H_2O$/hectare/30 cm.

Phosphogypsum plot requirement =

7 (meq Na/100g)	x	3.8 (mt/ha/30cm)	= 26.60 mt/ha/30cm
26.60 (mt/ha/30cm)	x	1.25	= 33.25 mt/ha/30cm
33.25 (mt/ha/30cm)	x	1.218	= 40.49 mt/ha/30cm (1.35 mt/ha/cm)
40.49 (mt/ha/30cm)	x	.0075	= .303 mt/plot/30cm

Magnesium chloride brine was available for use as a spoil amendment. The brine used at the Belle Fourche site was determined to be 40.8% $MgCl_2$ by method 3050 (EPA 1982). The brine had a density of 1.3 kg/L and was shipped in 208 L (55 gallon) drums. Magnesium chloride solubility is 542 g/L in cold water (Weast 1986).

The quantity of free sulfur (S) required to replace 1 meq of Na/100 g soil has been determined to be .32 tons/acre-foot (Richards 1969). The mechanism of free sulfur replacement of sodium is oxidation of S to SO_3, followed by reaction with water to form H_2SO_4. Reaction of H_2SO_4 with soil $CaCO_3$ produces $CaSO_4 \cdot 2H_2O$ (gypsum), which solubilizes to release Ca^{2+}.

The quantity of $CaSO_4 \cdot 2H_2O$ that is equivalent to 1 ton of free S has been determined to be 5.38 tons (Richards 1969). To calculate an application rate for magnesium chloride brine, equivalent weights of $MgCl_2$ and $CaSO_4 \cdot 2H_2O$ can be related to solve for the quantity of $MgCl_2$ that is equivalent to 1 ton of free S. This quantity can then be multiplied by .32 tons to ascertain the quantity of $MgCl_2$ required to replace 1 meq of Na/100 g soil per acre-foot.

Calculations for the magnesium chloride brine requirement are presented. A factor for the lack of quantitative replacement was not used due to the liquid physical nature of the amendment. The amendment purity factor was 2.451 and the plot size was .0075 hectare.

$MgCl_2$ equivalent weight = 47.61 g
$CaSO_4 \cdot 2H_2O$ equivalent weight = 86.10 g

One ton of free S equals 5.38 tons $CaSO_4 \cdot 2H_2O$.

Therefore: $\frac{86.10}{5.38} = \frac{47.61}{x}$, x = 2.97 tons $MgCl_2$ is equiv. to 1 ton S

Relative to S: .32 x 2.97 = .95 tons $MgCl_2$/ac-ft to replace 1 meq Na/100 g soil

Metric conversion: = 2.11 mt/ha/30cm

$MgCl_2$ brine plot requirement =

7 (meq Na/100g) x 2.11 (mt/ha/30cm) = 14.77 mt/ha/30cm

14.77 (mt/ha/30cm) x 2.451 = 36.20 mt/ha/30cm (1.20 mt/ha/cm)

36.20 (mt/ha/30cm) x .0075 = .271 mt brine/plot/30cm

Nitrogen levels on unamended spoil are typically low to moderate (Dollhopf and Bauman 1981). Nitrogen fertilizer (34-0-0), in the form of ammonium nitrate (NH_4NO_3), was tested for effects on seedling emergence. Each 5 x 15 m plot was subdivided into three, 5 x 5 m subplots. Treatment A was no N added; treatment B was 67 kg/ha; and treatment C was 134 kg/ha.

Field Plot Implementation

Following plot staking, two randomly located core samples were taken within the test plot area. Chemical amendments were manually applied and chisel plowed to a 35 cm depth. Plots were rototilled to a depth of approximately 20 cm to further incorporate the amendments.

All plots were broadcast seeded with 18 species chosen for saline-sodicity and/or drought tolerance (Table 2). Seeding rates for the forbs and warm season grasses were increased to prevent seed availability from being a limiting factor for these difficult to establish species. The total seeding rate was 84.1 kg of pure live seed (PLS)/ha.

Nitrogen fertilizer was broadcast onto the subplots at rates specified in Table 1. A wheat straw mulch was applied at the rate of 4500 kg/ha and stabilized by disk crimping. A two inch mesh fence enclosed all amended test plots.

stipa viridula

Table 2. Plant species seeded in Spring, 1986 at the Belle Fourche site.

SPECIES	PLS/m²
Grasses	
Agropyron cristatum (crested wheatgrass, var. Nordan)	105
A. dasystachyum (thickspike wheatgrass, var. Critana)	203
A. elongatum (tall wheatgrass)	60
A. riparium (streambank wheatgrass, var. Sodar)	128
A. smithii (western wheatgrass, var. Rosana)	92
A. trachycaulum (slender wheatgrass, var. Revenue)	256
Bouteloua curtipendula (sideoats grama)	267
Sporobolus airoides (alkali sacaton)	1703
Forbs	
Achillea millifolium (western yarrow)	3694
Astragalus cicer (cicer milkvetch)	228
Linum lewisii (Lewis flax, var. Appar)	391
Melilotus officinalis (yellow sweetclover)	137
Petalostemum purpureum (purple prairie clover)	825
Ratibida columnaris (prairie coneflower)	808
Shrubs	
Artemisia cana (silver sagebrush)	178
Atriplex canescens (fourwing saltbush)	34
A. confertifolia (shadscale)	17
A. nuttallii (Nuttall's saltbush)	87

shadscale
fourwing bush
salsola kali

Minesoil Physicochemical Analysis

Core samples were collected in the spring of 1986 (prior to amendment application), fall of 1986, and summer of 1987 for physicochemical analysis. A Giddings core sampler was used in the field to take 4.8 cm diameter cores. Each core sample was divided into six depth increments of 0 to 5, 5 to 10, 10 to 20, 20 to 35, 35 to 70, and 70 to 140

cm. In the spring of 1986, sampling consisted of taking two randomly located core samples within the test plot area following initial staking. The two core samples were composited into one sample for each depth increment. Results from spring, 1986 physicochemical analysis were used to help characterize unamended spoil at the study site.

The data collected in the spring of 1986 were used in combination with spoil chemistry data obtained from adjacent test plots to develop representative values for unamended spoil chemistry. Unamended spoil data from 1980 (Dollhopf and Bauman 1981), and unamended test plot data from the 1986 study (Dollhopf et al. 1988) were also included. These data were used to determine mean values for SAR and electrical conductivity (EC) that would be highly representative of unamended spoil across the entire research site.

In the fall of 1986, sampling consisted of removing two randomly located core samples from each test plot. The two cores were composited into one sample for each depth increment. An identical procedure was used to obtain core samples during the summer of 1987.

Core samples were prepared for analysis by air drying and weighing, followed by mechanical flailing. Particle size distribution was determined using a modification of the Day (1965) technique. Textural class was determined using particle size distribution data and the USDA textural triangle (SCS 1951).

Electrical conductivity, pH, and SAR were analyzed in the aqueous extract of a saturated paste (Richards 1969). Using meq/L values obtained for Ca, Mg, and Na, SAR was calculated by the equation:

$$SAR = Na / \sqrt{(Ca + Mg) / 2}$$

Saturation percentage, the percentage of water needed to saturate a soil paste, was determined for 1986 pre-amendment samples and 1987 test plot samples using methods 26 and 27b (Richards 1969). This parameter gives an indication of the clay mineralogy and swell potential of a soil material.

Infiltration Rate Study

On July 10 of 1987, infiltration rates were measured on the phosphogypsum and magnesium chloride brine treated plots, and at 3 random locations on unamended spoil directly adjacent to each treatment replication. An infiltrometer built from construction plans presented in Meeuwig (1971) was used to simulate rainfall. The infiltrometer was located at the 7.5 m point along diagonal transects within each test plot. A 48 x 48 cm runoff collection frame was positioned and tapped into the spoil to catch and funnel runoff into a container. Vegetation was clipped to ground level and all vegetative litter was removed.

Simulated rainfall was applied for 30 minutes at a constant rate of 12 cm/hr (Meeuwig 1971) and all runoff was collected. Runoff water was measured at the end of each 5 minute time interval. When necessary, plastic skirting was placed around the infiltrometer to reduce wind affects.

For each time interval, the volume of runoff collected was subtracted from the amount applied. The difference corresponds to the volume of water that infiltrated. This value was used to calculate an infiltration rate in cm/hr. An infiltration rate for each time interval was determined to evaluate infiltration rate reduction over time.

Vegetation Monitoring

Seedling density was measured on July 8, 1986, by counting individual seedlings within 20 x 50 cm microplots. Sampling of each subplot consisted of seedling counts in ten microplots spaced at 0.5 m intervals along a diagonal transect. Emergent seedlings were grouped into the classes of seeded grasses (perennial), annual grasses, seeded forbs and seeded shrubs. Annual grass is included as a plant class primarily for measurement of wheat (Triticum aestivum) seedlings which volunteered in substantial numbers from the applied wheat straw mulch.

Chemically amended bentonite spoil generally does not produce a favorable rooting medium during the first growing season due to inadequate amendment reaction time (Dollhopf

et al. 1988). Emergent seedling density on the test plots was relatively sparse during the first growing season. For this reason, no other vegetation monitoring occurred until the summer of 1987.

Plant canopy cover and above ground production were measured on July 7-9 of 1987. Plant canopy cover was estimated using the Daubenmire (1959) technique on fifteen 20 x 50 cm microplots per test plot. Microplots were located at 1 m intervals along a diagonal transect. Plant categories were the same as established for seedling emergence except for the addition of a class for non-seeded forbs. By the second growing season, the annual forbs rillscale (Atriplex dioica) and burning-bush (Koshia scoparia) had invaded the test plots in considerable numbers.

Above ground plant production was determined by clipping above ground biomass within six 50 x 50 cm microplots per test plot. Microplots were located at 3 m intervals along a diagonal transect. Clipped vegetation was separated in the field into the same plant classes used for canopy cover. In the laboratory, samples were oven dried at 60°C for 72 hours and weighed to the nearest tenth gram.

Root Biomass Study

Two randomly located 0 to 35 cm core samples (4.8 cm diameter) were taken and composited from each test plot for root biomass determination. Each composited core sample weighed approximately 2000 g.

In the laboratory, each sample was manually disaggregated and thoroughly mixed to create a homogeneous representation of the 0 to 35 cm depth. Samples were carefully split to obtain two representative 1000 g subsamples from each sample. Subsamples were soaked in a solution of .27% sodium hexametaphosphate for 24 hours to disperse the aggregates (Schuurman and Goedewaagen 1971). Dispersed subsamples were washed in a rotary root washing apparatus for 12 hours, or until all soil material had been removed. Coarse fragments were separated by decanting in water. The remaining organic material was dried at 70°C for 48 hours. Organic material other than root matter was manually separated. Dried root matter was weighed to the nearest on 0.01 gram to determine root biomass/1000 g soil.

Statistical Analysis

To allow for statistical summarization and comparison, analysis of variance (ANOVA) was conducted on all data sets. Components of ANOVA calculations are included in Appendix B. Least significant difference (LSD) at a 95% confidence

interval was calculated for mean values in each data set. Coefficients from LSD calculations are included in tables within the text. Data sets for canopy cover and above ground plant production had populations skewed to the left. To normalize population distributions for analysis of variance calculations, a logarithmic transformation of Log10 (x + 1.01) was used (LeClerg et al. 1962).

RESULTS AND DISCUSSION

Amendment Trace Element Concentrations

In the phosphogypsum amendment, total silver (Ag) concentration was 15% greater than the suspected phytotoxic level (EPA 1987b). Total cadmium (Cd) and selenium (Se) concentrations were enriched above expected background levels in soil (Kabata-Pendias and Pendias 1984, Shacklette and Boerngen 1984). Total concentrations of the other analyzed trace elements were within the normal range for soils (Table 3). No enrichment of trace elements was detected in the magnesium chloride brine.

Assuming that 1 acre-ft of spoil weighs approximately 4 million pounds, incorporation (35 cm) of the phosphogypsum amendment results in dilution of 40.4 (mt) into 4480 (mt) of spoil within 1 hectare. This represents a dilution ratio of approximately 110 : 1. Although several trace elements were enriched in the phosphogypsum, amendment dilution by incorporation clearly minimizes the potential for plant growth problems.

