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

FINAL REPORT

VOLUME 6: FIELD STUDY CONDUCTED IN FULFILLMENT OF PHASE 3 TITLED:
Use of FGD By-Product Gypsum Enriched with Magnesium Hydroxide as a Soil Amendment

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Wooster, OH 44691

Principle Authors: **J. M. Bigham, U. I. Soto, R. C. Stehouwer, H. Yibirin**
Ohio Agricultural Research Development Center

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ABSTRACT

A variety of flue gas desulfurization (FGD) technologies have been developed to meet environmental restrictions imposed by the federal Clean Air Act and its amendments. These technologies include wet scrubber systems that dramatically reduce sulfur dioxide (SO_2) emissions. Although such systems are effective, they also produce large volumes of sludge that must be dewatered, stabilized, and disposed of in landfills. Disposal is an expensive and environmentally questionable process for which suitable alternatives are needed.

Wet scrubbing of flue gases with magnesium (Mg)-enhanced lime has the potential to become a leading FGD technology. When combined with a forced oxidation system, the wet sludges resulting from this process can be modified and refined to produce gypsum ($CaSO_4 \cdot 2H_2O$) and magnesium hydroxide [$Mg(OH)_2$] of sufficient purity for beneficial re-use in the construction (wallboard) and pharmaceutical industries. The pilot plant at the CINERGY Zimmer Station near Cincinnati can also produce gypsum by-products formulated to contain varying amounts of $Mg(OH)_2$. Such materials may have value to the agriculture, forestry, and lawn-care industries as soil "conditioners", liming agents, and nutritional supplements capable of supplying calcium (Ca), Mg, and sulfur (S) for plant growth. This report describes three field studies designed to evaluate by-product gypsum and Mg-gypsum from the Zimmer Station power plant as amendments for improving the quality of mine spoils and agricultural soils that were unproductive because of phytotoxic levels of dissolved aluminum (Al) and low pH. The technical literature suggests that gypsum may be more effective than agricultural limestone for ameliorating Al toxicity below the immediate zone of application. Such considerations are important for deep-rooted plant species that attempt to utilize water and nutrients occurring at depth in the spoil/soil.

Bulk samples of FGD gypsum and Mg-gypsum (4 and 8% $Mg(OH)_2$) from the Zimmer Station were secured and analyzed for chemical and mineralogical composition. Part of the FGD gypsum was commercially pelletized to evaluate ease of handling; it was found to have excellent spreading characteristics using a standard drop spreader. The FGD gypsum contained significant impurities of both calcite ($CaCO_3$) and dolomite $(Ca,Mg)CO_3$. The Mg-gypsum samples were found to contain somewhat lower quantities of $Mg(OH)_2$ (3 and 6 wt %) than expected. Chemical analyses showed that trace elements of potential environmental concern were at or below detection limits in the by-products.

Two field experiments were established on abandoned mine land (AML) and previously reclaimed mine land (RML) located on properties of The Ohio State University at the Eastern Ohio Agricultural Research and Development Center (EORDC) - Unit 2 in Noble Co., OH. A third experiment was sited on natural agricultural soil (AS) located on private property in Ashtabula Co., OH. Characterization studies of samples from these locations confirmed that pHs in the upper 50 cm (20 in) of the spoil/soil columns were in the range of 3 to 5 and Al toxicities ranged from severe (no plant growth) to moderate (only tolerant species were present). Experimental designs and amendment rates were formulated on the basis of preliminary greenhouse work conducted to mimic field conditions.

In the AML study, agricultural limestone was compared to FGD gypsum and 4% Mg-gypsum with/without added yard-waste compost. Control plots receiving only inorganic fertilizer did not support plant growth, whereas vegetation was quickly established on all plots treated with by-products. The best early yields were obtained on plots amended with by-product gypsum alone; however, this response did not persist. By the end of the second growing season, dry matter production was highest on plots receiving 4% Mg-gypsum + compost. Final yields from compost-treated plots were consistently better than those from corresponding plots receiving only inorganic amendments. In the most severe cases, reduced yields were correlated with elevated concentrations of Al and iron (Fe) in plant tissue samples. Exchangeable Al exceeded 400 mg/kg thoughout the unamended spoil column. All by-products/amendments lowered exchangeable Al to non-toxic levels within the zone of incorporation and caused some downward leaching of Al. By the end of

the experiment, exchangeable Al concentrations in plots treated with gypsum (no compost) were below those of the unamended spoil throughout the 100-cm depth of measurement.

In the RML study, agricultural limestone was compared to FGD-gypsum and 4% Mg-gypsum applied at two rates (20 and 40 ton/ac) without disturbance of existing vegetation. The results from this experiment were less conclusive than at the AML site because the by-products were not incorporated and the graded spoil was less toxic but more variable in composition. Modifications of mine soil chemistry were limited to the upper 10 cm of the profile regardless of amendment used, and consistent reductions in exchangeable Al were achieved only with 40 ton/ac of gypsum and Mg-gypsum. Throughout the term of the study, FGD-gypsum produced the highest dry matter yields. Concentrations of Al and Fe were also lowest in tissues removed from the gypsum-amended plots.

Treatments at the Ashtabula Co. (AS) site consisted of agricultural limestone (12 ton/ac); increasing quantities of 4% Mg-gypsum (15, 30, and 60 ton/ac); and increasing Mg (0, 4, 8, 12%) in FGD gypsum applied at a rate of 60 ton/ac. Alfalfa was used as the test crop. All treatments produced significant improvements in alfalfa yield compared to the unamended control plots. Increasing 4% Mg-gypsum enhanced yield for the 1997 harvest and the 2-yr total; however, increasing the amount of Mg in gypsum had no effect on dry matter production. Plant tissue concentrations of Ca, Mg, and S were similar across all amendments. Concentrations of Al and Fe, on the other hand, were highest in vegetative matter from the control plots. Phytotoxic levels of exchangeable Al were present in the unamended soil, and all amendments produced major decreases in exchangeable Al within the zone of incorporation. By the last harvest, reductions of 50% or more were also observed in the subsoil of those plots treated with high rates (30 and 60 ton/ac) of 4, 8, and 12% Mg-gypsum. Significant improvements in the saturated hydraulic conductivity of the soil at a depth of 30 - 45 cm were also achieved with these treatments. These improvements may reflect better subsoil aggregation due to saturation of the CEC with Ca, increased porosity as a consequence of better root distributions in response to less phytotoxic conditions, or both. Such results suggest that land applications of gypsiferous by-products may produce improved soil chemical and physical properties, even in regions where gypsum has not been traditionally utilized as an agricultural amendment.

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1 INTRODUCTION

1.1 Background and Project Description

The Clean Air Act of 1976 was amended in 1990 to require a major reduction in annual sulfur dioxide (SO_2) emissions from coal-fired utilities in the United States. These reductions have been achieved by burning a higher percentage of low-sulfur coals and by using a variety of clean coal technologies to convert gaseous forms of sulfur (S) to non-volatile materials during or after the combustion process. Large quantities of flue gas desulfurization (FGD) by-products result from post-combustion treatment of flue gases with an absorbent to reduce S emissions. One of the primary expenses associated with any FGD technology is disposal of the solids generated by the scrubbing process. Disposal costs may be partially offset by converting the waste solids into products suitable for re-use.

At present, wet scrubbing of flue gases with magnesium (Mg) enhanced lime is the leading post-combustion technology for effective SO_2 removal in a cost-efficient manner. By-products of this process include magnesium hydroxide [$Mg(OH)_2$], gypsum ($CaSO_4 \cdot H_2O$), 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 treatment system. There are also established commercial markets, such as wallboard manufacture, for gypsum. The Mg-gypsum materials are not suitable for high purity applications of either magnesium hydroxide or gypsum but may be adequate for use in agricultural markets.

Gypsum is one of the earliest forms of fertilizer in the U.S., having been applied to agricultural soils for over 250 yr. (Tisdale et al., 1985). Gypsum is an excellent source of both calcium (Ca) and S for plant nutrition and is much more soluble than calcium carbonate ($CaCO_3$). Whereas the beneficial effects of $CaCO_3$ are mostly limited to the zone of incorporation, surface applications of gypsum may affect soil physical and chemical properties at depth. For example, gypsum has been extensively used to improve subsoil structure in arid region soils having high exchangeable sodium (Na) percentages. Calcium is mobilized by dissolution of gypsum and replaces Na on the cation exchange complex, thus promoting flocculation of these highly dispersed soils (Oster, 1982; Shainberg et al., 1989). Gypsum has also been shown to improve surface infiltration rates by inhibiting or delaying surface seal formation (Miller, 1987; Norton, 1995).

Gypsum applications to Ca-deficient soils in humid regions have shown beneficial effects because of Ca movement into the subsoil, thereby improving root growth and lowering water stress (Hammel et al., 1985; Pavan and Bingham, 1982; Pavan et al., 1984; Farina and Channon, 1988; Ritchey et al., 1995). An associated effect may be the amelioration of phytotoxic conditions arising from excess soluble aluminum (Al) in acid soils (Sumner, 1970; Reeve and Sumner, 1972). The decreased toxicity of Al following gypsum application appears to involve the sulfate (SO_4^{2-}) ion and may occur by several mechanisms. In some soils, sorption of SO_4^{2-} onto mineral surfaces may displace hydroxyl (OH^-) ions and thereby raise the pH. This process has been termed "self liming" (Reeve and Sumner, 1972). Another possibility is that Al displaced into the soil solution by Ca from gypsum may be physically removed from the soil profile by leaching, probably as aluminum sulfate (Oates and Caldwell, 1985). A third mechanism could involve the precipitation of aluminum-sulfate minerals at high SO_4^{2-} concentrations and low pH, thereby reducing the levels of toxic Al in the soil solution (Adams and Rawajfih, 1977). Finally, there may be no change in the total concentrations of soluble Al, but the phytotoxicity of the species present may be decreased. This possibility occurs when Al^{3+} species react with SO_4^{2-} to form the $AlSO_4^+$ ion pair, which is much less toxic to plants (Pavan and Bingham, 1982; Kinraide and Parker, 1987).

In many acidic soils, concerns also exist regarding Mg chemistry. Plant uptake of Mg is impaired when exchangeable Al saturation exceeds 65% of the soil cation exchange capacity (CEC) (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 calcitic limestone to correct the pH of some acid soils has also been shown to decrease exchangeable Mg concentrations, increase the exchangeable Ca:Mg ratio, and decrease plant uptake of Mg (Mclean and Carbonell, 1972; Sumner et al., 1978; Myers et al., 1988; Carran, 1991). Similar effects on soil Mg and plant uptake of Mg have been observed with applications of gypsum (Webster, 1990).

The negative effects of limestone and gypsum applications on plant growth appear to be the result of Ca:Mg imbalance. For most crops, the exchangeable Ca:Mg ratio should not exceed 7:1 (Tisdale et al., 1985). Carran (1991) reported Mg deficiencies in clover when the Ca:Mg ratio surpassed 20:1. The imbalances produced by limestone and gypsum applications have been overcome by adding supplemental Mg, usually as dolomite [$(Ca,Mg)CO_3$]. There is additional evidence that supplemental Mg may serve to ameliorate not only nutritional deficiencies but also Al phytotoxicity (Keltjens and Dijkstra, 1991; Edmeades et al., 1991). 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 could enhance its value as an agricultural amendment. The $Mg(OH)_2$ contained in FGD Mg-gypsum should have the same beneficial effects as conventional dolomite; that is, it could serve both as a liming agent and a source of Mg for plant nutrition.

1.2 Phase 3 Objectives

The Phase 3 objectives were to:

1. determine the effectiveness of FGD by-product gypsum and Mg-gypsum (as compared to conventional agricultural limestone) for alleviating aluminum toxicity in naturally acid soils and mine spoils.

2. evaluate the effectiveness of FGD by-product gypsum and Mg-gypsum for improving established vegetative cover on previously reclaimed mine land.

3. assess the effectiveness of FGD by-product gypsum and Mg-gypsum for improving the permeability (hydraulic conductivity) of subsoil materials.

4. evaluate the rate at which soluble components from FGD by-product gypsum and Mg-gypsum move into the soil/spoil column.

1.3 Approach

At least three field situations in Ohio may benefit from surface amendments with gypsum or Mg-gypsum. These include:

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

Field sites meeting these conditions were identified and experiments were established to compare the effects of different wet FGD by-products on plant growth and soil/spoil chemistry under natural environmental conditions. Application rates were varied based on the results of preliminary greenhouse studies conducted as phase 2 of this project (Yibirin et al., 1997), and data were collected over two growing seasons.

2. CHARACTERIZATION OF BY-PRODUCTS AND AMENDMENT MATERIALS

2.2 Methods Used

2.2.1 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 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.

2.2.2 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 at al. (1992).

2.2.3 X-ray Diffraction

X-ray diffraction (XRD) patterns were obtained from randomly oriented powder mounts using Cu Kα radiation and a Philips 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.

2.2.4 Chemical Analyses

The yard-waste compost was provided by Kurtz Bros. (Columbus, OH) and 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, pH and electrical conductivity (EC).

Chemical analyses of the FGD by-products and agricultural limestones 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 (SY-2) 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, S, Si, and Zn using inductively coupled plasma emission spectrometry (ICP) with a Leeman PS2000 instrument.

2.3 Properties of By-Products and Amendment Materials

2.3.1 Yard-waste Compost

Reclamation research on acid mine spoils has shown that the use of organic amendments, such as compost or sewage sludge, 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 properties 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, as in the current case, will result in a release of N. The total N content of the organic material may also have an influence 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 1.4%.

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

Element	μg g^{-1}	Element	g kg^{-1}
Boron	35.4	Phosphorus	3.0
Cadmium	<0.2	Potassium	4.0
Lead	35.6	Calcium	83
Nickel	122.2	Magnesium	15
Chromium	83.9	Sodium	0.3
Zinc	396.4	Manganese	0.3
Copper	53.9	Iron	7.0
Mercury	<1.0	Total N	14
Arsenic	9.9	Total C	214
Molybdenum	5.6	C/N ratio	15:1
Selenium	0.4	pH	7.4
Ammonium-N	<0.01	EC (dS m^{-1})	4.74
Nitrate-N	105		

2.3.2 FGD By-products and Agricultural Limestones

The FGD by-products used in phase 3 included a by-product gypsum ($CaSO_4 \cdot 2H_2O$) and two Mg-gypsums formulated to contain 4 and 8% brucite [$Mg(OH)_2$]. Part of the FGD gypsum was pelletized by a commercial operator to test the spreading characteristics using a conventional lime spreader. Two different agricultural limestones were also purchased and applied as standard treatments for comparison with the FGD by-products.

Unlike the high purity material used in preliminary greenhouse studies (Yibirin, et al., 1997), the pelletized FGD gypsum applied in the field experiments contained significant amounts of both calcite ($CaCO_3$) and dolomite [$(Ca,Mg)CO_3$] (Table 2, Fig. 1). These carbonates contributed some liming potential that would not otherwise have been available with pure gypsum. The dolomite also provided a slow-release source of Mg for plant nutrition (Table 3). The somewhat lower specific surface area of the pelletized gypsum (Table 1) as compared to that used in the greenhouse (Yibirin, et al., 1997) (1 vs. 8 m^2/g) could reflect the addition of lignin as a binding agent. Chemical analyses (Table 4) demonstrated that most trace elements were present in concentrations below instrumental (ICP) detection limits.

The $Mg(OH)_2$ contents of the Zimmer Mg-gypsums were slightly lower than formulated (Table 2) but were in the expected 2:1 ratio. Both materials also contained small amounts of calcite, and the $CaSO_4$ component in the 8% material was present mostly as bassanite ($CaSO_4 \cdot 0.5H_2O$) instead of gypsum (Fig. 2 and 3). Conversion of gypsum to bassanite probably occurred during the drying process but should not significantly affect the chemical properties of the by-product. Once again, most trace metals were below detection limits; however, B contents were significantly higher than in the FGD gypsum (Table 4).

Two commercial, agricultural limestones were also used in the field experiments. The materials were of comparable purity with quartz (SiO_2) as a minor (< 5%) impurity (Table 2; Fig. 4 and 5). The dolomite content of limestone #1 was approximately twice that of limestone #2 which would influence the long-term supply of Mg for plant growth.

Table 2. Surface area and estimated† mineralogy of FGD by-products and agricultural limestones.

Material	Surf. Area	Calcite	Dolomite	Gypsum	Bassanite	Brucite	Quartz
	m^2/g	----	----	%	----	----	----
FGD Gypsum	1.0	11	8	81			
FGD Mg-Gypsum - 4% $Mg(OH)_2$	1.5	2		91		3	
FGD Mg-Gypsum - 8% $Mg(OH)_2$	6.3	1		7	88	6	
Ag. Limestone (No. 1)	2.4	86	10				4
Ag. Limestone (No. 2)	2.5	74	20				5

† Error of analysis is ± 5% for any mineral species.

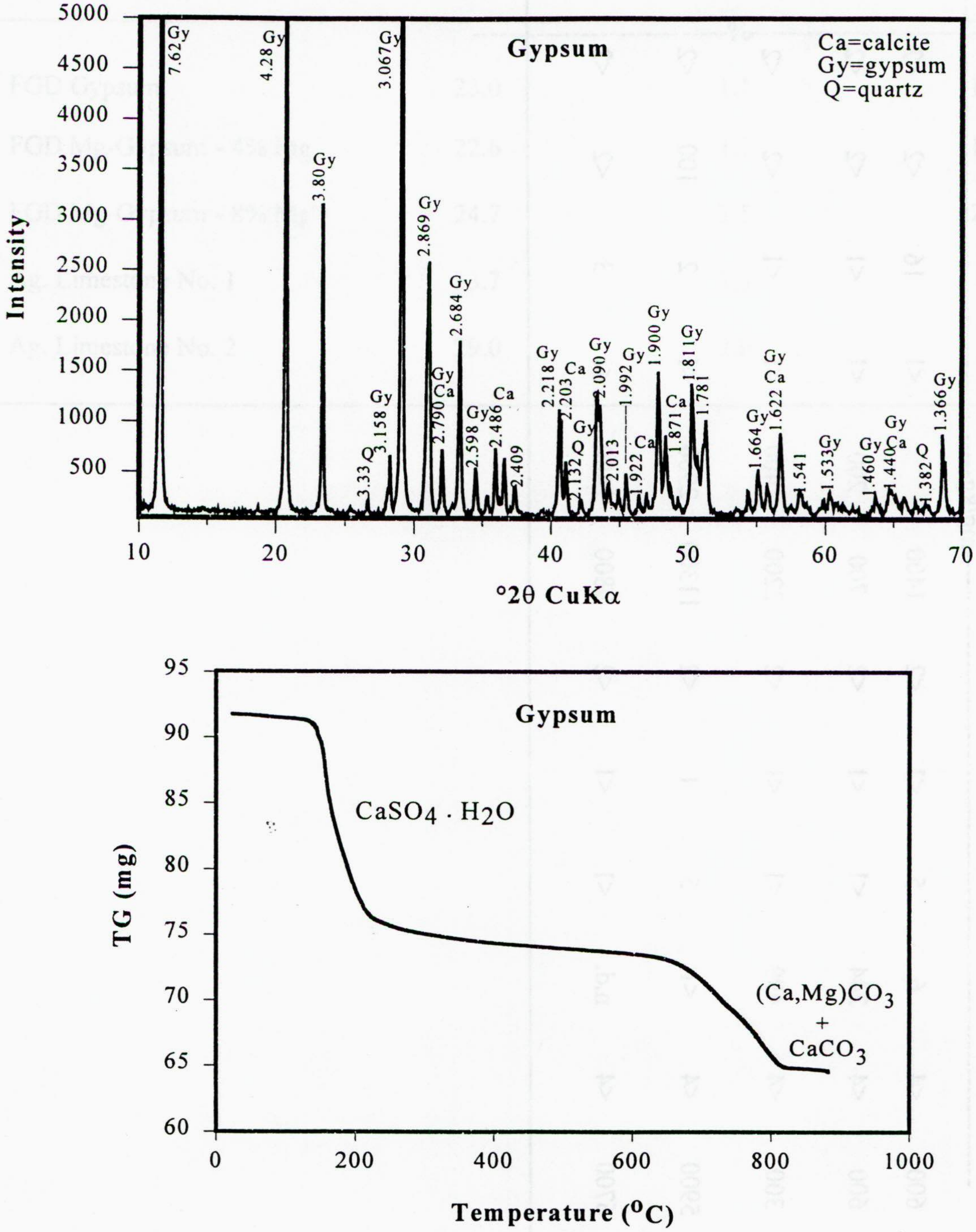


Figure 1. X-ray diffraction pattern (top) and thermogram (bottom) from by-product gypsum. X-ray peak positions are in Angstrom units.

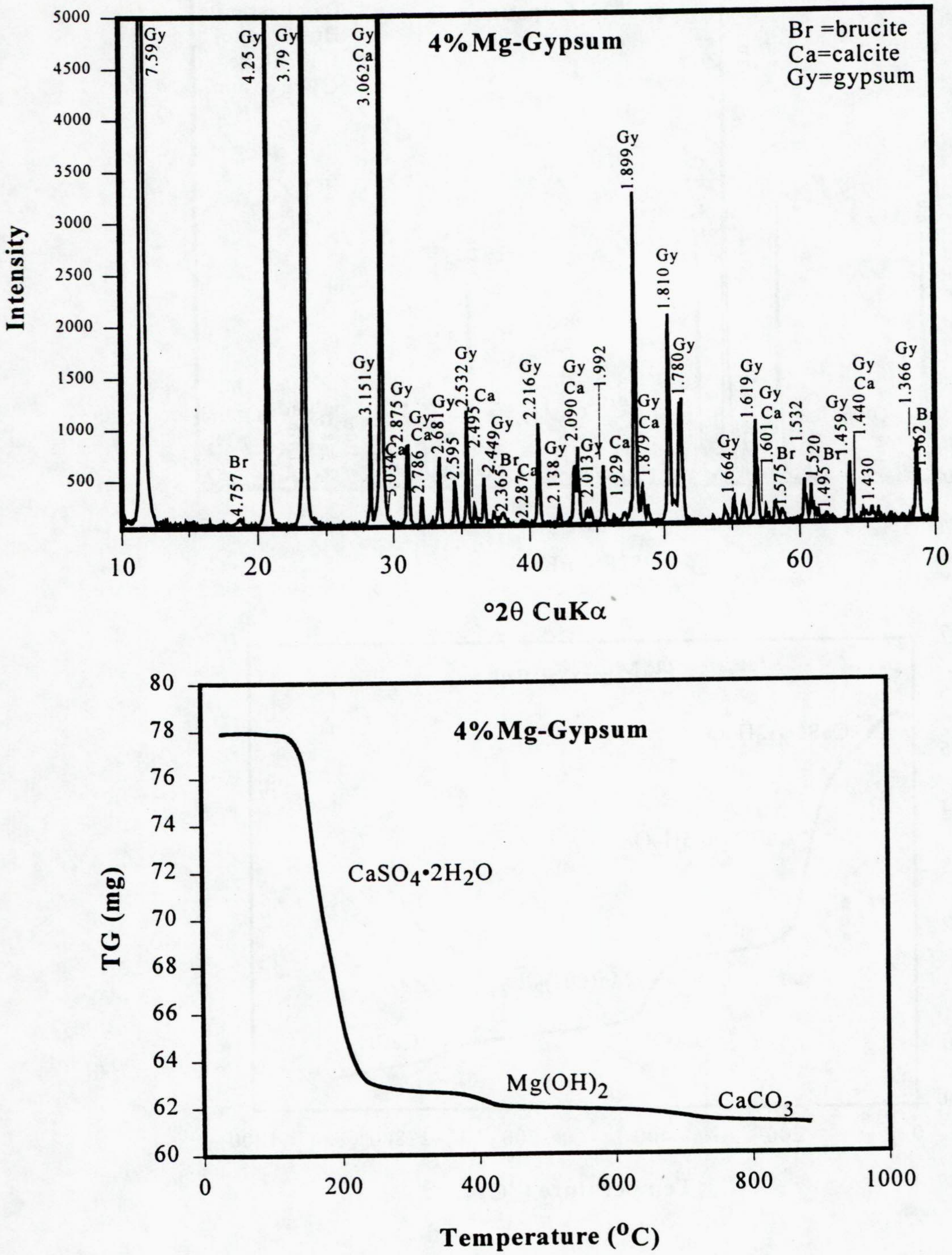


Fig 2. X-ray diffraction pattern (top) and thermogram (bottom) from 4% Mg-gypsum. X-ray peak positions are in Angstrom units.

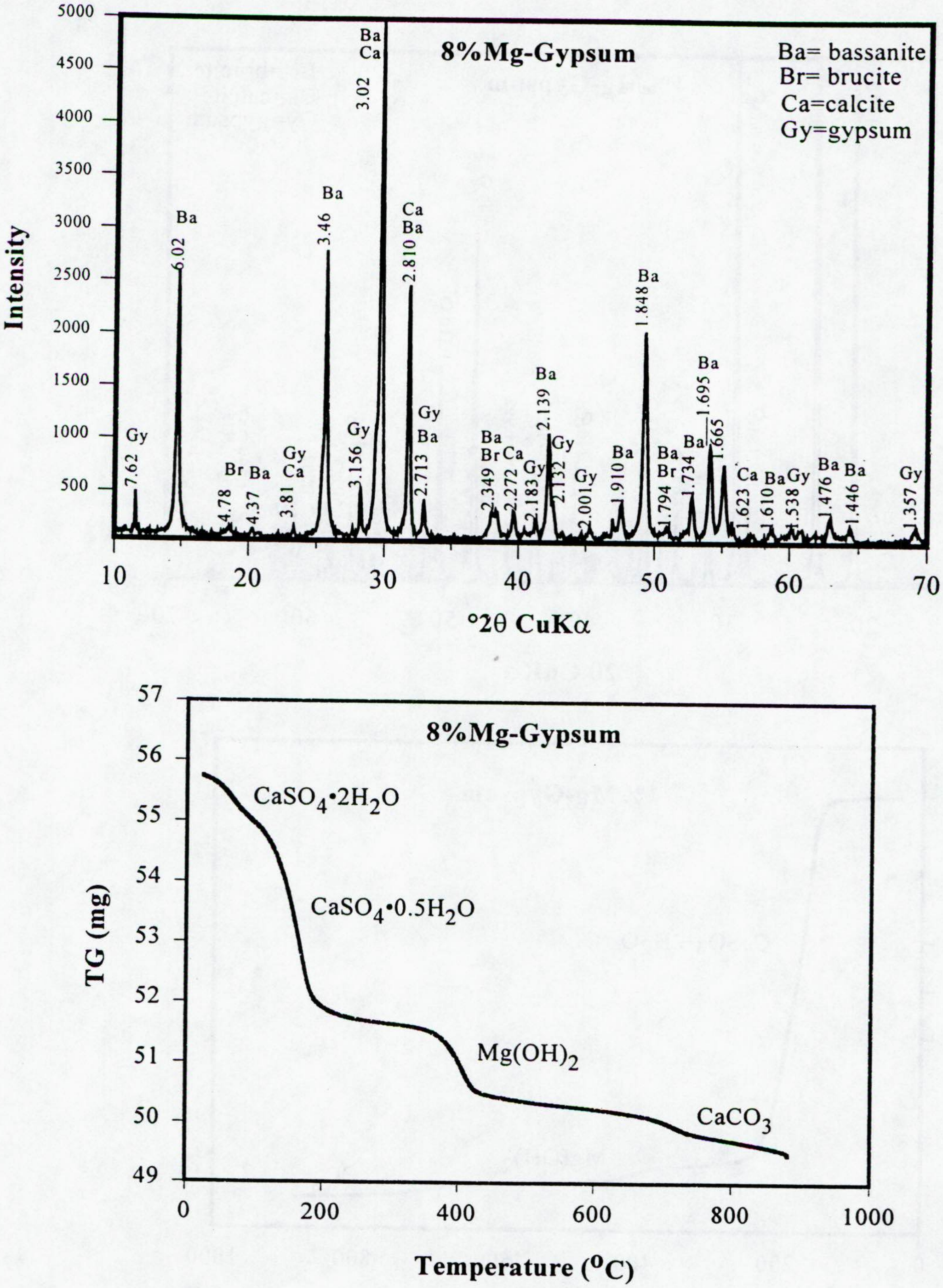


Figure 3. X-ray diffraction pattern (top) and thermogram (bottom) from 8% Mg-gypsum. X-ray peak positions are in Angstrom units

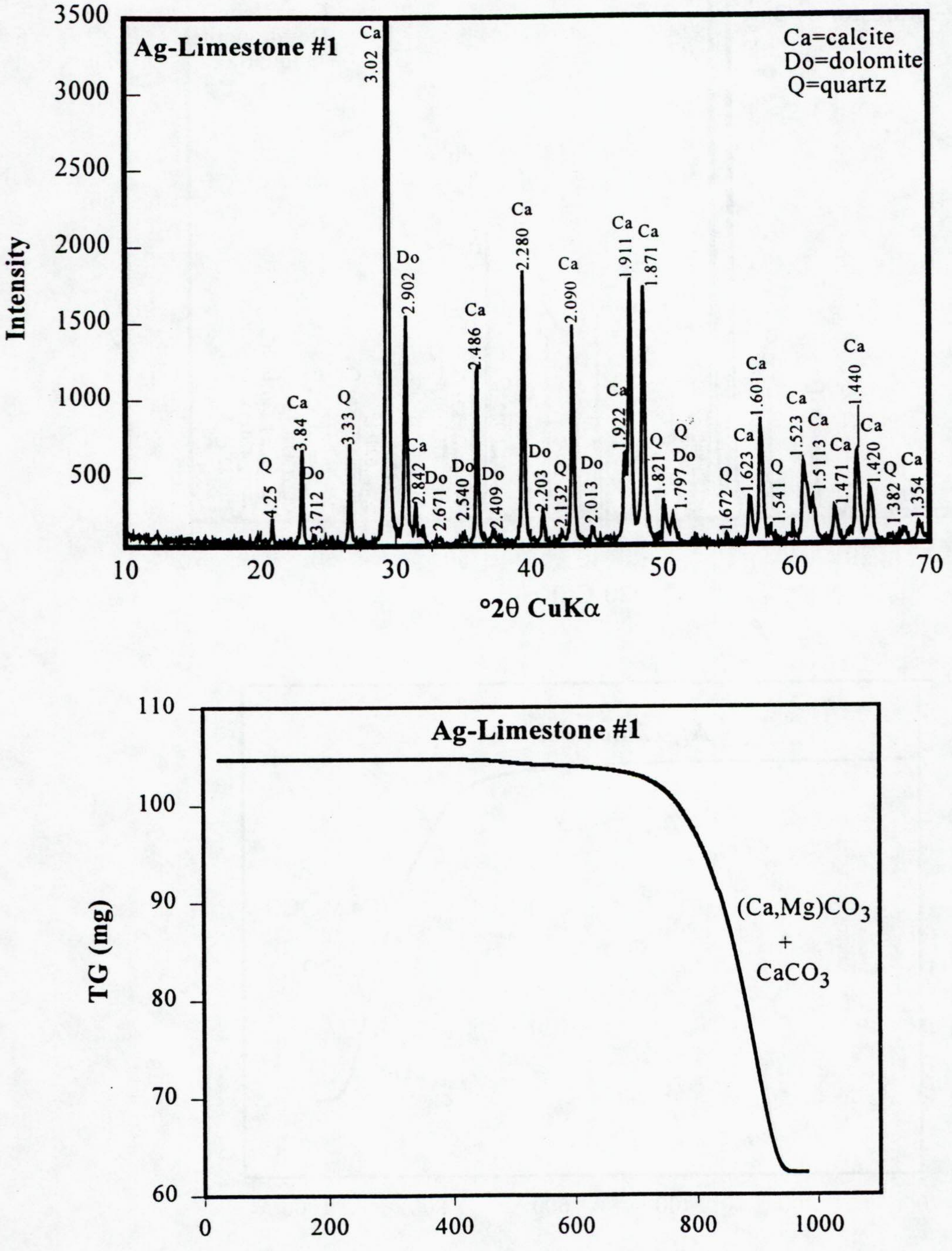


Figure 4. X-ray diffraction pattern (top) and thermogram (bottom) from Ag-limestone No. 1. X-ray peak positions are in Angstrom units.

