THE USE OF GYPSUM AND A COAL DESULFURIZATION BY-PRODUCT TO AMELIORATE SUBSOIL ACIDITY FOR ALFALFA GROWTH

A Dissertation

by

DENNIS JOHN CHESSMAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2003

Major Subject: Agronomy

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Approved as to style and content by:

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December 2003

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ABSTRACT

The Use of Gypsum and a Coal Desulfurization By-product to Ameliorate Subsoil
Acidity for Alfalfa Growth. (December 2003)
Dennis John Chessman, B.S., Stephen F. Austin State University;
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Acid soils limit the growth of aluminum-(Al) sensitive crops such as alfalfa (*Medicago sativa* L.). Management of acid subsoils can be difficult due to physical and economic constraints. Field experiments were conducted at two locations to evaluate the effectiveness of surface-applied gypsum and a flue gas desulfurization by-product for reducing the toxic effects of acid subsoils on alfalfa. The materials were applied at rates of 0, 5, 10, and 15 Mg ha^{-1}. In addition, a glasshouse experiment was conducted that used 0, 5, and 10 Mg ha^{-1} of gypsum only. Field studies were concluded 41 and 45 months after treatment application at the two locations. No effect of material on alfalfa yield or tissue mineral concentration was observed. Also, rate did not affect yield. However, there were differences in plant tissue mineral concentration in several harvests that were related to rate. Soil was sampled periodically to 120 cm and indicated movement of Ca and S into the soil profile to depths of 60 and 120 cm, respectively. Subsoil pHH_2O and $pHCaCl_2$ were not affected by treatment. Extractable and exchangeable Al were not reduced by movement of Ca and S into the soil. In the glasshouse study, alfalfa yields and root growth were not affected by gypsum rate. As gypsum rate increased, plant tissue S increased, but K and Mg decreased. Alfalfa roots did not grow below 60 cm, even though there was indication of material movement to 90 cm in the soil. Although sulfur moved to 75 cm, no effect on soil Al was observed. Leachate collected from the bottoms of columns indicated that soil cations were leached as a result of gypsum application. Gypsum and the flue gas desulfurization by-product did not significantly affect the acid soils used in these studies or improve alfalfa growth.

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CHAPTER I

INTRODUCTION

Soils of the Coastal Plain of the United States are predominantly Ultisols that are characterized as highly weathered and acidic (Buol et al., 1973). Acidity in these soils is primarily due to leaching of basic cations by rainfall averaging 1140 mm or more. On cultivated soils established to introduced forages, such as hybrid bermudagrasses, nitrification of ammonium sources of fertilizer nitrogen (N) contributes significant acidity to these soils. A primary detrimental aspect of acid soils is increased solubilization of aluminum (Al) at pH below 5.5 (Lindsay, 1979; Stumm and Furrer, 1987). In strongly acid soils, aluminum hydroxide minerals such as gibbsite react with free protons to release soluble Al^{3+} (Sposito, 1989). This form of Al is phytotoxic. Growth of sensitive plant roots into soils that contain phytotoxic levels of soluble aluminum is inhibited, thereby limiting water and nutrient uptake. Plant species and varieties differ in susceptibility to Al, and various mechanisms for this tolerance have been suggested (Bennet and Breen, 1991; Delhaize and Ryan, 1995).

Agriculture in the southern U.S. is predominantly grass-based forage production, with 24 million ha of perennial grass pasture being grown (Ball et al., 2002). Bermudagrass [*Cynodon dactylon* (L.) Pers.] and bahiagrass (*Paspalum notatum* Fluegge) are the most important warm season forages being grazed and harvested as hay across the region. In particular, the improved bermudagrasses can be highly productive and provide high nutritive value forage. An adaptive characteristic of bermudagrass and bahiagrass that, at least in part, has contributed to their successful use in the South is their high tolerance of acid soils (Rechcigl et al., 1993). However, for both species to maintain yield and nutritive value, nitrogen fertilizer must be applied regularly. As a result, soil acidity is increased.

Alfalfa (*Medicago sativa* L.) is a perennial herbaceous legume native to central Asia. Its importance as a forage crop is indicated by alfalfa commonly being referred

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to as the “Queen of Forages.” With good management, it is typically higher in protein and digestible energy than perennial grasses. Therefore, it is often preferred by farmers and ranchers who produce animals needing high nutritive value forage. An additional benefit of alfalfa is its ability to form a symbiotic relationship with bacteria of the genus *Rhizobium* which fix atmospheric nitrogen in nodules on plant roots that is then made available to the plant. Elimination of the need for nitrogen fertilizer inputs becomes increasingly significant as natural gas and therefore nitrogen fertilizer prices increase.

Historically, alfalfa production in the southeastern United States has been limited by the warm humid climate, infertile acid soils, and lack of grazing tolerance in the plants. ‘Alfagraze’ is a grazing-tolerant variety adapted to the climate and management systems typical of the Coastal Plain (Bouton et al., 1991). However, soil conditions related to acidity remain a serious constraint to alfalfa production (Haby et al., 1997). As is the case with most legumes, alfalfa roots are particularly sensitive to soluble Al (Joost and Hoveland, 1986; Baligar et al., 1989; Staley et al., 1989). This has been true regardless of variety, and selection for alfalfa varieties with tolerance to acid soils has met with only limited success (Bouton et al., 1986).

Surface acidity can usually be managed with applications of limestone ($CaCO_3$). However, limestone does not readily solubulize (15.3 mg L^{-1} in cold water), so surface applications have limited effect below the surface horizon (Pavan et al., 1984; Conradie, 1995). The pH of Coastal Plain soils typically decreases with depth in the profile, and can be below pH 5.5, thus containing phytotoxic levels of Al^{3+} (Sumner, 1995). Therefore, management of subsoil acidity becomes a concern for production of Al-sensitive crops on these soils. It is possible in some situations to incorporate limestone below surface layers with deep tillage equipment (Hammel et al., 1985). Deep tillage may not be an option because of soil physical constraints, the cost of specialized tillage equipment or the high power requirement to move the tillage implement through possibly one meter of soil.

With the benefits of limestone applications being primarily restricted to the soil zone of application, other more soluble materials may prove beneficial for ameliorating subsoil acidity. Surface application of a soluble material that can affect subsurface layers and ameliorate the deleterious effects of low pH should be more economical than deep incorporation of limestone or other materials. Gypsum, or calcium sulfate ($CaSO_4$), is a mineral associated with sedimentary deposits that is used in the building industry to manufacture wallboard and cement. It is more soluble than limestone (241 mg L^{-1} in water), and slowly solubilizes when applied to the soil surface. The dissociated calcium (Ca^{2+}) and sulfate (SO_4^{2-}) ions then move in a series of exchanges through the soil profile with water.

Sulfur dioxide (SO_2) emissions resulting from industrial processes are the most significant anthropogenic contribution to acid rain (Schlesinger, 1997). Coal combustion products (CCPs) are a group of varied materials that are byproducts of electricity generation by coal burning and efforts to remove SO_2 and other pollutants from stack gases. Flue gas desulfurization (FGD) byproducts are a specific class of CCPs that are produced when gas in the stacks of coal- or lignite-fired electric generators is scrubbed with limestone slurry (limestone + water) to remove SO_2 (Ritchey et al., 1997). Highly oxidized FGD by-products will consist primarily of $CaSO_4$, and have been utilized as a source of byproduct gypsum for industrial use and land application. The reaction of SO_2 and the limestone slurry in the FGD process is as follows:

$$SO_2 + CaCO_3 + \frac{1}{2}O_2 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

If oxidation is not complete, the by-product will contain some calcium sulfite ($CaSO_3^-$) as follows (Norton, 1995):

$$SO_2 + CaCO_3 \rightarrow CaSO_3^- + CO_2$$

Therefore, the less oxidized the FGD by-product, the greater the proportion of $CaSO_3^-$. Calcium sulfite can generate sulfur dioxide gas, which at sufficiently high concentrations is toxic to aboveground plant tissue (Windholz, 1976). However, high calcium sulfite materials still have the potential to be used as agricultural amendments since, over time, $CaSO_3^-$ oxidizes to $CaSO_4$ when exposed to air (Ritchey et al., 1994). If high calcium sulfite materials are soil applied, sufficient time must be allowed for oxidation to occur before planting or plant emergence.

Alfalfa could provide an option for livestock producers and dairy farmers in the southeastern United States who require high nutritive value forage. However, acid subsoils and the resulting high levels of soluble Al inhibit alfalfa growth. The effect of surface applications of gypsum and coal desulfurization by-products for the amelioration of acid Coastal Plain soils has not been adequately investigated. Therefore, research was conducted to evaluate the effects of surface treatment with gypsum and a by-product on soil parameters and alfalfa growth on three representative Coastal Plain soils.

CHAPTER II

LITERATURE REVIEW

Subsoil Acidity and Aluminum Toxicity

Subsoil acidity resulting from high rainfall and leaching of basic cations from the soil affects a large area of the humid tropics and subtropics, including the southeastern United States (Sumner, 1995). In these soils, surface charge is highly pH-dependent, and cation exchange capacity is low due to weathering of primary soil minerals. This leads to further loss of potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions (Fox et al., 1991). Although acid soils predominate in the world's humid regions, temperate environments also contain vast areas with acid subsoils (Farina, 1997). Some of these low pH conditions have resulted from long-term use of nitrogen fertilizers and other anthropogenic sources (Sumner, 1991). Soils arising from marine shale parent material can also develop acid subsoils without regard to the degree of weathering (McKenzie and Nyborg, 1984).

At low pH, metals can be solubilized and exist at phytotoxic levels in soil solution. In addition, Kidd and Proctor (2001) recently demonstrated that the high concentration of H^+ ion in soil solution that is responsible for acid soil conditions can be implicated in direct toxicity to plant roots. They found that native populations of the grass, *Holcus lanatus* L. and the tree, *Betula pendula* Roth. had developed race-specific tolerance to Al^{3+} or H^+ depending on soil characterisitics associated with the area where seed were collected. Plants growing in organic soils showed direct toxicity to H^+, while those found on mineral soils were more H^+ tolerant. Increased solubulization of manganese (Mn) is also a concern in acid subsoils where Mn-sensitive crops are grown (Vega et al., 1992). Hue et al. (2001) found a significant negative correlation between pH and water soluble Mn in a Hawaiian Oxisol. Applications of gypsum to these soils were effective in reducing the phytotoxic effects of Mn on soybean [*Glycine max* (L.) Merr.]. Copper (Cu) can reach phytotoxic levels at low soil pH. Additions of Ca as $CaCO_3$ or $CaSO_4$ ameliorated the effects of toxic levels of Cu on orange trees (Alva et al., 1983). In both the Hue et al. (2001), and Alva et al. (1983) works cited above, trace element phytoxicity was reduced by increased calcium levels in the root zone. Although pH-related phytotoxicity due to high levels of trace metals can be important for particular plant species, root inhibition due to high levels of soluble subsoil Al remains the most significant constraint to plant growth on acid soils (Matsumoto, 2000).