Radium 226 occurs in much of the phosphate ore from the Western United States. Phosphogypsum tailings produced in Idaho and Utah are reported to have concentrations of

Table 3. Trace element total concentrations[1] in phosphogypsum and magnesium chloride brine amendments.

ELEMENT	BACKGROUND LEVEL-SOURCE[2]		PHYTOTOXIC LEVEL-SOURCE		PHOSPHO-GYPSUM	MAGNESIUM CHLORIDE
Silver	.03-.09	g	2	b	2.3	.36
Aluminum	57,000	i	---		1380.0	.2
Arsenic	3.6-8.8	d	100	a	1.5	1.4
Barium	265-835	c	---		73.0	<1.0
Beryllium	1.6	c	10	f	<.5	.22
Cadmium	.07-1.1	c	100	a	10.0	.95
Cobalt	8.2	c	50	f	<1.0	.01
Chromium	20-85	d	100	f	34.0	.08
Copper	10-50	b	100	b	9.5	.3
Iron	27,500	c	---		330.0	28.8
Mercury	.04-.28	d	5	b	<.1	.004
Manganese	260-840	d	3000	e	3.3	1.32
Nickel	19	c	100	f	6.6	.08
Lead	17-26	d	1000	a	4.4	.06
Antimony	.9	c	10	f	<1.0	<1.0
Selenium	.2-.5	d	10	b	5.0	<.005
Tin	.6-1.7	d	50	f	<10.0	---
Thallium	.02-2.8	h	10	b	<1.0	.1
Vanadium	58	d	100	f	27.0	3.9
Zinc	34-83.5	d	500	a	37.0	4.0

1 - Concentrations are given in ppm on a dry weight basis.
2 - Source a is EPA (1987a). Source b is EPA (1987b). Source c is Kabata-Pendias and Pendias (1984). Source d is Shacklette and Boerngen (1984). Source e is Kovalskiy (1974). Source f is Kabata-Pendias (1979). Source g is Smith and Carson (1977a). Source h is Smith and Carson (1977b). Source i is Tidball and Severson (1975).

radium 226 exceeding the U.S. EPA suspect level of 5 picocuries/gram (Range Inventory and Analysis 1986).

In a Wyoming study, 12 inch incorporation of phospho-gypsum amendment (35.5 mt/ha) with an average of 26 picocuries/gram radium 226, resulted in no significant

increase in radium 226 levels compared to background levels (Range Inventory and Analysis 1986).

Minesoil Physicochemical Characteristics

Spoil material at the study site was predominantly composed of the Belle Fourche Shale. The Munsell color of the Belle Fourche Shale is dark gray (7.5 YR 4/0). Mowry Shale occasionally occurs near the spoil surface, but is generally located in pit bottoms. The Munsell color of the Mowry Shale is light gray (7.5 YR 7/0).

Representative unamended spoil SAR and EC over the depth of amendment incorporation (0-35 cm) were determined to be 33.8 and 8.0 mmhos/cm, respectively (Table 4). Values for representative unamended spoil chemistry were developed using data from the entire research site obtained over a 7 year period (Table 5).

Table 4. Representative values for unamended spoil chemistry at the Belle Fourche site.

SAMPLING UNIT	PARAMETER		
	SAR	EC(mmhos/cm)	pH
1980 Pre-amendment spoil (0-30cm)[1]	36.5	7.2	7.3
1986 Unamended control (0-35cm)[2]	31.5	6.9	7.3
1986 Unamended spoil (0-35cm)[3]	33.5	9.9	7.3
REPRESENTATIVE VALUES (mean)	33.8	8.0	7.3

1 - Values represent the pre-amendment site mean obtained by analysis of 39 test plots (Dollhopf and Bauman 1981).
2 - Values represent mean of 3 replications on 7 year old control plots (Dollhopf et al. 1988).
3 - Mean values from spring, 1986 pre-amendment sampling.

Table 5. Unamended spoil chemical characteristics over time at the Belle Fourche site.

DEPTH (cm)	1980 WHOLE SITE PRE-AMENDMENT SPOIL[1]		
	SAR	EC (mmhos/cm)	pH
0-30	38.7	6.9	6.9
0-30	33.8	7.5	7.4
0-30	33.9	8.4	7.5
0-30	34.8	7.5	7.4
0-30	32.5	6.6	7.7
0-30	36.9	7.5	7.1
0-30	34.8	7.0	7.3
0-30	38.1	7.8	7.3
0-30	47.7	7.2	6.9
0-30	38.4	6.9	7.1
0-30	33.5	7.2	7.1
0-30	35.8	6.1	7.4
0-30	35.8	7.2	7.6
Site Mean (0-30cm)	36.5	7.2	7.3

	1986 UNAMENDED CONTROL[2]		
	SAR	EC (mmhos/cm)	pH
0-5	31.6	6.1	7.3
5-10	32.1	7.0	7.0
10-20	32.3	6.9	7.5
20-35	30.1	7.6	7.4
Mean (0-35cm)	31.5	6.9	7.3

	SPRING, 1986 UNAMENDED SPOIL[3]		
	SAR	EC (mmhos/cm)	pH
0-5	39.0	8.4	8.2
5-10	30.2	10.1	7.0
10-15	34.7	11.9	7.0
20-35	30.2	9.1	6.9
Mean (0-35cm)	33.5	9.9	7.3

1 - Values represent the mean of 3 replications on pre-amendment test plots (Dollhopf and Bauman 1981).
2 - Values represent the mean of 3 replications on 7 year old control plots (Dollhopf et al. 1988).
3 - Values for composited samples on spring, 1986 pre-amendment spoil.

Precipitation at the research site over the 14 month sampling period was 23% above normal (NOAA 1986, NOAA 1987).

Core samples were collected and chemical analysis were performed for the 0 to 140 cm minesoil depth. Because chemical amendments did not impact the 35 to 140 cm depth zone, discussion was limited to the 0 to 35 cm depth. Data for the 35 to 140 cm depth is presented in Appendix A.

Spoil saturation percentage prior to amendment application was 128 on the 1986 test plot area (Table 6). The mean pre-amendment saturation percentage was 126.6 on the 1980 test plot area (Dollhopf and Bauman 1981). Near identical saturation percentages on 1980 and 1986 test plots suggests homogeneous physicochemical properties across the research site.

Table 6. Spring, 1986 physical analysis (%) of unamended spoil at the Belle Fourche site.

DEPTH (cm)	COARSE FRAGMENTS	SATURATION PERCENTAGE	PARTICLE SIZE DISTRIBUTION			TEXTURAL CLASS
			sand	silt	clay	
0-5	2	137	-	-	-	--
5-10	4	121	0	38	62	clay
10-20	7	123	3	45	52	clay
20-35	5	130	2	46	52	clay
Mean	4	128	2	43	55	

Mine spoil generated from the Belle Fourche Shale is dominated by clay size material. Dollhopf and Bauman (1981) reported that the clay mineralogy on adjacent test plots was dominated by smectite. High saturation percentage indicates similar clay mineralogy on the 1986 test plots.

Effects of Chemical Amendments on Minesoil Physicochemical Properties

Minesoil Sodium Adsorption Ratio (SAR)

In the fall of 1986, the SAR of saturated paste extracts from amended spoil (0-35 cm) ranged from 16.9 to 52.5 (Table 21, Appendix A). At the 0 to 5 cm depth, magnesium chloride treated plots had a mean SAR of 20.4 (Table 7). This value was significantly lower than the mean SAR of 30.7 exhibited on phosphogypsum treated plots (0-5 cm). The SAR reduction on magnesium chloride plots suggests that this amendment is highly effective within 4 months following application.

Table 7. Fall, 1986 minesoil SAR values[1] at the Belle Fourche site.

TREATMENT	SAR			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	30.7 A[2]a	31.6 Aa[3]	28.4 Aa	29.3 Aa
Magnesium chloride	20.4 Ba	32.0 Aa	33.8 Aa	35.2 Aa

1 - Values represent the mean of 3 replications.
2 - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).
3 - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

Reduction of SAR by 13.4 units on magnesium chloride treated plots (0-5 cm) indicates 67% effectiveness in attaining the SAR reduction goal during the first growing season. The SAR reduction of 33.8 to 30.7 on phosphogypsum treated plots (0-5 cm) corresponds to 15% effectiveness during the first growing season.

Lack of time and sufficient soil water moving through the minesoil profile is likely the reason that little change in SAR occurred with depth. Improvements in minesoil structure and permeability are necessary for surface water to infiltrate through the profile.

In the summer of 1987, minesoil sample analysis produced test plot SAR values ranging from 17.0 to 37.4 over the 0 to 35 cm depth (Table 22, Appendix A). No statistically significant differences in SAR were found between treatments or within treatment depths. Mean values for SAR at the 0 to 5 cm depth were 24.5 for phosphogypsum treated plots and 21.3 for magnesium chloride treated plots (Table 8). These values indicate considerable SAR reductions had occurred on amended test plots compared to the representative unamended spoil SAR of 33.8.

The SAR reduction of 9.3 units on phosphogypsum treated plots (0-5 cm) corresponds to 46% of the SAR reduction goal. Approximately one half of the applied phosphogypsum (0-5 cm) had reacted by the end of the second growing season (14 months). Smaller SAR reductions occurred with depth on

Table 8. Summer, 1987 minesoil SAR values[1] at the Belle Fourche site.

TREATMENT	SAR			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	24.5 A[2]a	29.3 Aa[3]	28.4 Aa	27.8 Aa
Magnesium chloride	21.3 Aa	26.3 Aa	26.3 Aa	31.7 Aa

1 - Values represent the mean of 3 replications.
2 - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).
3 - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

phosphogypsum plots indicating that improvements in physicochemical properties occurred to a lesser degree over the 5 to 35 cm depth. Inadequate soil water below the 5 cm depth was apparently inhibiting sodium exchange reactions at 14 months following amendment application.

The SAR on magnesium chloride brine treated plots (0-5 cm) was reduced by 12.5 units 14 months after amendment application. This reduction indicates 62% effectiveness in attaining the SAR reduction goal. Over 5 to 20 cm, magnesium chloride brine was 37% effective by reducing SAR 7.5 units.

Overall, the SAR analyses indicates that after two growing seasons (14 months), both chemical amendments promoted improvements in minesoil SAR. A statistically significant SAR reduction at the 0 to 5 cm depth occurred on phosphogypsum treated plots in the summer of 1987 compared to the fall of 1986 (Table 9). This SAR reduction from 30.7 to 24.5 suggests that two growing seasons may be required

Table 9. Minesoil SAR values[1] over time at the Belle Fourche site.

DEPTH (cm)	PHOSPHOGYPSUM		MAGNESIUM CHLORIDE	
	1986	1987	1986	1987
0-5	30.7 a[2]	24.5 b	20.4 a	21.3 a
5-10	31.6 a	29.3 a	32.0 a	26.3 a
10-20	28.4 a	28.4 a	33.8 a	26.3 a
20-35	29.3 a	27.8 a	35.2 a	31.7 a

1 - Values represent the mean of 3 replications.
2 - Means for each treatment followed by the same letter in the same row indicate no significant difference (P=0.05).

for an applied phosphogypsum amendment to reduce SAR near the surface.

Magnesium chloride brine appears to be slightly more effective in reducing SAR (Figures 3-6). Dollhopf et al. (1985) found that highly soluble chemical amendments resulted in more rapid SAR reductions. Prompt dissolution enables amendments to react sooner within the spoil system. The liquid physical nature of magnesium chloride brine provides a temporary solution in the minesoil. Sodium replacement reactions are possible immediately following amendment application.

The effectiveness of magnesium chloride brine in reducing SAR (0-5 cm) varied from 67% (4 months following application), to 62% (14 months following application). Maximum effectiveness over 0 to 5 cm appears to be achieved within 4 months following application.

