PRODUCT DEVELOPMENT AND UTILIZATION OF ZIMMER STATION WET FGD BY-PRODUCTS

FINAL REPORT

VOLUME 5: A LABORATORY AND GREENHOUSE STUDY CONDUCTED IN FULFILLMENT OF PHASE 2, OBJECTIVE 2 TITLED:
Use of FGD By-Product Gypsum Enriched with Magnesium Hydroxide as a Soil Amendment

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ABSTRACT

The Clean Air Act, as revised in 1992, has spurred the development of flue gas desulfurization (FGD) technologies that have resulted in large volumes of wet scrubber sludges. In general, these sludges must be dewatered, chemically treated, and disposed of in landfills. Disposal is an expensive and environmentally questionable process for which suitable alternatives must be found.

Wet scrubbing with magnesium (Mg)-enhanced lime has emerged as an efficient, cost-effective technology for SO_2 removal. When combined with an appropriate oxidation system, the wet scrubber sludge can be used to produce gypsum ($CaSO_4 \cdot 2H_2O$) and magnesium hydroxide [$Mg(OH)_2$] of sufficient purity for beneficial re-use. Product value generally increases with purity of the by-product(s).

The pilot plant at the CINERGY Zimmer Station near Cincinnati produces gypsum by-products that can be formulated to contain varying amounts of $Mg(OH)_2$. Such materials may have agricultural value as soil conditioners, liming agents and sources of plant nutrients (Ca, Mg, S). This report describes a greenhouse study designed to evaluate by-product gypsum and Mg-gypsum from the Zimmer Station pilot plant as amendments for improving the quality of agricultural soils and mine spoils that are currently unproductive because of phytotoxic conditions related to acidity and high levels of toxic dissolved aluminum (Al). In particular, the technical literature contains evidence to suggest that gypsum may be more effective than agricultural limestone in modifying soil chemical conditions below the immediate zone of application.

Representative samples of by-product gypsum and $Mg(OH)_2$ from the Zimmer Station were initially characterized. The gypsum was of high chemical purity and consisted of well-crystalline, lath-shaped particles of low specific surface area. By contrast, the by-product $Mg(OH)_2$ was a high surface area material ($50\ m^2\ g^{-1}$) that contained 20% $CaSO_4$ with variable hydration state. Artificial blends of these materials containing 4% and 8% $Mg(OH)_2$ were prepared for comparison with other liming agents in the form of agricultural limestone and gypsum amended with laboratory $Ca(OH)_2$.

Samples from a native agricultural soil (AS), abandoned mine spoil (AML) and a reclaimed mine soil (RML) were used to construct greenhouse columns. All samples had pHs in the range of 3.0 to 5.0 with high exchangeable Al contents. Both topsoil and subsoil/spoil were used to simulate profiles found in the field, and amendments were applied only to the surface layers.

Gypsum alone had no effect on pH of the amended surface layers; however, gypsum with alkalinity in the form of $Mg(OH)_2$ or $Ca(OH)_2$ produced similar, rapid pH increases. Although the pH response decreased with time, final soil/spoil reactions were comparable to those achieved using agricultural limestone. Only the 8% Mg-gypsum produced a significant improvement in the pH of the subsurface layers. All amendments, including pure gypsum, caused a marked reduction in toxic Al in the surface layers. The gypsum-based materials also decreased subsurface exhangeable Al and Fe. By comparison, agricultural limestone had no measurable effect on subsurface chemistry in the AS columns and was less efficient than gypsum-based materials in all

other cases. Major increases in subsurface concentrations of exchangeable Ca and Mg with the gypsum by-products suggest that toxic Al is displaced from the soil/spoil column through cation exchange and complexation reactions. These results further suggest that surface applications of Mg-gypsum by-products could improve the chances for successful mine land reclamation by decreasing subsurface Al concentrations and thereby increasing root proliferation within the normally toxic subsurface zone.

All columns were saturated and leached a total of 5 times during the course of the greenhouse study (165 days). Soil leachate conductivity (total dissolved salt load) and concentrations of Ca, Mg, S and Al increased over time. By comparison, leachate conductivities and concentrations of dissolved elements peaked with the AML and RML columns and then declined with time. This difference in behavior was probably a reflection of more coarse fragments and higher macroporosity in the spoil materials.

All alkaline amendments produced an environment adequate for plant growth. Some early yield reductions were observed at the highest rates of gypsum-based materials due to excessive salts and high pH, but these reductions disappeared over time. No plant response to improvements in subsurface soil/spoil chemistry were observed in these experiments. The columns were always adequately watered and fertilized, and the test crops were able to meet nutritional requirements by exploiting only the amended surface layers.

ACKNOWLEDGMENTS

This research was conducted as one component of a research project entitled "Product Development and Utilization of Zimmer Station Wet FGD By-Products." This project was a cooperative effort involving the Ohio Agricultural Research and Development Center, The Ohio State University, Dravo Lime Company, and the CINERGY Company. Financial support was received from the Ohio Coal Development Office, Columbus, OH as Grant No. CDO/D-931-008.

The investigators are indebted to Mr. Joel Beeghly, Dravo project leader, for his guidance, enthusiasm, and repeated efforts to secure appropriate by-product materials for testing. The efforts of Mr. Dan Horn, CINERGY, were also instrumental in securing by-product materials from the Zimmer Station. We are also indebted to Mr. Robert Meyer for permitting us to collect bulk soil samples from his property near Geneva, OH. Finally, Professor Emeritus Paul Sutton provided many valuable suggestions in the early stages of this research.

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1 INTRODUCTION

1.1 Background and Project Description

The Clean Air Act of 1990 mandated a ten million ton reduction in annual sulfur dioxide (SO_2) emissions from 261 coal-fired electric generating units in the United States. Forty-one of these units are located in Ohio and must account for 18% of the total reduction. Electric utilities consume 92% of Ohio's coal production, and continued combustion of Ohio's high sulfur coal requires the use of scrubbers to meet the Clean Air Act emission standards for existing and new coal-fired units. Wet scrubbing with magnesium (Mg) enhanced lime is the leading post-combustion technology for high SO_2 removal efficiency with high cost-effectiveness. One of the primary expenses associated with wet flue gas desulfurization (FGD) is disposal of the solids generated by the scrubbing process. Disposal costs may be partially offset by converting a portion of the solids generated into products suitable for re-use. Such products include magnesium hydroxide [$Mg(OH)_2$], gypsum ($CaSO_4 \cdot 2H_2O$), and gypsum containing some residual magnesium hydroxide (Mg-gypsum). Sufficiently pure $Mg(OH)_2$ may be sold to the chemical industry or re-utilized in the power plant acid treatment system. An established commercial market for gypsum is in wallboard production. The focus of this project is on the development of beneficial land application uses for the gypsum and, especially, the Mg-gypsum produced by the Zimmer plant near Cincinnati, OH..

Gypsum is one of the earliest forms of fertilizer used in the USA, having first been applied to agricultural soils over 250 years ago (Tisdale et al., 1985). Gypsum is more effective than agricultural limestone ($CaCO_3$) in modifying soil chemical conditions below the zone of application because the solubility of $CaSO_4$ is much greater than that of $CaCO_3$, which allows calcium (Ca) to leach downward more rapidly (Shainberg et al., 1989). Several studies have shown that surface applications of gypsum may improve the Ca status of acidic subsoils (Hammel et al., 1985; Pavan et al., 1982, 1984; Sumner et al., 1986; Farina and Channon, 1988). Although extensively used as a source of both sulfur (S) and Ca for plant nutrition, more recently gypsum has been effectively employed to ameliorate phytotoxic conditions arising from excess soluble aluminum (Al) in acid soils. Such an effect was first shown by Sumner (1970) and Reeve and Sumner (1972) who found that surface applications of gysum not only diminished toxic conditions in the zone of application, but also in the subsoil. Sumner (1970) attributed these effects to the improved Ca status of otherwise Ca deficient soils, decreased soil solution and exchangeable Al concentrations, and improved soil physical properties.

Three mechanisms have been proposed to account for the decreased toxicity of Al following gypsum application, each of which involves the sulfate (SO_4^{2-}) moiety. The first mechanism has been termed "self liming" (Reeve and Sumner, 1972) and refers to the release of hydroxyl ions (OH^-) by ligand exchange with SO_4^{2-}. Aluminum is then either polymerized or precipitated through reaction with OH^-. The second mechanism involves the precipitation of aluminum sulfate minerals due to the increased concentration of SO_4^{2-} in the subsoil (Adams and Rawajfih, 1977). The third mechanism does not actually result in a decrease in solution Al concentrations, but rather a reduction in the phytotoxicity of solution Al species. This decrease in Al toxicity occurs when highly toxic Al species react with SO_4^{2-} to form the $AlSO_4^+$ ion pair which is less phytotoxic (Pavan and Bingham, 1982). All three mechanisms appear to function to varying degrees in different soils, being most effective in soils whose cation exchange capacity is due predominantly to variable charge (ie, pH dependent) surfaces (Alva and Sumner, 1990; Alva et al., 1990). The variable charge surfaces which appear to be most important in determining the efficacy of gypsum application are those of kaolinitic clays and oxides and hydrous oxides of Fe and Al. Many of the acidic soils in eastern and southeastern Ohio are dominated by such minerals, which suggests that gypsum may well be effective in ameliorating Al toxicity in these soils.

In many acidic soils, plant uptake of Mg is impaired by high levels of exchangeable Al (exchangeable Al saturation > 65 to 70% of soil cation exchange capacity) (Tisdale et al., 1985; Godbold, 1991). In addition to adverse effects on plant growth, decreased Mg content of forages may lead to nutritional disorders such as grass tetany in foraging cattle.

The use of conventional agricultural limestone on some acid soils has also been shown to decrease exchangeable Mg concentrations, increase the exchangeable Ca:Mg ratio, and decrease plant uptake of Mg (Carran, 1991; Myers et al., 1988; Sumner et al., 1978; McClean and Carbonell, 1972). Similar effects on soil Mg and plant uptake of Mg have been observed with applications of pure gypsum (Webster, 1990). There is, however, evidence that supplemental Mg may help to ameliorate Al phytotoxicity and the negative effects of limestone and gypsum application. Several studies have shown that increasing Mg nutrition is more effective than increasing Ca nutrition in alleviating Al toxicity in some crop species (Keltjens and Dijkstra, 1991; Edmeades et al., 1991; Godbold, 1991).

The negative effects of liming and gypsum application on plant growth appear to be the result of Ca:Mg imbalance. For most crops, the exchangeable Ca:Mg ratio should ideally not exceed 7:1 (Tisdale et al., 1985). Carran (1991) reported Mg deficiencies in clover when the Ca:Mg ratio exceeded 20:1. The Ca:Mg imbalance resulting from limestone or gypsum application can be overcome by applying supplemental Mg. This is most frequently accomplished by the addition of dolomite. A unique aspect of the Zimmer plant FGD by-product is that it can be formulated to contain varying amounts of $Mg(OH)_2$ which may enhance its value as an amendment for acidic soils or mine spoils. The Mg contained in the by-product Mg-gypsum may have the same beneficial effects as conventional dolomite for ameliorating Al toxicity and preventing a Ca:Mg imbalance from developing in the soil.

1.2 Phase 2 Objectives

The Phase 2 objectives were to:

1. Characterize the chemical and mineralogical properties of representative gypsum and magnesium hydroxide products produced at the Zimmer station, and
2. Determine by means of greenhouse studies if the by-product gypsum and Mg-gypsum can be beneficially utilized as amendments for acidic agricultural soils and mine spoils.

1.3 Approach

Three field situations in Ohio are likely to benefit from surface amendments with gypsum or Mg-gypsum. These include:

1. abandoned, acidic mine spoils,
2. reclaimed acidic mine spoils with failing surface vegetation, and
3. naturally acidic agricultural soils with high levels of exchangeable Al.

Sites meeting these conditions were identified and soil/spoil materials were collected from the surface and subsurface layers for use in greenhouse experiments. Each of the soil, spoil, and by-product amendments used in the greenhouse study was chemically and mineralogically characterized in the laboratory.

2 CHARACTERIZATION OF STUDY MATERIALS

2.1 Materials

Greenhouse experiments were conducted to study the effects of surface amendments using $Mg(OH)_2$-enriched by-product gypsum (Mg-G) on plant growth, leachate composition and subsoil chemistry. The effects of Mg-G were compared to those produced using pure by-product gypsum (G), by-product gypsum enriched with laboratory calcium hydroxide [$Ca(OH)_2$] (Ca-G), and ground agricultural limestone (AL). The $Mg(OH)_2$ was produced at the Zimmer Station $Mg(OH)_2$ recovery plant located near Cincinnati, OH. The by-product gypsum was produced at the Miami Fort pilot FGD scrubber plant also located near Cincinnati, OH. Appropriate blends of these materials were prepared as described in Section 3. In some experiments, a yard-waste compost was also used as an amendment. The compost was obtained from a commercial composting facility located near Columbus, OH. Compost feedstock consisted of trees, leaves, branches, brush, and grass clippings. These materials were ground to less than 8 mm using a tub grinder and placed in windrows (2.5 to 3 m tall, 6 m wide at the base, 15 to 60 m long). Water was added to the ground material as it came off the grinder to increase moisture content to 60 wt %. Windrows were turned bi-weekly. Turning frequency and moisture content were adjusted to maintain windrow temperature in the 50 to 60°C range. After 7 months of composting, the material was passed through a 12-mm trommel screen and allowed to cure for one month to produce the finished compost.

Greenhouse columns were constructed using three different spoil/soil systems selected for their natural acidity and high levels of extractable Al. These included a native agricultural soil (AS) located on private property in Ashtabula Co., OH (Robert Meyer Farm, 6004 Cork Cold Springs Road, Geneva, OH), an abandoned mine spoil (AML), and a reclaimed mine soil (RML) constructed by placing local soil material over graded mine spoil. Both the AML and RML materials were obtained from Unit 2 of the Eastern Ohio Agricultural Research and Development Center (EORDC) in Noble Co., OH. All soil/spoil materials were collected in the autumn of 1994. At the Ashtabula site, both surface (0-15 cm) and subsurface (15-45 cm) soil materials were sampled in bulk. Likewise, soil material was separated from underlying spoil at the RML site. At the AML location, spoil material was collected in bulk only from the 0-40 cm depth due to the heterogeneous character of the abandoned spoil. All materials were air-dried, homogenized, and passed through a 10-mm screen before being subsampled for characterization.

2.2 Methods Used in Characterization Studies

2.2.1 By-Product and Amendment Materials

2.2.1.1 Specific Surface Area

Single-point determinations of specific surface area were performed using nitrogen adsorption by the continuous flow method (ASTM D4567; ASTM, 1990) with a Micromeritics Flowsorb II 300 instrument. The instrument was calibrated at the beginning of each operating period. Calibration was acheived by injecting a known volume of analytical grade nitrogen gas (N_2). Two standard reference materials (NIST 8570 and 8571) were analyzed at the beginning and end of every operating period. The quantities of both standards and samples were adjusted to yield surface areas in the range of 0.5 to 25 m^2 as per instrument manufacturer specifications. Sample materials were analyzed in triplicate or until individual analyses were within ± 10% of the mean values following removal of any outlying data points.

2.2.1.2 Thermal Analysis

Thermal studies were conducted using a Seiko SSC5020 instrument that provided simultaneous thermogravimetric (TGA) and differential thermal analysis (DTA). Samples were heated from 50 to 900°C at a rate of 20°C/min under a continuous flow (200 mL/min) of dry N_2 gas. Calibration of the temperature signal was achieved using the melting points of In and Sn. Calibration of the thermal balance was performed using a reference weight provided by the instrument manufacturer. Thermal events observed with heating of sample materials were assigned to phase transitions based on published literature and analyses of standard mineral samples. Mineral quantification was accomplished using the procedures of Fowler et al. (1992).

2.2.1.3 X-ray Diffraction

X-ray diffraction (XRD) patterns were obtained from randomly oriented powder mounts using Cu Kα radiation and a Philips PW 1216/90 wide-range goniometer equipped with a theta-compensating slit and a graphite monochromator. Diffraction patterns were recorded from 5 to 70°2θ with a step interval of 0.05°2θ and a counting time of 4 sec per step. The instrument was calibrated using both low (cholesterol) and high (NIST SRM 640b Si powder) angle diffraction standards. Crystalline phase assignments were based on published literature, searches of the International Center for Diffraction Data (ICDD) data base, and comparative analyses of reference mineral standards.

2.2.1.4 Scanning Electron Microscopy

Powdered specimens were mounted on aluminum sample stubs using double-sided adhesive tape and then coated with a gold film using a sputter coater. Scanning electron micrographs were prepared using a JEOL-JSM-820 instrument operated at 20 kV and 42 mA. Image recording times were about 200 sec.

2.2.1.5 Chemical Analyses

The yard-waste compost was analyzed as received by the Research Extension Analytical Laboratory in Wooster, OH. The compost was analyzed for As, B, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Se, Zn, C, N, NH_4-N, NO_3-N, volatile solids, pH and electrical conductivity (EC).

Chemical analyses of the FGD by-products and agricultural limestone were performed from digests obtained by dissolving 100-mg samples in Teflon decomposition vessels using a mixed, aqua regia-hydrofluoric (HF) acid solution. The vessels were then placed in stainless steel digestion bombs and heated at 110°C for 40 minutes. The digested samples were mixed with excess boric acid (H_3BO_4) and diluted to 100 mL total volume with distilled water. Individual samples were duplicated, and a standard reference material (NIST coal fly ash 2691) was included for quality control purposes.

The digests were analyzed for Al, As, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, P, Pb, Si, Sr, and Zn using inductively coupled plasma emission spectrometry (ICP) with a Leeman PS2000 instrument. Calcium and Mg in the digests were also analyzed by atomic absorption spectrometry using a Varian Techtron AA6 unit.

Total S was determined with a Leco Model 521 Induction Furnace equipped with a semi-automatic titrator. Measurements were performed by placing a small sample (4 - 250 mg) in a crucible containing an accelerator metal added in proportion to the sample size. The sample was heated to 3,000°C where, in the presence of oxygen, sulfur in the sample was converted to SO_2. The SO_2 so produced was bubbled through a blue standardized solution (KIO_3 + KI + HCl + starch) which faded as SO_2 was added. The color of the solution was monitored by a photoelectric cell and was back-titrated to the original blue color. Percent S was based on the amount of titrant used and was read directly from the calibrated buret. Standardization was performed by using a three-point calibration curve prepared from Leco metal rings containing known amounts of S.

2.2.2 Soil and Spoil Materials

2.2.2.1 Particle Size Distribution

Particle size distribution of the < 2-mm fraction was determined using a modification of the pipette method of Kilmer and Alexander (1949). Sample dispersion was accomplished using sodium hexametaphosphate and by shaking overnight on a reciprocating shaker. Twenty, 5, 2 and <0.2 µm fractions were determined by oven-drying aliqouts of suspension taken at times and depths calculated according to Stokes' Law. Sand subfractions were obtained by mechanical sieving using nested sieves.

2.2.2.2 Soil/Spoil Reaction

Soil/spoil reaction (pH) was determined from 1:1 soil:water mixtures and 1:2 soil:0.01 *M* $CaCl_2$ mixtures using a Beckman Expandomatic pH meter with a Ross combination electrode. The soil pastes were equilibrated for 1.5 hour and the pH electrode was calibrated against standard pH buffer solutions before pH measurements were made.

2.2.2.3 Total Carbon

The procedure for total C was adapted from that of Nelson and Sommers (1982). Two g of soil/spoil was mixed with 250 mg of MnO_2 in a ceramic boat and ignited for 10 minutes at 950°C under CO_2-free O_2 in a Lindberg furnace equipped with a Vycor glass combustion tube. The combustion gases were scrubbed by bubbling through an H_2SO_4 tower, ZnO granules, and $Mg(ClO_4)_2$ dessicant. Finally, evolved CO_2 was collected in an ascarite-filled Nesbit absorption bulb. The bulb was weighed before and after combustion of the sample. Bulbs were standardized by igniting and determining the recovery of CO_2 from reagent grade $CaCO_3$.

2.2.2.4 Extractable Acidity

Extractable acidity was determined using the method of Peech et al. (1947). Ten gram samples of soil/spoil were leached for 30 minutes with 50 mL of 0.5 *N* $BaCl_2$ and 0.2 *N* triethanolamine buffered at pH 8.2. The soil/spoil was then leached with 100 mL of 0.5 N $BaCl_2$ replacement solution, and the combined leachates were titrated with 0.15 *M* HCl using a mixed Bromcresol green and methyl red-methylene blue indicator solution.

2.2.2.5 Extractable Calcium, Magnesium, Potassium and Sodium

Extractable bases were determined using the procedure of Holmgren et al. (1977). A 2.5-g soil/spoil sample was placed in a 60-mL syringe and leached with 50 mL of M ammonium acetate (pH 7.0) over a 12 hour period using a mechanical extractor. The undiluted extract was analyzed for K and Na by flame emission spectroscopy, and 20-fold dilutions were analyzed for Ca and Mg by atomic absorption spectroscopy using a Varian Techtron Model AA-6 instrument.

2.2.2.6 KCl-extractable Aluminum

The method for determination of KCl-extractable Al was taken from Lin and Coleman (1960). Five g of air-dried soil/spoil and 30 mL of *M* KCl were added to a 100-mL centrifuge tube. The tube was stoppered and agitated for 30 minutes on a reciprocating shaker. The sample was then centrifuged and the clear supernatant was decanted and analyzed for extractable Al using a Varian Techtron AA-6 atomic absorption unit.

2.2.2.7 Lime Requirement

The amount of agricultural limestone needed to increase soil pH to 7 was determined according to the SMP buffer test (Shoemaker et al., 1962). Five ml of water and 10 ml of SMP buffer were added to 5 g of air-dry soil/spoil. Following shaking and equilibration the pH was determined. The final pH was multiplied by 10 to give the lime test index value. The lime requirement (tons $CaCO_3$ ac^{-1}) was determined from the lime test index table (Ohio State University, 1988).

2.3 Results of Characterization Studies

2.3.1 By-product and Amendment Materials

2.3.1.1 Yard-waste Compost

Reclamation research on acid mine spoils has shown that the use of organic amendments, such as sewage sludge or compost, produces superior revegetation under field conditions (Sutton and Dick, 1987). Therefore, a commercial yard-waste compost was used as an amendment on spoil materials examined in this study. Chemical characteristics of the yard-waste compost are given in Table 1. Levels of both major and minor elements are typical of such materials. The C/N ratio is significant because it will initially have an impact on nitrogen release (Tisdale et al., 1985). Generally, with C/N ratios wider than 30:1, there is immobilization of soil N during the initial decomposition process, whereas a ratio of less than 20:1 will usually result in a release of N. For ratios between 20 and 30, as in the current case, there may be neither immobilization nor release of mineral N. The total N content of the organic material may also have an effect on N release. Concentrations of at least 1.5% are usually adequate to minimize immobilization. The compost used in this study had a total N content of <1% (Table 1).

Table 1. Chemical characteristics of the yard-waste compost.

Element	ug g^{-1}	Element	g kg^{-1}
Boron	40.1	Phosphorus	10.0
Cadmium	0.2	Potassium	6.6
Lead	34.0	Calcium	59.9
Nickel	258.1	Magnesium	10.3
Chromium	202.7	Sodium	0.3
Zinc	93.4	Manganese	0.3
Copper	33.1	Iron	13.8
Mercury	1.0	Total N	7.4
Arsenic	10.5	Total C	173.7
Molybdenum	26.8	Volatile Solids	288.7
Selenium	0.05	pH	7.9
Ammonia-N	61.8	C/N ratio	23:1
Nitrate-N	3.0		
Electrical conductivity 0.168 S m^{-1}			

2.3.1.2 FGD-by products, Agricultural Limestone, and Laboratory Calcium Hydroxide

The by-product gypsum was a high purity material (Table 2) consisting of large, lath-like particles (Fig. 1) with low (7.9 m^2/g) specific surface area. X-ray diffraction data (Fig. 2) showed no crystalline impurities and TGA (Fig. 3) yielded a single dehydration event in the 125 - 220°C region arising from the conversion of gypsum ($CaSO_4 \cdot 2H_2O$) to anhydrite ($CaSO_4$). Chemical analyses (Tables 3 and 4) showed only a minor Mg impurity and also indicated that most trace elements were present in concentrations below instrumental (ICP) detection limits.

The Zimmer $Mg(OH)_2$, by contrast, was only 80% pure (Table 2), and x-ray results (Fig. 4) indicated the primary impurity was bassanite ($CaSO_4 \cdot 0.5H_2O$). Thermal (Fig. 5) and chemical analyses (Tables 3 and 4) suggested the presence of fully hydrated gypsum, but lath-like crystals typical of the by-product gypsum (Fig. 1) were mostly absent. Rather, the material was composed of finely divided particles with diameters < 5μm that yielded a high specific surface area of 49 m^2/g. Such material should be quite reactive and may also be susceptible to hydration-dehydration reactions.

The agricultural limestone and laboratory $Ca(OH)_2$ purchased as comparative, low sulfate liming agents were both high purity materials (Table 2). The limestone was 95% calcite in the form of irregular-shaped particles (Fig. 6) with low specific surface area (<2m^2 g^{-1}). Magnesium and S contents were both < 0.5 wt % (Table 3), and Fe was the major trace impurity (Table 4). X-ray and TGA results indicated the primary mineral contaminant was quartz (SiO_2) (Figs. 7 and 8). The laboratory $Ca(OH)_2$ contained 3% $CaCO_3$ as a consequence of minor re-carbonation with atmospheric CO_2 (Fig. 9 and 10). Otherwise, this material also contained <0.5% Mg and S (Table 3) and was composed of platy aggregates similar in morphology to the Zimmer $Mg(OH)_2$ (Fig. 6).

Table 2. Surface area (S.A.) and mineralogy of FGD by-products, agricultural limestone, and laboratory calcium hydroxide

Material	S.A.	Mineralogy*					
		Calcite	Gypsum	Bassanite	Brucite	Portlandite	Quartz
	m^2 g^{-1}	%					
FGD Gypsum	7.9		96				
FGD $Mg(OH)_2$	49.1			20	80		
Limestone	1.7	95					5
$Ca(OH)_2$	12.5	3				97	

* Calcite = $CaCO_3$; Gypsum = $CaSO_4 \cdot 2H_2O$; Bassanite = $CaSO_4 \cdot 0.5H_2O$; Brucite = $Mg(OH)_2$; Portlandite = $Ca(OH)_2$; Quartz = SiO_2

Table 3. Major element composition of FGD by-products, agricultural limestone, and laboratory calcium hydroxide.

Sample	Ca	Mg	S
	---	% ---	
FGD Gypsum	22.7	0.3	17.8
FGD $Mg(OH)_2$	5.2	32.2	3.9
Limestone	35.6	0.3	0.1
Laboratory $Ca(OH)_2$	53.6	0.2	0.01

Table 4. Minor/trace element composition of FGD by-products, agricultural limestone, and laboratory calcium hydroxide.

Sample	element													
	Al	As	Ba	Cd	Cr	Cu	Fe	K	Mn	Mo	P	Pb	Si	Zn
	mg/kg													
FGD Gypsum	380	<4	<1	<1	<1	<2	292	344	4	<1	<2	<2	2528	18
FGD $Mg(OH)_2$	2390	<4	<1	<1	<1	4	1009	998	31	90	<2	<2	9730	28
Limestone	1708	<4	414	1	6	9	7660	371	556	493	493	<2	12940	27
$Ca(OH)_2$	754	nd	nd	nd	nd	4	433	110	6	nd	68	nd	335	59

Figure 1. Scanning electron micrographs of (top) by-product gypsum and (bottom) by-product magnesium hydroxide.

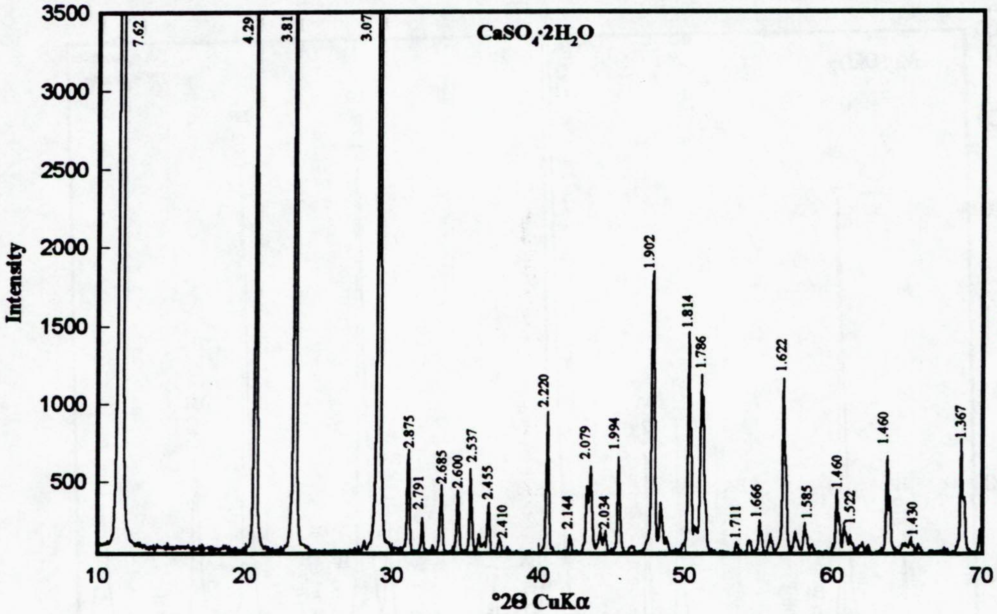

Figure 2. X-ray diffraction pattern of by-product gypsum. Peak positions in Angstrom units.

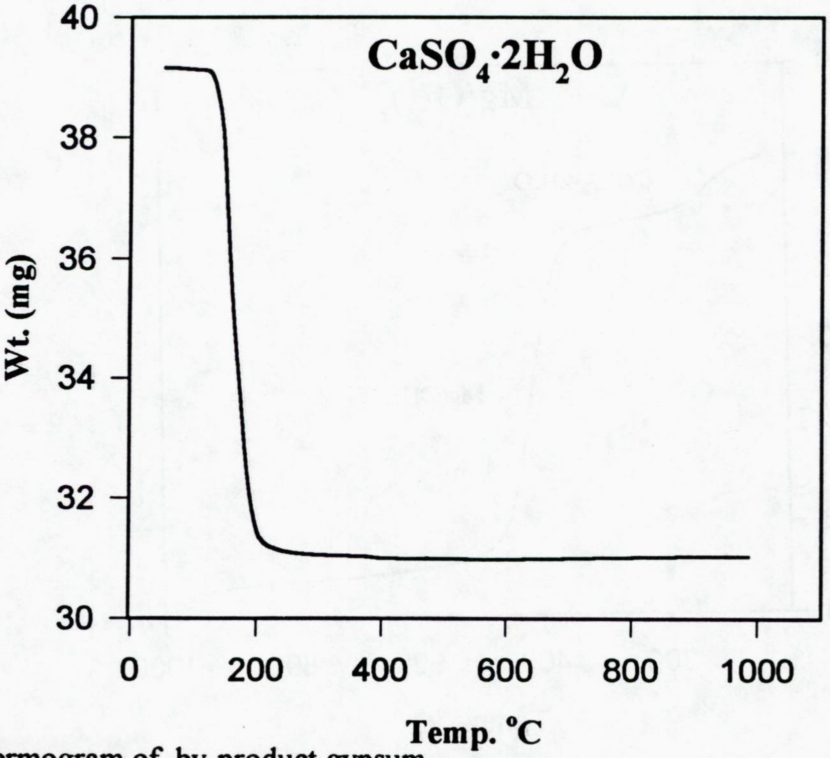

Figure 3. Thermogram of by-product gypsum.

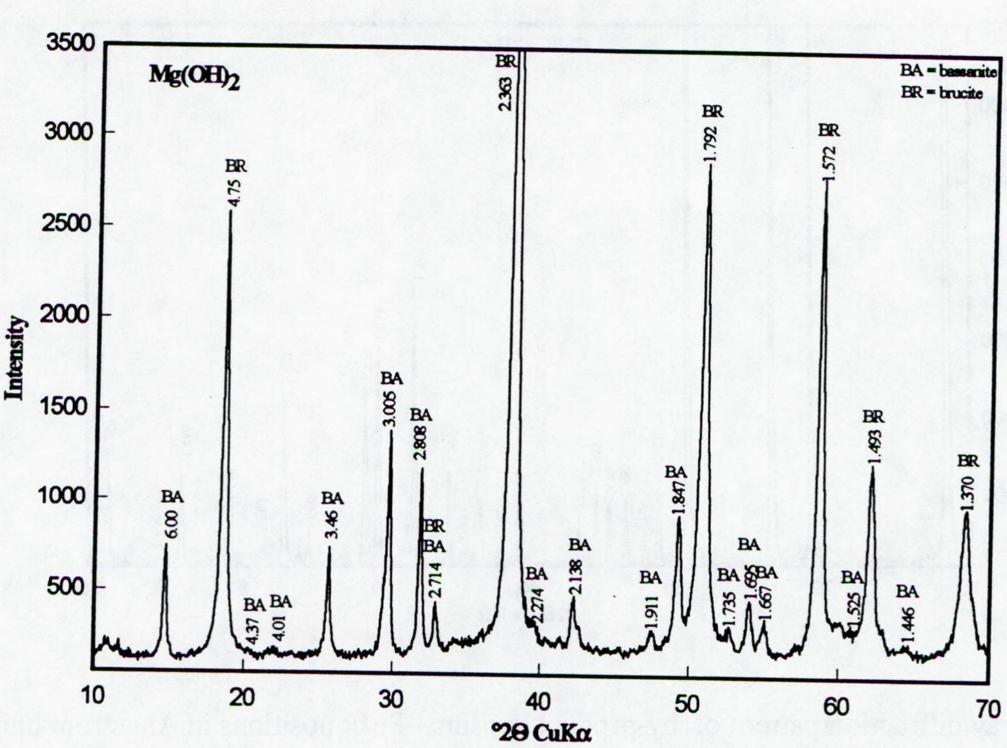

Figure 4. X-ray diffraction pattern of by-product magnesium hydroxide. Peak positions in Angstrom units.

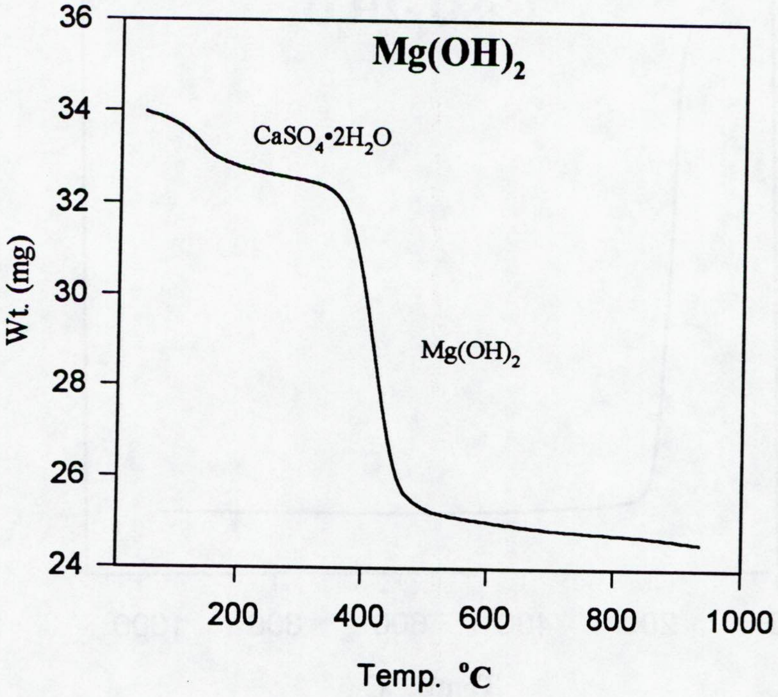

Figure 5. Thermogram of by-product magnesium hydroxide.

Figure 6. Scanning electron micrographs of (top) agricultural limestone and (bottom) laboratory calcium hydroxide.

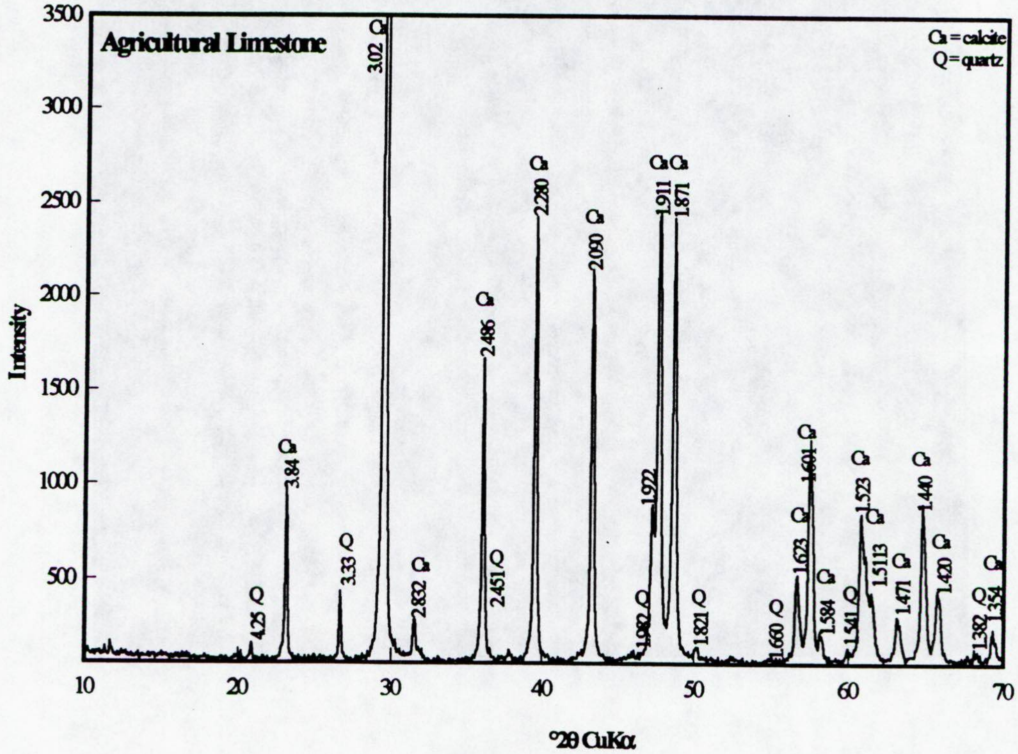

Figure 7. X-ray diffraction pattern of agricultural limestone. Peak positions in Angstrom units.

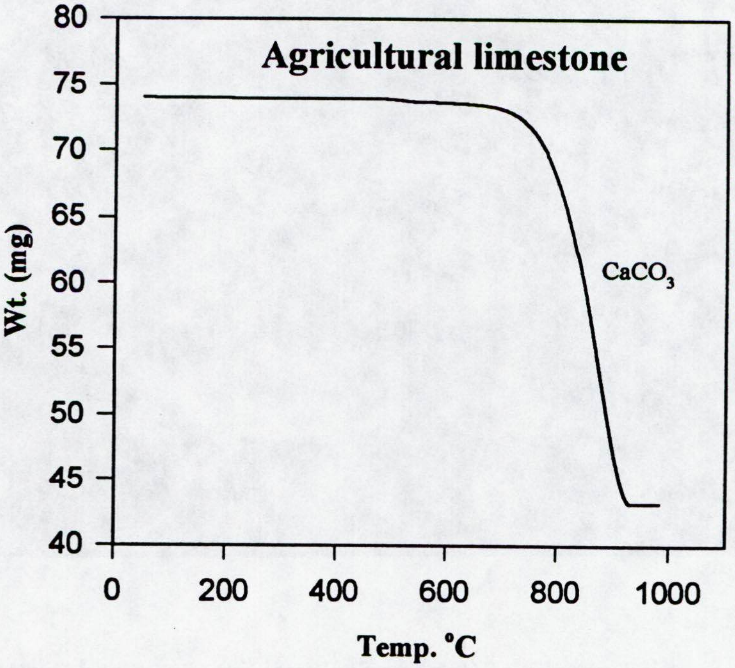

Figure 8. Thermogram of agricultural limestone.

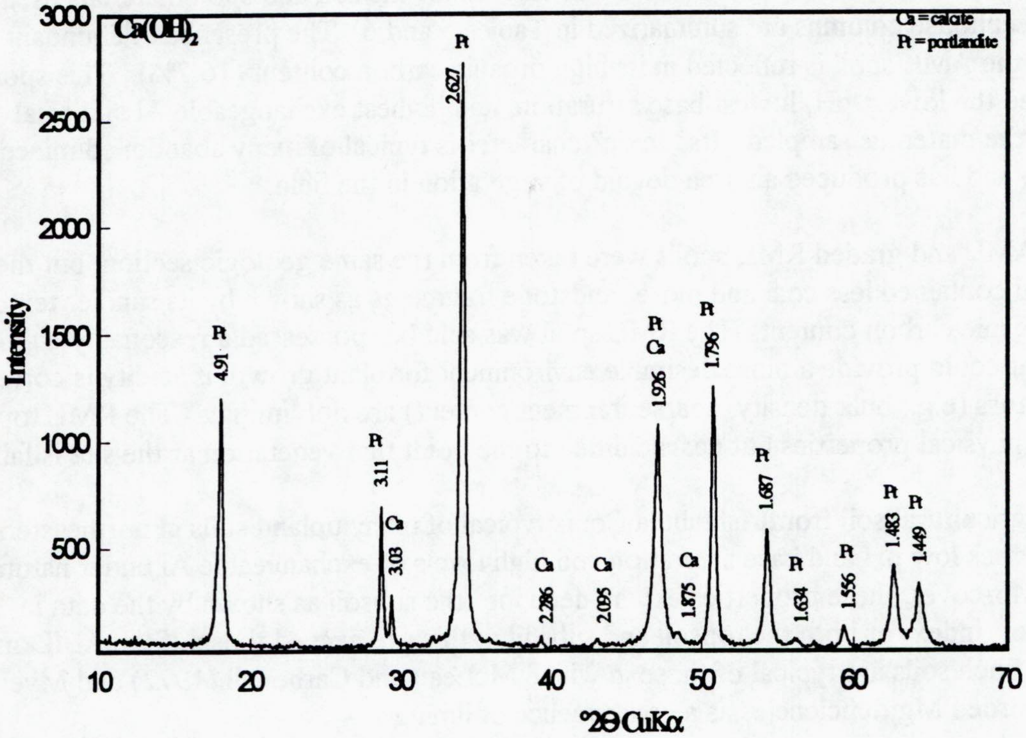

Figure 9. X-ray diffraction pattern of laboratory calcium hydroxide. Peak positions in Angstrom units.