Soil Al chemistry is complex and closely associated with pH (Kinraide, 1991). Solubulization of Al that occurs at soil pH below 5.0 – 5.5 has been shown to inhibit growth in Al sensitive plants. As soil pH decreases below 5.5, the Al^{3+} form of aluminum becomes more prevalent in solution (McBride, 1994). The Al^{3+} ion has been implicated as the primary contributor to aluminum toxicity (Blamey et al., 1983). In addition to Al^{3+}, aluminum can exist in soils in complex with other ions including fluoride (F^-) and sulfate (SO_4^{2-}). Some complexes are non-phytotoxic and complicate the task of distinguishing between Al toxic and nontoxic soils (Kinraide and Parker, 1987). Cameron et al. (1986) observed barley (*Hordeum vulgare* L.) and alfalfa root elongation in solutions with concentrations of Al^{3+}, and Al complexed with F^- and SO_4^{2-}. Seedling root growth in both species was inhibited at 1 μmol L^{-1} concentrations of Al^{3+}, but did not appear to be inhibited when F^- and SO_4^{2-} were added to the solutions. Similar results were reported for a red clover (*Trifolium pratense* L.) cultivar in the presence of Al^{3+} and $AlSO_4^+$ (Kinraide and Parker, 1987). Aluminum will also readily complex with soil phosphate. Aluminum phosphates are believed to be non-toxic to plant roots (Hue et al., 1986). Wright et al. (1989) also demonstrated that the form of soil aluminum affects phytotoxicity in wheat (*Triticum aestivium* L.). They used four different chemical extractants to measure soil Al, assuming that each of the unique solutions would represent a different Al fraction. Inhibition of growth in wheat seedling roots was only correlated with Al extracted by one of the solutions. However, speciation of Al proved difficult and their results were inconclusive. Adams and Moore (1983) found that soil horizon of occurrence greatly effects the predominant form of Al and therefore its toxicity. This is likely related to the predominant clay mineral and the degree of leaching of basic cations. In later work, Adams and Hathcock (1984) investigated whether phytotoxic Al levels in the subsoil could be predicted based on soil classification. Unlike the previous work, Al toxicity was not correlated with soil classification or zone of occurrence in the Coastal Plain soils they considered. Also, when they evaluated Al saturation, they found it was not a good predictor of Al toxicity. Therefore, soluble Al must be determined through sampling of the soil horizons of interest, use of the appropriate analysis method and possibly speciation of the Al complexes involved . Aluminum chemistry is further complicated by apparent differences that have been observed between bulk soil and rhizosphere Al^{3+} levels (Kirlew and Bouldin, 1987).

In addition to inhibiting root growth, another deleterious affect of acid subsoils and the concomitant high Al levels can be the reduction of beneficial soil bacteria. Although there are relatively acid-tolerant strains, the economically important N_2 fixing *Rhizobium* spp. are inhibited at low pH (Glenn and Dilworth, 1991). Thus nodulation and N_2 fixation of legumes dependent on these species is reduced.

Management of Subsoil Acidity and Soluble Aluminum

A variety of surface-applied or surface-incorporated materials have been successfully used to ameliorate subsoil acidity (Sumner, 1995). Although surface-applied limestone is slowly soluble with its benefits normally restricted to surface soil, in some severely weathered soils surface lime applications have resulted in increased subsoil pH and CEC (Friesen et al., 1982). Conradie (1995) evaluated the subsoil effects resulting from surface applications of three lime sources to two South African soils. Four years after treatment, KCl pH and Ca increased to 60 cm in plots treated with slaked lime ($Ca(OH)_2$). No attempt was made to determine any change in exchangeable Al or Al saturation. Deep incorporation of limestone is an approach that has been investigated for raising subsoil pH and reducing soluble Al for production of Al sensitive crops (Bouton et al., 1986; Sumner et al., 1986). Although positive results have been observed, some authors have noted that the effectiveness of deep incorporation has been limited to the zone of application (Farina and Channon, 1988a; Farina et al., 2000b).

Surface-applied gypsum, or calcium sulfate ($CaSO_4$), has been shown to reduce soluble Al in subsoil and improve soil physical characteristics (Sumner, 1993; Ritchey et al., 1995; Ritchey and deSousa, 1997; Toma et al., 1999). Hoveland (2000) marks the use of gypsum on forage lands as an important development for grass and alfalfa producers in the southern U.S. Even though widely used, the exact mode of reduction of toxic Al is not fully understood, and is likely due to several processes. It has been proposed that the gypsum-mediated reduction of toxic Al^{3+} is initiated by the exchange of SO_4^{2-} for OH^- on clay mineral surfaces followed by hydrolysis of Al^{3+} (Reeve and Sumner, 1972; Shainberg et al., 1989) as follows:

$$2\ \text{Exch-OH}^- + Ca^{2+} + SO_4^{2-} \rightarrow \text{Exch-}\ SO_4^{2-} + Ca(OH)_2$$
$$2\ Al^{3+} + 3\ Ca(OH)_2 \rightarrow 2\ Al(OH)_3 + 3\ Ca$$

In strongly acid soils, $Al(OH)_3$ can react with SO_4^{2-} to form the precipitate $AlOHSO_4$ by the following reaction (Sumner, 1993):

$$Al(OH)_3 + Ca^{2+} + SO_4^{2-} \rightarrow AlOHSO_4 + Ca(OH)_2$$

Al^{3+} is also known to form less toxic species with SO_4^{2-} as follows (Pavan et al., 1984):

$$Al^{3+} + SO_4^{2-} \rightarrow AlSO_4^+$$
$$Al^{3+} + 2\ SO_4^{2-} \rightarrow Al(SO_4)_2^-$$
$$2\ Al^{3+} + 3\ SO_4^{2-} \rightarrow Al_2(SO_4)_3$$

Rapid movement of Ca^{2+} and SO_4^{2-} after surface applications of gypsum has been observed. In a study using 10 Mg of gypsum ha^{-1} incorporated to 15 cm, McCray et al. (1991) reported Ca leaching to 80 cm after 5 mo. However, in the same plots, Al extractable in 1 *N* KCl was not reduced below 20 cm throughout the 17 mo duration of the experiment. Sumner et al. (1986) noted an increase in water-soluble Ca and a decrease in soluble Al after gypsum was surface-applied. After 4 years, alfalfa yields were increased 25% on the clayey, gypsum-treated, acid soils. Similar subsoil Ca and Al responses, including improved rooting depth, were achieved with gypsum treatments on soils planted to soybean and corn on soils with similar properties (Hammel et al., 1985). The importance of increased pH, monomeric Al species and $AlSO_4^+$ (Noble et al., 1988b), and increased Ca:Al ratio (calcium aluminum balance) (Noble et al., 1988a) in reducing phytotoxicity has been documented in high Al nutrient solutions to which $CaSO_4$ was added. Others have attributed beneficial subsoil effects of gypsum resulting from increased surface charge and corresponding retention of basic cations with a reduction of exchangeable Al (Alva et al., 1990). Glasshouse experiments utilizing gypsum on acid soils resulted in similar increased adsorption of Ca on pH-dependent charge sites and the corresponding exchange and leaching of soluble Al (Kotze and Deist, 1975; Singh, 1984).

The beneficial effects of gypsum applications can be relatively long lasting. The long-term effects of surface-applied gypsum on subsoil chemical properties have been documented on highly weathered South African soils (Farina et al., 2000b). The same authors report that maize yields from treated plots exceeded untreated plots by almost 4 Mg ha^{-1} eleven years after gypsum application (Farina et al., 2000a). Farina and Channon (1988b) reported increases in subsoil Ca, Mg, and SO_4 and decreases in exchangeable Al down to 90 cm four years after surface application of 10 Mg of gypsum ha^{-1} to a strongly acidic soil. Water pH increased, but KCl pH was not affected. Toma et al. (1999) evaluated plots where up to 35 Mg ha^{-1} of gypsum had been surface-incorporated sixteen years earlier. Exchangeable Ca and SO_4 and EC were higher down to 120 cm in the gypsum treatment. Exchangeable Al in the same plots was reduced down to 80 cm compared to the control treatment. No corresponding change in pH was observed. The two aforementioned experiments highlight an interesting aspect of gypsum and subsoil chemistry in that the effect of surface-applied gypsum on subsoil pH is not consistent with some authors reporting an increase (Ritchey et al., 1980), others a decrease (Simpson et al., 1979), while others observed no change (Pavan et al., 1984; Toma et al., 1999).

The specific role of calcium in alleviating Al toxicity has been documented (McCray and Sumner, 1990). Several authors have used solution culture experiments to demonstrate that increasing the ratio of Ca to Al is effective in reducing Al phytotoxicity in legumes (Brady et al., 1993; Yang and Chen, 2001). Rechcigl et al. (1986) demonstrated a similar relationship between solution Al and Ca for alfalfa growth. Calcium at 3 mM was required to ameliorate the detrimental effects of 0.08 mM Al regardless of solution pH. Glasshouse studies using acidic, high Al soils have also indicated positive correlation between Ca:Al ratios and root and shoot growth in several crops (Wright et al., 1987; Wright and Wright, 1987; Shamshuddin et al., 1991). Conversely, Keltjens and Dijkstra (1991) attributed a greater Al ameliorating effect to Mg than Ca in their nutrient solution experiments. Increased ionic strength due to Ca addition has been shown to improve legume root elongation in high Al solutions (Blamey et al., 1983). However, other authors have demonstrated a positive effect of high Ca levels apparently unrelated to solution ionic strength (Alva et al., 1986a, 1986b). Although their results were not conclusive, they propose that Al was excluded from roots by the presence of Ca.

Other researchers have evaluated varied materials such as sewage sludge, animal manures, and industrial byproducts as possible ameliorants of the effects of soil acidity (Hue, 1992; Cavallaro et al., 1993; Muse and Mitchell, 1995; Korcak, 1996). However, as with limestone, solubility of the products is low and the benefits were primarily restricted to the zone of application or incorporation.

Coal combustion products (CCPs) have been investigated as amendments for agricultural soils and have been shown to provide chemical and physical improvement to restrictive soils resulting in improved root distribution and plant growth (Korcak and Kemper, 1993; Korcak, 1996; Ritchey et al., 1996). Coal combustion products result from the burning of coal or lignite in electrical generating facilities. Production of CCPs has steadily increased over the past 40 years to the point where they are the third leading mineral resource produced in the United States (Stewart, 1999). Flue gas desulfurization (FGD) byproducts are a group of varied materials obtained by the removal of SO_2 from stack gasses whose specific characteristics depend on the product combusted and the desulfurization method (Korcak, 1998). Their principal constituents are sulfites, sulfates, carbonates, and hydroxides of Ca (Mattigod et al., 1990). Methods that utilize limestone slurry as the stack gas scrubber produce a sludge that is 16 to 43 percent moisture. Surface application of CCPs has resulted in improvement of subsoil chemical properties including higher pH, lower levels of soluble Al (Zaifnejad et al., 1996b), and increased leaching of Al from soil profiles (Oates and Caldwell, 1985; Wendell and Ritchey, 1996). Wendell and Ritchey (1996) also made comparisons between incorporation and surface application of several FGD byproducts. Their results relative to subsoil pH, exchangeable Al, and Al leached from columns were dependent on the material and how it was applied. Root growth and associated water and nutrient uptake were improved in wheat when various CCPs were applied to acid soils (Zaifnejad et al., 1996a). However, the flue gas desulfurization byproduct used in their study provided the least impressive results for the several plant and soil parameters measured. The FGD treatment performed significantly worse than the other materials, and only slightly better than the untreated soil. In a glasshouse study, Clark et al. (2001) looked at the effect of 15 CCPs on the ability of maize (*Zea maize* L.) to acquire nutrients from an acidic soil. At normal soil application rates, all of the CCPs improved phosphorus and magnesium uptake, and reduced phytotoxic soil Al levels.

High application rates of CCPs have been used in several studies. Growth of tall fescue (*Festuca arundinacea* Schreb.) was improved on coal mine overburden when FGD byproducts were mixed at rates up to 120 g kg^{-1} of soil (Stehouwer et al., 1995). Above that rate, plant growth was suppressed, likely due to cementing of the soil and increased salt concentration. Stehouwer et al. (1999) applied a CCP at rates up to 70 Mg ha^{-1} without negative effects on alfalfa yield. However, the authors did note dramatic differences in subsoil chemical parameters and plant response in the two Ohio soils they considered. In one soil, exchangeable subsoil Al decreased and in the other it increased. In another study, Korcak and Kemper (1993) applied a high gypsum FGD byproduct to an apple orchard at 112 Mg ha^{-1}. Eleven years after treatment, exchangeable Ca and S were higher in the treated plots from the surface to 114-cm.