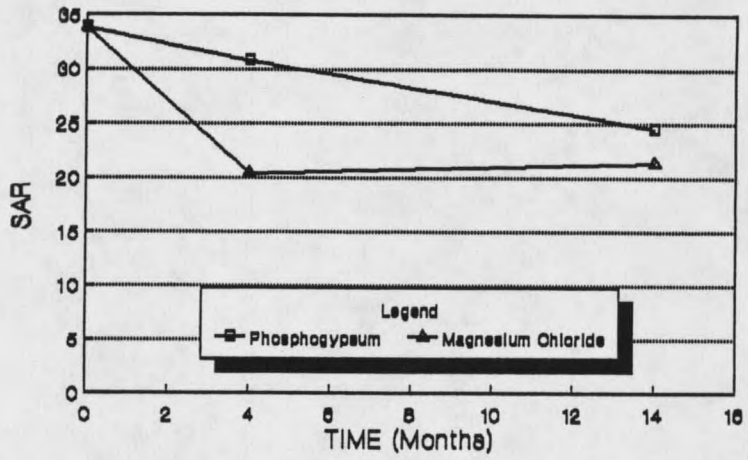


Figure 3. Minesoil (0-5 cm) SAR change over time at the Belle Fourche site.

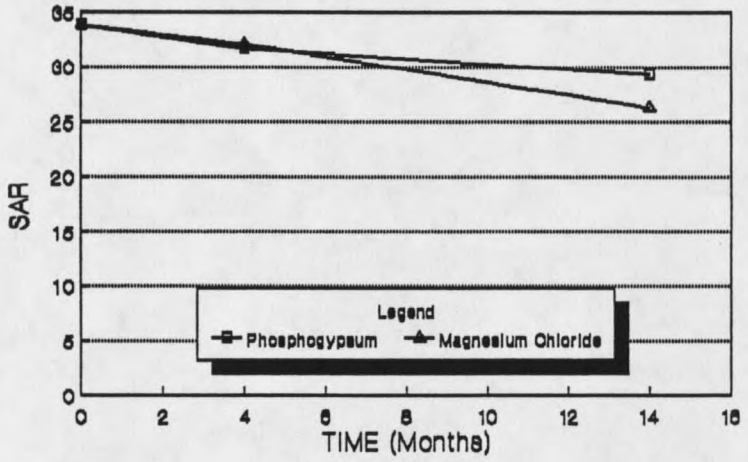


Figure 4. Minesoil (5-10 cm) SAR change over time at the Belle Fourche site.

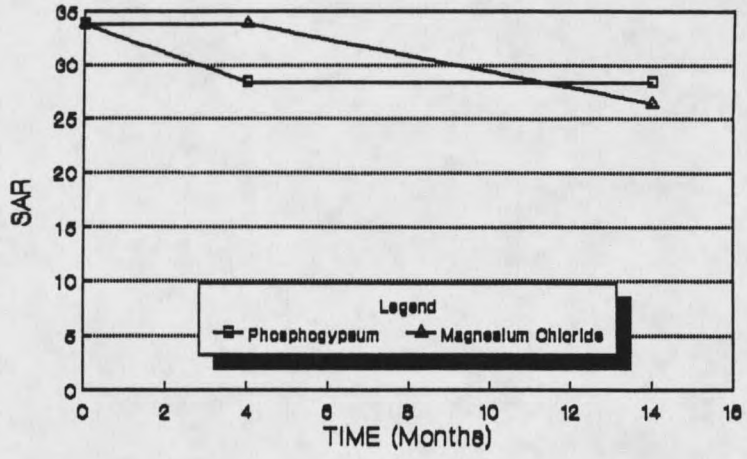


Figure 5. Minesoil (10-20 cm) SAR change over time at the Belle Fourche site.

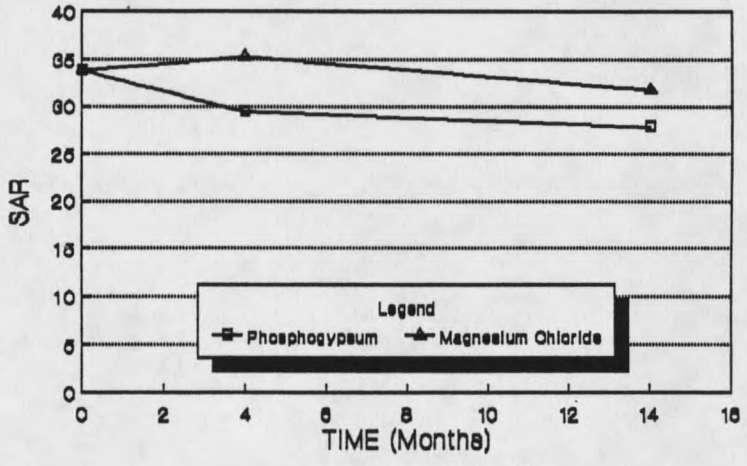


Figure 6. Minesoil (20-35 cm) SAR change over time at the Belle Fourche site.

Several years may be required for either amendment to be effective at depth. This may be especially true with the phosphogypsum amendment due to relatively low solubility.

Until surface water infiltrates deeper into the minesoil profile, phosphogypsum dissolution at depth will be inhibited. Although magnesium chloride brine is applied as a liquid, if soil water is limited, soluble magnesium salts will precipitate after a short time.

Minesoil SAR improvements were most apparent near the surface. As physical properties such as structure and permeability improve at the surface as a function of reduced SAR, more water will infiltrate into the profile. Progressively, minesoil physicochemical improvements should occur at depth as a function of increased infiltration.

A distinct moisture gradient was noted on the test plots. Block 1 plots (see Figure 2) received the most moisture, with block 3 plots receiving the least, and block 2 plots being intermediate. The mechanism was surface runoff from block 3, with accumulation in blocks 2 and block 1. The moisture gradient may have had an effect on the rate in which sodium exchange reactions occurred.

Minesoil Electrical Conductivity (EC)

Application of either phosphogypsum or magnesium chloride brine increased minesoil salinity levels compared to the unamended spoil EC value of 8.0 mmhos/cm. In the

fall of 1986, EC values on phosphogypsum treated plots ranged from 7.1 to 11.8 mmhos/cm over the 0 to 35 cm depth (Table 21, Appendix A). The range on magnesium chloride treated plots was 6.5 to 22.0 mmhos/cm over the 0 to 35 cm depth. Mean EC values (0-5 cm) increased 39% on phosphogypsum plots and 112% on magnesium chloride plots compared to unamended spoil (Table 10).

At the 5 to 10 cm depth, EC was significantly greater on magnesium chloride treated plots compared to phosphogypsum treated plots. A 139% increase in salinity had occurred on magnesium chloride plots compared to a 36% increase on phosphogypsum plots. At the 10 to 20 cm depth, EC increased by 19% on phosphogypsum treated plots and 55% on magnesium chloride treated plots. Over the 20 to 35 cm depth, minimal changes in EC occurred on the chemically amended plots.

Table 10. Fall, 1986 minesoil electrical conductivity (EC) values[1] at the Belle Fourche site.

TREATMENT	EC (mmhos/cm)			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	11.1 A[2]a	10.9 Aa[3]	9.5 Aa	8.9 Aa
Magnesium chloride	17.0 Aa	19.1 Ba	12.4 Aab	7.6 Ab

1 - Values represent the mean of 3 replications.
2 - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).
3 - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

No significant differences in EC were detected between depths on phosphogypsum treated plots. On magnesium chloride treated plots, EC was statistically greater over the 0 to 10 cm depth compared to the 20 to 35 cm depth.

Analysis from the summer of 1987 on phosphogypsum treated plots produced a range of EC values from 8.8 to 12.7 mmhos/cm over the 0 to 35 cm depth (Table 22, Appendix A). Magnesium chloride brine treated plots ranged from 10.1 to 22.1 mmhos/cm over the 0 to 35 cm depth. No statistically significant differences in EC were detected between phosphogypsum and magnesium chloride treatments, or within treatment depths (Table 11).

Electrical conductivity values on phosphogypsum treated plots were similar over the entire amended depth after 14 months. Mean EC (0-35 cm) was 10.8 mmhos/cm, indicating a 35% increase in salinity compared to pre-amendment levels.

Table 11. Summer, 1987 minesoil electrical conductivity (EC) values[1] at the Belle Fourche site.

TREATMENT	EC (mmhos/cm)			
	0-5cm	5-10cm	10-20cm	20-35cm
Phosphogypsum	10.1 A[2]a	11.6 Aa[3]	11.6 Aa	10.0 Aa
Magnesium chloride	15.9 Aa	14.0 Aa	12.8 Aa	12.9 Aa

1 - Values represent the mean of 3 replications.
2 - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).
3 - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

A trend of consistently higher EC values on magnesium chloride treated plots compared to phosphogypsum treated plots was apparent 14 months following amendment application. At the 0 to 5 cm depth, magnesium chloride plots were 57% higher in EC compared to phosphogypsum plots.

Over the remainder of the amended profile, magnesium chloride plots were consistently higher than phosphogypsum plots in EC, but to a lesser degree than at the 0 to 5 cm depth. The mean EC range on magnesium chloride treated plots indicated that even after 14 months, salinity remained 60 to 99% higher than pre-amendment levels. No significant differences were detected between fall, 1986 and summer, 1987 EC values for either treatment (Table 12).

Table 12. Minesoil electrical conductivity (EC) values[1] over time at the Belle Fourche site.

DEPTH (cm)	PHOSPHOGYPSUM		MAGNESIUM CHLORIDE	
	1986	1987	1986	1987
0-5	11.1 a[2]	10.1 a	17.0 a	15.9 a
5-10	10.9 a	11.6 a	19.1 a	14.0 a
10-20	9.5 a	11.6 a	12.4 a	12.8 a
20-35	8.9 a	10.0 a	7.6 a	12.9 a

1 - Values represent mean of 3 replications.
2 - Means for each treatment followed by the same letter in the same row indicate no significant difference (P=0.05).

Although data is limited, there appears to be a trend of initial increase in EC near the surface of magnesium chloride brine treated plots, followed by a decrease over time (Figures 7-8). In addition, salinity appears to be increasing at the 10 to 35 cm depth (Figures 9-10). These changes in EC suggest that salts are being leached near the surface and accumulating deeper in the profile. However, continued monitoring of the test plots will be necessary to determine if preliminary trends continue over time.

Plant growth is adversely effected by high salt concentrations due to osmotic stress (Bohn et al. 1985). The unamended spoil EC of 8.0 mmhos/cm indicates high salt concentration in the minespoil prior to amendment application. As a result of amendment application, salt concentrations increased above pre-amendment levels. Although high salinity inhibits water uptake by plants, there was a net improvement in the plant growth medium due to improved minesoil physical properties. High salt concentration and lower SAR result in reduced surface crusting and minesoil flocculation allowing precipitation to enter the profile.