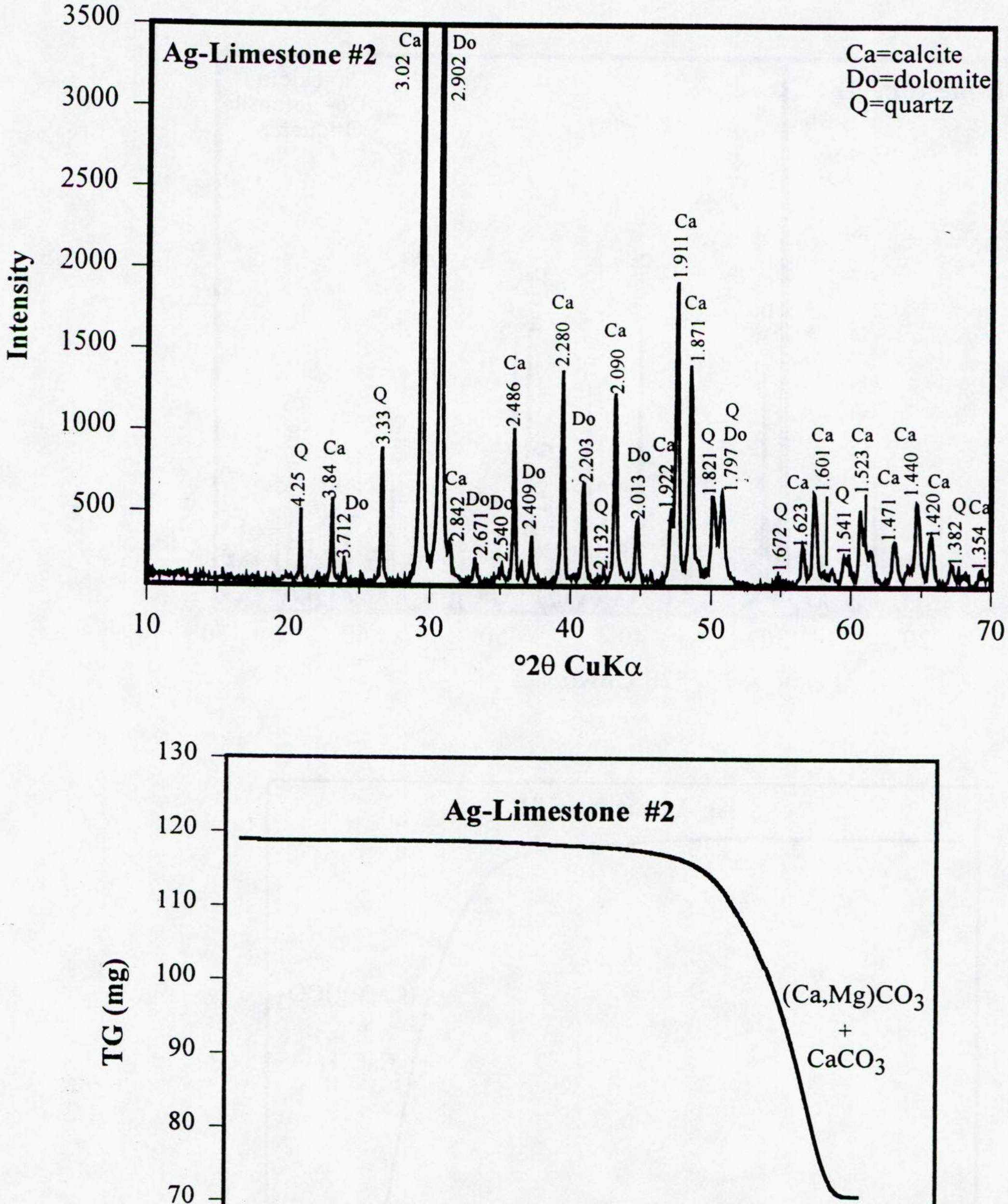


Figure 5. X-ray diffraction pattern (top) and thermogram (bottom) from Ag-limestone No. 2. X-ray peak positions are in Angtrom units.

3 FIELD STUDIES

Three field experiements were designed and conducted in parallel using different combinations of treatments and amendments.

3.1 Location of Field Sites

Field experiments were established on abandoned mine land (AML) and previously reclaimed mine land (RML) located on properties of The Ohio State University at the Eastern Ohio Agricultural Research and Devolpment Center (EORDC) - Unit 2 in Noble Co., OH (Table 5; Fig. 6). The third experiment was established on natural agricultural soil (AS) located on private property in Ashtabula Co., OH (Table 5; Fig. 6). The latitude and longitude of each site were determined with a global positioning system or from USGS topographic maps.

Table 5. Location and attributes of AML, RML, and AS field sites in Ohio.

Locator/Attribute	AML	RML	AS
County	Noble	Noble	Ashtabula
USGS Quadrangle	Macksburg	Macksburg	East Trumbull
Town, Range, Sec.	T. 6N, R. 8W, Sec. 27	T. 6N, R. 8W, Sec. 21	T. 11N, R. 5W
Latitude	39°41'14"	39°41'29"	41°43'33"
Longitude	81°24'22"	81°24'44"	80°58'11"
Soil Survey Field Sheet	Noble Co., Sheet 40	Noble Co., Sheet 40	Ashtabula Co., Sheet 36
Soil Mapping Unit	BaF, 25-70% slope	EnD, 15-25 % slope	PsB2, 2-6% slope
Soil Series	Barkcamp	Enoch	Platea
General	0.25 mi east of intersection of T-500 and S.R. 564	0.35 mi north of intersection of T-304 and S.R. 564	0.87 mi west on Cork-Cold Springs Rd from its intersection with S.R. 534; then 0.25 mi south. William Meyer farm, 6004 Cork-Cold Springs Rd.

Figure 6. General location map for field study sites.

3.2 Initial Characterization of Soil/Spoil Materials

Bulk samples of soil and spoil materials from the three study sites were collected and characterized prior to conducting the greenhouse studies described by Yibirin et al. (1997) and prior to initiating field experiments.

3.2.1 Laboratory Methods

3.2.1.1 Soil/Spoil Reaction

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

3.2.1.2 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 a lime test index table (Watson and Brown, 1998).

3.2.1.3 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 min 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.

3.2.1.4 Total Acidity

Total extractable acidity was determined using the method of Peech et al. (1947). Ten g samples of soil/spoil were leached for 30 min 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.

3.2.1.5 Ammonium Acetate Extractable Bases

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* NH_4OAc (pH 7.0) over a 12-hr 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.

3.2.1.6 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 min 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 H_2SO_4, 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 determining the recovery of CO_2 from reagent grade $CaCO_3$.

3.2.1.7 Particle Size Distribution

Particle size distribution of the < 2-mm fraction was determined by 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. Silt and Clay contents were determined by oven-drying aliquots of suspension taken at times and depths calculated according to Stokes' Law. Sands were obtained by mechanical sieving using nested sieves.

3.2.2 Results of Soil/Spoil Characterization

The results of characterization studies are reproduced in Tables 6 and 7. The presence of abundant coal fragments in the AML spoil is reflected in its high 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. Total acidity and exchangeable Al (KCl Al) are related parameters that are negatively correlated with the fertility of a soil or spoil material. A high base saturation (calculated as a percentage of the CEC occupied by the exchangeable Ca, Mg, K, and Na in Table 7), on the other hand, is a positive indicator of soil/spoil fertility. Plant root growth is essentially eliminated when the soil/spoil pH is lower than 5.0 and the exchangeable Al reaches 85% of the CEC. Consequently, the AML site was devoid of vegetation. The "toxic" nature of this site is typical of many abandoned mined lands in Ohio.

The AML and graded RML spoils were taken at similar elevations and from the same geologic section, but the RML material contained less coal and more sandstone as reflected in its sandier texture and lower carbon contents. The RML spoil contained sufficient exchangeable bases to support plant growth; however, the replaced topsoil had acidified to the point that vegetation at the site was failing.

The agricultural soil from Ashtabula Co. had low pH and base saturation and high levels of exchangeable Al under natural conditions. These properties extended into the subsoil as shown by the data in Table 6. The lime requirement for both the topsoil and subsoil at this site were comparable to that of the RML spoil.

Table 6. Texture and total carbon contents of bulk soil and spoil materials from the three field sites (taken from Yibirin et al., 1997)

Sample	Depth	Total C	Sand	Silt	Clay	Texture*
	cm	-------------------------	-------------------------	%	-------------------------	
AML spoil	0-20	16.70	17.1	43.7	39.2	SiCl
RML spoil	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 7. Soil and spoil chemical data (from Yibirin et al., 1997).

Site	Depth	pH		Lime Requirement†	KCl Al	Total Acidity	NH4OAC exchangeable				CEC†	Base Sat.
		H_2O	$CaCl_2$				Ca	Mg	K	Na		
	cm			ton/ac	cmol$_c$/kg							%
AML	0-40	3.0	2.9	>22.1‡	6.68	28 .9	0.5	0.1	0.32	0.19	30.0	4
RML	0-20	5.0	4.7	6.5	0.90	7.7	7.0	3.4	0.95	0.10	19.1	60
RML	20-45	3.6	3.5	16.9	2.54	9.7	6.3	0.1	0.39	0.06	16.6	41
AS	0-15	4.2	3.9	11.7	3.97	14.4	0.6	0.1	0.71	0.11	15.9	10
AS	15-45	4.8	3.9	13.7	4.78	12.1	1.2	0.1	0.69	0.13	14.2	15

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

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

3.3 Abandoned Mine Land (AML) Experiment: Design and Sampling

An area of abandoned mine spoil devoid of vegetation was identified at the Eastern Ohio Research and Development Center - Unit 2 in Noble Co., OH (Fig. 6). The site was graded to remove gullies and to prepare a uniform slope by using heavy earth moving equipment in the summer of 1995. Thirty-two plots, each 20 x 25 ft in size, were surveyed, and fertilizer was uniformly spread over all plots at a rate (65 lbs N/ac, 150 lbs P_2O_5/ac, 400 lbs K_2O/ac) determined by standard soil tests. Amendments were applied during September, 1995, at the rates shown in Fig. 7 using a split plot design (alkaline amendment main plot, compost as subplot) with four replications. Pelletized FGD gypsum was applied with a 3-m (10-ft), drop spreader designed for ag-limestone application. Mg-gypsum was supplied as a wet filter cake and was applied with a manure spreader. Fertilizer and amendments were incorporated to a depth of 10-cm using a roto-tiller. The plots were seeded on October 9 - 10 using approximately 4 kg/rep of winter wheat and 6 kg/rep of a standard reclamation mixture consisting of 16% orchardgrass, 20% timothy, 16% ladino clover, 14% birdsfoot trefoil, and 34% annual ryegrass. The plots and surrounding areas were mulched with wheat straw immediately after planting.

Vegetative samples were collected on 17 June 1996, 20 September 1996, 10 July 1997, and 17 September 1997 by mowing strips (2.7 x 20 ft) through the center of each plot. The fresh weight of all material collected from each strip was recorded and a subsample (~1 kg) was placed in a cloth bag and dried at 60°C for at least 48 hr to determine the dry matter yield. The dried plant material from selected harvests was then ground to pass a 1-mm sieve and analyzed as described in Secs. 3.6.5 and 3.6.6.

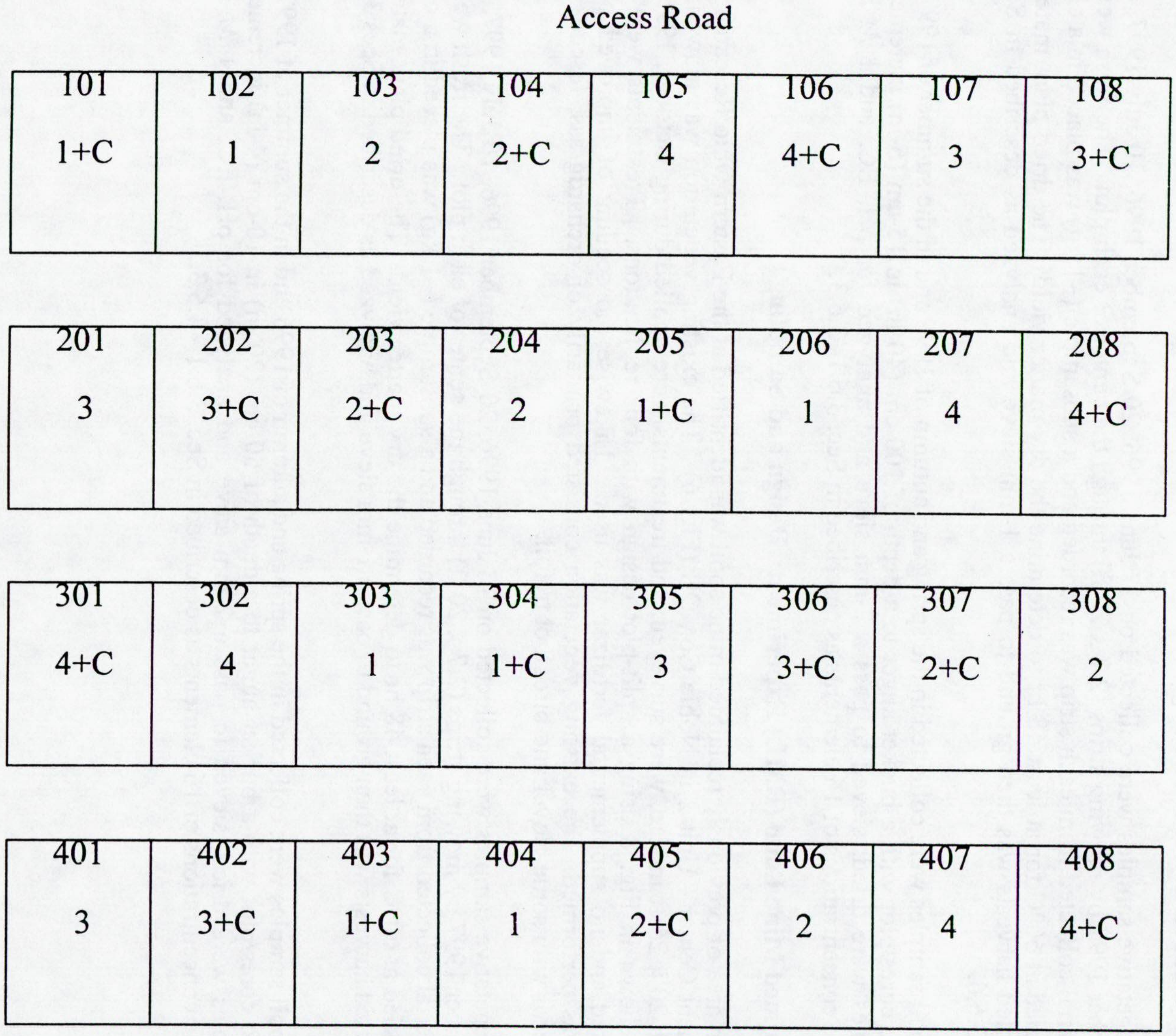
Spoil samples were collected in the spring and autumn of 1996 and in the summer of 1997 by taking two cores/plot with a bucket auger to a depth of 100 cm (40 in) in 15-cm (6-in) increments. The samples were dried, sieved to pass a 2-mm sieve and analyzed for pH, EC, and 1 *M* KCl extractable concentrations of 16 elements as described in Sec. 3.6.1- 3.6.3.

3.4 Reclaimed Mine Land (RML) Experiment: Design and Sampling

An area of previously reclaimed mine spoil was identified at the Eastern Ohio Research and Development Center - Unit 2 in Noble Co., OH (Fig. 6). The existing vegetation was mowed; 24 plots, each 20 x 25 ft in size, were surveyed; and treatments were applied during October, 1995, at the rates shown in Fig. 8 using a split-plot design with four replications. Treatments were not incorporated and no supplemental fertilizer was used. Likewise, no seeding of improved plant species was performed. The existing vegetation consisted primarily of orchardgrass, fescue, and annual weeds with some clover and birdsfoot trefoil.

Vegetative samples were collected on 18 June 1996, 20 September 1996, 10 July 1997, and 24 September 1997 by mowing strips (2.7 x 20 ft) through the center of each plot. The fresh weight of all material collected from each strip was recorded and a subsample (~1 kg) was placed in a cloth bag and dried at 60°C for at least 48 hr to determine the dry matter yield. The dried plant material from selected harvests was then ground to pass a 1-mm sieve and analyzed as described in Secs 3.6.5 and 3.6.6.

Spoil samples were collected in the spring and autumn of 1996 and in the summer of 1997 by taking two cores/plot with a bucket auger to a depth of 50 cm (20 in) in 10-cm (4-in) increments. The samples were dried, sieved to pass a 2-mm sieve and analyzed for pH, EC, and 1 *M* KCl extractable concentrations of 16 elements as described in Sec. 3.6.1 - 3.6.3..



101	102	103	104	105	106	107	108
1+C	1	2	2+C	4	4+C	3	3+C
201	202	203	204	205	206	207	208
3	3+C	2+C	2	1+C	1	4	4+C
301	302	303	304	305	306	307	308
4+C	4	1	1+C	3	3+C	2+C	2
401	402	403	404	405	406	407	408
3	3+C	1+C	1	2+C	2	4	4+C

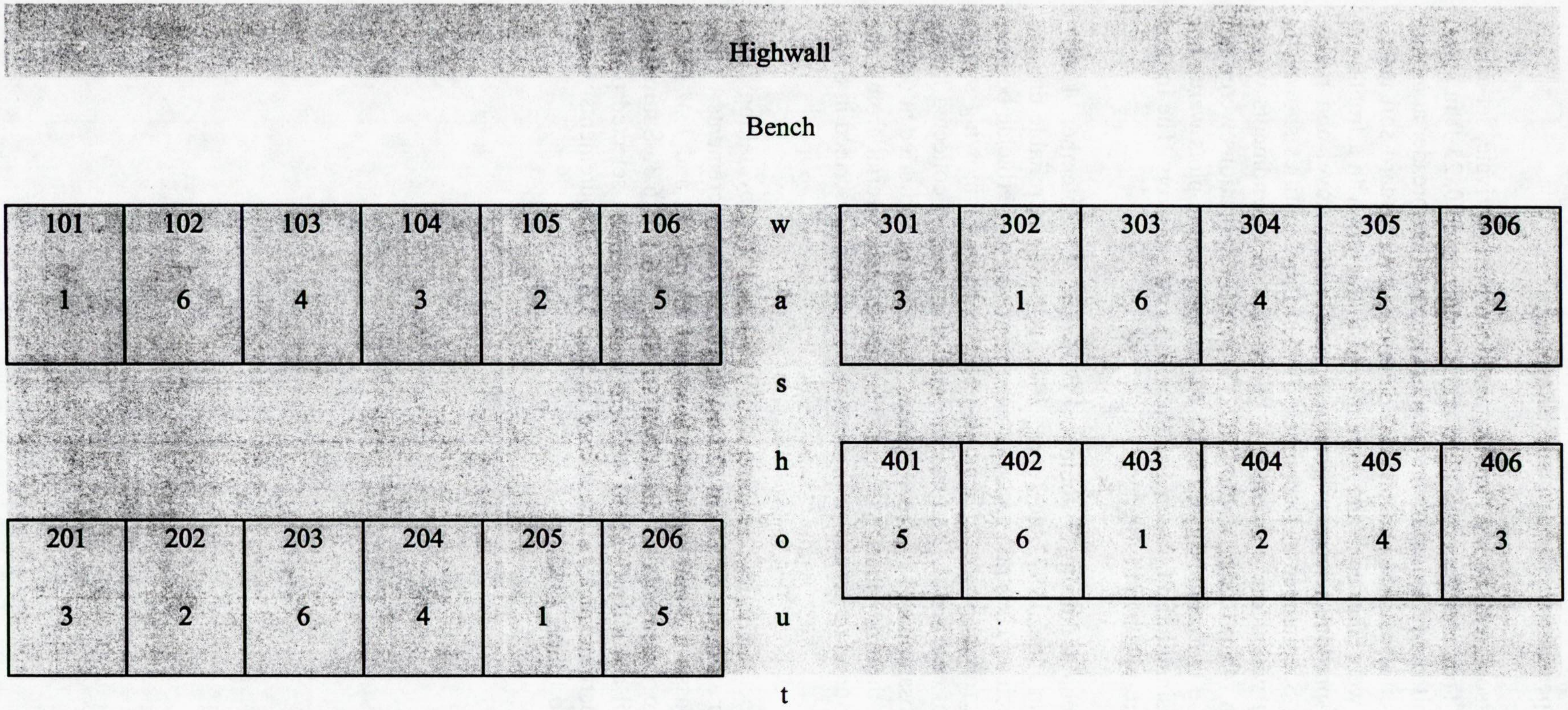
<u>Treatments</u>

1. Control (no amendment)
2. Ag. Limestone (45 ton/ac)
3. FGD Gypsum (100 ton/ac)
4. FGD Mg-Gypsum [4% $Mg(OH)_2$]

   (110 ton/ac)

+ C: Treatment + 50 ton/ac yard waste compost containing 15 lb dry matter per 0.028 Y^3

Figure 7. Treatments and experimental design for abandoned mine land (AML) using 20x25 ft plots at EORDC-Unit 2.



<u>Treatments</u>:

1. Control (no amendment)
2. Ag. Limestone, 6 ton/ac
3. FGD Gypsum, 20 ton/ac
4. FGD Gypsum, 40 ton/ac
5. FGD Mg-Gypsum [4% $Mg(OH)_2$], 20 ton/ac
6. FGD Mg-Gypsum [4% $Mg(OH)_2$], 40 ton/ac

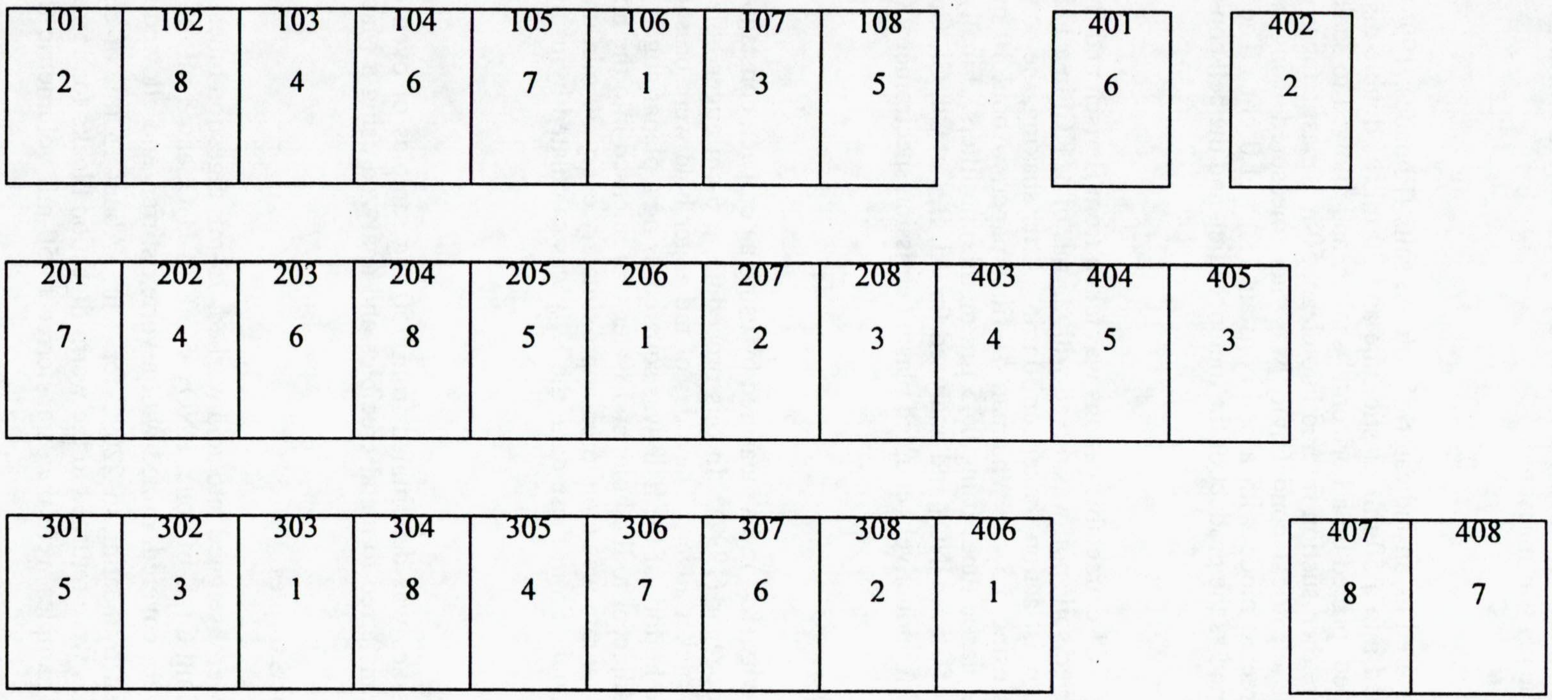
Figure 8. Treatments and experimental design for previously reclaimed mine land (RML) using 20x25 ft plots at EORDC-Unit 2

3.5 Agricultural Soil (AS) Experiment: Design and Sampling

An area of naturally acid soil with high Al toxicity was identified on private, set-aside land in Ashtabula Co. (Fig. 6). The area was roto-tilled and 32 plots, each 20x25 ft in size, were surveyed. Fertilizer was uniformly broadcast on the plots using a lime spreader at a rate (490 lb/ac KCl and 991 lb/ac total soluble phosphorus) determined by standard soil tests. FGD materials were supplied as wet filter cake and were moved to the plots with a front-end loader. Once deposited, the by-products were uniformly spread with a shovel and rake. Treatments were applied during September to December, 1995, in the quantities shown in Fig. 9 using a split plot design with four replications. Fertilizer and amendments were incorporated to a depth of 10 cm (4 in) using a roto-tiller. Treatment applications were not completed in a timely manner due to availability of FGD by-product, and the plots were not seeded until the spring of 1996 using alfalfa (*Medicago sativa* L.) as the test crop. The initial seeding failed and the plots were re-planted in July.

Vegetative samples were collected during 1 October 1996 and 11 September, 1997. Additional harvests were taken in June, 1997, and June, 1998, but were not reliable due to heavy infestations with grass species. The grass species were removed with herbicide before the second harvest in the 1997 growing season. Samples were collected by mowing strips (1.5 x 20 ft) through the center of each plot. The fresh weight of all material collected from each strip was recorded and a subsample (~1 kg) was placed in a cloth bag and dried at 60°C for at least 48 hr to determine the dry matter yield. The dried plant material from the September, 1997, harvest was ground to pass a 1-mm sieve and analyzed as described in Secs 3.6.5 and 3.6.6.

Soil samples were collected in the summers of 1996 and 1997 by taking two cores/plot with a bucket auger to a depth of 50 cm (20 in) in 10-cm (4-in) increments. The samples were dried, sieved to pass a 2-mm sieve and analyzed for pH, EC, and 1 *M* KCl extractable concentrations of 16 elements as described in Sec. 3.6.1 - 3.6.3. Saturated hydraulic conductivity of the soil at a depth of 30 - 45 cm was measured in selected plots using a compact, constant-head permeameter as described in Sec. 3.6.4. Measurements were taken during September, 1997, and June, 1998.



<u>Treatments:</u>

1. Control (no amendment)
2. Ag. Limestone, 12 ton/ac
3. FGD Gypsum, 60 ton/ac
4. FGD Mg-Gypsum, [4% $Mg(OH)_2$], 15 ton/ac
5. FGD Mg-Gypsum, [4% $Mg(OH)_2$], 30 ton/ac
6. FGD Mg-Gypsum, [4% $Mg(OH)_2$], 60 ton/ac
7. FGD Mg-Gypsum, [8% $Mg(OH)_2$], 60 ton/ac
8. FGD Mg-Gypsum, [12% $Mg(OH)_2$], 60 ton/ac (prepared by applying one, 50 lb. bag of technical grade $Mg(OH)_2$ + 60 ton/ac 8% Mg-gypsum to each plot)

Figure 9. Treatments and experimental design for natural agricultural soil (AS) using 20x25 ft plots in Ashtabula Co.

3.6 Analysis of Soil/Spoil Materials and Plant Tissue Samples

3.6.1 Soil/Spoil Reaction

Soil/spoil reaction (pH) was determined from 1:1 soil:water mixtures using a glass electrode and laboratory pH meter calibrated against standard buffer solutions. Five mL of double distilled water were added to 5 g of soil in a plastic tube. The soil:water mixtures were stirred and allowed to equilibrate for 15 to 30 minutes before the pH was measured.

3.6.2 Electrical Conductivity

Electrical conductivity was measured as an indicator of soluble salts (Rhoades, 1996). In this procedure, 15 g of soil were weighed into a 50-mL plastic tube and 30 mL of double distilled water were added. The tubes were capped, placed on a horizontal shaker, and allowed to shake for 60 min at a low speed. The samples were then suction filtered into clean, 50-mL plastic tubes using 5.5-cm Whatman #1 filter paper. The electrical conductivity was then measured using a YSI conductivity bridge in temperature corrected mode with a cell constant (K) = 1.0 cm. The final electrical conductivity (dS/m) was obtained as the product of the meter reading and the cell constant.

3.6.3 KCl-extractable Cations

The method for determination of KCl-extractable cations was taken from Bertsch and Bloom (1996). In this procedure, 2.5 g of air-dried soil/spoil was mixed with 25 mL of *M* KCl in a 125-mL flask. The flasks were them placed on a wrist-action shaker for 30 min. After shaking, the contents were suction filtered into 50-mL flasks using 5.5 cm Whatman #1 filter paper. About 10 mL of extract were then re-filtered into 15-mL plastic tubes using 0.45 µm membrane filters. Finally, 0.5 mL of sample was diluted with 10 mL of 2.5% HNO_3 and analyzed for Al, B, Ca, Cd, Cr, Cu, Fe, Mg, Mn, Na, Ni, P, Pb, S, Si, and Zn using inductively coupled plasma emission spectrometry (ICP) with a Leeman PS2000 instrument.

3.6.4 Saturated Hydraulic Conductivity

Saturated soil hydraulic conductivity (K_{sat}) was measured by using a compact, constant-head well permeameter as described by Amoozegar (1992). In this procedure, a 6-cm auger hole was bored to a depth of 30 - 45 cm using a bucket auger. The sides of the auger hole were brushed to eliminate smearing and, if necessary, the bottom of the hole was squared using a planar auger. The permeameter was placed on a flat area adjacent to the hole, and water was released into the hole to maintain a constant depth of 15 cm. Flow rate was monitored approximately every 30 min until at least three consecutive readings were equal. From these data, the K_{sat} was calculated by using the Glover equation.

3.6.5 Total Nitrogen in Plant Samples

The total N content of plant tissues was determined from 750 mg samples of oven dried material. The weighed samples were transferred to metal crucibles and analyzed using a Macro N analyzer (AOAC, 1968).

3.6.6 Total Elemental Analysis of Plant Samples

Oven dried plant tissues (1.0 g) were weighed into acid washed, 75-mL digestion tubes. The materials were then pre-digested by adding 6 mL of conc. HNO_3, 5 mL of H_2O, and 3 mL of 72% $HClO_4$ to each sample. The samples were covered, mixed with a vortex stirrer, and allowed to sit overnight. Final digestion was achieved by heating to 220°C for 4 hr. About 15 mL of double distilled H_2O were added and the samples were returned to the warm digestion blocks for 15 min to dissolve any precipitates. The digested samples were then transferred to 50-mL volumetric flasks, brought to volume with double distilled H_2O, filtered through 0.45 µm membranes, and stored in plastic bottles. The digests were analyzed for Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Se, Si, and Zn using inductively coupled plasma emission spectrometry (ICP) (Isaac and Johnson, 1985) with a Leeman PS2000 instrument.

3.6.7 Statistical analyses

Statistical analyses of the soil chemical data, plant yield, and tissue were conducted using the Mstat-C program (Microcomputer statistical program, Michigan State University, 1991).

4 RESULTS

4.1 Abandoned Mine Land (AML) Experiment

4.1.1 Plant Yield

Plant yields at the AML site were collected over the 1996 and 1997 growing seasons. Both spring and autumn harvests were conducted with the autumn harvests representing re-growth following the spring mowing. As expected, total dry matter yields were lower in the autumn than in the spring (Fig. 10). The control areas that received fertilizer but no amendments were devoid of vegetation throughout the study period (Fig. 11). Any seedlings produced on these plots quickly died as a result of the low pH and toxicity of the spoil. By contrast, vegetation was established on all plots receiving yard waste compost with or without other amendments. This result demonstrates the strong positive effect of organic matter when establishing vegetation on mine spoils.

The highest yields in the first spring harvest (6/17/96) were produced on plots treated with by-product gypsum. This result is surprising and could be due to the fact that the FGD gypsum contained significant quantities of calcite and dolomite (Table 2) that produced a direct liming effect. However, the ag-limestone used in this experiment also contained calcite and dolomite but produced lower initial yields. Any competitive advantage afforded by FGD gypsum as compared to other treatments was lost by the second harvest (9/20/96) unless compost was also added. Perhaps the binding agent used to prepare the pelletized gypsum had some short-term nutritive value that would account for the strong initial plant response to the by-product alone.