An additional benefit recently reported for soil-applied CCPs is their ability to reduce soluble phosphorus. In incubation studies, water-soluble P was significantly reduced in soils where FGD by-products were incorporated, while the treatments had only limited effect on extractable or plant-available P (Stout et al., 1998). This reduction in P resulting from application of CCPs may prove timely because of the interest in reducing the movement of soluble P from agricultural fields to surface waters where it contributes to eutrophication of fresh water lakes and ponds.

Ultimately, agricultural use of CCPs should result in improved plant performance without adverse environmental impact. Although they have provided benefit, particularly in acid soils, there remain concerns related to plant growth and environmental integrity. Problems that have been identified associated with CCPs include high soluble salts (Shahandeh and Sumner, 1993), Mg and K deficiency associated with high-Ca CCPs (Clark et al., 1997), P deficiency (Adriano et al., 1978), and high concentrations of trace metals leading to plant or animal toxicity (Jastrow et al., 1981; Clark et al., 1999). An element of particular interest is boron (B), since concentrations can be high in some products (Korcak, 1998). Boron toxicity has been demonstrated with several CCPs in a variety of grass and legume crops (Walker and Dowdy, 1980; Ransome and Dowdy, 1987; Kukier et al., 1994; Zaifnejad et al., 1998). Interestingly however, LeNoble et al. (1996) demonstrated that the presence of supplemental B in an acidic subsoil mitigated the effects of toxic Al on alfalfa root growth. There is also concern regarding adverse environmental impact resulting from land application of CCPs. Although some materials can contain trace amounts of heavy metals, levels are typically much lower than sewage sludge or other industrial and municipal byproducts (Stout et al., 1988) and there is little risk for adverse environmental impact from land application when CCPs are used at rates typical for soil amendment (Adriano et al., 1980; Carlson and Adriano, 1993).

The reported soil and plant responses to gypsum and CCP applications have been highly material, site, and plant dependent. Much of this variability can be explained by differences in amendments and the inherent heterogeneous nature of soil, even on a field or research plot scale.

Alfalfa Production on Acid Soils

The low pH, high Al subsoils of the southeastern United States present a particular challenge to sustainable alfalfa production (Morris et al., 1992). Alfalfa is extremely sensitive to Al^{3+}, with seedling root growth inhibited in nutrient solutions with concentrations as low as 1 μmol L^{-1} (Cameron et al., 1986). When alfalfa was grown on soils with a range of Al levels, root and shoot N concentration, and yield were reduced by extractable Al (*N* KCl) concentrations as low as 1.5 cmol kg^{-1} (Staley et al., 1989). Only limited success has been achieved from surface application of lime to acid Coastal Plain soils for alfalfa (Rechcigl et al., 1988). The complicated nature of low soil pH and alfalfa growth was recognized early by Foy (1959). He grew alfalfa on four acid Coastal Plain soils adjusted to a range of pH levels with $CaCO_3$. Yields between soils were most different at pH below 6.0. It was concluded that differences in Al saturation, and extractable Al and Ca did not explain the yield differences, and that continued work should be done to identify the “harmful factors” in acid soils. Additionally, the beneficial effects of applying gypsum to acid soils for alfalfa growth have been known for some time (Fried and Peech, 1946). The authors achieved significant yield differences with lime and gypsum, but they agreed with Foy in his conclusions some years later that soil Ca levels were not an adequate explanation for the results.

Studies have been conducted to evaluate the effectiveness of different materials and methods for the amelioration of subsoil acidity for alfalfa production. Deep incorporation of lime was shown to reduce exchangeable Al, and increase alfalfa rooting depth and exchangeable Ca levels (Carter and Richards, 2000). Other researchers have found that placement of lime and plant nutrients in the soil profile improved alfalfa root growth and yield (Rechcigl et al., 1991). Similarly, Sumner et al., (1986) observed that deep incorporation of lime resulted in soluble Al being precipitated, and alfalfa yields increasing significantly. Surface-applied gypsum achieved similar results in the same study. Stehouwer et al. (1999) found increases in extractable calcium and magnesium to a depth of 105 cm when a coal combustion by-product was applied to the surface of two Ohio soils. However, water-soluble Al was decreased to that depth in only one soil. Little effect was seen below the zone of incorporation on the other. Wolkowski (2000) evaluated land application of crushed gypsum wallboard waste for alfalfa production on four Wisconsin soils. Positive yield responses were achieved with high rates of application at three locations. No attempt was made to track Ca^{2+} or SO_4^{2-} movement through the soil, or to monitor changes in soluble subsoil Al.

CHAPTER III

SOIL AND ALFALFA RESPONSE TO APPLICATIONS OF GYPSUM AND A FLUE GAS DESULFURIZATION BY-PRODUCT

Alfalfa's ability to be potentially high quality and relatively high yielding without nitrogen fertilization makes it an attractive forage species. Much progress has been made with selection of alfalfa varieties for pest resistance, temperature stress tolerance, and tolerance to grazing. However, acid soils continue to limit the expansion of alfalfa into regions where it could otherwise prove an important alternative to existing pasture and hay production systems. The Coastal Plain is one such area where forage production for beef cattle and other livestock occupies a large portion of agricultural land. Subsoils are commonly acidic with high levels of soluble Al. Warm season grasses such as bermudagrass and bahiagrass are common in the region at least in part because they are relatively tolerant of acid soils and the associated high Al levels. Alfalfa could have a greater place in the forage landscape of the Coastal Plain if there were an economical solution for the subsoil acidity constraints.

The effectiveness of surface applications of gypsum and coal combustion products for reducing phytotoxic subsoil Al for alfalfa production on Coastal Plain soils has not been fully investigated. Therefore, the objectives of this research are (i) to evaluate and compare the effectiveness of surface applications of gypsum and a flue gas desulfurization co-product for the amelioration of subsoil soluble aluminum on selected Coastal Plain soils, (ii) to determine the effects of the two materials on alfalfa growth, persistence, and tissue mineral concentration, (iii) to determine appropriate alfalfa production rates for the two amendments, and (iv) to monitor changes in soil properties and movement through the profile of plant nutrients including potassium, calcium, magnesium and sulfur.

Materials and Methods

Field experiments were conducted between 1999 and 2002 at two east Texas sites with highly-weathered soils to evaluate the effectiveness of surface-applied gypsum and a coal desulfurization scrubber sludge for ameliorating high subsurface Al. One site is located in Nacogdoches County on the Walter Todd Beef Farm of Stephen F. Austin State University (31.76° N, 94.66° W) on a Sacul fine sandy loam (clayey, mixed, thermic Aquic Hapludult). The other site is in Rusk County near Overton on property leased to the Texas A&M University Agricultural Research and Extension Center (32.18° N, 94.58° W) on a Cuthbert fine sandy loam (clayey, mixed thermic Typic Hapludult). The locations were selected because of subsoil conditions that have been implicated in the inhibition of alfalfa growth, particularly soil pH below 5.0 (2:1, water:soil) and 0.01 M $CaCl_2$ exchangeable Al above 2 mg kg^{-1}. Initial evaluation of the locations indicated that pH was 4.6 and 4.4, and 0.01 M $CaCl_2$ exchangeable Al was 60 and 40 mg kg^{-1} in the 90- to120-cm soil depth for the Sacul and Cuthbert soils, respectively. Initial soil analysis data for both sites are presented in Table 1.

The following descriptions of materials and methods will apply to both experimental sites unless otherwise noted. A randomized complete block experimental design with four replications was used to evaluate the effects of gypsum and flue gas desulfurization scrubber sludge on soil parameters, alfalfa growth and tissue mineral concentration. Nine Mg ha^{-1} of limestone (ECCE = 72) was applied and incorporated into the surface 10 cm using a PTO-driven rotovator in March 1999. Limestone rate was designed to raise surface pH to about 7.0, and was determined based on water pH and Adams-Evans buffer pH measured in the surface 15 cm of both sites. One yr after limestone application surface pH remained low for alfalfa growth so an additional 9 Mg ha^{-1} of agricultural grade limestone (ECCE = 60) was applied.

Approximately 15 Mg of wet, coal desulfurization scrubber sludge generated at the Martin Lake Power Plant was obtained from the Texas Utilities Electric Company

Table 1. Soil parameters by depth sampled in June 1999 in Nacogdoches Co. (Sacul fine sandy loam) and Rusk Co. (Cuthbert fine sandy loam) TX, prior to surface application of gypsum and scrubber sludge. Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil.

Location	Depth (cm)	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		mg kg^{-1}													
Nacogdoches Co.	0-15	11.8	164	2259	481	21.9	306	30.0	0.60	3.45	3.32	1.6	34	5.01	5.81
	15-30	2.9	156	860	602	20.3	103	6.7	0.74	2.21	1.65	23.0	533	3.87	5.02
	30-60	1.9	162	327	637	17.6	115	1.6	0.95	3.52	0.46	48.2	962	3.61	4.91
	60-90	1.2	198	128	799	11.7	196	0.8	1.22	4.29	0.25	60.6	1258	3.45	4.83
	90-120	2.9	201	108	822	10.5	277	5.7	1.40	4.04	0.23	62.8	1426	3.32	4.76
Rusk Co.	0-15	28.4	226	2106	213	31.4	87.7	4.50	0.42	1.48	0.29	0.7	5	5.43	5.82
	15-30	7.2	139	885	244	30.8	36.8	1.71	0.36	1.12	0.37	12.5	284	4.14	4.72
	30-60	2.4	116	568	255	36.6	23.3	1.06	0.45	1.00	0.32	22.0	393	3.99	4.59
	60-90	2.0	101	240	244	28.2	23.5	0.55	0.60	0.91	0.21	32.5	420	3.87	4.54
	90-120	1.7	108	128	258	17.0	32.9	0.49	1.04	1.15	0.22	39.7	476	3.75	4.42

lignite mine site in Gregg County, Texas in June 1999. The material was spread under a cover, periodically mixed, and allowed to dry to approximately 170 g kg^{-1} moisture. Two Mg of bagged gypsum (calcium sulfate) were obtained from a distributor in Gregg County. Relevant chemical constituents of the materials are presented in Table 2. Gypsum and scrubber sludge treatments were hand-applied to 4- by 6-m plots on 6 and 7 July 1999 at the Rusk and Nacogdoches County sites, respectively, at rates of 0, 5 10 and 15 Mg ha^{-1} on a dry wt. basis and incorporated into the surface 5 cm using a PTO-driven rotovator. Care was taken to avoid treatment contamination in adjacent plots. Hybrid pearl millet (*Pennisetum glaucum* L. R. Br.) seed was planted at 35 kg ha^{-1} to ensure soil and treatment stability until alfalfa planting.

Plant nutrients were applied throughout the experiment according to Table 3. In addition, 90 kg ha^{-1} of nitrogen as NH_4NO_3 was applied to the Rusk County and Nacogdoches County sites on 2 and 5 May 2000, respectively. It was suspected that N_2-fixation rates were low and therefore limiting plant growth. The N was applied to aid with alfalfa establishment until adequate root nodulation could be realized.