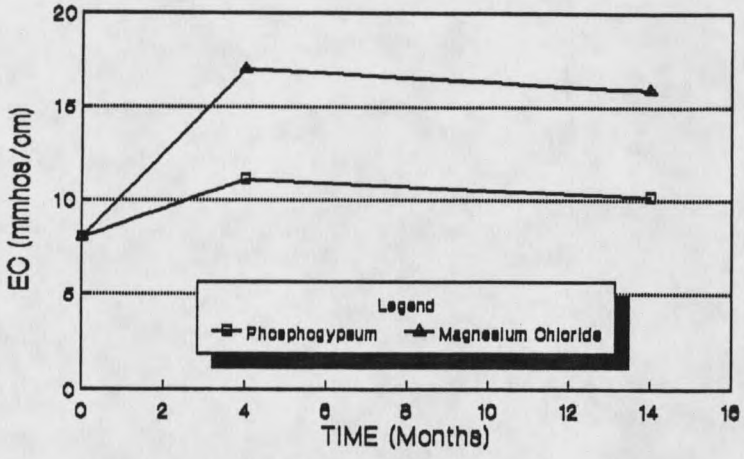


Figure 7. Minesoil (0-5 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

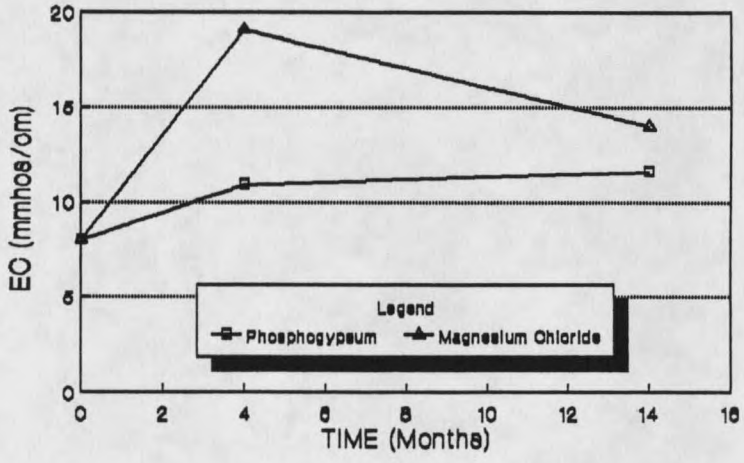


Figure 8. Minesoil (5-10 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

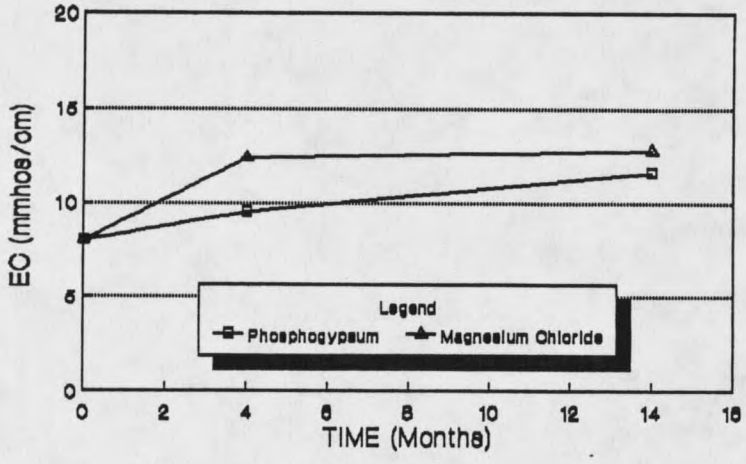


Figure 9. Minesoil (10-20 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

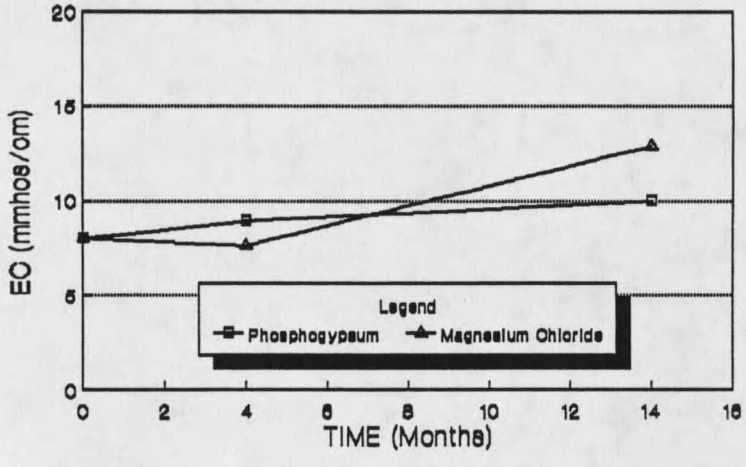


Figure 10. Minesoil (20-35 cm) electrical conductivity (EC) change over time at the Belle Fourche site.

Minesoil pH

Minesoil (0-35 cm) pH levels remained near neutral over the entire study period (Table 13). The range in pH values for the fall, 1986 sampling period was 6.4 to 7.8 (Table 21, Appendix A). The pH range for summer, 1987 sampling was 6.4 to 8.0 (Table 22, Appendix A).

A significant pH change over time was detected at the 10 to 20 cm depth on phosphogypsum plots between fall, 1986 and summer, 1987. This pH change from 6.6 in 1986, to 7.5 in 1987 was the only significant pH change and is difficult to attribute to the amendment. Natural variability in minesoil pH is likely the cause of differences in measured values.

Table 13. Minesoil pH values[1] over time at the Belle Fourche site.

DEPTH (cm)	PHOSPHOGYPSUM		MAGNESIUM CHLORIDE	
	1986	1987	1986	1987
0-5	7.4 a[2]	7.5 a	7.1 a	7.0 a
5-10	6.8 a	7.3 a	6.8 a	6.9 a
10-20	6.6 a	7.5 b	7.1 a	7.0 a
20-35	7.1 a	7.3 a	7.1 a	6.9 a

1 - Values represent the mean of 3 replications.
2 - Means for each treatment followed by the same letter in the same row indicate no significant difference (P=0.05).

Saturation Percentage

Saturation percentage determinations were performed on core samples taken in the summer of 1987 to relate improvements in minesoil SAR to physical properties. Saturation percentage gives an indication of the severity of soil structure breakdown due to clay mineral dispersion. In a dispersed condition, pore space is reduced or eliminated decreasing water transmission through the minesoil. Reduced values for saturation percentage correspond with improved minesoil physical properties.

Mean saturation percentage was significantly less on magnesium chloride treated plots (0-5 cm) at 73, compared to 95 on phosphogypsum treated plots (Table 14). Compared to the unamended spoil saturation percentage of 128, these values indicate a 43% reduction on magnesium chloride plots and a 26% reduction on phosphogypsum plots.

Table 14. Summer, 1987 minesoil saturation percentage[1] at the Belle Fourche site.

TREATMENT	SOIL DEPTH (cm)			
	0-5	5-10	10-20	20-35
Phosphogypsum	95 A[2]a	108 Aab	122 Ab	121 Ab
Magnesium chloride	73 Ba[3]	80 Ba	90 Aa	95 Aa

1 - Values represent the mean of 3 replications.
2 - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).
3 - Means followed by the same lower case letter in the same row indicate no significant difference (P=0.05).

At the 5 to 10 cm depth, saturation percentage on magnesium chloride treated plots was significantly less than phosphogypsum treated plots. A 16% decrease occurred on phosphogypsum plots (5-10 cm), while magnesium chloride plots were 37% less than the unamended spoil. Magnesium chloride plots exhibited reduced saturation percentage throughout the amended profile. Reductions of 30 and 26% were noted at 10 to 20 and 20 to 35 cm, respectively.

Within treatments, phosphogypsum treated plots were significantly lower in saturation percentage at the 0 to 5 cm depth compared to the 20 to 35 cm depth. Magnesium chloride treated plots did not significantly differ within the 0 to 35 cm depth.

Saturation percentage on amended test plots was reduced as a result of amendment application. Reductions suggest that the severity of swelling processes have been decreased. Minespoil with a saturation percentage greater than 85 is considered unsuitable for minesoil construction by some state mining regulatory agencies (MDSL 1983). Saturation percentage on magnesium chloride treated plots was less than 85 over the 0 to 10 cm depth. Although reductions in saturation percentage were substantial near the surface on phosphogypsum treated plots, the entire amended depth remained at a problem level.

Minesoil Infiltration Rate Study

The infiltration rate study was conducted to determine if the applied chemical amendments increased infiltration into the minesoil profile. Sodic minespoils typically allow near normal infiltration initially, but exhibit dramatic infiltration rate reductions within a short time due to soil pore blockage from clay dispersion.

Simulated rainfall at a rate of 12 cm/hr over 30 minutes was used to mimic the short duration-high intensity thundershowers common to the area. Infiltration rates in cm/hr were calculated at 5 minute intervals over a 30 minute period (Table 15). All infiltration rate data is included in Table 23, Appendix A.

Table 15. Summer, 1987 minesoil infiltration rates[1] over time at the Belle Fourche site.

MINUTES	INFILTRATION RATE (cm/hr)		
	Unamended spoil	Phosphogypsum	Magnesium chloride
0-5	8.5 A[2]a	11.8 A b[3]	11.1 A ab
5-10	3.2 B a	10.2 A b	6.8 B ab
10-15	1.3 BCa	6.3 B a	4.8 BCa
15-20	0.5 C a	4.9 BCb	4.4 C b
20-25	0.3 C a	3.5 CDb	4.0 C b
25-30	0.1 C a	2.8 D ab	3.8 C b

1 - Values represent the mean of 3 replications.
2 - Means followed by the same upper case letter in the same column indicate no significant difference (P=0.05).
3 - Means followed by the same lower case letter in same row indicate no significant difference (P=0.05).

At 5 minutes after initial wet-up, infiltration rates for both the unamended spoil and the amended test plots were in the moderately rapid infiltration category (SCS 1951). Phosphogypsum plots had a significantly greater infiltration rate compared to representative unamended spoil.

Over the 5 to 10 minute time interval, swelling processes resulted in a 62% drop in infiltration rate to 3.2 cm/hr on unamended spoil. A 39% infiltration rate reduction occurred on magnesium chloride plots. Phosphogypsum treated plots maintained a significantly higher infiltration rate, with only a minor reduction of 13%.

During the 10 to 15 minute time interval, infiltration rates declined across all treatments. Unamended spoil declined to a value of 1.3 cm/hr. This value is representative of the moderately slow infiltration rate classification (SCS 1951). Although reductions were noted on chemically amended plots, they were not dramatic. Infiltration rates on phosphogypsum plots remained moderately rapid. Magnesium chloride plots were classified as moderate.

The 5 to 10, and especially the 10 to 15 minute infiltration rates demonstrate an important feature of the chemical amendments. High intensity rainfall events often last for at least this amount of time. By 10 to 15 minutes, minimal infiltration was occurring on unamended spoil. Nearly all precipitation was being converted to runoff. Erosion potential increased and moisture needed in the root

zone was lost. Over the same time period, substantial infiltration was occurring on the amended test plots.

Between 15 and 20 minutes after initial wet-up, continued infiltration rate decreases occurred across all treatments. Phosphogypsum and magnesium chloride treated plots, while decreasing slightly, had stabilized at a level significantly greater than unamended spoil.

Infiltration rates remained relatively unchanged during the time intervals of 20 to 25 and 25 to 30 minutes. Rates of infiltration on unamended spoil were very near zero. Infiltration rates on chemically amended plots continued to decrease, but were statistically greater than unamended spoil. At 25 to 30 minute time interval, both phosphogypsum and magnesium chloride treated plots maintained moderate infiltration rates of 2.8 and 3.8 cm/hr, respectively.

Results from the infiltration rate study indicate that the combination of chisel plowing, chemical amendments, seeding, and a crimped straw mulch improved surface water infiltration into the minesoil (Figure 11). It is likely that a majority of the improvement in infiltration is due to the application of the chemical amendments. The effects of plowing and mulch may be minimized after 14 months due to minesoil shrink-swell processes and mulch decomposition. Dollhopf et al. (1988) reported minimal infiltration rate improvement on adjacent test plots amended by chisel plowing, mulch, and seeding.

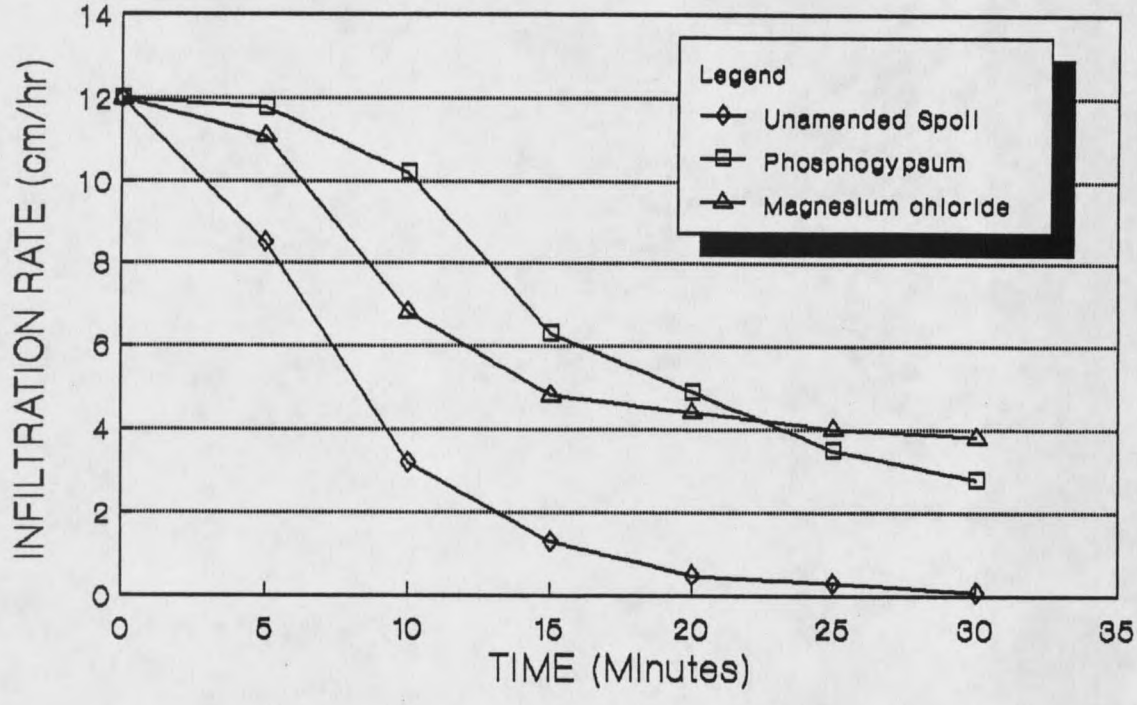


Figure 11. Minesoil infiltration rates over time at the Belle Fourche site.