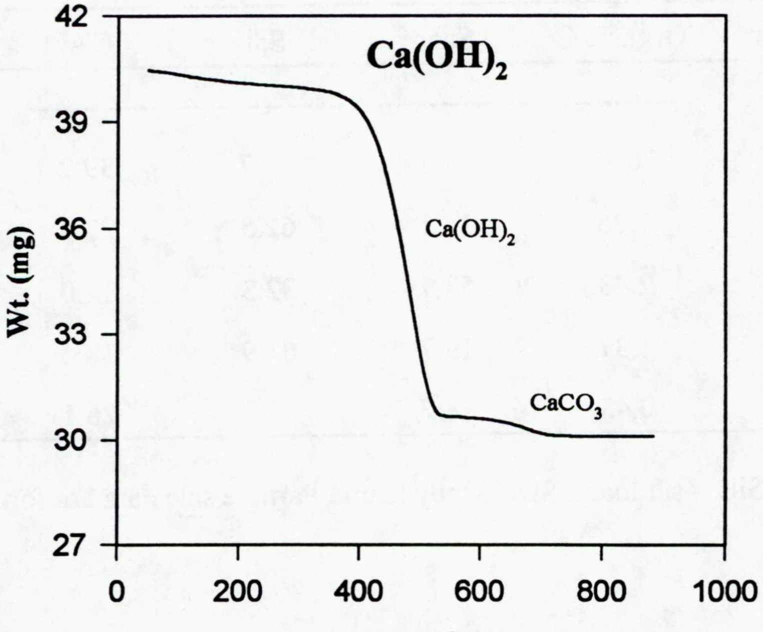

Figure 10. Thermogram of laboratory calcium hydroxide.

2.3.1.3 Soil and Spoil Materials

Basic physical and chemical characterization data for the soil and spoil materials used in preparing greenhouse columns are summarized in Tables 5 and 6. The presence of abundant coal fragments in the AML spoil is reflected in its high organic carbon content (16.7%). This spoil also possessed the lowest pH, lowest base saturation, and highest exchangeable Al and total acidity of all the materials sampled. Its "toxic" character is typical of many abandoned mined lands in Ohio and has produced an area devoid of vegetation in the field.

The AML and graded RML spoils were taken from the same geologic section, but the latter material contained less coal and more sandstone fragments as shown by its sandier texture and lower organic carbon content. The RML spoil was acid but possessed a reasonably high base saturation that could provide a more desirable environment for plant growth if acidity is corrected and other factors (e.g., bulk density, coarse fragment content) are not limiting. The RML topsoil has desirable physical properties but has acidified to the point that vegetation at the site is failing.

The agricultural soil from Ashtabula Co. is typical of many upland soils in northeastern Ohio in that it has low pH and base saturation and high levels of exchangeable Al under natural conditions. Moreover, these properties extend deep into the subsoil as shown by the data in Table 6. The lime test index for both the topsoil and subsoil at this site exceed those of the AML and RML spoils. Such soils are typical of those in which McLean and Carbonell (1972) and Myers et al. (1988) recorded Mg deficiencies as a consequence of liming.

Table 5. Texture and organic carbon contents of soil and spoil materials.

Sample	Depth	Organic C	Sand	Silt	Clay	Texture*
	cm	-----------	------------	%	-----------	
AML spoil	0-20	16.70	17.1	43.7	39.2	SiCl
RML soil	0-20	1.25	14.1	62.5	23.4	SiL
RML spoil	20-45	2.43	53.7	32.3	14.0	SL
AS-Topsoil	0-15	1.37	19.7	61.9	18.4	SiL
AS-Subsoil	15-45	0.43	18.7	55.2	26.1	SiL

* SiCl = silty clay loam; SiL = silt loam; SL = sandy loam. Particle size data are for the <2mm fraction only.

Table 6. Soil and spoil chemical data.

Sample	Depth	pH		Lime requirement†	Total Acidity	KCl exchangeable					CEC§	Base Sat.
		H_2O	$CaCl_2$			Al	Ca	Mg	K	Na		
	cm			tons/acre	--------------------------------cmol_c/kg--------------------------------							%
AML	0-40	3.0	2.9	>22.1‡	28.9	6.68	0.5	0.1	0.32	0.19	30.0	4
RML	0-20	5.0	4.7	6.5	7.7	0.90	7.0	3.4	0.95	0.10	19.1	60
RML	20-45	3.6	3.5	16.9	9.7	2.54	6.3	0.1	0.39	0.06	16.6	41
AS	0-15	4.2	3.9	11.7	14.4	3.97	0.6	0.1	0.71	0.11	15.9	10
AS	15-45	4.8	3.9	13.7	12.1	4.78	1.2	0.1	0.69	0.13	14.2	15

† Lime requirement as determined by the SMP buffer test (Shoemaker et al., 1962).

‡ Lime test index value was below the calibration range for the SMP buffer test.

§ CEC = Cation Exchange Capacity, sum of total acidity and exchangeable Ca, Mg, K, and Na.

3 GREENHOUSE STUDIES

Three greenhouse experiments were designed and conducted in parallel. Soil and spoil materials collected from the field locations were placed in columns to simulate field profiles. The experiments lasted for 165 days during which time column leachates were collected and plant growth was harvested. The primary objective was to compare the effects of by-product gypsum alone to gypsum with some level of alkalinity in the form of either $Mg(OH)_2$ or $Ca(OH)_2$. Inclusion of both Mg-G and Ca-G at equivalent alkalinities allowed a separation of the effects due to added alkalinity from those due to added Mg. Agricultural limestone (AL) was used in similar fashion to separate the effects due to alkalinity alone from those related to gypsum addition.

3.1 Materials and Methods

3.1.1 Amendment Rates

By-product gypsum and $Mg(OH)_2$ used in these experiments were produced at the Miami Fort and Zimmer Station power plants respectively. The Zimmer system can produce gypsum which ranges from relatively pure up to 8% $Mg(OH)_2$ content. To test this range three grades of by-product gypsum were used in the study; pure G, and Mg-G with 4 and 8% $Mg(OH)_2$. The 4 and 8% Mg-G was made by mixing by-product gypsum with the appropriate amount of Zimmer $Mg(OH)_2$. The 4 and 8% Ca-G was similarly produced by mixing by-product gypsum with reagent grade $Ca(OH)_2$. The terminology 4% is used to indicate that the amounts of reagent grade $Ca(OH)_2$ or by-product $Mg(OH)_2$ have the same acid neutralizing potential as 4 g of reagent grade material in 96 g of by-product gypsum. The terminology 8% is used in the same manner.

The amendment rates used in each experiment were based on the cation exchange capacity (CEC) of the soil/spoil material used in that experiment. Application rates of the gypsum materials (G, 4 and 8% Mg-G, 4 and 8% Ca-G) were selected to supply Ca (as gypsum) in amounts equivalent to 2.5, 5, and 10 times the CEC of the soil/spoil material in the column. The AL amendment was applied at a rate sufficient to raise the spoil or soil pH to 7. These rates were determined in preliminary incubation studies with AL and the various spoil/soil materials. The actual amounts of each amendment material used are given in Table 7.

3.1.2 Column design

The columns used for these experiments were constructed from 60 cm lengths of 15 cm diameter PVC pipe mounted on a flat PVC plate with a nipple in the center to allow for leachate collection. Unamended subsoil material was placed in the lower portion of the column and then covered with a layer of surface soil mixed with the various types and rates of amendments.

The amount of material and the column height used for sub-surface and surface layers varied in each experiment (Table 8). The appropriate weight of air-dry subsurface material was first poured into the column and tamped to achieve the desired bulk density. Amendments were thoroughly mixed with the appropriate amount of surface layer material for each experiment

(Table 8), placed in the column above the subsurface layer, and tamped to achieve the desired final column height. The depth of the treated surface layer varied according to the amount of amendment material added. A control treatment receiving no amendment was included in each experiment. All treatments in the AML study were applied with and without compost at a rate of 100 g kg^{-1}. Compost was included as an amendment because many studies and experience have indicated that minespoil revegetation success is improved by the inclusion of organic amendments.

Table 7. Application rates of G, Mg-G, Ca-G, and AL used in the greenhouse experiments.

	AML	RML	AS
Rate basis	Amendment rate		
	g kg^{-1}		
	G, 4 and 8% Mg-G, 4 and 8% Ca-G		
2.5 x CEC	63	40	34
5.0 x CEC	126	80	68
10.0 x CEC	252	160	136
	Calcitic Limestone		
pH 7	44	6	11

Table 8. Weight and column height of surface and subsurface layers for each experiment.

	Surface layer		Subsurface layer	
Experiment	weight	height	weight	height
	kg	cm	kg	cm
AML	3.43	15	8.00	36
RML	4.7	20	9.00	33
AS	3.7	15	9.50	38

3.1.3 Experimental Procedures

All columns were initially wetted and leached by adding deionized water to the column surface in 200 mL increments until approximately 200 mL of leachate had been collected from the bottom of the column. After measurement of pH and electrical conductivity (EC), leachates were passed through a 0.45 µm membrane filter and analyzed for As, Al, B, Ba, Be, Ca, Cd, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Se, Si, and Zn by ICP, and for SO_4^{2-}, Cl^-, F^-, and NO_3^- by ion chromatography (IC).

After the initial leaching, soil samples were collected from the 0-10 cm depth of each column. These samples were air-dried, ground, and analyzed for pH (1:1 soil:water) and EC (1:2 soil:water). Additional samples were extracted with 1*M* KCl (1:10 soil:water), and the extracts were analyzed for As, Al, B, Ba, Be, Ca, Cd, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Se, Si, and Zn by ICP. All columns were planted on 2 February, 1995; orchardgrass (*Dactylis glomerata* L.) was used in the AML and RML experiments and alfalfa (*Medicago sativa* L.) in the AS experiment.

Following an initial 75 day establishment and growth period, all columns were harvested by cutting the plants 1 cm above the column surface. The columns were similarly harvested every 30 days thereafter for a total of 4 harvests. The final harvest was performed on 17 July, 1995. Harvested plant tissues were dried at 60 °C for 48 h, weighed, and ground to pass a 1-mm sieve. Total elemental composition of plant tissues from the first and last harvests were measured by digesting 0.500-1.000 g of dried material in a 2:1 mixture of nitric and perchloric acids, and analyzing the digest for As, Al, B, Ba, Be, Ca, Cd, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Se, Si, and Zn by ICP.

A total of 1000 mm of water were added to each column during the course of the experiments. Each day, 50 to 500 mL of water were applied, depending on the growth stage and daily temperature, to meet plant water requirements. Immediately following each harvest, leachates were collected and analyzed as described above, providing a total of 5 leaching events.

After the final harvest and leaching, soil samples were collected from four depth increments in each of the columns (Table 9). Subsurface sampling depths are indicated relative to the surface-subsurface layer interface rather than to the column surface because of the variable thickness of the amended surface layer. Sampling was accomplished by sliding the entire soil column from the PVC cylinder and cutting it lengthwise in two halves. One half was sectioned at the designated depths, and each section was homogenized for analysis. The other half was discarded.

Table 9. Depth intervals of soil/spoil samples collected at the end of the experiments.

Column layer	AML	RML	AS
	Depth interval, cm		
Surface	0-15	0-20	0-15
Subsurface	1-10†	1-10	1-10
Subsurface	10-20	10-20	10-20
Subsurface	24-33	24-33	24-33

† The top 1 cm of the subsurface layer was discarded to avoid contamination from the surface layer.

3.2 Results and Discussion

3.2.1 Abandoned Mined Land (AML) Experiment

3.2.1.1 Treated Surface Spoil Layer

<u>pH</u>

As expected, the spoil pH was not affected by application of G because gypsum is a neutral salt with no acid neutralizing potential (Fig. 11). Spoil pH was increased by increasing application rates of 4 and 8% Mg-G and Ca-G, with the larger percentages of added alkalinity giving a greater pH response. There was no difference in the pH response due to the different forms of added alkalinity, therefore $Mg(OH)_2$ was equally effective as $Ca(OH)_2$ in terms of neutralizing spoil acidity. Spoil pH decreased during the course of the experiment with both Ca-G and Mg-G, while with AL it remained relatively constant near a pH of 7. The 252 g kg^{-1} application rates of 8% Mg-G and Ca-G initially raised the spoil pH above 8, which is higher than the optimum pH for plant growth.

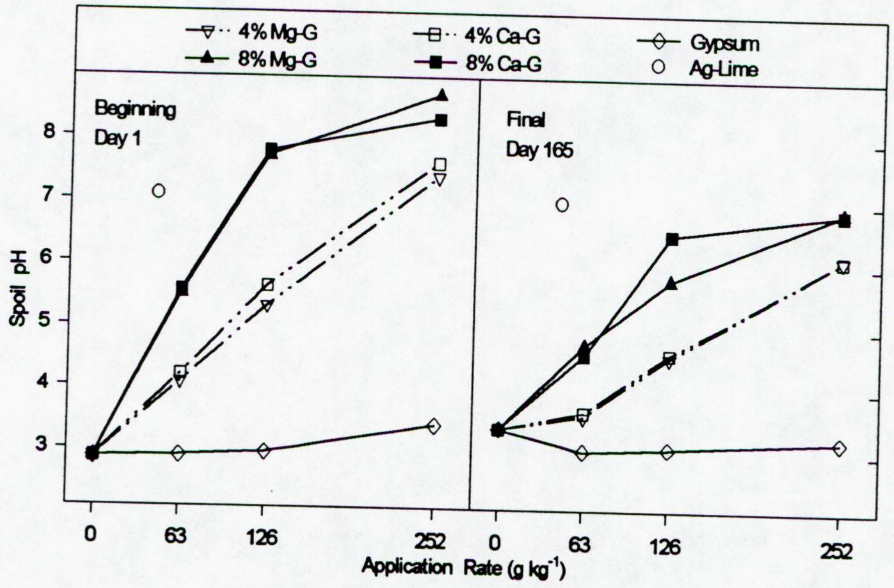

Figure 11. Effects of G, Mg-G, Ca-G, and AL on spoil pH in the treated layer at the beginning and end of the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Compost application (100 g kg^{-1}) increased the spoil pH both in the absence of alkaline amendments and when the alkaline amendment rate was not large enough to bring the pH to neutrality (Fig. 12). Where spoil pH was increased above 7 by 8% Ca-G and Mg-G, compost decreased the spoil pH, and held pH more constant over time (Fig. 12). Such composts contain a complex mixture of organic compounds with various functional groups which buffer pH by protonating in acid systems and de-protonating in basic systems. The buffering capacity of the compost is beneficial in that it stabilizes pH in a range desirable for plant growth, and thus can compensate for either insufficient or excess alkaline addition.

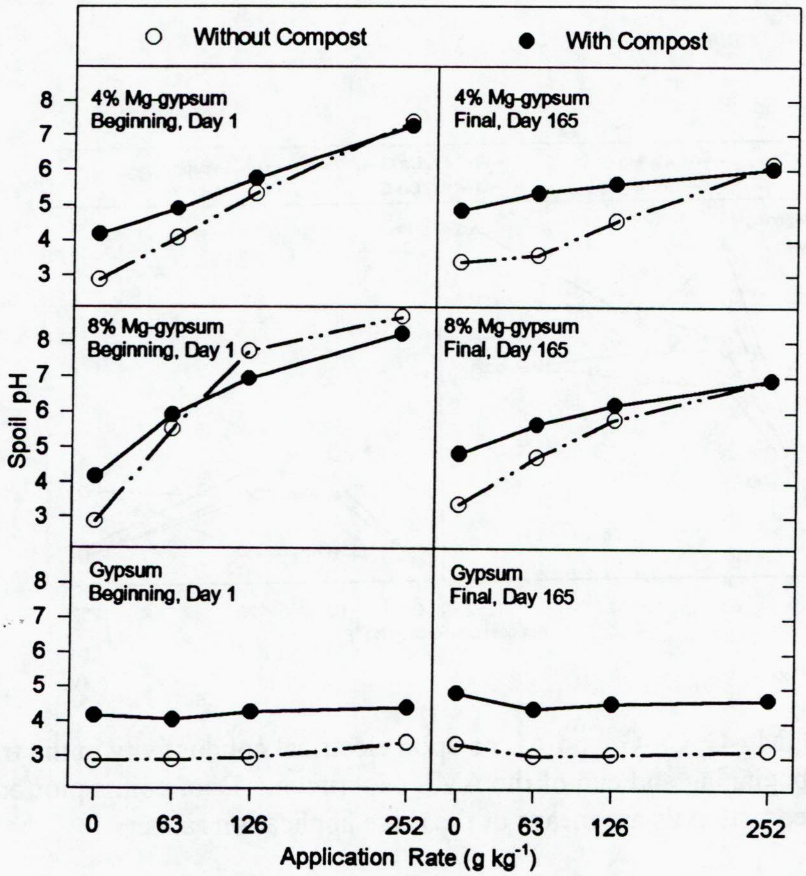

Figure 12. Effect of compost on spoil pH in the treated layer when applied with various rates of 4 and 8% Mg-G, and G at the beginning and end of the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Electrical Conductivity

All amendments except AL significantly increased the spoil EC at the beginning of the study (Fig. 13). The largest increases were caused by 4 and 8% Mg-G. Gypsum and 4 and 8% Ca-G produced similar but lower increases in EC compared to the Mg-containing amendments. These results are consistent with the findings of Stehouwer et al. (1994) who reported the presence of Mg in gypsum-containing FGD by-products led to large increases in soluble salts due to the high solubility of $MgSO_4$ and the stability of the $MgSO_4^o$ ion pair. Although Mg was not added as $MgSO_4$, the reaction of $Mg(OH)_2$ with spoil acidity released Mg^{2+} into solution while dissolution of gypsum released SO_4^{2-} into solution. The role of Mg in the observed increases in EC was further substantiated by changes in subsurface and leachate chemistry which will be discussed in subsequent sections.

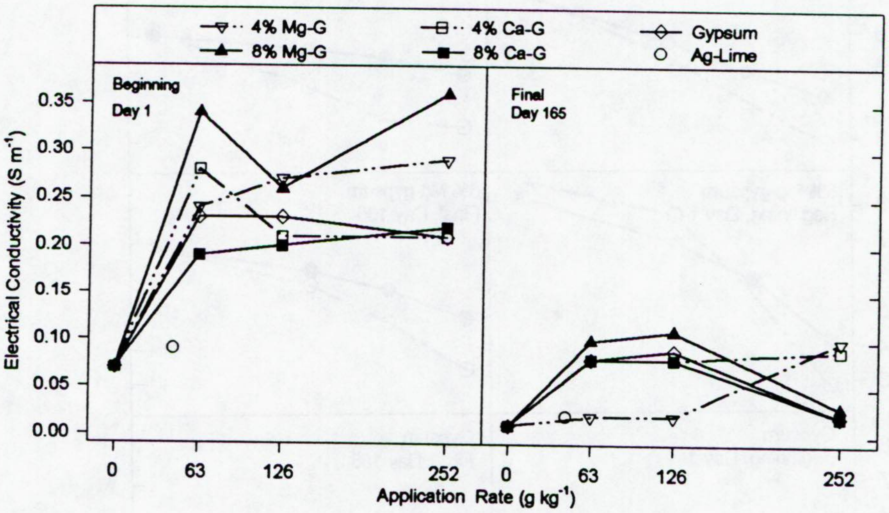

Figure 13. Effects of G, Mg-G, Ca-G, and AL on spoil electrical conductivity in the treated layer at the beginning and end of the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

By day 165 (Fig. 13), EC's of the treated-layers had decreased to near the background level observed for the unamended spoil at the beginning of the study. Clearly, increases in EC brought about by the use of any of the gypsum based amendments were temporary and disappeared as salts were removed by leaching of the treated layer. The amount of water applied to these columns was equivalent to the annual average rainfall for Eastern Ohio (approx. 1000 mm); however, the rate of decrease in EC relative to the amount of water applied was likely greater in the greenhouse than it would be in a field setting. In the greenhouse, all applied water infiltrated the spoil surface whereas in the field a large amount of rainfall may leave the area as runoff, particularly on steeply sloping terrain.

3.2.1.2 Column Leachate Chemistry

pH

Surface amendment with agricultural limestone or the gypsum-based materials had little effect on leachate pH, which ranged between 2.2 and 2.9 for the duration of the study (Fig. 14). Averaged across type and rate, the gypsum-based amendments caused a small reduction in leachate pH compared to the unamended spoil. These reductions were presumably due to the displacement of acid forming cations, such as Al or Fe, from the cation exchange complex of the spoil. Leachate pH, therefore, was mainly controlled by the chemical characteristics of the subsurface layer.

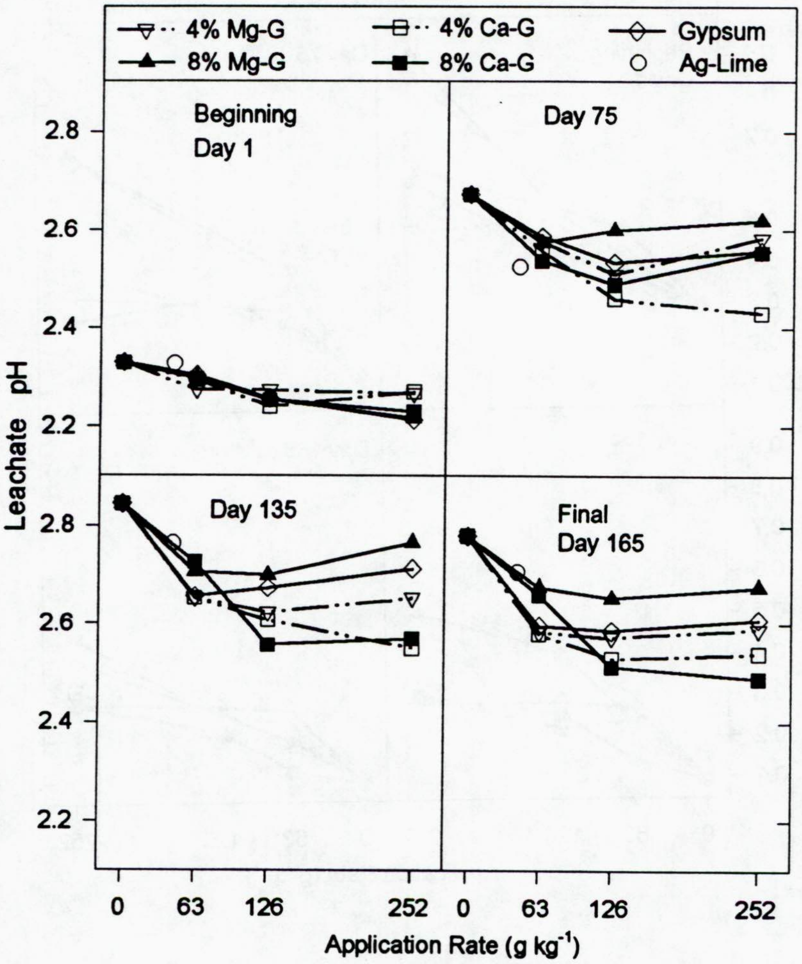

Figure 14. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the pH of column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Electrical Conductivity

Leachate EC showed the same treatment response as was observed with extracts of the treated surface layer, in that Mg-G produced the largest increases, Ca-G and G gave smaller increases, and AL produced almost no change (Fig. 15). In each leaching event, EC increased with increasing application rates of G, Ca-G, and Mg-G. Leachate EC decreased with time, showing a sharp decrease from planting to the first harvest, and smaller decreases after the first harvest. The EC is usually high in the first leachate collected from a dry spoil due to the dissolution of free salts, and then decreases after the spoil has remained wet for several days.

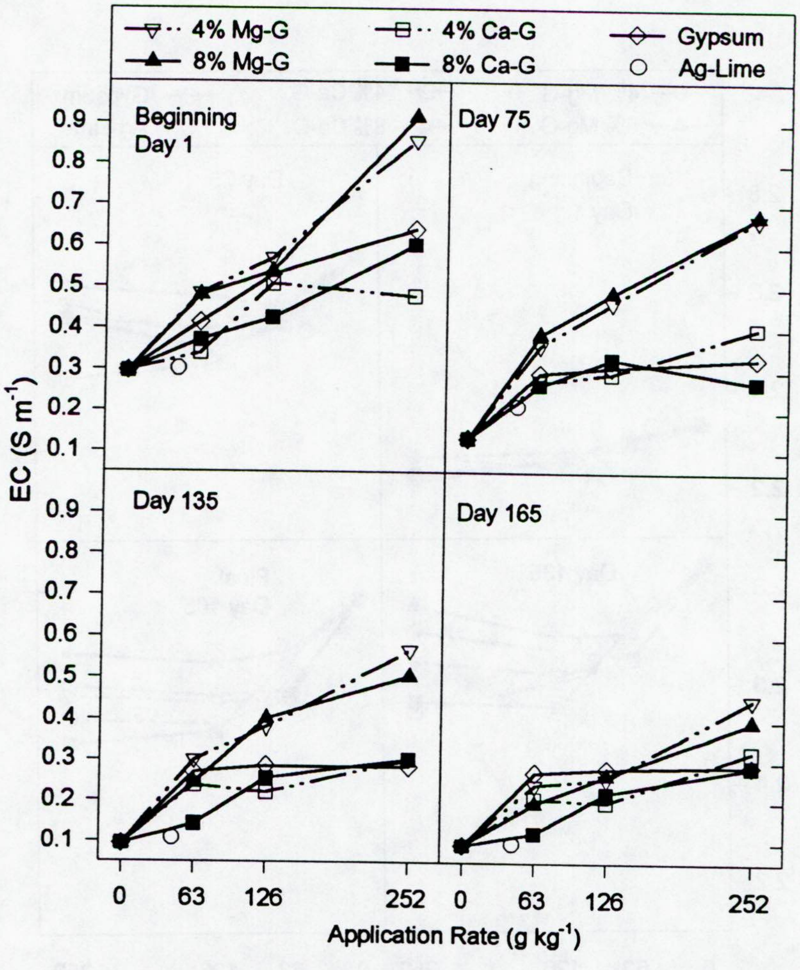

Figure 15. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the electrical conductivity of column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Calcium

Leachate Ca concentrations were increased by increasing application rates for each of the gypsum-based amendments, but were not significantly affected by agricultural limestone (Fig. 16). While increases with gypsum-based amendments were apparent in all leaching events, the rate effect became more prominent with time. By the end of the experiment, Ca concentrations were much larger with G than with either Ca-G or Mg-G due, presumably, to greater dissolution of gypsum in the more acidic environment of the G-treated spoil than in spoil amended with Ca-G or Mg-G. Gypsum is more soluble in acid than in water (Weast, 1972).

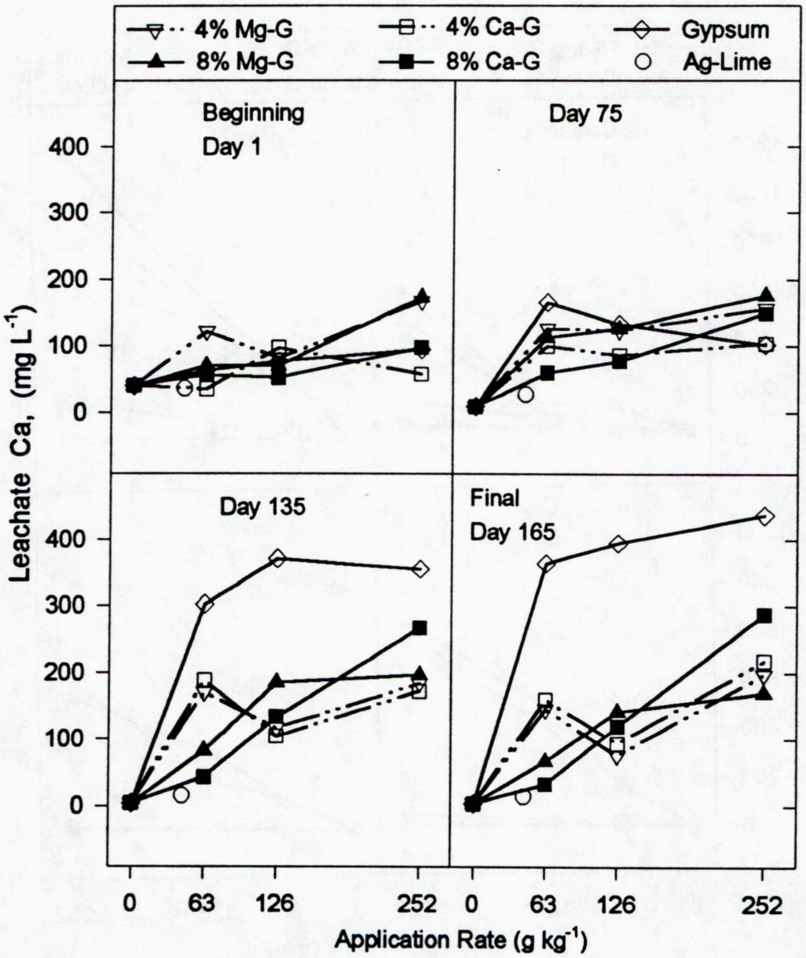

Figure 16. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on concentrations of Ca in column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Magnesium

Amendment with Mg-G caused large, linear increases in leachate Mg whereas all other amendments had almost no effect on dissolved Mg (Fig. 17). Increases in Mg were observed in the first leachate, but maximum concentrations were obtained in the 75-day leachates and subsequently decreased. With Ca (Fig. 16), initial responses were much smaller and maximum concentrations were not observed until 175 days. As will be discussed in subsequent sections, this rapid movement of relatively large concentrations of Mg had significant effects on the mobilization and transport of Al, Fe, and several trace elements.

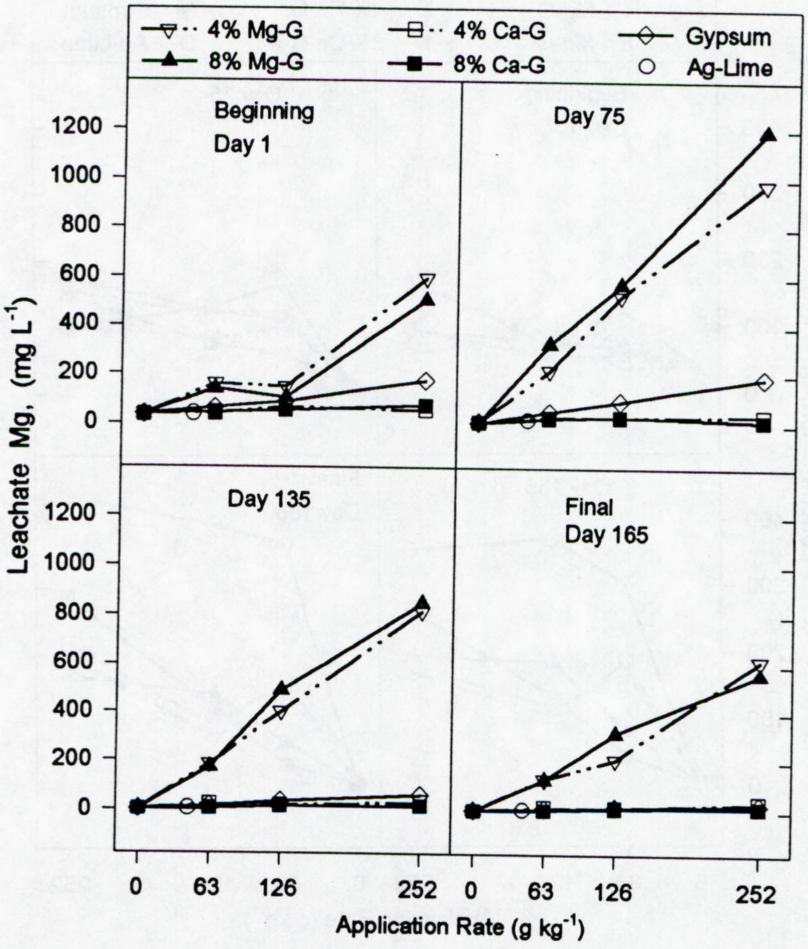

Figure 17. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on concentrations of Mg in column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Sulfur

All amendments except agricultural limestone enhanced leachate S concentrations, but the Mg-G materials clearly caused the largest increases (Fig. 18). Furthermore, while the amendment effects on leachate S (which is predominantly in the SO_4^{2-} form) showed a similar pattern to that of leachate Mg, on a molar basis the S concentrations are larger. The gypsum based amendments were the primary source for the increased SO_4^{2-} which, in the case of Mg-G, moved from the amended layer in association with Mg^{2+}. However the large differential between SO_4^{2-} and Mg^{2+} in the leachates suggests that significant cation exchange between Mg^{2+} and native spoil cations (mainly Al and Fe) occurred during transport through the spoil column (see Figs. 19 and 20). Large increases in subsurface exchangeable Mg^{2+} and decreases in exchangeable Al^{3+} with Mg-G amendment (Fig. 24) provide additional evidence for this cation exchange process.

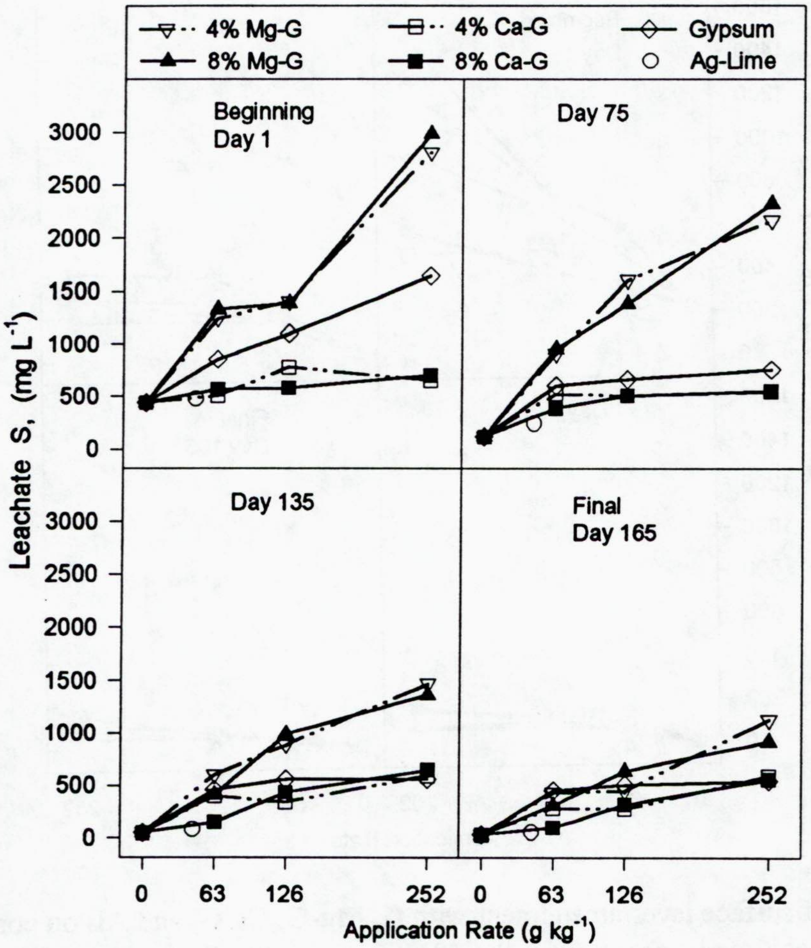

Figure 18. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on concentrations of S in column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Aluminum, Iron, and Trace Elements

Leachate Al and Fe concentrations were increased by all gypsum-based amendments but not by agricultural limestone (Figs. 19 and 20). The increases were largest in the first leachates and decreased with time following a similar pattern to those observed with leachate SO_4^{2-}, and EC. These data indicate that dissolution of the gypsum-based amendments resulted in downward transport of Ca^{2+} and SO_4^{2-}. The Ca^{2+} exchanged with native Al^{3+} and Fe^{3+}, which resulted in their mobilization and downward transport. With Mg-G, the same mechanism appeared to function but, because of the much larger solution concentrations of Mg^{2+} and SO_4^{2}, there was more effective mobilization and transport of phytotoxic Al and Fe from the plant rooting zone.

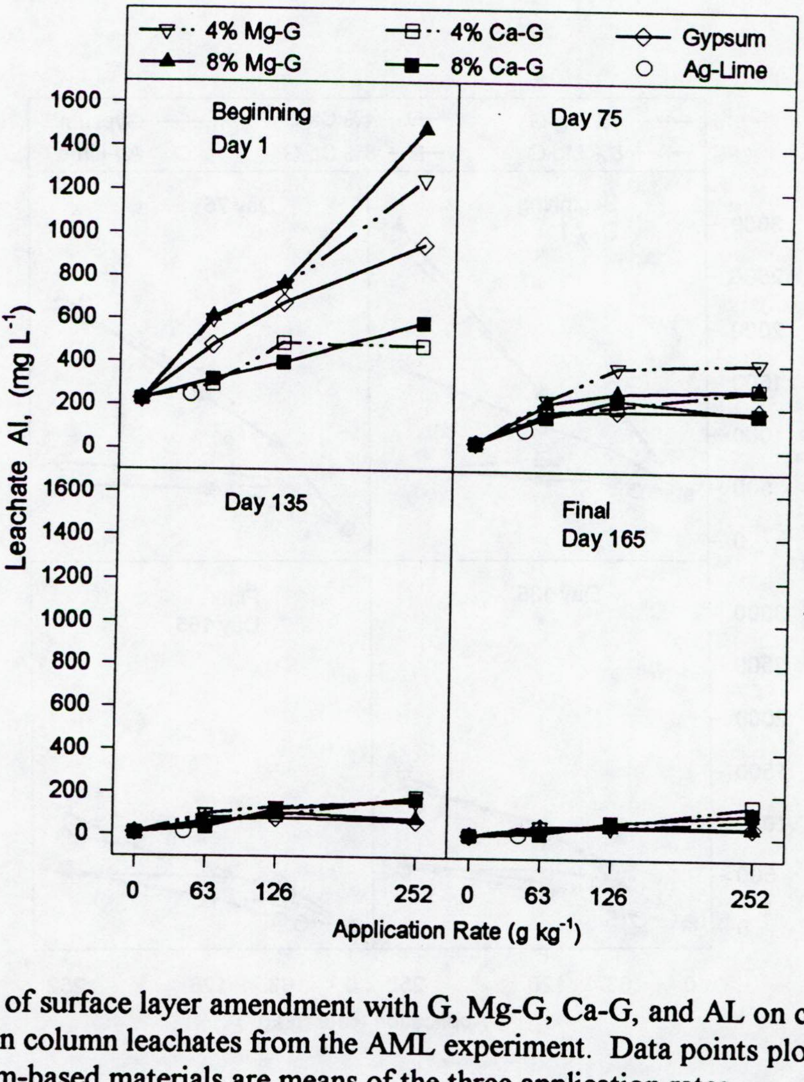

Figure 19. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on concentrations of Al in column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

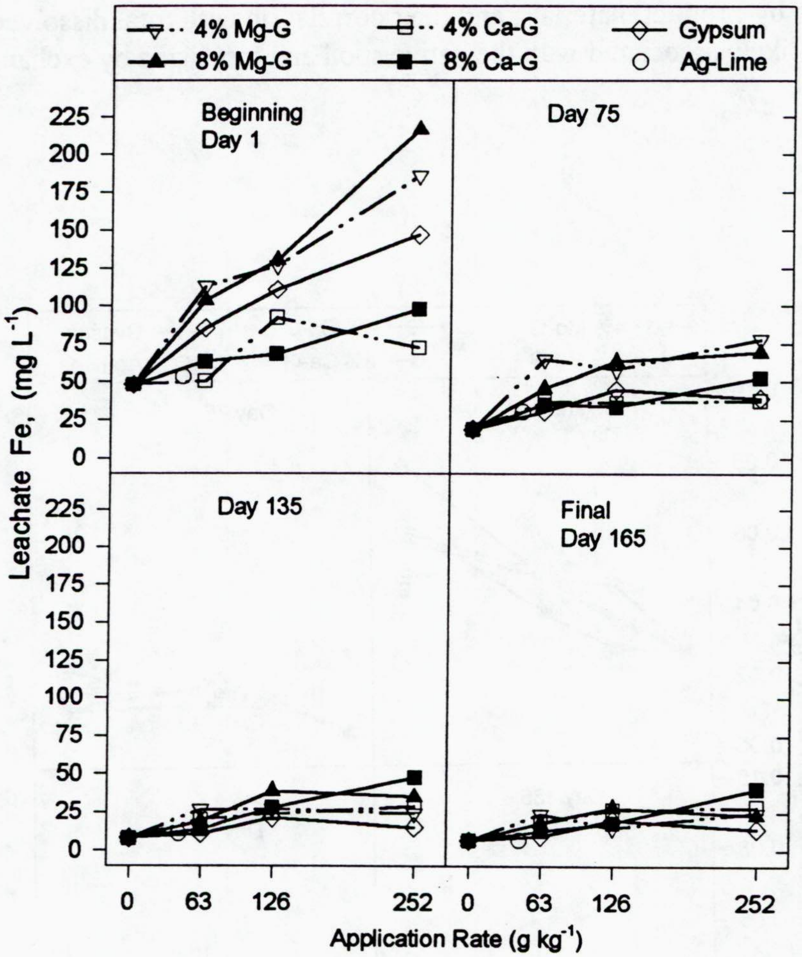

Figure 20. **Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on concentrations of Fe in column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.**

These mechanisms functioned similarly with respect to mobilization and transport of several trace elements. Among these were As, Cd (Fig. 21), Cu, Mn, and Pb (Appendix A, Tables 12, 13, 15, and 16). Concentrations of these elements in the first leachates were increased by some or all of the gypsum-based amendments. In subsequent leachates, trace metal yields were much lower. Nevertheless, these data indicate that an initial flush of trace elements could result from application of gypsum-based amendments. The highest trace metal concentrations occurred with Mg-G, whereas Ca-G caused the smallest increases. Given the very low concentrations of these elements in the by-product materials, and their correlation with total dissolved salts, these trace elements were likely associated with the native spoil and mobilized by exchange with salts in the leachates.