Millet was mowed and then hoed prior to planting pre-inoculated 'Amerigraze 702' alfalfa seed 0.6 cm deep in rows 18 cm apart at a rate of 28 kg ha^{-1} using a Hege drill on 25 Oct. 1999 at Nacogdoches County and 1 Nov. 1999 at Rusk County. Soil moisture was low at planting and drought continued through November at both sites. Monthly rainfall and mean temperatures from the time of treatment application until completion of the study are shown in Table 4. By April 2000 root nodulation appeared to be inadequate so *Rhizobium* inoculum was mixed with water and sprayed at rates in excess of recommendations for post-planting inoculation. Due to poor stand at the Rusk County site, alfalfa was replanted on 20 Oct. 2000 using the initial planting specifications. On the same date at Nacogdoches, sections in rows longer than 0.3 m that did not have viable plants were replanted by hand. Plant populations in all plots at both sites allowed for canopy closure at plant maturity by February 2001.

Alfalfa was harvested three times in 2000 and 2002 and four times in 2001. A Hege 211-B forage harvester was used to cut approximately 6 m^2 from the middle of each plot to a height of 5 cm. Total weight of harvested alfalfa was determined in the field. Subsamples from each plot were randomly taken during harvesting for dry matter determination after drying in a forced-air oven at 60˚C for 72 h. Dry matter yield was calculated from harvest weight, dry matter percentage and area harvested. After measurement of harvested areas, the unharvested portion of the plots was cut at a height of 5 cm and the alfalfa removed.

Samples used for dry matter determination were ground in a Udy cyclone mill to pass a 1-mm screen. Ground samples were digested with nitric acid and analyzed for P, K, Mg, Ca, S, Mn, Na, Fe, Cu, Al and Zn using ICAP (Havlin and Soltanpour, 1980). Also, plant tissue nitrogen was determined on a 200-mg sample using a Leco CN-2000 combustion analyzer that was calibrated using an alfalfa standard.

Soil was sampled on five dates at each location. Soil samples were taken at both locations in June 1999 prior to treatment application. At the Nacogdoches County site, subsequent samples were taken in August 1999, May 2000, April 2001, and March 2003. At the Rusk County site, subsequent samples were taken in August 1999, April 2000, April 2001, and November 2002. All samples were taken with a 19-mm inside diameter probe mounted on a Giddings hydraulic soil sampling unit. Four subsamples were taken in each plot at each sampling date. The August 1999 sampling at both locations was to a depth of 60 cm with the sample separated in increments of zero to 15, 15 to 30, and 30 to 60 cm. On all other dates, sampling was to 120 cm with the top 60 cm separated as the August 1999 sampling and the 60 to 120 cm depth separated at depths of 60 to 90 and 90 to 120 cm. The August 1999 sampling was two months after treatment. Therefore, any movement and effects of treatments were not expected to be observed below 60 cm at that time. Upon removal of soil cores, holes were filled with a mixture of 3 % bentonite and 97 % grade 5 blasting sand to inhibit downward movement of treatments or fertilizer in core holes.

Samples were air-dried and ground to pass through a 2 mm sieve. The Mehlich-3 extraction procedure was used to remove exchangeable bases in addition to

Table 2. Elemental composition of gypsum and scrubber sludge.

Element	Material	
	Gypsum	Sludge
	%	
Ca	25.2	28.1
S	17.5	19.9
	mg kg^{-1}	
Al	326	1435
B	–	158
Cu	13	7
Fe	204	2660
K	149	245
Mn	40	53
Mo	–	–
P	67	105
Zn	1	4
As	–	16
Ba	12	21
Cd	–	–
Co	–	–
Cr	3	7
Ni	–	–
Pb	–	–
Se	–	8

Table 3. Plant nutrients added to the Nacogdoches and Rusk County sites, 1999 to 2002.

Year	Date	P	K	Mg	S	B	Cu	Zn
		kg ha^{-1}						
		Nacogdoches County						
1999	25 Oct.	59	56	—	15	3.5	—	—
2000	5 May	—	141	—	—	—	—	—
	23 June	35	141	—	—	—	—	—
2001	7 Feb.	25	134	33	62	4.2	—	—
	1 June	—	141	—	—	—	—	—
	22 June	—	112	17	33	—	—	—
2002	22 Mar.	39	136	55	106	4.3	—	—
	29 Aug.	—	112	17	33	—	—	—
		Rusk County						
1999	22 Oct.	59	56	—	15	3.5	—	—
2000	19 Apr.	35	141	22	37	1.4	0.6	0.8
	21 June	35	141	—	—	—	—	—
2001	7 Feb.	25	134	33	62	4.2	—	—
	1 June	—	141	—	—	—	—	—
	21 June	—	112	17	33	—	—	—
2002	21 Mar.	39	136	55	106	4.3	—	—
	26 Aug.	—	112	17	33	—	—	—

Table 4. Total monthly rainfall (mm) and mean monthly temperature (°C) at Nacogdoches and Rusk Co. sites, July 1999 to Dec. 2002.

		Location			
Year	Month	Nacogdoches Co.		Rusk Co.	
		Rainfall	Temperature	Rainfall	Temperature
1999	July	42	30	92	27
	Aug.	8	31	5	29
	Sep.	9	25	69	23
	Oct.	91	20	47	18
	Nov.	10	16	6	15
	Dec.	69	11	93	10
2000	Jan.	49	12	58	10
	Feb.	47	16	37	14
	Mar.	164	18	91	16
	Apr.	194	19	120	18
	May	164	26	187	24
	June	108	27	61	25
	July	43	30	3	29
	Aug.	52	31	2	30
	Sep.	42	27	21	24
	Oct.	23	21	66	20
	Nov.	337	13	298	11
	Dec.	179	7	128	4
2001	Jan.	141	7	136	6
	Feb.	142	13	147	11
	Mar.	256	11	171	12
	Apr.	19	21	11	20
	May	109	24	222	23
	June	215	26	215	25
	July	18	29	11	28
	Aug.	47	29	84	27
	Sep.	288	25	133	22
	Oct.	122	19	77	17
	Nov.	107	17	79	15
	Dec.	105	12	168	11
2002	Jan.	60	12	62	19
	Feb.	67	10	67	8
	Mar.	128	15	137	13
	Apr.	72	22	85	18
	May	129	25	97	18
	June	107	27	149	25
	July	136	29	94	28
	Aug.	61	29	39	28
	Sep.	26	27	97	25
	Oct.	150	21	81	18
	Nov.	128	13	77	12
	Dec.	215	11	262	9

P, S, Al, Fe, Mn, Cu, and Zn (Mehlich, 1984). Extractable Al was determined using normal KCl (Bertsch and Bloom, 1996). Aluminum and manganese exchangeable in 0.01 *M* $CaCl_2$ were also determined (Hoyt and Nyborg, 1972). Filtrates of all extractions were analyzed using ICAP (Soltanpour et al., 1996). In addition, pH in a 1:2 soil to water suspension, and 1:2 soil to 0.01 *M* $CaCl_2$ were measured on all samples. Electrical conductivity was measured beginning with the 2000 samplings at both sites.

Herbicides and insecticides were applied throughout the experiment as warranted by pest pressure (Table 5). Agridox oil was added to herbicide solutions as a surfactant. Insects causing damage were common to both locations and included alfalfa weevil larvae (*Hypera postica* Gyll.), three-corned alfalfa hopper (*Spissistilus festinus* Say), and grasshoppers (*Melanoplus* spp.). Some of the more troublesome weed species managed were common bermudagrass (*Cynodon dactylon* (L.) Pers.), broadleaf signalgrass (*Urochloa platyphylla* (Munro x Wright) R. Webster), annual ryegrass (*Lolium multiflorum* Lam.), annual bluegrass (*Poa annua* L.), barnyardgrass (*Echinochloa crus-galli*), and hairy buttercup (*Ranunculus sardous* Crantz).

Analysis of variance for the effects of material and rate on yield, tissue mineral concentrations and soil parameters was performed using the General Linear Models procedure in SAS (1994). Response differences between treatment means were evaluated using the Student-Newman-Keuls (SNK) multiple comparison procedure. Soil data were analyzed to determine both differences by depth and changes at each depth during the experiment. Simple correlations of significant soil parameters at each depth with alfalfa yield and mineral concentrations for each harvest were determined using PROC CORR in SAS.

Table 5. Pesticides applied at the Nacogdoches and Rusk County sites, 2000 to 2002.

Year	Date	Pesticide	Rate
		Nacogdoches County	
2000	17 Feb.	Poast Plus[¶]	0.23 L ha^{-1}
	3 Mar.	Sevin XLR[#]	0.57 L ha^{-1}
	13 Mar.	Poast Plus + Pursuit[¥]	0.23 L ha^{-1}; 24 g ha^{-1}
	18 Aug.	Sevin XLR	0.57 L ha^{-1}
	6 Oct.	Sevin XLR	0.57 L ha^{-1}
	20 Oct.	Poast Plus	0.23 L ha^{-1}
2001	19 Feb	Poast Plus + Pursuit	0.23 L ha^{-1}; 24 g ha^{-1}
	5 Mar	Sevin XLR	0.57 L ha^{-1}
	3 Apr.	Sevin XLR	0.57 L ha^{-1}
	22 May	Poast Plus	0.23 L ha^{-1}
	29 June	Fusion[‡]	0.20 L ha^{-1}
2002	28 Jan	Treflan[ϕ]	0.76 L ha^{-1}
	20 Feb.	Sevin XLR	0.57 L ha^{-1}
	17 May	Poast Plus + Pursuit	0.23 L ha^{-1}; 24 g ha^{-1}
	29 Aug.	Poast Plus + Fusion	0.23 L ha^{-1}; 1.2 L ha^{-1}
		Rusk County	
2000	10 Feb.	Poast Plus	0.23 L ha^{-1}
	28 Feb.	Lannate L[§]	0.57 L ha^{-1}
	6 July	Sevin XLR	0.57 L ha^{-1}
2001	6 Feb	Poast Plus + Pursuit	0.23 L ha^{-1}; 24 g ha^{-1}
	9 Mar	Sevin XLR	0.57 L ha^{-1}
	3 Apr.	Sevin XLR	0.57 L ha^{-1}
	12 July	Sevin XLR	0.57 L ha^{-1}
	17 July	Fusion	0.20 L ha^{-1}
2002	11 Jan	Poast Plus	0.23 L ha^{-1}
	15 Feb.	Sevin XLR	0.57 L ha^{-1}
	21 Mar.	Sevin XLR	0.57 L ha^{-1}
	2 Apr.	Sevin XLR	0.57 L ha^{-1}
	2 July	Fury[†]	48 g ha^{-1}

[†] Fury: *s*-Cyano (3-phenoxyphenyl)methyl (±) cis/trans 3-(2,2-dichloroethenyl)-2,2 imethylchloropropane caboxylate

[‡] Fusion: Fluazifop-P-butyl {Butyl(*R*)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate} 24.15% and Fenoxaprop-P-ethyl {(+)-ethyl-2-[4-[6-(chloro-2-benzoxazolyl)oxy]phenoxy]propanoate} 6.76%

[§] Lannate L: Methomyl(S-methyl-N-[(methylcarbamoyl)oxy]-thioacetimidate)

[¶] Poast Plus: Sethoxydim [2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one

[¥] Pursuit DG: Imazethapyr (±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecaboxylic acid

[#] Sevin XLR: Carbaryl (1-napthyl N-methylcarbamate)

[ϕ] Treflan: Trifluralin α,α,α–trifluoro-2,6-dinitro-*N*, *N*-dipropyl-*p*-toluidine

Results and Discussion

Treatment Effect on Extractable Soil Elements

Sacul Soil, Nacogdoches County. Throughout the study, there were no significant effects on any measured soil parameters due to differences in gypsum and scrubber sludge. Since the effects of material were not significant, no attempt will be made to distinguish between them in the discussion. Also, for almost all measured parameters at all samplings the effect of depth was highly significant. Chemical changes in soil with depth are common and well documented. Therefore, only those differences by depth that are associated with treatment rate will be discussed.