Vegetation Monitoring

Seedling Density

Emergent seedling density was evaluated on amended test plots as a function of the chemical amendments and nitrogen fertilizer rates. All amended test plots exhibited seedling emergence. In comparing the treatments of phosphogypsum and magnesium chloride brine, emergent seedling density was

significantly greater on magnesium chloride plots for seeded grasses, seeded forbs, and seeded shrubs (Table 16).

Density of annual grasses was significantly greater on phosphogypsum treated plots compared to magnesium chloride treated plots. Total seedling density did not significantly differ between chemical amendment treatments.

In comparing nitrogen rate treatments, total seedling density was significantly greater with 67 kg/ha nitrogen compared to the other nitrogen rates (Table 17).

Table 16. Seedling density[1] (plants/m²) in 1986, by chemical amendment at the Belle Fourche site.

TREATMENT	SEEDED GRASS	ANNUAL GRASS	SEEDED FORB	SEEDED SHRUB	TOTAL
Phosphogypsum	47.3 b[2]	75.3 a	19.0 b	1.5 b	143.2 a
Magnesium chloride	93.1 a	8.2 b	36.5 a	3.1 a	139.0 a

1 - N = 3.
2 - Means followed by the same letter in the same column indicate no significant difference (P=0.05).

Table 17. Seedling density[1] (plants/m²) in 1986, by fertilizer rate at the Belle Fourche site.

NITROGEN RATE (kg/ha)	SEEDED GRASS	ANNUAL GRASS	SEEDED FORB	SEEDED SHRUB	TOTAL
0	51.5 b[2]	21.5 a	30.1 a	1.2 b	104.3 b
67	97.1 a	63.6 a	28.6 a	3.1 a	191.8 a
134	62.0 b	40.1 a	24.5 a	2.7 a	127.2 b

1 - N = 6.
2 - Means followed by the same letter in the same column indicate no significant difference (P=0.05).

Emergence of seeded grasses was significantly greater on subplots receiving 67 kg/ha nitrogen compared to the other nitrogen rates. Seedling density of annual grasses and seeded forbs did not significantly differ between nitrogen rate treatments. Density of seeded shrubs was significantly less on subplots receiving no nitrogen as compared to the other nitrogen rates.

Canopy Cover

Plant canopy cover on the amended test plots in July of 1987 was dominated by the pioneering forbs, burning-bush and rillscale. These plants readily invaded the amended test plots. Rillscale is one of the few species that naturally exists on unamended bentonite spoil. Serving as a source of shade and protection to seeded vegetation, these forbs are welcomed early successional species. Neither rillscale nor burning-bush were observed during the 1986 seedling emergence study.

Total plant canopy cover was statistically greater on magnesium chloride brine treated plots compared to phospho-gypsum treated plots (Table 18). Canopy cover of non-seeded forbs was also significantly greater on magnesium chloride treated plots. No other significant differences between treatments were detected in canopy cover by plant class.

Table 18. Summer, 1987 percent canopy cover[1] at the Belle Fourche site.

PLANT CLASS	TREATMENT			
	Phosphogypsum		Magnesium chloride	
Seeded Grass	7.5	a[2]	6.4	a
Annual Grass	2.6	a	3.0	a
Seeded Forb	0.9	a	2.4	a
Non-Seeded Forb	15.2	b	26.7	a
Seeded Shrub	2.5	a	0.8	a
Total	28.6	b	39.3	a

1 - N = 3.
2 - Means followed by the same letter in the same row indicate no significant difference (P=0.05).

Canopy cover on all test plots was generally greatest for non-seeded forbs and seeded grasses. Members of every plant class were established and contributed to canopy cover across all test plots.

Above Ground Plant Production

Above ground plant production on the study plots was dominated by burning-bush and rillscale. On disturbed sites, annual species often dominate vegetation temporarily. Within several years, perennial species typically replace annuals and become dominant.

Some plant species, particularly yellow sweetclover (Melilotus officinalis), suffered grasshopper damage. These insects reduced measurable seeded plant production. Total production on phosphogypsum treated plots was not significantly different from magnesium chloride treated plots (Table 19). Non-seeded annual forbs contributed 60% of the

Table 19. Summer, 1987 plant production[1] (kg/ha) at the Belle Fourche site.

PLANT CLASS	TREATMENT			
	Phosphogypsum		Magnesium chloride	
Seeded Grass	326.8	a[2]	230.8	a
Annual Grass	286.4	a	63.6	b
Seeded Forb	35.5	a	7.6	a
Non-seeded Forb	1058.4	b	2271.2	a
Seeded Shrub	46.0	a	144.0	a
Total	1753.1	a	2717.2	a

1 - N = 3.
2 - Means followed by the same letter in the same row indicate no significant difference (P=0.05).

total production on phosphogypsum treated plots and 83% on magnesium chloride treated plots.

Total above ground production of seeded species was 694.7 kg/ha on phosphogypsum treated plots and 446.0 kg/ha on magnesium chloride treated plots. Production of annual grasses was significantly greater on phosphogypsum treated plots compared to magnesium chloride treated plots. Non-seeded forb production was significantly greater on magnesium chloride treated plots.

Seedling density, canopy cover, and above ground production were positively affected by the addition of chemical amendments. Unamended spoil at the research site is nearly devoid of vegetation.

Root Biomass

Root biomass per 1000 g soil over the 0 to 35 cm depth zone was determined by weighing root material extracted from core samples.

Root biomass was significantly greater on magnesium chloride treated plots compared to phosphogypsum treated plots (Table 20). Observation of root sample cores revealed that minimal root material was present. This was due, at least in part, to the root study being conducted a short time following plot implementation. Minesoil physicochemical improvements are incomplete resulting in limited root development.

Table 20. Summer, 1987 root biomass (g/1000 g soil) at the Belle Fourche site.

BLOCK	OBSERVATION	TREATMENT	
		Phosphogypsum	Magnesium chloride
1	1	.11	.26
1	2	.17	.36
2	1	.08	.08
2	2	.09	.09
3	1	.06	.04
3	2	.06	.04
Mean		.09 b[1]	.14 a

[1] - Mean values followed by the same letter in the same row indicate no significant difference (P=0.05).

SUMMARY AND CONCLUSIONS

Minesoil Physicochemical Response

Application of either phosphogypsum (40.4 mt/ha) or magnesium chloride brine (36.2 mt/ha) resulted in bentonite minesoil SAR reduction near the surface. Four months following amendment application, mean SAR on magnesium chloride brine treated plots (0-5 cm) declined from an unamended spoil SAR of 33.8, to 20.4. Sodium adsorption ratio on phosphogypsum treated plots (0-5 cm) was significantly greater at 30.7. Fourteen months following amendment application, mean SAR (0-5 cm) on magnesium chloride treated plots was 21.3, and 24.5 on phosphogypsum treated plots. These results suggest that application of either amendment will result in SAR reduction. However, SAR reduction occurs more rapidly with magnesium chloride brine.

Several growing seasons may be required for improvements in minesoil physicochemical properties to occur throughout the root zone. Beneath the 20 cm depth, only minimal SAR reductions resulted from application of either amendment. The indication is that infiltration of water remained inadequate with depth at 14 months following amendment application.

Overall, magnesium chloride brine was slightly more effective than phosphogypsum in reducing SAR and saturation percentage over the test period. Superiority of the more soluble amendment in promoting initial spoil physicochemical improvements was demonstrated.

An initial rise in EC near the surface occurred following application of phosphogypsum or magnesium chloride brine. Four months following amendment application, EC (0-10 cm) increased an average of 37% on phosphogypsum treated plots and 125% on magnesium chloride treated plots. After two growing seasons (14 months), a possible trend of EC reduction near the amended surface was noted. However, limited data makes this trend difficult to confirm.

Minesoil infiltration rates were significantly increased by the application of either phosphogypsum and magnesium chloride brine amendments. After 30 minutes of simulated rainfall, amended test plots maintained moderate (2-6 cm/hr) infiltration rates. Over the same time period, the infiltration rate on unamended spoil dropped to .1 cm/hr.

A specific effect of magnesium (hydraulic conductivity reduction) resulting from magnesium chloride brine application was not apparent.

Vegetation Response

Chemical amendment application resulted in germination and establishment of seeded vegetation. Unamended spoil at the research site supports very minimal vegetative cover. Total seedling density was not significantly different between phosphogypsum and magnesium chloride brine treated plots. Test plots with nitrogen fertilizer at 67 kg/ha had the greatest seedling density compared to 0 and 134 kg/ha nitrogen. Wheat straw mulch which contained viable seed heads resulted in substantial germination and establishment of annual wheat plants. The presence of this species was desirable as a quickly establishing cover crop.

Magnesium chloride brine treated plots had significantly greater plant canopy cover at 39.3%, compared to 28.6% on phosphogypsum treated plots. For both treatments, non-seeded annual forbs provided the majority of canopy cover compared to the other plant classes.

Above ground plant production of non-seeded annual forbs was greatest among plant classes for both treatments. Production of non-seeded annual forbs on phosphogypsum treated plots was 60% of total production. On magnesium chloride treated plots, non-seeded forbs contributed 83% of the total production.

Among seeded species, perennial grasses consistently produced the greatest biomass. Seeded shrubs and forbs

contributed moderately to total production and were established in limited numbers across the site.

Magnesium chloride treated plots had significantly greater root biomass production than phosphogypsum treated plots. Due to the relatively short time period since plot implementation, root development was limited.

Annual pioneer species were the dominate vegetative type on reclaimed test plots over the first two growing seasons. Robust annuals are desirable sources of protection for establishing seeded species. Over time, seeded perennial species will replace the annuals and dominate the site.

Conclusions

Abandoned sodium bentonite minespoils are a difficult reclamation challenge. Chemical amendments used for reclamation of abandoned bentonite disturbances must be effective, yet cost feasible. Phosphogypsum and magnesium chloride brine application to these minesoils decreased the SAR and saturation percentage. Infiltration rates improved and vegetation was established.

As industrial waste products, these amendments are cost effective for large scale projects. Phosphogypsum and magnesium chloride brine are considerably less expensive than their counterparts, mined (agricultural) gypsum and calcium chloride. The phosphogypsum amendment was enriched

above background levels in cadmium and selenium, and contained a silver concentration slightly above suspected phytotoxic levels. However, because of dilution by amendment incorporation, phytotoxic trace element accumulations are unlikely.

One notable shortcoming of both phosphogypsum and magnesium chloride brine was their inability to promote establishment of vegetative cover during the first growing season. Dollhopf and Bauman (1981) reported similar first year vegetation performance with agricultural gypsum and calcium chloride amendments on adjacent test plots. Limited effectiveness during the first growing season appears to be a common characteristic of chemical amendments on bentonite minespoils. Two growing seasons appear to be required for minesoil physicochemical improvements to progress to the stage at which a stable ground cover can establish. One option may be to postpone seeding for approximately one year following amendment application. The delay would allow time for applied amendments to improve minesoil conditions.

The use of an organic amendment such as manure or woodchips in combination with a chemical amendment is another alternative. This was the amendment scheme used by the Wyoming Department of Environmental Quality for abandoned bentonite minesite reclamation (Anselmi 1986). Organic amendments promote initial vegetative establishment, while chemical amendments induce amelioration of adverse

minesoil physicochemical properties. Phosphogypsum or magnesium chloride brine would be effective and cost feasible in an organic/chemical amendment combination.

RECOMMENDATIONS

1) Magnesium chloride brine or phosphogypsum should be used as amendments for abandoned bentonite spoil reclamation due to their ability to reduce SAR and improve minesoil physical properties.