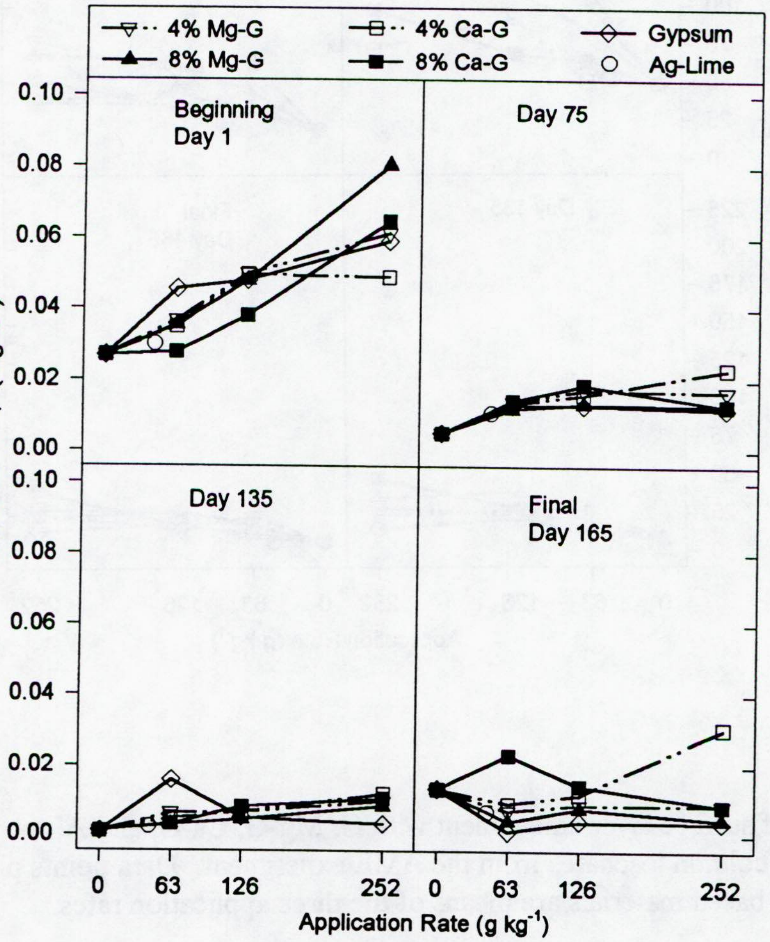

Figure 21. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on concentrations of Cd in column leachates from the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.1.3 Untreated Subsurface Spoil Layers

The preceding section showed that surface amendments with gypsum-based materials had a major effect on column leachates that were transported through the unamended subsurface spoil layer. Consequently, the surface amendments must have had significant effects on subsurface chemistry, particularly on the exchangeable cation composition.

pH

Surface applied amendments had little effect on subsurface pH with the exception of 8% Mg-G which increased the pH 1-10 cm below the treated layer (Fig. 22). At this depth, spoil pH increased to 4.1 with 252 g kg^{-1} of 8% Mg-G, and to 4.9 when compost was added (Appendix A, Table 10). By contrast, pH at the same depth with AL was 3.3 and 3.7 with AL+compost. Although pHs in the range of 4.1 to 4.9 are still below optimum for plant growth, surface amendment with Mg-G and compost reduced subsurface phytotoxicity more than any other treatment.

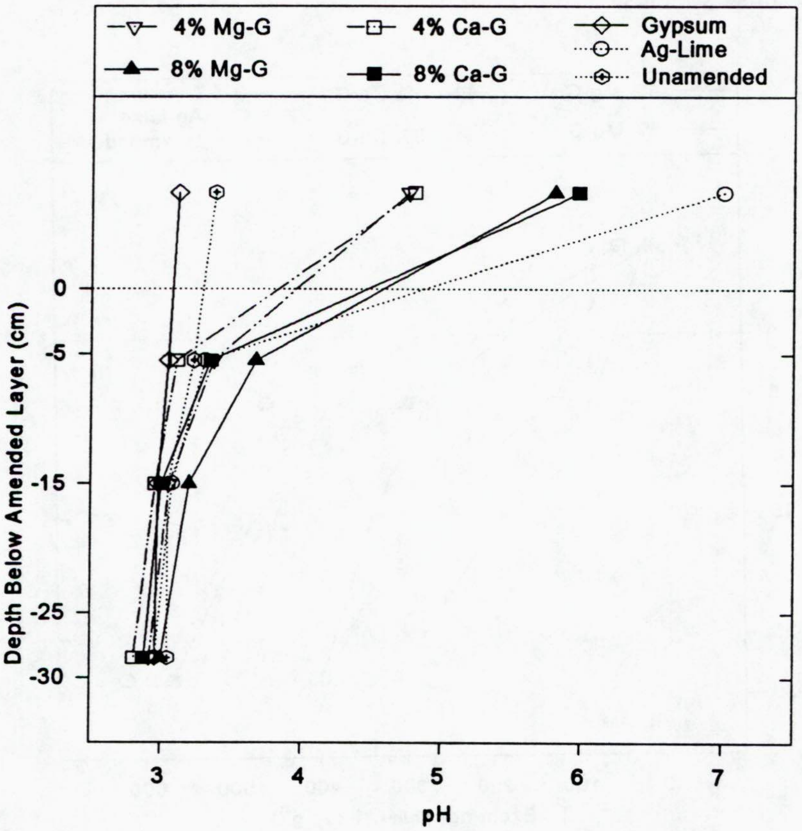

Figure 22. Effect of surface amendment with G, Mg-G, Ca-G, and AL on spoil pH at the conclusion of the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Aluminum and Iron

Exchangeable Al in the subsurface layer was considerably reduced with the application of 4 and 8% Mg-G compared to the application of AL (Fig. 23). For example, Al at a depth of 1-10 cm depth below the treated layer was 60 and 46 µg g^{-1} with 252 g kg^{-1} of 4 and 8% Mg-G, respectively, compared to 460 µg g^{-1} with AL and 337 µg g^{-1} with 252 g kg^{-1} of G (Appendix A, Table 10). The reduction of exchangeable Al in the subsurface layer with 4 or 8% Mg-G compared to AL and G should improve the chances for reclamation success by decreasing Al toxicity and increasing root growth below the amended layer. Exchangeable Fe concentrations were similarly affected by the surface amendments in that increasing application rates of all the gypsum-based amendments decreased subsurface exchangeable Fe relative to the control (Fig. 24; Appendix A, Table 11). Once again, the largest decreases in Fe occurred with the Mg-G amendments. As was indicated by the leachate data, the mechanism for these decreases in Al and Fe appeared to be exchange with Ca^{2+} and Mg^{2+} as these solutes were leached through the spoil column. The higher concentrations of Mg^{2+} resulting from Mg-G application apparently caused the greatest exchange and mobilization of Al^{3+} and Fe^{3+}. Conversely, this mechanism functioned to only a limited extent with AL amendment due to the limited solubility of $CaCO_3$ and the limited transport of Ca^{2+} from the surface. Transport of Al and Fe with the gypsum-based amendments may also have been facilitated by the formation of $FeSO_4^+$ or $AlSO_4^+$ complexes, thereby reducing the positive charge on these species.

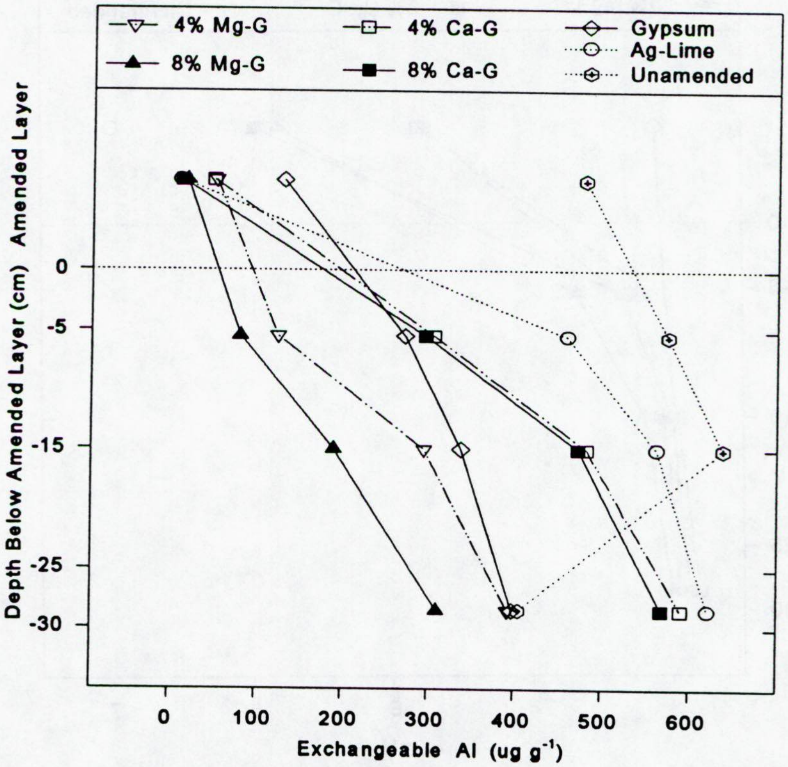

Figure 23. Effect of surface amendment with G, Mg-G, Ca-G, and AL on the distribution of exchangeable Al in the spoil columns at the conclusion of the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

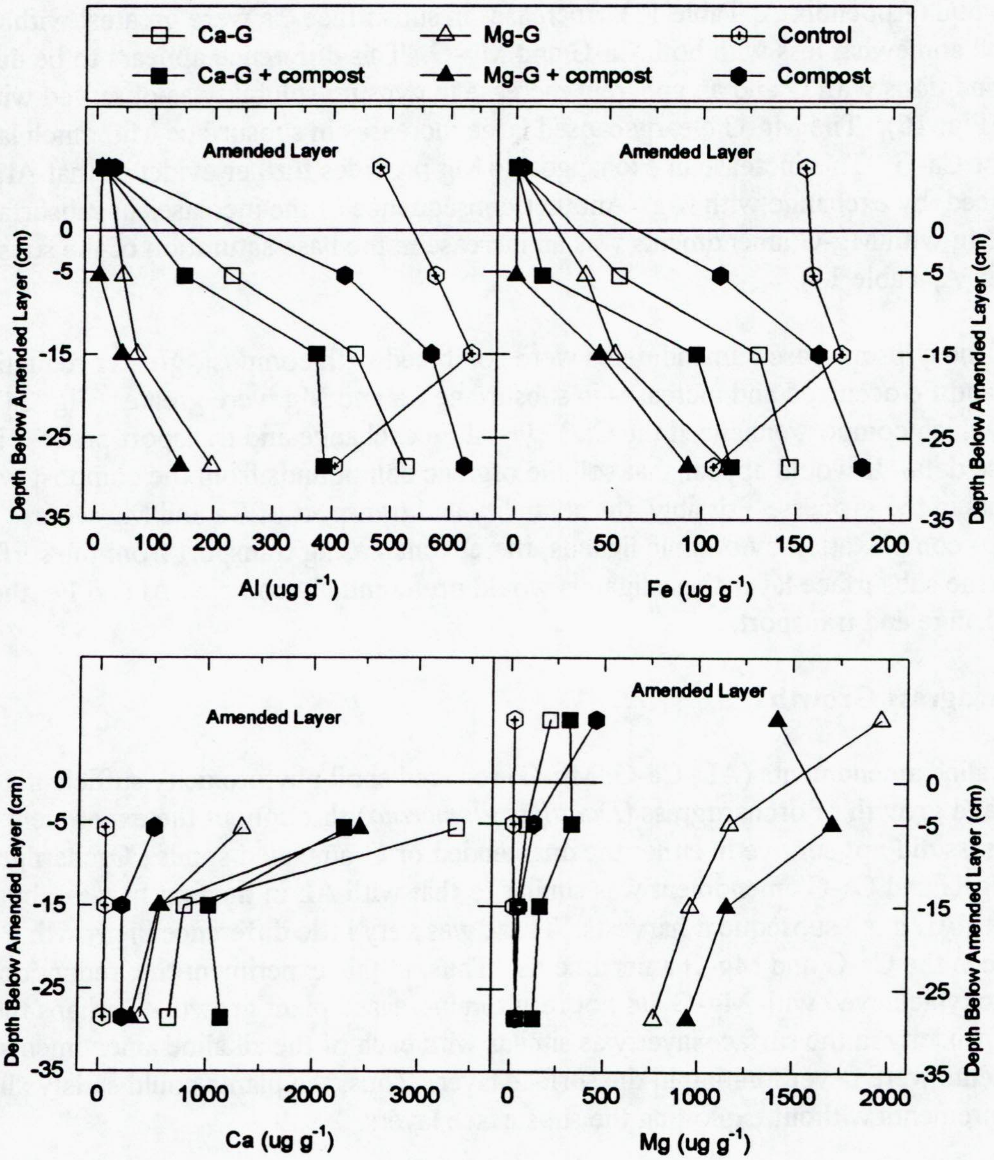

Figure 24. **Effect of surface amendment with Mg-G, and Ca-G, with and without compost (C) on the distribution of exchangeable Al, Fe, Ca, and Mg in spoil columns at the conclusion of the AML experiment. Data points plotted for the gypsum-based materials are for the highest application rates.**

Calcium and magnesium

Concentrations of exchangeable Ca and Mg in the subsurface layers were increased by increasing rates of the gypsum-based amendments relative to both the unamended spoil and the AL-amended spoil (Appendix A, Table 11). Increases in subsurface Ca were greatest with G amendment and somewhat less with both Ca-G and Mg-G. This difference appears to be due to more acidic conditions with G and an apparent increase in gypsum solubility as observed with the leachate data (Fig. 16). The Mg-G clearly caused large increases in subsurface Mg, much larger than either G or Ca-G. This increase in exchangeable Mg provides further evidence that Al and Fe were displaced by exchange with Mg. Another consequence of the increases in subsurface exchangeable Mg with Mg-G amendments was an increase in the base saturation of the subsurface spoil (Appendix A, Table 11).

When the gypsum-based amendments were combined with compost, greater reductions in subsurface Al and Fe occurred and increases in subsurface Ca and Mg were greater (Fig. 24). The means by which compost enhanced the Ca/Mg→Al/Fe exchange and transport process is not clear from these data. It would appear that soluble organic compounds from the compost were the active agents in the process. Possibly, the solubility and transport of Ca and Mg were increased due to complexation by organic ligands, thereby increasing transport from the surface layer. Once in the subsurface layer these ligands would preferentially complex Al and Fe, thereby facilitating exchange and transport.

3.2.1.4 Orchardgrass Growth

All alkaline amendments (AL, Ca-G, Mg-G) reduced spoil phytotoxicity sufficiently to allow survival and growth of orchardgrass (*Dactilyis glomerata*) throughout the experiment (Fig. 25). Orchardgrass did not survive in either the unamended or G-amended spoils. Orchardgrass growth with Mg-G and Ca-G amendment was similar to that with AL in the first harvest, but was greater than with AL in all subsequent harvests. There was very little difference in growth, however, between the Ca-G and Mg-G amendments. Thus, in this experiment the reductions in subsurface toxicity achieved with Mg-G did not result in increased plant growth. Perhaps the amelioration of toxicity in the surface layer was similar with each of the alkaline amendments, and water and nutrients were never limiting in the surface layer. Thus, the plants could satisfy all their nutritional requirements without exploiting the subsurface layers.

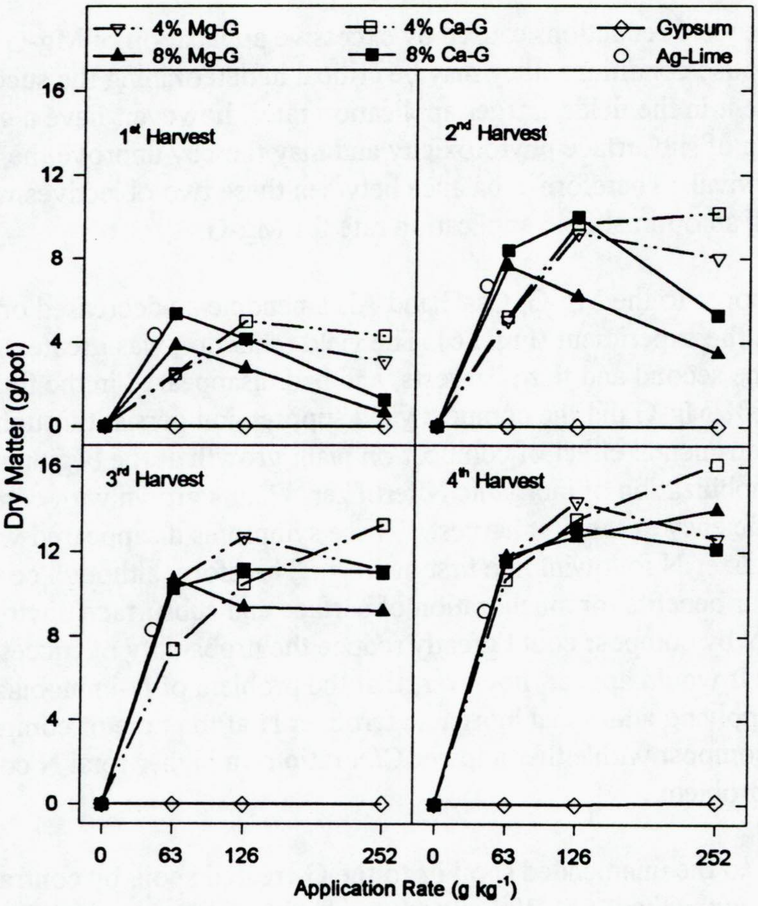

Figure 25. **Effect of G, Mg-G, Ca-G, and AL on growth of orchardgrass in the AML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.**

The magnitude of the increase in dry matter accumulation with Mg-G and Ca-G was dependent on both the application rate and time. With the 4% Mg-G and Ca-G amendments, yield response appeared to plateau between the amendment rates of 126 and 252 g kg^{-1}. With the 8% Mg-G and Ca-G amendments, however, yield response initially showed a decline above the 63 g kg^{-1} rate. The negative effect of the larger 8% Mg-G and Ca-G amendment rates decreased with each subsequent harvest and was no longer apparent in the third and fourth harvests. High pH and soluble salts at the beginning of the experiment appeared to be the cause for this yield response. Both of these amendments caused the initial pH to rise above 8 at the highest rates, but

pH decreased to less than 7 by the end of the experiment. Yields with 8% Mg-G were consistently lower than with 8% Ca-G which would appear to be the result of higher EC's with the Mg-G amendment. Because these parameters were not measured in the surface layer during the course of the experiment, correlations between yield response and pH and EC cannot be firmly established.

Even though the yield reductions caused by excessive application of Mg-G were temporary under greenhouse conditions, they may be critical in determining the success or failure of vegetation establishment in the field. Larger application rates, however, have a greater potential for amelioration of subsurface phytotoxicity and may thereby improve the potential for long-term vegetation survival. Therefore, a balance between these two objectives would need to be sought when selecting an optimal field application rate for Mg-G.

Addition of compost to the Mg-G, Ca-G and AL amendments decreased orchardgrass growth in early stages of the experiment (Fig. 26). The yield reduction was greatest in the first harvest, became less in the second and third harvests, and had disappeared in the fourth harvest. Only with 252 g kg^{-1} of 8% Mg-G did the compost yield suppression persist through the fourth harvest (Fig. 27). The detrimental effect of compost on plant growth at the beginning of the study may be attributed to immobilization of inorganic N fertilizer. Plants grown with compost showed evidence of severe N-deficiency at the first harvest. These symptoms disappeared with the addition of inorganic fertilizer N following the first harvest. Therefore, although compost-gypsum interactions exhibited clear benefits for amelioration of surface and subsurface phytotoxicity, initial immobilization of N by compost could greatly reduce the probability of successful revegetation in the field. It would appear, however, that the problem of N-immobilization could be easily overcome by supplying additional inorganic fertilizer N at the time of compost application. The use of compost with either a lower C/N ratio or a higher total N content would also likely eliminate this problem.

Adding compost to the unamended spoil or to the G-treated spoil, by contrast, caused a major increase in plant growth (Fig. 26). Without compost, plants did not grow. With compost, all rates of G and the unamended spoil gave plant growth similar to or higher than that obtained with AL. This beneficial effect of compost was observed in all harvests.

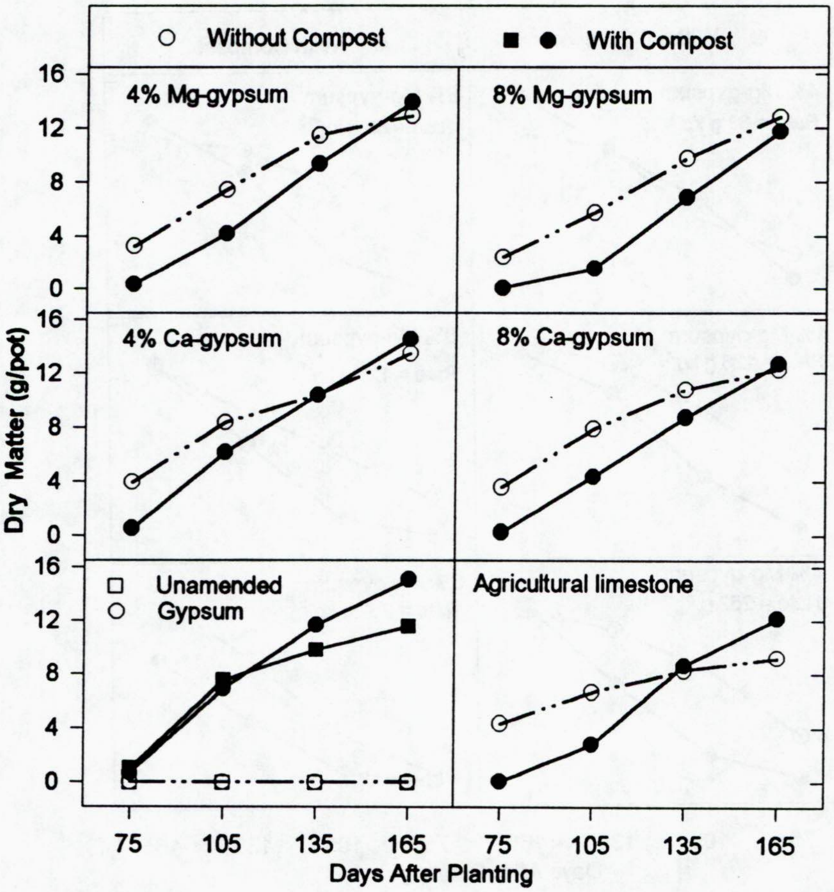

Figure 26. Effect of surface-applied G, Mg-G, Ca-G, and AL with and without compost on yield of orchardgrass in the AML experiment.

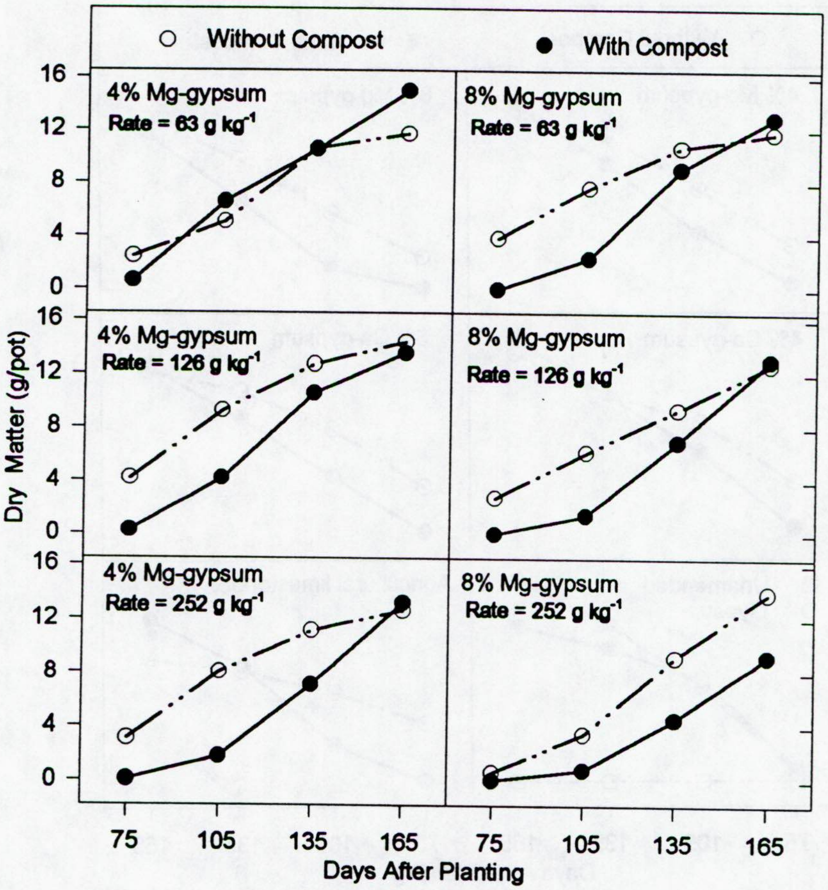

Figure 27. Effect of several rates of surface-applied Mg-G with and without compost on growth of orchardgrass in the AML experiment.

3.2.2 Reclaimed Mined Land (RML) Experiment

3.2.2.1 Treated Surface Soil Layer

pH

The effects of the various gypsum-based by-products and agricultural limestone on RML surface soil pH were similar to those observed in the AML study (section 3.2.1.1). The relatively pure by-product gypsum (G) had no effect on pH either initially or at the end of the study (Fig. 28). The gypsum materials with added alkalinity in the form of either $Mg(OH)_2$ or $Ca(OH)_2$ produced similar increases in soil pH with increasing application rates. With both Mg-G and Ca-G the largest pH response was produced by the 8% blends. The 160 g kg^{-1} application rates of both 4 and 8% Mg-G and Ca-G initially increased soil pH above 8. However, pH decreased during the course of the experiment and at the end was 7 or less for all amendments. The pH with ag-lime and gypsum did not change with time.

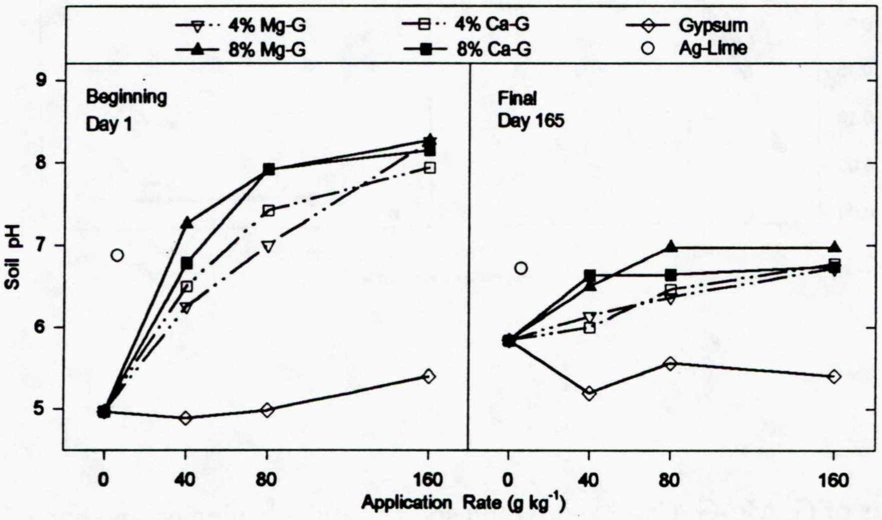

Figure 28. Effects of G, Mg-G, Ca-G and AL on soil pH at the beginning and end of the RML experiment.

Electrical Conductivity

All amendments, including agricultural limestone, increased soil EC compared to the unamended control at the beginning of the study (Fig. 29). In all cases, increasing the amendment rate from 40 to 160 g kg^{-1} did not cause further increases in EC. Among the gypsum-based amendments the largest increases in EC occurred with 8% Mg-G, intermediate increases with 4% Mg-gypsum, and the smallest with G and Ca-G. The effect of AL on soil EC was less than any of the gypsum-containing amendments. These results are consistent with those observed in the AML experiment where the presence of increasing amounts of Mg was found to increase EC. Due to the leaching of soluble salts, soil EC decreased during the course of the experiment. By the conclusion of the experiment, the increases in EC due to the gypsum-based amendments were small and similar among the various materials. These data suggest that any increase in EC from application of gypsum or Mg-enriched gypsum will be a temporary phenomenon.

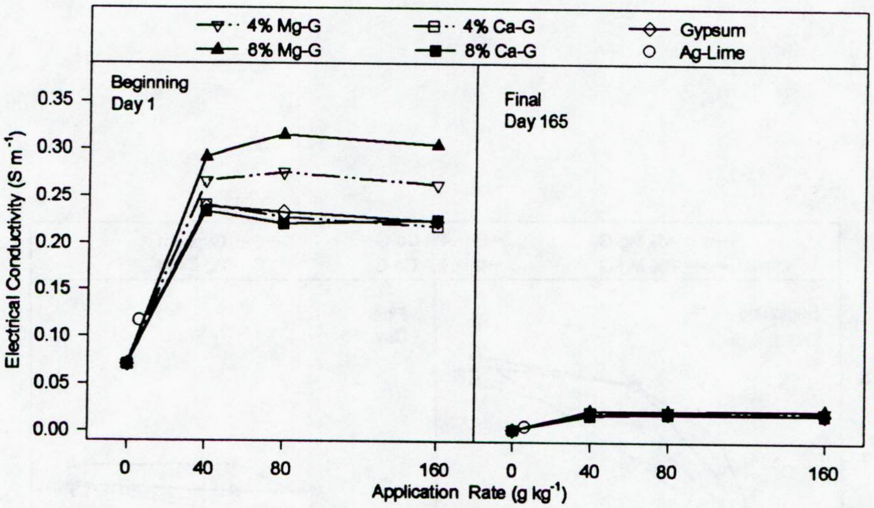

Figure 29. Effects of G, Mg-G, Ca-G and AL on soil EC at the beginning and end of the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.2.2 Column Leachate Chemistry

pH

The leachate pH, which ranged from 3.1 to 3.6 during the course of the study, showed little change due to amendment application (Fig. 30). The use of 160 g kg^{-1} of 8% Mg-G and Ca-G increased leachate pH from 3.4 in the unamended soil to 3.6 in the third harvest, and from 3.2 to 3.5 in the fourth harvest. This small, but measurable increase in pH suggests there was some movement of alkalinity from the treated layer to the untreated subsoil or that there was a decrease in acidity due to leaching of Al^{3+} and H^{+}. Ag-lime had no effect on leachate pH.

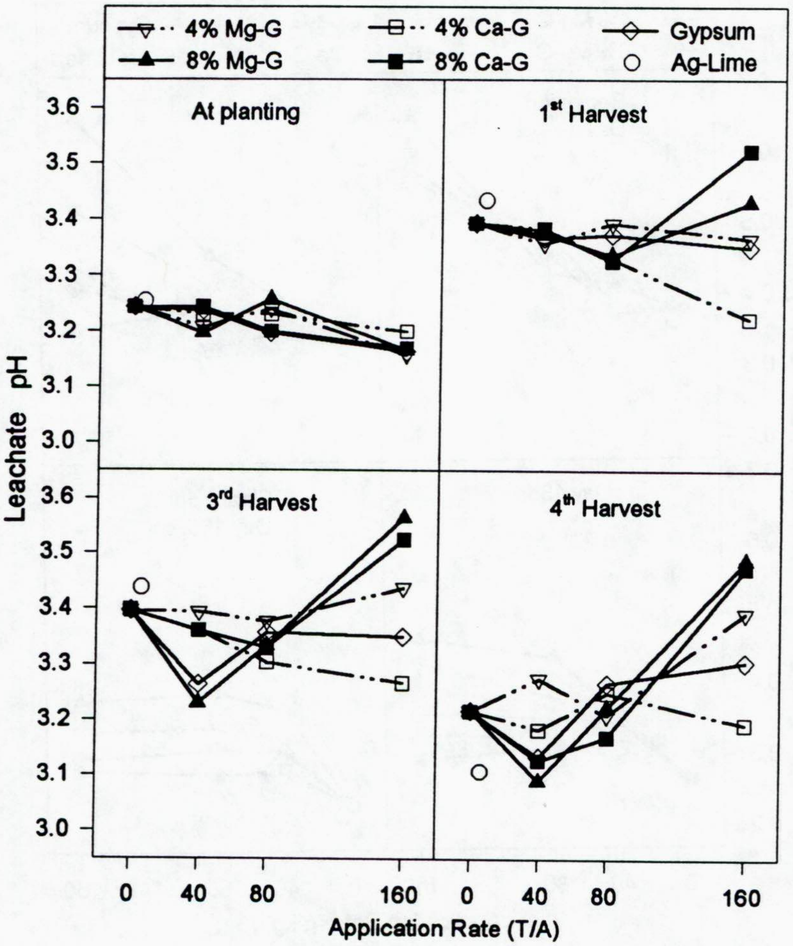

Figure 30. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on the pH of column leachates from the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Electrical Conductivity

The column leachate EC increased with increasing application rates of all the gypsum-based by-products (Fig. 31). Leachate EC responses to surface treatments were similar to results from saturation extracts of the surface layer (Fig. 29). Gypsum with 8% $Mg(OH)_2$ produced the largest EC increases, 4% Mg-G produced intermediate increases, and G and both 4 and 8% Ca-G produced smaller increases. There was no effect on leachate EC by surface amendment with Ag-lime. Leachate EC decreased with time in all treatments as salt concentrations were reduced by leaching.

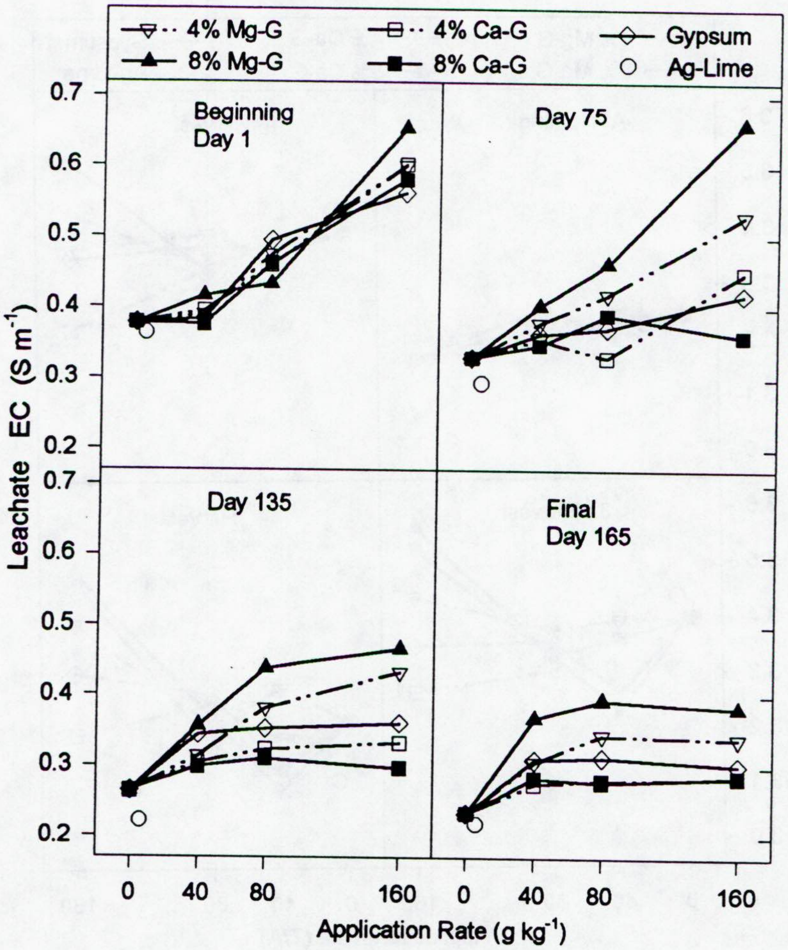

Figure 31. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on the EC of column leachates from the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Calcium

Each of the gypsum-based amendments caused similar, large increases in Ca concentrations of the leachates collected at the beginning of the experiment (Fig. 32). In subsequent leachings, however, amendment effects on leachate Ca changed substantially. In the leachates collected after 75 days 4% Ca-G caused an increase in Ca, 8% Ca-G and G had no effect on soluble Ca, and the Mg-G amendments caused a decrease in leachate Ca. In the 135 and 165 day leachates this pattern continued except that 4% Ca-G also showed no effect on leachate Ca. This trend of decreasing Ca in response to the gypsum amendments is counter to that observed in the AML experiment where leachate Ca tended to increase with time (Fig. 16). While the reason for the different response in the two experiments is not clear, it may be due to the much lower acidity of the RML soil and spoil compared to the AML spoil. The more alkaline RML system may have resulted in less dissolution of the amendments than occurred in the AML columns.

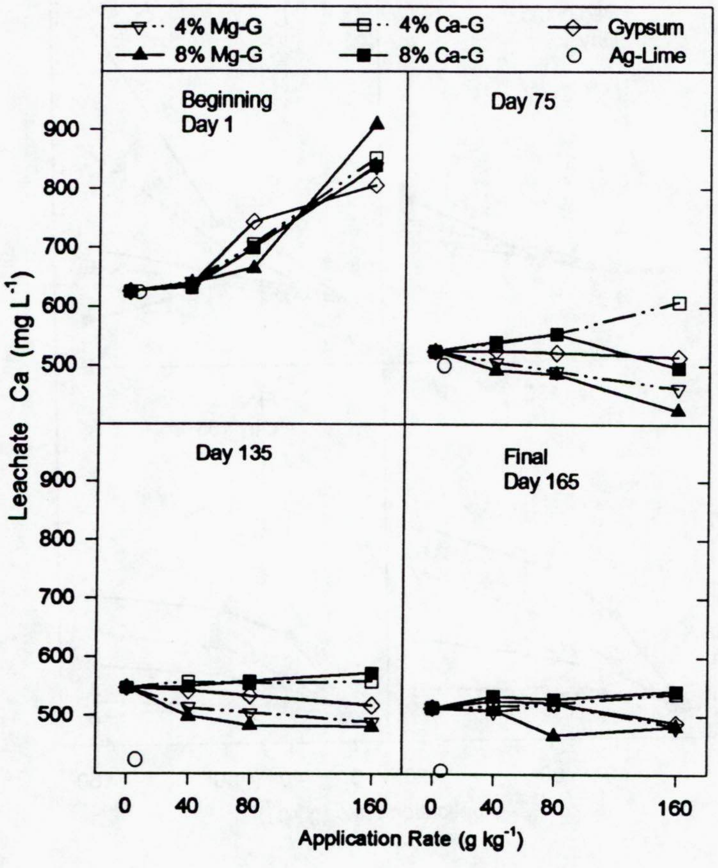

Figure 32. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on calcium concentrations in leachates from the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Magnesium

Leachate Mg concentrations were directly related to the amount of Mg added in the surface amendments. The largest increases resulted from 8% Mg-G, intermediate increases from 4% Mg-G, and the smallest increases from Ca-G and G (Fig. 33). The small increases in Mg from G and Ca-G were most likely due to displacement of native Mg from the soil exchange complex. These results are similar to those observed in the AML experiment (Fig. 17), and again indicate that Mg is very mobile when it is added with gypsum. These results also indicate that surface amendment with Mg-G will cause a pulse of soluble Mg to move through the profile. The magnitude, duration, and rate of movement of the Mg pulse will be dependent on amendment rate and soil hydrologic characteristics.

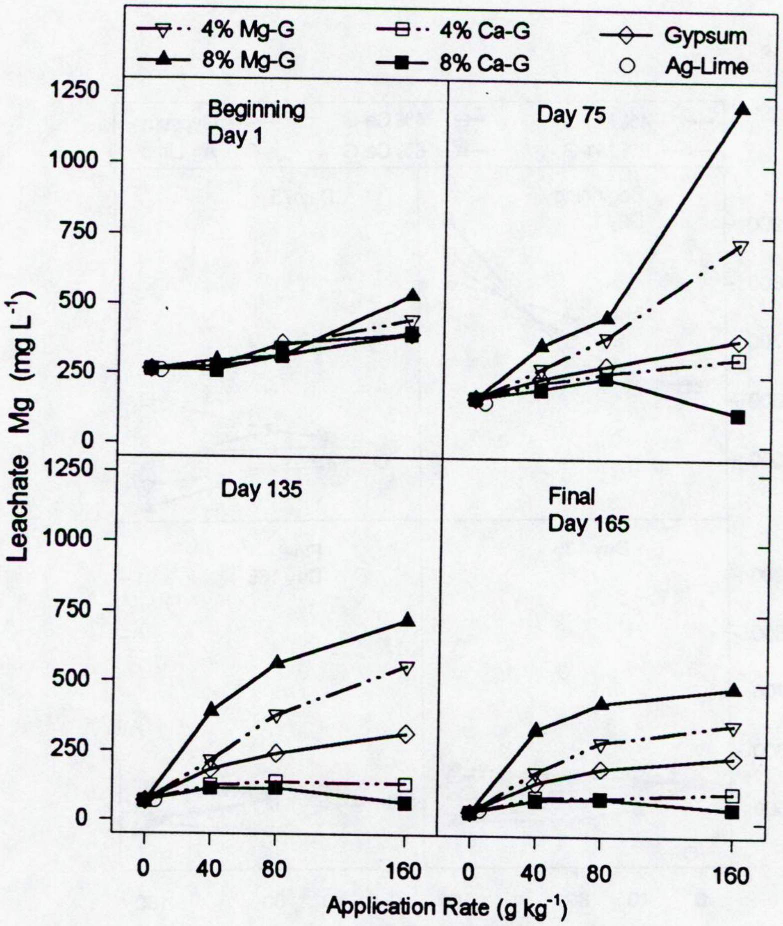

Figure 33. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on magnesium concentrations in leachates from the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Sulfur

Amendment effects on leachate S were similar to the effects on leachate Mg, which again indicated these elements moved through the column as the $MgSO_4^0$ complex (Fig. 34) when amendments contained $Mg(OH)_2$. As in the AML experiment, S concentrations were larger than the Mg concentrations (1.9 to 4.3 times larger on a molar basis). The largest differences occurred at low application rates where little Mg was present in the system. Thus, SO_4^{2-} was also moving in association with other cations, predominantly Ca^{2+} and Al^{3+}.

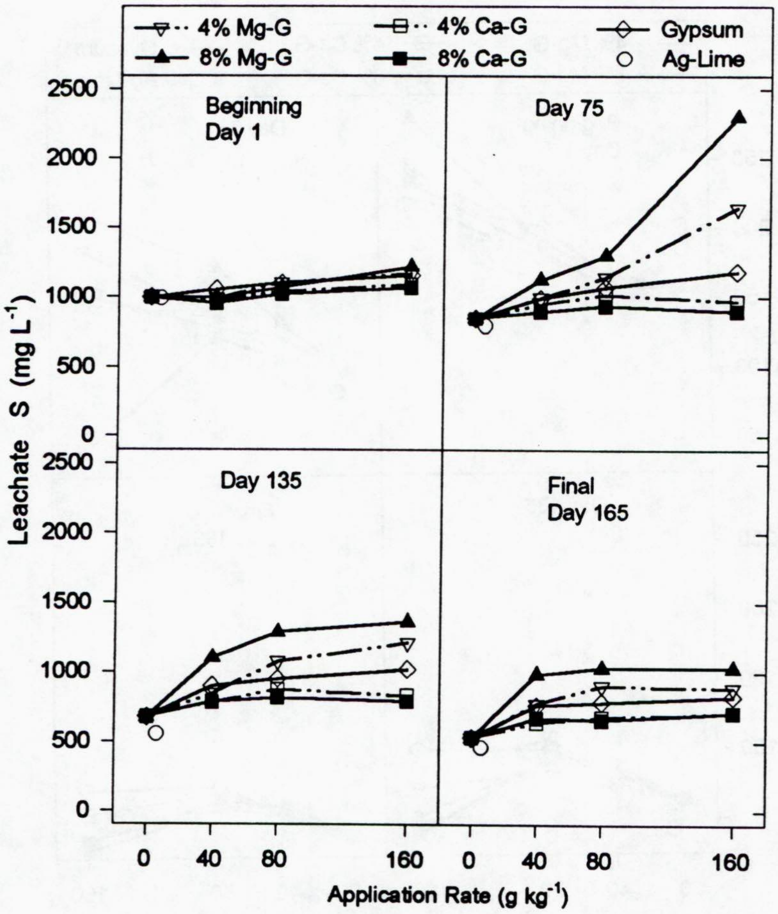

Figure 34. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on sulfur concentrations in leachates from the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Aluminum

Concentrations of Al in the leachates (Fig. 35) paralleled the total salt concentrations (Fig. 31) which were dominated by Ca (Fig. 32) and Mg (Fig. 33). Apparently, the most labile Al in the soil and spoil was mobilized through ion exchange with Ca and Mg and transported from the columns. This mechanism is substantiated by the decrease in exchangeable Al noted in the subsurface layers (Fig. 38).