Soil samples taken to 60 cm one month after treatment (MAT) indicated significant rate effects on Mehlich-3 extractable Ca and S (Table 6). Calcium was lowest in the zero rate plots, but the low, medium and high rates were not significantly different (Table 7). Sulfur levels increased with increasing rate. However, the low and medium rate plots were not significantly different from each other. These results were not surprising considering the amount of Ca and S in the treatment materials (Table 2). Soil pH determined in a 2:1 suspension of water to soil (pH_{H_2O}) was significantly affected by rate (Table 6). Soil pH was highest for the zero and low rate plots while the medium and high rates were significantly lower and similar to each other (Table 7). This also would be expected from the high rates of $CaSO_4$ and the resulting salt effect on pH measurement. The salt effect arises when soil solutions with relatively low salt concentrations act as cation exchangers causing a disproportionate diffusion of K^+ relative to Cl^- across the liquid junction of the pH electrode. This can result in a reduction in measured pH (Thomas, 1996). When pH was measured in 0.01 M $CaCl_2$ (pH_{CaCl_2}), there was not a significant difference between rates (Table 7). Figure 1 shows that the higher pH in the zero plots was consistent down to the 60-cm sample depth.

Table 6. Analysis of variance for the effects of gypsum and scrubber sludge at three soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in Aug. 1999.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
			x 10^3	x 10^4	x 10^4	x 10^4	x 10^4	x 10^2				x 10^2	x 10^5	x 10^{-1}	x 10^{-1}
Material (M)	1	2.99	11.08	0.65	0.20	3.35	0.14	0.12	0.23	0.56	2.64	0.41	3.35	0.13	0.21
Rate (R)	3	7.41	13.87	77.84^{*}	4.53	68.22^{***}	0.15	0.73	0.25	4.24	0.35	2.83	6.85	2.08	10.59^{**}
M x R	3	1.19	7.87	4.79	0.43	0.61	0.49	0.15	0.13	0.27	1.03	0.18	1.62	1.13	1.05
Block	3	12.39	6.51	8.61	13.52	1.73	0.30	0.19	0.69	12.96^{***}	2.44	8.15^{**}	5.57	7.54^{**}	6.91^{*}
Error (a)	21	6.26	7.01	23.70	6.97	2.86	0.24	0.35	0.34	1.48	1.13	1.05	4.73	1.53	1.50
Depth (D)	2	68.62^{***}	0.41	43.46^{***}	16.04^{***}	34.64^{***}	24.92^{***}	56.53^{***}	0.54	5.10^{***}	87.47^{***}	82.09^{***}	92.76^{***}	77.02^{***}	25.55^{***}
M x D	2	1.05	0.49	0.71	0.64	1.28	0.50^{*}	0.52	0.19	0.38	0.76	0.31	0.42	0.70	0.26
R x D	6	14.32^{**}	1.60	46.87^{*}	1.54	18.59^{***}	0.36^{*}	0.31	0.19	0.28	0.34	0.99	2.03	0.62	0.60
M x R x D	6	0.70	0.80	3.80	0.21	0.32	0.77	0.23	0.18	0.17	0.29	0.26	0.68	0.47	0.52
Error (b)	48	4.03	0.90	19.83	1.07	2.54	0.14	0.22	0.17	0.39	0.84	0.73	1.12	0.61	0.51

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 7. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in Aug. 1999.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		mg kg^{-1}													
Material	Gypsum	4.6	176	1524	645	214	172	14.3	0.97	2.09	2.08	22.1	797	4.05	4.68
	Sludge	4.9	198	1529	636	252	165	15.1	1.07	2.24	2.41	20.8	679	4.07	4.71
Rate (Mg ha^{-1})	0	5.3	159	1270^b	637	31^c	178	15.9	0.97	2.22	2.29	18.2	552	4.07	4.96^a
	5	5.1	213	1654^a	696	203^b	169	16.5	1.15	2.69	2.26	18.8	697	4.16	4.76^{ab}
	10	4.2	199	1531^a	641	258^b	168	13.3	1.05	2.07	2.24	24.0	960	3.93	4.51^b
	15	4.4	176	1651^a	589	440^a	159	13.2	0.92	1.68	2.20	24.8	742	4.07	4.53^b
Depth (cm)	0-15	10.0^a	187	2848^a	559^b	466^a	270^a	30.0^a	0.90^b	2.41	4.15^a	5.3^c	112^c	4.62^a	4.97^a
	15-30	2.6^b	183	1084^b	689^a	81^b	109^b	7.2^b	1.01^{ab}	1.70	1.40^b	21.8^b	885^b	3.86^b	4.70^b
	30-60	1.5^c	190	647^c	674^a	152^b	127^b	6.9^b	1.16^a	2.38	1.19^b	37.3^a	1217^a	3.70^c	4.40^c

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

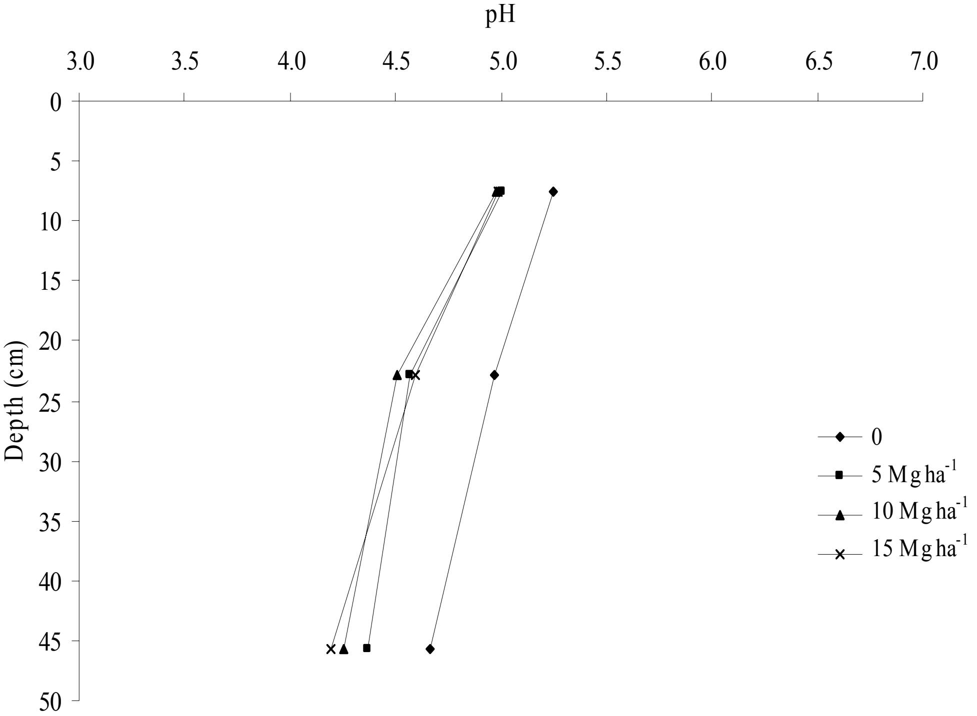


Figure 1. 2:1 water to soil pH at different depths in the Sacul soil, Nacogdoches Co. TX, 1 mo after treatment with four rates of gypsum.

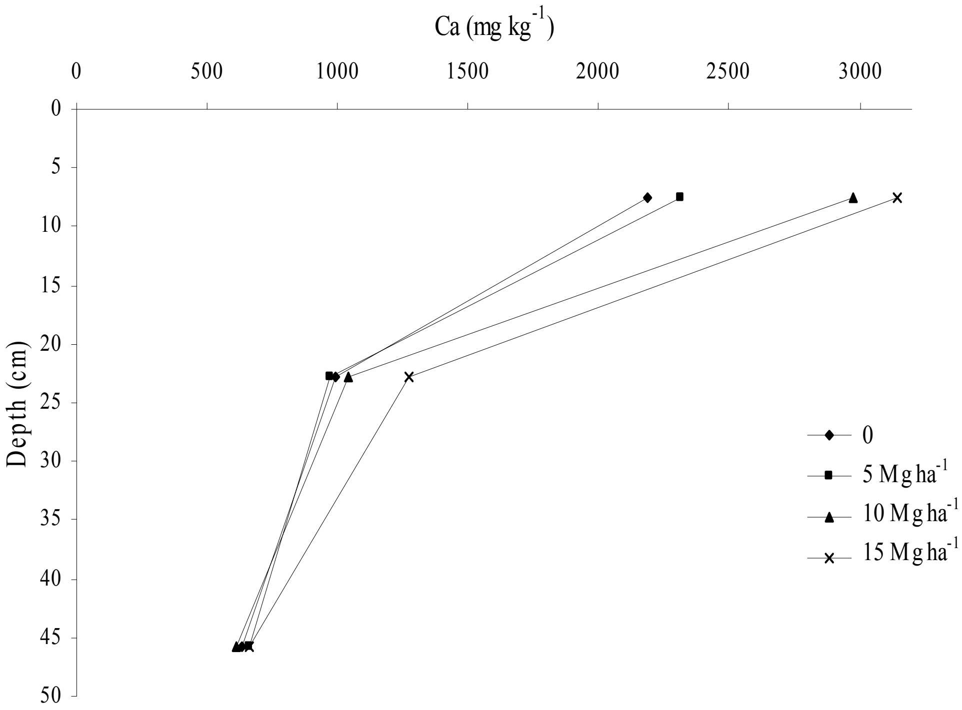


Figure 2. Mehlich-3 extractable calcium at different depths in the Sacul soil, Nacogdoches Co. TX, 1 mo after treatment with four rates of gypsum.

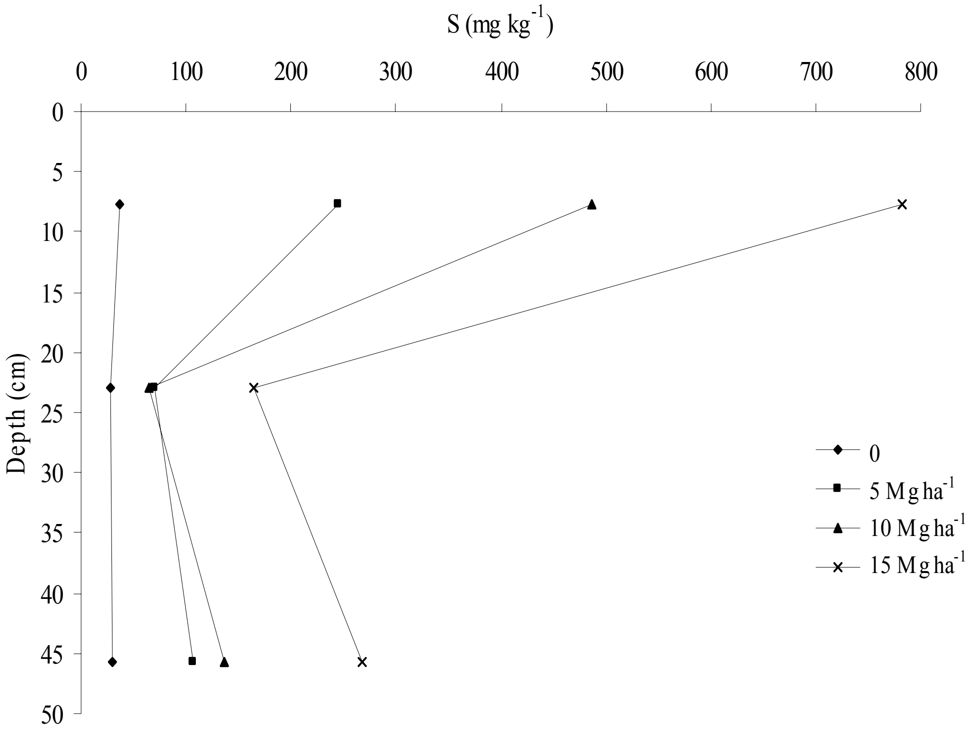


Figure 3. Mehlich-3 extractable sulfur at different depths in the Sacul soil, Nacogdoches Co. TX, 1 mo after treatment with four rates of gypsum.