Except for the gypsum and gypsum + compost plots, 1997 yields were higher across all treatments for both the spring and autumn harvests when compared to 1996 production. The highest yields were obtained with 4% Mg-gypsum and the lowest with gypsum alone. Statistical analyses using a split-plot design showed significant effects from treatments (4 levels), compost (2 levels), and treatment x compost interactions for the first, second, and total harvests.

4.1.2 Plant Tissue Analyses

Concentrations of major by-product elements (Ca, Mg, S) in tissue samples from the first spring harvest (6/17/96) showed no significant differences according to amendment (Fig. 12). Similar results were obtained for the second spring harvest except that concentrations of all elements were higher by a factor of 2 - 4 times (data not shown). Concentrations of Mg and S were similar across all treatments in the Au 97 samples, but Ca contents were significantly lower in the gypsum and control + compost plots (Fig. 13). Boron concentrations never exceeded 500 mg/kg, and were highest in tissues from plants grown on plots amended with 4% Mg-gypsum (Fig. 14 and 15). This result is consistent with the higher B contents of this by-product material as compared to the FGD gypsum and Ag-limestone (Table 4). The concentrations of potentially toxic Al and Fe were initially highest in plants grown on plots amended with Ag-limestone, 4% Mg-gypsum, and compost alone (Fig. 14). By the Au 97 harvest, however, high concentrations of Al and Fe were observed in tissues from the FGD-gypsum plots (Fig. 15) and are probably related to the greatly diminished yields on these plots (Fig. 10).

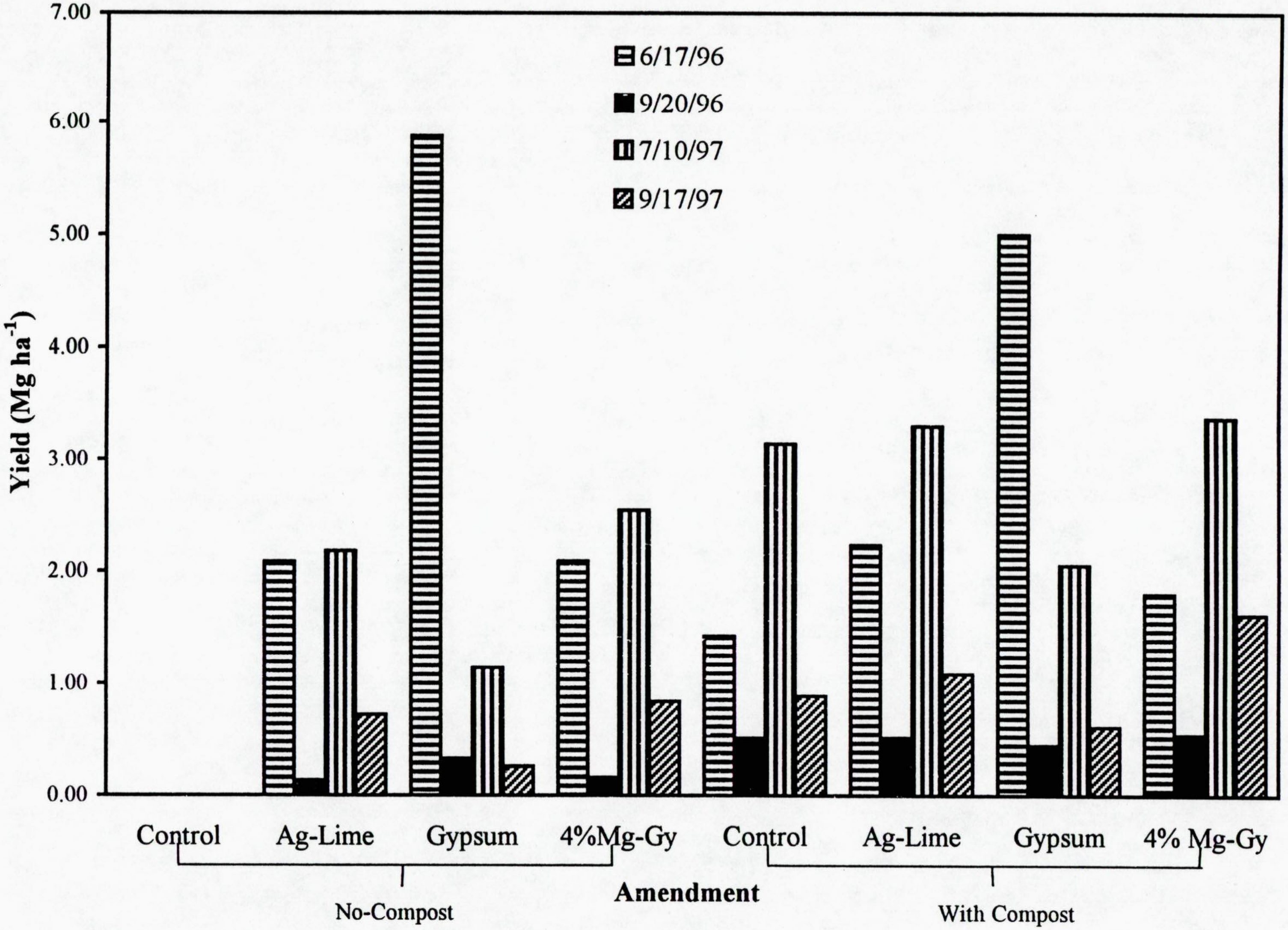


Figure 10. Effect of amendment on plant yield (dry matter production) at the AML field site. Multiply yield (Mg ha^{-1}) by 0.45 to obtain ton ac^{-1}.

Figure 11. Photograph showing AML control plot devoid of vegetation (left) and plot treated with 4%Mg-gypsum (right).

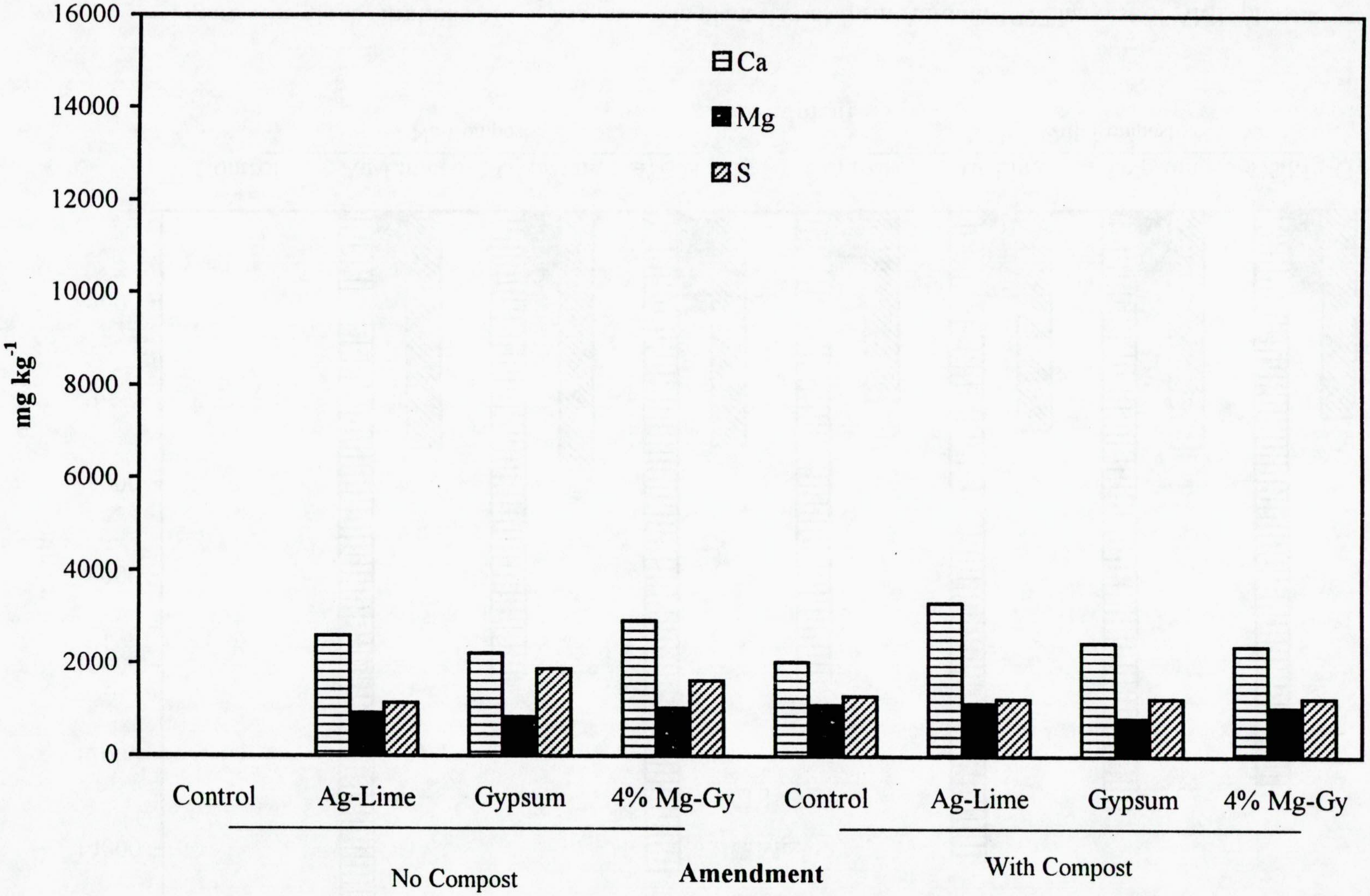


Figure 12. Concentration of Ca, Mg, and S in plant tissues from Spring 1996 harvest of AML plots.

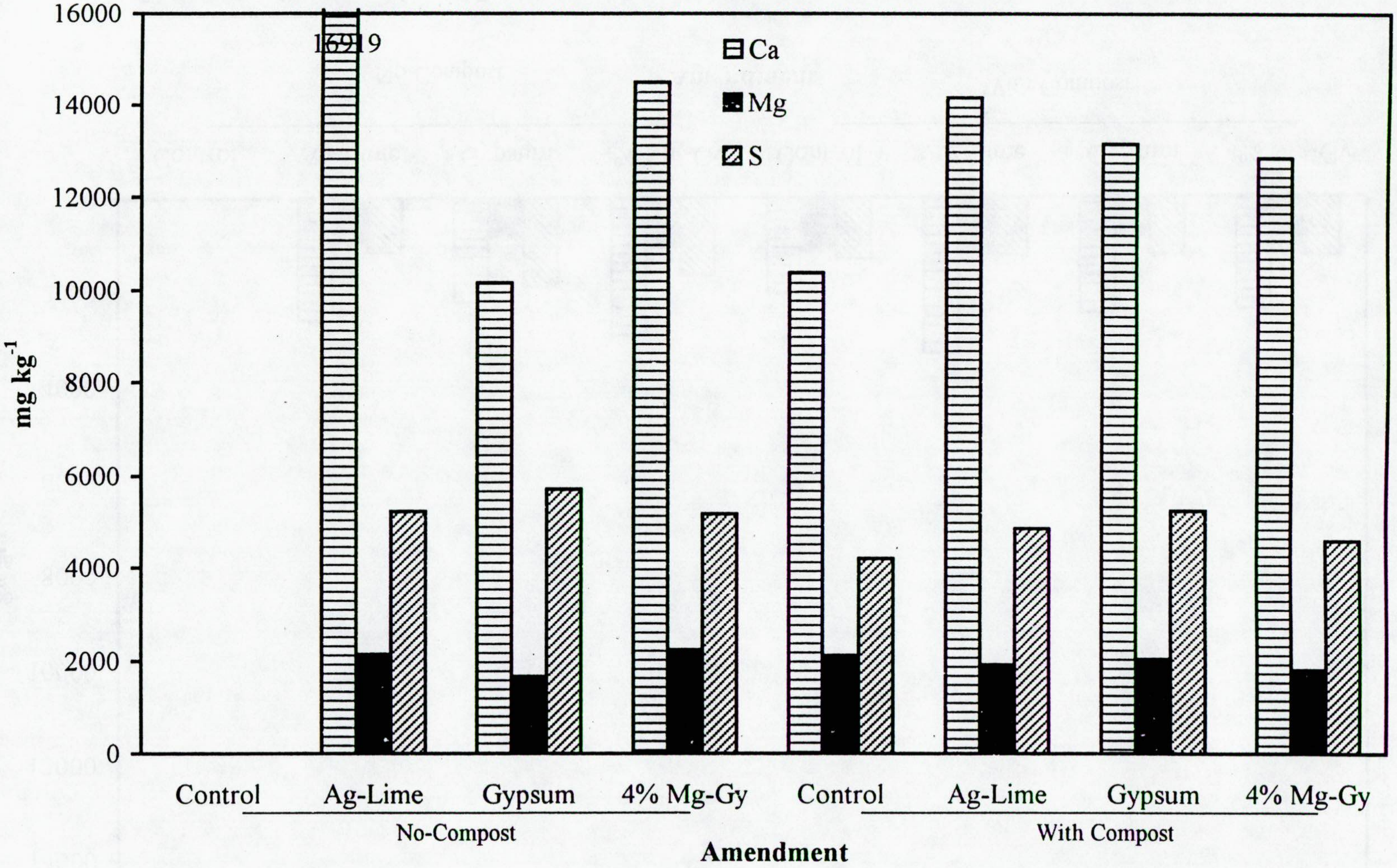


Figure 13. Concentrations of Ca, Mg, and S in plant tissues from Autumn 1997 harvest of AML plots.

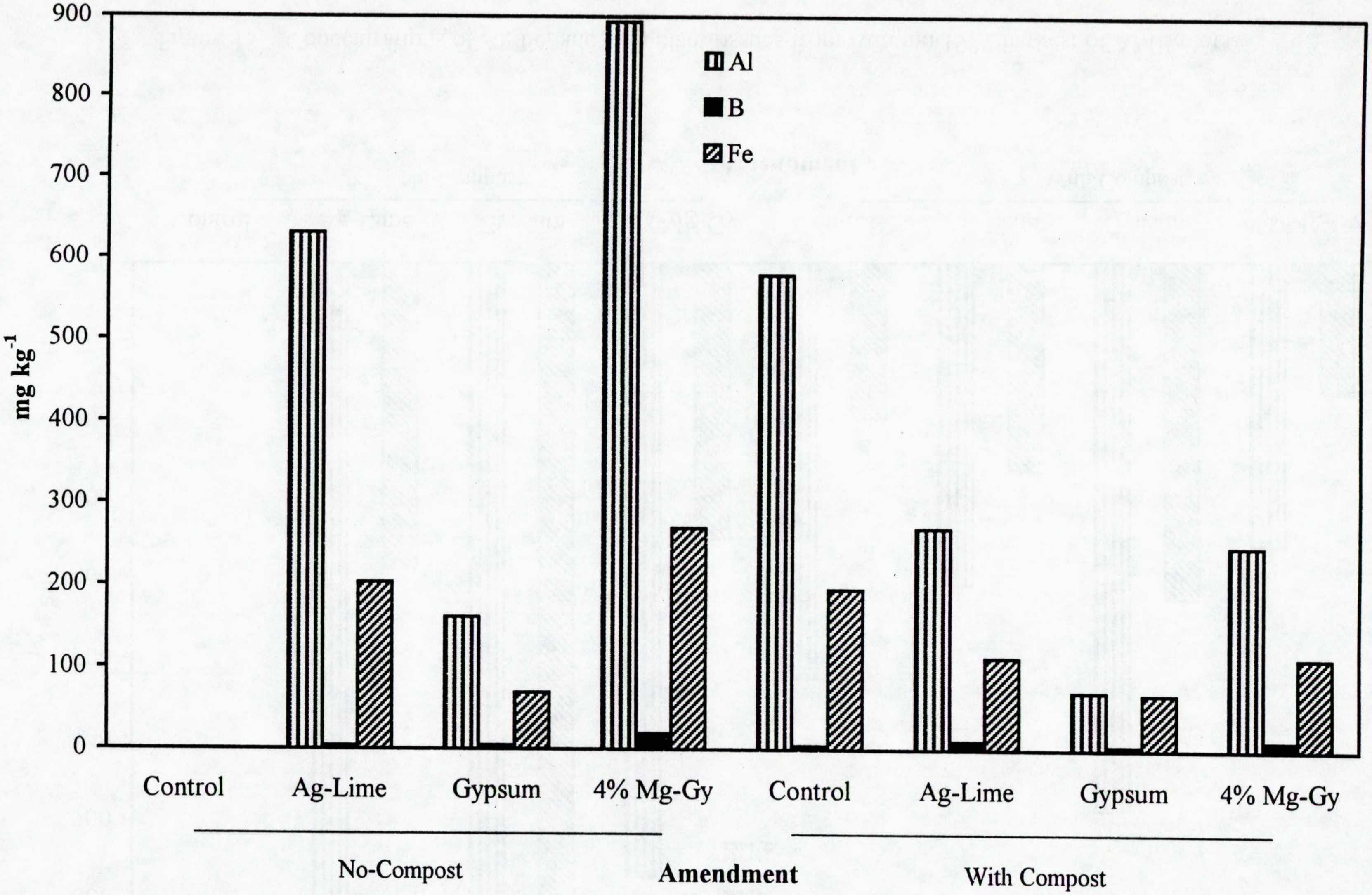


Figure 14. Concentrations of Al, Fe, and B in plant tissues from Spring 1996 harvest of AML plots.

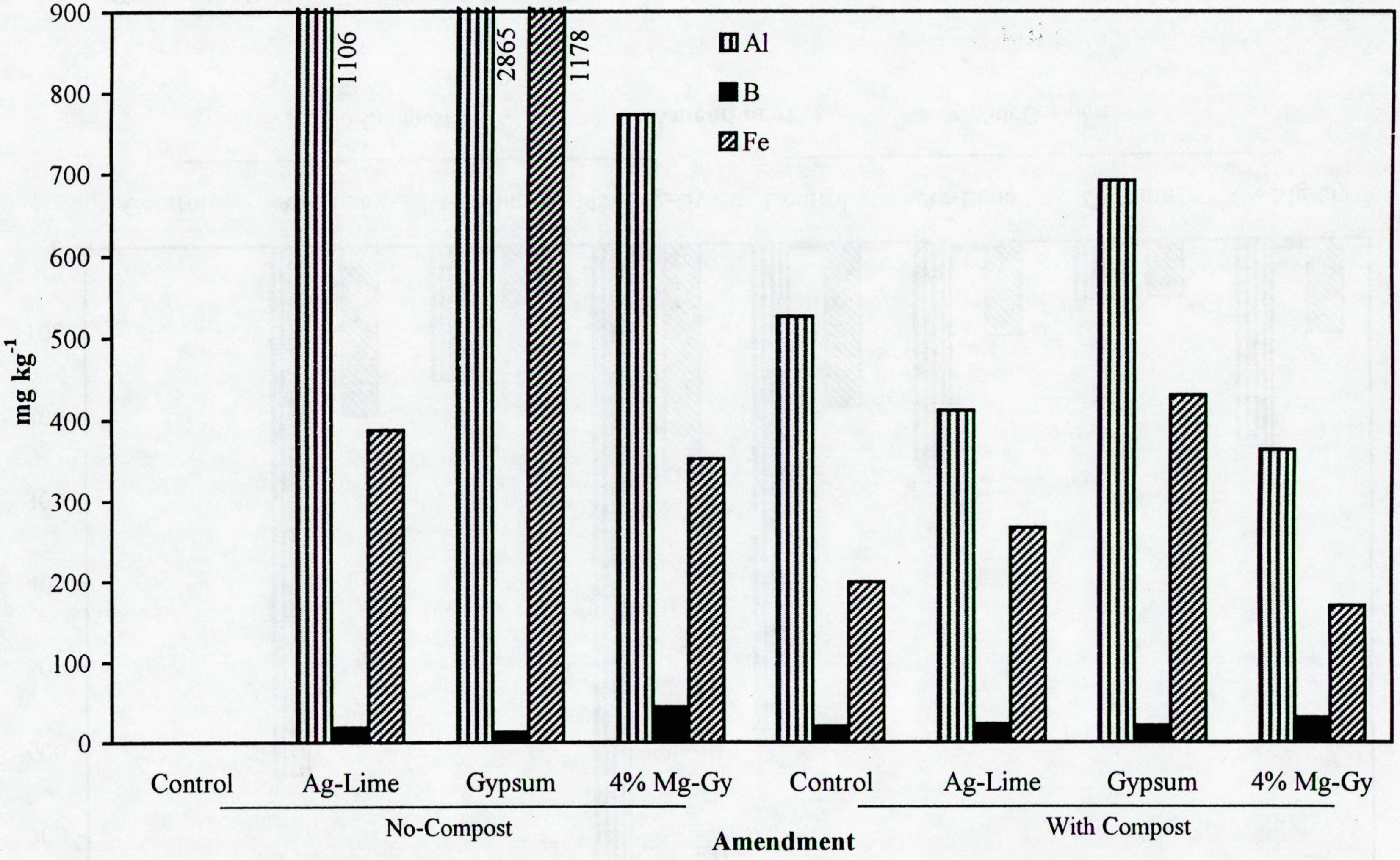


Figure 15. Concentrations of Al, Fe, and B in plant tissues from Autumn 1997 harvest of AML plots.

4.1.3 Spoil Chemistry

The spoil at the AML site was re-graded just prior to application of treatments. Because time is needed to achieve equilibrium in such heterogeneous materials, variability in many chemical properties should be expected. The control plots receiving no by-products were extremely acid (pH 3.0 - 3.5) throughout the 100 cm sampling depth and throughout the 2-yr study period (Fig. 16). All by-products, including the yard waste compost, produced a significant liming effect within the zone of incorporation. As expected, 4% Mg-gypsum and agricultural limestone yielded the greatest increases in pH, and these increases persisted throughout the study. The increase in spoil pH produced by the FGD-gypsum must be attributed to its impurities of calcite and dolomite (Table 2) because no increase in reaction should occur with pure gypsum. Slight improvement in spoil pH with depth over time was observed, but only in the plots amended with agricultural limestone.

All amendments, except compost, produced a significant increase in the EC of the spoil (Fig. 17) by release of major elements (Ca, Mg, S) to solution both within and below the zone of application (Fig. 18 - 20). The increase in EC, Ca, and Mg was most pronounced with the FGD gypsum and Mg-gypsum because of the relatively high solubilities of $CaSO_4$ and $MgSO_4$ compared to $CaCO_3$ or $(Ca,Mg)CO_3$. A "flush" of soluble salts was especially apparent in the plots amended with Mg-gypsum. In these plots, an elevated EC was observed throughout the 100-cm sampling depth within 6 months after treatment application (spring 1996).

Exchangeable Al exceeded 400 mg/kg throughout the unamended spoil column (Fig. 21). All by-products, including yard waste compost, reduced exchangeable Al to non-toxic levels within the zone of incorporation. By-product application also appeared to cause some downward leaching of Al as reflected in increased Al with depth compared to the control samples collected in the spring of 1996. By the summer of 1997, exchangeable Al concentrations in plots treated with gypsum (no compost) had fallen below those of the un-amended spoil throughout the 100 cm sampling depth.

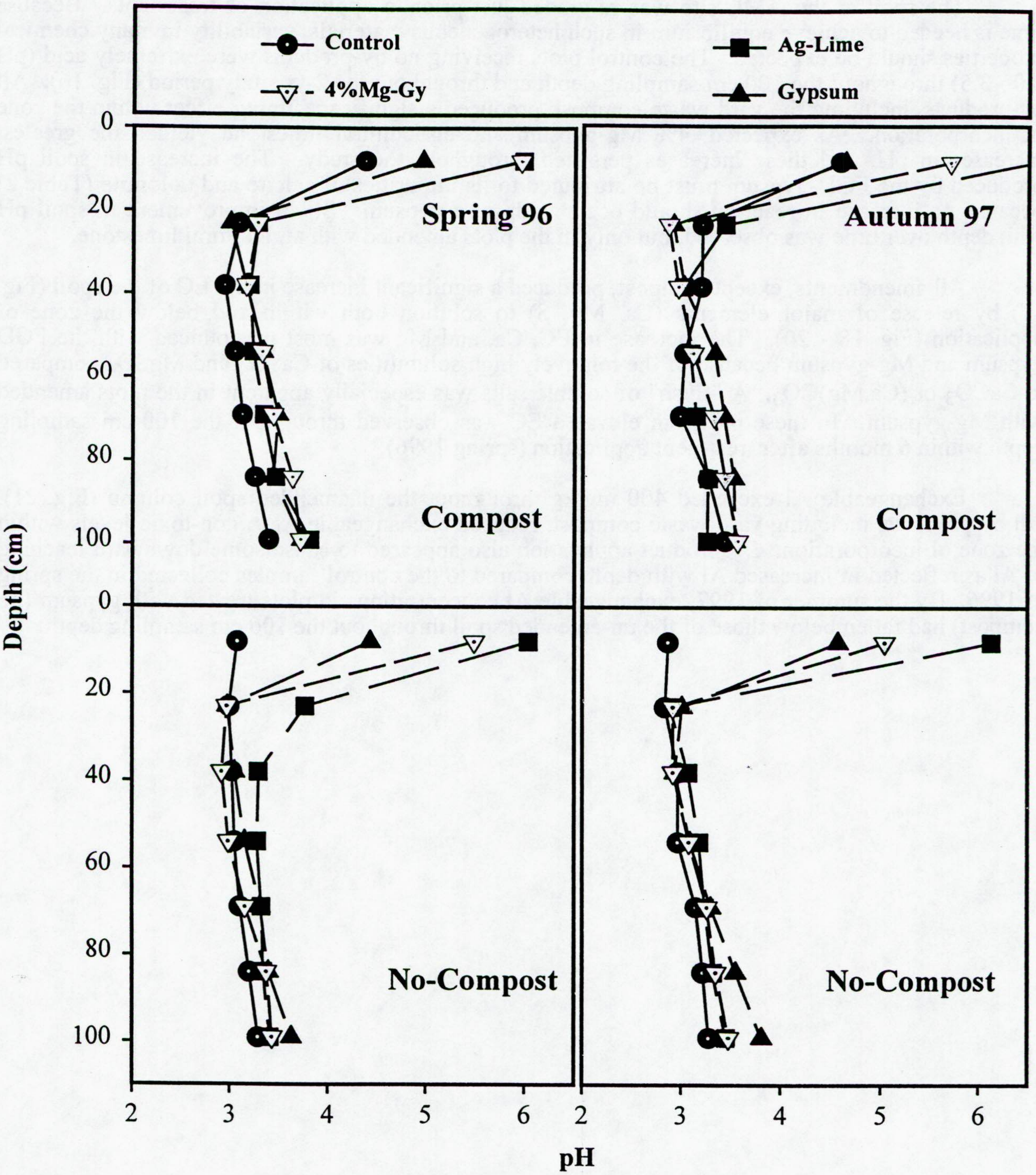


Figure 16. Effect of amendments on spoil pH with depth at the AML site.

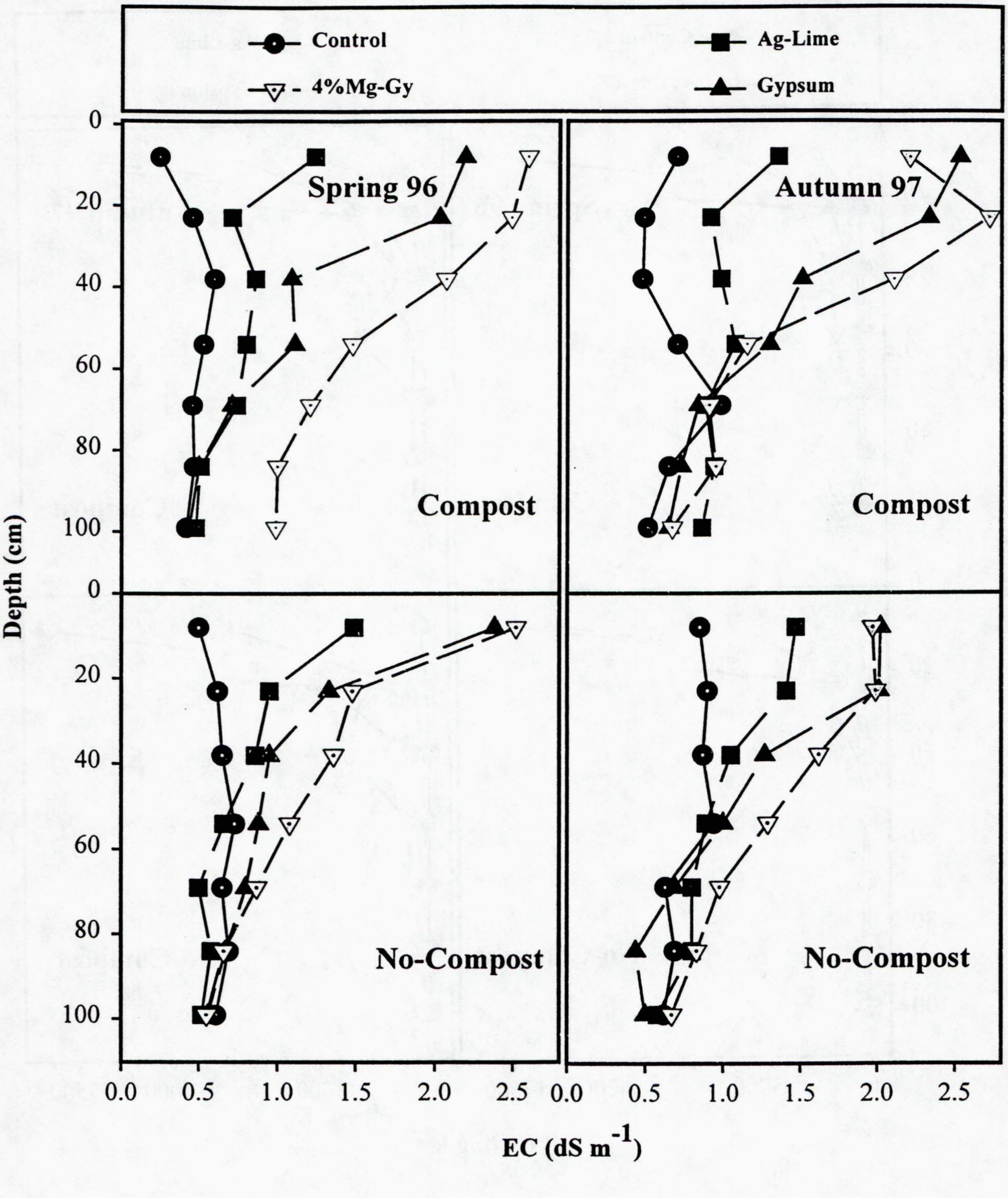
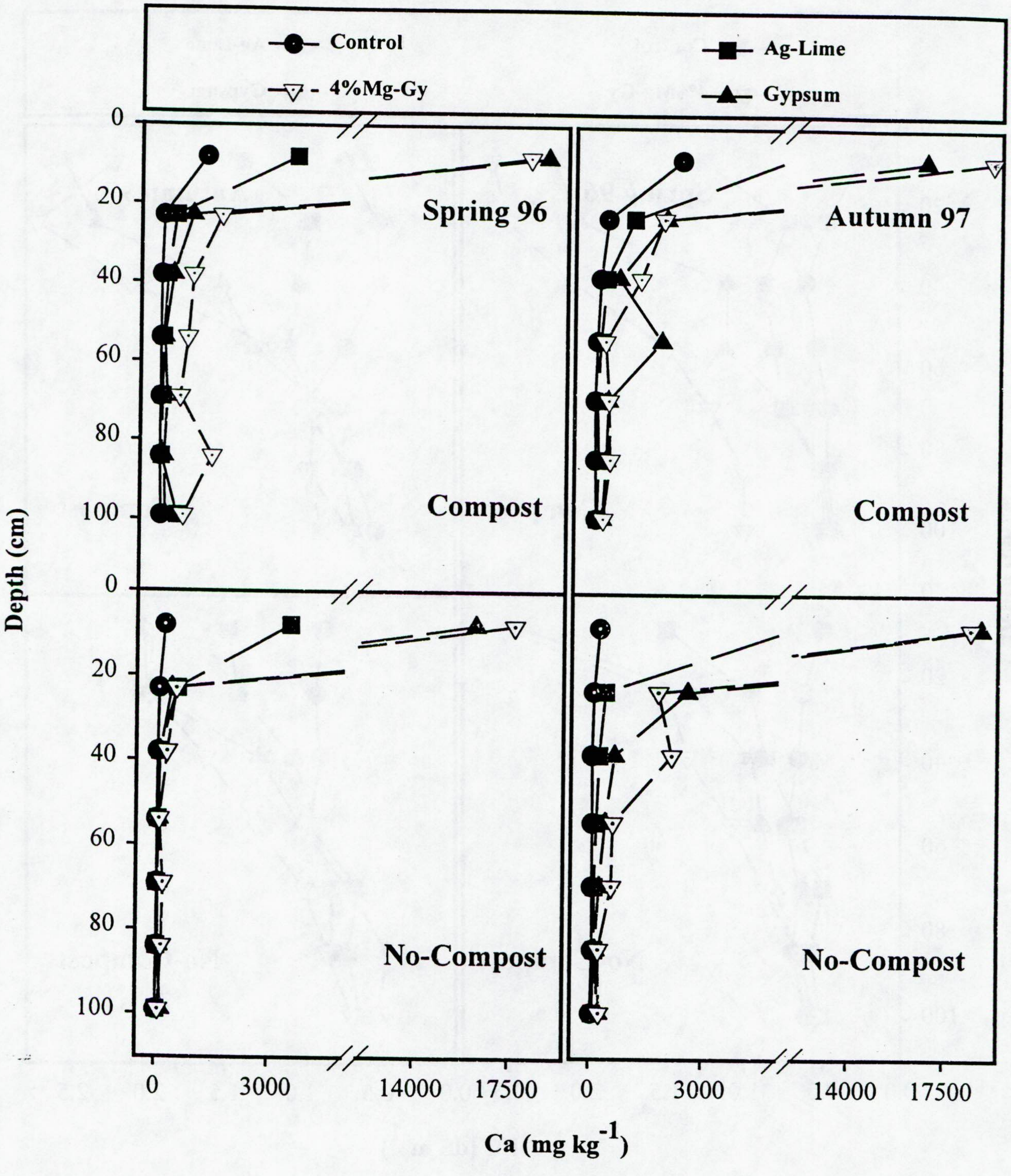


Figure 17. Effect of amendments on electrical conductivity with spoil depth at the AML site.