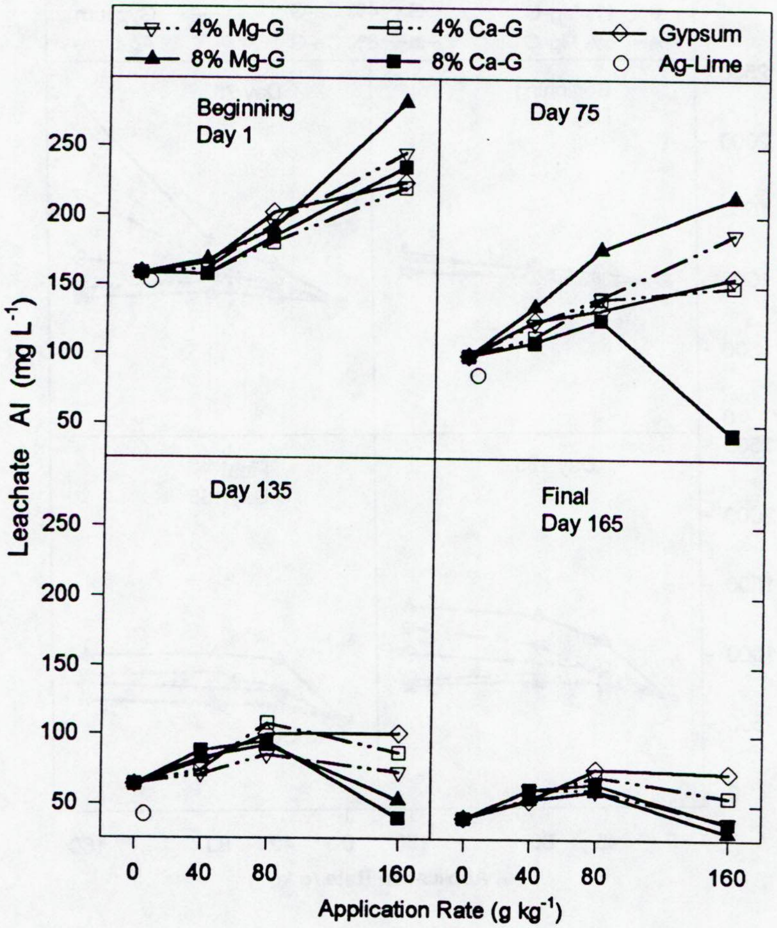

Figure 35. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on aluminum concentrations in leachates from the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Trace Elements

All the gypsum-based amendments increased Cd in the first leachates (Fig. 36). As was observed in the AML experiment, this effect appeared to be the result of initially large soluble salt concentrations mobilizing labile Cd in the RML materials. After 75 days, only 4% Ca-G caused an increase in leachate Cd, and in subsequent leachates no amendment increased leachate Cd. Lead concentrations in the leachates exhibited a similar response to that observed with Cd (Appendix B, Tables 23, 24, 26, and 27). Concentrations of As, Cu, and Cr were at background levels in all leachates.

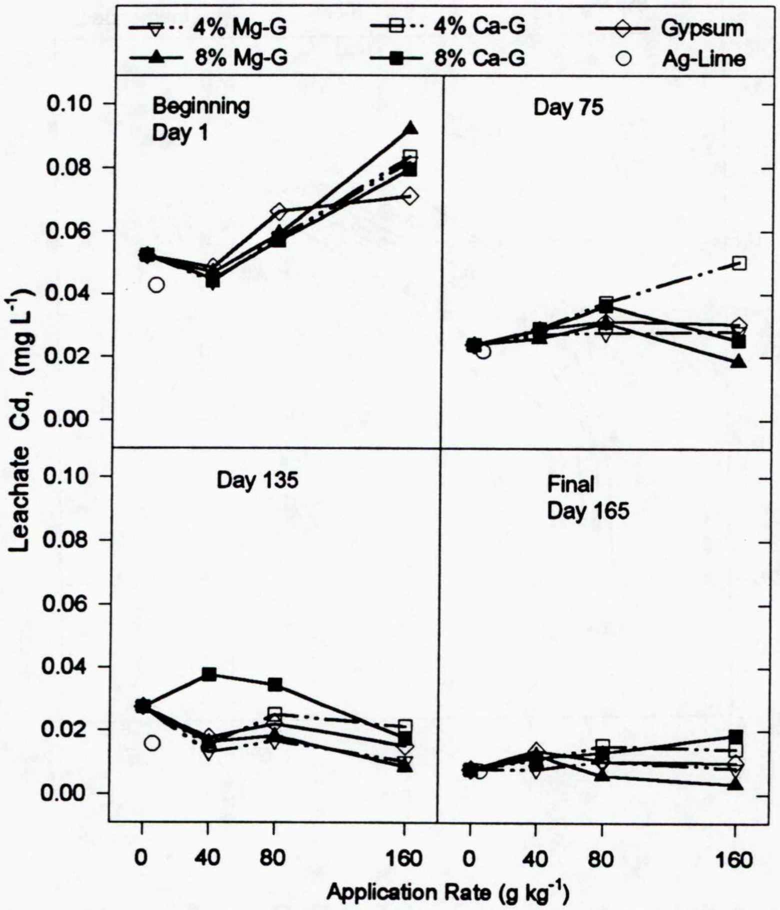

Figure 36. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on cadmium concentrations in leachates from the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.2.3 Untreated Subsurface Spoil Layer

pH

Surface amendments had little effect on subsurface pH with the exception of 8% Mg-G which increased the pH at a depth of 1-10 cm below the treated layer (Fig. 37). At this depth, spoil pH increased to 5.43 with 160 g kg^{-1} of 8% Mg-G (Appendix B, Table 21). By contrast, pH at the same depth was 3.8 in the unamended columns and with AL-amended material. The increase in pH with Mg-G was associated with a decrease in exchangeable Al (Fig. 38). It is not entirely clear from these data if there was downward movement of alkalinity with the 8% Mg-G, which caused the decrease in Al, or if removal of labile Al by exchange with Ca and Mg caused an increase in pH. Both the increased pH and decreased Al in the subsurface spoil represent a potential decrease in phytotoxicity from surface application of Mg-G.

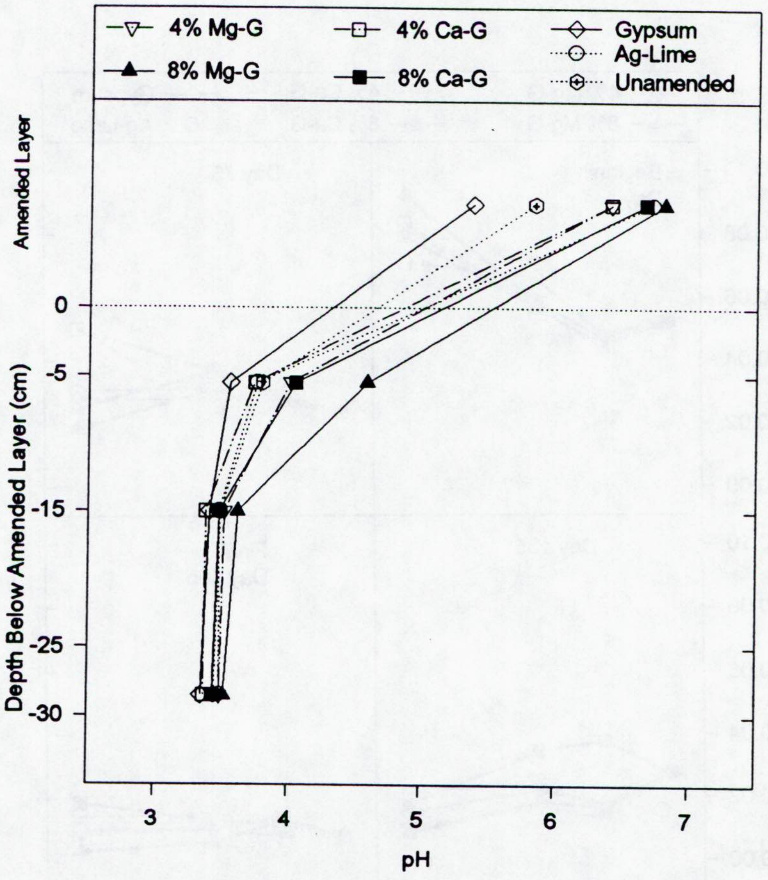

Figure 37. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the distribution of soil and spoil pH at the conclusion of the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Aluminum

Each of the amendments caused some reduction in exchangeable Al in the spoil at a depth of 1 to 10 cm below the amended surface soil (Fig. 38). However, only with the Mg-G material did this effect extend deeper in the column. The efficacy of the Mg-G in the displacement of subsurface Al was increased by doubling the amount of $Mg(OH)_2$ from 4 to 8%. Clearly, the addition of $Mg(OH)_2$ increased the ability of gypsum to displace subsurface Al. The mechanism for this enhanced reduction of subsurface Al appears to be exchange with Mg^{2+} driven by the large concentrations of Mg in the soil solution moving through the column. Evidence for this reaction is also provided by the large increases in subsurface exchangeable Mg which resulted from surface application of Mg-G (Appendix B, Table 22).

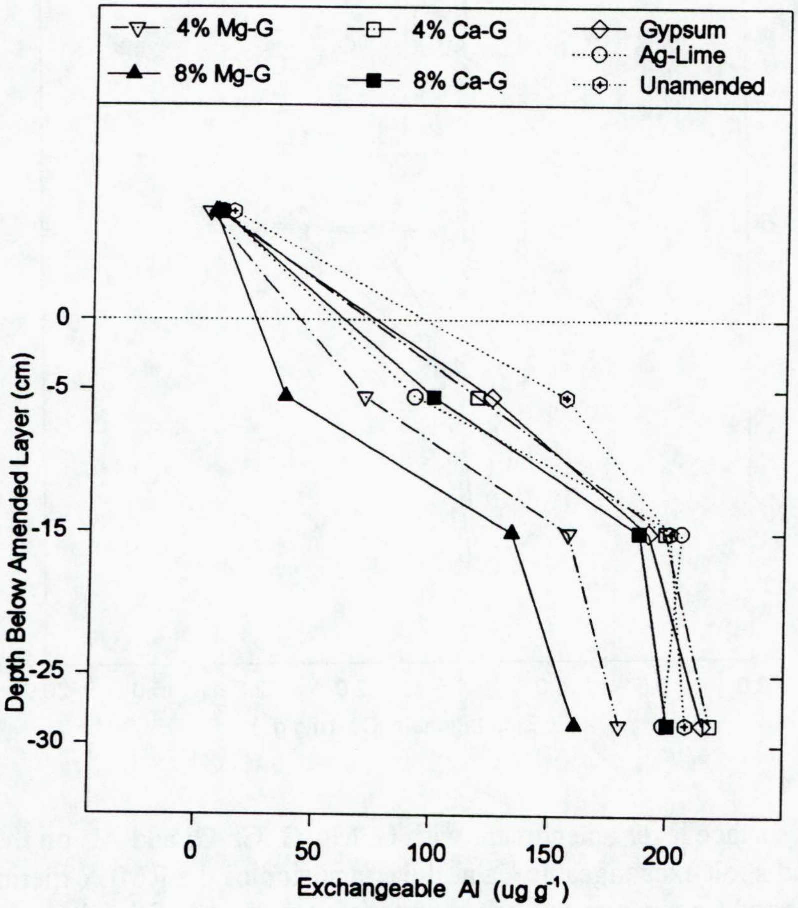

Figure 38. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the distribution of soil and spoil exchangeable Al at the conclusion of the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Calcium

Surface layer exchangeable Ca was greatly increased by each of the gypsum-based amendments, while a much smaller increase resulted from AL application (Fig. 39). The gypsum-based amendments were also more effective than AL in increasing subsurface exchangeable Ca. The Ca-G amendments caused larger increases in exchangeable Ca than did the Mg-G amendments in the 10 cm of spoil subjacent to the treated layer. This difference is likely due to competition between Ca and Mg for exchange sites when the Mg-G materials were used.

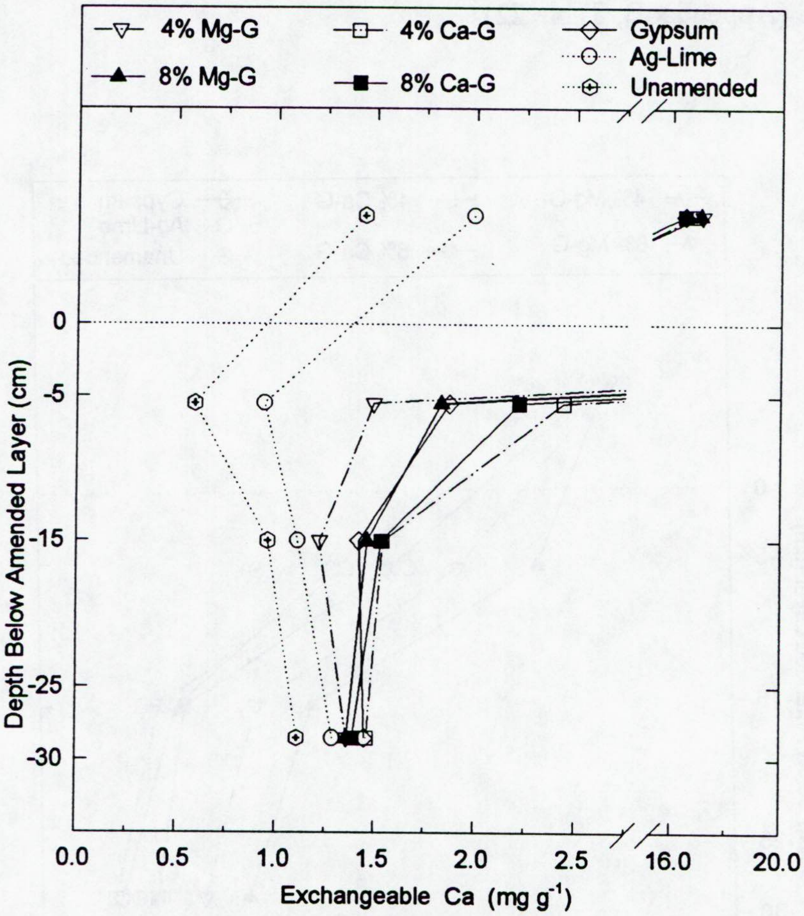

Figure 39. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the distribution of soil and spoil exchangeable Ca at the conclusion of the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Magnesium

Surface layer exchangeable Mg was increased relative to the unamended soil only by 8% Mg-G, and was not affected by 4% Mg-G (Fig. 40). All other amendments decreased surface layer exchangeable Mg. Both 4% and 8% Mg-G increased subsurface exchangeable Mg at all measured depths. Similar results were obtained in both the AML and AS experiments (Figs. 24, 53, and 54). The large increases in subsurface Mg substantiate the hypothesis that the enhanced ability of Mg-G to decrease subsurface Al resulted from the greater solubility of Mg in the presence of SO_4^{2-}.

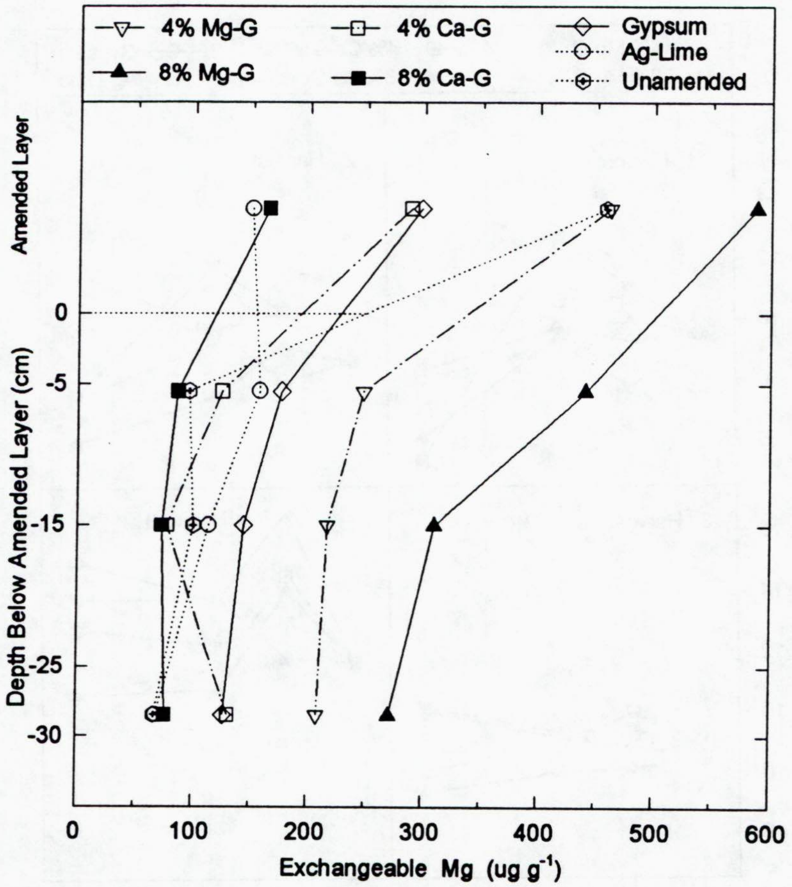

Figure 40. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the distribution of soil and spoil exchangeable Mg at the conclusion of the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.2.4 Orchardgrass Growth

With the exception of a negative effect on plant growth in the first two harvests by application of 160 g kg^{-1} 8% Mg-G and Ca-G, none of the gypsum-based amendments had a clear effect on orchardgrass growth (Fig. 41). The yield suppression by large amounts of 8% Mg-G and Ca-G were likely due to the high pH and EC at the beginning of the experiment (Fig. 28). The general absence of a yield effect from all amendments was likely due to the fact that the surface soil was only mildly acidic and all required water and plant nutrients were supplied throughout the experiment. Therefore, the plants were able to obtain all nutritional requirements from the surface layer.

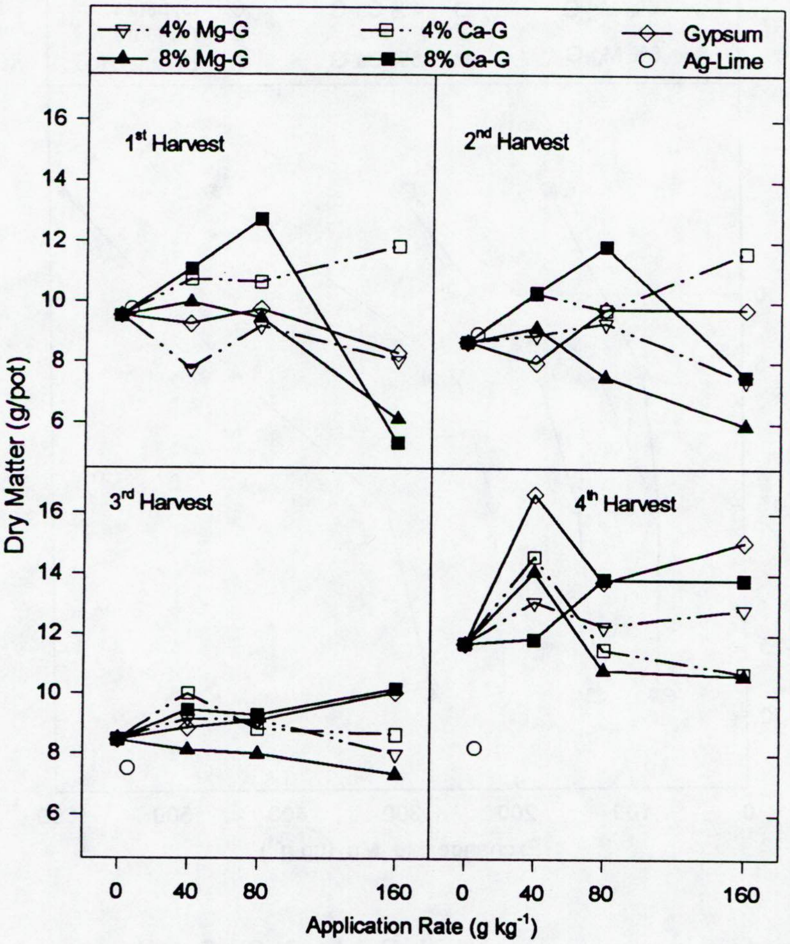

Figure 41. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on orchardgrass growth in the RML experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.3 Agricultural Soil (AS) Experiment

3.2.3.1 Treated Surface Soil Layer

pH

All amendments, except for G, increased the surface soil pH compared to the unamended soil (Fig. 42). Soil pH subsequently decreased throughout the experiment with all amendments. There was little difference in the pH response between applications of gypsum with alkalinity added in the form of $Ca(OH)_2$ vs. $Mg(OH)_2$. The slightly higher pH with $Ca(OH)_2$ at the beginning of the experiment was due to the fact that $Ca(OH)_2$ is approximately 200 times more soluble than $Mg(OH)_2$ and thus more reactive. This effect was short-lived. By the end of the experiment, Mg-G and Ca-G gave similar pH increases with the 8% material resulting in a larger pH increase than the 4% material. Both Mg-G and Ca-G were able to produce a sustained pH increase equivalent to that achieved with agricultural limestone.

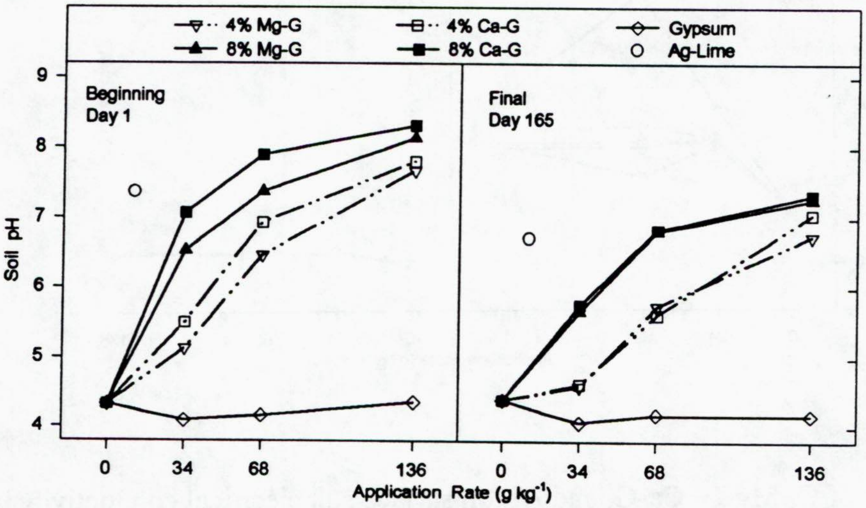

Figure 42. Effect of G, Mg-G, Ca-G, and AL on surface soil pH in the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Electrical Conductivity

All amendments except AL increased the surface soil EC at the beginning of the study compared to the unamended soil (Fig. 43). For all the gypsum-based amendments, with the exception of 8% Mg-G, soil EC appeared to be independent of application rate. With each of these amendments, soil EC tended to be in the range of 0.22 to 0.24 S m^{-1}. Similar EC levels were observed in both the AML and RML experiments which used larger application rates. This again indicates that soluble salt levels are controlled by gypsum solubility where Mg is not a major constituent in the system. Addition of Mg greatly increased the soluble salt load in each experiment due to the greater solubility of $MgSO_4$ relative to $CaSO_4$. Soil EC was considerably reduced with time due to downward transport of salts in the leachates. At the end of the experiment, there were only minimal increases in EC with any amendment.

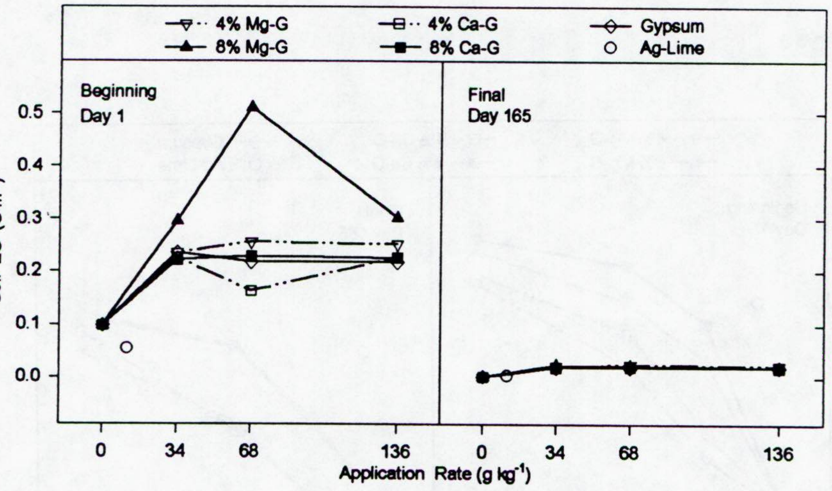

Figure 43. Effect of G, Mg-G, Ca-G, and AL on surface soil electrical conductivity in the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.3.2 Column Leachate Chemistry

pH

The leachate pH ranged between 3.7 and 4.5 during the course of the study (Fig. 44). Each of the gypsum-based amendments decreased the leachate pH compared to the unamended control or the soil treated with AL. Although this effect was observed throughout the experiment, it became more pronounced with each leaching event. The use of 136 g kg^{-1} compared to 34 g kg^{-1} material accentuated, when averaged across all types of FGD-amendments, the drop in pH in all but the last leachate.

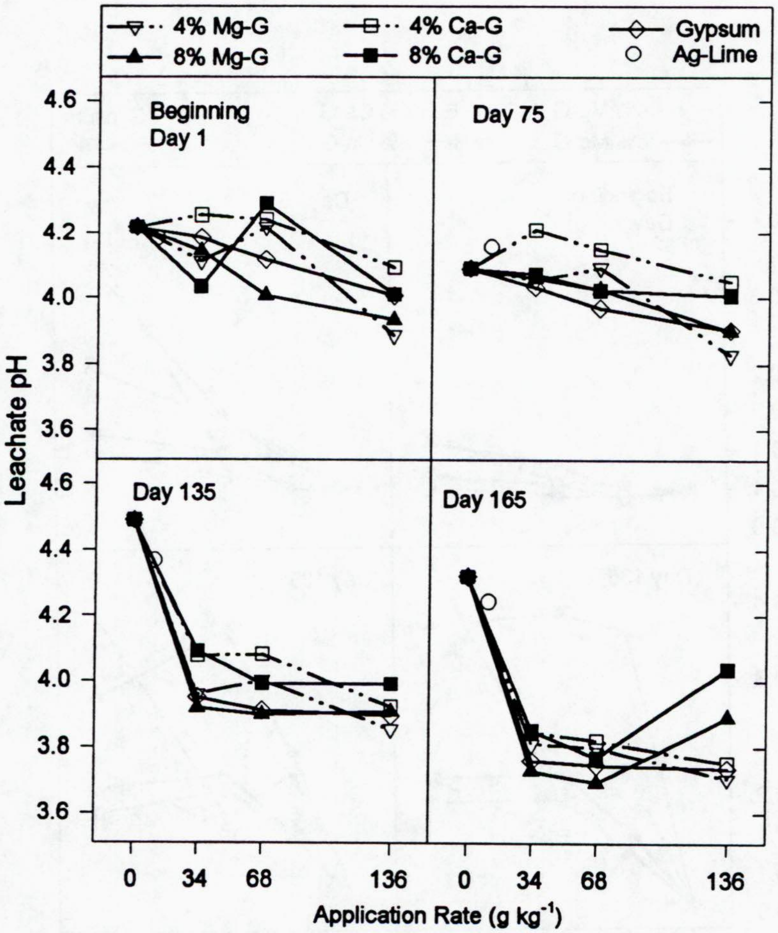

Figure 44. Effects of surface layer amendment with G, Mg-G, Ca-G, and AL on the pH of column leachates from the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Electrical Conductivity

Leachate EC was increased by the gypsum-based amendments in every leaching event; however, the amendment effect on EC gradually increased with time (Fig. 45). This response was opposite to that observed in the AML and RML experiments where leachate EC was highest in the first leaching and decreased with time. The much slower downward transport of surface applied salts in the soil columns relative to the rapid transport in the AML and RML spoil columns is likely due to the finer textured material in the AS columns. The spoil materials contained a greater proportion of coarse fragments which could have allowed leachates to move rapidly through the column via preferential flow paths with little interaction with the soil matrix. Although infiltration rates were not measured, casual observation indicated slower infiltration and hydraulic conductivity in the AS columns.

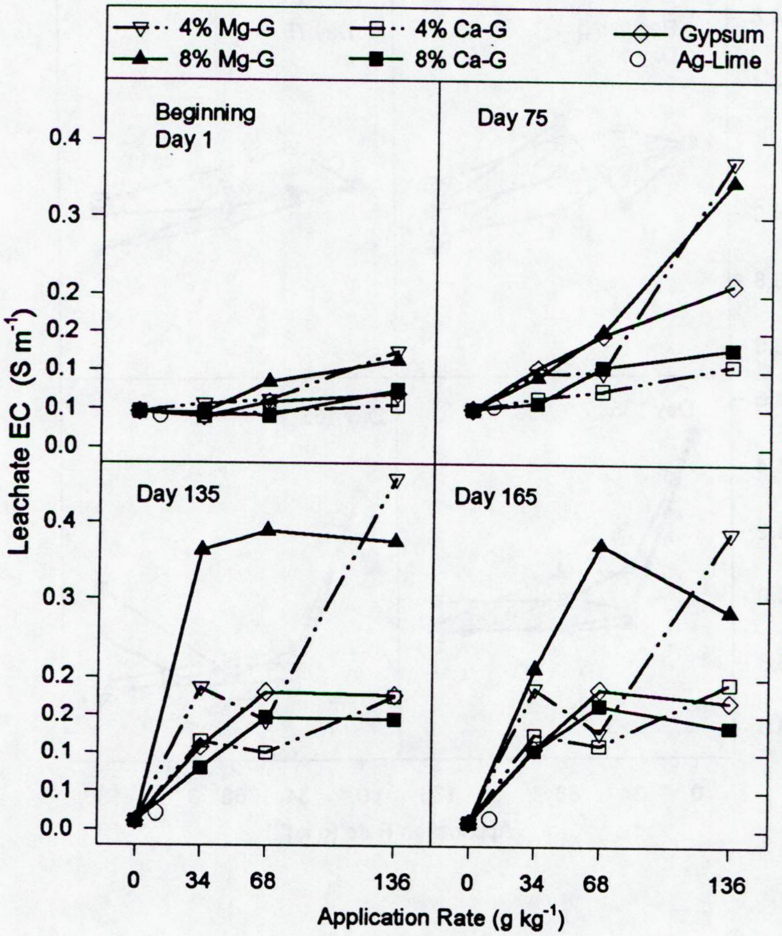

Figure 45. Effects of surface layer amendment with G, Mg-G, Ca-G, and AL on the EC of column leachates from the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Calcium

Each of the gypsum-based amendments increased leachate Ca, whereas agricultural limestone had no effect on the transport of Ca from the AS columns (Fig. 46). The overall tendency for the gypsum-based amendments to increase leachate Ca was similar to that observed in the AML and RML experiments. However, the effect of the individual gypsum amendments on the magnitude of Ca transport was quite different. In the AS experiment, Mg-G increased (more than either G or Ca-G) leachate Ca in both the day 1 and day 75 leachings. The differences in leachate Ca among the various gypsum amendments decreased in the day 135 and day 165 leachings. This behavior was different from the other experiments. In the AML study, all gypsum materials behaved similarly throughout the time course, whereas Mg-G tended to decrease Ca transport in the RML study.

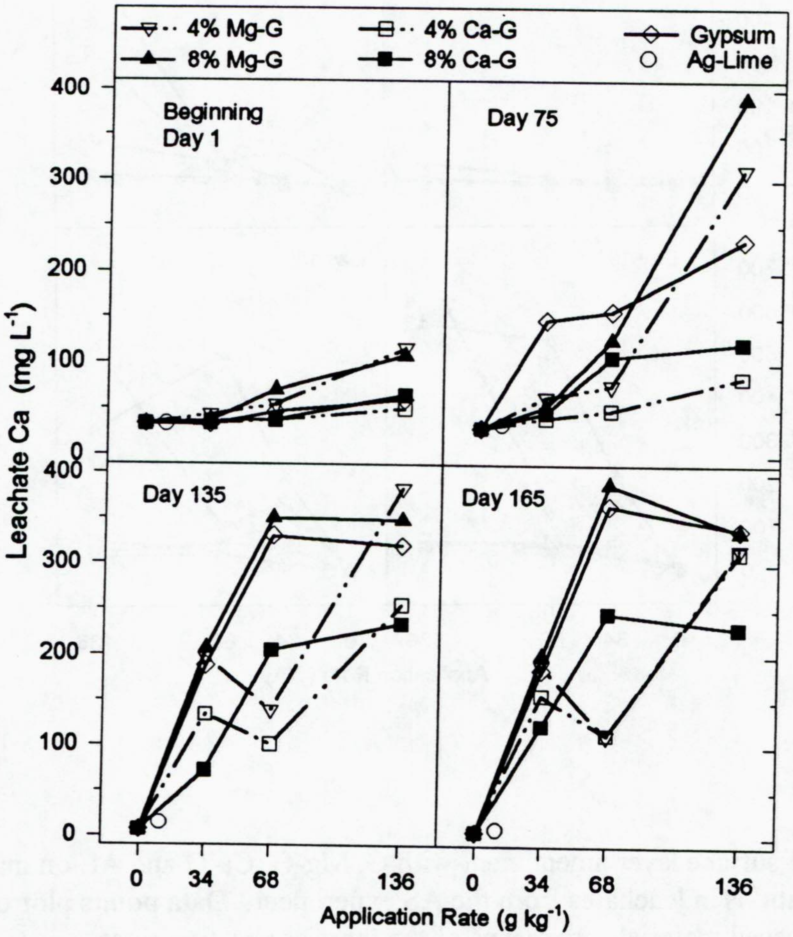

Figure 46. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on calcium concentrations in leachates from the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Magnesium

Surface amendment with Mg-G clearly increased leachate Mg, and the 8% blend consistently produced the largest increases at all rates (Fig. 47). These results are consistent with the AML and RML experiments. However, as was observed with the overall salt concentrations (EC), transport of Mg from the surface down through the unamended soil layers was slower in the AS columns than in the unamended spoil of the AML and RML experiments.

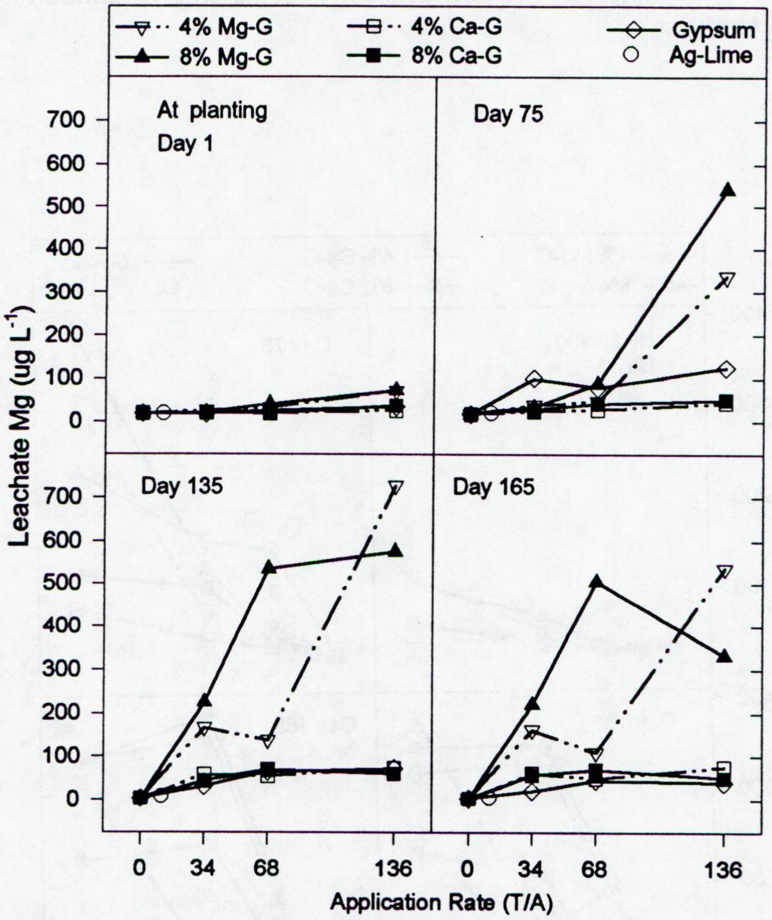

Figure 47. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on magnesium concentrations in leachates from the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Sulfur

While each of the gypsum-based amendments increased leachate S concentrations (Fig. 48), the large increases in the day 75, 135 and 165 leachates were clearly associated with the mobilization and transport of Mg from the Mg-G amendments. With G and Ca-G, leachate S concentrations paralleled changes in leachate Ca. Apparently, when large amounts of Mg were present, S concentrations were controlled by epsomite ($MgSO_4 \cdot 7H_2O$) solubility, whereas in the absence of Mg, S concentrations were controlled by gypsum ($CaSO_4 \cdot 2H_2O$) solubility.

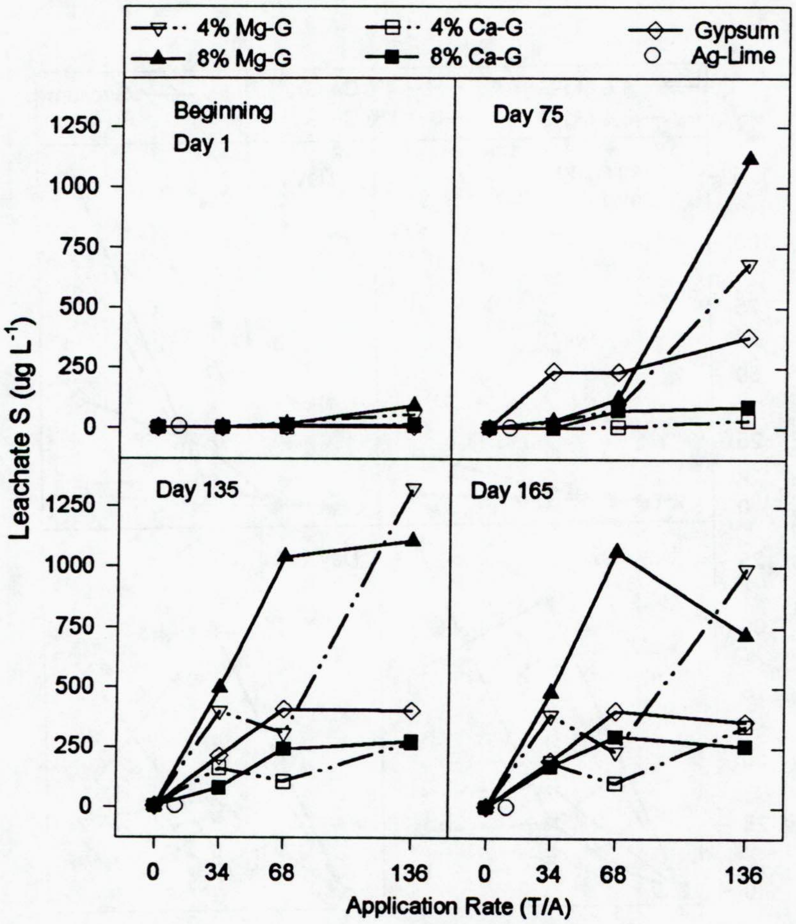

Figure 48. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on sulfur concentrations in leachates from the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Aluminum

Each of the gypsum-based amendments increased Al concentrations in the leachates, whereas agricultural limestone had no effect on leachate Al (Fig. 49). Mobilization of Al from the subsurface layers was clearly associated with the overall salt load of the leachates and specifically with the major ions such as SO_4^{2-}, Ca^{2+}, and Mg^{2+}. These data again support the hypothesis that Al mobilization and downward transport were due to exchange of labile Al with Ca and Mg. The large concentrations of Mg which resulted from application of Mg-gypsum clearly resulted in greater exchange and movement of Al. The associated concentrations of SO_4^{2-} may have increased the mobility of Al^{3+} by the formation of ion pairs with lower or no charge. Increases in subsurface exchangeable Ca and Mg and decreases in subsurface exchangeable Al lend further support to this hypothesis.

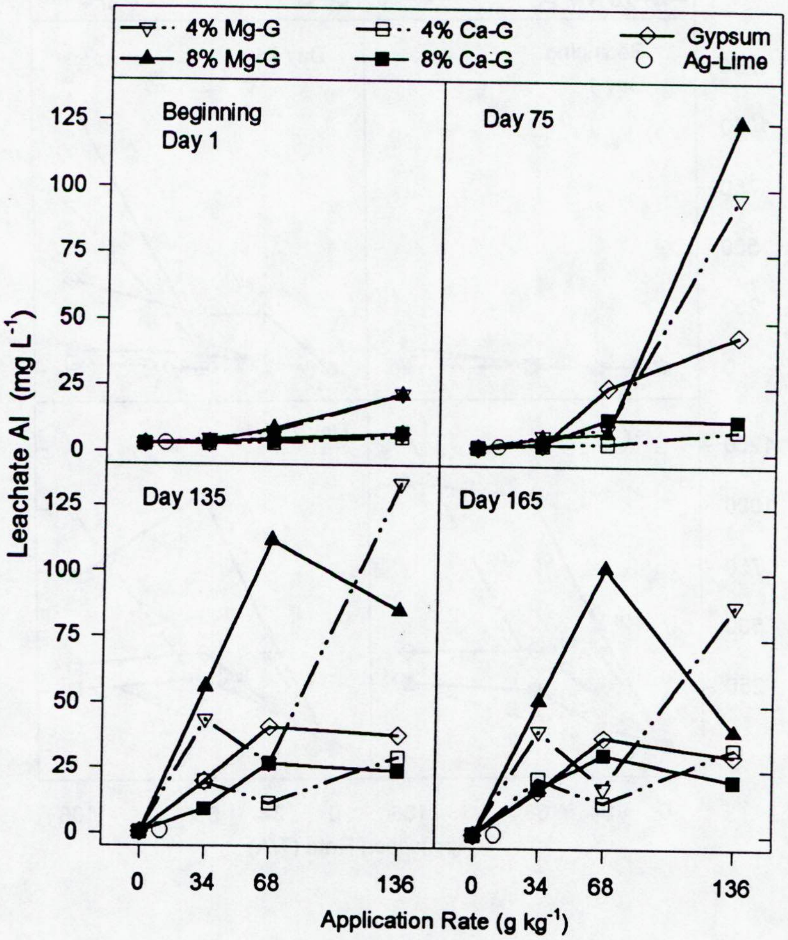

Figure 49. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on aluminum concentrations in leachates from the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Trace elements

Leachate concentrations of several trace elements were increased by the gypsum-based amendments and also changed with time (Appendix C, Tables 34, 35, 37, and 38). Arsenic concentrations were increased by Mg-G but decreased to background level with time. Although Cu and Cr were affected by the gypsum amendments, leachate concentrations remained near background levels in all leachates. Lead and Ni were increased by the gypsum-based amendments. The smallest effects occurred in the day 1 leachates and larger increases were observed in day 135 and 165 leachates which corresponded to the increase in leachate soluble salt load. Amendment effects on leachate Pb and Ni were similar to those for Cd (Fig. 50). This correlation between trace element concentrations and leachate dissolved salts again indicates the increase is due to mobilization of trace elements associated with the native soil.