There were significant rate by depth effects for P, Ca, and S (Table 6). For Ca and S, the relationship between rates was not consistent with depth. Calcium decreased with depth in all treatments (Figure 2). The medium and high rates had Ca levels in the surface 15 cm that were similar to each other as did the zero and low rates. At 15 to 30 cm the high rate was significantly greater than the other three rates. At 30 to 60 cm there was no difference in Ca levels between rates. Sulfur was highest in the surface 15 cm on plots receiving material, decreased in the 15- to 30-cm depth and then slightly increased at 30 to 60 cm (Figure 3). The high treatment rate had significantly higher S levels throughout the profile. The location received 67 mm of rain between treatment application in July 1999 and the Aug. 1999 sampling. Figures 2 and 3 indicate how readily S, and to a lesser extent Ca, in the treatments moved into the soil with the water. Mehlich-3 extractable S at 30 to 60 cm was approximately 250 mg kg^{-1} greater in the high rate than in the zero plots.

The rate effect was significant for Mehlich-3 P, Ca, S and Mn and electrical conductivity (EC) in year 2000 soil samples (Table 8). Phosphorus in the zero plots was significantly greater than in those that received gypsum or sludge (Table 9). Soil Ca levels were lower than the 1999 sampling, and only the high rate was significantly greater than the zero rate. Sulfur was also lower than in 1999, indicating continued movement through the soil profile. Although Ca and S levels averaged across all depths were lower, both were higher in the surface soil during 2000. The higher Ca levels are primarily due to application of 9 Mg ha^{-1} of limestone to all plots 6 wk before the 2000 sampling. Continued solubilization of SO_4 from the materials during the year following application is the probable cause of higher S levels in 2000. Both Ca and S in the surface layer decreased in subsequent samplings (Tables 10 and 11). All the rates had S levels significantly different from each other, increasing from the zero to the high rate. Manganese was highest in the check plots and significantly greater than in those receiving gypsum and sludge. Similar to S levels, EC increased as rate increased. This would be expected due to the increased electrolyte concentration resulting from dissolution of $CaSO_4$ (Keren, 2000). The effect of gypsum on EC can

Table 8. Analysis of variance for the effects of gypsum and scrubber sludge at five soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in May 2000.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		Mean Squares														
		x 10^{1}	x 10^{4}	x 10^{5}	x 10^{4}	x 10^{4}	x 10^{3}	x 10^{1}					x 10^{5}	x 10^{-1}	x 10^{-1}	x 10^{5}
Material (M)	1	1.69	0.20	0.47	2.46	1.98	2.66	0.26	0.31	0.34	0.16	3.26	7.40	2.88	1.83	0.62
Rate (R)	3	4.95^{*}	1.58	8.40^{**}	2.79	54.93^{***}	4.42	13.05^{**}	1.78	5.65	0.47	0.86	2.32	0.87	1.14	4.63^{***}
M x R	3	1.09	0.24	4.19	1.40	5.12	0.79	0.28	0.48	0.30	0.38	2.00	1.74	0.54	0.46	0.11
Block	3	6.30^{**}	0.97	11.83^{***}	5.52	1.11	5.83	3.78	4.38	3.75	0.92	8.21	12.85^{*}	1.88	0.28	0.47
Error (a)	21	1.14	0.56	1.69	4.10	0.68	2.92	1.71	2.15	3.65	0.80	3.05	3.89	0.98	1.01	0.16
Depth (D)	4	81.53^{***}	3.65^{***}	69.02^{***}	43.03^{***}	95.21^{***}	27.24^{***}	34.69^{***}	1.50^{*}	13.76^{***}	48.13^{***}	64.99^{***}	30.78^{***}	56.43^{***}	45.57^{***}	36.38^{***}
M x D	4	1.49	0.32	0.37	2.38	2.32^{*}	7.58^{***}	0.13	0.53	0.43	0.44	0.34	1.25	0.89	0.57	0.10
R x D	12	0.75	0.59^{**}	5.10^{***}	3.23	43.23^{***}	0.91	2.24	0.67	0.70	1.23^{**}	0.63	1.39	0.78^{*}	1.24^{**}	4.07^{***}
M x R x D	12	1.03	0.10	1.38	0.48	5.42^{***}	1.37	0.26	0.47	0.65	0.10	0.26	0.86	0.24	0.24	0.86
Error (b)	96	0.97	0.24	1.27	1.78	0.69	1.38	2.05	0.48	0.66	0.47	1.10	1.34	0.38	0.51	0.18

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 9. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in May 2000.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		mg kg^{-1}														dS m^{-1}
Material	Gypsum	5.0	181	1153	624	156	182	7.8	1.32	2.25	1.28	43.2	1052	3.90	4.63	0.26
	Sludge	5.6	174	1108	600	134	174	7.5	1.23	2.22	1.22	40.4	916	3.98	4.70	0.24
Rate (Mg ha^{-1})	0	6.9^{a}	198	1036^{b}	604	18^{d}	193	10.3^{a}	1.02	1.72	1.33	43.3	1024	3.94	4.71	0.12^{d}
	5	4.6^{b}	189	1019^{b}	650	100^{c}	175	7.3^{b}	1.24	2.46	1.33	42.3	1064	3.88	4.61	0.21^{c}
	10	4.5^{b}	166	1157^{b}	589	165^{b}	174	6.2^{b}	1.31	2.22	1.24	41.8	890	3.95	4.63	0.29^{b}
	15	5.2^{b}	156	1311^{a}	604	295^{a}	169	6.8^{b}	1.53	2.56	1.10	39.8	960	4.00	4.71	0.38^{a}
Depth (cm)	0-15	18.8^{a}	230^{a}	3662^{a}	449^{d}	583^{a}	264^{a}	25.8^{a}	1.06^{b}	2.20^{bc}	3.13^{a}	1.2^{e}	16^{e}	5.14^{a}	5.32^{a}	0.85^{a}
	15-30	2.6^{b}	149^{c}	1132^{b}	586^{c}	87^{b}	101^{c}	6.8^{b}	1.20^{ab}	1.48^{d}	1.86^{b}	24.7^{d}	742^{d}	3.91^{b}	4.45^{c}	0.18^{b}
	30-60	1.6^{b}	150^{c}	426^{c}	592^{c}	28^{c}	107^{c}	1.8^{c}	1.14^{b}	1.87^{cd}	0.53^{c}	48.4^{c}	1114^{c}	3.70^{c}	4.59^{b}	0.06^{c}
	60-90	1.4^{b}	166^{bc}	228^{d}	670^{b}	14^{c}	149^{b}	1.2^{c}	1.36^{ab}	2.42^{b}	0.34^{c}	64.6^{b}	1389^{b}	3.57^{d}	4.59^{b}	0.06^{c}
	90-120	2.2^{b}	190^{b}	205^{d}	763^{a}	11^{c}	268^{a}	2.6^{c}	1.61^{a}	3.23^{a}	0.38^{c}	70.3^{a}	1661^{a}	3.39^{e}	4.37^{c}	0.10^{c}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

Table 10. Analysis of variance for the effects of gypsum and scrubber sludge at five soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in Apr. 2001.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		Mean Squares														
		x 10^1	x 10^4	x 10^5	x 10^4	x 10^4	x 10^3	x 10^1	x 10^{-1}			x 10^2	x 10^5	x 10^{-1}	x 10^{-1}	x 10^5
Material (M)	1	1.65	0.35	0.97	2.01	0.92	15.76	3.65	0.13	3.47	1.57	4.02	3.14	1.61	3.78	0.69
Rate (R)	3	0.98	0.57	5.61^*	1.75	34.68^{***}	1.66	0.45	9.20^*	0.32	2.52	2.32	0.81	1.10	3.62	4.74^{***}
M x R	3	1.34	0.32	1.37	0.86	0.36	3.30	0.98	0.51	1.88	1.22	1.70	0.56	0.38	1.25	0.18
Block	3	0.33	0.92	2.28	4.61	0.77	0.83	3.40	33.72^{***}	19.12^{**}	8.06	69.49^{***}	28.30^{***}	0.42	1.30	1.09
Error (a)	21	1.50	0.63	1.56	3.65	1.19	4.00	1.33	2.11	2.47	2.97	5.18	3.19	1.45	1.63	0.48
Depth (D)	4	78.14^{***}	3.43^{***}	76.01^{***}	95.55^{***}	88.99^{***}	61.04^{***}	95.64^{***}	47.23^{***}	41.02^{***}	87.99^{***}	83.73^{***}	87.96^{***}	97.32^{***}	83.04^{***}	13.97^{***}
M x D	4	0.21	0.13	0.10	0.59	0.36	4.02^*	2.61^{**}	0.66	1.29	2.09	0.14	0.40	0.25	0.44	0.11
R x D	12	0.31	0.10	2.85^{***}	0.87	22.52^{***}	0.73	0.48	0.60	1.86	1.51	1.66	0.34	0.16	0.65	1.76^{***}
M x R x D	12	0.41	0.10	0.45	0.82	0.42	0.61	0.44	0.64	0.53	0.80	1.31	0.21	0.14	0.36	0.12
Error (b)	96	1.11	0.15	0.42	1.25	1.04	1.40	0.64	1.02	1.53	1.05	2.17	0.98	0.39	0.60	0.34

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 11. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in Apr. 2001.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		mg kg^{-1}														dS m^{-1}
Material	Gypsum	6.7	238	1150	633	126	215	7.6	1.42	3.15	1.80	46.2	951	3.91	4.60	0.24
	Sludge	7.3	229	1130	610	127	196	6.6	1.40	3.44	1.60	43.1	867	3.97	4.70	0.23
Rate (Mg ha^{-1})	0	6.3	223	1027^{b}	604	31^{c}	206	7.6	1.21^{b}	3.34	1.35	46.0	881	3.96	4.74	0.11^{b}
	5	7.5	242	1073^{b}	643	72^{c}	200	7.1	1.47^{ab}	3.20	1.69	43.9	942	3.95	4.71	0.19^{b}
	10	7.0	245	1189^{ab}	636	163^{b}	214	6.8	1.57^{a}	3.40	1.83	47.1	947	3.87	4.53	0.30^{a}
	15	7.2	223	1270^{a}	603	239^{a}	202	7.0	1.40^{ab}	3.23	1.92	41.7	867	3.99	4.61	0.35^{a}
Depth (cm)	0-15	26.3^{a}	228^{bc}	3316^{a}	387^{d}	415^{a}	273^{b}	23.7^{a}	1.09^{d}	3.24^{bc}	4.23^{a}	3.0^{d}	18^{e}	5.26^{a}	5.55^{a}	0.60^{a}
	15-30	4.4^{b}	195^{d}	1282^{b}	565^{c}	126^{b}	127^{d}	7.2^{b}	1.05^{d}	1.95^{d}	2.54^{b}	25.1^{c}	581^{d}	4.01^{b}	4.53^{b}	0.23^{b}
	30-60	1.9^{c}	217^{c}	545^{c}	600^{c}	51^{c}	135^{d}	2.3^{c}	1.33^{c}	2.65^{c}	0.83^{c}	54.4^{b}	1134^{c}	3.66^{c}	4.40^{bc}	0.12^{bc}
	60-90	1.3^{c}	244^{b}	291^{d}	700^{b}	24^{c}	192^{c}	1.2^{c}	1.61^{b}	3.65^{b}	0.46^{c}	69.8^{a}	1273^{b}	3.47^{d}	4.47^{b}	0.13^{bc}
	90-120	1.1^{c}	283^{a}	264^{d}	855^{a}	17^{c}	302^{a}	1.2^{c}	1.97^{a}	4.96^{a}	0.43^{c}	71.1^{a}	1540^{a}	3.30^{e}	4.30^{c}	0.10^{c}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

be long lasting. Toma et al. (1999) were working with plots where 10 and 35 Mg of gypsum ha^{-1} had been surface incorporated and found that EC was higher in gypsum plots than in control plots from 20 to 120 cm 16 yr after treatment.