2) Even though magnesium chloride brine is applied as a liquid, a factor for lack of quantitative replacement should be included in amendment rate calculations.

3) When possible, these amendments should be applied at least one growing season prior to seeding, or used in combination with an organic amendment.

4) Proper plant species selection is important for successful vegetative establishment on amended bentonite spoils. Selection of species for saline-sodic and drought tolerance is essential for plant survival because of initially limited physicochemical improvements with depth.

5) Recommendations presented here are based on a 14 month data base. Therefore, minesoil SAR and salinity should be monitored periodically to determine long-term amendment effectiveness and to investigate trends in salinity. The calcium:magnesium ratio in vegetation and in the minesoil warrants further study on magnesium chloride brine treated test plots.

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APPENDICES

APPENDIX A

MINESOIL PHYSICAL AND CHEMICAL DATA

Table 21. Fall, 1986 minesoil chemical analysis at the Belle Fourche site.

TREATMENT[1]	BLOCK	DEPTH[2]	pH	EC (mmhos/cm)	SAR
1	1	1	7.8	11.8	30.3
1	1	2	6.7	11.2	32.1
1	1	3	6.4	9.6	29.1
1	1	4	6.4	8.0	24.5
1	1	5	7.6	8.8	25.1
1	1	6	7.4	11.1	31.4
2	1	1	7.3	10.9	23.9
2	1	2	6.8	22.0	32.0
2	1	3	7.1	10.4	28.1
2	1	4	6.9	8.6	23.6
2	1	5	7.2	8.9	21.4
2	1	6	7.0	7.2	26.1
1	2	1	7.1	11.3	32.4
1	2	2	6.8	11.8	34.9
1	2	3	6.6	10.6	29.8
1	2	4	7.6	7.1	31.6
1	2	5	7.0	12.2	32.5
1	2	6	8.1	8.8	23.2
2	2	1	7.0	21.1	20.6
2	2	2	7.0	19.2	26.6
2	2	3	6.9	12.7	33.9
2	2	4	7.7	7.8	29.6
2	2	5	7.2	9.7	23.2
2	2	6	7.4	8.4	23.2
1	3	1	7.5	10.4	29.4
1	3	2	7.1	9.9	28.0
1	3	3	6.9	8.5	26.4
1	3	4	7.4	11.7	32.0
1	3	5	7.1	8.2	34.0
1	3	6	8.4	6.6	24.3
2	3	1	7.2	19.0	16.9
2	3	2	6.8	16.3	37.0
2	3	3	7.3	14.2	39.5
2	3	4	6.9	6.5	52.5
2	3	5	6.7	9.1	30.1
2	3	6	7.3	8.2	23.1

[1] - Treatment 1 is phosphogypsum. Treatment 2 is magnesium chloride brine.

[2] - Depth 1 is 0-5cm, depth 2 is 5-10cm, depth 3 is 10-20cm, depth 4 is 20-35cm, depth 5 is 35-70cm, depth 6 is 70-140cm.

Table 22. Summer, 1987 physicochemical analysis at the Belle Fourche site.

TREATMENT[1]	BLOCK	DEPTH[2]	pH	EC (mmhos/cm)	SAR	SATURATION PERCENTAGE
1	1	1	6.9	8.8	22.0	105
1	1	2	6.9	11.4	27.6	101
1	1	3	7.2	11.8	27.8	125
1	1	4	7.1	10.2	36.4	136
1	1	5	6.8	8.9	25.6	114
1	1	6	7.6	11.0	23.6	99
2	1	1	7.3	11.2	17.0	77
2	1	2	7.4	11.4	18.6	75
2	1	3	7.0	13.8	23.4	69
2	1	4	6.9	11.2	37.4	119
2	1	5	7.1	13.1	32.3	110
2	1	6	7.3	9.3	21.0	96
1	2	1	7.6	11.3	26.7	109
1	2	2	7.0	12.7	34.5	127
1	2	3	7.7	10.5	27.6	141
1	2	4	7.6	8.9	25.3	135
1	2	5	7.5	10.3	22.5	100
1	2	6	7.2	11.8	23.5	98
2	2	1	6.9	22.1	22.8	62
2	2	2	7.3	14.2	28.9	81
2	2	3	7.5	10.1	27.7	110
2	2	4	7.1	14.8	32.7	85
2	2	5	6.8	12.7	28.5	74
2	2	6	7.0	9.6	21.6	88
1	3	1	8.0	10.1	24.9	97
1	3	2	8.0	10.7	25.8	106
1	3	3	7.7	12.7	29.8	119
1	3	4	7.4	11.0	21.9	97
1	3	5	7.8	10.0	18.5	101
1	3	6	7.8	9.7	20.5	142
2	3	1	6.8	14.3	24.2	82
2	3	2	6.4	16.6	31.5	86
2	3	3	6.8	14.5	28.0	92
2	3	4	6.7	12.7	25.2	81
2	3	5	7.0	9.5	16.2	97
2	3	6	7.5	7.5	16.8	103

[1] - Treatment 1 is phosphogypsum. Treatment 2 is magnesium chloride brine.

[2] - Depth 1 is 0-5cm, depth 2 is 5-10cm, depth 3 is 10-20cm, depth 4 is 20-35cm, depth 5 is 35-70cm, depth 6 is 70-140cm.

Table 23. Summer, 1987 minesoil infiltration rates (cm/hr) over time at the Belle Fourche site.

TREATMENT[1]	BLOCK	TIME (minutes)					
		5	10	15	20	25	30
1	1	12.0	11.3	9.4	6.6	5.2	4.8
1	2	11.5	9.0	5.0	3.2	2.6	2.3
1	3	12.0	10.3	4.6	4.9	2.6	1.3
2	1	11.9	11.4	8.4	7.0	6.2	6.1
2	2	11.3	4.6	3.7	2.6	3.1	3.7
2	3	10.2	4.3	2.2	3.7	2.8	1.6
3	1	8.3	3.2	1.8	1.4	.4	.2
3	2	6.4	.1	0	0	0	0
3	3	10.7	6.4	2.2	.2	.4	.2

[1] - Treatment 1 is phosphogypsum. Treatment 2 is magnesium chloride brine. Treatment 3 is unamended spoil.

APPENDIX B

ANOVA AND LSD TABLES

Table 24. Analysis of variance and least significant difference of fall, 1986 SAR data by depth (P=0.05).

SAR (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	18.123			
Treatments	1	157.08	157.08	28.19	.0337
Error	2	11.143	5.5717		
Total	5	186.35			

LSD Analysis		
Factor	Identity	Mean
SAR 0-5 cm	Phosphogypsum	30.7 a
	Magnesium chloride	20.4 b

SAR (5-10 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	3.7633			
Treatments	1	.24000	.24000	.01	.9435
Error	2	74.83	37.415		
Total	5	78.833			

LSD Analysis		
Factor	Identity	Mean
SAR 5-10 cm	Phosphogypsum	31.6 a
	Magnesium chloride	32.0 a

SAR (10-20 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	20.463			
Treatments	1	43.74	43.74	1.72	.3204
Error	2	50.97	25.485		
Total	5	115.17			

LSD Analysis		
Factor	Identity	Mean
SAR 10-20 cm	Phosphogypsum	28.4 a
	Magnesium chloride	33.8 a

Table 24. Continued.

SAR (20-35 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	339.91			
Treatments	1	51.627	51.627	.64	.5071
Error	2	160.90	80.452		
Total	5	522.44			

LSD Analysis		
Factor	Identity	Mean
SAR 20-35 cm	Phosphogypsum	29.3 a
	Magnesium chloride	35.2 a

Table 25. Analysis of variance and least significant difference of fall, 1986 SAR data by treatment (P=0.05).

Phosphogypsum SAR

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	27.312			
Treatments	3	18.349	6.1164	.84	.5199
Error	6	43.568	7.2614		
Total	11	89.229			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum	0-5 cm	30.7 a
	5-10 cm	31.6 a
	10-20 cm	28.4 a
	20-35 cm	29.3 a

Magnesium chloride SAR

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	221.55			
Treatments	3	410.13	136.71	2.12	.1995
Error	6	387.79	64.632		
Total	11	1019.5			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride	0-5 cm	20.4 a
	5-10 cm	32.1 a
	10-20 cm	33.8 a
	20-35 cm	35.2 a

Table 26. Analysis of variance and least significant difference of summer, 1987 SAR data by depth (P=0.05).

SAR (0-5 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	35.403			
Treatments	1	15.36	15.36	6.16	.1312
Error	2	4.9900	2.4950		
Total	5	55.753			

LSD Analysis

Factor	Identity	Mean
SAR 0-5 cm	Phosphogypsum	24.5 a
	Magnesium chloride	21.3 b

SAR (5-10 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	75.88			
Treatments	1	13.500	13.500	.46	.5666
Error	2	58.360	29.180		
Total	5	147.74			

LSD Analysis

Factor	Identity	Mean
SAR 5-10 cm	Phosphogypsum	29.3 a
	Magnesium chloride	26.3 a

SAR (10-20 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	11.103			
Treatments	1	6.2016	6.2016	2.43	.2593
Error	2	5.1033	2.5517		
Total	5	22.408			

LSD Analysis

Factor	Identity	Mean
SAR 10-20 cm	Phosphogypsum	28.4 a
	Magnesium chloride	26.3 a

Table 26. Continued.

SAR (20-35 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	180.22			
Treatments	1	22.815	22.815	4.34	.1726
Error	2	10.510	5.2550		
Total	5	213.55			

LSD Analysis		
Factor	Identity	Mean
SAR 20-35 cm	Phosphogypsum	27.8 a
	Magnesium chloride	31.7 a

Table 27. Analysis of variance and least significant difference of summer, 1987 SAR data by treatment (P=0.05).

Phosphogypsum SAR

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	22.245			
Treatments	3	38.949	12.983	.52	.6848
Error	6	149.15	24.858		
Total	11	210.34			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum	0-5 cm	24.5 a
	5-10 cm	29.3 a
	10-20 cm	28.4 a
	20-35 cm	27.8 a

Magnesium chloride SAR

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	34.262			
Treatments	3	163.43	54.476	1.86	.2372
Error	6	175.92	29.320		
Total	11	373.61			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride	0-5 cm	21.3 a
	5-10 cm	26.3 a
	10-20 cm	26.3 a
	20-35 cm	31.7 a

Table 28. Analysis of variance and least significant difference of phosphogypsum plot SAR change over time (P=0.05).

Phosphogypsum SAR (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	12.213			
Treatments	1	57.042	57.042	30.23	.0315
Error	2	3.7733	1.8867		
Total	5	73.028			

LSD Analysis		
Factor	Identity	Mean
Phosphosgypsum (0-5cm)	1986	30.7 a
	1987	24.5 b

Phosphogypsum SAR (5-10 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	62.043			
Treatments	1	8.4017	8.4017	3.98	.1842
Error	2	4.2233	2.1117		
Total	5	74.668			

LSD Analysis		
Factor	Identity	Mean
Phosphosgypsum (5-10cm)	1986	31.6 a
	1987	29.3 a

Phosphogypsum SAR (10-20 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.36334			
Treatments	1	.16669E-02	.16669E-02	.00	.9864
Error	2	9.0433	4.5217		
Total	5	9.4083			

LSD Analysis		
Factor	Identity	Mean
Phosphosgypsum (10-20cm)	1986	28.4 a
	1987	28.4 a

Table 28. Continued.

Phosphogypsum SAR (20-35 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	12.333			
Treatments	1	3.3750	3.3750	.05	.8456
Error	2	138.28	69.140		
Total	5	153.99			
		LSD Analysis			
Factor		Identity			Mean
Phosphosgypsum (20-35cm)		1986			29.3 a
		1987			27.8 a

Table 29. Analysis of variance and least significant difference of magnesium chloride plot SAR change over time (P=0.05).