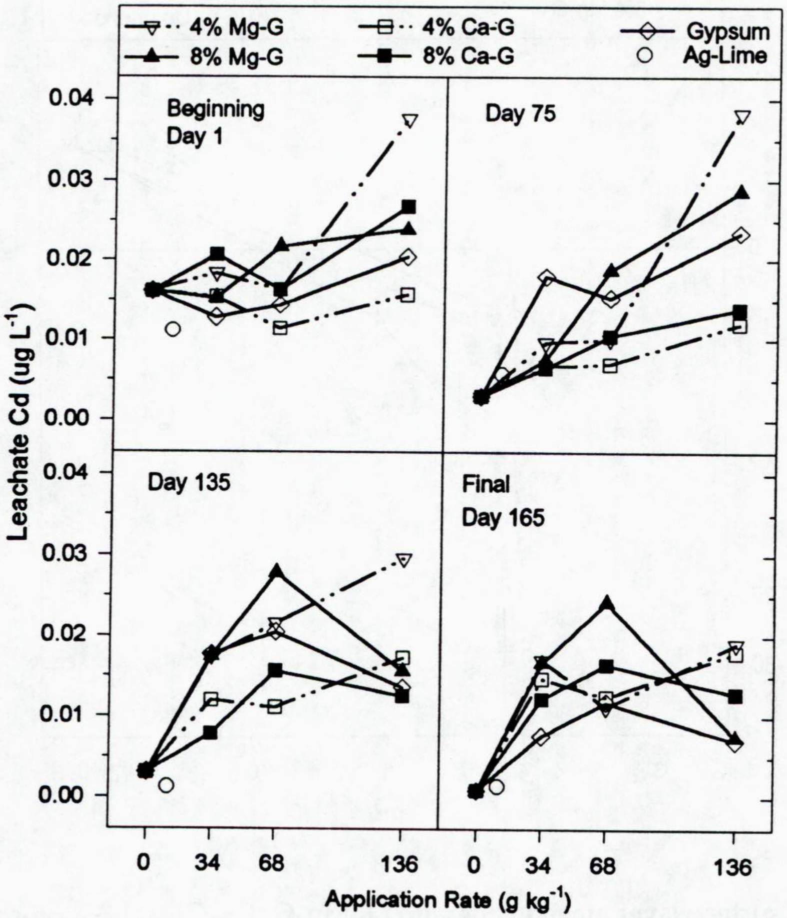

Figure 50. Effects of surface layer amendment with G, Mg-G, Ca-G and AL on cadmium concentrations in leachates from the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.3.3 Untreated Subsurface Soil Layers

pH

Although each of the alkaline materials was effective in increasing soil pH in the amended surface soil, they had very little effect on soil pH below the amended layer (Fig. 51). The only material to increase subsoil pH was 8% Mg-G, and that effect was limited to the 10 cm of soil immediately below the amended surface layer. With this exception, all the gypsum-based materials decreased subsurface soil pH relative to the unamended and the AL-amended soil columns. Some of that decrease may be a salt-induced pH effect which would not have been present in the much lower salt environment of the unamended and AL-amended soils.

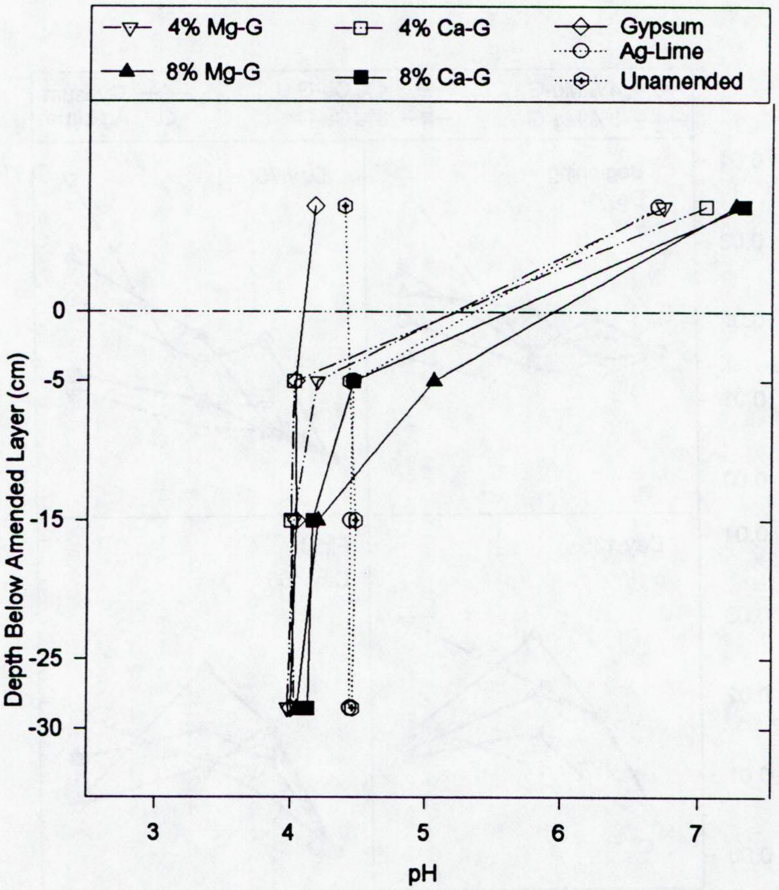

Figure 51. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on soil pH at the conclusion of the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Aluminum

All the amendment materials decreased exchangeable Al in the soil surface layer, but only the gypsum-based materials decreased exchangeable Al in the subsoil (Fig. 52). The decrease in exchangeable Al extended to a depth of 19 cm below the amended layer. While this effect was most pronounced with 8% Mg-G, 4% Mg-G and 8% Ca-G also appeared to be more effective than G at reducing subsurface exchangeable Al. These results are consistent with those observed in the AML and RML experiments, and demonstrate that the presence of Mg with gypsum enhances the efficacy of gypsum to ameliorate subsoil phytotoxicity associated with exchangeable Al.

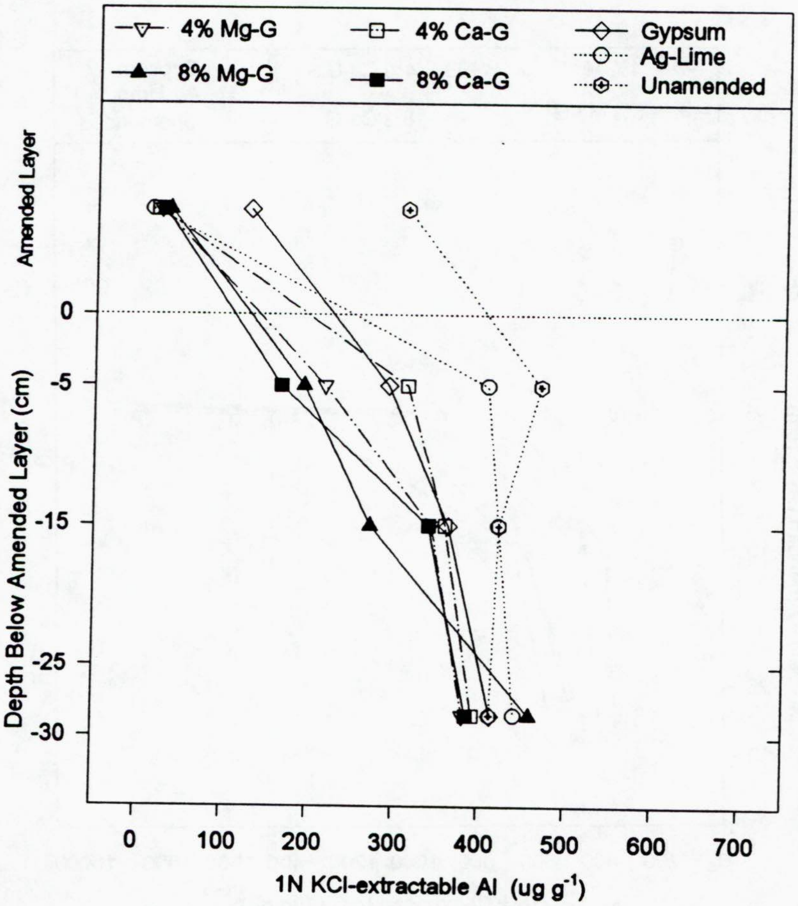

Figure 52. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the distribution of exchangeable Al at the conclusion of the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Calcium

Each of the gypsum-based amendment materials increased exchangeable Ca relative to both the unamended soil and the AL-amended soil (Fig. 53). The largest increases occurred with the Ca-G and G materials, and somewhat smaller increases were produced by the Mg-G materials. The lower subsurface exchangeable Ca with Mg-G was likely due to the large solution concentrations of Mg^{2+} with these amendments which would have decreased Ca^{2+} sorption due to increased sorption of Mg^{2+} on cation exchange sites (Fig. 54).

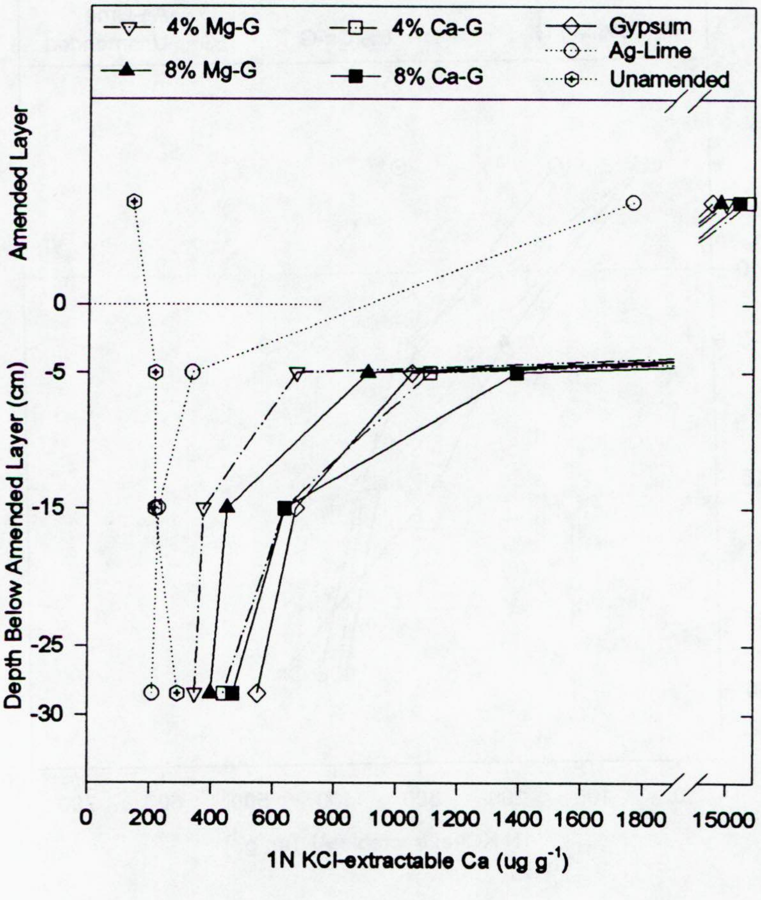

Figure 53. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the distribution of exchangeable Ca at the conclusion of the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

Magnesium

Increases in subsurface exchangeable Mg resulted from surface amendment with both 4 and 8% Mg-G (Fig. 54). Relatively small increases with the other amendments reflect the small level of Mg impurity in the by-product gypsum material. These data provide further evidence that the enhanced mobilization and transport of Al and the decrease in subsurface exchangeable Al with Mg-G is due primarily to $Al^{3+} \rightarrow Mg^{2+}$ exchange.

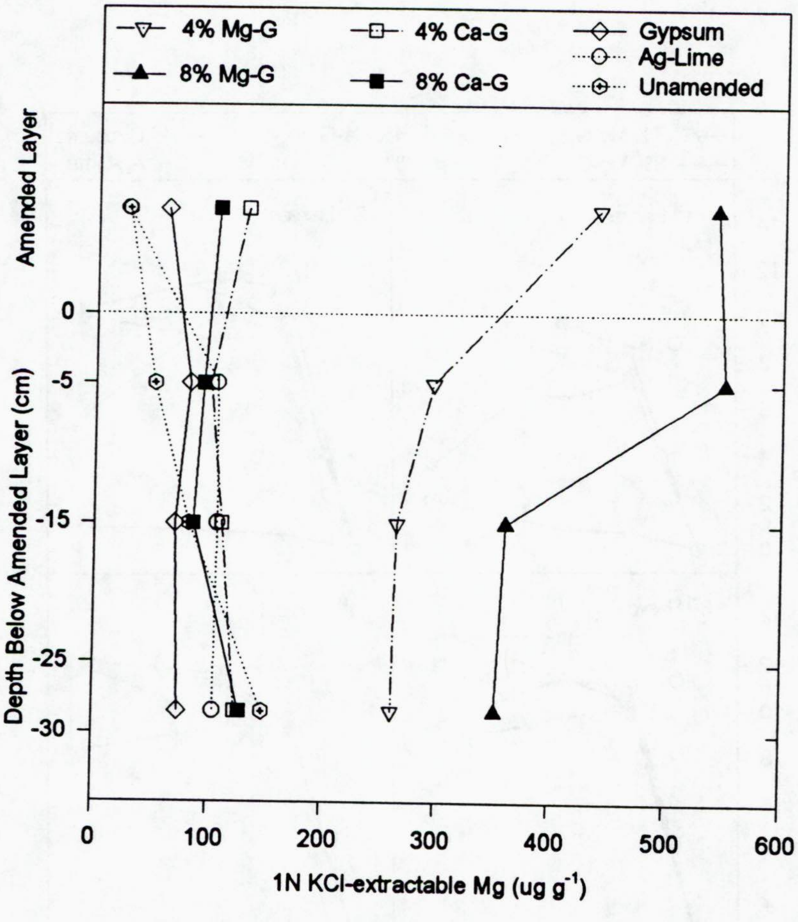

Figure 54. Effect of surface layer amendment with G, Mg-G, Ca-G, and AL on the distribution of exchangeable Mg at the conclusion of the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

3.2.3.4 Alfalfa Growth

Both Mg-G and Ca-G increased alfalfa growth to a level similar to that with AL, whereas G produced almost no increase in growth relative to the unamended soil (Fig. 55). Initially, there was a decline in alfalfa yield with application of the largest rates of 8% Mg-G and Ca-G which was likely a reflection of the initially high soil pH (>8) and large soluble salt concentrations with Mg-G. Both of these parameters decreased with time and thus the yield depression became less with each subsequent harvest and was no longer present at the fourth harvest. As was noted in both the AML and RML experiments, these responses of alfalfa growth to the amendments primarily reflect changes in the surface soil chemistry. Because the columns were adequately watered at all times, and mineral nutrients were applied to the soil surface following each harvest, the plants were able to meet their moisture and nutrition needs by exploiting only the surface soil layer. Therefore, amelioration of subsurface phytotoxicity had little if any effect on plant growth.

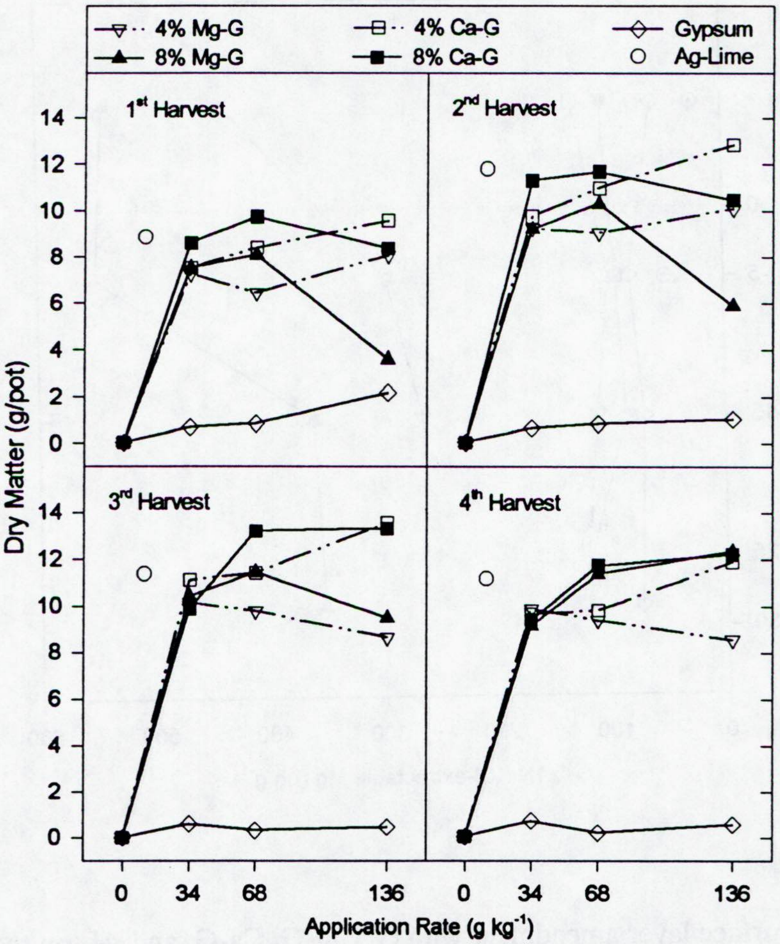

Figure 55. Effect of surface soil amendment with G, Mg-G, Ca-G, and AL on the growth of alfalfa in the AS experiment. Data points plotted for the gypsum-based materials are means of the three application rates.

4 CONCLUSIONS

Representative samples of by-product gypsum and magnesium hydroxide from the Miami Fort and Zimmer Station power plants were characterized in this study. The by-product gypsum was of high chemical purity and consisted of well-crystalline, lath-shaped particles having a specific surface area < 2 m^2 g^{-1}. By contrast, the by-product magnesium hydroxide was a high surface area material (50 m^2 g^{-1}) that contained 80% $Mg(OH)_2$ with $CaSO_4$ of variable hydration state as the primary contaminant. The pure gypsum and artificial blends containing 4% and 8% $Mg(OH)_2$ were used as surface amendments in a greenhouse study designed to test their effectiveness for alleviating toxicities produced by low pH and high exchangeable aluminum in soil and spoil materials typical of those occurring in eastern Ohio. Commercial agricultural limestone and laboratory calcium hydroxide were used as comparative treatments to separate the effects of added alkalinity and Ca/Mg nutrition on plant yields. A yard-waste compost was also added to some spoil materials in order to achieve a condition conducive to plant growth.

Samples from a native agricultural soil (AS), abandoned mine spoil (AML), and reclaimed mine soil (RML) were collected to construct greenhouse columns. Laboratory tests confirmed that the soil and spoil samples had initial pHs in the range of 3.0 to 5.0 and exchangeable aluminum contents equivalent to 30 - 50% of the total cation exchange capacities. Both topsoil and subsoil/spoil were used to reconstruct profiles comparable to those found in the field, and amendments were applied only to the surface layers.

Gypsum alone had no effect on the pH of the amended surface layers; however, gypsum with alkalinity added in the form of $Mg(OH)_2$ or $Ca(OH)_2$ produced similar, rapid pH increases. Although the pH response decreased with time, the final soil/spoil reactions were comparable to those achieved using conventional agricultural limestone. All amendments, including pure gypsum, caused a marked reduction in exchangeable Al within the surface layers of the AS, AML and RML columns. As expected, all amendments except agricultural limestone initially increased the electrical conductivity (total soluble salt load) of the treated surface layers. Similar results were observed in all soils/spoils amended with gypsum-based materials even though the AML and RML columns received higher rates. Additions of Mg-G induced the greatest initial increases in soluble salt load, presumably due to the much higher solubility of $MgSO_4$ as compared to $CaSO_4$. In all cases, conductivities decreased to background levels over the time course of the study.

Only the 8% Mg-G blend had a significant influence on the pH of the unamended subsurface layers. This effect was limited to the 10-cm zone subjacent to the treated layer and consisted of a 0.5 - 1.0 unit increase in the natural pH. By contrast, the gypsum-based materials caused a significant decrease in subsurface exchangeable aluminum in all soil/spoil columns. Mg-G was most effective and, in the case of the AML columns, decreased exchangeable Al in the upper 20 cm of the subsurface spoil from 600 to less than 100 mg kg^{-1}. Exchangeable Fe concentrations were likewise reduced. When compost was added to these gypsum-based amendments, subsurface exchangeable Al and Fe were further decreased. These results suggest that surface applications of Mg-G by-products could improve the chances for successful mine land reclamation by decreasing Al concentrations and thereby increasing root proliferation within the normally toxic subsurface zone of abandoned spoil materials. By comparison, agricultural limestone had no measurable affect on subsurface exchangeable Al in the AS columns and was less efficient than gypsum-based materials in all other cases. Major increases in subsurface concentrations of exchangeable Ca and Mg with the gypsum-based by-products suggest that Al is effectively displaced from the soil/spoil column through cation exchange and complexation reactions. Combining the gypsum-based amendments with compost resulted in greater increases in subsurface exchangeable Ca and Mg. The limited solubility of conventional calcitic and dolomitic limestones prevents the mobilization and downward transport of Ca and Mg from surface layers amended with these materials.

All columns were saturated and leached a total of 5 times during the course of the greenhouse work. Surface amendments had no influence on leachate pH from either the AML or RML columns; however, gypsum-based materials caused the pH of leachates from the agricultural soil to gradually decrease from 4.2 to 3.7 over a 165 day period. Soil leachate EC, and concentrations of Ca, Mg, S and Al also increased over time. By comparison, leachate EC's and concentrations of dissolved elements peaked early with the AML and RML materials and then gradually declined with time. This difference in behavior was probably due to the fact that the spoils contained a much higher proportion of coarse fragments than the agricultural soil materials. Consequently, the macroporosity was probably greater.

All alkaline amendments (AL, Mg-G, Ca-G) produced an environment adequate for orchardgrass growth on the AML spoil, and there was no appreciable difference among amendments over the full term of the experiment. However, yield reductions at the highest rates of gypsum-based materials were observed in early harvests due to excessive salts and high pH. These reductions disappeared over time. Similar results were achieved in the AS (alfalfa) and RML (orchardgrass) experiments. Additions of compost to the AML spoil in combination with alkaline amendments decreased orchardgrass growth in the early harvests due, presumably, to nitrogen immobilization. In contrast, compost added to the unamended and to the G-amended spoil caused a major improvement in growth. Without compost or alkaline amendments, orchargrass did not survive on the unamended or G-amended spoil. No plant response to improvements in subsurface soil/spoil chemistry were observed in these experiments. Because the columns were always adequately watered and fertilized, the test plants were able to meet their nutritional requirements by primarily exploiting only the surface (amended) layers.

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6 APPENDIX A: TABULAR DATA FROM THE AML EXPERIMENT

Table 10. Spoil pH and EC in the treated layer (TL) and below the treated layer (BTL) at the beginning and the end of the AML experiment.

Amendment type	Amendment rate	Initial	Final				Initial	Final
		TL	TL	1-10 cm BTL	10-20 cm BTL	24-33 cm BTL	TL	TL
	g/ kg	pH					S/m	
			Without Compost					
4% Mg-G	63	4.07	3.59	3.19	3.04	2.93	0.244	0.020
4% Mg-G	126	5.32	4.55	3.39	3.06	2.93	0.274	0.024
4% Mg-G	252	7.40	6.15	3.54	3.09	2.91	0.294	0.104
8% Mg-G	63	5.51	4.74	3.45	3.22	3.00	0.343	0.105
8% Mg-G	126	7.72	5.79	3.49	3.15	2.99	0.263	0.113
8% Mg-G	252	8.71	6.90	4.05	3.24	3.01	0.356	0.029
4% Ca-G	63	4.20	3.65	3.20	3.01	2.87	0.276	0.081
4% Ca-G	126	5.64	4.60	3.10	3.01	2.85	0.213	0.082
4% Ca-G	252	7.62	6.14	3.03	2.87	2.72	0.205	0.087
8% Ca-G	63	5.57	4.57	3.18	3.12	2.94	0.195	0.082
8% Ca-G	126	7.80	6.51	3.28	2.93	2.84	0.201	0.083
8% Ca-G	252	8.33	6.87	3.61	2.96	2.85	0.222	0.020
Gypsum (G)	63	2.90	3.04	3.01	2.95	2.94	0.226	0.080
Gypsum	126	2.96	3.09	3.04	2.99	2.94	0.231	0.086
Gypsum	252	3.42	3.22	3.10	3.01	2.98	0.210	0.021
None	0	2.87	3.38	3.23	3.05	3.05	0.069	0.015
Ag-lime	44	7.09	7.01	3.31	3.08	2.96	0.088	0.016
			With Compost					
4% Mg-G	63	4.89	5.34	3.34	3.08	2.93	0.219	0.021
4% Mg-G	126	5.75	5.60	3.35	3.06	2.94	0.206	0.100
4% Mg-G	252	7.26	6.03	3.94	3.17	3.03	0.229	0.102
8% Mg-G	63	5.91	5.66	3.42	3.20	2.94	0.284	0.092
8% Mg-G	126	6.93	6.21	3.41	3.16	3.03	0.256	0.117
8% Mg-G	252	8.22	6.91	4.92	3.52	3.12	0.273	0.026
4% Ca-G	63	4.90	4.95	3.25	3.00	2.86	0.205	0.019
4% Ca-G	126	5.55	5.78	3.42	3.07	2.86	0.224	0.020
4% Ca-G	252	7.34	6.37	3.34	3.04	2.81	0.201	0.087
8% Ca-G	63	5.49	5.60	3.27	3.04	2.83	0.195	0.035
8% Ca-G	126	7.20	6.31	3.45	3.03	2.82	0.208	0.087
8% Ca-G	252	7.92	6.88	4.22	3.05	3.04	0.204	0.083
Gypsum	63	4.06	4.39	3.25	3.01	2.82	0.207	0.020
Gypsum	126	4.28	4.55	3.21	3.03	2.82	0.198	0.083
Gypsum	252	4.42	4.67	3.19	2.96	2.83	0.184	0.081
None	0	4.17	4.84	3.50	3.20	3.04	0.067	0.007
Ag-lime	44	7.14	7.09	3.72	3.15	3.04	0.044	0.015
lsd 0.05		0.54	0.32	0.45	0.17	0.14	0.077	NS
MS Error		0.1081	0.0375	0.0756	0.0108	0.0070	0.0022	0.0036

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 11. Extractable (1*N* KCl) Al, Fe, Ca, and S in spoil treated layer (TL) and at three depths below the treated layer in the AML experiment.

Amendment type	Amendment rate	Depth, cm																			
		TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33
		Al				Ca				Fe				Mg				S			
	g/ kg	ug/g																			
		Without Compost																			
4% Mg-G	63	113	201	369	473	17237	1085	496	341	16.4	78.2	116.8	141.7	177	264	254	219	12527	322	127	167
4% Mg-G	126	29	112	275	393	18146	751	493	225	4.1	62.9	115.5	146.3	807	599	444	373	13643	203	251	186
4% Mg-G	252	14	60	240	311	17617	2063	580	429	1.2	23.5	96.8	136.7	1061	1127	591	705	13181	1195	277	388
8% Mg-G	63	26	93	293	422	16741	2407	724	384	3.0	52.8	116.5	148.8	1151	645	434	343	12985	1002	193	250
8% Mg-G	126	11	101	207	313	17429	2117	548	402	1.7	47.0	109.8	131.9	1566	819	612	501	13505	1320	287	310
8% Mg-G	252	20	46	70	197	17054	1328	572	387	1.4	37.5	53.6	114.1	1961	1167	961	767	13327	657	217	379
4% Ca-G	63	113	281	446	526	18153	1158	561	428	16.9	95.1	128.6	153.4	164	70	53	47	13354	249	205	201
4% Ca-G	126	21	321	525	612	18379	1016	653	309	3.7	91.5	144.9	168.7	332	107	57	35	13286	271	151	154
4% Ca-G	252	13	316	479	634	18611	1007	990	649	1.1	98.6	158.6	187.1	397	125	72	44	13581	402	283	482
8% Ca-G	63	10	402	521	598	18290	1102	337	191	4.3	89.5	141.9	160.7	216	43	22	17	12715	420	100	182
8% Ca-G	126	14	257	460	582	18833	1160	628	483	1.5	76.7	139.7	176.3	228	74	87	44	13092	375	365	273
8% Ca-G	252	13	229	439	527	12648	3361	791	653	0.3	55.7	130.0	147.6	210	86	40	32	13241	409	218	290
Gypsum (G)	63	166	337	384	430	16155	1174	978	835	55.4	94.0	111.1	132.7	55	24	33	90	11885	385	359	379
Gypsum	126	128	259	337	409	17635	1324	1267	911	40.9	82.8	98.5	121.7	59	104	54	45	13231	474	353	285
Gypsum	252	96	220	292	355	17476	1384	1118	877	29.8	70.7	89.9	107.0	44	107	37	50	12960	317	319	231
None	0	480	575	638	405	92	50	49	36	154.1	158.4	173.7	106.6	17	16	18	134	54	92	99	42
Ag-lime	44	11	460	563	621	4680	2018	445	187	0.9	104.8	158.9	173.8	37	26	53	30	250	123	135	148
		With Compost (100 g/kg)																			
4% Mg-G	63	16	132	317	395	18418	1636	603	383	1.1	51.7	103.8	122.6	662	428	296	259	13053	578	168	186
4% Mg-G	126	12	125	314	413	18560	861	622	454	1.4	64.9	122.1	148.2	992	474	419	344	13797	203	238	248
4% Mg-G	252	11	53	161	287	18415	2381	443	303	0.8	21.9	78.3	116.8	944	953	747	589	13484	1144	237	208
8% Mg-G	63	20	89	244	362	17044	1036	932	533	1.3	52.0	101.8	123.5	1068	549	423	353	12548	285	170	199
8% Mg-G	126	9	42	180	317	18327	471	729	409	1.1	27.8	92.7	124.5	1726	578	640	530	14178	194	226	288
8% Mg-G	252	9	5	45	143	17281	2443	552	300	0.8	0.4	45.5	92.8	1418	1707	1152	947	13100	1070	262	277
4% Ca-G	63	8	234	406	532	15279	1070	664	410	2.6	76.5	118.4	161.9	325	122	87	112	10103	247	203	311
4% Ca-G	126	21	170	385	521	18482	1323	718	527	1.5	51.1	109.2	155.4	357	190	102	75	12523	286	131	219
4% Ca-G	252	11	205	364	584	19083	1529	811	547	0.7	70.3	116.3	155.1	477	174	302	73	13451	339	233	425
8% Ca-G	63	193	269	371	319	17307	1962	961	450	52.1	84.7	111.1	95.2	300	136	96	188	11506	856	350	416
8% Ca-G	126	16	213	413	537	18669	1564	742	503	0.8	50.2	120.3	159.7	293	114	58	28	12793	421	206	181
8% Ca-G	252	12	149	373	387	18383	2293	1016	1139	0.6	14.9	97.2	116.1	313	327	160	125	12639	722	456	337
Gypsum	63	42	288	470	514	17440	798	414	358	5.5	85.3	130.1	148.0	270	137	96	87	12385	109	173	204
Gypsum	126	31	207	354	501	17936	1237	649	452	3.9	71.2	107.9	151.7	217	176	149	126	12632	331	222	297
Gypsum	252	17	162	335	484	17447	994	974	506	4.0	64.4	102.6	139.6	259	315	251	210	13229	450	250	299
None	0	31	420	569	627	2460	371	108	108	4.3	109.5	161.8	184.7	456	126	51	28	204	90	56	80
Ag-lime	44	5	340	560	594	4263	509	213	216	0.7	83.8	163.3	161.3	115	71	34	24	132	121	117	121
lsd 0.05		92	116	95	157	3425	1503	464	227	24.4	39.9	24.5	46.1	320	248	193	107	1263	481	172	149
MS Error		3209	5058	3414	9233	4405631	848321	80904	19381	223.9	597.8	225.2	797.3	38364	23075	13973	4311	598942	173506	11084	8393

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 12. Chemical composition of leachates collected at day 1 of the AML experiment.

Amendment type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
												Without Compost													
4% Mg-G	63	2.27	0.49	597	<0.04	3.47	0.074	0.035	122	0.037	0.197	0.610	113	7.73	1.90	159	2.30	54	1.11	<0.02	0.19	1250	<0.09	61.1	22.2
4% Mg-G	126	2.27	0.57	750	<0.04	4.06	0.082	0.036	81	0.050	0.257	0.617	126	5.52	2.35	147	2.56	37	1.29	0.02	0.13	1405	<0.09	65.4	22.1
4% Mg-G	252	2.27	0.86	1249	<0.04	5.70	0.055	0.047	168	0.061	0.382	0.705	186	7.46	2.00	597	3.05	55	1.56	0.17	0.33	2808	<0.09	61.4	28.6
8% Mg-G	63	2.30	0.48	607	<0.04	4.62	0.054	0.032	70	0.035	0.203	0.505	103	4.32	1.32	137	1.97	26	1.02	0.06	0.16	1332	<0.09	45.4	22.1
8% Mg-G	126	2.25	0.54	762	<0.04	2.31	0.067	0.039	71	0.048	0.258	0.604	130	6.25	2.57	103	2.69	27	1.37	0.22	0.16	1391	<0.09	69.9	24.7
8% Mg-G	252	2.22	0.92	1482	<0.04	4.80	0.050	0.054	174	0.081	0.437	0.847	217	9.34	2.31	506	3.63	65	1.80	0.11	0.30	2987	<0.09	68.0	38.0
4% Ca-G	63	2.29	0.34	293	<0.04	0.31	0.043	0.025	36	0.035	0.113	0.323	50	3.76	1.87	38	1.52	20	0.78	0.21	0.02	505	0.18	59.1	16.3
4% Ca-G	126	2.24	0.51	486	<0.04	0.48	0.119	0.039	98	0.050	0.160	0.692	92	8.64	2.60	66	2.42	53	1.15	<0.02	0.14	781	<0.09	69.9	24.1
4% Ca-G	252	2.27	0.48	474	<0.04	0.41	0.063	0.029	58	0.049	0.156	0.479	72	4.82	2.09	54	2.11	23	1.08	0.07	0.18	653	<0.09	58.1	22.6
8% Ca-G	63	2.30	0.37	317	<0.04	0.26	0.071	0.022	57	0.028	0.112	0.428	63	6.22	1.74	44	1.61	33	0.84	0.04	0.10	567	<0.09	53.6	14.3
8% Ca-G	126	2.25	0.43	396	<0.04	0.60	0.058	0.029	53	0.038	0.147	0.487	68	5.16	2.34	51	1.97	32	1.01	0.02	0.08	582	0.17	65.6	22.5
8% Ca-G	252	2.23	0.60	583	<0.04	0.18	0.114	0.039	97	0.065	0.189	0.644	98	7.51	2.63	74	2.72	51	1.32	0.14	0.10	701	0.11	66.9	25.0
Gypsum	63	2.30	0.42	476	<0.04	0.54	0.069	0.029	63	0.045	0.200	0.485	85	6.86	1.89	61	2.00	30	1.01	0.03	0.07	854	<0.09	71.2	19.7
Gypsum	126	2.26	0.53	673	<0.04	0.88	0.064	0.040	77	0.048	0.222	0.648	111	6.56	2.42	87	2.57	54	1.30	0.03	0.24	1103	<0.09	81.9	24.1
Gypsum	252	2.21	0.64	949	<0.04	2.49	0.094	0.041	95	0.059	0.285	0.752	147	4.23	2.54	174	3.01	49	1.48	0.11	0.25	1647	<0.09	86.8	26.6
None	0	2.33	0.30	227	<0.04	0.27	0.065	0.020	40	0.027	0.089	0.353	48	5.98	1.86	35	1.37	30	0.67	0.06	0.08	440	0.11	63.6	16.4
Ag-lime	44	2.33	0.30	246	<0.04	0.23	0.048	0.019	36	0.030	0.084	0.325	53	4.79	1.60	37	1.32	33	0.68	<0.02	0.19	479	<0.09	51.7	12.2
												With Compost (100 g/kg)													
4% Mg-G	63	2.23	0.57	635	<0.04	3.07	0.086	0.037	74	0.050	0.201	0.665	122	5.65	2.21	98	2.55	45	1.24	<0.02	0.25	1113	<0.09	65.0	26.4
4% Mg-G	126	2.27	0.56	700	<0.04	3.98	0.056	0.033	77	0.052	0.224	0.527	111	5.38	2.13	173	2.44	29	1.23	0.08	0.11	1319	<0.09	62.9	25.3
4% Mg-G	252	2.22	0.88	1390	<0.04	3.43	0.066	0.053	150	0.079	0.404	0.886	191	8.02	2.49	354	3.73	62	1.83	0.20	0.43	2591	<0.09	68.7	37.6
8% Mg-G	63	2.30	0.47	567	<0.04	3.61	0.055	0.030	66	0.036	0.178	0.485	94	5.28	1.71	109	2.02	24	1.03	0.09	0.10	1088	<0.09	54.0	21.5
8% Mg-G	126	2.20	0.86	1318	<0.04	3.70	0.066	0.053	108	0.076	0.412	0.799	188	6.05	2.63	251	3.70	41	1.85	<0.02	0.24	2207	0.10	68.8	33.4
8% Mg-G	252	2.22	1.00	1838	<0.04	3.95	0.038	0.062	213	0.103	0.523	0.902	243	8.34	2.48	553	4.54	63	2.08	0.17	0.54	3540	<0.09	72.9	49.7
4% Ca-G	63	2.30	0.40	349	<0.04	0.32	0.067	0.026	53	0.040	0.129	0.451	72	6.05	2.30	48	1.77	46	0.91	0.06	0.13	630	0.19	69.8	17.7
4% Ca-G	126	2.25	0.52	521	<0.04	0.27	0.089	0.034	92	0.054	0.175	0.543	88	6.50	2.32	69	2.33	64	1.17	0.03	0.13	724	<0.09	62.1	21.8
4% Ca-G	252	2.21	0.66	679	<0.04	0.11	0.090	0.040	85	0.067	0.214	0.608	97	7.12	2.73	78	2.97	45	1.46	0.14	0.15	835	<0.09	69.7	30.7
8% Ca-G	63	2.31	0.34	283	<0.04	0.31	0.057	0.024	38	0.030	0.107	0.407	59	5.50	1.78	40	1.44	31	0.78	<0.02	0.14	538	0.22	58.0	13.9
8% Ca-G	126	2.35	0.28	233	<0.04	0.29	0.047	0.019	37	0.016	0.092	0.303	52	3.38	1.82	31	1.22	20	0.63	0.06	0.04	513	0.13	61.3	12.8
8% Ca-G	252	2.21	0.64	667	<0.04	0.27	0.089	0.041	92	0.070	0.194	0.648	87	6.78	2.65	77	2.89	39	1.38	<0.02	0.18	689	<0.09	69.4	26.7
Gypsum	63	2.31	0.40	409	<0.04	0.37	0.073	0.028	52	0.042	0.158	0.458	79	4.50	2.15	52	1.90	37	0.97	0.14	0.11	691	<0.09	65.9	16.0
Gypsum	126	2.29	0.45	453	<0.04	0.70	0.051	0.030	59	0.047	0.156	0.476	74	5.75	2.11	60	2.23	28	1.00	<0.02	0.13	745	<0.09	66.1	22.9
Gypsum	252	2.24	0.59	699	<0.04	2.02	0.086	0.035	116	0.055	0.214	0.592	95	15.27	2.20	151	3.32	42	1.21	0.16	0.14	1172	0.09	68.6	23.7
None	0	2.36	0.30	253	<0.04	0.28	0.033	0.019	36	0.019	0.107	0.315	45	4.25	1.70	35	1.37	21	0.71	0.03	0.11	426	<0.09	55.4	16.8
Ag-lime	44	2.29	0.42	367	<0.04	0.21	0.073	0.028	51	0.038	0.132	0.473	73	5.86	2.09	50	1.86	39	0.92	<0.02	0.11	578	<0.09	64.5	18.9
lsd 0.05		0.10	0.02	416	NS	1.71	NS	0.015	54	0.027	0.112	0.254	55	NS	NS	139	0.95	26	0.49	NS	0.20	631	NS	13.9	9.5
MS Error		0.00	0.02	65000	NS	1.10	0.001	0.000	1087	0.000	0.005	0.024	1129	10.74	0.27	7276	0.34	260	0.09	0.02	0.02	149702	0.01	72.1	34.2

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 13. Chemical composition of leachates collected at day 75 of the AML experiment.