Figue 18. Effect of amendments on KCl-extractable Ca with spoil depth at the AML site.

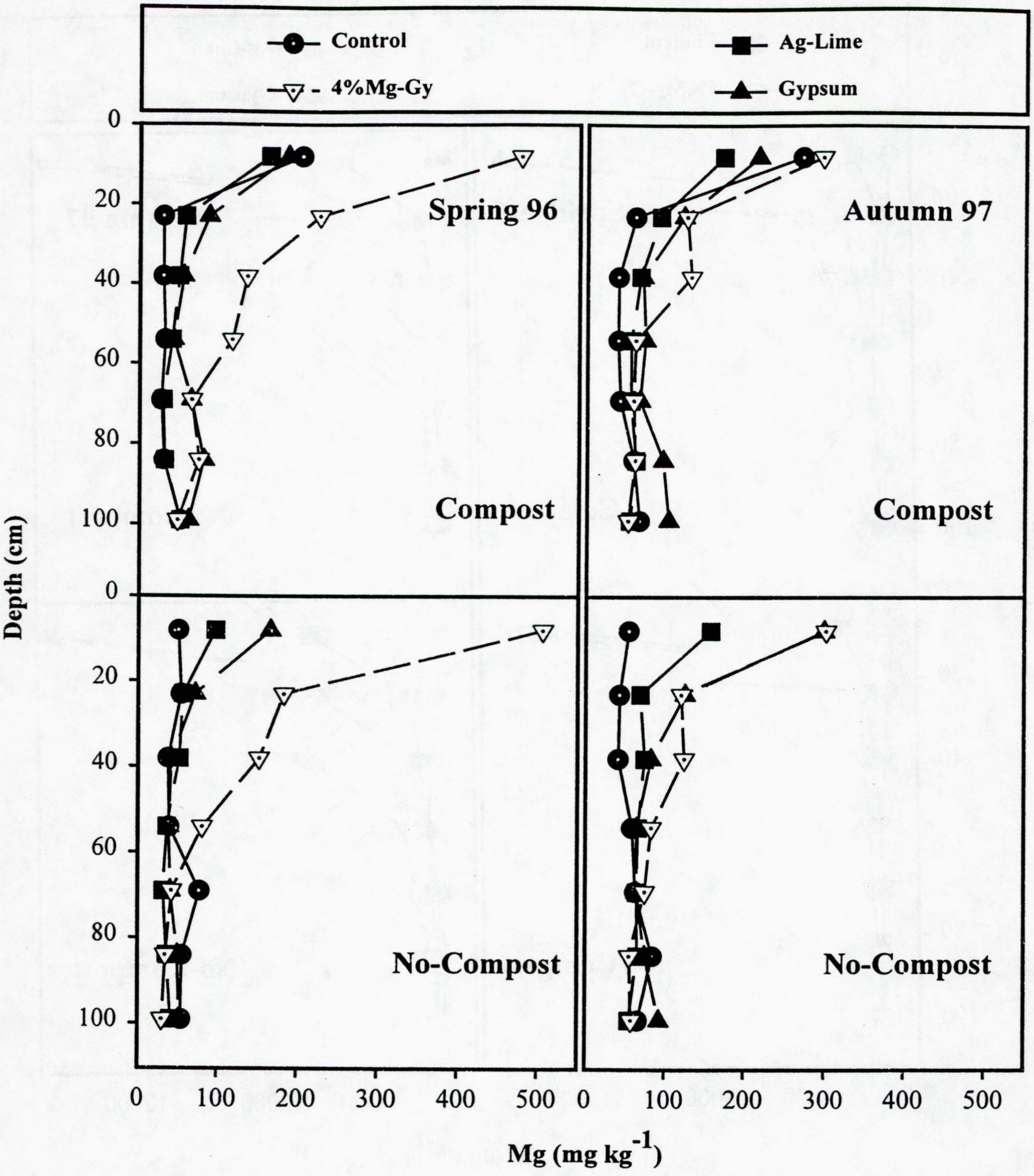


Figure 19. Effect of amendments on KCl-extractable Mg with spoil depth at the AML site.

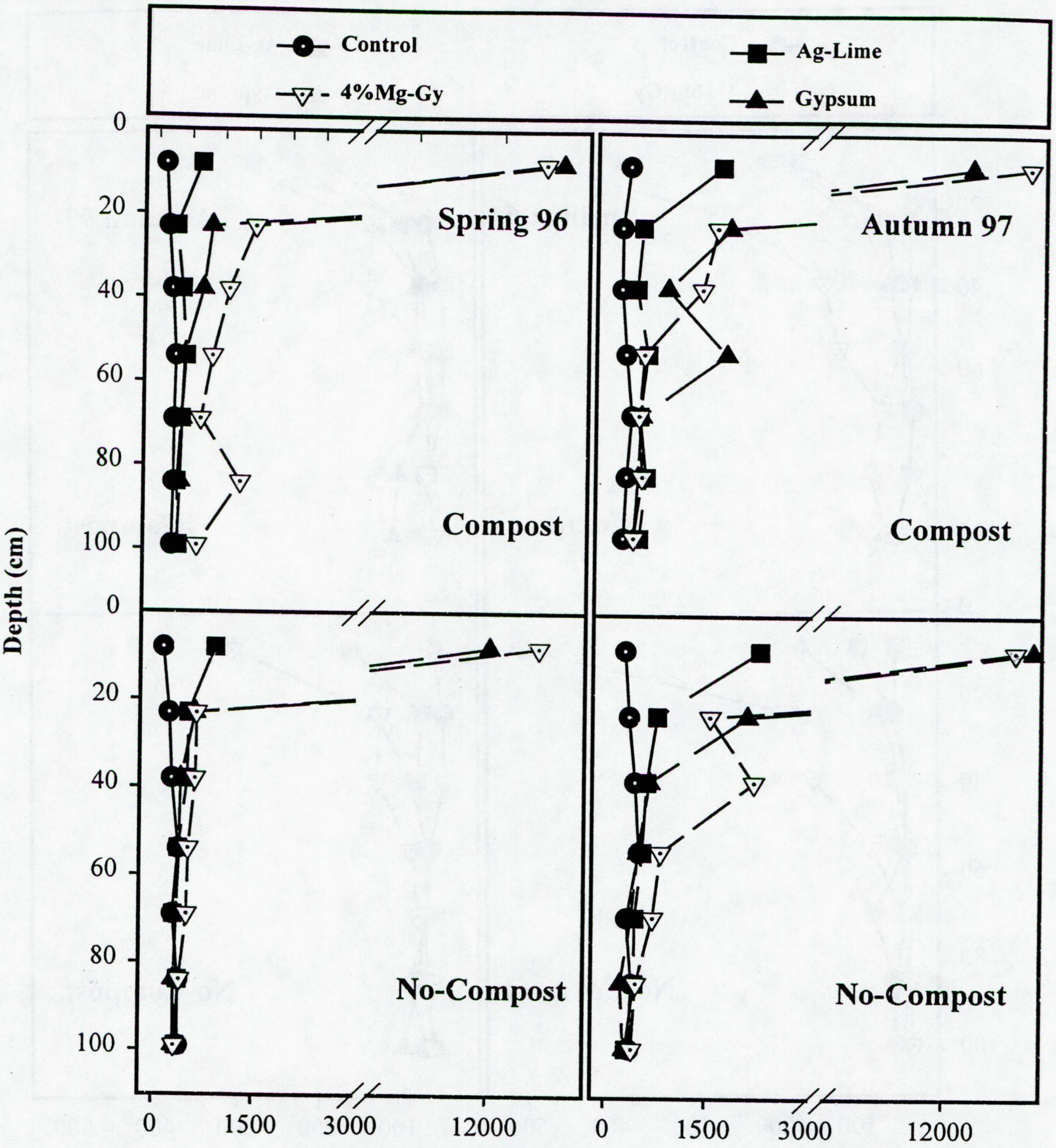


Figure 20. Effect of amendments on KCl-extractable S with spoil depth at the AML site.

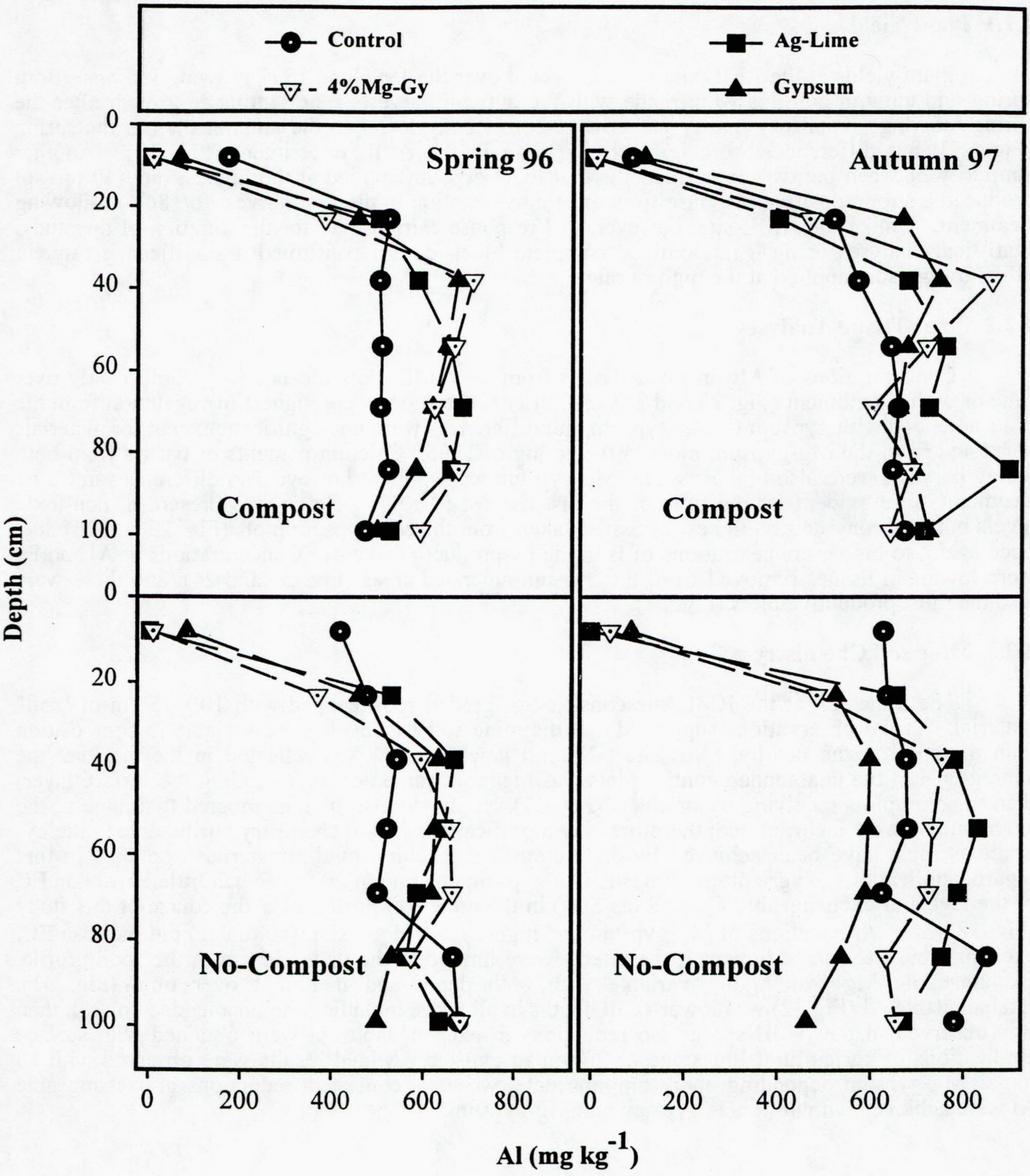


Figure 21. Effect of amendments on KCl-extractable Al with spoil depth at the AML site.

4.2 Reclaimed Mine Land (RML) Experiment

4.2.1 Plant Yield

Plant yields at the RML site were collected over the 1996 and 1997 growing seasons. Both spring and autumn cuttings were made with the autumn harvests representing re-growth after the spring mowing. Total dry matter yields were consistently lower in the autumn than in the spring (Fig. 22), but differences were less striking than in the AML experiment (Fig. 10). Another similarity between the two experiments is that FGD gypsum applied at the highest rate (40 ton/ac) produced a strong positive response from existing vegetation in the first harvest (6/18/96) following treatment. Unlike the AML site, however, this response carried over for the duration of the study. Statistical analyses using a randomized complete block design confirmed a significant treatment effect for gypsum applied at the highest rate.

4.2.2 Plant Tissue Analyses

Concentrations of Mg in plant tissues from the RML plots did not vary significantly over time or with amendment (Fig. 23 and 24). Sulfur concentrations were highest in vegetation from the plots amended with gypsum or Mg-gypsum, but differences were not significant except for materials harvested from the Mg-gypsum plots in the spring of 1996. Calcium contents of tissues from both spring harvests were also highest where Mg-gypsum was applied; however, no differences in Ca by treatment were evident by the time of the last harvest (Au 97). Boron was present in non-toxic levels but was consistently highest in tissues taken from the Mg-gypsum plots (Fig. 25 and 26) due, once again, to higher concentrations of B in the by-product (Table 4). Concentrations of Al and Fe were lowest in tissues removed from the gypsum-amended areas (Fig. 25 and 26), and these were also the most productive plots (Fig. 22).

4.2.3 Mine soil Chemistry

The mine soil at the RML site consisted of graded spoil capped with 10 - 15 cm of "soil" material. Visual observations suggested that the mine soil was even more variable in composition than the spoil at the nearby AML site. Natural heterogeneity was reflected in the fact that the average pH of the unamended control plots was higher at some depths (including the surface layer) than in some plots receiving by-products (Fig. 27). It should also be remembered that none of the amendments were incorporated; therefore, any modifications in soil chemistry attributable to the by-products must have been achieved by dissolution and leaching of the materials applied. In that regard, applications of agricultural limestone or gypsum at a rate of 20 ton/ac had little impact on EC or the levels of exchangeable Ca or S (as SO_4) in the mine soil profile over the course of this study (Fig. 28 - 30). Applications of Mg-gypsum and higher rates of gypsum (40 ton/ac) did increase EC, exchangeable Ca, and S; however, the effects were limited to the upper 10 cm of the spoil profile. Exchangeable Mg was highly variable with both depth and treatment over time (Fig. 31). Exchangeable Al (Fig 32) was lower at all depths in all plots, including the unamended control, than was observed in the AML spoil. No reductions in exchangeable Al were obtained with surface applications of agricultural limestone or 20 ton/ac gypsum. Mixed results were observed with 20 ton/ac Mg-gypsum depending upon sampling date; whereas, consistent reductions in exchangeable Al were achieved with 40 ton/ac gypsum and Mg-gypsum.

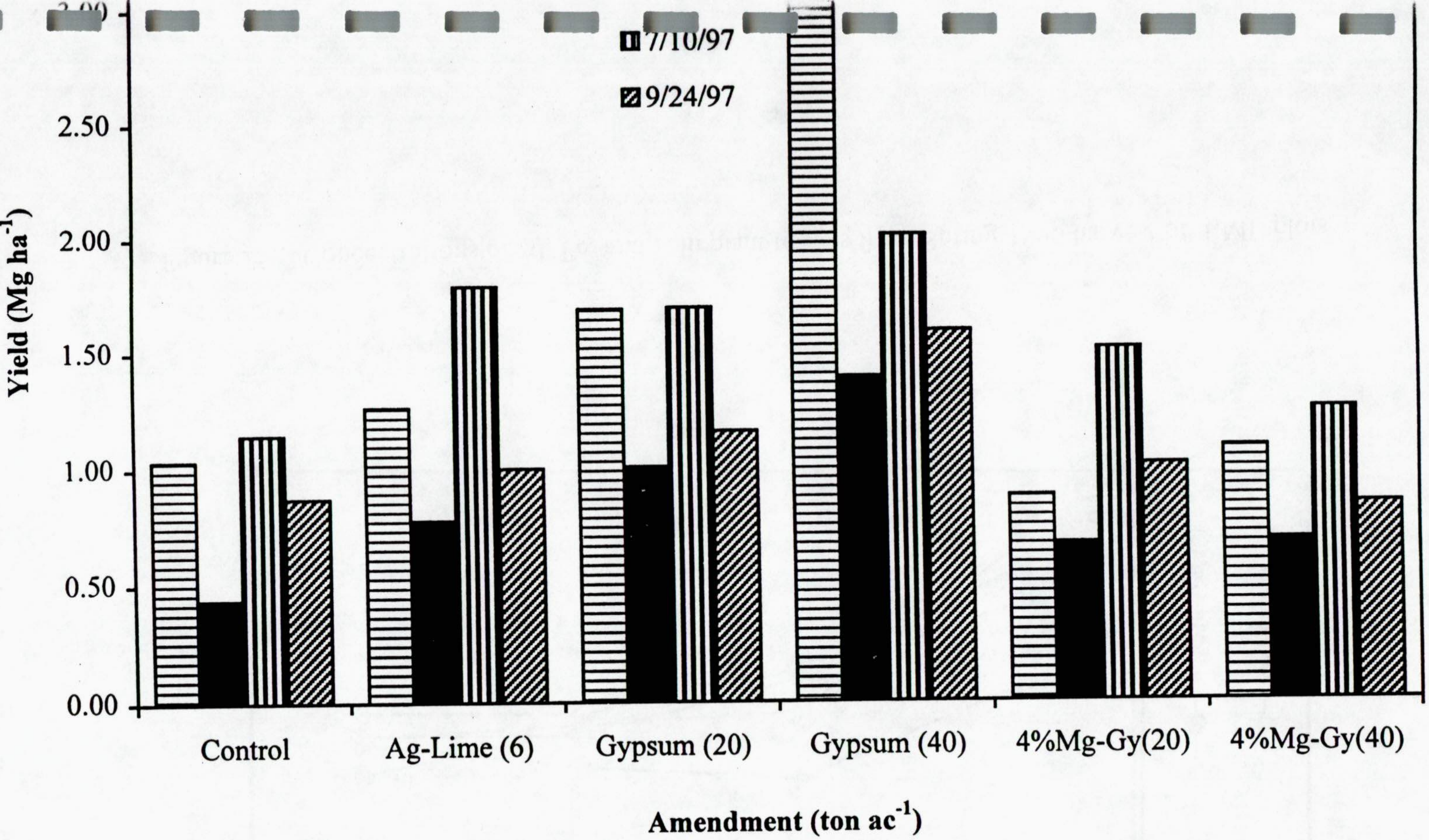


Figure 22. Effects of amendments and rates on plant yield (dry matter production) at the RML site. Multiply yield (Mg ha^{-1}) by 0.45 to obtain ton ac^{-1}.

Figure 26. Concentrations of Al, Fe, and B in plant tissues from Autumn 1997 harvest of RML plots.

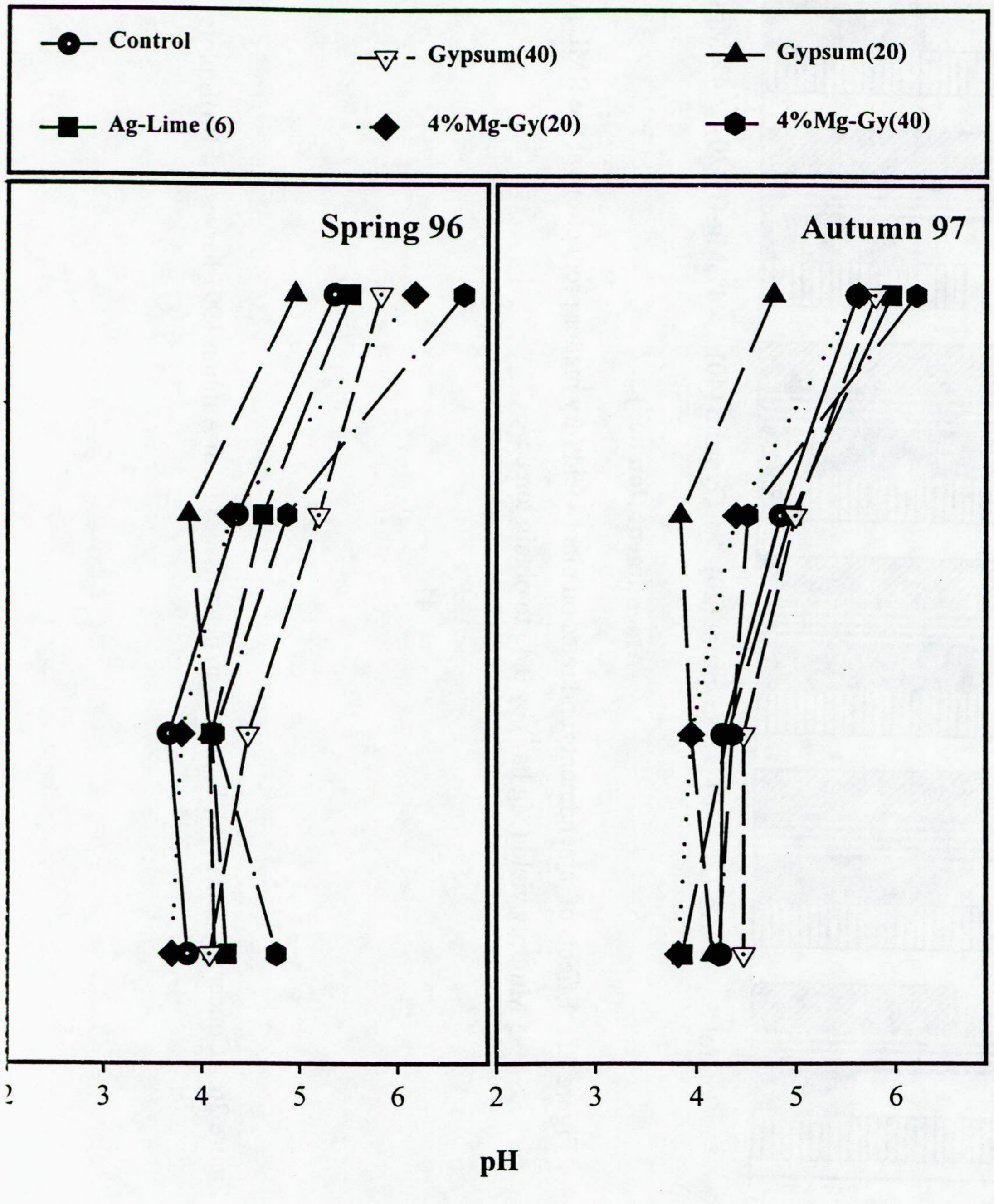


Figure 27. Effects of amendments and rates on minesoil pH with depth at the RML site.

Figure 25. Concentrations of Al, Fe, and B in plant tissues from Spring 1996 harvest of RML plots.

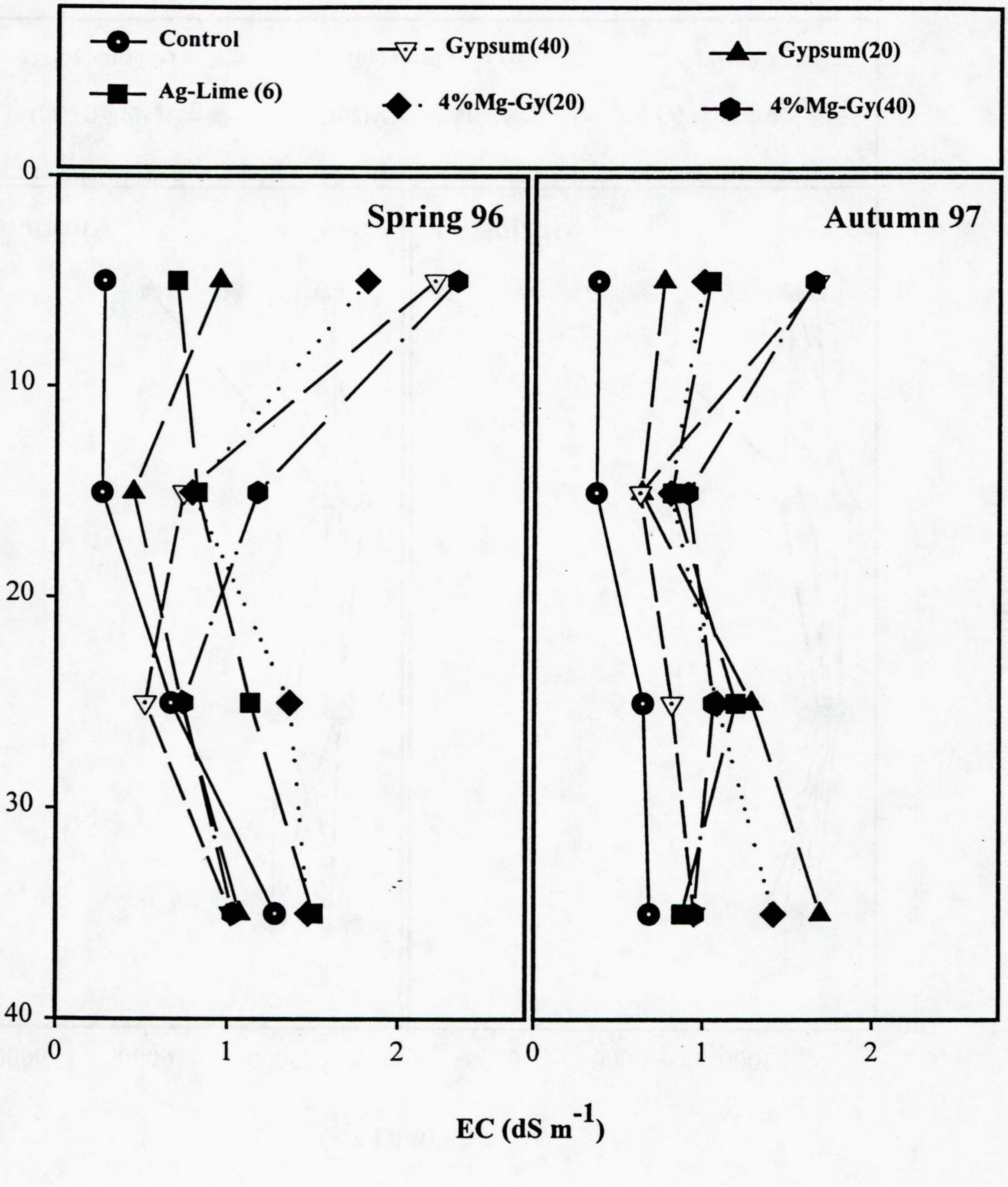


Figure 28. Effects of amendments and rates on electrical conductivity with minesoil depth at the RML site.

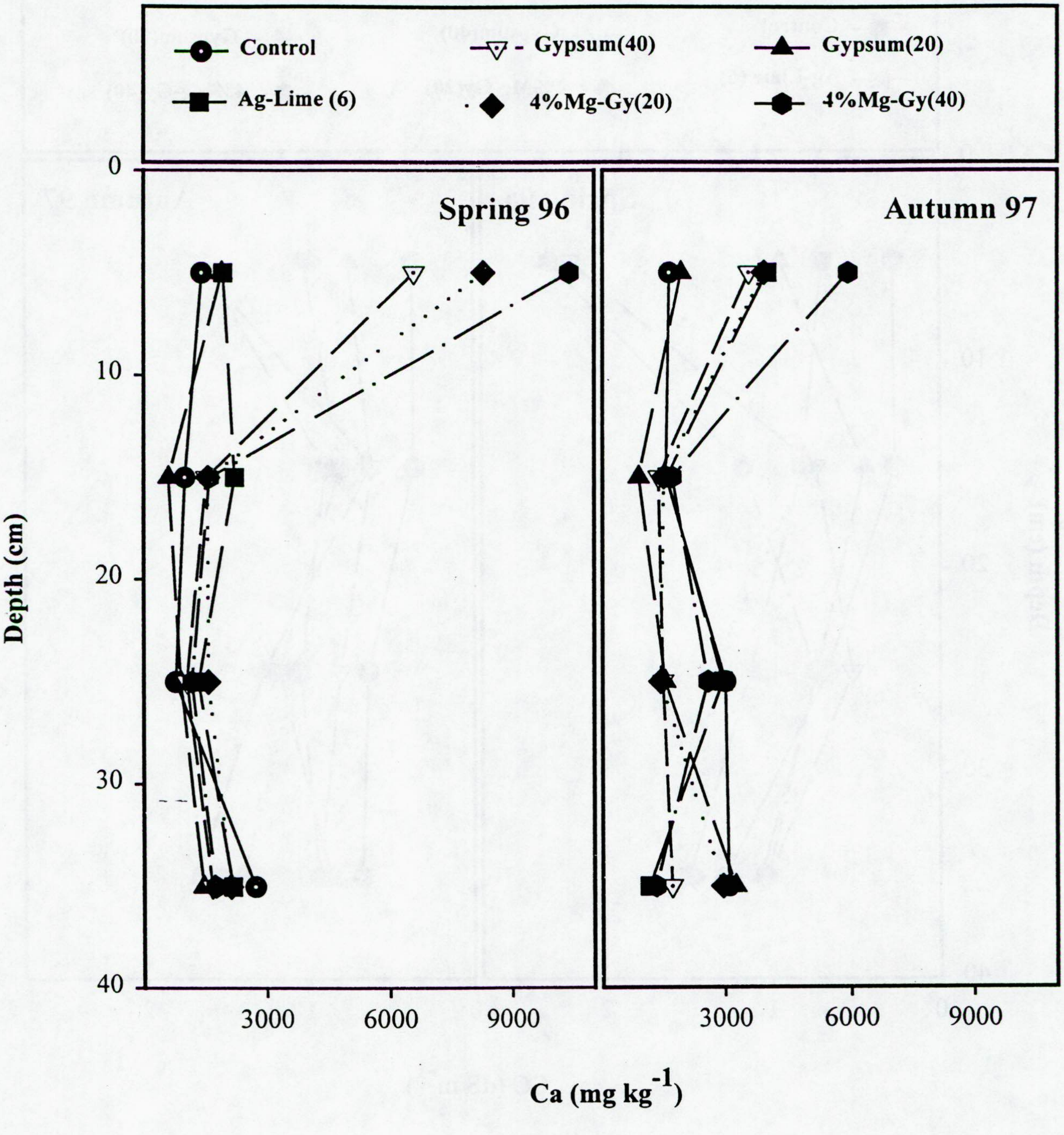


Figure 29. Effects of amendments and rates on KCl-extractable Ca with minespoil depth at the RML site.