Rate by depth interactions were significant for K, Ca, S, 0.01 *M* $CaCl_2$ exchangeable Mn, pH_{CaCl_2}, pH_{H_2O}, and EC in 2000 (Table 8). In addition, S and Fe had significant material by depth interactions, and the interaction between material, rate, and depth was significant for S. Potassium levels in the 0- to 15-cm depth were highest in the zero plots, and at 15 to 30 cm, were highest in the zero and low rate plots (Figure 4). Below 30 cm there were no significant differences. The high levels of exchangeable Ca^{2+} resulting from the treatments would cause K^+ to move into soil solution and thus potentially move deeper in the profile (Syed-Omar et al., 1991). The trend that appeared to be developing in the Aug. 1999 sampling related to Ca at 15 to 30 cm (Figure 2) was obscured in the 2000 sampling (Figure 5). This may in part be associated with the 18 Mg ha^{-1} of limestone applied to raise surface pH. Even the zero plots had Ca levels at this depth similar to the high rate. Sulfur movement to 15 to 30 cm in the 5, 10, and 15 Mg gypsum ha^{-1} plots is observable (Figure 6). There were almost 1200 mg kg^{-1} of extractable S remaining in the surface 15 cm 11 MAT. Soil pH was highest in the zero plots in both the surface and 15- to 30-cm depths (Figure 7). Increasing rates significantly increased EC in the surface, with the same trend, though less obvious, observable at 15 to 30 cm. The salt effect associated with the application of $CaSO_4$ probably contributed to lower pH and higher EC.

As with previous samplings, there were no measurable soil effects due to material in the 2001 sampling (Table 10). Significant rate effects were seen for Ca, S, Cu, and EC. The Cu effect was not consistent in relation to rate (Table 11) and was not observed at any other sampling from either location. Therefore, it was considered an anomaly due to soil variability unrelated to rate. Calcium, S, and EC values were similar to those measured in 2000 (Table 11), and rate effects on S and EC remained highly significant.

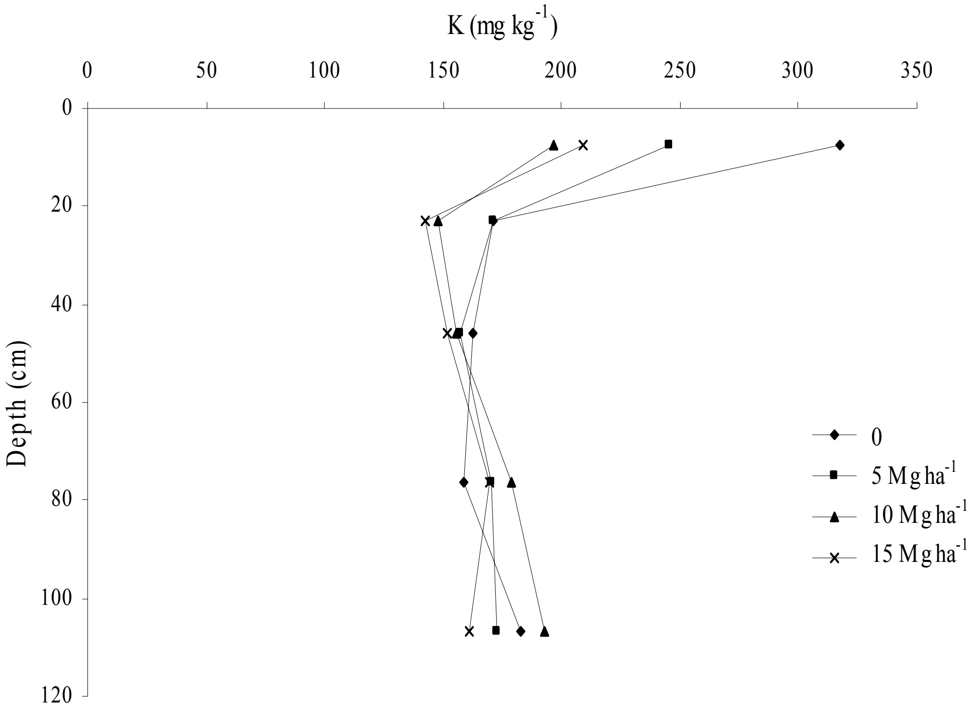


Figure 4. Mehlich-3 extractable potassium at different depths in the Sacul soil, Nacogdoches Co. TX, sampled in May 2000, 12 mo after treatment with four rates of gypsum.

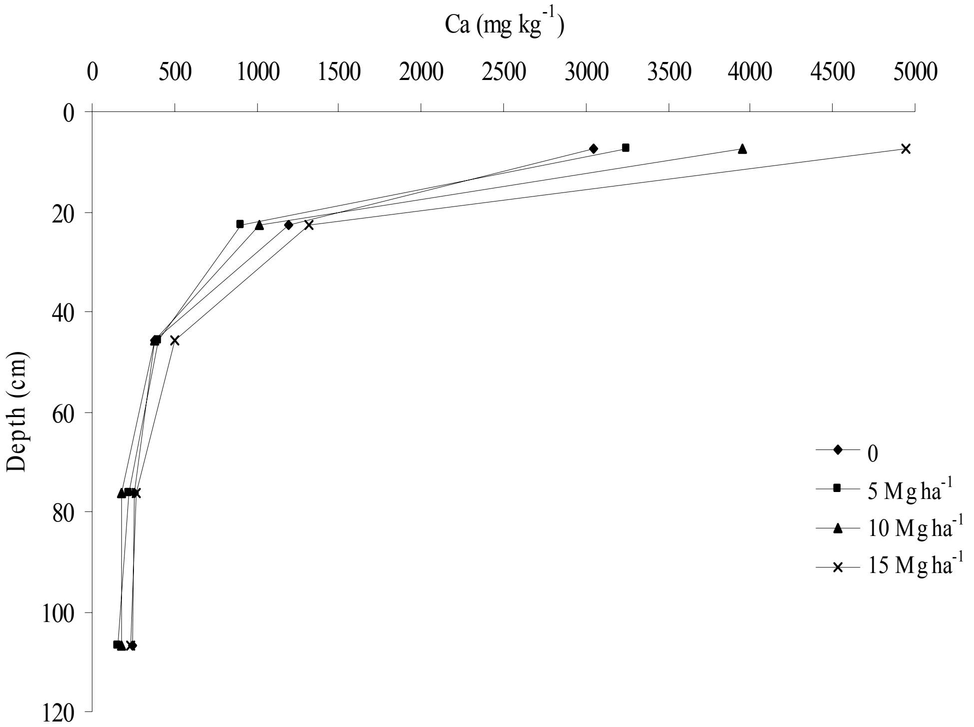


Figure 5. Mehlich-3 extractable calcium at different depths in the Sacul soil, Nacogdoches Co. TX, sampled in May 2000, 12 mo after treatment with four rates of gypsum.

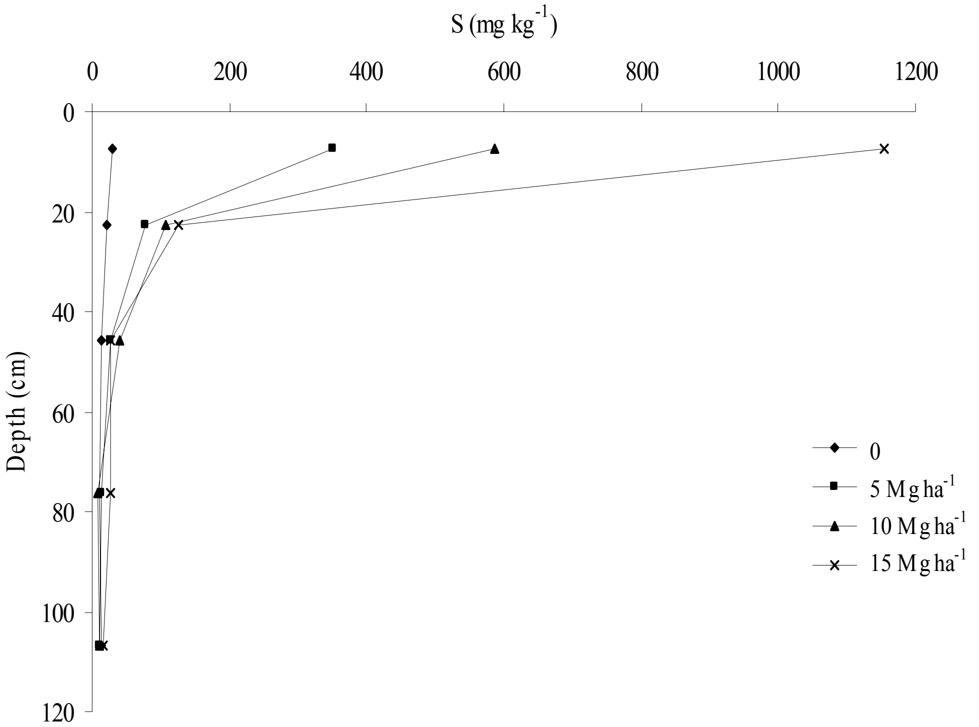
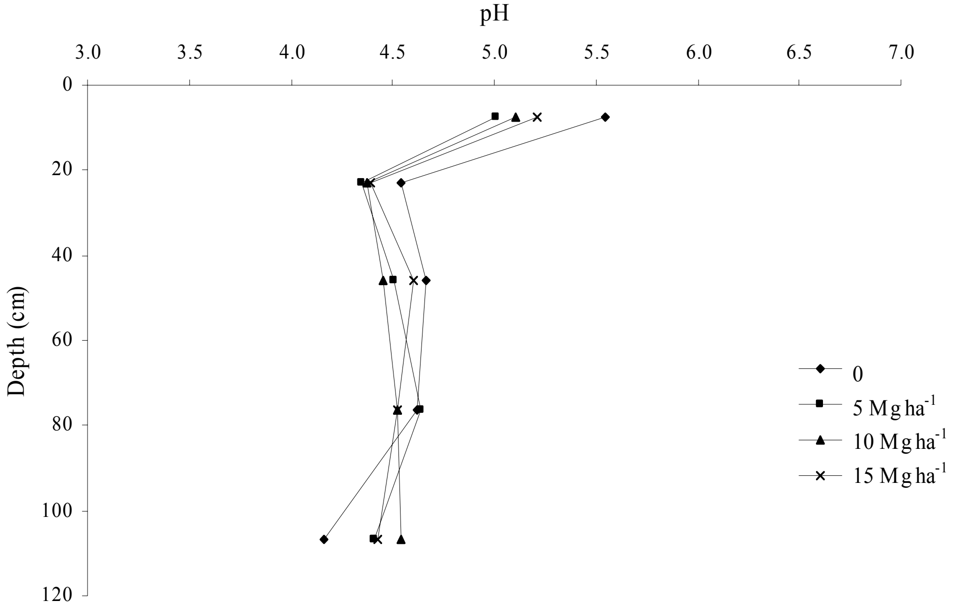


Figure 6. Mehlich-3 extractable sulfur at different depths in the Sacul soil, Nacogdoches Co. TX, sampled in May 2000, 12 mo after treatment with four rates of gypsum.