Magnesium chloride SAR (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	1.9300			
Treatments	1	1.1267	1.1267	.04	.8540
Error	2	51.743	25.872		
Total	5	54.800			
		LSD Analysis			
Factor		Identity			Mean
Magnesium chloride		1986			20.4 a
(0-5 cm)		1987			21.3 a

Magnesium chloride SAR (5-10 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	80.123			
Treatments	1	49.882	49.882	1.50	.3452
Error	2	66.443	33.222		
Total	5	196.45			
		LSD Analysis			
Factor		Identity			Mean
Magnesium chloride		1986			32.0 a
(5-10 cm)		1987			26.3 a

Table 29. Continued

Magnesium chloride SAR (10-20 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	65.470			
Treatments	1	83.627	83.627	13.10	.0686
Error	2	12.763	6.3816		
Total	5	161.86			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride (10-20 cm)	1986	33.8 a
	1987	26.3 a

Magnesium chloride SAR (20-35 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	86.290			
Treatments	1	18.027	18.027	.08	.8047
Error	2	454.64	227.32		
Total	5	558.96			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride (20-35 cm)	1986	35.2 a
	1987	31.7 a

Table 30. Analysis of variance and least significant difference of fall, 1986 EC data by depth (P=0.05).

EC (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	24.663			
Treatments	1	51.042	51.042	2.97	.2269
Error	2	34.363	17.182		
Total	5	110.07			

LSD Analysis		
Factor	Identity	Mean
EC 0-5 cm	Phosphogypsum	11.1 a
	Magnesium chloride	17.0 a

Table 30. Continued

EC (5-10 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	12.813			
Treatments	1	100.86	100.86	37.92	.0254
Error	2	5.3200	2.6600		
Total	5	118.99			

LSD Analysis

Factor	Identity	Mean
EC 5-10 cm	Phosphogypsum	10.9 a
	Magnesium chloride	19.1 a

EC (10-20 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	3.0900			
Treatments	1	12.327	12.327	3.83	.1896
Error	2	6.4433	3.2217		
Total	5	21.860			

LSD Analysis

Factor	Identity	Mean
EC 10-20 cm	Phosphogypsum	9.5 a
	Magnesium chloride	12.4 a

EC (20-35 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	2.8900			
Treatments	1	2.4067	2.4067	.44	.5767
Error	2	11.023	5.5117		
Total	5	16.320			

LSD Analysis

Factor	Identity	Mean
EC 20-35 cm	Phosphogypsum	8.9 a
	Magnesium chloride	7.6 a

Table 31. Analysis of variance and least significant difference of fall, 1986 EC data by treatment (P=0.05).

Phosphogypsum EC

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.11667E-01			
Treatments	3	10.563	3.5208	1.24	.3739
Error	6	16.975	2.8292		
Total	11	27.549			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum EC	0-5 cm	11.1 a
	5-10 cm	10.9 a
	10-20 cm	9.5 a
	20-35 cm	8.9 a

Magnesium chloride EC

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	9.9217			
Treatments	3	236.01	78.670	6.39	.0274
Error	6	73.918	12.320		
Total	11	319.85			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride EC	0-5 cm	17.0 a
	5-10 cm	19.1 a
	10-20 cm	12.4 ab
	20-35 cm	7.6 b

Table 32. Analysis of variance and least significant difference of summer, 1987 EC data by depth (P=0.05).

EC (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	47.250			
Treatments	1	50.460	50.460	5.34	.1471
Error	2	18.910	9.4550		
Total	5	116.62			

LSD Analysis		
Factor	Identity	Mean
EC 0-5 cm	Phosphogypsum	10.1 a
	Magnesium chloride	15.9 a

Table 32. Continued

EC (5-10 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	6.2033			
Treatments	1	9.1267	9.1267	1.94	.2982
Error	2	9.4033	4.7017		
Total	5	24.733			

LSD Analysis

Factor	Identity	Mean
EC 5-10 cm	Phosphogypsum	11.6 a
	Magnesium chloride	14.0 a

EC (10-20 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	11.853			
Treatments	1	1.9267	1.9267	2.17	.2784
Error	2	1.7733	.88667		
Total	5	15.553			

LSD Analysis

Factor	Identity	Mean
EC 10-20 cm	Phosphogypsum	11.6 a
	Magnesium chloride	12.8 a

EC (20-35 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	1.7633			
Treatments	1	12.327	12.327	3.51	.2019
Error	2	7.0233	3.5117		
Total	5	21.113			

LSD Analysis

Factor	Identity	Mean
EC 20-35 cm	Phosphogypsum	10.0 a
	Magnesium chloride	12.9 a

Table 33. Analysis of variance and least significant difference of summer, 1987 EC by treatment (P=0.05).

Phosphogypsum EC

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.66166			
Treatments	3	7.5292	2.5097	1.63	.2782
Error	6	9.2183	1.5364		
Total	11	17.409			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum EC	0-5 cm	10.0 a
	5-10 cm	11.6 a
	10-20 cm	11.6 a
	20-35 cm	10.0 a

Magnesium chloride EC

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	25.402			
Treatments	3	18.316	6.1053	.53	.6795
Error	6	68.952	11.492		
Total	11	112.67			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride EC	0-5 cm	15.8 a
	5-10 cm	14.0 a
	10-20 cm	12.8 a
	20-35 cm	12.9 a

Table 34. Analysis of variance and least significant difference of phosphogypsum plot EC change over time (P=0.05).

Phosphogypsum EC (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	1.4033			
Treatments	1	1.8150	1.8150	1.33	.3681
Error	2	2.7300	1.3650		
Total	5	5.9483			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum (0-5cm)	1986	11.1 a
	1987	10.0 a

Table 34. Continued

Phosphogypsum EC (5-10 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	3.8033			
Treatments	1	.60167	.60167	8.40	.1013
Error	2	.14333	.71665E-01		
Total	5	4.5483			

LSD Analysis

Factor	Identity	Mean
Phosphogypsum (5-10 cm)	1986	10.9 a
	1987	11.6 a

Phosphogypsum EC (10-20 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.23333E-01			
Treatments	1	6.6150	6.6150	2.86	.2330
Error	2	4.6300	2.3150		
Total	5	11.268			

LSD Analysis

Factor	Identity	Mean
Phosphogypsum (10-20 cm)	1986	9.5 a
	1987	11.6 a

Phosphogypsum EC (20-35 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	12.040			
Treatments	1	1.7067	1.7067	1.29	.3744
Error	2	2.6533	1.3267		
Total	5	16.400			

LSD Analysis

Factor	Identity	Mean
Phosphogypsum (20-35 cm)	1986	8.9 a
	1987	10.0 a

Table 35. Analysis of variance and least significant difference of magnesium chloride plot EC change over time (P=0.05).

Magnesium chloride EC (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	111.44			
Treatments	1	1.9267	1.9267	.40	.5923
Error	2	9.6634	4.8317		
Total	5	123.03			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride (0-5 cm)	1986	17.0 a
	1987	15.8 a

Magnesium chloride EC (5-10 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.08333			
Treatments	1	39.015	39.015	2.63	.2465
Error	2	29.710	14.855		
Total	5	68.808			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride (5-10 cm)	1986	19.1 a
	1987	14.0 a

Magnesium chloride EC (10-20 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	9.8533			
Treatments	1	.16667	.16667	.04	.8653
Error	2	9.0133	4.5067		
Total	5	19.033			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride (10-20 cm)	1986	12.4 a
	1987	12.8 a

Table 35. Continued

Magnesium chloride EC (20-35 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	3.1633			
Treatments	1	41.082	41.082	15.21	.0599
Error	2	5.4033	2.7017		
Total	5	49.648			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride (20-35 cm)	1986	7.6 a
	1987	12.9 a

Table 36. Analysis of variance and least significant difference of phosphogypsum plot pH change over time (P=0.05)

Phosphogypsum pH (0-5 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.21333			
Treatments	1	.00166	.00166	.01	.9496
Error	2	.65333	.32667		
Total	5	.86833			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum (0-5 cm)	1986	7.4 a
	1987	7.5 a

Phosphogypsum pH (5-10 cm)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.66333			
Treatments	1	.28167	.28167	3.45	.2044
Error	2	.16333	.08166		
Total	5	1.1083			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum (5-10 cm)	1986	6.8 a
	1987	7.3 a

Table 36. Continued

Phosphogypsum pH (10-20 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.26333			
Treatments	1	1.2150	1.2150	81.00	.0121
Error	2	.03000	.01500		
Total	5	1.5083			

LSD Analysis

Factor	Identity	Mean
Phosphogypsum (10-20 cm)	1986	6.6 a
	1987	7.5 b

Phosphogypsum pH (20-35 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.79000			
Treatments	1	.08166	.08166	1.00	.4226
Error	2	.16333	.08166		
Total	5	1.0350			

LSD Analysis

Factor	Identity	Mean
Phosphogypsum (20-35cm)	1986	7.1 a
	1987	7.3 a

Table 37. Analysis of variance and least significant difference of magnesium chloride plot pH change over time (P=0.05).

Magnesium chloride pH (0-5 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.19000			
Treatments	1	.02666	.02666	.84	.4557
Error	2	.06333	.03166		
Total	5	.28000			

LSD Analysis

Factor	Identity	Mean
Magnesium chloride (0-5 cm)	1986	7.1 a
	1987	7.0 a

Table 37. Continued.

Magnesium chloride pH (5-10 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.30333			
Treatments	1	.00166	.00166	.02	.8928
Error	2	.14333	.07166		
Total	5	.44833			

LSD Analysis

Factor	Identity	Mean
Magnesium chloride (5-10 cm)	1986	6.8 a
	1987	6.9 a

Magnesium chloride pH (10-20 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.04333			
Treatments	1	.00166	.00166	.01	.9284
Error	2	.32333	.16167		
Total	5	.36833			

LSD Analysis

Factor	Identity	Mean
Magnesium chloride (10-20 cm)	1986	7.1 a
	1987	7.0 a

Magnesium chloride pH (20-35 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.37333			
Treatments	1	.06000	.06000	.75	.4778
Error	2	.16000	.08000		
Total	5	.59333			

LSD Analysis

Factor	Identity	Mean
Magnesium chloride (20-35 cm)	1986	7.1 a
	1987	6.9 a

Table 38. Analysis of variance and least significant difference of summer, 1987 saturation percentage data by depth (P=0.05)

Saturation Percentage (0-5 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	399.00			
Treatments	1	704.17	704.17	33.27	.0288
Error	2	42.333	21.167		
Total	5	1145.5			

LSD Analysis

Factor	Identity	Mean
Saturation percentage (0-5 cm)	Phosphogypsum	95.3 a
	Magnesium chloride	73.6 b

Saturation Percentage (5-10 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	149.33			
Treatments	1	1176.0	1176.0	28.00	.0339
Error	2	84.000	42.000		
Total	5	1409.3			

LSD Analysis

Factor	Identity	Mean
Saturation percentage (5-10 cm)	Phosphogypsum	108.7 a
	Magnesium chloride	80.6 b

Saturation Percentage (10-20 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	382.33			
Treatments	1	1536.0	1536.0	6.39	.1273
Error	2	481.00	240.50		
Total	5	2399.3			

LSD Analysis

Factor	Identity	Mean
Saturation percentage (10-20 cm)	Phosphogypsum	122.3 a
	Magnesium chloride	90.3 a

Table 38. Continued.

Saturation Percentage (20-35 cm)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	1482.3			
Treatments	1	1040.2	1040.2	7.17	.1158
Error	2	290.33	145.17		
Total	5	2812.8			

LSD Analysis

Factor	Identity	Mean
Saturation percentage (20-35 cm)	Phosphogypsum	121.3 a
	Magnesium chloride	95.0 a

Table 39. Analysis of variance and least significant difference of summer, 1987 saturation percentage data by treatment (P=0.05).

Phosphogypsum saturation percentage

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	320.67			
Treatments	3	1448.2	482.75	2.91	.1232
Error	6	996.00	166.00		
Total	11	2764.9			

LSD Analysis

Factor	Identity	Mean
Phosphogypsum SP	0-5 cm	95.3 a
	5-10 cm	108.7 ab
	10-20 cm	122.3 b
	20-35 cm	121.3 b

$MgCl_2$ saturation percentage

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	1.1667			
Treatments	3	826.92	275.64	.83	.5254
Error	6	1992.8	332.14		
Total	11	2820.9			

LSD Analysis

Factor	Identity	Mean
Magnesium chloride SP	0-5 cm	73.6 a
	5-10 cm	80.6 a
	10-20 cm	90.3 a
	20-35 cm	95.0 a

Table 40. Analysis of variance and least significant difference of summer, 1987 infiltration rate data by time increment (P=0.05).