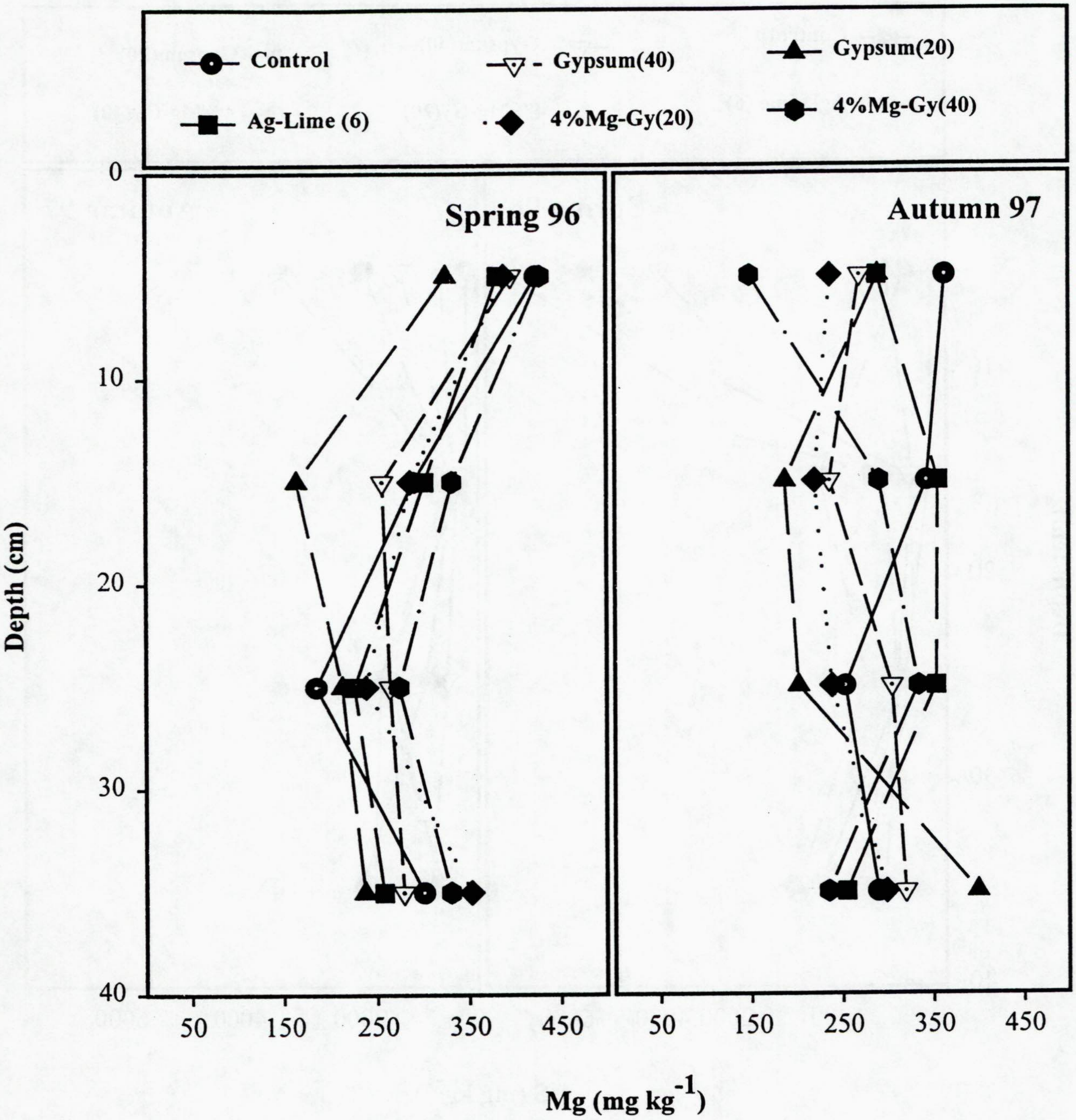


Figure 30. Effects of amendments and rates on KCl-extractable Mg with minespoil depth at the RML site.

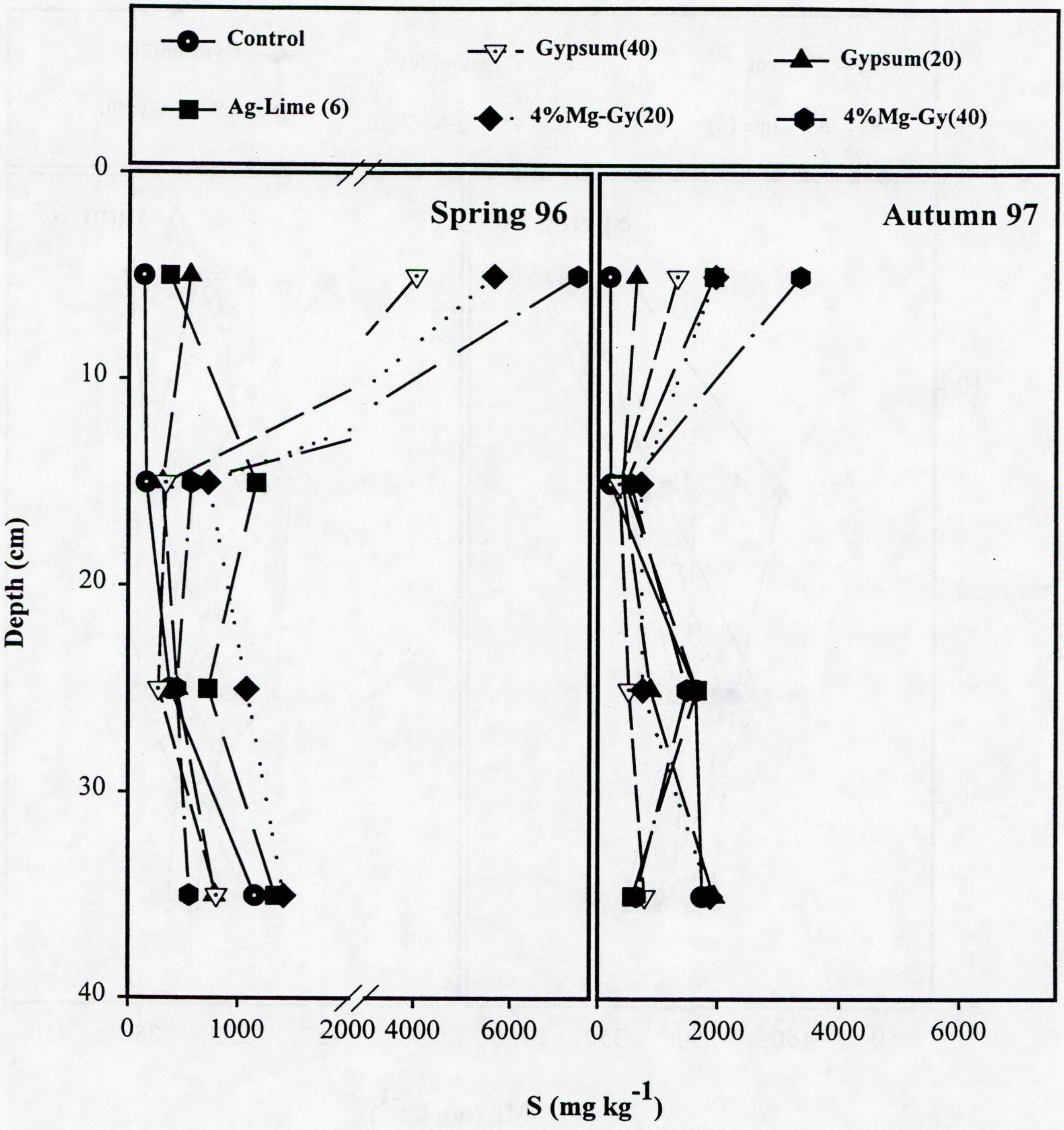


Figure 31. Effects of amendments and rates on KCl-extractable S with minespoil depth at the RML site.

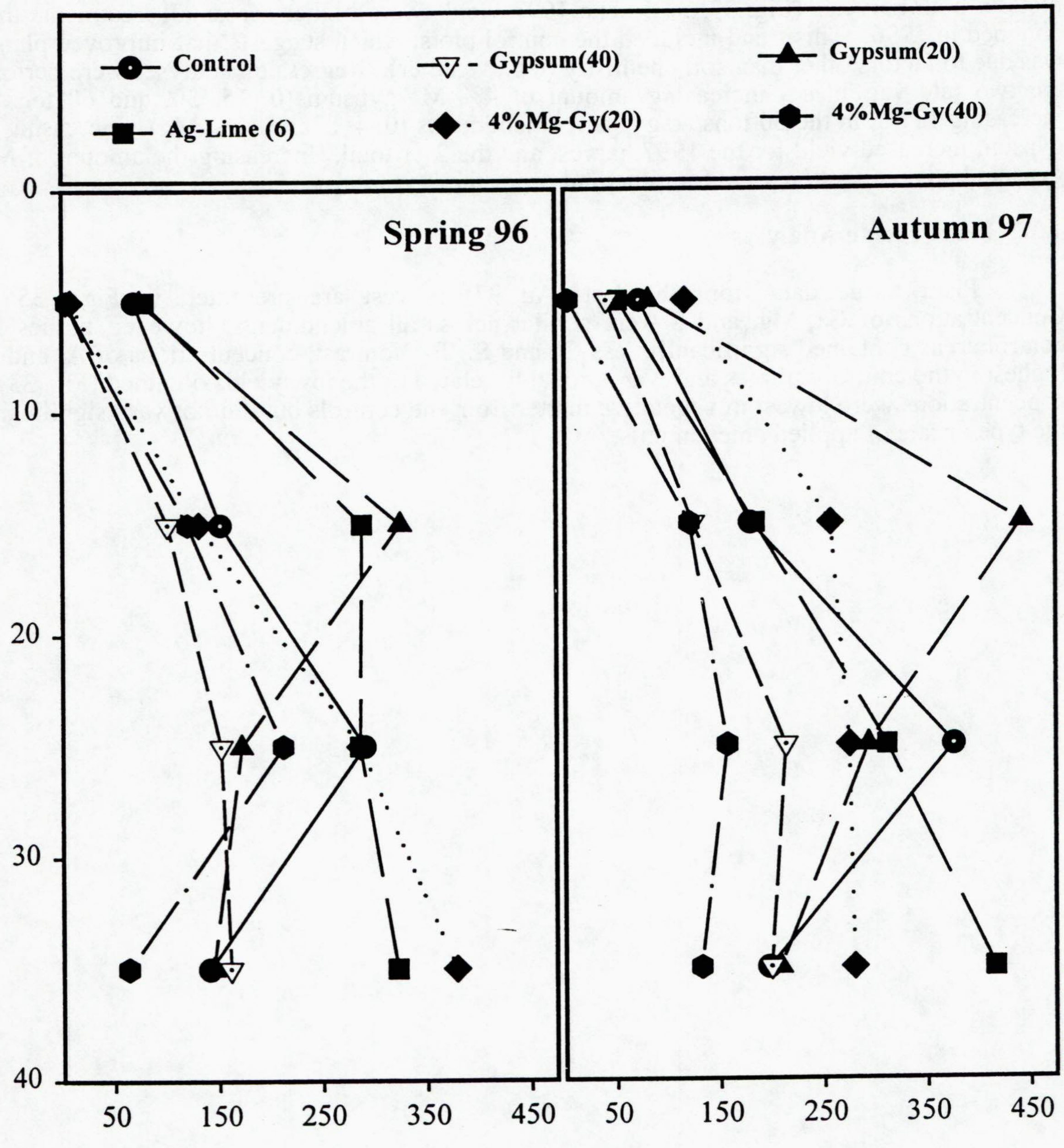


Figure 32. Effects of amendments and rates on KCl-extractable Al with minespoil depth at the RML site.

4.3 Agricultural Soil (AS) Experiment

4.3.1 Plant Yield

Only two successful harvests of alfalfa were taken from natural agricultural soil at the Ashtabula site; however, all treatments produced significant yield increases compared to the control plots in both harvests (Fig. 33, 34). The 1997 yields were higher across all treatments than those obtained in 1996. This trend included the control plots, which suggests that improved plant growth was due to factors other than soil chemistry (e.g., weather). Regression analyses were performed for the two rate variables - increasing amount of 4% Mg-gypsum (0, 15, 30, and 60 tons/ac), and increasing % Mg in the 60 tons/ac gypsum amendments (0, 4, 8, and 12% Mg). Increasing 4% Mg-gypsum increased yield for the 1997 harvest and the 2-yr total. Increasing the amount of Mg in the gypsum had no effect on yield for either cut or for the 2-yr total.

4.3.2 Plant Tissue Analyses

Plant tissue data from the last (Au 97) harvest are presented in Figs. 35 and 36. Concentrations of Ca, Mg, and S were similar across all amendments; however, tissues from the control areas contained significantly less Ca and S. By contrast, concentrations of Al and Fe were highest in the control samples and were probably related to the low yields obtained (Fig. 33). Boron concentrations were lowest in vegetative matter from the controls but did not vary significantly with the type or rate of applied amendments.

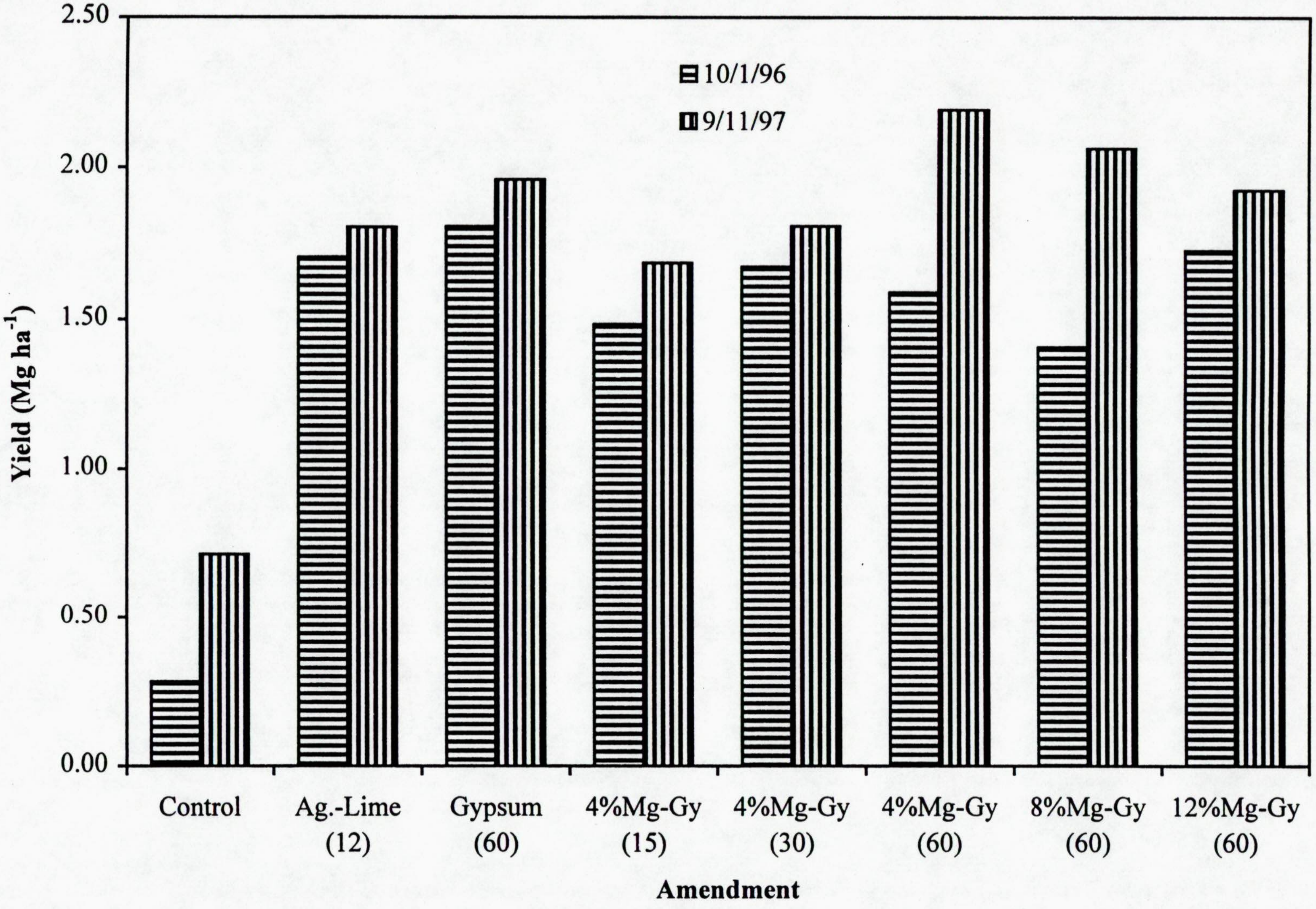


Figure 33. Effects of amendments and rates on plant yield (dry matter production) at the AS field site. Multiply yield (Mg ha^{-1}) by 0.45 to obtain ton ac^{-1}.

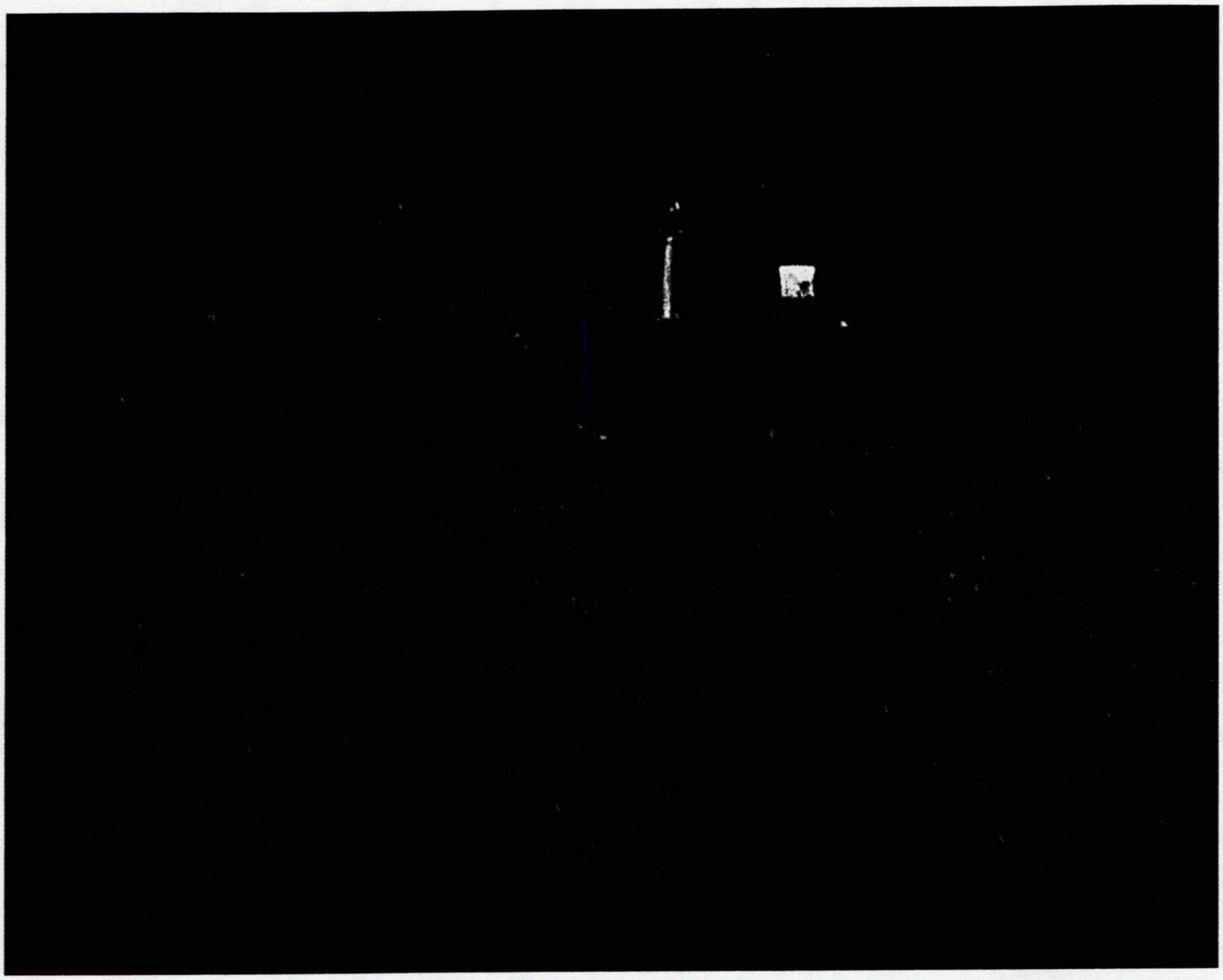


Figure 34. Photograph showing field plots and the compact, constant-head permeameter used for saturated hydraulic conductivity measurements. Plot in foreground is a control.

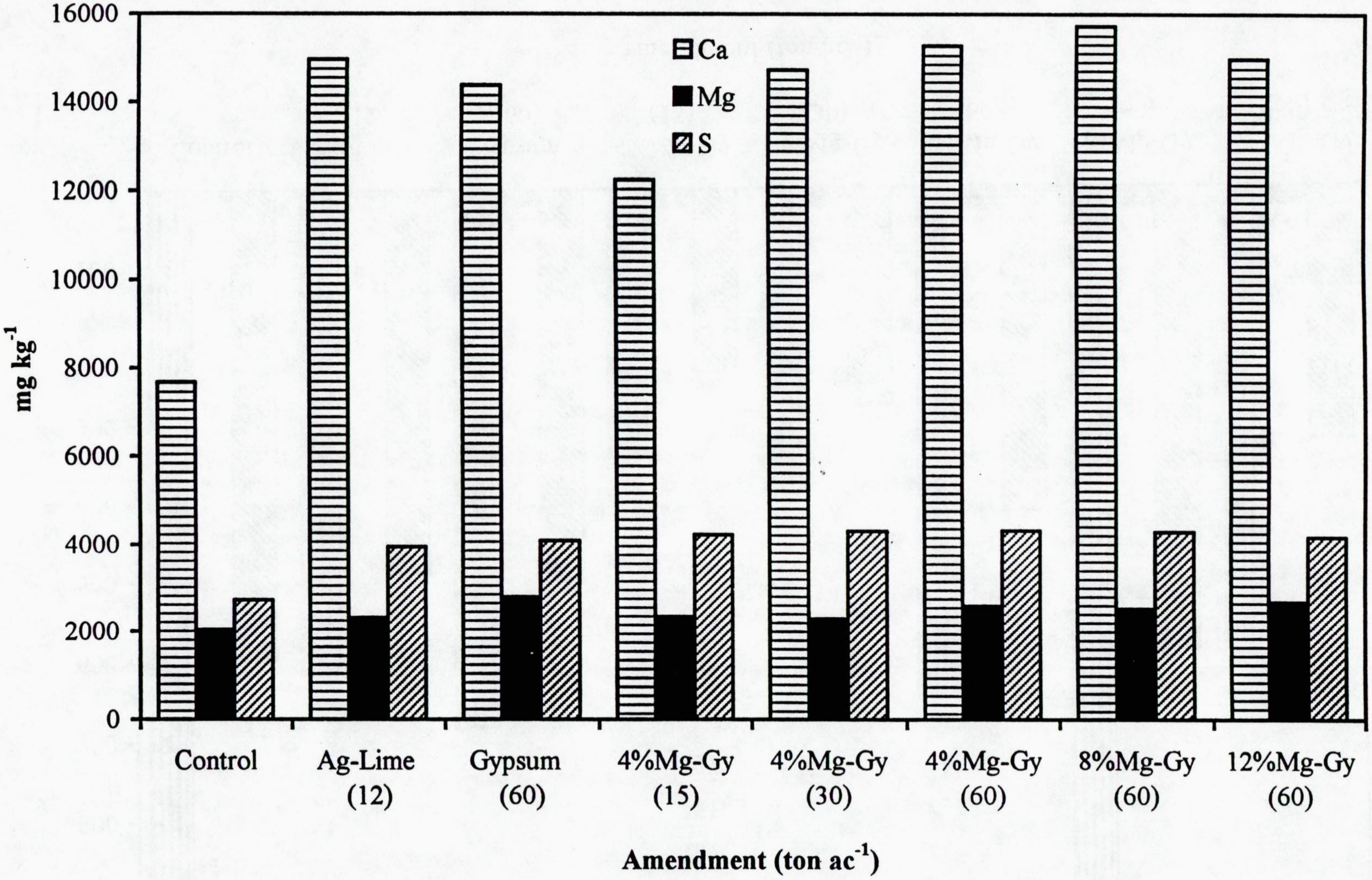


Figure 35. Concentrations of Ca, Mg, and S in plant tissues from Autumn 1997 harvest of AS plots.

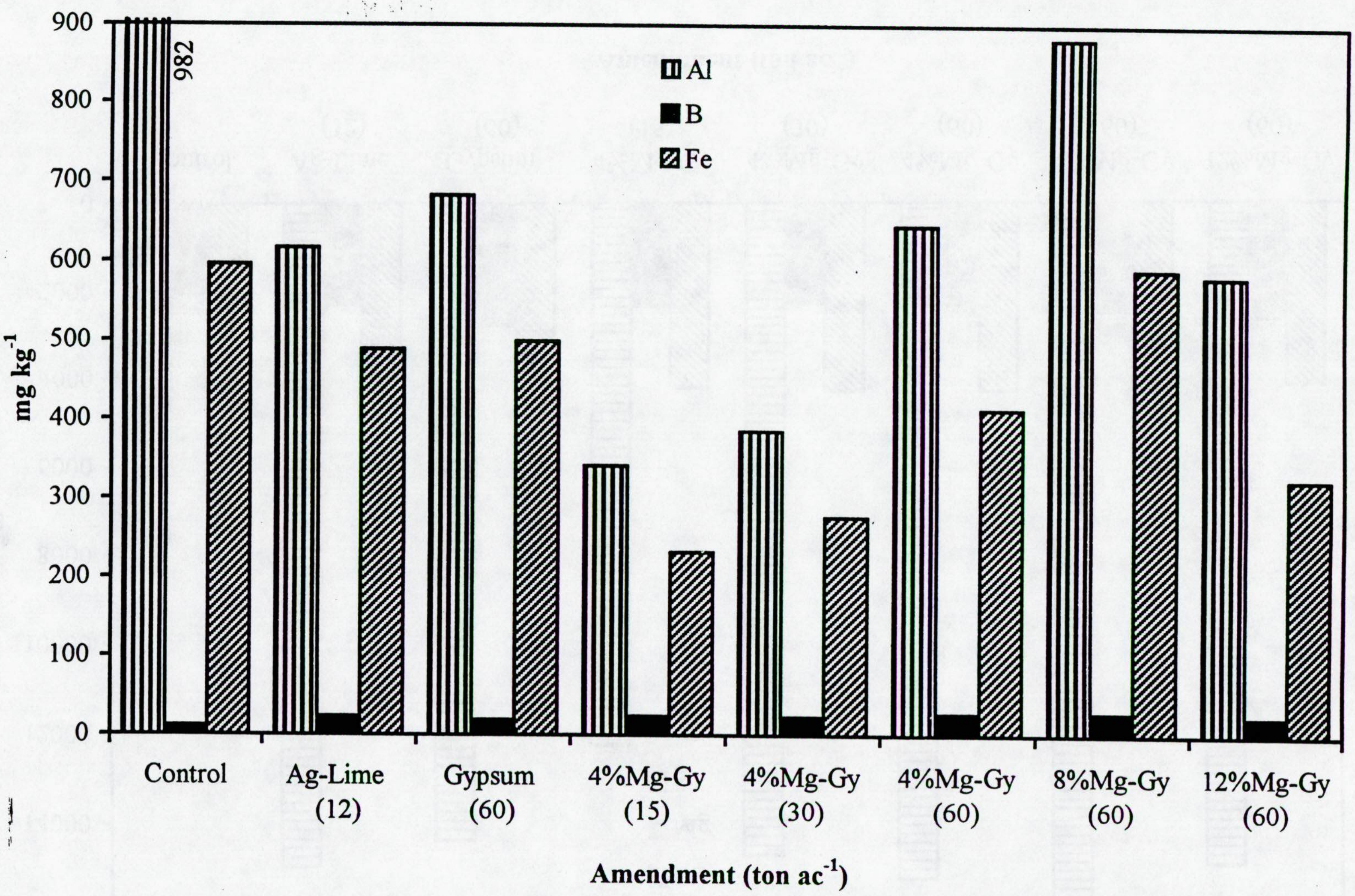


Figure 36. Concentrations of Al, Fe, and B in plant tissues from Autumn 1997 harvest of AS plots.

4.3.3 Soil Chemistry

The average pH of the control plots at the Ashtabula site was between 4.0 and 4.5 throughout the upper 50-cm of the soil profile (Fig. 37). By the first sampling (Spring 1996), all amendments had increased the pH to $\geq$ 5.5 within the zone of application, but there was no apparent effect on soil reaction below the 10 cm depth of incorporation. There was also no trend in pH that could be related to the type or amount of amendments applied. As noted previously, the strong liming effect of the FGD-gypsum can be attributed to impurities of calcite and dolomite in the by-product. By the summer of 1997, plots receiving Mg-gypsum at the highest rates (60 ton/ac) had the highest pH (about 6.5), and the liming effect from the Mg-gypsum extended to a depth of 40 cm. Initial increases in soil pH from the FGD-gypsum had declined in the surface layer.

Similar, but more pronounced trends over depth and time were observed in measurements of soil EC (Fig. 38) and major elements (Ca, Mg, S) released from the by-products (Fig. 39 - 41). Rapid downward movement of soluble S is expected because it is present as the $SO4^{2-}$ ion, and there is no electrostatic attraction to the soil CEC. Calcium and Mg, on the other hand, generally occur as divalent cations in solution and may be retained by cation exchange sites on soil clay. Because of the high concentrations of dissolved $SO4^{2-}$, however, neutral ion pairs of $MgSO4^{o}$ and $CaSO4^{o}$ may form and be mobilized in the soil solution (Stehouwer et al., 1995). The higher total salt load (EC) with depth in those plots treated with Mg-gypsum as compared to gypsum apparently reflects the greater solubility of $MgSO_4$ formed through reaction of $Mg(OH)_2$ with gypsum in the early stages of by-product dissolution. Similar results were observed in the preliminary greenhouse study of Phase 2 (Yibirin et al., 1997).

Major decreases in the surface-soil concentrations of exchangeable Al, which was clearly phytotoxic in the control plots, were obtained with all the amendments used in this study (Fig. 42). By the summer of 1997, reductions in exchangeable Al of 50% or more were also obtained in the subsoil of those plots amended with high rates of 4, 8 and 12% Mg-gypsum. Apparently, Al displaced from the CEC by Mg and Ca was leached below the depth of sampling as suggested by Oates and Caldwell (1985). The rapid downward movement of Ca and Mg and the substantial increase in the base status of the subsoil at the Ashtabula site represents a beneficial effect from the FGD by-products that is not realized with conventional agricultural limestones.

4.3.4 Soil Hydraulic Conductivity (K_{sat})

Saturated soil hydraulic conductivity (permeability) was measured at a depth of 30 - 45 cm in the autumn of 1997. Measurements were repeated for the same plots at the same depth in June, 1998. Measurements were made at this depth to determine if downward leaching of Ca from the amendment materials would improve soil aggregation and thereby enhance subsoil permeability. Significantly greater conductivity readings were obtained in 1997 for those plots amended with the highest rates of by-product (30 and 60 ton/ac) as compared to the control and those plots receiving either agricultural limestone or a lower rate (15 ton/ac) of gypsum (Fig. 43). In 1998, all amended plots yielded saturated conductivities that were higher than the controls. It is impossible to say if the improvements reflect changes in the physicochemical properties of the subsoil (i.e., better aggregation due to saturation of the CEC with Ca) or increased porosity as a result of better root distributions in the amended plots. Certainly, alfalfa growth in the control plots was poor. In order to answer this question, unvegetated plots would need to be studied.

Conductivities measured in 1998 were, in general, two to three times higher than those obtained in 1997 (FGD-gypsum excepted). These differences may reflect continued improvements in subsoil properties and/or root distributions but may also be part of the inherent variability of the measurement technique.

Regression analyses performed for the two rate variables - increasing amount of 4% Mg-gypsum (0, 15, 30, and 60 tons/ac) and increasing % Mg in the 60 tons/ac gypsum amendments (0, 4, 8, and 12% Mg) - produced no statistically significant effects in either year.