Amendment type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m	mg/L																					
Without Compost																									
4% Mg-G	63	2.58	0.36	231	<0.04	0.54	0.011	0.013	126	0.014	0.053	0.215	65	0.52	0.40	219	0.62	14	0.35	<0.02	0.05	910	0.20	60.4	10.5
4% Mg-G	126	2.51	0.47	383	<0.04	1.50	0.009	0.015	124	0.017	0.092	0.317	58	<0.18	0.45	527	0.66	16	0.42	<0.02	0.08	1607	0.30	64.1	14.9
4% Mg-G	252	2.58	0.67	408	<0.04	2.90	0.008	0.015	157	0.017	0.093	0.282	78	<0.18	0.39	983	0.54	19	0.38	<0.02	0.09	2166	0.34	60.6	11.1
8% Mg-G	63	2.57	0.39	216	<0.04	1.07	0.010	0.010	113	0.012	0.053	0.223	46	<0.18	0.24	327	0.33	9	0.24	<0.02	0.03	962	0.13	52.7	9.2
8% Mg-G	126	2.60	0.49	266	<0.04	1.68	0.009	0.011	126	0.013	0.065	0.247	64	<0.18	0.26	576	0.33	9	0.27	<0.02	0.06	1386	0.37	55.0	9.5
8% Mg-G	252	2.62	0.67	287	<0.04	4.64	0.009	0.010	176	0.013	0.069	0.242	69	<0.18	0.25	1197	0.24	11	0.22	<0.02	0.05	2324	0.45	54.6	7.2
4% Ca-G	63	2.56	0.27	180	<0.04	0.09	0.012	0.012	100	0.013	0.050	0.246	37	0.26	0.36	29	0.61	12	0.37	<0.02	0.04	528	0.21	57.7	12.7
4% Ca-G	126	2.46	0.29	203	<0.04	0.11	0.015	0.016	87	0.016	0.053	0.232	36	<0.18	0.65	31	0.95	19	0.48	<0.02	0.05	509	0.24	62.1	15.8
4% Ca-G	252	2.43	0.40	284	<0.04	0.14	0.018	0.019	104	0.023	0.069	0.341	38	0.37	0.91	38	1.28	17	0.65	<0.02	0.05	549	<0.09	59.9	25.1
8% Ca-G	63	2.54	0.26	154	<0.04	0.05	0.018	0.013	60	0.014	0.044	0.215	35	0.25	0.57	24	0.77	12	0.42	<0.02	0.04	390	<0.09	59.1	13.5
8% Ca-G	126	2.49	0.33	234	<0.04	0.07	0.016	0.018	77	0.019	0.063	0.295	34	<0.18	0.83	32	1.06	13	0.57	<0.02	0.05	507	0.30	63.2	20.1
8% Ca-G	252	2.55	0.27	172	<0.04	0.07	0.012	0.012	150	0.013	0.048	0.218	53	0.29	0.30	17	0.54	8	0.34	<0.02	0.03	554	0.14	59.8	9.9
Gypsum	63	2.59	0.29	171	<0.04	0.11	0.012	0.010	166	0.013	0.047	0.234	30	0.71	0.26	51	0.42	6	0.27	<0.02	0.04	606	0.12	55.1	8.9
Gypsum	126	2.53	0.31	186	<0.04	0.10	0.011	0.011	133	0.013	0.051	0.232	45	0.19	0.28	96	0.52	8	0.29	<0.02	0.04	668	0.24	61.5	9.4
Gypsum	252	2.56	0.33	184	<0.04	0.31	0.011	0.010	102	0.012	0.050	0.214	39	<0.18	0.31	192	0.58	10	0.26	<0.02	0.03	759	0.26	65.0	9.6
None	0	2.67	0.13	29	<0.04	0.05	0.020	0.005	10	0.005	0.010	0.083	19	1.28	0.24	8	0.27	6	0.15	<0.02	<0.02	119	0.17	50.0	6.0
Ag-lime	44	2.52	0.21	92	<0.04	0.06	0.016	0.010	28	0.011	0.028	0.164	30	0.43	0.47	18	0.59	10	0.32	<0.02	0.02	244	0.27	55.9	8.9
With Compost (100 g/kg)																									
4% Mg-G	63	2.51	0.34	191	<0.04	0.47	0.014	0.009	103	0.011	0.052	0.222	41	<0.18	0.25	204	0.79	14	0.24	<0.02	0.04	807	0.21	56.0	9.2
4% Mg-G	126	2.58	0.38	181	<0.04	1.12	0.010	0.009	111	0.011	0.048	0.204	42	<0.18	0.22	324	0.53	12	0.22	<0.02	0.04	887	0.14	49.8	7.8
4% Mg-G	252	2.67	0.59	273	<0.04	3.78	0.009	0.011	179	0.014	0.060	0.235	119	0.27	0.24	925	0.44	17	0.24	<0.02	0.06	1952	0.13	46.8	8.6
8% Mg-G	63	2.59	0.34	151	<0.04	1.06	0.010	0.007	110	0.009	0.041	0.190	34	0.23	0.16	280	0.36	9	0.17	<0.02	0.03	769	0.14	47.3	6.9
8% Mg-G	126	2.65	0.41	151	<0.04	2.27	0.009	0.006	117	0.007	0.041	0.180	36	<0.18	0.16	520	0.20	10	0.14	<0.02	0.03	1048	0.17	47.0	4.6
8% Mg-G	252	2.62	0.82	336	<0.04	5.78	0.008	0.012	190	0.016	0.071	0.245	181	<0.18	0.24	1564	0.31	16	0.23	<0.02	0.07	3013	0.11	57.6	9.0
4% Ca-G	63	2.49	0.29	182	<0.04	0.10	0.011	0.012	113	0.014	0.052	0.239	45	0.48	0.29	42	0.76	15	0.35	<0.02	0.04	589	0.26	58.9	10.7
4% Ca-G	126	2.54	0.28	170	<0.04	0.09	0.011	0.011	151	0.012	0.048	0.222	38	0.76	0.21	36	0.50	13	0.30	<0.02	0.03	582	0.11	55.6	8.5
4% Ca-G	252	2.59	0.28	195	<0.04	0.06	0.012	0.015	114	0.014	0.051	0.226	85	0.28	0.41	23	0.67	24	0.42	<0.02	0.03	557	<0.09	65.2	11.8
8% Ca-G	63	2.56	0.28	176	<0.04	0.06	0.013	0.012	128	0.013	0.051	0.236	41	0.43	0.26	29	0.55	11	0.34	<0.02	0.03	545	0.23	55.7	11.6
8% Ca-G	126	2.47	0.26	179	<0.04	0.09	0.015	0.013	121	0.016	0.047	0.242	87	<0.18	0.41	26	0.69	12	0.40	<0.02	0.04	510	<0.09	57.8	16.7
8% Ca-G	252	2.62	0.27	156	<0.04	0.06	0.012	0.013	116	0.014	0.037	0.184	188	<0.18	0.23	17	0.54	21	0.33	<0.02	0.04	574	<0.09	56.6	9.6
Gypsum	63	2.55	0.28	172	<0.04	0.09	0.012	0.011	97	0.013	0.046	0.209	47	0.37	0.33	55	1.35	13	0.33	<0.02	0.04	559	0.14	56.6	9.6
Gypsum	126	2.53	0.31	217	<0.04	0.11	0.010	0.013	104	0.015	0.059	0.255	53	<0.18	0.34	94	1.65	15	0.34	<0.02	0.04	703	0.30	60.0	13.0
Gypsum	252	2.56	0.35	218	<0.04	0.26	0.010	0.011	115	0.013	0.056	0.231	55	2.16	0.36	176	1.86	22	0.31	<0.02	0.05	825	0.17	61.0	13.5
None	0	2.62	0.16	55	<0.04	0.06	0.016	0.006	18	0.007	0.018	0.117	25	0.36	0.27	14	0.50	9	0.20	<0.02	<0.02	188	0.14	51.8	7.7
Ag-lime	44	2.67	0.16	56	<0.04	0.05	0.016	0.006	33	0.006	0.018	0.107	19	1.30	0.18	12	0.35	7	0.18	<0.02	<0.02	199	0.20	44.8	6.4
lsd 0.05		0.08	0.07	70	NS	0.74	0.004	0.004	37	0.005	0.014	0.054	71	NS	0.23	174	0.27	6	0.12	NS	0.03	362	0.20	8.9	6.8

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 14. Electrical conductivity (EC) and pH of leachates collected at day 105 of the AML experiment.

Amendment type	Amendment rate	pH	EC
	g/ kg		S/m
		Without Compost	
4% Mg-G	63	2.66	0.325
4% Mg-G	126	2.63	0.455
4% Mg-G	252	2.67	0.580
8% Mg-G	63	2.69	0.327
8% Mg-G	126	2.68	0.438
8% Mg-G	252	2.74	0.528
4% Ca-G	63	2.59	0.268
4% Ca-G	126	2.59	0.250
4% Ca-G	252	2.53	0.293
8% Ca-G	63	2.63	0.200
8% Ca-G	126	2.54	0.267
8% Ca-G	252	2.59	0.281
Gypsum (G)	63	2.60	0.282
Gypsum	126	2.59	0.300
Gypsum	252	2.64	0.299
None	0	2.72	0.125
Ag-lime	44	2.66	0.148
		With Compost (100g/kg)	
4% Mg-G	63	2.65	0.333
4% Mg-G	126	2.71	0.301
4% Mg-G	252	2.81	0.418
8% Mg-G	63	2.70	0.295
8% Mg-G	126	2.74	0.337
8% Mg-G	252	2.88	0.489
4% Ca-G	63	2.60	0.258
4% Ca-G	126	2.65	0.253
4% Ca-G	252	2.62	0.255
8% Ca-G	63	2.59	0.263
8% Ca-G	126	3.15	0.308
8% Ca-G	252	2.67	0.271
Gypsum	63	2.62	0.259
Gypsum	126	2.64	0.282
Gypsum	252	2.68	0.303
None	0	2.72	0.130
Ag-lime	44	2.78	0.117
lsd 0.05		NS	0.054
MS Error		0.0319	0.0011

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 15. Chemical composition of leachates collected at day 135 of the AML experiment.

Amendment type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m	mg/L																					
												Without Compost													
4% Mg-G	63	2.65	0.300	100	<0.04	0.51	0.013	0.005	171	0.006	0.022	0.124	26.5	2.04	0.24	185	0.18	3.81	0.125	<0.02	0.031	604	0.10	52	3.77
4% Mg-G	126	2.62	0.381	132	<0.04	1.28	0.011	0.006	117	0.007	0.034	0.194	27.2	<0.18	0.24	401	0.18	5.87	0.141	<0.02	0.032	890	<0.09	50	4.73
4% Mg-G	252	2.65	0.567	159	<0.04	3.02	0.012	0.008	185	0.010	0.042	0.161	24.3	<0.18	0.27	818	0.14	6.18	0.135	<0.02	0.056	1472	0.14	52	3.61
8% Mg-G	63	2.71	0.242	51	<0.04	0.90	0.013	0.002	83	0.003	0.012	0.095	19.0	<0.18	0.16	173	0.06	3.15	0.060	<0.02	<0.02	410	<0.09	41	2.80
8% Mg-G	126	2.70	0.402	105	<0.04	2.21	0.010	0.004	186	0.005	0.024	0.156	38.7	<0.18	0.16	491	0.07	3.58	0.083	<0.02	0.028	991	<0.09	48	2.73
8% Mg-G	252	2.77	0.505	79	<0.04	5.81	0.013	0.008	197	0.008	0.023	0.132	35.2	0.27	0.15	850	0.05	2.88	0.066	<0.02	0.032	1363	0.12	42	1.57
4% Ca-G	63	2.65	0.238	85	<0.04	0.08	0.012	0.005	189	0.005	0.022	0.167	20.1	1.67	0.17	23	0.17	3.56	0.119	<0.02	0.023	400	<0.09	41	4.45
4% Ca-G	126	2.61	0.220	92	<0.04	0.10	0.015	0.007	104	0.007	0.024	0.158	24.0	<0.18	0.25	20	0.29	6.73	0.195	<0.02	0.030	341	<0.09	51	6.22
4% Ca-G	252	2.55	0.301	180	<0.04	0.12	0.012	0.011	173	0.012	0.047	0.265	29.2	<0.18	0.36	33	0.46	10.87	0.316	<0.02	0.052	593	<0.09	53	11.32
8% Ca-G	63	2.73	0.143	34	<0.04	0.08	0.018	0.003	44	0.003	0.009	0.085	14.0	0.20	0.14	7	0.14	2.35	0.106	<0.02	<0.02	150	<0.09	37	3.52
8% Ca-G	126	2.56	0.255	122	<0.04	0.08	0.015	0.009	134	0.008	0.033	0.220	28.0	<0.18	0.25	16	0.33	4.96	0.246	<0.02	0.045	436	<0.09	54	8.51
8% Ca-G	252	2.57	0.302	168	<0.04	0.08	0.014	0.011	268	0.011	0.038	0.224	47.6	<0.18	0.32	19	0.38	8.19	0.260	<0.02	0.032	646	<0.09	58	7.19
Gypsum	63	2.66	0.270	68	<0.04	0.14	0.019	0.016	302	0.016	0.030	0.186	10.9	15.87	0.10	17	0.09	1.78	0.082	<0.02	0.028	458	<0.09	36	2.02
Gypsum	126	2.67	0.286	80	<0.04	0.17	0.011	0.004	371	0.005	0.020	0.127	21.2	17.39	0.10	34	0.11	1.63	0.083	<0.02	0.020	558	<0.09	40	2.70
Gypsum	252	2.71	0.284	67	<0.04	0.30	0.011	0.001	356	0.003	0.015	0.100	15.2	21.47	0.11	60	0.14	1.68	0.072	<0.02	<0.02	558	<0.09	42	2.41
None	0	2.84	0.094	9	<0.04	0.07	0.035	0.003	5	0.001	0.003	0.041	8.1	9.82	0.11	3	0.09	1.34	0.058	<0.02	<0.02	48	<0.09	37	2.29
Ag-lime	44	2.76	0.107	15	<0.04	0.07	0.024	0.003	16	0.002	0.006	0.053	10.9	0.32	0.12	5	0.13	1.88	0.075	0.02	<0.02	79	<0.09	35	1.98
												With Compost (100 g/kg)													
4% Mg-G	63	2.62	0.292	90	<0.04	0.41	0.013	0.006	141	0.007	0.024	0.170	24.6	1.53	0.19	175	0.49	4.62	0.095	<0.02	0.034	560	<0.09	48	3.75
4% Mg-G	126	2.70	0.297	94	<0.04	1.13	0.011	0.004	148	0.005	0.024	0.144	32.1	0.99	0.18	326	0.20	4.27	0.086	<0.02	0.027	743	<0.09	48	3.45
4% Mg-G	252	2.80	0.375	53	<0.04	2.92	0.010	0.002	178	0.002	0.013	0.121	38.3	8.46	0.15	492	0.14	4.42	0.042	<0.02	<0.02	869	<0.09	42	1.57
8% Mg-G	63	2.72	0.271	56	<0.04	0.87	0.018	0.013	147	0.014	0.024	0.132	22.4	7.30	0.13	200	0.18	3.25	0.057	<0.02	0.020	515	<0.09	41	1.78
8% Mg-G	126	2.79	0.301	48	<0.04	1.88	0.010	0.002	146	0.002	0.013	0.098	26.9	5.88	0.13	323	0.09	3.45	0.038	<0.02	<0.02	642	<0.09	41	1.22
8% Mg-G	252	2.93	0.391	32	<0.04	5.69	0.017	0.012	111	0.012	0.018	0.069	47.7	7.50	0.11	656	0.05	3.34	0.035	<0.02	0.023	970	<0.09	35	0.59
4% Ca-G	63	2.61	0.258	100	<0.04	0.10	0.013	0.007	184	0.008	0.025	0.172	32.1	2.58	0.19	43	0.47	5.24	0.132	<0.02	0.031	462	<0.09	53	4.01
4% Ca-G	126	2.62	0.268	95	<0.04	0.07	0.016	0.010	182	0.011	0.028	0.153	21.0	1.87	0.18	36	0.24	4.93	0.126	<0.02	0.040	434	<0.09	46	3.03
4% Ca-G	252	2.57	0.290	164	<0.04	0.07	0.013	0.010	210	0.009	0.039	0.217	29.4	<0.18	0.29	27	0.37	13.54	0.252	<0.02	0.024	606	<0.09	60	7.59
8% Ca-G	63	2.58	0.264	95	<0.04	0.10	0.014	0.006	185	0.006	0.025	0.174	29.1	0.79	0.18	27	0.19	4.73	0.143	<0.02	0.028	427	<0.09	49	4.51
8% Ca-G	126	2.57	0.297	126	<0.04	0.11	0.017	0.013	205	0.015	0.032	0.207	98.2	0.42	0.32	28	0.41	8.88	0.240	<0.02	0.050	502	<0.09	57	8.84
8% Ca-G	252	2.63	0.276	113	<0.04	0.12	0.014	0.010	230	0.009	0.025	0.169	107.5	1.08	0.22	23	0.19	13.29	0.150	<0.02	0.043	528	<0.09	53	4.80
Gypsum	63	2.66	0.247	93	<0.04	0.11	0.014	0.006	161	0.007	0.021	0.146	28.3	3.73	0.21	52	1.02	4.35	0.130	<0.02	0.023	438	<0.09	50	3.67
Gypsum	126	2.54	0.319	145	<0.04	0.14	0.014	0.009	174	0.009	0.038	0.229	36.4	1.95	0.26	104	1.54	5.33	0.176	<0.02	0.039	620	<0.09	56	6.21
Gypsum	252	2.61	0.322	114	<0.04	0.26	0.012	0.009	179	0.009	0.031	0.173	17.6	8.09	0.22	154	1.54	5.04	0.143	<0.02	0.044	609	0.11	49	5.78
None	0	2.79	0.108	14	<0.04	0.05	0.023	0.002	9	0.003	0.003	0.054	9.9	0.92	0.15	6	0.19	3.02	0.071	<0.02	<0.02	78	<0.09	40	2.99
Ag-lime	44	2.82	0.098	12	<0.04	0.07	0.026	0.002	18	0.002	0.005	0.060	8.7	1.92	0.11	4	0.09	2.48	0.057	<0.02	<0.02	72	<0.09	35	1.79
lsd 0.05		0.10	0.052	47	0.01	0.44	0.007	NS	57	NS	0.015	0.063	NS	4.02	0.11	87	0.23	4.11	0.097	NS	NS	171	0.08	10	3.59

lsd 0.05 = least significant difference at 0.05 probability level.

Table 16. Chemical composition of leachates collected at day 165 of the AML experiment.

Amendment type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
												Without Compost													
4% Mg-G	63	2.58	0.24	54	<0.04	0.58	0.017	0.006	146	0.007	0.017	0.104	24	2.11	0.23	129	0.12	2.5	0.09	<0.02	0.02	434	<0.09	57.3	2.4
4% Mg-G	126	2.57	0.26	48	<0.04	1.27	0.019	0.009	77	0.009	0.021	0.120	15	0.21	0.21	211	0.10	3.8	0.08	0.02	<0.02	454	0.12	53.3	2.2
4% Mg-G	252	2.59	0.45	89	<0.04	3.21	0.015	0.008	198	0.009	0.029	0.132	25	0.46	0.24	623	0.08	4.5	0.09	0.05	0.03	1134	<0.09	58.3	2.0
8% Mg-G	63	2.68	0.20	31	<0.04	0.97	0.019	0.003	67	0.004	0.011	0.086	18	<0.18	0.17	127	0.05	2.6	0.05	<0.02	<0.02	313	<0.09	48.8	2.2
8% Mg-G	126	2.65	0.27	50	<0.04	1.92	0.015	0.006	142	0.008	0.017	0.107	28	<0.18	0.17	319	0.05	2.7	0.06	<0.02	<0.02	637	<0.09	51.6	1.6
8% Mg-G	252	2.68	0.40	45	<0.04	4.68	0.013	0.004	170	0.005	0.015	0.094	23	0.42	0.18	564	0.03	2.2	0.05	0.02	<0.02	928	0.16	51.3	0.9
4% Ca-G	63	2.58	0.21	46	<0.04	0.16	0.023	0.010	160	0.009	0.019	0.135	18	2.52	0.18	18	0.11	3.0	0.08	<0.02	0.02	287	<0.09	47.2	2.5
4% Ca-G	126	2.53	0.20	59	<0.04	0.13	0.026	0.011	94	0.012	0.023	0.133	27	<0.18	0.28	18	0.20	5.0	0.14	<0.02	0.03	278	<0.09	55.1	4.2
4% Ca-G	252	2.54	0.32	151	<0.04	0.21	0.033	0.032	218	0.031	0.059	0.296	29	<0.18	0.40	38	0.37	10.2	0.29	<0.02	0.04	592	0.10	58.3	8.8
8% Ca-G	63	2.66	0.12	17	<0.04	0.12	0.042	0.021	33	0.023	0.025	0.084	13	0.58	0.17	6	0.10	2.6	0.09	0.02	0.02	102	<0.09	43.0	2.1
8% Ca-G	126	2.51	0.22	73	<0.04	0.10	0.024	0.014	120	0.014	0.031	0.191	18	<0.18	0.24	12	0.19	3.5	0.16	<0.02	0.04	321	<0.09	55.9	5.3
8% Ca-G	252	2.49	0.29	116	<0.04	0.21	0.016	0.008	288	0.009	0.030	0.193	40	<0.18	0.26	18	0.18	6.2	0.19	0.04	0.03	561	0.11	57.6	3.5
Gypsum	63	2.60	0.27	50	<0.04	0.15	0.010	0.002	364	0.001	0.013	0.112	9	21.11	0.10	12	0.05	3.3	0.05	<0.02	<0.02	456	<0.09	39.3	1.3
Gypsum	126	2.59	0.28	55	<0.04	0.20	0.010	0.002	395	0.004	0.016	0.112	20	20.85	0.11	20	0.06	2.2	0.06	0.02	<0.02	508	<0.09	43.9	1.7
Gypsum	252	2.61	0.29	48	<0.04	0.35	0.011	0.002	438	0.004	0.012	0.088	14	23.14	0.11	31	0.08	2.3	0.05	<0.02	<0.02	545	<0.09	45.1	1.4
None	0	2.78	0.09	5	<0.04	0.10	0.071	0.013	4	0.013	0.015	0.040	7	16.77	0.14	3	0.07	1.7	0.05	<0.02	<0.02	31	<0.09	38.4	1.5
Ag-lime	44	2.71	0.10	8	<0.04	0.10	0.043	0.006	15	0.007	0.008	0.041	7	0.78	0.13	4	0.08	2.0	0.05	<0.02	<0.02	57	<0.09	37.7	1.2
												With Compost (100 g/kg)													
4% Mg-G	63	2.58	0.21	39	<0.04	0.43	0.016	0.004	98	0.005	0.016	0.111	14	3.44	0.18	96	0.30	3.4	0.05	0.03	<0.02	333	<0.09	50.8	1.9
4% Mg-G	126	2.59	0.29	62	<0.04	0.90	0.019	0.010	146	0.010	0.024	0.131	19	1.94	0.24	211	0.24	3.8	0.09	<0.02	<0.02	556	<0.09	56.8	2.7
4% Mg-G	252	2.71	0.31	39	<0.04	2.39	0.013	0.005	147	0.006	0.014	0.088	13	6.34	0.21	368	0.12	4.5	0.05	0.06	<0.02	674	<0.09	48.9	1.3
8% Mg-G	63	2.68	0.21	26	<0.04	0.93	0.016	0.002	107	0.002	0.009	0.074	6	10.90	0.16	121	0.10	2.4	0.03	<0.02	<0.02	319	<0.09	48.2	1.0
8% Mg-G	126	2.70	0.27	31	<0.04	1.77	0.011	0.002	135	0.002	0.010	0.072	18	7.73	0.16	262	0.10	3.0	0.04	<0.02	<0.02	516	<0.09	50.3	1.0
8% Mg-G	252	2.87	0.32	22	<0.04	4.66	0.014	0.004	113	0.004	0.011	0.051	39	8.57	0.15	502	0.04	3.2	0.02	<0.02	<0.02	760	<0.09	45.2	0.5
4% Ca-G	63	2.54	0.26	49	<0.04	0.13	0.016	0.004	128	0.004	0.014	0.125	14	3.19	0.18	27	0.28	3.3	0.08	<0.02	<0.02	291	<0.09	54.0	2.3
4% Ca-G	126	2.50	0.25	76	<0.04	0.12	0.015	0.005	189	0.005	0.021	0.154	18	2.33	0.24	36	0.19	4.2	0.11	<0.02	<0.02	413	<0.09	61.5	2.5
4% Ca-G	252	2.40	0.25	134	<0.04	0.14	0.015	0.010	201	0.008	0.036	0.223	25	0.44	0.33	31	0.28	11.3	0.23	0.07	0.04	549	<0.09	59.9	5.6
8% Ca-G	63	2.54	0.21	53	<0.04	0.10	0.018	0.005	143	0.005	0.017	0.143	18	1.97	0.19	20	0.13	4.1	0.09	0.02	<0.02	303	<0.09	51.8	2.7
8% Ca-G	126	2.50	0.27	95	<0.04	0.13	0.023	0.013	194	0.015	0.027	0.194	115	0.77	0.37	24	0.35	8.2	0.21	0.03	0.03	447	<0.09	67.3	6.9
8% Ca-G	252	2.57	0.26	88	<0.04	0.12	0.015	0.009	260	0.009	0.024	0.141	84	1.52	0.19	29	0.13	7.8	0.11	<0.02	0.03	513	<0.09	53.5	2.8
Gypsum	63	2.54	0.23	59	<0.04	0.16	0.015	0.005	152	0.005	0.015	0.125	33	5.95	0.23	45	0.81	3.8	0.10	<0.02	<0.02	366	<0.09	58.1	2.6
Gypsum	126	2.51	0.28	91	<0.04	0.17	0.021	0.015	176	0.017	0.033	0.185	29	5.04	0.30	78	1.13	4.1	0.12	<0.02	0.03	492	<0.09	60.9	3.6
Gypsum	252	2.53	0.24	104	<0.04	0.35	0.013	0.007	183	0.007	0.027	0.179	17	10.35	0.31	149	1.50	4.3	0.13	<0.02	0.03	596	<0.09	64.0	4.5
None	0	2.72	0.10	10	<0.04	0.11	0.040	0.008	9	0.009	0.009	0.061	12	2.53	0.17	5	0.15	2.9	0.06	<0.02	0.02	69	<0.09	44.5	2.0
Ag-lime	44	2.81	0.09	10	<0.04	0.08	0.038	0.002	13	0.002	0.005	0.037	3	3.40	0.14	4	0.08	3.0	0.04	<0.02	<0.02	60	<0.09	36.8	1.4
lsd 0.05		0.11	0.08	33	NS	0.36	0.012	NS	52	NS	0.016	0.050	NS	4.53	0.11	66	0.18	3.2	0.08	NS	0.02	137	0.08	10.9	2.4

lsd 0.05 = least significant difference at 0.05 probability level.

Table 17. Concentrations of anions in leachates collected during the AML experiment.

Amendment type	Amendment rate	Day																			
		1	75	135	165	1	75	135	165	1	75	135	165	1	75	135	165	1	75	135	165
		Fluoride				Chloride				Phosphate				Nitrate				Sulfate			
	g/ kg	mg/L																			
		Without Compost																			
4% Mg-G	63	<4.63	<1.84	<2.53	<2.48	719	45.9	17.8	6	<53.3	<31.2	<53.7	<54.9	165.1	<16.5	95.2	<21.7	3752	2799	1606	1098
4% Mg-G	126	<4.63	<1.84	<2.53	<2.48	929	32.6	18.8	11	<53.3	<31.2	<53.7	<54.9	151.3	<16.5	73.2	<21.7	3987	2442	2500	1166
4% Mg-G	252	<4.63	<1.84	<2.53	<2.48	1466	53.7	15.7	15	<53.3	<31.2	<53.7	<54.9	206.3	<16.5	73.2	<21.7	5171	3717	3964	3447
8% Mg-G	63	<4.63	<1.84	<2.53	<2.48	487	39.2	11.5	6	<53.3	<31.2	<53.7	<54.9	137.6	<16.5	109.9	<21.7	3786	3191	1086	879
8% Mg-G	126	<4.63	<1.84	<2.53	<2.48	883	33.4	17.8	10	<53.3	<31.2	<53.7	<54.9	123.8	<16.5	102.5	36.2	4020	3710	2692	1966
8% Mg-G	252	<4.63	<1.84	<2.53	<2.48	919	46.8	16.8	13	<53.3	<31.2	<53.7	<54.9	206.3	<16.5	73.2	36.2	8063	4904	3269	2828
4% Ca-G	63	<4.63	<1.84	<2.53	<2.48	447	43.4	13.6	9	<53.3	<31.2	<53.7	<54.9	96.3	<16.5	109.9	<21.7	1508	1708	1086	873
4% Ca-G	126	<4.63	<1.84	<2.53	<2.48	1001	168.6	16.8	13	<53.3	<31.2	<53.7	<54.9	178.8	55.1	102.5	29.0	2111	1496	944	806
4% Ca-G	252	<4.63	<1.84	<2.53	<2.48	1019	305.6	33.5	20	<53.3	<31.2	<53.7	<54.9	137.6	77.1	87.9	<21.7	1742	1483	1810	1881
8% Ca-G	63	<4.63	<1.84	<2.53	<2.48	513	133.6	7.3	11	<53.3	<31.2	<53.7	<54.9	123.8	<16.5	102.5	29.0	1664	1228	441	293
8% Ca-G	126	<4.63	<1.84	<2.53	<2.48	813	272.2	14.7	13	<53.3	<31.2	<53.7	<54.9	151.3	55.1	95.2	<21.7	1642	1567	1171	980
8% Ca-G	252	<4.63	<1.84	<2.53	<2.48	1558	51.8	25.1	14	<53.3	<31.2	<53.7	<54.9	151.3	<16.5	95.2	<21.7	2066	1620	1770	1628
Gypsum	63	<4.63	<1.84	<2.53	<2.48	561	16.7	5.2	12	<53.3	<31.2	<53.7	<54.9	123.8	<16.5	139.2	86.9	2580	1901	1238	1448
Gypsum	126	<4.63	<1.84	<2.53	<2.48	1037	18.4	6.3	9	<53.3	<31.2	<53.7	<54.9	165.1	<16.5	183.1	65.2	3138	2148	1504	1589
Gypsum	252	<4.63	<1.84	<2.53	<2.48	1266	21.7	4.2	9	<53.3	<31.2	<53.7	<54.9	233.8	<16.5	117.2	72.4	4411	2319	1549	1465
None	0	<4.63	<1.84	<2.53	<2.48	346	21.9	22.0	13	<53.3	<31.2	<53.7	<54.9	55.0	<16.5	747.1	108.7	1351	399	464	84
Ag-lime	44	<4.63	<1.84	<2.53	<2.48	338	95.5	17.8	11	<53.3	<31.2	<53.7	<54.9	110.0	<16.5	395.5	50.7	1552	787	565	158
		With Compost (100 g/kg)																			
4% Mg-G	63	<4.63	<1.84	<2.53	<2.48	1039	21.7	19.9	13	<53.3	<31.2	<53.7	<54.9	165.1	<16.5	80.6	<21.7	3105	2456	1431	975
4% Mg-G	126	<4.63	<1.84	<2.53	<2.48	927	28.4	16.8	10	<53.3	<31.2	<53.7	<54.9	137.6	<16.5	102.5	<21.7	3920	2927	1747	1667
4% Mg-G	252	<4.63	<1.84	<2.53	<2.48	1985	43.6	10.5	12	<53.3	<31.2	<53.7	<54.9	206.3	<16.5	73.2	36.2	6968	6337	1855	1955
8% Mg-G	63	<4.63	<1.84	<2.53	<2.48	637	30.9	14.7	5	<53.3	<31.2	<53.7	<54.9	110.0	<16.5	102.5	<21.7	3194	2495	1431	969
8% Mg-G	126	<4.63	<1.84	<2.53	<2.48	1983	22.5	14.7	7	<53.3	<31.2	<53.7	<54.9	247.6	<16.5	117.2	50.7	6153	3433	1798	1583
8% Mg-G	252	<4.63	5.981	<2.53	<2.48	2508	40.7	6.3	6	<53.3	<31.2	<53.7	<54.9	288.9	<16.5	<22.0	<21.7	9180	9194	1425	1949
4% Ca-G	63	<4.63	<1.84	<2.53	<2.48	559	39.2	23.0	9	<53.3	<31.2	<53.7	<54.9	96.3	<16.5	80.6	<21.7	1887	1747	1272	800
4% Ca-G	126	<4.63	<1.84	<2.53	<2.48	1214	21.7	23.0	16	<53.3	<31.2	<53.7	<54.9	206.3	<16.5	80.6	<21.7	2066	1391	1318	1189
4% Ca-G	252	<4.63	<1.84	<2.53	<2.48	1767	96.0	16.8	11	<53.3	<31.2	<53.7	<54.9	178.8	<16.5	80.6	<21.7	2200	1743	1651	1656
8% Ca-G	63	<4.63	<1.84	<2.53	<2.48	393	53.4	22.0	10	<53.3	<31.2	<53.7	<54.9	110.0	<16.5	102.5	<21.7	1586	1738	1205	862
8% Ca-G	126	<4.63	<1.84	<2.53	<2.48	220	173.6	104.7	87	<53.3	<31.2	<53.7	<54.9	82.5	<16.5	102.5	<21.7	1575	1602	1414	1369
8% Ca-G	252	<4.63	<1.84	<2.53	<2.48	1967	25.9	31.4	9	<53.3	<31.2	<53.7	<54.9	123.8	<16.5	95.2	<21.7	2010	1840	1374	1555
Gypsum	63	<4.63	<1.84	<2.53	<2.48	655	43.4	18.8	9	<53.3	<31.2	<53.7	<54.9	123.8	<16.5	80.6	<21.7	2133	1677	1199	907
Gypsum	126	<4.63	<1.84	<2.53	<2.48	775	34.2	23.0	18	<53.3	<31.2	<53.7	<54.9	137.6	<16.5	87.9	<21.7	2066	2200	1663	1470
Gypsum	252	<4.63	<1.84	<2.53	<2.48	1350	24.2	20.9	21	<53.3	<31.2	<53.7	<54.9	206.3	<16.5	102.5	<21.7	3105	2641	1725	1865
None	0	<4.63	<1.84	<2.53	<2.48	427	27.0	32.5	9	<53.3	<31.2	<53.7	<54.9	110.0	<16.5	512.7	<21.7	2144	635	780	203
Ag-lime	44	<4.63	<1.84	<2.53	<2.48	665	13.8	28.3	7	<53.3	<31.2	<53.7	<54.9	178.8	<16.5	542.0	29.0	1753	674	707	169
lsd 0.05		NS	2.42	NS	NS	903	132.6	NS	NS	NS	NS	NS	NS	106.6	20.4	114.8	37.4	1941	1738	688	512

lsd 0.05 = least significant difference at 0.05 probability level, N/A = not applicable.

Table 18. Orchardgrass yield from four consecutive harvests in the AML experiment.

Amendment					
type	rate	First harvest	Second harvest	Third harvest	Fourth harvest
	g/ kg	g/pot			
		Without Compost			
4% Mg-G	63	2.44	5.06	10.54	11.68
4% Mg-G	126	4.17	9.22	12.68	14.35
4% Mg-G	252	3.08	8.04	11.12	12.62
8% Mg-G	63	3.84	7.66	10.70	11.78
8% Mg-G	126	2.74	6.19	9.40	12.72
8% Mg-G	252	0.64	3.47	9.19	13.95
4% Ca-G	63	2.49	5.20	7.37	10.70
4% Ca-G	126	4.99	9.71	10.50	13.48
4% Ca-G	252	4.29	10.19	13.24	16.11
8% Ca-G	63	5.34	8.41	10.28	11.55
8% Ca-G	126	4.14	10.02	11.15	13.10
8% Ca-G	252	1.26	5.29	11.02	12.15
Gypsum	63	0.00	0.00	0.00	0.00
Gypsum	126	0.00	0.00	0.00	0.00
Gypsum	252	0.00	0.00	0.02	0.15
None	0	0.00	0.00	0.00	0.00
Ag-lime	44	4.34	6.67	8.29	9.20
		With Compost			
4% Mg-G	63	0.61	6.55	10.48	14.94
4% Mg-G	126	0.25	4.17	10.53	13.53
4% Mg-G	252	0.08	1.79	7.09	13.21
8% Mg-G	63	0.07	2.34	9.06	12.94
8% Mg-G	126	0.02	1.44	6.98	13.03
8% Mg-G	252	0.05	0.84	4.59	9.24
4% Ca-G	63	0.39	5.73	10.51	14.74
4% Ca-G	126	0.40	5.72	10.21	14.50
4% Ca-G	252	0.75	6.99	10.44	14.22
8% Ca-G	63	0.50	6.33	8.38	14.34
8% Ca-G	126	0.13	3.47	8.61	13.33
8% Ca-G	252	0.16	3.33	9.31	7.94
Gypsum	63	0.93	6.88	12.17	15.18
Gypsum	126	0.62	6.99	11.45	14.18
Gypsum	252	0.49	6.79	11.37	15.83
None	0	1.05	7.52	9.82	11.60
Ag-lime	44	0.08	2.82	8.65	12.19
lsd 0.05		0.65	2.02	2.52	3.22

lsd 0.05 = least significant difference at 0.05 probability level.

Table 19. Chemical composition of orchardgrass tissues from the first harvest in the AML experiment.

Amendment type	rate	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg											ug/g											
												Without Compost											
4% Mg-G	63	25.5	<1.75	141.40	0.57	<0.015	2674	<0.050	<0.100	7.3	52.0	20753	0.43	2407	36	17.1	0.70	1027	<0.95	3619	<4.65	24.0	22.1
4% Mg-G	126	26.3	<1.75	389.41	1.11	<0.015	2918	0.056	<0.100	8.9	57.7	18934	<0.2	3959	304	16.1	0.61	2037	<0.95	2100	6.80	29.0	24.1
4% Mg-G	252	25.9	<1.75	713.89	0.84	<0.015	3217	0.058	<0.100	10.1	45.1	20374	4.20	5892	184	21.2	1.04	2587	<0.95	2369	5.75	29.8	21.3
8% Mg-G	63	21.3	<1.75	375.12	1.18	<0.015	2448	0.103	0.122	12.4	57.0	20121	1.89	3687	210	25.7	1.09	2073	1.37	2675	<4.65	29.6	30.7
8% Mg-G	126	25.3	<1.75	667.39	0.78	<0.015	2792	0.054	0.141	10.3	47.6	21333	0.24	6125	117	27.8	0.66	2900	<0.95	2495	<4.65	30.0	52.4
8% Mg-G	252	32.3	<1.75	691.15	1.25	<0.015	3889	0.079	<0.100	14.4	74.6	32372	5.59	6989	67	43.2	0.71	2103	<0.95	3194	9.07	47.1	45.0
4% Ca-G	63	41.7	<1.75	56.41	1.26	<0.015	4251	0.086	<0.100	8.0	57.0	19654	5.80	1346	30	25.2	1.13	970	<0.95	3911	<4.65	24.8	50.4
4% Ca-G	126	28.4	<1.75	65.99	2.95	<0.015	4753	0.120	0.216	6.4	72.1	18838	0.30	2785	226	15.4	0.72	1323	<0.95	1769	<4.65	26.0	24.0
4% Ca-G	252	35.4	<1.75	86.14	2.03	<0.015	7621	<0.050	<0.100	6.2	45.6	22240	0.72	3925	88	25.8	0.64	1932	<0.95	1556	6.31	31.9	48.6
8% Ca-G	63	18.5	<1.75	24.34	2.39	<0.015	4506	0.091	<0.100	9.5	65.2	20090	1.38	1953	143	23.9	0.77	1288	1.19	1474	<4.65	29.0	39.1
8% Ca-G	126	31.3	<1.75	25.43	1.75	<0.015	7217	0.062	<0.100	8.3	47.3	16278	2.69	3469	63	22.7	0.65	2088	<0.95	1719	5.89	36.3	77.9
8% Ca-G	252	65.0	<1.75	46.35	2.60	<0.015	8975	0.056	0.275	22.1	153.4	29515	0.71	3415	34	70.2	1.45	1410	<0.95	2253	17.05	39.5	69.8
Gypsum	63	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gypsum	126	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gypsum	252	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
None	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ag-lime	44	23.5	<1.75	4.37	3.70	<0.015	6893	0.099	<0.100	7.7	46.0	18387	0.31	2566	690	27.5	1.18	1459	<0.95	1732	<4.65	32.5	21.3
												With Compost (100 g/kg)											
4% Mg-G	63	35.6	<1.75	176.70	8.91	<0.015	6866	0.276	0.525	10.8	59.6	24001	0.29	4506	1483	33.6	2.78	5631	<0.95	3649	<4.65	61.4	53.2
4% Mg-G	126	61.0	<1.75	433.09	7.01	<0.015	5818	<0.050	0.926	9.2	78.0	27124	4.10	5887	1055	108.6	0.81	4759	<0.95	2918	<4.65	64.7	38.5
4% Mg-G	252	31.1	2.38	435.16	5.26	<0.015	7924	0.359	0.738	11.8	137.6	29268	0.97	9551	1010	36.2	1.04	5484	3.07	3263	6.78	99.2	57.6
8% Mg-G	63	53.2	2.10	274.79	9.78	0.345	7781	0.710	2.074	18.1	100.2	38605	1.90	5322	888	77.5	2.62	4831	2.18	1831	<4.65	46.6	89.8
8% Mg-G	126	77.8	<1.75	420.40	5.93	0.172	5621	0.419	1.284	13.1	78.0	26653	1.61	5002	542	65.3	1.80	2950	3.47	1999	6.93	34.6	73.0
8% Mg-G	252	102.5	<1.75	566.00	2.08	<0.015	3461	0.127	0.494	8.1	55.8	14701	1.33	4683	197	53.2	0.98	1069	4.75	2167	13.85	22.6	56.3
4% Ca-G	63	20.3	<1.75	77.26	9.74	<0.015	7152	0.204	0.329	14.6	68.7	30200	1.64	3924	1443	68.5	1.33	6168	1.37	3699	<4.65	53.5	44.2
4% Ca-G	126	123.7	<1.75	176.15	24.23	<0.015	13996	0.406	0.777	29.8	148.2	39618	0.39	6109	2330	44.7	3.22	6152	4.33	3610	<4.65	204.3	73.4
4% Ca-G	252	52.4	<1.75	120.77	4.22	<0.015	12002	0.095	0.198	13.9	70.0	25485	1.31	4002	722	26.5	1.59	5009	1.42	1746	5.09	60.8	63.7
8% Ca-G	63	85.7	<1.75	48.98	10.35	<0.015	9869	0.180	0.359	15.1	84.4	33715	0.94	4403	1296	36.1	0.92	5670	1.50	2797	<4.65	57.5	74.9
8% Ca-G	126	23.7	<1.75	51.70	4.52	<0.015	10662	0.074	<0.100	10.7	66.8	33487	3.45	4362	697	44.9	0.56	7982	<0.95	2492	<4.65	55.3	61.0
8% Ca-G	252	55.0	<1.75	103.23	4.11	<0.015	11585	<0.050	0.631	7.3	97.3	31203	0.86	2727	466	65.1	0.78	2945	<0.95	2406	<4.65	63.6	34.0
Gypsum	63	40.0	<1.75	106.80	4.54	<0.015	7415	0.081	0.164	7.7	56.6	22798	0.73	4627	1122	28.5	1.06	4824	<0.95	3108	<4.65	56.8	36.8
Gypsum	126	30.7	<1.75	114.07	4.25	<0.015	7916	0.169	0.270	9.4	139.3	28319	0.94	4586	1883	23.1	0.77	5627	1.38	2926	<4.65	60.3	136.0
Gypsum	252	30.3	<1.75	127.29	3.29	<0.015	8100	0.374	0.402	13.5	75.3	32924	12.31	4070	1487	32.2	0.92	6145	3.89	2005	<4.65	58.3	351.2
None	0	36.0	<1.75	35.37	17.93	<0.015	6903	0.093	0.255	7.2	59.2	20619	0.42	4720	1536	22.5	0.83	5119	<0.95	3150	<4.65	49.7	47.9
Ag-lime	44	34.8	5.18	31.10	16.35	<0.015	12895	0.468	0.331	22.4	80.1	37799	2.11	4420	649	59.3	2.35	5725	2.87	2839	<4.65	82.1	43.1
lsd 0.05		44.8	1.96	217.94	4.70	0.103	3086	0.314	0.715	9.6	NS	12059	NS	1840	572	NS	1.34	1085	2.88	1162	5.83	45.4	NS

lsd 0.05 = least significant difference at 0.05 probability level; N/A = not applicable.

Table 20. Chemical composition of orchardgrass tissues from the fourth harvest in the AML experiment.