Infiltration rate (5 minutes)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Treatments	2	18.936	9.4678	5.19	.0491
Residual	6	10.940	1.8233		

LSD Analysis		
Factor	Identity	Mean
IR (5 minutes)	Unamended spoil	8.4 a
	Phosphogypsum plots	11.8 b
	Magnesium chloride plots	11.1 ab

Infiltration rate (10 minutes)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Treatments	2	72.807	36.403	3.99	.0789
Residual	6	54.753	9.1256		

LSD Analysis		
Factor	Identity	Mean
IR (10 minutes)	Unamended spoil	3.2 a
	Phosphogypsum plots	10.2 b
	Magnesium chloride plots	6.7 ab

Infiltration rate (15 minutes)

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Treatments	2	39.242	19.621	3.11	.1182
Residual	6	37.860	6.3100		

LSD Analysis		
Factor	Identity	Mean
IR (15 minutes)	Unamended spoil	1.3 a
	Phosphogypsum plots	6.3 a
	Magnesium chloride plots	4.7 a

Table 40. Continued.

Infiltration rate (20 minutes)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Treatments	2	34.496	17.248	5.94	.0378
Residual	6	17.413	2.9022		

LSD Analysis

Factor	Identity	Mean
IR (20 minutes)	Unamended spoil	0.5 a
	Phosphogypsum plots	4.9 b
	Magnesium chloride plots	4.4 b

Infiltration rate (25 minutes)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Treatments	2	24.749	12.374	6.35	.0332
Residual	6	11.700	1.9500		

LSD Analysis

Factor	Identity	Mean
IR (25 minutes)	Unamended spoil	0.3 a
	Phosphogypsum plots	3.4 b
	Magnesium chloride plots	4.0 b

Infiltration rate (30 minutes)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Treatments	2	21.556	10.778	3.88	.0827
Residual	6	16.667	2.7778		

LSD Analysis

Factor	Identity	Mean
IR (30 minutes)	Unamended spoil	0.1 a
	Phosphogypsum plots	2.8 ab
	Magnesium chloride plots	3.8 b

Table 41. Analysis of variance and least significant difference of summer, 1987 infiltration rate data by treatment (P=0.05).

Unamended spoil IR

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	15.858			
Treatments	5	155.34	31.067	17.96	.0000
Error	10	17.302	1.7302		
Total	17	54.800			

LSD Analysis		
Factor	Identity	Mean
Unamended spoil IR	5 minutes	8.4 a
	10 minutes	3.2 b
	15 minutes	1.3 bc
	20 minutes	0.5 c
	25 minutes	0.3 c
	30 minutes	0.1 c

Phosphogypsum plot IR

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	24.214			
Treatments	5	202.70	40.540	42.29	.0000
Error	10	9.5855	.95855		
Total	17	236.50			

LSD Analysis		
Factor	Identity	Mean
Phosphogypsum plot IR	5 minutes	11.8 a
	10 minutes	10.2 a
	15 minutes	6.3 b
	20 minutes	4.9 bc
	25 minutes	3.4 cd
	30 minutes	2.8 d

Table 41. Continued.

Magnesium chloride IR

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	66.004			
Treatments	5	118.30	23.660	14.45	.0005
Error	10	16.369	1.6369		
Total	17	200.67			

LSD Analysis		
Factor	Identity	Mean
Magnesium chloride plot IR	5 minutes	11.1 a
	10 minutes	6.7 b
	15 minutes	4.7 bc
	20 minutes	4.4 c
	25 minutes	4.0 c
	30 minutes	3.8 c

Table 42. Analysis of variance and least significant difference of seedling density by chemical amendment and fertilizer treatment (P=0.05).

Total seedling density

ANOVA					
Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	62440	31220		
Treatments	1	80.222	80.222	.00	.9696
Whole plot Error	2	86865	43432		
Fert	2	24719	12359	1.17	.3586
Trt*Fert	2	2768.8	1384.4	.13	.8783
Residual	8	84329	10541		

LSD Analysis		
Factor	Identity	Mean
Total seedling density	Phosphogypsum	143.2 a
	Magnesium chloride	139.0 a
Total seedling density	N Fertilizer (0)	104.3 a
	N Fertilizer (67 kg/ha)	191.8 b
	N Fertilizer (134 kg/ha)	127.2 a

Table 42. Continued.

Seedling density (seeded grasses)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	3100.1	1550.1		
Treatments	1	9430.2	9430.2	2.17	.2787
Whole plot Error	2	8694.1	4347.1		
Fert	2	6864.8	3432.4	1.26	.3344
Trt*Fert	2	1960.8	980.39	.36	.7115
Residual	8	21753	2719.1		

LSD Analysis

Factor	Identity	Mean
Seeded grass density	Phosphogypsum	47.3 a
	Magnesium chloride	93.1 b
Seeded grass density	N Fertilizer (0)	51.5 a
	N Fertilizer (67 kg/ha)	97.1 b
	N Fertilizer (134 kg/ha)	62.0 a

Seedling density (annual grasses)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	34568	17284		
Treatments	1	20268	20268	1.45	.3514
Whole plot Error	2	27910	13955		
Fert	2	5357.4	2678.7	.87	.4561
Trt*Fert	2	4530.8	2265.4	.74	.5103
Residual	8	24493	3061.6		

LSD Analysis

Factor	Identity	Mean
Annual grass density	Phosphogypsum	75.3 a
	Magnesium chloride	8.2 b
Annual grass density	N Fertilizer (0)	21.5 a
	N Fertilizer (67 kg/ha)	63.6 a
	N Fertilizer (134 kg/ha)	40.1 a

Table 42. Continued

Seedling density (seeded forbs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	970.78	485.39		
Treatments	1	1386.9	1386.9	2.99	.2258
Whole plot Error	2	926.78	463.39		
Fert	2	103.44	51.722	.12	.8868
Trt*Fert	2	155.44	77.722	.18	.8371
Residual	8	3411.8	426.47		

LSD Analysis

Factor	Identity	Mean
Seeded forb density	Phosphogypsum	19.0 a
	Magnesium chloride	36.5 b
Seeded forb density	N Fertilizer (0)	30.1 a
	N Fertilizer (67 kg/ha)	28.6 a
	N Fertilizer (134 kg/ha)	24.5 a

Seedling density (seeded shrubs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.43521E-13	.21760E-13		
Treatments	1	10.889	10.889	1.58	.3356
Whole plot Error	2	13.778	6.8889		
Fert	2	13.000	6.5000	1.34	.3158
Trt*Fert	2	13.444	6.7222	1.38	.3051
Residual	8	38.889	4.8611		

LSD Analysis

Factor	Identity	Mean
Seeded shrub density	Phosphogypsum	1.5 a
	Magnesium chloride	3.1 b
Seeded shrub density	N Fertilizer (0)	1.1 a
	N Fertilizer (67 kg/ha)	3.1 b
	N Fertilizer (134 kg/ha)	2.6 b

Table 43. Analysis of variance and least significant difference of transformed (Log10) plant canopy cover data by plant class (P=0.05).

Canopy cover (seeded grasses)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	4.9738	2.4869	10.61	.0000
Treatments	1	.14532E-02	.14532E-02	.01	.9374
Block*Trt	2	.94658	.47329	2.02	.1371
Residual	84	19.688	.23438		

LSD Analysis

Factor	Identity	Mean
Seeded grasses	Phosphogypsum	.5988 a
	Magnesium chloride	.6068 a

Canopy cover (annual grasses)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	3.1162	1.5581	10.97	.0000
Treatments	1	.65198E-03	.65198E-03	.00	.9461
Block*Trt	2	2.5859	1.2930	9.11	.0000
Residual	84	11.927	.14199		

LSD Analysis

Factor	Identity	Mean
Annual grasses	Phosphogypsum	.2657 a
	Magnesium chloride	.2603 a

Canopy cover (seeded forbs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	1.1116	.55582	5.16	.0079
Treatments	1	.49398E-01	.49398E-01	.46	.5003
Block*Trt	2	1.2240	.61201	5.68	.0052
Residual	84	9.0559	.10781		

LSD Analysis

Factor	Identity	Mean
Seeded forbs	Phosphogypsum	.1373 a
	Magnesium chloride	.1841 a

Table 43. Continued

Canopy cover (non-seeded forbs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	2.9911	1.4955	7.81	.0011
Treatments	1	1.8513	1.8513	9.67	.0026
Block*Trt	2	.90931	.45465	2.37	.0973
Residual	84				

LSD Analysis

Factor	Identity	Mean
Non-seeded forbs	Phosphogypsum	.9970 a
	Magnesium chloride	1.2840 b

Canopy cover (seeded shrubs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	1.3442	.67210	5.47	.0061
Treatments	1	.90533E-01	.90533E-01	.74	.3929
Block*Trt	2	.35910	.17955	1.46	.2361
Residual	84	10.313	.12277		

LSD Analysis

Factor	Identity	Mean
Seeded shrubs	Phosphogypsum	.2112 a
	Magnesium chloride	.1478 a

Total canopy cover

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	7.1558	3.5779	18.54	.0000
Treatments	1	.77385	.77385	4.01	.0485
Block*Trt	2	.24672	.12336	.64	.5350
Residual	84	16.212	.19300		

LSD Analysis

Factor	Identity	Mean
Total cover	Phosphogypsum	1.267 a
	Magnesium chloride	1.452 b

Table 44. Analysis of variance and least significant difference of transformed (Log10) plant production data by plant class (P=0.05).

Production (seeded grasses)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	4.1735	2.0868	15.28	.0000
Treatments	1	.15528	.15528	1.14	.2948
Block*Trt	2	.21067E-01	.10533E-01	.08	.9255
Residual	30	4.0968	.13656		

LSD Analysis

Factor	Identity	Mean
Seeded grasses	Phosphogypsum	.6972 a
	Magnesium chloride	.5658 a

Production (annual grasses)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	2.2265	1.1133	6.33	.0053
Treatments	1	.89122	.89122	5.07	.0318
Block*Trt	2	.95020	.47510	2.70	.0817
Residual	30	5.2741	.17580		

LSD Analysis

Factor	Identity	Mean
Annual grasses	Phosphogypsum	.5267 a
	Magnesium chloride	.2120 b

Production (seeded forbs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.40967E-01	.20484E-01	.40	.6776
Treatments	1	.12827	.12827	2.52	.1229
Block*Trt	2	.27422E-01	.13711E-01	.27	.7691
Residual	30	1.5274	.50912E-01		

LSD Analysis

Factor	Identity	Mean
Seeded forbs	Phosphogypsum	.1759 a
	Magnesium chloride	.0564 a

Table 44. Continued

Production (non-seeded forbs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	3.5817	1.7908	7.07	.0035
Treatments	1	1.2500	1.2500	4.94	.0340
Block*Trt	2	1.0310	.51548	2.04	.1465
Residual	30	7.5945	.25315		

LSD Analysis

Factor	Identity	Mean
Non-seeded forbs	Phosphogypsum	1.157 a
	Magnesium chloride	1.530 b

Production (seeded shrubs)

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.31264	.15632	.93	.4071
Treatments	1	.19982	.19982	1.19	.2836
Block*Trt	2	.11778	.58888E-01	.35	.7114
Residual	30	5.0292	.16764		

LSD Analysis

Factor	Identity	Mean
Seeded shrubs	Phosphogypsum	.2066 a
	Magnesium chloride	.3556 a

Total production

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	4.5094	2.2547	11.95	.0000
Treatments	1	.16973	.16973	.90	.3504
Block*Trt	2	.27897	.13948	.74	.4899
Residual	30	5.6583	.18861		

LSD Analysis

Factor	Identity	Mean
Total production	Phosphogypsum	1.482 a
	Magnesium chloride	1.619 a

Table 45. Analysis of variance and least significant difference of root biomass production data (P=0.05).

Root biomass production

ANOVA

Source	D.F.	S.S.	M.S.	F-value	P-value
Blocks	2	.68600E-01	.34300E-01	29.83	.0013
Treatments	1	.75000E-01	.75000E-01	6.52	.0433
Block*Trt	2	.21800E-01	.10900E-01	9.48	.0144
Residual	6	.69000E-02	.11500E-02		

LSD Analysis

Factor	Identity	Mean
Root biomass	Phosphogypsum	.0950 a
	Magnesium chloride	.1450 b

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