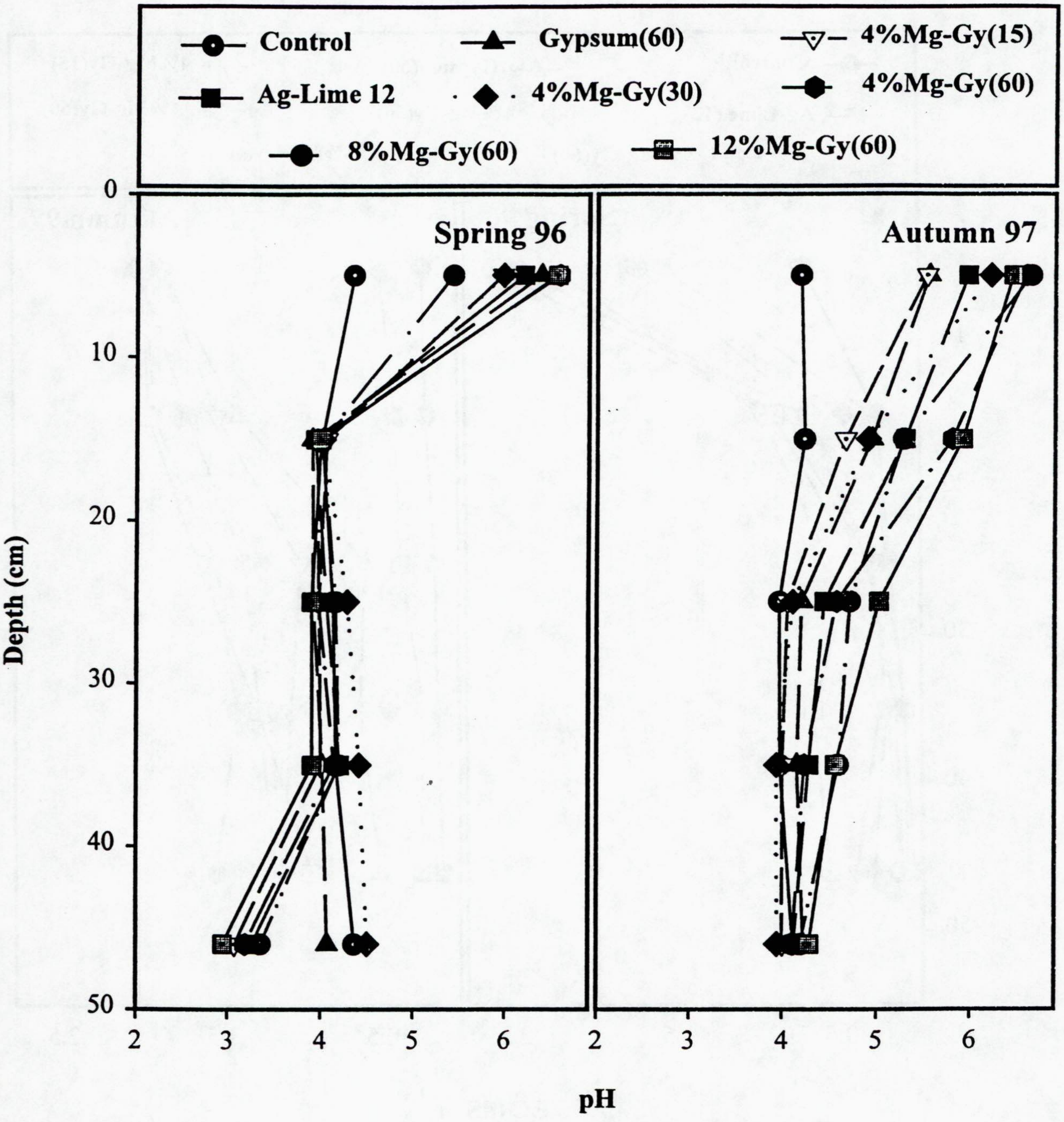


Figure 37. Effects of amendments and rates on pH with soil depth at the AS site.

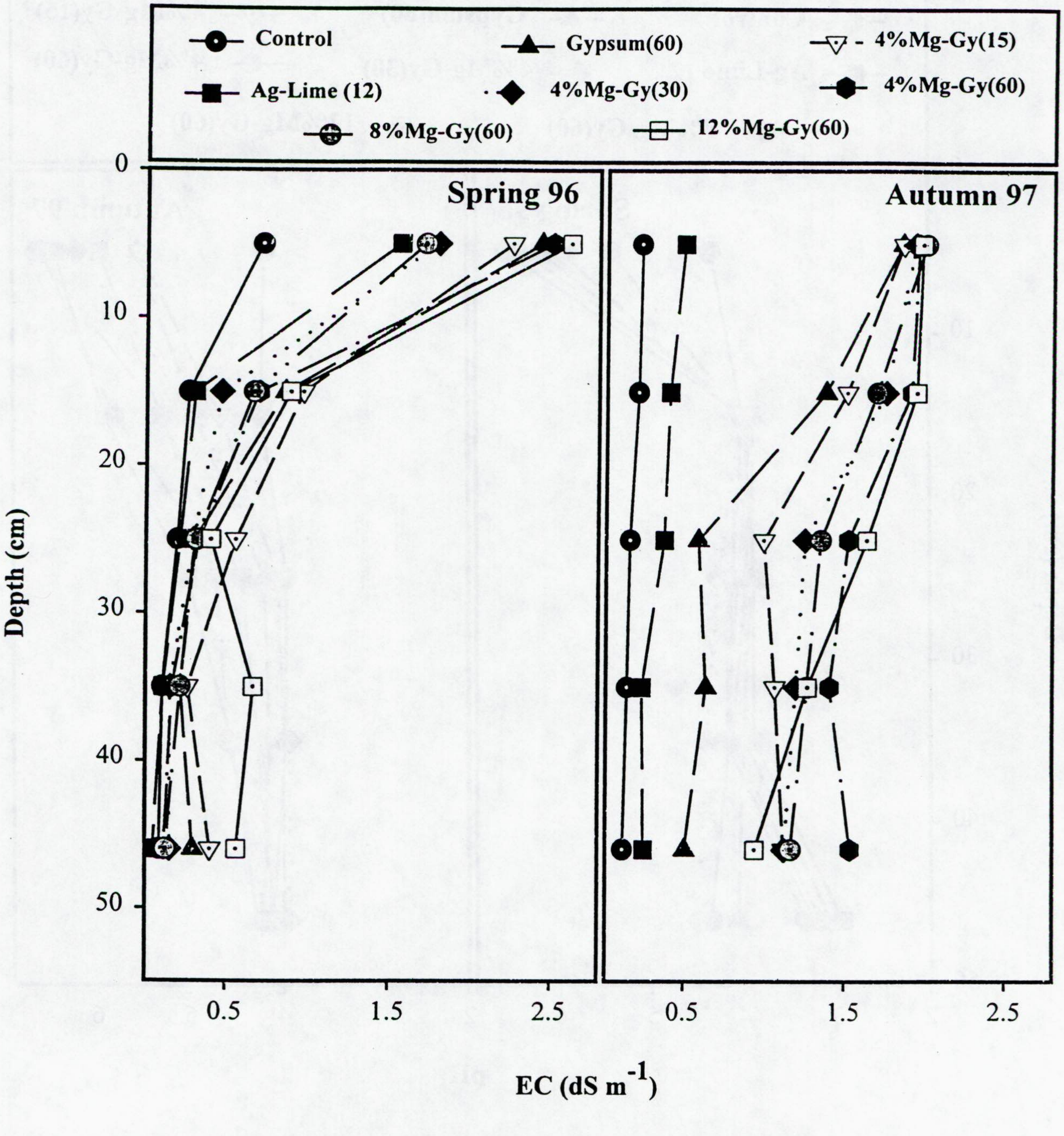


Figure 38. Effects of amendments and rates on electrical conductivity with soil depth at the AS site.

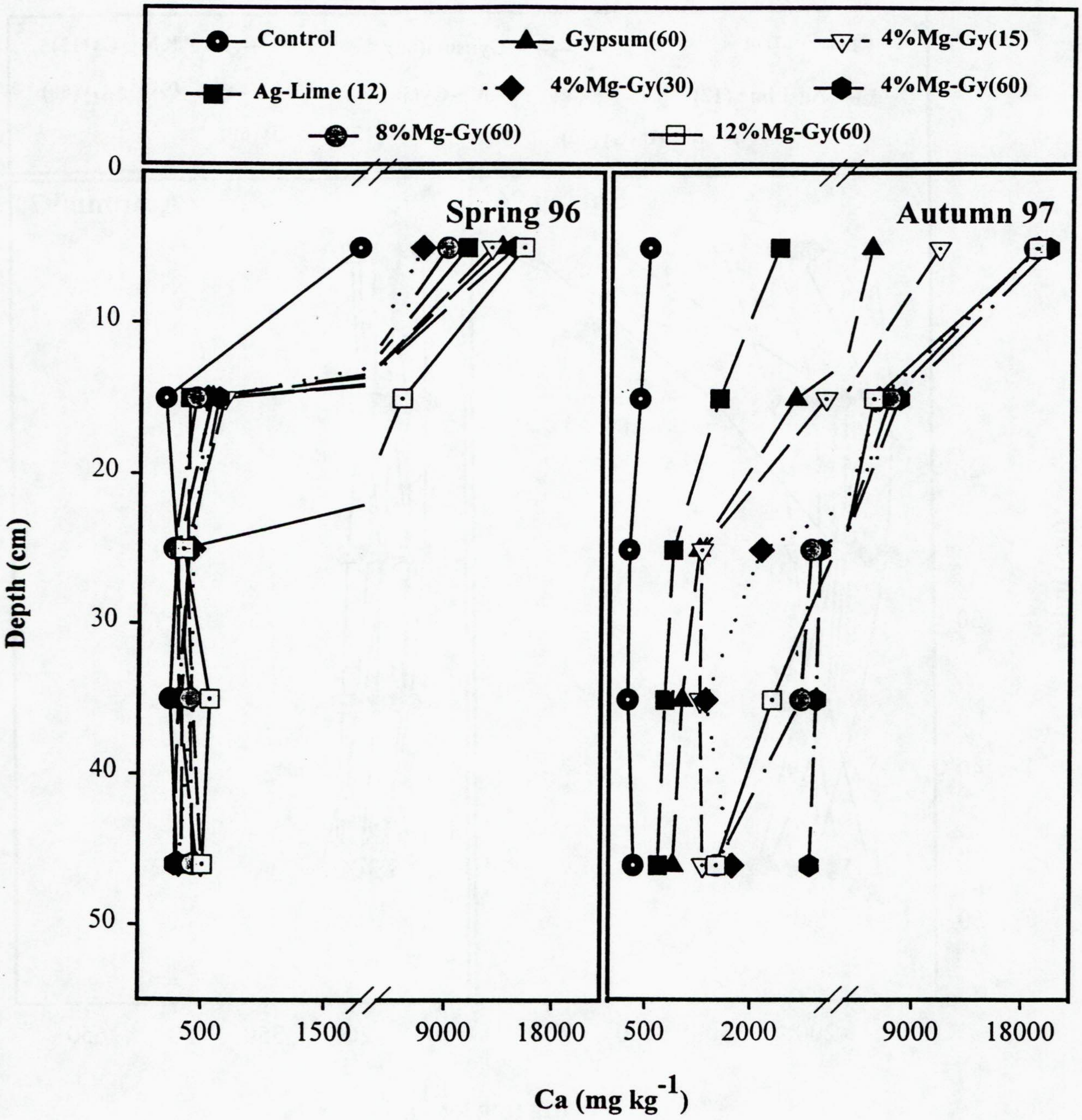


Figure 39. Effects of amendments and rates on KCl-extractable Ca with soil depth at the AS site.

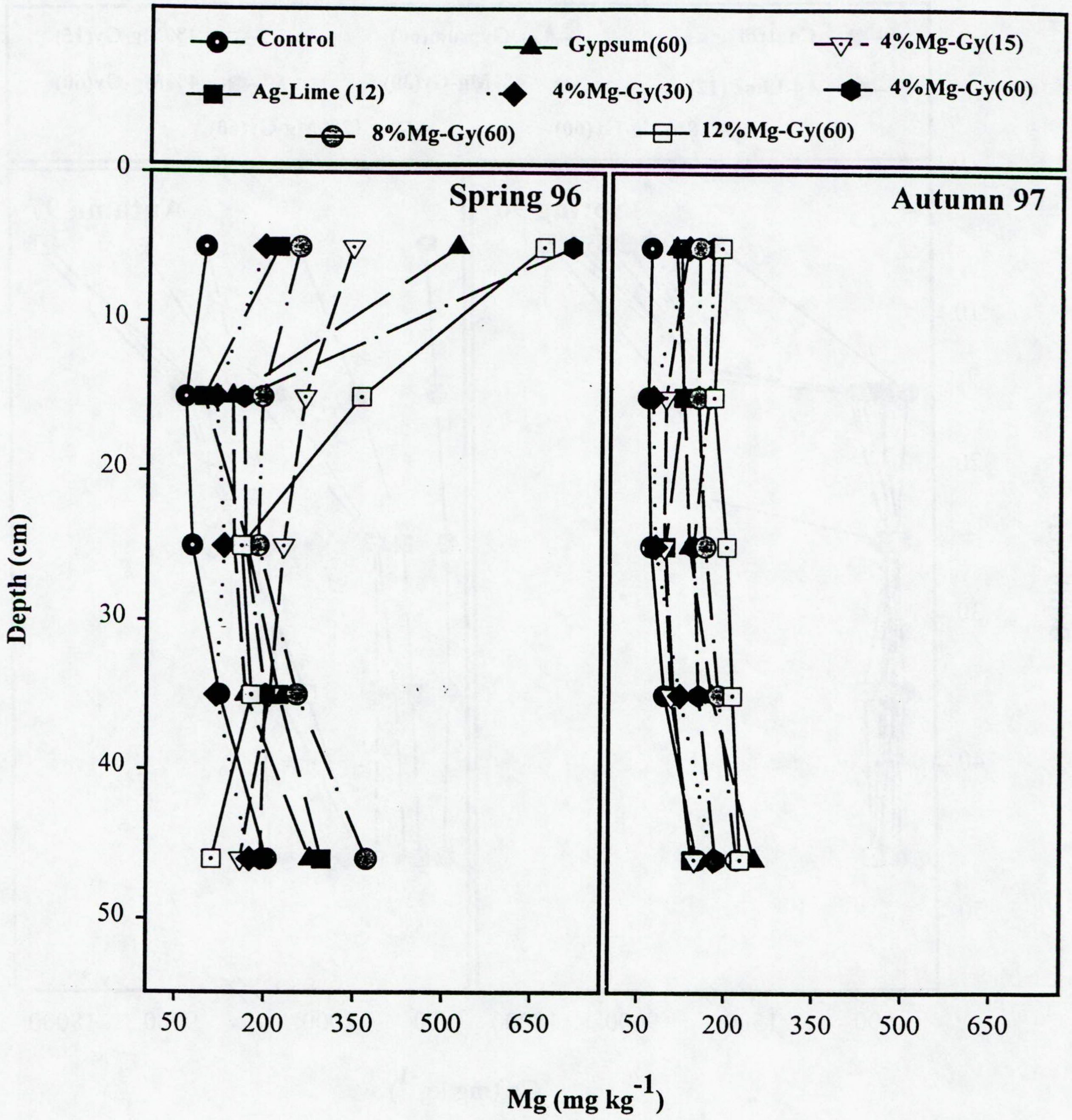


Figure 40. Effects of amendments and rates on KCl-extractable Mg with soil depth at the AS site.

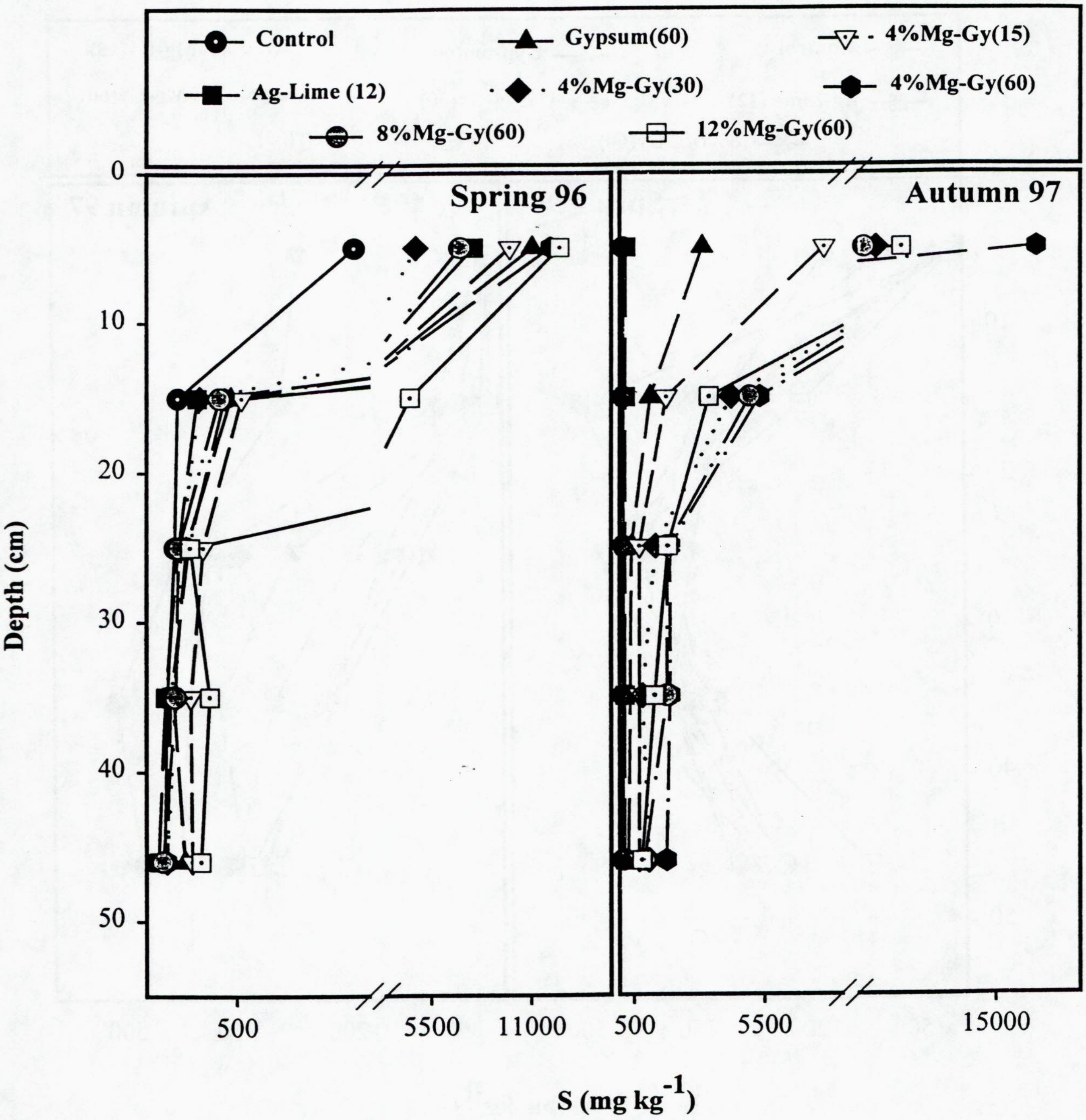


Figure 41. Effects of amendments and rates on KCl-extractable S with soil depth at the AS site.

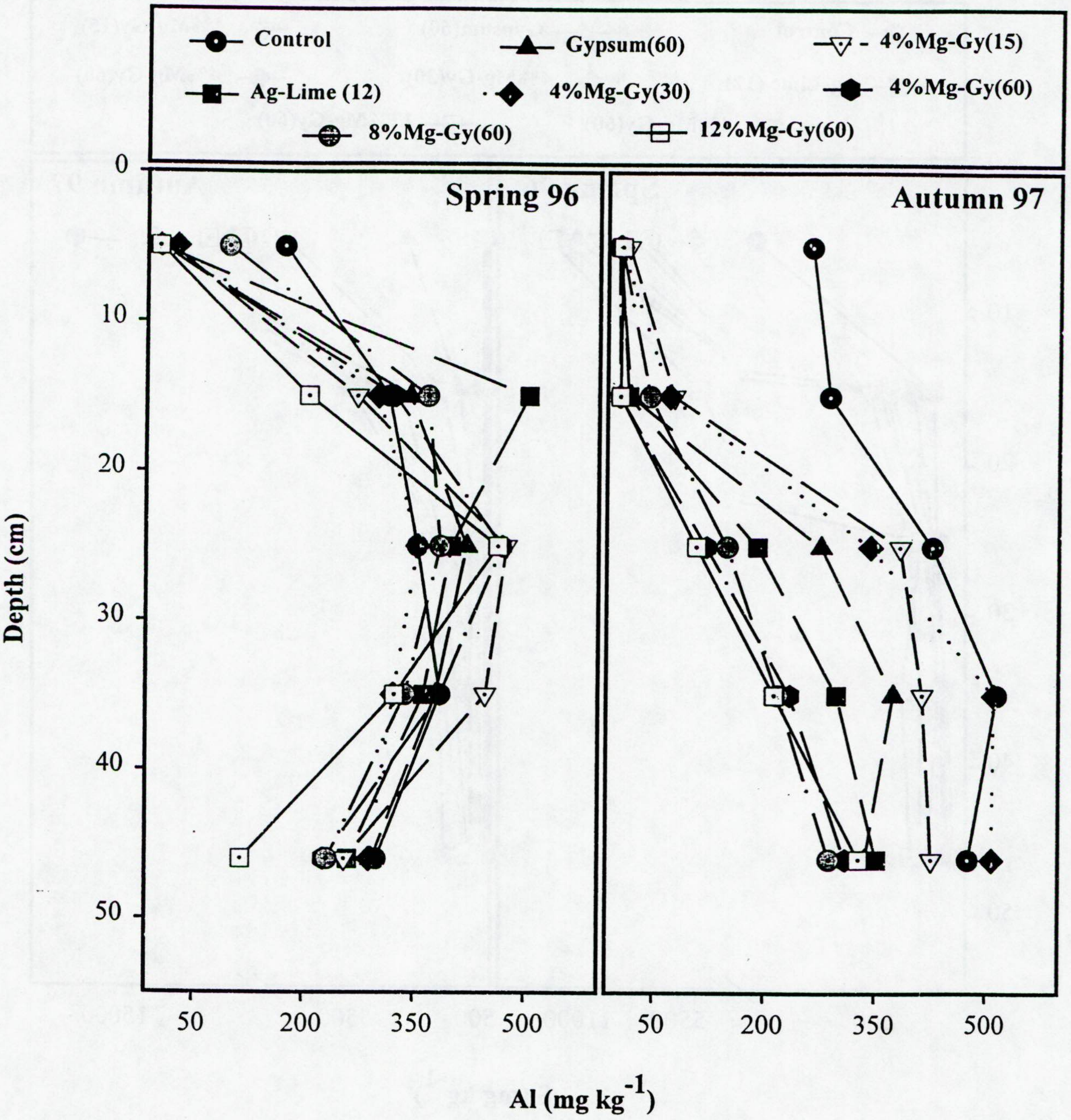


Figure 42. Effects of amendments and rates on KCl-extractable Al with soil depth at the AS site.

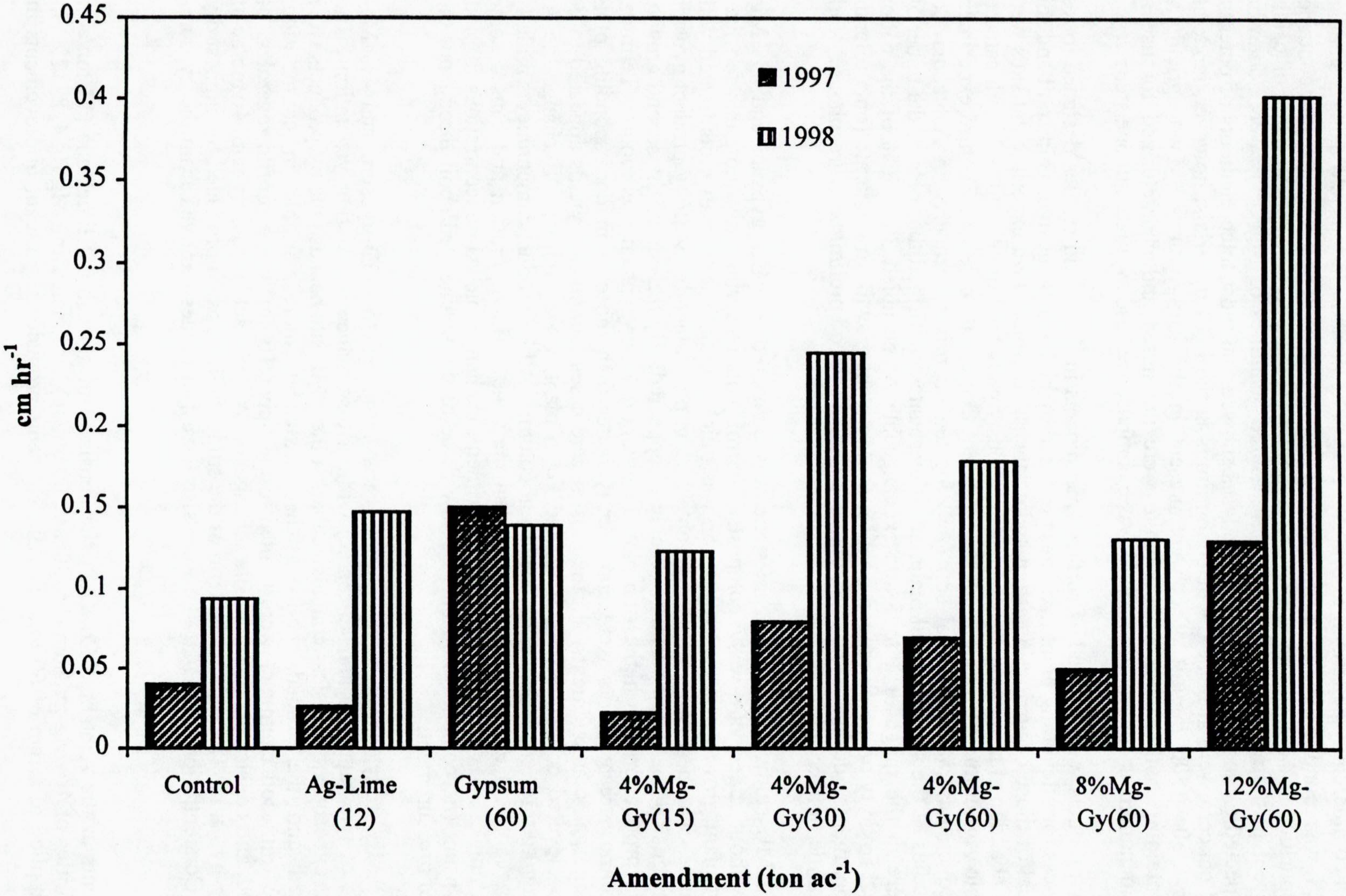


Figure 43. Effects of amendment and rates on saturated hydraulic conductivity (K_{sat}) at a depth of 30-45 cm in the soil at the AS site.

5 SUMMARY AND CONCLUSIONS

Samples of FGD by-product gypsum formulated to contain 0, 4, and 8% $Mg(OH)_2$ were obtained from the Zimmer Station power plant for use in this study. Some of the FGD-gypsum [0% $Mg(OH)_2$] was commercially pelletized to evaluate ease of application in the field using a standard lime spreader; it was found to have excellent handling characteristics. The no-Mg gypsum contained significant impurities of both calcite (11%) and dolomite (8%). Trace (<2%) amounts of calcite were also present in the Mg-gypsums, and the measured quantities of $Mg(OH)_2$ were somewhat lower than expected (3 and 6%). Chemical analyses showed that most trace elements of potential environmental concern were at or below detection limits in the FGD materials; however, moderate concentrations (250 - 500 mg/kg) of B were present in the Mg-gypsums. Two agricultural limestones containing both calcite and dolomite were purchased and characterized for use as comparative amendments. A commercial yard-waste compost was also evaluated in one study.

The by-products were applied as surface amendments in three field studies designed to test their effectiveness for alleviating plant toxicities produced by high exchangeable Al in spoil and soil materials typical of those occurring in eastern and northeastern Ohio. Two experimental sites were established on abandoned mine land (AML) and previously reclaimed mine land (RML) located at the Eastern Ohio Agricultural Research and Development Center in Noble Co. A third experiment was established on natural agricultural soil (AS) located on private property in Ashtabula Co. Preliminary studies of the spoil and soil materials at these sites confirmed that pHs in the upper 50 cm (20 in) were in the range of 3 to 5 and exchangeable Al occupied 30 - 50% of the cation exchange sites. Toxicity of the Al ranged from severe (no plant growth) to moderate (only tolerant species). Experimental designs were formulated on the basis of preliminary greenhouse work conducted to mimic field conditions.

In the AML study, agricultural limestone was compared to FGD gypsum and 4% Mg-gypsum with/without added yard-waste compost. Control plots receiving only inorganic fertilizer did not support plant growth, whereas vegetation was quickly established on all plots treated with other amendments. The best early yields were obtained on plots amended with by-product gypsum alone; however, this competitive advantage quickly disappeared. By the end of the second growth-year, dry matter production was highest on plots receiving 4% Mg-gypsum + compost. Terminal yields from compost-treated plots were consistently better than those from corresponding plots receiving only inorganic amendments. In the most severe cases, diminished yields appeared to be correlated with elevated concentrations of Al and Fe in plant tissue samples. Exchangeable Al exceeded 400 mg/kg throughout the unamended spoil column. All by-products/amendments initially reduced exchangeable Al to non-toxic levels within the zone of incorporation and caused some downward leaching of Al. By the end of the experiment, exchangeable Al concentrations in plots treated with gypsum (no compost) had fallen below those of the unamended spoil throughout the 100-cm depth of measurement.

In the RML study, agricultural limestone was compared to FGD-gypsum and 4% Mg-gypsum applied at two rates (20 and 40 ton/ac) without disturbance of existing vegetation. The results from this experiment were less conclusive than at the AML site because the by-products were not incorporated and the graded spoil was less toxic but more variable in composition. Modifications of minesoil chemistry were limited to the upper 10 cm of the profile regardless of amendment used, and consistent reductions in exchangeable Al were achieved only with 40 ton/ac of gypsum and Mg-gypsum. Throughout the term of the study, FGD-gypsum produced the highest dry matter yields. Concentrations of Al and Fe were also lowest in tissues removed from the gypsum-amended plots.

Treatments at the Ashtabula Co. (AS) site consisted of agricultural limestone (12 ton/ac); increasing quantities of 4% Mg-gypsum (15, 30, and 60 ton/ac); and increasing Mg (0, 4, 8, 12%) in FGD gypsum applied at a rate of 60 ton/ac. All treatments produced significant improvements in

alfalfa yield compared to the unamended control plots. Increasing 4% Mg-gypsum enhanced yield for the 1997 harvest and the 2-yr total; however, increasing the amount of Mg in gypsum had no effect on dry matter production. Plant tissue concentrations of Ca, Mg, and S were similar across all amendments. Concentrations of Al and Fe, on the other hand, were highest in vegetative matter from the control plots. Phytotoxic levels of exchangeable Al were present in the unamended soil, and all amendments produced major decreases in exchangeable Al within the zone of incorporation. By the last harvest (Au 97), reductions of 50% or more were also observed in the subsoil of those plots treated with high rates (30 and 60 ton/ac) of 4, 8, and 12% Mg-gypsum. Significant improvements in the saturated hydraulic conductivity of the soil at a depth of 30 - 45 cm were also achieved with these treatments. The improvements may reflect better subsoil aggregation due to saturation of the CEC with Ca, increased porosity as a consequence of better root distributions in response to less phytotoxic conditions, or both. Such results suggest that land applications of gypsiferous by-products may produce improved soil chemical and physical properties, even in regions where gypsum has not been traditionally utilized as an agricultural amendment.

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7 APPENDIX A: TABULAR DATA FROM THE AML EXPERIMENT

Table 8. Yield from four consecutive harvests at the AML site.

Amendment	6/17/96	9/20/96	7/10/97	9/17/97
	--------------------Mg ha^{-1}			---------------------
		No-compost		
Control	0.00	0.00	0.00	0.00
Ag-Lime	2.08	0.13	2.18	0.72
Gypsum	5.87	0.33	1.14	0.26
4%Mg-Gy	2.09	0.16	2.54	0.84
		With-compost		
Control	1.43	0.51	3.15	0.89
Ag-Lime	2.24	0.52	3.30	1.09
Gypsum	5.00	0.45	2.05	0.61
4% Mg-Gy	1.80	0.54	3.37	1.62
lsd =	1.70	0.35	1.03	0.36

Means of four replications

lsd = least significant difference at 0.05 probability level.