Amendment type	rate	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg											ug/g											
Without Compost																							
4% Mg-G	63	194	<1.75	32.7	3.66	0.070	2636	0.197	0.738	6.0	120.4	23309	2.05	2987	17	241.3	1.00	1763	<0.95	5196	10.18	24.7	26.5
4% Mg-G	126	32	1.95	64.0	3.52	0.321	2988	0.361	0.326	5.5	78.6	29789	1.02	5021	24	233.3	0.90	1887	<0.95	3878	7.54	27.5	39.5
4% Mg-G	252	275	<1.75	73.8	3.01	<0.015	3663	<0.050	2.637	4.3	109.9	27280	1.35	4953	42	181.9	0.44	2217	<0.95	3691	<4.65	24.2	24.1
8% Mg-G	63	131	<1.75	68.8	3.01	0.178	2643	0.272	0.348	5.0	84.5	30428	4.41	5155	23	50.5	1.43	1846	<0.95	4490	8.24	30.7	31.3
8% Mg-G	126	262	1.96	111.1	3.05	0.111	2765	0.273	0.668	5.7	87.8	32863	1.41	5615	35	60.3	0.47	2007	<0.95	3694	8.81	28.4	24.3
8% Mg-G	252	81	<1.75	232.5	1.57	<0.015	3712	<0.050	0.178	5.6	65.1	32797	2.44	5004	27	136.8	<0.20	2142	<0.95	2801	<4.65	28.9	14.6
4% Ca-G	63	54	<1.75	24.8	1.88	0.077	3234	0.236	0.213	7.3	64.6	24525	6.67	2080	33	303.2	1.59	1810	<0.95	4329	<4.65	20.7	30.7
4% Ca-G	126	24	2.07	26.7	5.64	0.233	3536	0.503	0.955	7.5	137.5	30477	1.80	4009	26	217.0	1.06	2052	<0.95	3934	7.83	29.5	32.9
4% Ca-G	252	69	2.49	22.4	4.80	0.310	4271	0.416	0.420	4.3	54.3	30242	1.71	5160	39	115.7	0.53	2252	<0.95	3061	<4.65	37.2	24.7
8% Ca-G	63	31	<1.75	20.2	4.37	0.425	3443	0.675	0.569	6.5	111.1	32536	2.27	3514	29	97.9	1.27	1918	<0.95	3576	10.50	27.8	34.7
8% Ca-G	126	35	<1.75	14.6	3.74	0.026	4284	0.149	0.162	5.7	80.2	31772	4.66	4579	28	136.3	0.60	2288	<0.95	3543	7.77	32.5	28.6
8% Ca-G	252	73	<1.75	38.0	3.73	0.426	5060	0.479	0.595	4.1	118.0	28066	1.61	3275	40	140.5	0.78	1788	<0.95	2862	9.67	30.2	13.8
Gypsum	63	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gypsum	126	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Gypsum	252	1881	5.81	47.7	17.49	<0.015	4684	0.272	3.021	6.4	410.9	39972	8.53	3665	273	111.8	6.71	2468	2.72	4459	22.61	49.0	45.6
None	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ag-lime	44	33	2.68	10.3	10.46	0.280	5216	0.340	0.402	5.9	55.0	32566	1.84	2825	202	144.2	0.76	1724	<0.95	3790	9.54	26.3	18.9
With Compost (100 g/kg)																							
4% Mg-G	63	44	<1.75	31.2	5.67	<0.015	3449	<0.050	0.194	5.3	71.3	40485	0.34	4042	286	28.4	<0.20	2446	<0.95	4155	6.53	26.1	47.5
4% Mg-G	126	41	<1.75	44.1	4.74	0.752	3199	0.999	0.737	6.4	60.2	37856	1.76	3907	200	18.5	0.88	2520	<0.95	3465	8.26	27.4	34.8
4% Mg-G	252	80	<1.75	103.0	2.42	0.026	3784	0.116	0.149	5.3	66.9	36343	0.79	4152	163	32.5	0.23	2397	<0.95	3028	<4.65	27.6	25.2
8% Mg-G	63	56	<1.75	48.8	5.20	0.051	3570	0.141	0.259	6.1	80.0	40483	0.30	4007	187	23.4	<0.20	2371	<0.95	3867	7.28	21.9	32.7
8% Mg-G	126	160	<1.75	145.6	3.73	0.585	6626	0.861	0.759	5.5	113.1	33055	3.03	5381	98	59.4	1.45	2212	<0.95	4575	5.64	24.8	34.8
8% Mg-G	252	133	<1.75	186.3	3.24	0.435	5138	0.532	0.804	6.7	145.0	36394	1.14	4369	116	59.5	0.76	2820	<0.95	2683	4.72	26.2	17.0
4% Ca-G	63	137	<1.75	20.3	6.71	<0.015	3419	0.090	0.286	5.9	84.3	40939	2.55	3387	325	18.3	0.25	2336	<0.95	3971	5.30	22.7	44.6
4% Ca-G	126	80	<1.75	12.3	5.19	0.070	4021	0.128	<0.100	4.6	69.0	38897	1.29	3662	149	16.8	0.65	2420	<0.95	3630	10.64	27.3	32.9
4% Ca-G	252	26	<1.75	18.4	3.53	0.617	4064	1.147	0.565	5.4	48.2	32947	2.24	3534	157	20.6	0.81	2321	<0.95	2818	7.07	28.4	36.8
8% Ca-G	63	49	<1.75	14.4	5.80	0.463	3578	0.675	0.636	5.4	63.7	39046	1.02	3794	186	24.2	0.70	2558	<0.95	3723	7.65	23.7	41.4
8% Ca-G	126	42	<1.75	24.3	7.73	0.262	7409	0.360	1.232	6.4	261.7	36670	4.09	3515	139	142.8	0.98	2464	1.18	3735	10.80	25.3	30.2
8% Ca-G	252	55	<1.75	36.2	5.06	<0.015	8788	<0.050	0.147	5.4	78.4	31273	0.54	3523	329	75.1	0.64	2989	<0.95	3332	7.14	29.6	24.9
Gypsum	63	36	<1.75	22.4	4.24	0.074	3100	0.116	<0.100	5.3	56.3	37829	0.44	3444	396	37.0	0.53	2152	<0.95	4059	5.85	26.3	46.6
Gypsum	126	47	<1.75	27.5	4.13	0.221	3611	0.417	0.432	6.7	66.2	38053	1.14	3680	446	34.4	0.94	2804	<0.95	4090	7.12	24.6	51.2
Gypsum	252	34	2.90	26.3	4.14	0.346	3768	0.528	0.592	6.4	61.0	36441	5.74	3565	500	51.1	0.80	3012	<0.95	3812	5.09	22.1	49.8
None	0	65	2.02	14.7	22.42	0.526	2708	0.773	0.606	5.8	74.2	40031	1.63	3586	410	32.8	0.82	2290	<0.95	3618	<4.65	22.8	48.7
Ag-lime	44	47	<1.75	9.0	13.87	0.402	4693	0.575	0.527	5.5	54.4	39880	0.77	3042	96	19.0	0.64	2067	<0.95	2980	11.71	24.8	22.9
lsd 0.05		216	NS	36.7	4.16	NS	2457	NS	NS	NS	129.1	4326	3.80	916	103	123.6	NS	492	0.95	772	6.88	10.2	12.1

lsd 0.05 = least significant difference at 0.05 probability level; N/A = not applicable.

7 APPENDIX B: TABULAR DATA FROM THE RML EXPERIMENT

Table 21. Spoil pH and EC in the treated layer (TL) and below the treated layer (BTL) at the beginning and the end of the RML experiment.

Amendment		Initial	Final				Initial	Final
type	rate	TL	TL	1-10 cm BTL	10-20 cm BTL	24-33 cm BTL	TL	TL
	g/ kg	pH					S/m	
4% Mg-G	40	6.25	6.14	3.70	3.51	3.50	0.266	0.022
4% Mg-G	80	6.99	6.37	3.82	3.52	3.47	0.275	0.023
4% Mg-G	160	8.25	6.72	4.52	3.53	3.49	0.263	0.022
8% Mg-G	40	7.25	6.50	4.03	3.41	3.39	0.291	0.023
8% Mg-G	80	7.90	6.97	4.32	3.61	3.54	0.315	0.023
8% Mg-G	160	8.26	6.97	5.43	3.83	3.63	0.304	0.024
4% Ca-G	40	6.50	6.00	3.61	3.36	3.38	0.241	0.021
4% Ca-G	80	7.41	6.46	3.60	3.40	3.38	0.228	0.021
4% Ca-G	160	7.93	6.77	4.01	3.39	3.36	0.219	0.020
8% Ca-G	40	6.78	6.63	3.67	3.48	3.46	0.234	0.018
8% Ca-G	80	7.91	6.64	3.77	3.36	3.38	0.221	0.020
8% Ca-G	160	8.15	6.74	4.70	3.59	3.49	0.225	0.019
Gypsum	40	4.89	5.19	3.48	3.31	3.28	0.239	0.020
Gypsum	80	4.98	5.56	3.58	3.41	3.38	0.233	0.020
Gypsum	160	5.39	5.40	3.62	3.51	3.40	0.224	0.019
None	0	4.97	5.84	3.80	3.49	3.45	0.071	0.002
Ag-lime	6	6.88	6.72	3.76	3.48	3.49	0.117	0.006
lsd 0.05		0.59	0.47	0.63	NS	NS	0.028	0.002

lsd 0.05 = least significant difference at 0.05 probability level.

Table 22. Extractable (1*N* KCl) Al, Fe, Ca, and S in soil treated layer (TL) and at three depths below the treated layer in the RML experiment.

Amendment		, cm																			
type	rate	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33
		Al				Ca				Fe				Mg				S			
	g/ kg											ug/g									
4% Mg-G	40	0.80	93.8	189	205	16048	1177	862	1363	0.55	3.38	6.09	8.74	310	117	139	178	11212	1250	913	1087
4% Mg-G	80	9.27	90.5	166	197	18114	1468	1329	1421	1.65	2.87	4.89	5.28	606	220	183	166	13124	966	965	1053
4% Mg-G	160	2.37	28.5	117	138	17138	1815	1472	1304	0.31	6.05	7.02	6.53	469	407	329	281	12194	1116	1151	1037
8% Mg-G	40	8.56	63.4	174	186	15722	1909	1428	1229	0.83	2.39	6.27	7.23	529	381	223	198	11143	1260	1038	957
8% Mg-G	80	1.95	39.5	150	180	17872	1834	1371	1480	1.03	1.86	3.67	5.09	589	363	317	287	12377	1149	1038	1189
8% Mg-G	160	8.96	8.5	79	118	17545	1753	1567	1370	0.36	1.43	3.74	3.80	646	579	390	328	12868	1050	1191	1141
4% Ca-G	40	6.98	116.9	182	204	15282	2465	1285	1383	1.95	4.86	6.87	7.42	341	114	71	139	10673	1662	903	1107
4% Ca-G	80	6.99	156.8	218	239	17930	2145	1630	1592	0.58	4.11	7.52	5.08	283	93	67	171	13216	1379	1130	1268
4% Ca-G	160	13.58	82.7	196	212	17399	2721	1702	1404	0.00	0.24	3.68	5.98	241	168	94	84	12100	1677	1210	1001
8% Ca-G	40	6.53	163.1	191	193	18039	1913	1570	1381	2.14	6.46	6.18	4.78	149	115	76	106	8636	1355	1091	928
8% Ca-G	80	8.40	81.2	212	227	12955	2453	1537	1382	0.27	1.05	4.12	4.07	126	67	47	53	8957	1628	1141	986
8% Ca-G	160	12.35	56.4	160	181	18425	2284	1496	1392	1.60	1.34	5.38	5.17	219	77	96	71	13186	1211	1022	1033
Gypsum	40	10.31	150.8	199	212	13282	1872	1208	1300	0.00	3.84	5.80	4.65	262	146	114	104	9060	1314	944	1030
Gypsum	80	7.59	96.3	194	221	17814	1643	1417	1607	0.39	2.75	3.39	3.49	355	176	155	126	13627	1112	1050	1271
Gypsum	160	4.80	127.5	185	212	18338	2110	1624	1448	2.78	4.80	5.65	5.90	277	208	163	151	13298	1520	1253	1171
None	0	14.15	156.5	201	208	1440	594	964	1111	0.69	3.40	9.50	6.11	458	96	100	67	176	256	703	777
Ag-lime	6	9.42	92.4	206	199	1994	935	1110	1289	1.97	2.45	8.88	6.49	150	157	114	69	436	520	840	925
lsd 0.05		NS	64.3	44	41	4635	832	481	NS	NS	NS	NS	NS	139	95	99	80	4639	517	NS	NS

lsd 0.05 = least significant difference at 0.05 probability level.

Table 23. Chemical composition of leachates collected at day 1 of the RML experiment.

Amendment type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
4% Mg-G	40	3.21	0.389	162	<0.04	1.01	0.016	0.070	641	0.044	0.029	0.013	4.16	8.81	0.49	284	54.2	25.7	2.70	0.07	0.045	990	0.44	42.2	15.8
4% Mg-G	80	3.24	0.475	194	<0.04	1.23	0.028	0.085	703	0.058	0.036	0.034	2.96	11.83	0.57	346	69.3	37.8	3.24	0.13	0.109	1099	0.31	43.2	20.5
4% Mg-G	160	3.16	0.600	245	<0.04	1.45	0.020	0.098	837	0.082	0.044	0.036	7.68	12.60	0.66	444	82.2	42.4	4.02	0.16	0.024	1166	0.15	52.8	25.1
8% Mg-G	40	3.20	0.416	168	<0.04	1.05	0.015	0.073	639	0.047	0.030	0.005	2.51	8.73	0.51	295	54.7	26.4	2.80	0.03	0.098	995	0.14	45.4	18.3
8% Mg-G	80	3.26	0.433	191	<0.04	0.90	0.016	0.082	664	0.059	0.025	0.007	1.60	10.35	0.59	311	66.0	33.4	3.11	0.06	0.033	1063	<0.09	50.2	19.0
8% Mg-G	160	3.17	0.654	282	<0.04	1.40	0.029	0.109	909	0.092	0.032	0.035	7.73	15.21	0.71	532	97.4	46.8	4.44	0.02	0.078	1214	0.34	54.1	33.4
4% Ca-G	40	3.23	0.395	158	<0.04	0.21	0.016	0.072	637	0.044	0.031	0.007	1.41	9.27	0.55	270	55.7	29.6	2.83	0.09	0.025	976	<0.09	46.7	17.4
4% Ca-G	80	3.23	0.460	181	<0.04	0.25	0.027	0.089	705	0.058	0.034	0.037	10.62	12.29	0.60	310	66.6	31.8	3.19	0.10	0.100	1036	0.30	47.6	18.7
4% Ca-G	160	3.20	0.602	220	<0.04	0.32	0.024	0.091	852	0.084	0.031	0.023	2.69	14.19	0.69	397	83.5	39.0	3.79	0.05	0.076	1087	0.33	51.2	27.0
8% Ca-G	40	3.24	0.375	158	<0.04	0.22	0.014	0.071	631	0.045	0.021	0.003	1.80	9.69	0.50	258	55.7	26.7	2.68	0.04	0.047	950	0.22	42.7	16.0
8% Ca-G	80	3.20	0.463	185	<0.04	0.25	0.018	0.080	699	0.057	0.036	0.004	2.03	11.55	0.62	315	66.0	33.9	3.19	0.16	0.119	1016	0.29	48.4	20.0
8% Ca-G	160	3.17	0.580	235	<0.04	0.25	0.022	0.098	839	0.080	0.035	0.030	6.54	11.84	0.68	390	82.4	35.8	3.88	0.13	0.064	1064	0.32	51.6	27.7
Gypsum	40	3.24	0.383	166	<0.04	0.38	0.021	0.078	637	0.048	0.038	0.016	10.27	10.65	0.52	275	57.0	29.9	2.81	0.09	0.064	1050	0.10	43.5	17.1
Gypsum	80	3.20	0.494	202	<0.04	0.73	0.025	0.091	743	0.066	0.037	0.023	3.54	12.15	0.64	356	74.3	40.5	3.51	0.14	0.032	1094	0.33	50.3	21.7
Gypsum	160	3.16	0.561	224	<0.04	1.84	0.022	0.093	806	0.071	0.037	0.056	8.28	11.48	0.58	391	72.4	42.3	3.60	<0.02	0.023	1151	0.34	49.5	23.2
None	0	3.24	0.378	159	<0.04	0.29	0.022	0.074	625	0.052	0.029	0.016	8.43	11.06	0.54	264	56.3	31.0	2.72	0.04	0.075	995	0.13	44.4	16.9
Ag-lime	6	3.25	0.362	152	<0.04	0.25	0.022	0.074	623	0.042	0.047	0.029	6.55	11.05	0.54	257	53.6	29.6	2.69	0.15	0.041	986	0.58	43.9	17.2
lsd 0.05		0.06	0.105	46	NS	0.60	NS	0.021	100	0.020	NS	NS	NS	NS	0.13	93	18.8	11.8	0.72	NS	NS	NS	NS	6.0	4.5

lsd 0.05 = least significant difference at 0.05 probability level.

Table 24. Chemical composition of leachates collected at day 75 of the RML experiment.

Amendment																									
type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
4% Mg-G	40	3.36	0.378	123	<0.04	0.48	0.014	0.058	506	0.027	0.010	0.050	2.86	11.13	0.44	272	35.8	12.6	2.02	<0.02	0.046	993	0.30	47.6	19.9
4% Mg-G	80	3.39	0.419	142	<0.04	1.13	0.013	0.063	491	0.028	0.012	0.050	7.22	12.66	0.39	386	35.2	16.2	2.12	<0.02	0.058	1142	0.33	47.7	21.3
4% Mg-G	160	3.37	0.530	188	<0.04	3.62	0.013	0.073	462	0.028	0.013	0.063	5.85	12.28	0.39	728	30.8	18.7	2.16	<0.02	0.070	1646	0.31	47.4	19.5
8% Mg-G	40	3.37	0.403	135	<0.04	1.22	0.012	0.061	493	0.026	0.011	0.075	8.02	10.51	0.37	355	34.8	11.5	2.00	<0.02	0.043	1122	0.35	45.8	20.1
8% Mg-G	80	3.34	0.463	177	<0.04	1.48	0.013	0.075	486	0.031	0.013	0.057	7.21	11.71	0.44	460	36.0	14.1	2.40	<0.02	0.068	1299	0.21	51.6	23.2
8% Mg-G	160	3.43	0.660	214	<0.04	8.66	0.012	0.074	424	0.019	0.013	0.070	11.09	14.10	0.24	1211	12.9	10.2	1.61	<0.02	0.064	2304	0.31	43.2	13.5
4% Ca-G	40	3.38	0.356	113	<0.04	0.14	0.014	0.054	537	0.029	0.010	0.044	2.21	9.37	0.48	221	45.6	15.1	2.16	<0.02	0.048	948	0.33	49.6	23.2
4% Ca-G	80	3.33	0.329	141	<0.04	0.14	0.015	0.069	554	0.037	0.015	0.061	1.00	12.57	0.59	258	58.1	19.4	2.52	<0.02	0.062	1017	0.42	53.4	24.6
4% Ca-G	160	3.22	0.450	150	<0.04	0.13	0.016	0.073	608	0.050	0.014	0.081	0.82	13.16	0.65	312	69.4	23.2	2.91	<0.02	0.061	972	0.44	53.2	31.2
8% Ca-G	40	3.38	0.347	109	<0.04	0.16	0.016	0.053	540	0.029	0.010	0.043	3.50	10.96	0.49	198	44.6	13.9	2.02	<0.02	0.041	897	0.26	49.1	22.2
8% Ca-G	80	3.33	0.390	126	<0.04	0.12	0.014	0.061	553	0.036	0.012	0.052	1.61	11.37	0.57	242	53.0	16.5	2.40	<0.02	0.057	939	0.34	50.0	27.9
8% Ca-G	160	3.52	0.360	43	<0.04	0.13	0.015	0.026	497	0.025	0.005	0.006	4.11	10.88	0.30	117	36.3	10.7	1.66	<0.02	0.028	901	<0.09	42.4	16.9
Gypsum	40	3.37	0.363	125	<0.04	0.15	0.014	0.061	526	0.029	0.010	0.061	5.83	12.36	0.45	238	41.2	16.5	2.16	<0.02	0.054	989	0.31	51.5	21.7
Gypsum	80	3.37	0.371	133	<0.04	0.30	0.015	0.064	522	0.031	0.011	0.049	8.31	10.89	0.44	284	42.5	19.7	2.32	<0.02	0.052	1067	0.41	49.3	23.9
Gypsum	160	3.35	0.419	157	<0.04	0.71	0.013	0.070	515	0.030	0.012	0.076	4.11	11.69	0.45	378	39.6	27.8	2.28	<0.02	0.062	1182	0.41	51.8	21.0
None	0	3.39	0.329	99	<0.04	0.14	0.014	0.052	524	0.024	0.010	0.046	5.42	10.14	0.41	164	34.9	11.8	1.85	<0.02	0.039	847	0.21	47.7	18.6
Ag-lime	6	3.43	0.293	85	<0.04	0.17	0.014	0.044	500	0.022	0.010	0.045	1.75	9.97	0.36	149	31.3	10.0	1.60	<0.02	0.046	793	0.24	42.6	18.3
lsd 0.05		0.12	0.074	35	NS	1.15	0.002	0.014	37	0.008	0.004	0.032	NS	NS	0.14	108	13.6	6.0	0.52	0.27	0.021	198	0.47	NS	7.5

lsd 0.05 = least significant difference at 0.05 probability level.

Table 25. Electrical conductivity (EC) and pH of leachates collected at day 105 of the RML experiment.

Amendment			
type	rate	pH	EC
	g/ kg		S/m
4% Mg-G	40	3.43	0.336
4% Mg-G	80	3.49	0.359
4% Mg-G	160	3.48	0.473
8% Mg-G	40	3.37	0.378
8% Mg-G	80	3.44	0.438
8% Mg-G	160	3.58	0.522
4% Ca-G	40	3.35	0.305
4% Ca-G	80	3.40	0.353
4% Ca-G	160	3.36	0.331
8% Ca-G	40	4.48	0.304
8% Ca-G	80	3.39	0.316
8% Ca-G	160	3.68	0.283
Gypsum	40	3.37	0.313
Gypsum	80	3.43	0.351
Gypsum	160	3.48	0.386
None	0	3.48	0.269
Ag-lime	6	3.56	0.233
lsd 0.05		NS	0.056

lsd 0.05 = least significant difference at 0.05 probability level.

Table 26. Chemical composition of leachates collected at day 135 of the RML experiment.

Amendment type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
4% Mg-G	40	3.39	0.314	71	<0.04	0.84	0.015	0.040	513	0.013	0.008	0.062	1.58	8.42	0.18	215	8.5	3.8	0.86	<0.02	0.037	845	0.11	32.7	7.1
4% Mg-G	80	3.38	0.382	85	<0.04	2.02	0.017	0.046	504	0.017	0.010	0.046	39.38	10.04	0.21	379	10.6	4.6	1.06	<0.02	0.037	1076	<0.09	41.0	9.3
4% Mg-G	160	3.44	0.433	73	<0.04	4.38	0.015	0.036	488	0.010	0.008	0.047	16.28	9.38	0.13	558	3.5	3.8	0.61	<0.02	0.036	1215	0.17	30.7	4.1
8% Mg-G	40	3.23	0.356	83	<0.04	2.01	0.014	0.042	498	0.016	0.008	0.056	41.42	9.46	0.22	390	14.8	5.8	1.16	<0.02	0.024	1102	<0.09	41.4	9.0
8% Mg-G	80	3.33	0.439	92	<0.04	4.40	0.019	0.049	483	0.018	0.013	0.056	33.34	9.33	0.17	564	4.9	4.4	0.78	<0.02	0.034	1290	<0.09	38.2	5.7
8% Mg-G	160	3.56	0.467	53	<0.04	7.78	0.018	0.031	481	0.009	0.008	0.046	16.91	9.78	0.11	722	1.5	2.7	0.32	<0.02	0.028	1366	<0.09	30.2	2.1
4% Ca-G	40	3.36	0.305	74	<0.04	0.18	0.015	0.043	557	0.015	0.008	0.041	7.59	7.83	0.27	125	15.8	4.9	1.20	<0.02	0.031	782	0.09	42.8	10.7
4% Ca-G	80	3.30	0.323	108	<0.04	0.17	0.018	0.064	554	0.025	0.013	0.073	8.58	11.52	0.41	138	27.7	9.6	1.79	<0.02	0.044	874	<0.09	52.4	15.0
4% Ca-G	160	3.27	0.333	87	<0.04	0.27	0.015	0.051	558	0.021	0.010	0.059	26.08	10.77	0.35	133	24.9	13.1	1.58	<0.02	0.055	832	<0.09	48.8	14.6
8% Ca-G	40	3.36	0.299	88	<0.04	0.23	0.032	0.070	549	0.038	0.026	0.092	0.69	9.38	0.36	114	21.2	7.0	1.45	<0.02	0.062	789	0.09	46.0	14.1
8% Ca-G	80	3.33	0.310	95	<0.04	0.17	0.028	0.068	558	0.034	0.022	0.085	14.17	9.59	0.37	115	21.9	7.7	1.57	<0.02	0.063	817	0.12	49.0	15.2
8% Ca-G	160	3.52	0.298	40	<0.04	0.17	0.016	0.030	572	0.018	0.005	0.027	0.83	15.58	0.25	66	19.2	8.0	1.16	<0.02	0.023	793	0.11	43.5	10.6
Gypsum (G	40	3.26	0.344	80	<0.04	0.21	0.015	0.045	541	0.018	0.008	0.070	1.29	10.82	0.25	182	17.6	6.9	1.30	<0.02	0.027	901	0.10	43.3	10.6
Gypsum	80	3.36	0.352	100	<0.04	0.35	0.019	0.059	533	0.022	0.014	0.064	2.65	9.85	0.28	240	13.5	7.4	1.29	<0.02	0.041	951	0.13	46.1	10.6
Gypsum	160	3.35	0.360	101	<0.04	0.74	0.014	0.052	517	0.015	0.009	0.070	2.48	10.54	0.25	314	12.1	7.9	1.17	<0.02	0.045	1022	<0.09	41.8	8.6
None	0	3.40	0.265	64	<0.04	0.15	0.028	0.053	547	0.028	0.020	0.055	8.92	9.73	0.24	68	12.3	3.6	1.07	0.02	0.033	678	<0.09	40.9	9.3
Ag-lime	6	3.44	0.222	42	<0.04	0.10	0.023	0.030	424	0.016	0.009	0.056	38.48	6.91	0.21	68	14.0	4.5	0.83	<0.02	0.027	553	<0.09	31.0	7.8
lsd 0.05		0.13	0.074	29	NS	0.69	NS	0.021	NS	NS	NS	NS	NS	NS	0.09	91	6.6	3.0	0.37	NS	0.024	201	NS	10.8	3.9

lsd 0.05 = least significant difference at 0.05 probability level.

Table 27. Chemical composition of leachates collected at day 165 of the RML experiment.

Amendment																									
type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
4% Mg-G	40	3.28	0.306	61	<0.04	0.87	0.011	0.035	507	0.008	0.006	0.021	2.27	7.87	0.24	181	6.2	4.0	0.74	0.05	<0.02	776	<0.09	39.7	5.5
4% Mg-G	80	3.21	0.345	61	<0.04	1.96	0.014	0.038	521	0.010	0.007	0.031	6.87	8.53	0.22	290	5.9	4.1	0.70	<0.02	<0.02	905	<0.09	41.7	5.6
4% Mg-G	160	3.39	0.340	38	<0.04	3.29	0.015	0.026	482	0.008	0.008	0.021	12.78	6.27	0.15	354	1.6	3.3	0.32	0.05	<0.02	890	<0.09	29.4	2.0
8% Mg-G	40	3.09	0.368	54	<0.04	2.20	0.014	0.031	509	0.012	0.006	0.025	102.5	8.49	0.20	332	11.2	5.7	0.86	<0.02	<0.02	988	<0.09	42.2	5.7
8% Mg-G	80	3.22	0.394	60	<0.04	3.73	0.011	0.032	467	0.006	0.004	0.015	21.88	7.36	0.20	430	3.2	4.3	0.48	0.03	<0.02	1034	<0.09	38.9	3.3
8% Mg-G	160	3.49	0.383	30	<0.04	5.70	0.015	0.019	482	0.003	0.007	0.015	15.97	7.09	0.12	487	1.3	2.7	0.20	0.02	<0.02	1033	<0.09	30.5	1.4
4% Ca-G	40	3.18	0.275	55	<0.04	0.17	0.011	0.035	516	0.011	0.008	0.020	6.78	6.49	0.26	91	8.7	3.7	0.94	0.07	0.02	643	<0.09	41.5	7.4
4% Ca-G	80	3.25	0.282	71	<0.04	0.19	0.011	0.045	521	0.015	0.007	0.037	34.02	8.60	0.29	89	14.8	7.0	1.25	<0.02	0.03	681	<0.09	46.4	9.5
4% Ca-G	160	3.19	0.286	56	<0.04	0.41	0.014	0.038	537	0.014	0.006	0.031	58.24	8.81	0.26	109	14.3	10.1	1.11	<0.02	<0.02	711	<0.09	45.4	10.0
8% Ca-G	40	3.13	0.284	61	<0.04	0.19	0.011	0.036	533	0.011	0.005	0.021	12.10	6.92	0.29	79	12.7	5.9	1.06	0.10	<0.02	673	<0.09	42.7	9.6
8% Ca-G	80	3.17	0.278	65	<0.04	0.20	0.011	0.040	528	0.013	0.006	0.033	21.12	7.63	0.28	86	14.0	7.3	1.15	<0.02	0.02	661	<0.09	43.4	10.6
8% Ca-G	160	3.47	0.287	37	<0.04	0.20	0.018	0.031	542	0.019	0.006	0.059	202.4	16.3	0.27	51	15.2	7.2	1.08	0.06	<0.02	711	<0.09	43.2	8.8
Gypsum	40	3.13	0.310	53	<0.04	0.22	0.013	0.036	525	0.014	0.008	0.034	109.4	9.58	0.22	141	12.9	5.8	0.99	0.04	<0.02	762	0.10	42.5	7.4
Gypsum	80	3.27	0.313	76	<0.04	0.36	0.011	0.046	521	0.010	0.005	0.037	0.58	9.00	0.29	195	7.8	4.5	1.02	0.13	<0.02	787	<0.09	46.5	7.3
Gypsum	160	3.31	0.303	73	<0.04	0.69	0.015	0.046	488	0.010	0.007	0.064	0.38	9.95	0.24	237	6.8	4.5	0.86	0.05	<0.02	829	<0.09	41.7	5.2
None	0	3.22	0.234	40	<0.04	0.14	0.016	0.030	513	0.008	0.005	0.023	3.70	7.68	0.22	34	7.1	3.3	0.72	0.07	<0.02	533	<0.09	40.7	5.4
Ag-lime	6	3.11	0.219	24	<0.04	0.08	0.017	0.016	407	0.007	<0.002	0.011	42.72	5.99	0.14	41	9.7	4.6	0.64	<0.02	<0.02	460	<0.09	27.7	5.4
lsd 0.05		0.23	0.056	23	NS	0.41	NS	0.015	NS	0.007	NS	NS	NS	3.25	0.09	62	5.9	3.1	0.29	NS	NS	186	NS	10.1	2.9

lsd 0.05 = least significant difference at 0.05 probability level.

Table 28. Concentrations of anions in leachates collected during the RML experiment.

Amendment type	rate	Harvest number																			
		1	75	135	165	1	75	135	165	1	75	135	165	1	75	135	165	1	75	135	165
		Fluoride				Chloride				Phosphate				Nitrate				Sulfate			
	g/ kg											mg/L									
4% Mg-G	40	13.9	3.68	<2.53	<2.48	541	98.5	6.3	4	<53.3	<31.2	<53.7	<54.9	303	<16.5	<22.0	<21.7	6064	3257	2443	2586
4% Mg-G	80	17.0	4.29	<2.53	<2.48	1104	126.1	10.5	6	<53.3	<31.2	<53.7	<54.9	426	<16.5	<22.0	<21.7	6198	3873	3155	3059
4% Mg-G	160	17.0	2.39	<2.53	<2.48	2183	161.4	<3.14	4	<53.3	<31.2	<53.7	<54.9	481	21.5	<22.0	29.0	6053	6977	1798	3155
8% Mg-G	40	13.9	3.06	<2.53	<2.48	801	86.8	14.7	9	<53.3	<31.2	<53.7	<54.9	316	<16.5	<22.0	<21.7	6109	3697	3280	3408
8% Mg-G	80	15.4	4.84	<2.53	<2.48	725	158.9	6.3	5	<53.3	<31.2	<53.7	<54.9	261	64.5	<22.0	<21.7	6343	5947	3291	3667
8% Mg-G	160	21.6	2.39	<2.53	<2.48	3305	11.4	<3.14	5	<53.3	<31.2	<53.7	<54.9	647	43.0	<22.0	29.0	6243	7733	2166	3509
4% Ca-G	40	13.9	2.45	<2.53	<2.48	487	129.4	5.2	5	<53.3	<31.2	<53.7	<54.9	316	35.9	<22.0	<21.7	5919	2979	2347	2326
4% Ca-G	80	13.9	3.06	<2.53	<2.48	967	210.4	25.1	6	<53.3	<31.2	<53.7	<54.9	426	<16.5	<22.0	<21.7	5941	3041	2573	2484
4% Ca-G	160	18.5	5.51	<2.53	<2.48	2383	718.0	32.5	12	<53.3	<31.2	<53.7	<54.9	440	<16.5	<22.0	<21.7	5561	3125	2443	2501
8% Ca-G	40	12.3	3.06	<2.53	<2.48	459	132.7	12.6	5	<53.3	<31.2	<53.7	<54.9	289	<16.5	<22.0	<21.7	5863	2861	2285	2315
8% Ca-G	80	15.4	4.29	<2.53	<2.48	1098	293.0	22.0	7	<53.3	<31.2	<53.7	<54.9	275	<16.5	<22.0	<21.7	5896	3010	2409	2400
8% Ca-G	160	21.6	<1.84	<2.53	<2.48	2021	84.3	26.2	10	<53.3	<31.2	<53.7	<54.9	330	<16.5	<22.0	<21.7	5606	2993	2228	2512
Gypsum	40	20.1	3.06	<2.53	<2.48	423	116.0	22.0	14	<53.3	<31.2	<53.7	<54.9	275	<16.5	<22.0	<21.7	6142	3081	2630	2704
Gypsum	80	15.4	3.06	<2.53	<2.48	1280	121.9	11.5	4	<53.3	<31.2	<53.7	<54.9	633	<16.5	<22.0	<21.7	6220	3301	2827	2783
Gypsum	160	20.1	4.84	<2.53	<2.48	1843	264.5	12.6	4	<53.3	<31.2	<53.7	<54.9	633	<16.5	<22.0	<21.7	5975	4784	2533	2780
None	0	13.9	2.45	<2.53	<2.48	439	63.4	6.3	6	<53.3	<31.2	<53.7	<54.9	399	<16.5	<22.0	<21.7	6053	2777	2002	1808
Ag-lime	6	15.4	2.45	<2.53	<2.48	359	45.9	13.6	10	<53.3	<31.2	<53.7	<54.9	316	<16.5	<22.0	<21.7	5997	2486	1646	1594
lsd 0.05		NS	NS	NS	NS	931	119.1	16.6	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	1976	737	603

lsd 0.05 = least significant difference at 0.05 probability level, N/A = not applicable.

Table 29. Orchardgrass yield from four consecutive harvests in the RML experiment.

Amendment type	rate	First harvest	Second harvest	Third harvest	Fourth harvest
	g/ kg	g/pot			
4% Mg-G	40	7.75	8.89	9.14	13.08
4% Mg-G	80	9.15	9.29	9.11	12.28
4% Mg-G	160	8.04	7.42	7.99	12.85
8% Mg-G	40	9.95	9.12	8.10	14.08
8% Mg-G	80	9.44	7.53	7.98	10.82
8% Mg-G	160	6.13	5.94	7.32	10.62
4% Ca-G	40	10.73	10.29	9.99	14.58
4% Ca-G	80	10.64	9.72	8.79	11.50
4% Ca-G	160	11.85	11.66	8.63	10.72
8% Ca-G	40	11.08	10.31	9.43	11.84
8% Ca-G	80	12.73	11.86	9.26	13.84
8% Ca-G	160	5.35	7.55	10.16	13.81
Gypsum	40	9.22	7.98	8.83	16.64
Gypsum	80	9.73	9.76	9.08	13.75
Gypsum	160	8.27	9.76	10.03	15.07
None	0	9.52	8.65	8.45	11.68
Ag-lime	6	9.74	8.91	7.50	8.21
lsd 0.05		3.53	2.26	1.13	NS

lsd 0.05 = least significant difference at 0.05 probability level.

Table 30. Chemical composition of orchardgrass tissues from the first harvest in the RML experiment.

Amendment type	rate	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg											μg/g											
4% Mg-G	40	26.0	<1.75	215.9	2.12	0.164	4517	0.425	0.410	7.60	52.0	27349	0.45	5003	129	100.1	1.76	2342	<0.95	3157	<4.65	22.4	28.0
4% Mg-G	80	43.8	<1.75	332.2	1.99	0.090	4192	0.284	0.316	7.10	81.7	24510	0.45	5366	124	111.4	1.43	2356	3.59	2627	<4.65	21.6	29.7
4% Mg-G	160	24.4	<1.75	468.7	2.24	<0.015	3569	0.115	0.158	7.58	56.2	21765	0.28	5482	109	63.7	1.24	2362	<0.95	2371	<4.65	24.1	23.9
8% Mg-G	40	30.7	<1.75	304.5	2.05	0.514	4302	0.806	0.681	7.19	54.1	24833	0.59	5749	151	113.6	1.98	2105	1.33	3069	<4.65	24.7	31.0
8% Mg-G	80	32.5	<1.75	499.8	2.45	0.492	3264	0.722	0.580	7.52	58.2	24724	0.97	7305	135	118.0	1.79	2438	1.08	3174	<4.65	24.9	23.7
8% Mg-G	160	22.6	<1.75	460.7	2.73	0.364	2967	0.511	0.492	9.36	55.0	25403	0.53	6695	146	52.8	1.85	2892	1.21	4305	<4.65	27.2	22.8
4% Ca-G	40	35.3	<1.75	35.5	4.49	0.435	5460	0.640	0.640	5.96	52.7	23743	1.50	3400	102	82.2	2.23	1733	1.07	1960	<4.65	20.3	41.4
4% Ca-G	80	50.9	<1.75	79.0	3.41	0.586	7198	0.785	0.768	8.13	71.3	21305	0.93	4523	129	183.2	2.26	1816	1.65	2625	<4.65	22.1	46.6
4% Ca-G	160	30.2	<1.75	74.6	2.83	<0.015	6941	0.127	0.143	7.67	61.3	24308	0.50	4137	229	217.5	1.69	1536	<0.95	2342	<4.65	22.2	32.5
8% Ca-G	40	53.0	<1.75	33.7	2.78	<0.015	8928	0.175	0.180	10.39	91.4	26615	0.81	3908	137	259.4	1.88	1845	<0.95	2472	<4.65	24.3	29.7
8% Ca-G	80	33.9	<1.75	66.9	2.93	0.029	6649	0.300	0.265	8.79	71.3	21561	0.48	3779	202	213.1	1.69	1690	0.96	2346	<4.65	22.3	44.4
8% Ca-G	160	21.4	<1.75	51.5	3.49	0.322	9031	0.489	0.465	10.71	76.4	26708	0.69	2400	267	159.6	2.17	1943	1.41	3042	<4.65	23.8	32.0
Gypsum	40	36.0	<1.75	36.1	1.85	0.063	4469	0.269	0.234	5.61	50.0	22806	0.44	3888	240	30.9	2.30	2054	<0.95	3078	<4.65	22.5	37.4
Gypsum	80	33.3	<1.75	77.1	1.69	0.046	4434	0.222	0.164	10.17	54.6	23939	0.87	4458	191	37.1	2.23	1990	1.37	2926	<4.65	25.5	46.1
Gypsum	160	29.5	<1.75	93.0	1.96	0.145	4068	0.574	0.243	6.19	46.7	24853	1.20	3972	178	41.6	1.91	2033	<0.95	3128	<4.65	23.3	27.0
None	0	31.3	<1.75	25.8	3.44	<0.015	4100	0.184	0.131	6.38	52.2	26183	0.72	3777	187	44.4	2.31	2067	<0.95	2655	<4.65	24.5	40.8
Ag-lime	6	34.6	<1.75	10.0	4.41	0.546	6533	0.770	0.680	6.12	56.4	22953	1.02	3534	115	62.2	2.09	1961	1.45	2263	<4.65	20.2	36.7
lsd 0.05		NS	NS	90.9	NS	NS	2085	NS	NS	3.25	NS	NS	NS	1261	58	97.8	NS	597	NS	NS	NS	NS	NS

lsd 0.05 = least significant difference at 0.05 probability level.

Table 31. Chemical composition of orchardgrass tissues from the fourth harvest in the RML experiment.

Amendment type	rate	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg											µg/g											
4% Mg-G	40	55.7	<1.75	63.4	2.10	0.428	5174	0.700	0.758	7.98	68.6	20817	0.78	5483	111	118.1	2.21	3031	<0.95	4359	<4.65	20.0	47.3
4% Mg-G	80	90.6	<1.75	114.1	2.16	<0.015	6132	0.260	0.440	7.23	92.4	21201	0.48	6096	103	410.8	1.13	3049	<0.95	3911	<4.65	23.6	34.9
4% Mg-G	160	226.4	<1.75	124.4	2.83	<0.015	6375	0.473	0.689	7.16	332.0	19874	1.21	5328	68	206.3	1.41	2486	<0.95	3382	<4.65	15.1	35.1
8% Mg-G	40	371.3	<1.75	59.7	5.37	0.246	6316	0.582	1.032	5.88	331.9	20445	0.81	4813	177	359.6	2.21	2516	1.11	4874	<4.65	17.7	40.6
8% Mg-G	80	185.1	<1.75	155.2	2.33	<0.015	6327	0.142	0.489	7.11	159.5	22676	0.53	5946	120	599.5	1.29	2923	<0.95	3328	<4.65	21.9	26.0
8% Mg-G	160	133.8	<1.75	268.9	1.80	<0.015	5870	0.059	0.458	8.29	129.7	22378	0.28	6436	81	396.9	1.18	2708	<0.95	3428	<4.65	20.9	20.6
4% Ca-G	40	53.3	<1.75	21.0	2.37	<0.015	5560	0.181	0.296	6.95	66.9	22497	0.78	4838	112	430.2	1.37	2871	<0.95	3349	<4.65	23.4	37.8
4% Ca-G	80	52.7	<1.75	36.9	2.77	0.419	6951	0.964	0.790	7.43	67.8	23164	1.98	4441	128	446.3	1.77	3005	<0.95	3698	<4.65	13.3	43.6
4% Ca-G	160	76.1	<1.75	41.4	2.57	0.172	8656	0.343	0.566	6.63	80.3	20153	0.52	3772	189	545.1	1.52	2884	<0.95	3434	<4.65	22.0	28.6
8% Ca-G	40	40.1	<1.75	28.8	2.69	0.404	7066	0.639	0.734	7.04	59.7	23615	1.30	4657	134	438.0	1.78	3009	<0.95	3559	<4.65	22.7	33.3
8% Ca-G	80	63.0	<1.75	34.0	2.76	0.325	8155	0.536	0.804	13.31	77.7	21784	1.64	3941	165	603.3	1.82	2800	1.84	3394	<4.65	18.3	35.8
8% Ca-G	160	24.1	<1.75	36.6	4.37	0.223	7004	0.606	1.042	6.87	367.4	21853	1.14	3412	226	724.5	1.61	2548	1.08	2538	<4.65	32.9	25.6
Gypsum	40	90.2	<1.75	27.4	2.52	<0.015	4762	0.235	0.692	7.15	97.0	22249	0.73	4652	316	152.1	2.56	2678	<0.95	5390	<4.65	24.2	38.4
Gypsum	80	66.2	<1.75	29.9	2.87	0.221	5697	0.643	0.609	7.33	75.1	23223	1.22	4750	213	191.0	2.58	2993	1.04	4226	<4.65	25.5	41.6
Gypsum	160	67.2	<1.75	38.4	2.91	0.251	5536	0.547	0.629	7.93	73.5	21465	1.09	4716	180	166.6	2.32	3042	<0.95	4100	<4.65	27.6	32.8
None	0	85.7	<1.75	22.0	9.22	0.098	4659	0.257	0.471	6.92	93.8	21683	0.60	5004	180	230.8	2.55	2533	<0.95	3054	<4.65	21.9	41.2
Ag-lime	6	111.5	<1.75	17.3	9.44	0.246	7698	0.464	0.804	7.32	210.6	20680	0.85	3483	181	415.8	2.20	2912	<0.95	3249	<4.65	19.5	39.4
lsd 0.05		NS	NS	30.1	3.48	NS	1488	NS	NS	NS	NS	NS	NS	1086	72	309.5	0.89	NS	NS	961	NS	NS	NS

lsd 0.05 = least significant difference at 0.05 probability level.

8 APPENDIX C: TABULAR DATA FROM THE AS EXPERIMENT

Table 32. Soil pH and EC in the treated layer (TL) and below the treated layer (BTL) at the beginning and the end of the AS experiment.

Amendment type	Amendment rate	Initial	Final				Initial	Final
		TL	TL	1-10 cm BTL	10-20 cm BTL	24-33 cm BTL	TL	TL
	g/ kg	pH					S/m	
4% Mg-G	34	5.13	4.59	4.13	4.10	4.07	0.235	0.021
4% Mg-G	68	6.45	5.74	4.12	4.10	4.10	0.255	0.025
4% Mg-G	136	7.67	6.74	4.19	4.02	3.98	0.251	0.022
8% Mg-G	34	6.52	5.67	4.08	4.03	4.01	0.295	0.023
8% Mg-G	68	7.37	6.80	4.26	4.07	3.95	0.511	0.022
8% Mg-G	136	8.14	7.27	5.06	4.20	4.05	0.302	0.019
4% Ca-G	34	5.50	4.62	4.09	4.08	4.09	0.225	0.020
4% Ca-G	68	6.92	5.61	4.07	4.01	4.09	0.163	0.020
4% Ca-G	136	7.80	7.05	4.02	4.00	4.03	0.226	0.020
8% Ca-G	34	7.06	5.76	4.13	4.08	4.11	0.220	0.019
8% Ca-G	68	7.89	6.83	4.15	4.06	4.05	0.228	0.020
8% Ca-G	136	8.31	7.33	4.46	4.16	4.13	0.225	0.019
Gypsum (G)	34	4.08	4.07	4.10	4.08	4.08	0.235	0.019
Gypsum	68	4.15	4.18	4.03	4.04	4.03	0.217	0.019
Gypsum	136	4.35	4.17	4.03	4.04	4.00	0.217	0.020
None	0	4.32	4.39	4.43	4.48	4.46	0.098	0.001
Ag-lime	11	7.36	6.70	4.46	4.44	4.44	0.055	0.003
lsd 0.05		0.32	0.30	0.52	0.12	0.12	0.116	0.004
MS Error		0.0363	0.0333	0.0964	0.0054	0.0051	0.0049	5.49E-06

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 33. Extractable (1*N* KCl) Al, Fe, Ca, and S in soil treated layer (TL) and at three depths below the treated layer in the AS experiment.

Amendment		Depth, cm																			
type	rate	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33	TL	1-10	10-20	24-33
		Al				Ca				Fe				Mg				S			
	g/ kg											ug/g									
4% Mg-G	34	75.6	310	392	416	10391	568	339	341	2.56	2.03	1.38	2.59	202	243	196	221	7809	357	244	270
4% Mg-G	68	20.1	352	395	407	17225	489	341	332	1.69	1.59	1.58	1.89	646	164	190	163	13256	245	217	317
4% Mg-G	136	24.4	217	343	382	17251	965	440	364	1.36	1.80	2.17	2.11	471	481	408	402	13273	714	455	476
8% Mg-G	34	21.2	296	378	418	10520	585	351	342	1.78	2.29	1.63	3.22	498	348	265	279	7861	462	296	365
8% Mg-G	68	15.9	222	327	417	16324	673	435	355	1.25	2.08	2.18	1.75	435	560	435	358	12341	1231	452	461
8% Mg-G	136	34.8	193	272	459	16881	1465	562	495	1.82	3.10	3.53	4.08	693	742	384	423	17469	2530	387	444
4% Ca-G	34	64.0	303	409	425	14384	1050	504	379	3.12	3.07	2.13	2.12	107	101	103	117	10818	526	287	238
4% Ca-G	68	39.0	418	497	517	17864	1141	661	477	1.53	2.91	3.38	3.86	168	112	117	138	13245	518	311	261
4% Ca-G	136	20.5	314	359	393	17526	1137	743	459	1.93	2.40	2.32	2.36	118	87	112	116	12893	606	393	281
8% Ca-G	34	19.0	323	398	422	12467	816	486	384	1.76	2.43	2.23	2.39	132	73	76	136	9000	350	224	269
8% Ca-G	68	17.8	322	386	386	17202	823	684	479	0.43	1.14	2.78	2.86	69	75	87	119	12289	319	332	258
8% Ca-G	136	27.7	166	340	386	18234	2539	740	550	3.04	4.01	3.83	4.06	115	134	94	130	13070	1163	297	225
G	34	203.4	359	404	441	7502	742	526	467	3.73	2.35	2.46	2.39	35	60	47	61	5615	311	274	236
G	68	149.0	325	384	407	16850	1276	726	601	4.95	4.79	3.58	2.57	56	123	100	82	12829	721	393	337
G	136	128.3	292	363	414	17548	1131	766	580	4.67	2.49	2.98	2.46	91	64	62	79	13596	488	344	312
None	0	311.8	469	422	413	142	215	216	290	7.37	2.82	2.53	3.30	27	51	82	148	31	63	43	178
AL	11	13.9	408	422	442	1767	336	228	208	1.47	3.22	2.46	2.49	26	106	107	105	87	160	144	88
lsd 0.05		23.8	118	93	NS	2204	471	230	163	2.48	NS	NS	NS	249	118	78	112	3370	1177	155	165
MS Error		204	5038	3158	3744	1754567	80141	19061	9656	2.22	2.50	1.68	3.30	22423	5064	2172	4513	4101235	500073	8643	9800

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 34. Chemical composition of leachates collected at day 1 of the AS experiment.

Amendment																									
type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
4% Mg-G	34	4.11	0.055	4.49	0.08	0.70	0.563	0.005	43.4	0.018	0.016	<0.002	0.02	0.57	0.01	25.5	0.94	18.4	0.06	0.08	0.089	2.68	<0.09	8.33	1.36
4% Mg-G	68	4.22	0.061	7.54	0.12	0.75	0.420	0.004	54.2	0.016	0.010	<0.002	0.02	2.03	0.02	31.7	1.18	18.8	0.06	<0.02	0.034	21.40	<0.09	9.67	1.50
4% Mg-G	136	3.89	0.125	22.04	<0.04	1.46	0.590	0.011	116.0	0.038	0.007	<0.002	0.04	3.10	0.01	71.6	2.54	32.5	0.16	0.10	0.061	55.16	0.14	12.50	3.41
8% Mg-G	34	4.14	0.045	3.37	0.08	0.44	0.511	0.004	36.7	0.015	0.009	<0.002	0.02	0.52	0.02	20.8	0.79	18.0	0.04	0.10	0.091	3.59	<0.09	8.55	0.90
8% Mg-G	68	4.01	0.084	8.76	0.09	1.09	0.865	0.004	70.2	0.022	0.012	<0.002	0.01	0.81	0.01	41.2	1.50	24.4	0.07	0.13	0.063	15.85	0.35	10.32	2.27
8% Mg-G	136	3.93	0.113	21.71	0.06	1.43	0.408	0.007	107.4	0.024	0.015	<0.002	0.05	2.86	0.01	72.6	2.18	22.7	0.15	0.12	0.026	92.73	0.26	12.92	2.64
4% Ca-G	34	4.25	0.039	2.95	<0.04	0.23	0.432	0.005	34.3	0.015	0.017	<0.002	<0.01	0.28	0.01	19.1	0.73	16.1	0.02	0.04	0.033	3.41	0.10	8.23	0.93
4% Ca-G	68	4.24	0.046	3.16	0.05	0.29	0.448	0.003	37.5	0.011	0.005	<0.002	0.02	<0.18	0.02	20.3	0.77	17.0	0.03	0.15	<0.019	4.04	<0.09	8.05	1.24
4% Ca-G	136	4.09	0.055	5.66	0.05	0.24	0.632	0.004	50.5	0.016	0.007	<0.002	0.01	1.26	0.01	26.0	1.05	17.8	0.06	0.07	<0.019	16.88	0.16	9.05	1.26
8% Ca-G	34	4.03	0.044	3.58	0.06	0.23	0.472	0.003	36.0	0.021	0.009	<0.002	0.08	0.70	0.01	20.5	0.77	16.5	0.02	<0.02	0.030	2.88	0.10	8.34	1.05
8% Ca-G	68	4.29	0.041	4.00	<0.04	0.23	0.451	0.005	38.5	0.016	0.010	<0.002	0.03	<0.18	0.02	18.9	0.78	14.0	0.01	0.10	<0.019	14.41	<0.09	8.18	1.08
8% Ca-G	136	4.01	0.074	7.10	<0.04	0.31	0.840	0.005	65.1	0.027	0.024	<0.002	0.06	1.55	0.02	38.3	1.40	22.5	0.08	0.10	<0.019	10.75	<0.09	9.49	1.83
G	34	4.18	0.040	3.09	0.06	0.16	0.441	0.004	32.8	0.013	0.007	<0.002	0.01	1.25	0.01	17.6	0.71	16.3	0.03	<0.02	0.070	1.76	0.12	7.61	1.04
G	68	4.12	0.058	4.78	<0.04	0.39	0.598	0.004	46.7	0.014	0.013	<0.002	<0.01	0.53	0.02	25.9	1.04	19.7	0.04	0.13	<0.019	4.30	0.12	7.85	1.44
G	136	4.01	0.069	7.08	0.04	0.47	0.832	0.005	60.3	0.020	0.019	<0.002	0.03	1.98	0.02	34.2	1.34	25.6	0.08	<0.02	0.031	6.86	0.12	9.60	1.75
None	0	4.22	0.046	2.82	0.10	0.25	0.448	0.003	33.7	0.016	0.017	<0.002	0.01	<0.18	<0.004	18.9	0.73	17.0	0.03	<0.02	0.039	2.96	0.20	8.15	0.92
Ag-lime	11	4.18	0.040	2.98	0.06	0.20	0.437	0.004	33.2	0.011	0.010	<0.002	0.02	0.64	0.02	18.4	0.69	16.9	0.01	0.07	<0.019	4.67	<0.09	8.17	0.97
lsd 0.05		NS	0.038	8.76	NS	0.65	NS	NS	37.6	NS	NS	NS	NS	NS	NS	24.4	0.78	NS	0.06	NS	NS	44.65	NS	NS	0.97
MS Error		0.025	0.001	27.71	0.0032	0.15	0.061	0.00001	510.3	0.0001	0.0001		0.0015	1.77	0.0001	214.6	0.22	33.3	0.0014	0.009	0.003	720.20	0.026	3.71	0.34

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 35. Chemical composition of leachates collected at day 75 of the AS experiment.

Amendment type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
4% Mg-G	34	4.05	0.098	6.42	<0.04	0.84	0.647	0.006	63.6	0.010	0.002	0.012	0.02	4.45	0.01	39.4	1.66	20.1	0.11	<0.02	0.024	25.81	<0.09	8.34	4.89
4% Mg-G	68	4.09	0.099	9.35	<0.04	1.44	0.380	0.005	76.3	0.010	0.002	0.014	0.03	5.23	0.01	48.7	1.93	16.0	0.12	<0.02	0.025	85.00	<0.09	11.17	5.38
4% Mg-G	136	3.83	0.374	97.01	<0.04	4.27	0.100	0.017	312.4	0.038	0.007	0.063	0.13	9.33	0.01	337.8	6.51	25.6	0.40	<0.02	0.085	684.30	<0.09	12.64	16.54
8% Mg-G	34	4.06	0.092	5.78	<0.04	0.90	0.486	0.004	53.1	0.007	<0.002	0.013	0.02	4.21	<0.004	33.9	1.21	13.5	0.08	<0.02	<0.019	32.55	<0.09	8.83	2.81
8% Mg-G	68	4.03	0.152	17.82	<0.04	1.66	0.375	0.007	126.2	0.019	0.003	0.019	0.03	5.85	0.01	88.0	3.10	20.2	0.20	<0.02	0.025	123.84	<0.09	10.70	9.52
8% Mg-G	136	3.90	0.347	124.88	<0.04	6.14	0.049	0.018	389.9	0.029	0.008	0.061	0.22	9.57	0.01	541.0	5.42	11.4	0.35	<0.02	0.088	1116.53	0.14	11.89	13.72
4% Ca-G	34	4.21	0.065	3.13	<0.04	0.12	0.537	0.004	41.2	0.007	<0.002	0.011	0.01	3.84	<0.004	24.5	1.04	17.6	0.07	<0.02	0.032	2.85	<0.09	7.06	2.85
4% Ca-G	68	4.15	0.074	3.71	<0.04	0.18	0.618	0.004	49.7	0.007	<0.002	0.007	0.01	4.32	0.01	28.8	1.23	19.2	0.08	<0.02	0.025	8.19	<0.09	7.86	4.30
4% Ca-G	136	4.05	0.107	8.70	<0.04	0.17	0.812	0.006	84.8	0.012	0.002	0.017	0.02	5.76	<0.004	43.3	1.92	18.7	0.12	<0.02	0.037	35.06	<0.09	9.46	5.46
8% Ca-G	34	4.07	0.058	3.53	0.06	0.11	0.613	0.004	46.6	0.007	<0.002	0.010	0.02	4.51	<0.004	28.0	1.18	19.5	0.08	0.26	0.023	3.01	<0.09	7.48	3.56
8% Ca-G	68	4.02	0.105	13.12	<0.04	0.18	0.520	0.006	107.3	0.011	<0.002	0.017	0.03	5.06	0.01	41.7	1.70	15.9	0.12	<0.02	0.026	75.64	<0.09	8.59	5.52
8% Ca-G	136	4.01	0.129	12.62	<0.04	0.19	0.625	0.008	122.7	0.014	0.003	0.020	0.08	6.04	0.01	50.8	2.44	14.0	0.14	<0.02	0.051	90.60	<0.09	10.45	5.25
G	34	4.03	0.104	30.13	<0.04	1.10	0.148	0.007	147.1	0.018	0.004	0.031	0.06	6.90	0.01	101.1	3.06	20.2	0.18	<0.02	0.032	237.04	<0.09	11.89	9.20
G	68	3.97	0.148	25.07	<0.04	0.58	0.109	0.008	157.2	0.015	0.003	0.024	0.06	6.22	0.01	79.5	3.07	14.6	0.20	<0.02	0.024	234.64	0.11	12.91	8.04
G	136	3.90	0.213	44.53	<0.04	1.00	0.114	0.011	234.4	0.023	0.005	0.036	0.09	7.49	0.02	125.7	4.41	18.6	0.28	<0.02	0.051	378.80	<0.09	14.37	10.13
None	0	4.09	0.049	2.02	<0.04	0.12	0.424	0.003	29.6	0.003	<0.002	0.005	<0.01	4.25	0.01	17.5	0.74	9.8	0.05	<0.02	<0.019	1.73	<0.09	7.22	2.04
AL	11	4.16	0.054	2.46	<0.04	0.09	0.455	0.004	33.6	0.006	<0.002	0.007	0.01	3.73	0.01	19.7	0.85	16.0	0.06	<0.02	0.022	2.06	<0.09	6.58	3.04
lsd 0.05		0.09	0.093	29.95	0.09	1.06	0.388	0.004	64.4	0.009	0.003	0.016	0.04	2.50	NS	90.0	1.59	NS	0.10	NS	0.029	176.95	NS	2.54	4.02
MS Error		0.003	0.003	324.08	3E-03	0.41	0.054	5E-06	1498	3E-05	2E-06	1E-04	7E-04	2.25	4E-05	2924	0.91	25.5	4E-03	0.035	3E-04	11310	0.010	2.33	5.83

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 36. Electrical conductivity (EC) and pH of leachates collected at day 105 of the AS experiment.

Amendment			
type	rate	pH	EC
	g/ kg		S/m
4% Mg-G	34	4.15	0.159
4% Mg-G	68	4.18	0.126
4% Mg-G	136	4.02	0.438
8% Mg-G	34	4.18	0.136
8% Mg-G	68	4.10	0.273
8% Mg-G	136	4.15	0.327
4% Ca-G	34	4.30	0.083
4% Ca-G	68	4.24	0.084
4% Ca-G	136	4.15	0.130
8% Ca-G	34	4.23	0.072
8% Ca-G	68	4.16	0.107
8% Ca-G	136	4.16	0.139
G	34	4.14	0.124
G	68	4.12	0.157
G	136	4.05	0.196
None	0	4.33	0.031
AL	11	4.40	0.036
lsd 0.05		0.13	0.094
MS Error		0.0059	0.0032

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 37. Chemical composition of leachates collected at day 135 of the AS experiment.

Amendment																									
type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg		S/m											mg/L											
4% Mg-G	34	3.96	0.186	43.69	<0.04	1.62	0.058	0.010	196.4	0.017	0.004	0.047	0.08	5.53	0.02	166.7	3.29	12.4	0.24	<0.02	0.059	399.32	0.13	11.61	9.99
4% Mg-G	68	4.00	0.142	26.80	<0.04	1.64	0.057	0.018	138.9	0.022	0.013	0.046	0.35	6.55	0.03	137.7	2.19	7.1	0.16	<0.02	0.044	307.31	<0.09	10.83	5.53
4% Mg-G	136	3.85	0.458	133.21	<0.04	7.16	0.044	0.025	383.1	0.030	0.013	0.089	0.40	10.44	0.02	725.9	5.05	14.0	0.29	0.02	0.117	1326.45	0.14	11.38	13.46
8% Mg-G	34	3.92	0.363	56.04	<0.04	2.66	0.066	0.011	206.4	0.017	0.003	0.047	0.09	6.68	0.02	225.1	3.07	11.5	0.24	<0.02	0.057	707.63	<0.09	11.54	7.27
8% Mg-G	68	3.90	0.389	111.80	<0.04	5.70	0.044	0.020	349.7	0.028	0.009	0.083	0.21	8.76	0.02	534.8	4.59	12.4	0.34	<0.02	0.104	1038.87	<0.09	12.37	12.77
8% Mg-G	136	3.91	0.376	85.24	<0.04	6.36	0.036	0.018	347.8	0.016	0.007	0.071	1.03	11.96	0.02	575.4	2.44	5.4	0.19	0.05	0.107	1104.89	0.15	11.28	7.95
4% Ca-G	34	4.08	0.115	19.50	<0.04	0.32	0.170	0.006	133.6	0.012	<0.002	0.035	0.06	4.83	0.01	58.5	2.18	13.0	0.16	<0.02	0.032	238.69	<0.09	11.49	5.37
4% Ca-G	68	4.08	0.100	11.41	<0.04	0.31	0.297	0.006	100.8	0.011	0.003	0.024	0.23	4.85	0.02	53.4	2.34	12.2	0.14	<0.02	0.028	162.68	<0.09	11.05	7.80
4% Ca-G	136	3.92	0.175	29.45	<0.04	0.65	0.088	0.009	254.5	0.017	<0.002	0.043	0.08	7.76	0.02	74.0	3.02	10.5	0.19	<0.02	0.055	270.55	<0.09	10.80	8.53
8% Ca-G	34	4.09	0.080	9.12	<0.04	0.23	0.330	0.004	72.4	0.008	<0.002	0.019	0.05	4.56	0.02	43.3	1.69	11.4	0.11	<0.02	0.025	120.49	<0.09	11.70	5.37
8% Ca-G	68	3.99	0.147	26.59	<0.04	0.38	0.102	0.009	204.7	0.016	0.004	0.038	0.10	5.95	0.02	70.0	2.71	9.6	0.19	<0.02	0.037	243.60	<0.09	11.39	9.63
8% Ca-G	136	3.99	0.145	24.15	<0.04	0.33	0.069	0.008	233.7	0.013	0.003	0.034	0.09	7.58	0.02	60.1	2.67	5.4	0.17	<0.02	0.048	274.14	0.13	10.81	6.56
Gypsum	34	3.95	0.107	19.68	<0.04	0.21	0.053	0.016	187.5	0.018	0.011	0.036	0.07	8.71	0.02	31.5	1.44	2.1	0.10	0.03	0.038	212.10	<0.09	8.18	4.52
Gypsum	68	3.91	0.180	40.93	<0.04	0.38	0.064	0.018	330.3	0.020	0.010	0.067	0.22	12.50	0.03	64.3	2.77	3.9	0.13	<0.02	0.072	408.03	0.12	11.02	6.59
Gypsum	136	3.89	0.177	37.84	<0.04	0.43	0.052	0.015	319.4	0.014	0.008	0.046	0.07	10.63	0.02	72.5	1.77	2.9	0.10	<0.02	0.061	402.77	<0.09	10.74	5.03
None	0	4.49	0.011	0.41	<0.04	0.12	0.073	0.003	7.1	0.003	0.003	0.009	0.02	1.44	0.01	3.9	0.15	1.8	0.01	<0.02	<0.019	5.49	<0.09	6.93	0.50
AL	11	4.37	0.021	0.83	<0.04	0.11	0.166	0.002	14.3	0.001	<0.002	0.007	0.05	2.24	0.02	8.6	0.32	4.9	0.02	<0.02	<0.019	4.34	<0.09	7.23	1.19
lsd 0.05		0.13	0.108	39.63	0.01	1.55	0.121	0.011	116.0	0.014	NS	0.033	NS	4.02	NS	179.1	1.89	5.4	0.14	NS	0.038	171.38	NS	2.56	5.70
MS Error		0.006	0.004	567.41	6E-05	0.87	0.005	4E-05	4864	7E-05	4E-05	4E-04	0.152	5.85	6E-05	11583	1.28	10.7	7E-03	3E-04	5E-04	31832	0.003	2.37	11.74

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 38. Chemical composition of leachates collected at day 165 of the AS experiment.

Amendment																									
type	rate	pH	EC	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/kg		S/m											mg/L											
4% Mg-G	34	3.81	0.187	40.14	<0.04	1.51	0.050	0.010	189.3	0.017	0.003	0.036	0.08	5.71	0.01	162.2	2.98	10.4	0.21	<0.02	0.044	387.36	0.10	12.11	8.91
4% Mg-G	68	3.80	0.129	18.27	<0.04	1.45	0.042	0.007	112.6	0.011	0.003	0.020	1.20	5.88	0.01	109.6	1.84	5.3	0.12	<0.02	<0.019	236.28	<0.09	11.69	4.56
4% Mg-G	136	3.71	0.389	87.85	<0.04	5.68	0.036	0.018	317.1	0.019	0.008	0.065	0.50	10.38	0.02	537.4	3.84	11.4	0.21	<0.02	0.083	993.19	<0.09	11.60	10.31
8% Mg-G	34	3.73	0.212	51.64	<0.04	2.39	0.061	0.013	200.1	0.017	0.004	0.042	0.09	7.40	0.02	221.0	2.72	9.3	0.21	<0.02	0.058	481.72	0.10	12.42	7.56
8% Mg-G	68	3.69	0.372	102.03	<0.04	5.77	0.040	0.027	388.7	0.024	0.009	0.072	0.23	10.20	0.08	505.9	6.27	9.0	0.48	<0.02	0.086	1064.65	0.14	20.53	10.96
8% Mg-G	136	3.89	0.285	40.03	<0.04	3.83	0.033	0.011	336.4	0.008	0.004	0.029	3.58	8.59	0.01	332.5	1.41	4.5	0.08	0.02	0.074	723.85	<0.09	9.19	3.85
4% Ca-G	34	3.85	0.126	21.67	<0.04	0.36	0.196	0.008	156.3	0.015	0.003	0.024	0.05	5.22	0.01	61.0	2.46	12.6	0.17	<0.02	0.036	308.77	<0.09	13.16	6.44
4% Ca-G	68	3.82	0.112	12.44	<0.04	0.44	0.185	0.007	113.4	0.012	0.005	0.020	0.04	5.15	0.01	49.1	2.08	11.4	0.14	<0.02	0.044	104.63	<0.09	13.04	7.29
4% Ca-G	136	3.75	0.194	33.30	<0.04	0.82	0.078	0.010	313.1	0.018	0.004	0.040	0.08	8.64	0.01	76.7	3.12	9.9	0.20	0.02	0.030	340.76	<0.09	11.52	8.55
8% Ca-G	34	3.85	0.104	17.70	<0.04	0.26	0.241	0.007	122.4	0.012	0.003	0.021	0.06	5.13	0.01	56.9	2.32	7.5	0.16	<0.02	0.020	172.89	<0.09	13.24	6.72
8% Ca-G	68	3.77	0.165	30.95	<0.04	0.44	0.072	0.010	246.4	0.017	0.004	0.037	0.07	6.65	0.01	69.8	3.06	8.5	0.21	<0.02	0.019	299.45	<0.09	12.27	10.12
8% Ca-G	136	4.04	0.136	20.85	<0.04	0.38	0.050	0.008	230.5	0.013	0.003	0.030	0.06	8.21	0.01	51.0	2.38	4.7	0.15	<0.02	0.044	259.16	<0.09	12.09	5.94
Gypsum	34	3.76	0.107	16.77	<0.04	0.18	0.047	0.008	184.1	0.008	0.003	0.021	0.06	9.63	0.01	20.6	1.10	4.3	0.06	<0.02	<0.019	194.26	<0.09	9.47	3.74
Gypsum	68	3.75	0.186	37.58	<0.04	0.35	0.053	0.012	364.7	0.012	0.004	0.032	1.00	13.43	0.01	45.5	3.56	3.6	0.09	<0.02	0.049	406.46	<0.09	12.52	5.87
Gypsum	136	3.74	0.170	30.33	<0.04	0.34	0.046	0.010	338.7	0.007	0.002	0.029	0.07	11.57	0.01	40.4	1.16	4.2	0.05	<0.02	0.036	359.59	<0.09	11.23	3.63
None	0	4.32	0.010	0.22	<0.04	0.12	0.066	0.000	5.1	<0.001	<0.002	0.003	<0.01	1.43	0.01	2.9	0.13	2.2	0.01	0.03	<0.019	3.90	<0.09	7.89	0.43
AL	11	4.24	0.015	0.40	<0.04	0.12	0.113	0.001	8.5	0.001	<0.002	<0.002	0.03	1.82	0.01	4.8	0.21	3.8	0.01	0.02	<0.019	2.96	<0.09	8.15	0.79
lsd 0.05		0.15	0.116	36.07	NS	1.62	0.096	0.008	156.2	0.011	0.004	0.026	NS	3.90	NS	151.1	2.61	4.0	0.19	NS	0.046	315.03	NS	5.48	5.29
MS Error		0.009	0.005	469.83	2E-04	0.95	0.003	3E-05	8810	4E-05	5E-06	2E-04	2.507	5.48	8E-04	8247	2.46	5.8	1E-02	3E-04	8E-04	35450	0.003	10.84	10.11

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 39. Concentrations of anions in leachates collected during the AS experiment.

Amendment type	Day 1	75	135	165	165	1	75	135	165	1	75	135	165	1	75	135	165	1	75	135	165
		Fluoride				Chloride				Phosphate				Nitrate				Sulfate			
	g/kg										mg/L										
4% Mg-G	34	<4.63	<1.84	1.25	<2.48	393	45.7	86.2	53.2	<53.4	<31.2	<2.60	<54.9	330	90.8	48.8	36.2	<33.5	90	488	1279
4% Mg-G	68	<4.63	<1.84	0.48	<2.48	475	76.3	10.5	25.6	<53.4	<31.2	<2.60	<54.9	275	32.8	14.0	50.7	190	232	631	727
4% Mg-G	136	<4.63	5.66	0.40	<2.48	1166	359.8	16.3	91.6	<53.4	<31.2	<2.60	<54.9	481	63.8	3.5	<21.7	391	2280	460	3380
8% Mg-G	34	<4.63	<1.84	1.13	<2.48	342	90.2	98.4	25.6	<53.4	<31.2	<2.60	<54.9	289	70.8	42.2	50.7	45	110	731	1667
8% Mg-G	68	<4.63	<1.84	0.80	3.31	679	164.6	69.8	78.8	<53.4	<31.2	<2.60	<54.9	358	72.2	7.0	<21.7	112	375	288	3566
8% Mg-G	136	6.2	5.51	0.12	<2.48	855	125.2	1.5	18.1	<53.4	<31.2	<2.60	<54.9	330	181.8	<1.00	<21.7	771	3697	447	2445
4% Ca-G	34	<4.63	<1.84	1.09	<2.48	290	82.7	107.2	80.9	<53.4	<31.2	<2.60	<54.9	275	77.4	51.6	36.2	<33.5	<13.20	539	620
4% Ca-G	68	<4.63	<1.84	1.21	<2.48	328	49.3	137.6	70.3	<53.4	<31.2	<2.60	<54.9	248	64.0	46.4	65.2	45	<13.20	590	214
4% Ca-G	136	<4.63	<1.84	1.49	<2.48	427	<2.50	220.9	137.4	<53.4	<31.2	<2.60	<54.9	220	43.0	18.5	<21.7	112	82	459	1082
8% Ca-G	34	<4.63	<1.84	0.88	<2.48	320	<2.50	97.2	27.7	<53.4	<31.2	<2.60	<54.9	330	88.4	43.6	72.4	<33.5	<13.20	277	586
8% Ca-G	68	<4.63	<1.84	1.05	<2.48	284	46.5	96.9	78.8	<53.4	<31.2	<2.60	<54.9	206	78.7	29.6	<21.7	112	255	755	941
8% Ca-G	136	<4.63	<1.84	1.13	<2.48	705	91.0	65.3	44.7	<53.4	<31.2	<2.60	<54.9	193	74.3	3.5	<21.7	45	253	340	828
Gypsum	34	<4.63	2.33	0.12	<2.48	280	132.0	0.7	7.5	<53.4	<31.2	<2.60	<54.9	275	42.0	7.3	<21.7	<33.5	757	60	620
Gypsum	68	<4.63	2.04	0.24	<2.48	427	69.6	1.7	11.7	<53.4	<31.2	<2.60	<54.9	344	36.7	7.3	<21.7	<33.5	784	350	1324
Gypsum	136	<4.63	3.79	0.24	<2.48	615	110.1	0.7	6.4	<53.4	<31.2	<2.60	<54.9	344	44.6	7.0	29.0	45	1324	233	1166
None	0	<4.63	<1.84	<0.12	<2.48	234	36.6	8.3	5.3	<53.4	<31.2	<2.60	<54.9	426	174.7	16.0	<21.7	45	<13.20	19	<16.90
AL	6	<4.63	<1.84	0.48	<2.48	274	127.6	24.6	17.0	<53.4	<31.2	<2.60	<54.9	344	79.8	38.4	<21.7	45	<13.20	56	<16.90
lsd 0.05		NS	1.85	0.79	NS	331	140.8	81.1	42.2	NS	NS	NS	NS	NS	54.2	29.3	NS	358	614	NS	1103
MS Error		3.9	1.24	0.226	N/A	39591	7161	2375	642	N/A	1	N/A	N/A	10838	1061	309	891	46249	136017	220933	439708

lsd 0.05 = least significant difference at 0.05 probability level, N/A = not applicable.
MS Error = Mean square for the error term.

Table 40. Alfalfa yield from four consecutive harvests in the AS experiment.

Amendment type	Amendment rate	First harvest	Second harvest	Third harvest	Fourth harvest
	g/kg	g/pot			
4% Mg-G	34	7.27	9.26	10.16	9.89
4% Mg-G	68	6.45	9.07	9.79	9.41
4% Mg-G	136	8.08	10.12	8.65	8.56
8% Mg-G	34	7.53	9.23	10.41	9.17
8% Mg-G	68	8.09	10.34	11.46	11.38
8% Mg-G	136	3.62	5.91	9.50	12.36
4% Ca-G	34	7.53	9.79	11.12	9.67
4% Ca-G	68	8.41	11.01	11.43	9.83
4% Ca-G	136	9.60	12.85	13.56	11.90
8% Ca-G	34	8.61	11.32	9.88	9.42
8% Ca-G	68	9.76	11.70	13.21	11.75
8% Ca-G	136	7.33	10.49	13.31	12.22
Gypsum	34	0.70	0.69	0.61	0.75
Gypsum	68	0.86	0.86	0.32	0.23
Gypsum	136	2.19	1.07	0.46	0.59
None	0	0.05	0.06	0.01	0.05
AL	11	8.87	11.81	11.38	11.17
lsd 0.05		1.13	1.67	2.16	1.98
MS Error		0.4584	1.0045	1.6907	1.4193

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 41. Chemical composition of alfalfa tissues from the first harvest in the AS experiment.

Amendment type	rate	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/kg											mg/kg											
4% Mg-G	34	101.6	<1.75	140.5	1.80	0.019	14915	0.508	0.377	11.42	119.2	22546	0.59	5451	114	149.7	0.83	2421	1.93	5263	<4.65	<0.7	95.2
4% Mg-G	68	114.4	<1.75	188.7	6.11	1.319	15989	1.712	1.736	14.97	127.1	18991	1.86	8388	56	280.3	1.80	2021	2.58	5944	<4.65	1.0	60.3
4% Mg-G	136	105.2	<1.75	178.5	2.18	0.138	13935	0.451	0.616	12.54	116.7	20955	0.71	8802	82	178.6	0.86	2221	1.65	4341	<4.65	0.8	42.1
8% Mg-G	34	97.2	<1.75	178.4	1.92	0.073	15194	0.386	0.408	12.84	110.6	22313	0.52	7800	58	189.2	0.72	2506	1.30	5013	<4.65	0.7	52.2
8% Mg-G	68	57.2	<1.75	169.6	2.62	0.457	12577	0.699	0.730	10.93	81.3	18550	0.86	9747	72	192.6	0.99	1994	1.48	4091	<4.65	0.7	36.0
8% Mg-G	136	188.6	<1.75	172.4	4.85	1.827	15752	2.180	2.414	16.23	197.1	36688	6.66	9901	101	265.8	1.69	2737	2.59	6590	<4.65	33.9	42.9
4% Ca-G	34	80.5	<1.75	80.1	3.57	0.685	22332	1.283	0.927	13.99	97.3	22063	1.21	2861	118	202.7	1.95	2486	3.36	5822	5.03	0.9	90.9
4% Ca-G	68	105.8	<1.75	70.2	3.80	0.175	25124	0.619	0.607	12.36	116.7	19712	0.72	2939	70	243.7	0.94	2359	1.65	4838	<4.65	1.0	58.8
4% Ca-G	136	91.2	<1.75	69.9	2.84	<0.015	28243	0.198	0.336	12.00	141.1	17108	0.55	2701	72	253.9	0.98	2124	1.39	4504	<4.65	1.1	29.9
8% Ca-G	34	102.6	<1.75	74.2	4.43	0.243	28234	0.522	0.646	11.80	117.8	21616	0.77	2526	73	251.7	1.20	2583	1.91	5185	<4.65	0.9	52.4
8% Ca-G	68	65.5	<1.75	63.3	3.19	0.376	29265	0.575	0.679	11.31	83.4	18798	0.74	1999	59	195.9	0.99	2284	1.90	3816	<4.65	0.9	25.3
8% Ca-G	136	65.4	<1.75	60.8	3.04	0.413	33522	0.645	0.693	8.92	90.2	22215	0.81	2714	46	263.8	0.89	2297	1.43	4051	<4.65	1.3	30.2
Gypsum	34	318.8	<1.75	80.0	2.38	0.315	19612	1.283	0.506	10.29	93.8	25381	1.04	3658	270	167.0	2.58	2488	2.10	11481	<4.65	3.7	435.7
Gypsum	68	237.9	2.41	77.9	3.12	2.036	14202	2.876	2.084	13.11	70.8	26032	3.16	3367	171	117.5	3.42	2551	3.82	8857	<4.65	5.5	310.9
Gypsum	136	248.2	<1.75	102.7	1.82	0.234	15854	1.154	0.507	9.70	84.7	28525	0.74	4777	237	132.8	2.01	3068	2.00	8902	<4.65	1.4	311.2
None	0	19.9	<1.75	4.2	6.61	0.532	963	0.772	0.576	1.14	18.8	2335	0.85	247	33	44.7	1.05	213	1.44	477	<4.65	<0.7	42.8
AL	11	77.2	<1.75	31.1	9.62	<0.015	27872	0.203	0.307	10.67	107.4	19806	0.52	1477	58	230.0	1.17	2259	1.24	4648	<4.65	0.8	39.5
lsd 0.05		68.0	NS	28.8	2.62	NS	5167	NS	NS	5.47	51.5	9285	NS	1586	45	92.8	NS	701	NS	1608	NS	NS	51.2
MS Error		1672	1.012	299	2.47	1.358	9643635	1.363	1	11	957	31141025	7.78	908034	740	3112	0.84	177425	1.22	933572	3.38	191.8	946

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.

Table 42. Chemical composition of alfalfa tissues from the fourth harvest in the AS experiment.

Amendment type	Amendment rate	Al	As	B	Ba	Be	Ca	Cd	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	g/ kg											µg/g											
4% Mg-G	34	345.8	<1.75	83.2	6.17	0.242	17656	0.755	0.802	9.80	251.6	16381	0.33	3228	93	166.8	1.51	3184	1.04	6297	4.87	5.3	94.7
4% Mg-G	68	302.2	<1.75	168.5	2.97	<0.015	15952	0.101	0.441	9.09	234.2	15160	<0.20	8406	73	206.9	0.66	3357	<0.95	9070	<4.65	7.9	76.3
4% Mg-G	136	264.6	<1.75	117.8	3.08	0.040	19746	0.194	0.412	9.39	206.5	19711	<0.20	5375	61	213.6	0.33	3637	<0.95	7373	5.00	6.1	36.8
8% Mg-G	34	360.4	<1.75	102.3	4.70	0.162	15809	0.306	0.575	9.36	258.3	17459	0.29	4430	45	306.2	0.74	3602	1.12	5418	6.58	4.7	48.1
8% Mg-G	68	274.4	<1.75	128.3	3.00	<0.015	19571	0.075	0.397	9.18	228.4	15010	<0.20	6378	89	297.8	0.49	3424	<0.95	8047	<4.65	7.3	54.5
8% Mg-G	136	223.0	<1.75	173.9	2.24	<0.015	16833	0.065	1.014	10.48	200.1	16792	0.66	6386	50	142.2	<0.20	2435	1.63	7147	<4.65	17.9	68.9
4% Ca-G	34	202.9	<1.75	58.3	5.53	<0.015	19795	0.205	0.320	9.35	166.1	17652	<0.20	2009	117	260.1	1.27	3261	<0.95	6248	<4.65	8.6	89.0
4% Ca-G	68	105.8	<1.75	68.5	2.96	<0.015	20838	1.308	0.191	10.32	124.6	17075	0.61	2582	47	248.4	0.60	3819	<0.95	5799	<4.65	6.0	82.7
4% Ca-G	136	130.0	<1.75	60.9	2.51	0.075	21956	0.143	0.242	10.34	136.8	14786	<0.20	2344	84	324.7	0.90	3362	<0.95	5779	<4.65	4.5	24.5
8% Ca-G	34	220.3	<1.75	60.5	5.55	0.374	22537	0.653	0.823	11.20	192.0	16814	0.38	2142	62	268.4	1.08	3746	1.13	6306	<4.65	5.0	45.9
8% Ca-G	68	203.6	<1.75	53.3	3.24	0.033	21578	0.241	0.526	10.17	169.3	14553	<0.20	1881	76	204.9	0.73	3333	<0.95	4851	<4.65	8.9	55.1
8% Ca-G	136	154.8	<1.75	64.8	2.49	0.249	24249	0.501	0.455	9.61	156.0	15711	0.21	2482	73	235.8	0.48	2691	<0.95	5623	5.33	1.4	76.4
Gypsum (G)	34	455.1	<1.75	93.9	3.69	0.290	28234	1.044	1.118	13.89	191.5	28162	0.77	2646	184	144.0	2.44	4640	1.71	13320	5.83	17.5	335.9
Gypsum	68	340.9	<1.75	84.1	2.80	<0.015	31383	0.232	<0.100	14.58	165.3	26628	<0.20	2893	140	211.8	1.36	4633	3.91	12945	15.25	<0.7	267.4
Gypsum	136	262.9	<1.75	66.0	4.90	0.678	22078	1.166	1.176	13.93	211.7	27922	3.38	2576	156	165.3	4.53	5415	1.60	10354	6.10	17.4	140.3
None	0	327.2	<1.75	138.8	14.70	<0.015	13424	0.416	1.590	15.19	275.7	21400	1.89	5100	155	168.4	3.36	3305	1.92	5627	7.11	35.2	78.3
Ag-lime	11	139.7	<1.75	34.6	9.06	<0.015	18845	0.065	0.298	10.27	143.2	16490	<0.20	1550	62	229.6	0.93	3177	<0.95	3469	<4.65	3.7	52.3
lsd 0.05		NS	NS	42.6	2.76	NS	6113	0.809	NS	2.93	NS	2948	0.89	2339	35	NS	2.06	701	1.45	3202	6.71	NS	49.5
MS Error		23415	0.220	655	2.75	0.064	13498269	0.236	0.352	3.09	9447	3139185	0.29	1976799	442	6852	1.53	177567	0.76	3703398	16.25	115.5	884

lsd 0.05 = least significant difference at 0.05 probability level.

MS Error = Mean square for the error term.