Table 9. Chemical composition of plant tissues at the AML site, Spring 1996

Amendme	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	mg kg^{-1}																						
											No-compost												
Control	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Ag-Lime	631	<1.75	4.3	6.5	0.03	2,604	0.18	0.57	0.39	2.8	204	8,900	1.26	926	82	23.9	0.60	1,218	<0.95	1,142	9.43	56.1	12.3
Gypsum	162	<1.75	4.9	2.0	0.03	2,217	0.13	0.46	0.27	3.9	69	14,698	0.43	844	164	26.4	0.70	1,278	<0.95	1,880	36.78	33.4	19.8
4%MgGyp	894	<1.75	19.4	5.5	0.03	2,918	0.07	0.38	0.63	3.0	270	9,260	1.66	1,028	73	28.8	0.73	1,178	<0.95	1,630	13.27	54.8	9.8
											With-compost												
Control	579	<1.75	4.7	12.6	0.04	2,034	0.07	0.39	0.53	3.0	195	12,195	1.11	1,101	132	21.6	0.66	1,838	<0.95	1,294	18.32	45.2	34.5
A-Lime	269	<1.75	10.8	6.7	0.02	3,319	0.06	0.35	0.27	2.8	113	12,603	0.61	1,143	53	18.9	0.42	1,706	<0.95	1,238	27.97	43.7	18.6
Gypsum	71	<1.75	5.0	2.4	0.02	2,461	0.16	0.27	0.15	3.4	68	17,923	0.25	815	174	19.2	0.42	1,997	<0.95	1,246	22.93	33.4	26.6
4%MgGyp	248	<1.75	11.5	4.1	0.02	2,379	0.12	0.38	0.30	3.1	113	9,699	0.56	1,060	42	20.6	0.35	1,785	<0.95	1,261	25.75	48.0	17.6
lsd =	640	NS	6.79	4.50	NS	958	NS	0.23	0.36	0.78	170	3,165	1.13	174	30	8.57	0.39	232	NS	344	17.41	10.47	3.58

Means of four replications; NS = not significant

lsd = least significant difference at 0.05 probability level.

ns = not sampled

Table 10. Chemical composition of plant tissues at the AML site, Autumn 1997

Amendment	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	mg kg^{-1}																						
											No-Compost												
Control	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Ag-Lime	1106	<1.75	19.1	5.3	<0.01	16919	0.15	0.86	1.00	9.1	388	21291	2.05	2135	51	15.3	2.81	2305	0.95	5234	<4.65	3.2	27.4
Gypsum	2865	2.19	12.8	13.8	0.07	10153	0.15	0.83	2.19	7.4	1178	13077	8.33	1666	169	49.4	1.76	1783	1.57	5715	<4.65	9.7	18.9
4%Mg-Gy	773	<1.75	44.7	5.4	0.02	14495	0.12	0.80	0.86	8.4	353	17963	1.62	2239	58	13.5	2.51	2347	<0.95	5183	4.79	3.3	32.2
											With-Compost												
Control	526	<1.75	20.2	5.7	<0.01	10372	0.14	0.56	0.60	7.3	199	24494	1.47	2121	72	16.3	0.84	2968	<0.95	4213	<4.65	3.7	46.6
Ag-Lime	412	<1.75	23.1	3.0	<0.01	14156	0.10	0.56	0.56	8.6	267	22198	0.86	1922	31	8.6	1.05	3178	<0.95	4860	<4.65	3.5	35.9
Gypsum	691	<1.75	20.9	4.4	<0.01	13143	0.11	0.52	0.66	7.5	430	19155	2.17	2045	80	29.3	0.56	2924	<0.95	5253	<4.65	7.9	35.8
4%Mg-Gy	364	<1.75	30.8	3.0	<0.01	12834	0.09	0.57	0.47	8.3	170	21398	1.02	1809	41	28.0	0.77	3370	<0.95	4596	<4.65	4.4	34.1
lsd =	NS	NS	9	1.38	NS	3,067	NS	0	0	1.32	121	2050	NS	459	50	6.3	1.27	129	0.62	663	NS	3.16	3.81

Means of four replications; NS= not significant

lsd = least significant difference at 0.05 probability level.

ns = not sampled

Table 11. Chemical composition of *M* KCl extracts from soil cores at AML site, Spring 1996.

Amendment	Depth	pH	EC	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Na	Ni	P	Pb	S	Si	Zn
	cm		dS m^{-1}	mg/kg															
Control	0-15	3.1	0.5	419	15.1	251	<0.21	<0.42	1.59	104.0	51	0.61	27.5	<1.05	<4.2	<4.2	147	1.01	<0.21
Control	15-30	3.0	0.6	477	9.7	107	<0.21	<0.42	3.28	121.2	55	1.10	17.4	<1.05	<4.2	<4.2	241	1.20	0.32
Control	30-46	3.0	0.6	543	6.2	75	<0.21	<0.42	2.41	100.9	38	2.46	29.6	1.34	<4.2	<4.2	288	1.27	0.83
Control	46-61	3.1	0.7	522	6.7	48	<0.21	<0.42	4.84	154.6	40	2.50	24.7	<1.05	<4.2	<4.2	385	1.15	0.86
Control	61-76	3.1	0.7	502	7.1	58	<0.21	<0.42	3.43	90.3	78	1.86	28.6	<1.05	<4.2	<4.2	305	1.27	0.48
Control	76-91	3.2	0.7	667	7.4	40	<0.21	<0.42	6.16	72.4	56	4.26	42.0	<1.05	<4.2	<4.2	392	1.17	1.25
Control	91-107	3.3	0.6	678	6.8	30	<0.21	<0.42	11.43	77.5	55	6.37	21.4	2.18	<4.2	<4.2	394	1.63	2.44
Control + C	0-15	4.4	0.3	172	9.7	1241	<0.21	<0.42	<0.42	12.8	205	3.09	20.3	<1.05	<4.2	<4.2	110	2.16	4.55
Control + C	15-30	3.1	0.5	524	8.9	107	<0.21	<0.42	1.19	89.4	30	0.70	25.9	<1.05	<4.2	<4.2	160	1.24	<0.21
Control + C	30-46	2.9	0.6	503	9.6	53	<0.21	<0.42	2.92	147.5	30	0.98	16.2	<1.05	<4.2	<4.2	227	1.58	0.38
Control + C	46-61	3.1	0.5	508	9.9	38	<0.21	<0.42	5.24	130.3	32	3.40	23.4	1.21	<4.2	<4.2	279	1.06	2.04
Control + C	61-76	3.1	0.5	505	11.4	36	<0.21	<0.42	3.72	93.1	28	3.34	19.7	<1.05	<4.2	<4.2	257	1.75	0.61
Control + C	76-91	3.3	0.5	523	10.4	35	<0.21	<0.42	3.52	89.3	31	11.80	10.9	<1.05	<4.2	<4.2	250	1.43	0.81
Control + C	91-107	3.4	0.4	473	11.0	63	<0.21	<0.42	2.89	77.9	52	23.59	37.1	<1.05	<4.2	<4.2	228	1.39	0.75
Ag-Lime	0-15	6.0	1.5	<5.67	5.9	3588	<0.21	<0.42	<0.42	3.9	98	2.30	19.0	<1.05	<4.2	<4.2	926	2.92	<0.21
Ag-Lime	15-30	3.8	1.0	530	6.1	583	<0.21	<0.42	9.16	104.7	57	3.27	24.3	2.24	<4.2	<4.2	531	2.30	1.19
Ag-Lime	30-46	3.3	0.9	669	8.9	129	<0.21	<0.42	1.88	128.1	52	2.63	28.0	1.21	<4.2	<4.2	516	2.45	0.70
Ag-Lime	46-61	3.3	0.7	647	10.1	80	<0.21	<0.42	2.05	88.1	37	2.01	21.5	<1.05	<4.2	<4.2	388	2.90	0.61
Ag-Lime	61-76	3.3	0.5	586	10.1	57	<0.21	<0.42	2.35	81.0	32	2.50	30.7	<1.05	<4.2	<4.2	314	2.22	0.47
Ag-Lime	76-91	3.3	0.6	564	10.0	50	<0.21	<0.42	3.39	92.3	37	4.03	28.5	1.69	<4.2	<4.2	380	2.30	1.20
Ag-Lime	91-107	3.4	0.5	636	8.7	44	<0.21	<0.42	1.76	68.0	42	5.65	41.2	<1.05	<4.2	<4.2	360	2.36	1.18
Ag-Lime + C	0-15	6.0	1.2	<5.67	5.2	3657	<0.21	<0.42	<0.42	<2.10	164	1.18	25.9	<1.05	<4.2	<4.2	649	1.31	<0.21
Ag-Lime + C	15-30	3.3	0.7	502	4.8	439	<0.21	<0.42	2.47	86.0	59	1.30	24.1	<1.05	<4.2	<4.2	273	1.42	0.38
Ag-Lime + C	30-46	3.2	0.9	586	4.6	214	<0.21	<0.42	4.28	130.0	50	1.97	22.6	<1.05	<4.2	<4.2	372	1.24	0.77
Ag-Lime + C	46-61	3.2	0.8	658	3.5	110	<0.21	<0.42	5.88	112.2	41	2.63	31.1	1.15	<4.2	<4.2	429	1.29	0.92
Ag-Lime + C	61-76	3.3	0.7	684	3.5	97	<0.21	<0.42	4.38	51.0	30	2.16	24.8	<1.05	<4.2	<4.2	366	1.40	0.56
Ag-Lime + C	76-91	3.5	0.5	659	4.7	66	<0.21	<0.42	1.37	49.6	32	2.52	35.6	1.44	<4.2	<4.2	300	2.83	1.02
Ag-Lime + C	91-107	3.8	0.5	526	7.0	498	<0.21	<0.42	1.77	59.6	52	4.10	20.8	1.35	<4.2	<4.2	328	4.13	2.78
Gypsum	0-15	4.4	2.4	85	6.3	16278	<0.21	<0.42	<0.42	15.1	167	3.50	11.6	<1.05	<4.2	<4.2	12044	3.33	0.26
Gypsum	15-30	3.0	1.3	461	8.8	437	<0.21	<0.42	3.50	245.8	73	2.88	30.5	1.55	<4.2	<4.2	631	3.18	0.47
Gypsum	30-46	3.1	1.0	633	9.0	136	<0.21	<0.42	5.01	130.6	43	2.53	28.9	<1.05	<4.2	<4.2	419	2.96	0.64
Gypsum	46-61	3.2	0.9	625	11.0	98	<0.21	<0.42	5.14	140.4	39	3.04	22.5	1.15	<4.2	<4.2	403	2.81	1.05
Gypsum	61-76	3.3	0.8	618	11.2	80	<0.21	<0.42	3.58	105.0	42	4.14	32.2	1.88	<4.2	<4.2	367	2.58	2.50
Gypsum	76-91	3.4	0.7	532	11.4	100	<0.21	0.59	2.85	83.4	51	33.58	40.9	<1.05	<4.2	4.42	320	3.18	1.39
Gypsum	91-107	3.6	0.6	499	13.7	162	<0.21	0.73	2.71	29.7	52	18.45	19.4	1.61	<4.2	<4.2	323	2.93	5.44
Gypsum + C	0-15	5.0	2.2	67	12.9	18321	<0.21	<0.42	<0.42	9.5	187	6.48	3.5	<1.05	<4.2	<4.2	13392	3.25	3.36
Gypsum + C	15-30	3.0	2.0	457	16.9	872	<0.21	0.60	6.68	191.0	88	3.87	24.9	1.27	<4.2	<4.2	810	2.67	0.76
Gypsum + C	30-46	3.2	1.1	673	13.8	370	<0.21	<0.42	2.83	179.1	56	4.69	49.3	1.43	<4.2	<4.2	685	1.56	0.90
Gypsum + C	46-61	3.3	1.1	651	9.5	143	<0.21	0.43	2.05	80.0	43	6.37	46.0	<1.05	<4.2	4.55	406	1.18	1.91
Gypsum + C	61-76	3.5	0.7	619	9.7	221	<0.21	<0.42	2.37	60.9	66	24.40	43.2	1.36	<4.2	<4.2	372	2.12	1.69
Gypsum + C	76-91	3.4	0.5	582	10.3	139	<0.21	<0.42	2.92	93.3	82	18.84	22.3	1.27	<4.2	<4.2	348	1.84	2.60
Gypsum + C	91-107	3.7	0.4	499	9.9	181	<0.21	0.53	3.70	67.4	62	68.89	41.2	1.37	<4.2	<4.2	305	1.34	1.46

1:10 KCl extracts, means of 4 replications

Table 11. continued.

Amendment	Depth	pH	EC	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Na	Ni	P	Pb	S	Si	Zn
	cm		dS m^{-1}	mg/kg															
4%Mg-Gy	0-15	5.5	2.5	11	18.2	17710	<0.21	<0.42	<0.42	4.3	507	0.90	15.4	<1.05	<4.2	0.24	13321	3.66	<0.21
4%Mg-Gy	15-30	3.0	1.5	371	13.3	559	<0.21	0.43	2.28	174.8	184	1.41	9.4	<1.05	<4.2	0.93	653	1.80	0.36
4%Mg-Gy	30-46	2.9	1.4	595	13.6	326	<0.21	<0.42	2.92	192.9	153	1.92	36.9	1.26	<4.2	1.23	637	1.74	0.68
4%Mg-Gy	46-61	3.0	1.1	660	16.6	120	<0.21	<0.42	4.93	138.2	82	2.14	37.6	1.47	<4.2	3.41	536	2.21	1.23
4%Mg-Gy	61-76	3.2	0.9	665	15.4	225	<0.21	<0.42	2.70	89.1	43	1.89	26.7	<1.05	<4.2	0.74	515	2.45	1.08
4%Mg-Gy	76-91	3.4	0.7	574	15.7	186	<0.21	<0.42	4.02	78.6	35	2.19	35.4	<1.05	<4.2	2.60	410	2.41	1.22
4%Mg-Gy	91-107	3.4	0.5	683	15.9	98	<0.21	<0.42	0.94	50.4	31	3.21	30.7	<1.05	<4.2	3.16	333	2.08	1.55
4%Mg-Gy + C	0-15	6.0	2.6	8	18.7	17724	<0.21	<0.42	<0.42	<2.10	478	1.76	4.9	<1.05	<4.2	0.48	12985	3.45	<0.21
4%Mg-Gy + C	15-30	3.3	2.5	384	13.4	1650	<0.21	<0.42	2.67	199.5	227	2.70	25.5	1.25	<4.2	2.96	1460	2.40	1.80
4%Mg-Gy + C	30-46	3.2	2.1	707	13.6	895	<0.21	<0.42	2.39	142.4	136	3.32	25.6	2.06	<4.2	2.30	1073	2.43	2.86
4%Mg-Gy + C	46-61	3.3	1.5	667	12.6	760	<0.21	<0.42	1.16	76.7	117	2.62	25.0	1.17	<4.2	2.50	829	1.67	1.85
4%Mg-Gy + C	61-76	3.4	1.2	623	13.0	565	<0.21	<0.42	2.27	50.9	67	3.38	36.4	1.23	<4.2	3.87	657	2.66	4.70
4%Mg-Gy + C	76-91	3.6	1.7	676	14.9	1421	<0.21	<0.42	<0.42	28.7	76	3.81	52.0	<1.05	<4.2	2.83	1258	2.86	2.28
4%Mg-Gy + C	91-107	3.7	1.0	592	15.5	665	<0.21	<0.42	0.65	23.8	49	4.92	26.6	<1.05	<4.2	3.13	612	2.39	2.61
lsd =		0.42	0.52	NS	NS	1,230	NS	NS	NS	NS	86	NS	NS	NS	NS	NS	850	NS	NS

1:10 KCl extracts, means of 4 replications

lsd = least significant difference at 0.05 probability level.

Table 12. Chemical composition of *M* KCl extracts from soil cores at AML site, Autumn 1997.

Amendment	Depth	pH	EC	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Mo1	Na	Ni	P	Pb	S	Si	Sr1	Zn
	cm		dS m^{-1}	mg/kg																	
Control	0-15	2.87	0.85	627	2.9	252	<0.21	<0.42	2.13	117	54	2.06	0.36	25.1	<1.05	<4.2	<4.2	290	22.19	0.46	0.55
Control	15-30	2.84	0.90	636	2.2	106	<0.21	<0.42	2.85	146	43	2.80	0.07	32.4	1.12	<4.2	<4.2	354	22.85	0.39	1.42
Control	30-46	2.97	0.87	676	2.6	68	<0.21	<0.42	5.42	161	41	3.62	-0.13	44.3	2.93	<4.2	<4.2	449	24.84	0.34	2.62
Control	46-61	2.97	0.94	679	4.3	83	<0.21	<0.42	4.90	198	59	4.39	0.87	48.8	2.07	<4.2	4.39	511	27.00	0.39	2.22
Control	61-76	3.15	0.63	624	3.6	74	<0.21	<0.42	3.91	86	63	3.69	0.00	45.9	1.57	<4.2	5.12	331	28.00	0.37	1.70
Control	76-91	3.22	0.69	852	4.2	92	<0.21	<0.42	4.02	91	85	4.53	0.39	33.7	2.71	<4.2	<4.2	411	27.54	0.75	3.53
Control	91-107	3.28	0.62	781	3.7	52	<0.21	<0.42	2.66	88	66	5.27	-0.40	57.7	1.92	<4.2	<4.2	374	30.00	0.62	2.96
Control + C	0-15	4.59	0.63	85	5.0	2341	<0.21	<0.42	<0.42	9	271	5.76	0.40	37.1	1.16	4.85	<4.2	290	29.06	4.54	6.58
Control + C	15-30	3.21	0.44	518	4.4	376	<0.21	<0.42	0.47	70	61	1.88	-0.46	27.5	<1.05	<4.2	<4.2	181	26.37	1.01	0.73
Control + C	30-46	3.20	0.43	571	3.9	187	<0.21	<0.42	1.28	63	39	2.01	-1.01	43.5	<1.05	<4.2	4.45	179	26.18	0.71	0.83
Control + C	46-61	3.03	0.63	641	3.6	105	<0.21	<0.42	3.63	118	39	3.01	-0.05	39.9	<1.05	<4.2	<4.2	251	27.92	0.55	1.20
Control + C	61-76	2.99	0.88	657	3.3	58	<0.21	<0.42	2.30	187	42	4.66	0.12	36.1	<1.05	<4.2	<4.2	338	27.18	0.46	1.40
Control + C	76-91	3.27	0.58	646	4.6	68	<0.21	<0.42	1.90	93	59	12.48	-0.04	37.8	1.75	<4.2	<4.2	266	26.43	0.54	3.68
Control + C	91-107	3.44	0.46	671	4.6	96	0.32	<0.42	0.68	56	66	35.23	0.28	30.2	1.85	<4.2	<4.2	224	28.71	0.68	1.73
Ag-Lime	0-15	6.13	1.47	<5.67	3.2	5423	<0.21	<0.42	<0.42	<2.10	159	4.05	0.01	33.4	<1.05	<4.2	<4.2	2278	21.67	6.63	<0.21
Ag-Lime	15-30	2.89	1.41	654	2.7	418	<0.21	<0.42	10.60	267	69	4.59	0.50	26.6	3.28	<4.2	<4.2	775	18.87	0.74	1.32
Ag-Lime	30-46	3.07	1.05	779	3.7	257	<0.21	<0.42	7.24	120	75	3.89	0.06	50.1	2.61	<4.2	<4.2	624	18.68	0.71	1.59
Ag-Lime	46-61	3.18	0.89	831	3.5	194	<0.21	<0.42	2.96	80	66	3.46	-0.45	43.7	2.31	<4.2	<4.2	562	19.69	0.79	1.45
Ag-Lime	61-76	3.24	0.80	788	3.7	136	<0.21	<0.42	2.15	78	64	3.35	0.10	25.2	1.85	<4.2	<4.2	453	20.10	0.68	1.22
Ag-Lime	76-91	3.32	0.80	753	3.8	144	<0.21	<0.42	2.74	83	65	4.33	-0.07	29.1	1.84	<4.2	<4.2	450	18.97	0.59	1.85
Ag-Lime	91-107	3.45	0.58	671	3.2	100	<0.21	<0.42	2.23	50	55	3.58	-0.03	34.8	2.01	4.87	<4.2	323	17.84	0.47	1.38
Ag-Lime + C	0-15	6.56	1.21	<5.67	5.0	5153	<0.21	<0.42	<0.42	<2.10	172	<0.21	-0.60	20.2	<1.05	<4.2	<4.2	1651	27.96	6.87	<0.21
Ag-Lime + C	15-30	3.44	0.82	400	3.7	1085	<0.21	<0.42	1.17	79	93	1.32	-0.18	13.8	<1.05	<4.2	<4.2	484	21.96	1.91	<0.21
Ag-Lime + C	30-46	3.02	0.88	677	2.9	350	<0.21	<0.42	4.10	108	67	1.35	-0.06	36.1	<1.05	<4.2	<4.2	406	23.80	0.89	<0.21
Ag-Lime + C	46-61	3.09	0.96	760	3.2	204	<0.21	<0.42	7.88	118	55	2.24	-0.73	15.4	1.84	<4.2	<4.2	575	20.75	0.67	0.49
Ag-Lime + C	61-76	3.15	0.79	723	3.0	115	<0.21	<0.42	2.87	114	55	2.06	0.70	39.7	1.94	<4.2	<4.2	459	21.45	0.47	1.87
Ag-Lime + C	76-91	3.27	0.84	897	3.2	168	<0.21	<0.42	3.04	98	62	4.65	0.22	19.8	2.88	<4.2	<4.2	561	28.91	0.68	1.70
Ag-Lime + C	91-107	3.26	0.77	714	4.8	117	<0.21	<0.42	1.15	109	55	4.66	0.83	37.2	3.08	<4.2	<4.2	462	19.66	0.55	4.15
Gypsum	0-15	4.57	2.02	86	4.6	18879	<0.21	<0.42	<0.42	11	300	5.03	0.75	3.0	<1.05	<4.2	<4.2	14294	35.11	30.68	<0.21
Gypsum	15-30	3.01	2.01	525	5.3	2609	<0.21	<0.42	3.16	132	126	4.10	-0.08	47.7	1.34	<4.2	<4.2	2098	31.54	5.40	0.38
Gypsum	30-46	2.94	1.27	598	5.0	674	<0.21	0.47	2.67	163	82	7.04	-0.03	31.3	2.88	<4.2	<4.2	666	33.46	2.20	1.77
Gypsum	46-61	3.09	1.00	595	5.9	424	<0.21	<0.42	4.10	90	64	9.28	0.94	33.0	2.14	<4.2	<4.2	496	35.52	1.52	0.96
Gypsum	61-76	3.30	0.69	588	4.9	270	0.24	<0.42	3.03	45	65	14.28	0.03	33.6	2.32	<4.2	<4.2	400	34.87	0.98	3.35
Gypsum	76-91	3.55	0.44	537	4.6	166	<0.21	0.48	1.68	28	75	39.91	0.50	28.1	1.05	<4.2	<4.2	244	35.19	0.84	1.64
Gypsum	91-107	3.81	0.50	462	4.1	254	<0.21	<0.42	2.87	39	93	64.20	0.72	23.4	2.87	<4.2	<4.2	298	34.44	1.10	2.05
Gypsum + C	0-15	4.64	2.26	113	5.4	16725	<0.21	0.42	1.01	230	216	4.56	0.97	23.0	1.10	<4.2	<4.2	12620	34.80	25.13	2.00
Gypsum + C	15-30	2.92	2.08	667	2.8	1943	<0.21	0.42	8.98	207	122	3.19	-0.92	28.7	3.70	<4.2	<4.2	1780	22.41	3.40	0.75
Gypsum + C	30-46	3.03	1.35	745	2.7	688	<0.21	0.10	2.12	95	70	2.40	0.16	30.0	<1.05	<4.2	<4.2	875	20.93	1.41	0.42
Gypsum + C	46-61	3.34	1.16	677	3.4	1831	<0.21	<0.42	0.86	49	73	4.69	0.11	36.2	<1.05	<4.2	<4.2	1742	20.19	2.64	<0.21
Gypsum + C	61-76	3.43	0.75	657	3.8	410	<0.21	0.50	1.03	64	67	32.43	-0.05	40.5	<1.05	<4.2	<4.2	485	24.42	1.13	0.21
Gypsum + C	76-91	3.53	0.65	691	3.3	362	<0.21	<0.42	2.45	70	97	48.62	-0.08	43.8	1.23	<4.2	<4.2	436	24.37	1.25	0.59
Gypsum + C	91-107	3.54	0.58	722	3.6	254	<0.21	<0.42	0.88	53	104	81.22	-0.78	28.9	<1.05	<4.2	<4.2	378	21.65	1.05	0.27

1:10 KCl extracts, means of four replications

Table 12. Continued.

Amendment	Depth	pH	EC	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Na	Ni	P	Pb	S	Si	Zn
	cm		dS m-1	mg/kg															
4%Mg-Gy	0-15	5.04	1.97	40	7.7	18495	<0.21	<0.42	1.24	1	302	5.06	9.5	0.46	<4.2	<4.2	13832	24.65	0.32
4%Mg-Gy	15-30	2.92	1.99	484	2.6	1834	<0.21	<0.42	4.18	114	121	2.20	37.8	1.90	<4.2	<4.2	1552	21.23	0.75
4%Mg-Gy	30-46	2.92	1.62	753	2.3	2192	<0.21	0.54	5.50	268	125	3.16	39.6	3.46	<4.2	<4.2	2203	23.59	1.88
4%Mg-Gy	46-61	3.08	1.29	733	2.5	636	<0.21	<0.42	2.19	87	83	2.61	31.7	1.49	<4.2	<4.2	835	22.46	1.64
4%Mg-Gy	61-76	3.26	0.98	725	4.7	596	<0.21	<0.42	2.60	71	75	2.69	48.0	1.29	<4.2	<4.2	720	24.38	1.65
4%Mg-Gy	76-91	3.35	0.83	635	3.3	253	<0.21	0.44	2.38	67	56	3.11	52.4	1.08	<4.2	<4.2	478	24.05	1.95
4%Mg-Gy	91-107	3.48	0.67	654	2.7	277	<0.21	<0.42	1.06	39	58	3.06	41.0	0.69	<4.2	<4.2	416	23.68	1.40
4%Mg-Gy + C	0-15	5.70	1.97	8	7.9	19177	<0.21	0.43	<0.42	1	296	2.53	27.0	<1.05	<4.2	<4.2	14100	29.13	0.53
4%Mg-Gy + C	15-30	2.87	2.43	467	2.6	1875	<0.21	0.42	5.85	157	127	2.71	45.1	0.37	<4.2	<4.2	1592	24.06	1.78
4%Mg-Gy + C	30-46	2.97	1.88	859	3.4	1268	<0.21	<0.42	2.55	164	132	4.37	57.1	2.76	<4.2	<4.2	1377	23.85	2.62
4%Mg-Gy + C	46-61	3.12	1.03	719	3.7	330	<0.21	<0.42	1.29	115	61	3.24	51.2	2.57	<4.2	<4.2	525	23.23	3.86
4%Mg-Gy + C	61-76	3.33	0.81	602	2.9.	427	<0.21	<0.42	0.96	45	59	2.36	69.0	1.39	<4.2	<4.2	448	22.88	1.50
4%Mg-Gy + C	76-91	3.44	0.85	684	2.4	469	<0.21	<0.42	1.93	34	61	3.20	59.5	0.95	<4.2	<4.2	500	24.77	2.38
4%Mg-Gy + C	91-107	3.57	0.60	641	1.8	289	<0.21	<0.42	0.91	27	52	5.61	58.9	1.19	<4.2	<4.2	375	23.57	3.45
lsd =		0.48	0.65	NS	NS	1561	NS	NS	NS	NS	63.2	NS	NS	NS	NS	NS	1246	NS	NS

1:10 KCl extracts, means of four replications

lsd = least significant difference at 0.05 probability level.

8 APPENDIX B: TABULAR DATA FROM THE RML EXPERIMENT

Table 13. Yield from four consecutive harvests at the RML site.

Amendments	6/18/96	9/20/96	7/10/97	9/24/97
	------------------------Mg ha^{-1}	---------------------		
Control	1.04	0.44	1.15	0.87
Ag-Lime (6)	1.26	0.78	1.79	1.00
Gypsum (20)	1.69	1.01	1.69	1.16
Gypsum (40)	3.28	1.39	2.01	1.59
4%Mg-Gy(20)	0.88	0.67	1.51	1.01
4%Mg-Gy(40)	1.08	0.68	1.25	0.84
lsd =	0.98	0.57	0.68	0.47

Means of four replications

Amendment rates (ton ac^{-1})

lsd = least significant difference at 0.05 probability level.

Table 14. Chemical composition of plant tissues at the RML site, Spring 1996

Amendment	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	mg kg^{-1}	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------
Control	295	<1.75	10.44	6.43	<0.01	4,991	0.24	0.56	0.40	4.66	224	15,828	0.39	2,145	158	13.4	2.00	1,407	1.44	3,603	<4.65	29.7	19.5
Ag-Lime (6)	206	<1.75	10.04	6.32	<0.01	6,612	0.18	0.84	0.37	4.55	173	16,380	0.91	2,223	197	13.8	1.29	1,705	1.91	3,628	17.51	28.6	24.7
Gypsum (20)	84	<1.75	7.35	2.16	<0.01	5,887	0.26	0.83	0.25	4.31	75	19,120	5.64	1,928	191	10.3	2.10	1,280	<0.95	4,448	6.46	27.1	18.5
Gypsum (40)	69	<1.75	6.96	2.17	<0.01	5,484	0.23	0.27	0.29	4.72	76	19,233	1.89	1,868	117	31.2	1.34	1,426	1.96	4,483	9.45	24.3	20.9
4% Mg-Gyp (20)	268	<1.75	20.42	3.71	<0.01	12,593	0.16	0.54	0.54	4.56	186	15,220	0.36	1,634	118	10.8	1.84	1,325	1.62	7,510	<4.65	28.7	21.5
4% Mg-Gyp (40)	72	<1.75	15.27	1.67	<0.01	7,609	0.07	0.53	0.26	4.52	81	19,298	5.00	1,797	116	12.8	2.06	1,337	1.37	6,084	<4.65	26.8	20.2
lsd =	NS	NS	3.87	1.93	NS	3,602	0.13	NS	0.60	NS	NS	NS	NS	NS	NS	15.22	NS	NS	NS	2,096	NS	NS	NS

Means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac^{-1})

Table 15. Chemical composition of plant tissues at the RML site, Autumn 1997

Amendment	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	---------- mg kg^{-1} ----------																						
Control	689	1.75	6.27	12.13	0.02	5613	0.15	0.71	0.59	5.24	492	12391	0.51	2389	212	16.30	1.88	1490	1.04	3138	<4.65	18.58	27.41
Ag-Lime (6)	757	1.75	8.72	10.02	0.04	7135	0.18	0.96	0.76	5.46	506	12898	1.11	2308	249	10.24	2.28	1854	1.24	3292	<4.65	18.75	24.42
Gypsum (20)	347	1.75	6.59	6.78	0.02	6228	0.16	0.92	0.36	5.22	264	14277	0.52	2727	234	8.38	2.29	1817	<0.95	3521	<4.65	15.06	28.05
Gypsum (40)	232	1.75	5.78	6.03	<0.01	6613	0.15	0.43	0.32	5.32	171	17316	0.72	2669	127	10.57	1.26	2030	<0.95	4483	<4.65	18.90	23.00
4% Mg-G(20)	284	1.75	8.61	5.20	<0.01	7031	0.10	0.66	0.22	5.18	188	13249	0.20	2144	196	9.34	2.02	1632	1.13	4056	<4.65	18.97	25.55
4% Mg-G(40)	461	1.75	8.31	5.02	0.03	7268	0.15	0.81	0.55	5.37	405	16834	0.59	2227	137	11.68	2.08	1741	<0.95	4939	<4.65	17.23	23.49
lsd =	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac^{-1})

Table 16. Chemical composition of *M* KCl extracts from soil cores at RML site, Spring 1996

Amendment	Depth	pH	EC	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Na	Ni	P	Pb	S	Si	Zn
	cm		dS m^{-1}	mg/kg															
Control	0-10	5.36	0.28	70	8.03	1435	0.37	0.19	0.12	3	424	46.5	42.2	0.00	0.00	1.94	137	4.65	0.72
Control	10-20	4.36	0.27	152	6.92	1021	0.44	0.00	0.00	30	289	28.0	30.8	0.04	0.00	5.17	164	5.53	0.38
Control	20-30	3.67	0.67	291	6.75	795	0.38	0.00	1.60	72	185	15.6	40.0	0.68	1.28	6.41	385	4.86	0.15
Control	30-41	3.86	1.28	142	6.79	2730	0.48	0.08	0.17	63	301	37.8	33.5	1.45	0.00	4.02	1156	4.51	1.65
Ag-lime (6)	0-10	5.52	0.70	80	6.77	1951	0.50	0.14	0.00	3	381	57.3	28.1	0.32	0.00	5.17	374	4.61	0.76
Ag-lime (6)	10-20	4.62	0.82	288	7.92	2226	0.77	0.00	0.38	6	302	39.9	45.3	0.89	0.00	5.45	1166	6.22	0.89
Ag-lime (6)	20-30	4.10	1.13	286	7.76	1352	0.61	0.00	0.26	88	226	20.5	38.1	1.34	0.00	4.79	732	5.62	0.69
Ag-lime (6)	30-41	4.25	1.50	322	7.40	2172	0.54	0.00	0.28	106	257	18.5	32.7	1.06	0.00	4.09	1341	5.40	1.18
Gypsum (20)	0-10	4.95	0.95	76	6.54	1922	0.57	0.00	0.00	1	325	67.1	40.0	0.73	2.33	5.69	564	5.19	1.32
Gypsum (20)	10-20	3.87	0.45	325	7.26	616	0.53	0.00	0.00	53	164	30.4	37.0	0.16	0.00	7.08	313	5.40	1.11
Gypsum (20)	20-30	4.08	0.73	173	7.17	918	0.53	0.00	0.00	91	213	47.5	39.4	1.22	0.00	4.68	452	5.13	1.14
Gypsum (20)	30-41	4.13	1.07	144	6.98	1465	0.37	0.03	0.00	109	237	43.4	29.6	1.87	2.13	2.83	794	5.86	3.20
Gypsum (40)	0-10	5.83	2.21	4	7.02	6585	0.35	0.00	0.00	3	396	43.5	29.6	0.22	1.33	1.12	4037	3.67	0.00
Gypsum (40)	10-20	5.20	0.74	102	7.36	1544	0.14	0.00	0.00	47	256	16.7	36.6	0.18	0.26	9.40	345	3.11	0.07
Gypsum (40)	20-30	4.47	0.52	152	7.32	1065	0.52	0.02	0.05	51	264	12.6	30.0	0.45	0.00	3.57	278	4.01	0.75
Gypsum (40)	30-41	4.08	1.02	162	7.96	1678	0.80	0.05	0.00	45	279	17.4	38.1	0.79	0.44	1.61	810	4.44	1.04
4% Mg-G (20)	0-10	6.17	1.81	8	9.77	8287	0.15	0.00	0.00	3	388	26.0	30.0	0.00	0.00	0.99	5653	3.74	0.82
4% Mg-G (20)	10-20	4.29	0.79	131	8.41	1574	0.30	0.00	0.02	8	286	22.7	30.0	0.06	0.00	7.00	732	4.01	0.38
4% Mg-G (20)	20-30	3.80	1.36	286	7.23	1588	0.34	0.06	0.22	108	238	34.8	38.5	0.65	0.00	6.23	1081	4.97	2.20
4% Mg-G (20)	30-41	3.70	1.47	378	6.95	2125	0.32	0.00	0.74	73	353	42.9	30.3	1.80	0.00	5.29	1415	4.92	3.29
4% Mg-G (40)	0-10	6.66	2.34	4	8.82	10402	0.46	0.08	0.00	1	428	19.0	28.6	0.09	0.00	2.30	7381	2.28	0.00
4% Mg-G (40)	10-20	4.87	1.17	121	6.96	1615	0.75	0.01	0.00	10	331	25.2	31.7	0.00	0.00	4.98	578	3.48	0.37
4% Mg-G (40)	20-30	4.13	0.74	213	7.02	1191	0.24	0.05	0.00	84	274	31.1	33.3	0.03	1.00	3.32	447	4.13	0.64
4% Mg-G (40)	30-41	4.76	1.03	64	7.47	1760	0.14	0.00	0.00	45	331	20.4	38.8	0.36	0.00	2.80	561	4.32	0.57
lsd =		NS	0.81	NS	1.58	3,133	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	2,365	NS	NS

1:10 KCl extracts, means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac^{-1})

Table 17. Chemical composition of *M* KCl extracts from soil cores at RML site, Autumn 1997.

Amendment	Depth	pH	EC	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Na	Ni	P	Pb	S	Si	Zn
	cm		$dS\ m^{-1}$	mg/kg															
Control	0-10	5.61	0.38	73	7.54	1632	<0.21	<0.21	<0.42	38	363	34.37	57.1	4.79	<4.2	<4.2	189	40.0	1.4
Control	10-20	4.84	0.37	180	7.41	1551	<0.21	0.08	<0.42	8	343	20.62	52.9	1.20	<4.2	<4.2	214	41.9	0.7
Control	20-30	4.26	0.65	376	7.29	3019	0.06	<0.21	<0.42	32	253	33.95	71.2	2.97	<4.2	<4.2	1643	41.9	3.3
Control	30-41	4.24	0.69	197	7.59	3092	<0.21	<0.21	<0.42	38	290	34.79	90.3	2.19	<4.2	<4.2	1750	43.1	2.8
Control	41-51	4.27	0.71	170	6.63	1706	<0.21	<0.21	<0.42	39	372	27.49	71.9	1.24	<4.2	<4.2	564	46.8	1.2
Control	51-61	4.51	0.49	116	5.27	1223	0.11	0.21	<0.42	78	297	24.83	87.8	<1.05	<4.2	<4.2	370	40.6	0.7
Ag-Lime (6)	0-10	5.95	1.04	52	4.45	4030	<0.21	<0.21	<0.42	<2.10	289	14.04	56.9	<1.05	<4.2	<4.2	1927	34.5	<0.21
Ag-Lime (6)	10-20	4.95	0.82	184	3.99	1573	<0.21	<0.21	<0.42	2	355	43.24	53.7	<1.05	<4.2	<4.2	461	37.4	0.5
Ag-Lime (6)	20-30	4.31	1.19	312	3.68	2957	<0.21	0.17	0.69	23	353	30.81	51.6	1.62	<4.2	<4.2	1661	29.6	1.0
Ag-Lime (6)	30-41	3.86	0.88	416	3.10	1139	<0.21	0.18	1.12	45	255	34.61	46.1	1.53	<4.2	<4.2	582	28.5	1.1
Ag-Lime (6)	41-51	4.13	0.97	306	4.14	1453	<0.21	<0.21	0.84	49	313	44.92	49.7	2.04	<4.2	<4.2	683	25.8	1.2
Ag-Lime (6)	51-61	3.90	0.73	217	3.72	1107	<0.21	0.10	0.64	54	271	44.70	55.2	3.18	<4.2	<4.2	415	28.4	1.5
Gypsum (20)	0-10	4.77	0.77	82	5.68	1928	0.01	<0.21	<0.42	<2.10	290	65.09	64.4	1.18	5.34	<4.2	636	35.6	1.1
Gypsum (20)	10-20	3.84	0.64	442	5.12	885	<0.21	<0.21	<0.42	6	187	40.77	52.4	<1.05	<4.2	4.48	420	37.0	1.1
Gypsum (20)	20-30	3.95	1.28	293	5.02	1534	<0.21	<0.21	<0.42	53	202	50.79	67.9	2.55	<4.2	<4.2	885	37.5	2.0
Gypsum (20)	30-41	4.16	1.69	208	5.58	3261	<0.21	<0.21	0.64	96	399	36.09	55.8	3.42	<4.2	<4.2	1944	39.3	3.51
Gypsum (20)	41-51	4.41	1.66	128	4.48	2835	<0.21	<0.21	<0.42	49	402	27.18	61.4	1.11	<4.2	<4.2	1613	35.3	1.78
Gypsum (20)	51-61	4.79	1.30	141	3.94	2213	<0.21	<0.21	0.48	67	443	29.60	57.4	<1.05	<4.2	5.56	929	38.8	0.87
Gypsum (40)	0-10	5.79	1.67	41	6.73	3591	0.03	<0.21	<0.42	<2.10	269	10.79	56.9	<1.05	<4.2	<4.2	1326	38.2	<0.21
Gypsum (40)	10-20	4.99	0.63	125	6.55	1369	<0.21	0.08	<0.42	3	236	12.48	64.1	<1.05	<4.2	<4.2	361	36.7	<0.21
Gypsum (40)	20-30	4.47	0.82	213	7.32	1477	<0.21	0.14	<0.42	26	305	9.36	69.6	<1.05	7.12	<4.2	523	37.5	0.46
Gypsum (40)	30-41	4.47	0.95	199	7.01	1700	<0.21	<0.21	<0.42	58	320	10.72	74.2	<1.05	<4.2	<4.2	793	38.8	0.55
Gypsum (40)	41-51	4.34	0.85	179	7.07	2077	<0.21	<0.21	<0.42	67	318	22.19	52.8	<1.05	4.68	<4.2	1068	39.6	0.90
Gypsum (40)	51-61	4.28	0.79	252	7.81	1399	<0.21	<0.21	<0.42	61	257	44.06	52.8	1.30	<4.2	<4.2	637	39.1	2.19
4%Mg-Gy (20)	0-10	5.62	1.00	118	3.95	3957	<0.21	0.07	<0.42	<2.10	237	18.33	45.6	1.11	4.29	<4.2	1952	27.6	<0.21
4%Mg-Gy (20)	10-20	4.39	0.81	257	2.92	1499	<0.21	<0.21	0.67	10	220	15.88	59.4	<1.05	<4.2	<4.2	725	25.9	0.70
4%Mg-Gy (20)	20-30	3.95	1.08	275	4.02	1423	<0.21	0.02	<0.42	64	239	24.01	51.3	1.13	<4.2	4.69	755	28.9	1.32
4%Mg-Gy (20)	30-41	3.82	1.41	279	4.49	2952	<0.21	0.44	<0.42	77	299	61.33	66.0	3.38	<4.2	<4.2	1883	28.6	4.00
4%Mg-Gy (20)	41-51	3.84	1.19	262	6.14	1555	<0.21	0.10	<0.42	32	318	33.40	66.8	2.09	<4.2	<4.2	727	27.6	1.54
4%Mg-Gy (20)	51-61	4.00	0.77	226	4.58	1394	<0.21	0.02	0.48	20	373	36.88	62.2	1.36	<4.2	<4.2	386	28.2	1.09
4%Mg-Gy (40)	0-10	6.20	1.65	<5.67	6.08	5933	<0.21	<0.21	<0.42	7	149	34.11	64.7	<1.05	<4.2	<4.2	3341	35.4	<0.21
4%Mg-Gy (40)	10-20	4.51	0.91	122	5.02	1711	<0.21	<0.21	<0.42	7	291	15.68	56.4	1.59	<4.2	<4.2	553	42.3	<0.21
4%Mg-Gy (40)	20-30	4.36	1.06	157	5.36	2592	<0.21	<0.21	0.44	72	334	15.51	68.1	<1.05	<4.2	<4.2	1494	42.8	0.28
4%Mg-Gy (40)	30-41	4.22	0.95	132	7.27	1301	<0.21	<0.21	<0.42	47	235	39.47	73.9	1.11	<4.2	<4.2	650	45.3	0.64
4%Mg-Gy (40)	41-51	4.18	1.00	146	6.54	1305	<0.21	<0.21	<0.42	49	264	42.42	48.3	1.31	<4.2	<4.2	580	48.7	0.62
4%Mg-Gy (40)	51-61	3.78	0.89	111	6.89	824	<0.21	0.07	<0.42	50	116	18.56	64.7	<1.05	4.63	<4.2	445	45.5	0.52
lsd =		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

1:10 KCl extracts, means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac-1)

9 APPENDIX C: TABULAR DATA FROM THE AS EXPERIMENT

Table 18. Yield from harvests at the AS site.

Amendment	10/1/96	9/11/97
	--------- Mg ha^{-1}---------	
Control	0.28	0.71
Ag-Lime (20)	1.71	1.81
Gypsum (60)	1.81	1.96
4%Mg-Gy (15)	1.48	1.69
4%Mg-Gy (30)	1.67	1.81
4%Mg-Gy (60)	1.59	2.19
8%Mg-Gy (60)	1.41	2.06
12% Mg-Gy (60)	1.73	1.93
lsd =	0.43	0.48

Means of four replications

Amendment rates (ton ac^{-1})

lsd = least significant difference at 0.05 probability level.

Table 19. Chemical composition of plant tissues at the AS site, Autumn 1996.

Amendment	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	mg kg^{-1}																						
Control	435.4	<1.75	32.06	27.88	0.0298	15388	0.91	1.04	0.67	7.20	262	25565	0.50	3027	411	66.89	2.24	2508	1.87	3372	<4.65	4.54	111
Ag-L (12)	542.8	<1.75	33.19	8.36	0.0098	18293	0.17	0.42	0.88	9.22	387	26075	0.61	1861	69	58.21	0.56	2990	1.27	3500	<4.65	3.85	20.1
Gypsum (60)	539.1	<1.75	31.01	4.51	0.02	18628	0.17	0.68	0.88	8.61	386	23919	0.56	2687	103	82.37	0.66	2729	1.35	4529	<4.65	4.02	20.0
4%Mg-G (15)	427.1	<1.75	48.25	3.56	0.01	14518	0.23	0.40	0.73	7.25	302	24438	0.50	2593	95	46.72	0.64	2452	<0.95	3707	<4.65	3.59	23.2
4%Mg-G (30)	596.5	<1.75	39.45	4.41	0.0103	17597	0.19	0.76	0.92	8.89	402	26678	0.58	2537	132	78.70	0.77	2818	<0.95	4364	<4.65	4.00	23.4
4%Mg-G(60)	528.3	<1.75	58.76	4.10	0.01	14194	0.18	2.34	0.86	8.51	347	24898	0.54	3529	269	48.34	0.76	2753	1.21	4335	<4.65	3.80	23.6
8%Mg-G(60)	390.9	<1.75	54.26	3.03	<0.01	13769	0.14	0.64	0.66	9.23	266	25060	0.38	3338	64	77.42	0.52	2860	<0.95	3712	<4.65	3.62	16.0
12% Mg-G(60)	472	<1.75	53.57	3.29	<0.01	12059	0.13	0.58	0.75	10.97	289	27525	2.06	4152	61	53.10	0.43	2846	1.31	4028	<4.65	4.04	18.2
lsd =	NS	NS	18.97	13.82	NS	4,442	0.16	NS	NS	2.52	NS	NS	NS	1,390	233	NS	0.43	NS	0.69	847	NS	NS	28.5

Means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac-1)

Table 20. Chemical composition of plant tissues at the AS site, Autumn 1997

Amendment	Al	As	B	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe	K	Li	Mg	Mn	Na	Ni	P	Pb	S	Se	Si	Zn
	mg kg^{-1}																						
Control	982	<1.75	11.14	30.80	0.03	7678	0.67	0.89	1.06	7.34	595	15960	1.19	2047	346	50	1.92	2468	2.08	2724	<4.65	6.17	52.7
Ag-L (12)	616	<1.75	23.56	10.64	0.01	14958	0.19	0.39	1.00	11.13	488	24431	0.79	2319	125	108	1.01	3546	1.00	3939	<4.65	2.85	29.8
Gypsum (60)	681	<1.75	19.24	8.22	0.01	14360	0.16	0.46	1.01	11.68	499	23506	1.38	2799	145	103	0.72	3535	0.48	4085	<4.65	2.79	26.9
4%Mg-G (15)	342	<1.75	23.85	6.64	<0.01	12237	0.18	0.35	0.60	11.03	233	26436	0.55	2344	155	76	0.79	3467	0.39	4223	<4.65	3.69	34.6
4%Mg-G (30)	386	<1.75	23.21	6.12	0.00	14721	0.20	0.28	0.65	11.17	277	26005	0.45	2289	178	90	0.73	3660	<0.95	4305	<4.65	3.22	29.2
4%Mg-G (60)	644	<1.75	27.43	7.14	0.00	15275	0.16	0.29	0.97	14.06	414	24218	2.63	2597	127	96	0.64	3539	0.62	4319	<4.65	2.91	29.5
8%Mg-G (60)	882	<1.75	28.34	9.08	0.00	15728	0.20	0.29	1.24	11.62	590	24379	0.96	2539	162	88	0.82	3693	0.48	4294	<4.65	3.46	26.7
12%Mg-G (60)	582	<1.75	23.51	6.42	0.01	14969	0.13	0.12	0.75	11.71	326	26160	0.84	2679	104	93	0.68	3527	0.96	4183	<4.65	3.22	24.1
lsd =	192	NS	NS	5.86	0.46	NS	0.24	0.38	0.23	1.54	NS	NS	NS	NS	97	NS	0.25	390	NS	755	NS	NS	8.1

Means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac-1)

Table 21. Chemical composition of *M* KCl from soil cores at the AS site, Spring 1996.

Amendment	Depth	pH	EC	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Na	Ni	P	Pb	S	Si	Zn
	cm		dS m^{-1}	mg/kg															
Control	0-10	4.35	0.72	174	11.0	1768	0.84	<0.42	<0.42	22.8	98	8.71	25.5	<1.05	<4.2	7.21	1210	0.13	2.22
Control	10-20	4.01	0.27	315	11.0	190	0.39	<0.42	<0.42	14.5	65	4.36	18.3	<1.05	<4.2	6.87	142	0.39	1.70
Control	20-30	4.13	0.20	355	11.0	290	<0.21	<0.42	<0.42	10.5	78	4.45	25.8	<1.05	<4.2	4.92	123	1.93	0.76
Control	30-41	4.17	0.11	386	9.6	238	0.36	<0.42	<0.42	17.0	125	5.34	24.8	<1.05	<4.2	7.49	78	2.03	0.86
Control	41-51	4.37	0.09	300	8.7	304	<0.21	<0.42	<0.42	28.9	205	17.05	31.8	<1.05	<4.2	9.66	62	2.46	0.63
Ag-Lime (12)	0-10	6.21	1.57	<5.67	13.3	10635	0.29	<0.42	<0.42	<2.10	221	3.62	5.5	<1.05	<4.2	1.61	7798	0.67	0.32
Ag-Lime (12)	10-20	3.94	0.31	504	9.5	390	0.68	<0.42	<0.42	14.3	96	9.14	24.0	<1.05	<4.2	4.61	262	2.17	1.48
Ag-Lime (12)	20-30	4.07	0.22	400	9.8	378	0.34	<0.42	<0.42	8.9	171	7.28	25.7	<1.05	<4.2	6.77	147	2.93	0.75
Ag-Lime (12)	30-41	4.21	0.11	363	9.8	338	0.56	<0.42	<0.42	5.5	224	6.74	27.8	<1.05	<4.2	7.55	67	3.99	0.40
Ag-Lime (12)	41-51	3.26	0.05	261	7.3	338	0.54	<0.42	<0.42	5.1	297	5.48	22.9	1.51	<4.2	<4.2	24	3.00	0.90
Gypsum (60)	0-10	6.39	2.43	<5.67	14.8	13522	0.31	<0.42	<0.42	<2.10	521	1.81	3.8	<1.05	<4.2	6.23	11056	0.16	0.14
Gypsum (60)	10-20	3.91	0.86	344	10.0	574	0.35	<0.42	<0.42	12.1	145	7.19	15.8	<1.05	<4.2	6.35	466	0.31	1.31
Gypsum (60)	20-30	3.92	0.31	421	9.5	297	<0.21	<0.42	<0.42	13.2	149	5.06	23.3	1.06	<4.2	10.86	195	1.03	0.48
Gypsum (60)	30-41	4.02	0.22	380	10.1	311	0.30	<0.42	<0.42	3.7	169	4.08	27.7	<1.05	<4.2	8.69	117	1.81	0.37
Gypsum (60)	41-51	4.07	0.30	294	10.4	464	0.24	<0.42	<0.42	20.4	277	8.89	23.4	<1.05	<4.2	6.45	189	1.68	1.19
4%Mg-G (15)	0-10	5.97	2.25	18	14.0	12680	0.30	<0.42	<0.42	7.3	345	2.27	8.1	1.07	<4.2	<4.2	9806	2.08	1.28
4%Mg-G (15)	10-20	4.06	0.97	272	9.2	676	0.31	<0.42	<0.42	21.7	266	3.34	25.5	<1.05	<4.2	5.45	530	2.13	0.57
4%Mg-G (15)	20-30	3.98	0.56	474	10.2	366	0.96	0.634	<0.42	13.5	231	6.85	25.3	<1.05	<4.2	5.52	299	2.77	1.53
4%Mg-G (15)	30-41	4.00	0.27	447	10.5	421	0.92	<0.42	<0.42	14.9	209	5.07	29.9	<1.05	<4.2	6.09	225	3.48	1.44
4%Mg-G (15)	41-51	3.08	0.41	257	6.7	500	0.21	<0.42	<0.42	7.8	160	5.74	18.7	<1.05	<4.2	5.91	233	2.42	0.56
4%Mg-G (30)	0-10	5.98	1.80	26	12.2	6931	0.32	<0.42	<0.42	2.2	197	2.32	16.0	<1.05	<4.2	<4.2	4633	0.38	0.32
4%Mg-G (30)	10-20	4.03	0.47	300	11.3	535	<0.21	<0.42	<0.42	15.4	117	4.87	17.5	<1.05	<4.2	5.92	278	0.44	0.82
4%Mg-G (30)	20-30	4.29	0.30	355	10.8	423	0.40	<0.42	<0.42	6.0	132	4.05	24.4	<1.05	<4.2	10.84	165	1.21	0.59
4%Mg-G (30)	30-41	4.42	0.15	322	10.4	416	0.28	<0.42	<0.42	6.1	120	3.42	17.7	<1.05	<4.2	6.58	133	1.17	0.34
4%Mg-G (30)	41-51	4.50	0.15	290	9.8	316	0.54	<0.42	<0.42	2.3	176	10.56	13.2	<1.05	<4.2	6.52	77	1.67	1.24
4%Mg-G (60)	0-10	6.59	2.51	<5.67	16.6	14614	0.36	<0.42	<0.42	<2.10	717	3.88	7.4	<1.05	<4.2	<4.2	12067	0.82	0.52
4%Mg-G (60)	10-20	3.96	0.70	323	10.2	627	0.44	<0.42	<0.42	34.6	163	11.01	23.6	<1.05	<4.2	8.38	428	2.61	1.06
4%Mg-G (60)	20-30	3.98	0.33	469	10.7	392	0.30	<0.42	<0.42	19.9	168	7.93	24.2	<1.05	<4.2	7.91	210	2.78	1.25
4%Mg-G (60)	30-41	4.14	0.17	386	11.6	306	0.53	<0.42	<0.42	10.5	202	7.29	39.1	<1.05	<4.2	9.11	101	3.94	1.59
4%Mg-G (60)	41-51	3.19	0.12	228	8.5	277	0.29	<0.42	<0.42	8.2	194	5.01	24.6	<1.05	<4.2	7.15	78	2.77	0.81
8%Mg-G (60)	0-10	5.43	1.72	98	12.5	8990	0.55	<0.42	<0.42	7.2	257	5.70	9.1	<1.05	<4.2	4.31	7068	1.38	0.47
8%Mg-G (60)	10-20	4.02	0.67	368	9.8	445	<0.21	<0.42	<0.42	10.0	194	4.78	28.6	<1.05	<4.2	5.88	398	1.84	1.19
8%Mg-G (60)	20-30	4.16	0.32	385	10.4	267	0.35	<0.42	<0.42	19.9	189	4.13	19.7	<1.05	<4.2	5.07	149	2.41	0.98
8%Mg-G (60)	30-41	4.20	0.22	338	10.5	402	0.55	<0.42	<0.42	9.1	255	5.36	23.0	<1.05	<4.2	6.90	131	2.88	0.46
8%Mg-G (60)	41-51	3.36	0.13	233	7.0	430	0.31	<0.42	<0.42	6.1	372	7.66	30.7	<1.05	<4.2	<4.2	53	3.35	0.40
12%Mg-G (60)	0-10	6.57	2.62	<5.67	17.5	15421	<0.21	<0.42	<0.42	<2.10	668	1.48	5.3	<1.05	<4.2	<4.2	12600	0.95	0.46
12%Mg-G (60)	10-20	4.00	0.89	207	14.3	5303	0.25	<0.42	<0.42	9.0	360	3.38	15.5	<1.05	<4.2	5.52	4323	0.49	0.71
12%Mg-G (60)	20-30	3.90	0.41	463	11.6	348	<0.21	<0.42	<0.42	40.5	161	5.72	28.6	<1.05	<4.2	6.02	221	1.65	1.03
12%Mg-G (60)	30-41	3.91	0.66	324	11.8	566	0.23	<0.42	<0.42	11.0	178	6.32	39.7	<1.05	<4.2	7.49	339	0.88	0.67
12%Mg-G (60	41-51	2.05	0.57	116	6.5	511	0.24	<0.42	<0.42	29.7	113	5.48	16.3	<1.05	<4.2	<4.2	287	0.90	<0.21
lsd =		0.54	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

1:10 KCl extracts, means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac^{-1})

Table 22. Chemical composition of *M* KCl extracts from soil cores at the AS site, Autumn 1997.

Amendment	Depth cm	pH	EC dS m^{-1}	Al	B	Ca	Cd	Cr	Cu	Fe	Mg	Mn	Na	Ni	P	Pb	S	Si	Zn
				----	----	----	----	----	----	----	mg/kg	----	----	----	----	----	----	----	----
Control	0-10	4.19	0.22	263	3.04	525	<0.21	<0.42	<0.42	13	70	21.04	21.4	1.25	<4.2	7.99	69	15.79	2.38
Control	10-20	4.23	0.20	287	3.37	396	<0.21	0.42	1.50	22	65	9.09	24.9	1.11	<4.2	11.12	92	20.16	1.21
Control	20-30	3.97	0.15	427	2.40	255	<0.21	0.62	0.75	19	72	6.58	14.6	1.56	<4.2	6.81	102	18.44	1.31
Control	30-41	3.98	0.14	515	3.14	246	<0.21	<0.42	0.64	15	96	7.23	43.7	2.07	<4.2	7.30	103	19.67	1.56
Control	41-51	4.12	0.11	476	3.01	333	<0.21	<0.42	0.47	15	154	6.96	37.7	1.63	<4.2	8.15	88	23.27	1.19
Ag-Lime (12)	0-10	5.97	0.50	<5.67	6.07	2366	<0.21	<0.42	<0.42	<2.10	122	7.42	15.9	4.27	6.13	<4.2	192	15.78	<0.21
Ag-Lime (12)	10-20	5.30	0.41	14	5.19	1534	<0.21	<0.42	<0.42	2	126	12.24	6.5	<1.05	<4.2	<4.2	166	14.73	<0.21
Ag-Lime (12)	20-30	4.44	0.37	191	4.98	888	<0.21	<0.42	<0.42	28	97	11.64	34.1	<1.05	<4.2	<4.2	180	16.52	0.28
Ag-Lime (12)	30-41	4.28	0.23	298	4.69	777	<0.21	<0.42	<0.42	14	112	15.71	32.1	<1.05	<4.2	<4.2	153	17.52	<0.21
Ag-Lime (12)	41-51	4.13	0.24	352	3.74	683	<0.21	<0.42	<0.42	12	143	13.70	25.5	1.57	<4.2	<4.2	163	18.01	<0.21
Gypsum (60)	0-10	5.56	1.86	<5.67	2.98	5457	<0.21	<0.42	<0.42	<2.10	112	5.89	2.8	<1.05	<4.2	<4.2	3107	10.37	<0.21
Gypsum (60)	10-20	4.94	1.38	17	2.29	2608	<0.21	<0.42	<0.42	6	128	13.54	38.5	<1.05	<4.2	<4.2	1125	11.05	<0.21
Gypsum (60)	20-30	4.21	0.59	277	3.39	1259	<0.21	0.46	0.44	10	139	12.73	23.1	<1.05	<4.2	8.28	410	13.28	<0.21
Gypsum (60)	30-41	4.16	0.64	374	2.82	1026	<0.21	<0.42	<0.42	14	178	8.48	14.9	1.43	<4.2	9.46	361	14.21	0.29
Gypsum (60)	41-51	4.23	0.51	337	3.82	899	<0.21	<0.42	<0.42	22	252	7.48	37.4	1.36	<4.2	10.09	299	18.19	<0.21
4%Mg-G (15)	0-10	5.53	1.86	14	7.49	11029	<0.21	<0.42	<0.42	6	133	6.53	25.8	<1.05	<4.2	<4.2	7812	17.25	<0.21
4%Mg-G (15)	10-20	4.67	1.51	77	3.95	3030	<0.21	<0.42	<0.42	12	96	5.37	22.6	<1.05	<4.2	<4.2	1730	18.50	<0.21
4%Mg-G (15)	20-30	4.06	1.00	383	3.76	1300	<0.21	<0.42	<0.42	14	95	4.25	20.6	<1.05	<4.2	<4.2	712	18.97	0.49
4%Mg-G (15)	30-41	4.00	1.07	413	3.74	1278	<0.21	<0.42	<0.42	14	108	4.91	30.0	1.74	<4.2	<4.2	720	19.70	0.61
4%Mg-G (15)	41-51	4.00	1.12	426	3.50	1325	<0.21	<0.42	<0.42	13	149	8.27	29.0	3.25	<4.2	<4.2	705	19.45	0.71
4%Mg-G (30)	0-10	6.22	1.94	<5.67	10.41	19136	<0.21	0.43	<0.42	<2.10	135	8.07	2.6	<1.05	<4.2	<4.2	14243	17.62	<0.21
4%Mg-G (30)	10-20	4.91	1.76	71	6.19	6095	<0.21	<0.42	<0.42	9	74	9.09	3.7	<1.05	<4.2	5.92	4219	16.31	<0.21
4%Mg-G (30)	20-30	4.11	1.25	343	5.27	2137	<0.21	<0.42	<0.42	10	79	9.24	14.7	1.08	<4.2	4.65	1334	18.42	0.66
4%Mg-G (30)	30-41	3.94	1.20	511	4.09	1363	<0.21	0.43	<0.42	10	123	7.80	30.0	1.77	<4.2	9.15	832	19.15	0.63
4%Mg-G (30)	41-51	3.95	1.13	508	3.75	1738	<0.21	0.64	<0.42	14	181	7.75	24.3	2.33	<4.2	9.66	1083	21.80	0.75
4%Mg-G (60)	0-10	6.59	1.96	<5.67	10.54	20044	<0.21	<0.42	<0.42	<2.10	177	3.43	-0.7	<1.05	<4.2	<4.2	15239	15.14	<0.21
4%Mg-G (60)	10-20	5.80	1.92	<5.67	6.97	7795	<0.21	<0.42	<0.42	11	171	7.36	10.2	<1.05	<4.2	<4.2	5324	15.66	<0.21
4%Mg-G (60)	20-30	4.57	1.52	122	6.64	2965	<0.21	<0.42	<0.42	14	146	7.20	15.0	<1.05	<4.2	<4.2	1881	18.50	<0.21
4%Mg-G (60)	30-41	4.23	1.41	235	4.56	2912	<0.21	<0.42	<0.42	16	156	9.50	29.2	<1.05	<4.2	<4.2	1883	17.82	0.34
4%Mg-G (60)	41-51	4.11	1.54	310	4.68	2826	<0.21	<0.42	<0.42	10	186	8.55	17.4	1.68	<4.2	<4.2	1749	21.58	0.57
8%Mg-G (60)	0-10	6.65	2.00	<5.67	8.39	18869	<0.21	<0.42	<0.42	<2.10	153	1.58	2.9	<1.05	8.56	<4.2	14229	17.40	<0.21
8%Mg-G (60)	10-20	5.29	1.70	44	4.00	7055	<0.21	<0.42	<0.42	8	152	5.05	2.0	<1.05	<4.2	<4.2	4933	15.05	<0.21
8%Mg-G (60)	20-30	4.72	1.35	150	3.39	2837	<0.21	<0.42	<0.42	20	166	5.01	1.6	<1.05	<4.2	<4.2	1774	15.82	<0.21
8%Mg-G (60)	30-41	4.59	1.26	219	3.45	2704	<0.21	<0.42	<0.42	12	190	4.40	25.8	1.40	<4.2	4.44	1759	15.83	<0.21
8%Mg-G (60)	41-51	4.19	1.17	288	2.72	1523	<0.21	<0.42	<0.42	11	222	6.65	17.2	2.55	4.42	5.96	922	17.66	<0.21
12%Mg-G (60)	0-10	6.45	1.98	<5.67	9.60	19063	<0.21	<0.42	<0.42	<2.10	191	0.66	3.0	<1.05	5.39	<4.2	14272	15.41	<0.21
12%Mg-G (60)	10-20	5.92	1.95	<5.67	5.41	5658	<0.21	<0.42	<0.42	6	179	1.73	14.5	<1.05	<4.2	<4.2	3364	13.04	<0.21
12%Mg-G (60)	20-30	5.03	1.64	108	4.06	3167	<0.21	<0.42	<0.42	6	203	3.06	9.5	<1.05	<4.2	<4.2	1789	13.47	<0.21
12%Mg-G (60)	30-41	4.56	1.27	214	5.29	2298	<0.21	<0.42	<0.42	24	214	4.04	9.1	1.30	<4.2	<4.2	1297	13.42	<0.21
12%Mg-G (60)	41-51	4.29	0.94	328	4.47	1521	<0.21	<0.42	0.48	26	228	4.57	26.9	1.25	<4.2	<4.2	811	20.37	0.79
lsd =		0.54	NS	129.00	2.77	2830	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	2205	NS	NS

1:10 KCl extracts, means of four replications

lsd = least significant difference at 0.05 probability level.

Amendment rates (ton ac-1)