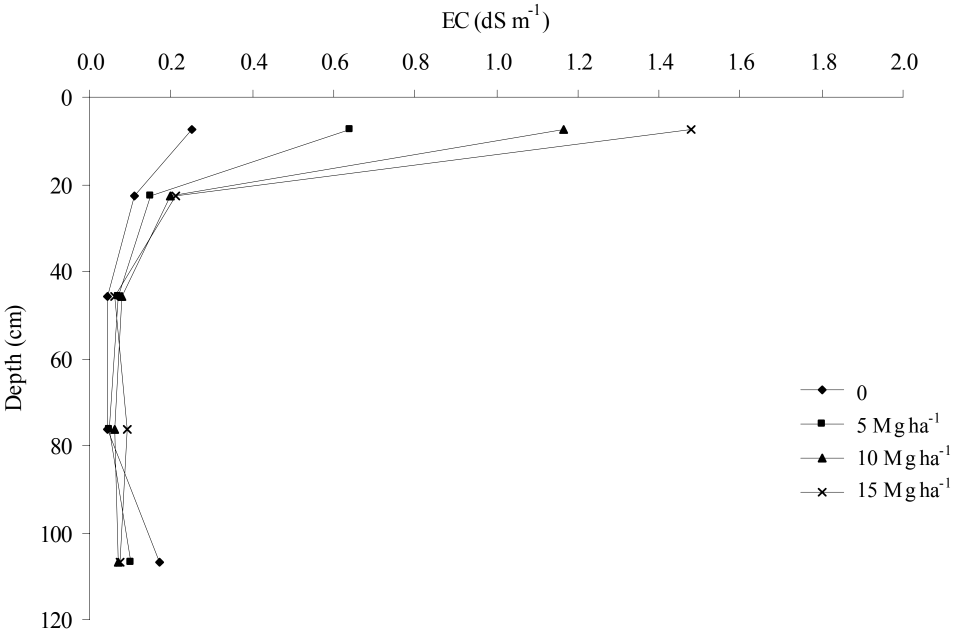


Figure 7. 2:1 water to soil pH and electrical conductivity at different depths in the Sacul soil, Nacogdoches Co. TX, sampled in May 2000, 12 mo after treatment with four rates of gypsum.

By 22 MAT differences in soil Ca levels due to rate were observable down to 60 cm (Figure 8). At the 15 to 30 and 30- to 60-cm depths, the medium and high rates were essentially the same, as were the zero and low rates. Sulfur and EC values for the medium and high treatments remained high in the surface soil, and differences between rates at 15 to 30 cm were significant (Figures 9 and 10).

By the 2003 sampling, 45 MAT, only S and EC showed significant effects due to rate (Table 12). The high treatment rate had significantly higher S and EC than the lower rates (Table 13). There were no differences due to material. Rate by depth interactions were significant for P, Ca, S, and EC. Surface Ca levels for the high gypsum rate remained approximately 1000 mg kg^{-1} higher than in the check plots, and were higher at all depths than the other rates (Figure 11). Calcium levels decreased with depth, but Figure 12 shows that for the first time S was higher at 15 to 30 cm than in the surface for the zero, low, and medium rates for both materials. This indicates that S continued to move down in the profile. Downward movement of S, usually as SO_4, from application of high-sulfate materials has been shown by other researchers (Farina, 1997; Farina et al., 2000b; Ritchey et al., 1995; Stehouwer et al., 1999). Another indication of S movement is that at the high gypsum rate, levels continued to decrease with depth, but were significantly greater than the other rates at 60 cm. These results are similar to those reported by Farina (1997). He found that depth of SO_4 movement in the profile of a clayey Paleudult sampled eight years after surface application of five rates of gypsum was dependent on rate. Figure 13 shows plots of EC, which as in previous samplings, closely track S trends.

Although treatment effects were not significant, potassium levels were highest in the surface soil, but changed little with depth (Figure 14). There was not an obvious rate effect on extractable soil K. A concern associated with applying high rates of Ca to the soil is the displacement of K^+ and Mg^{2+} from exchange sites and the potential movement of the cations deeper into the soil profile. There is not a clear indication that

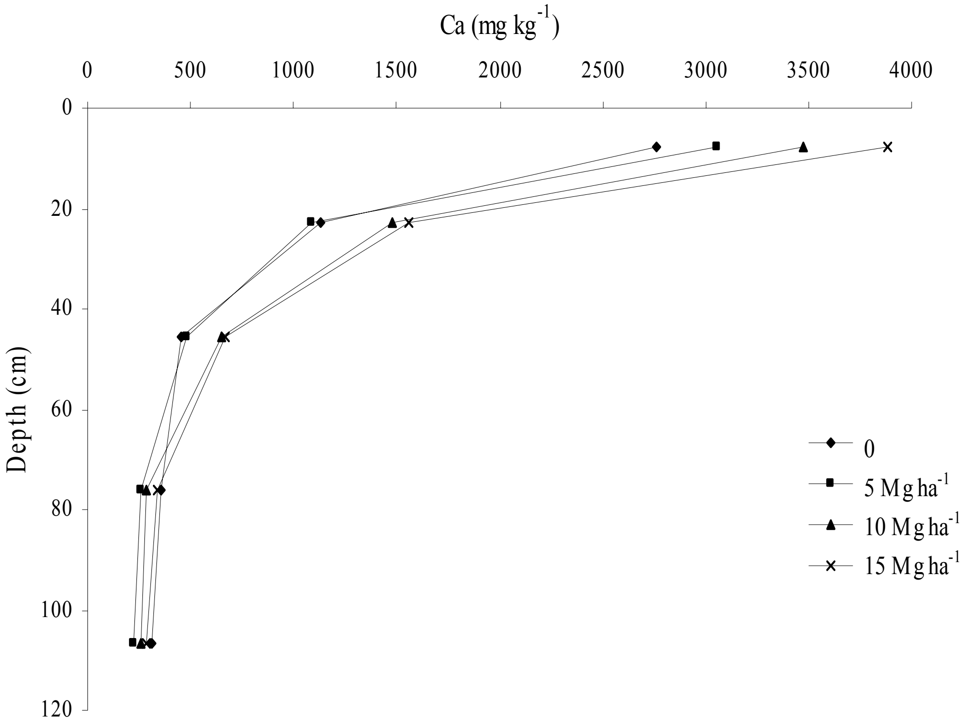


Figure 8. Mehlich-3 extractable calcium at different depths in the Sacul soil, Nacogdoches Co. TX, sampled Apr. 2001, 22 mo after treatment with four rates of gypsum.

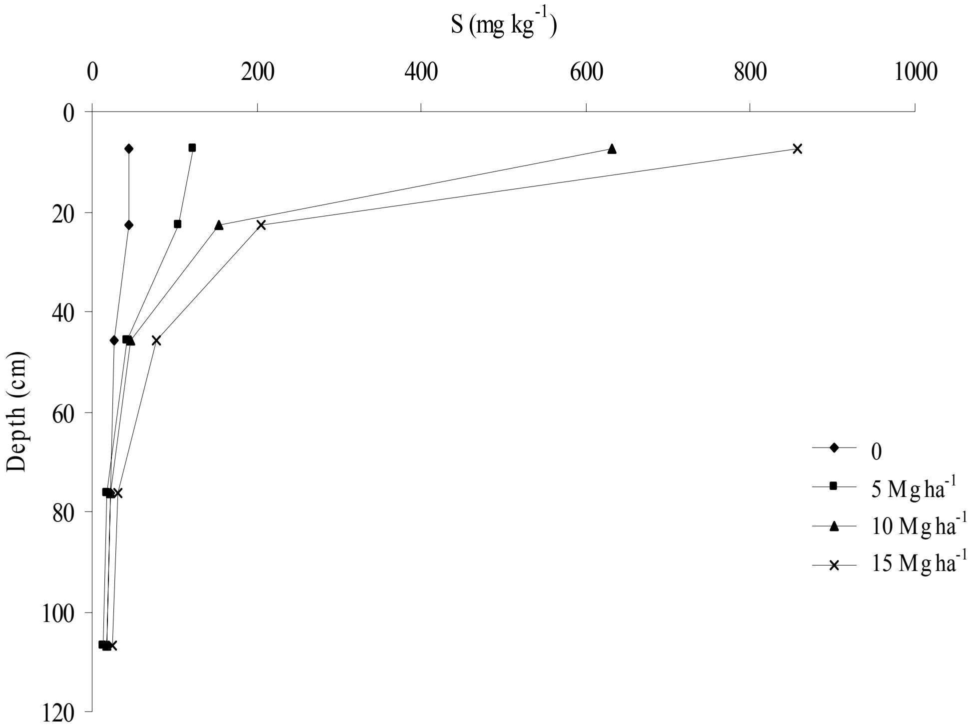


Figure 9. Mehlich-3 extractable sulfur at different depths in the Sacul soil, Nacogdoches Co. TX, sampled Apr. 2001, 22 mo after treatment with four rates of gypsum.

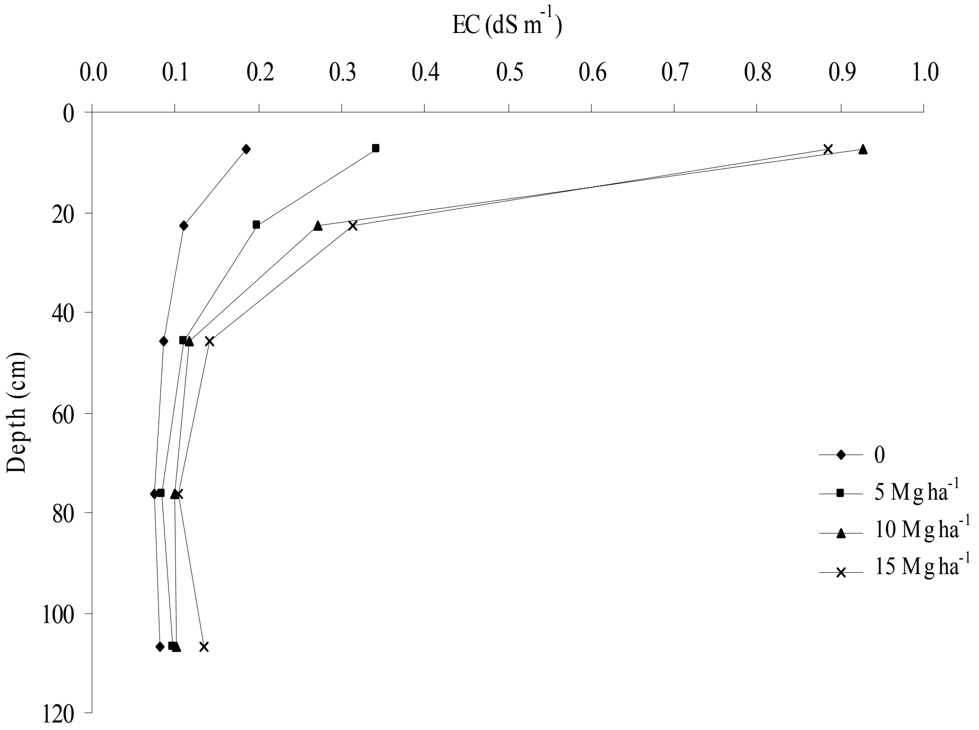


Figure 10. Electrical conductivity at different depths in the Sacul soil, Nacogdoches Co. TX, sampled Apr. 2001, 22 mo after treatment with four rates of gypsum.

Table 12. Analysis of variance for the effects of gypsum and scrubber sludge at five soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in Mar. 2003.

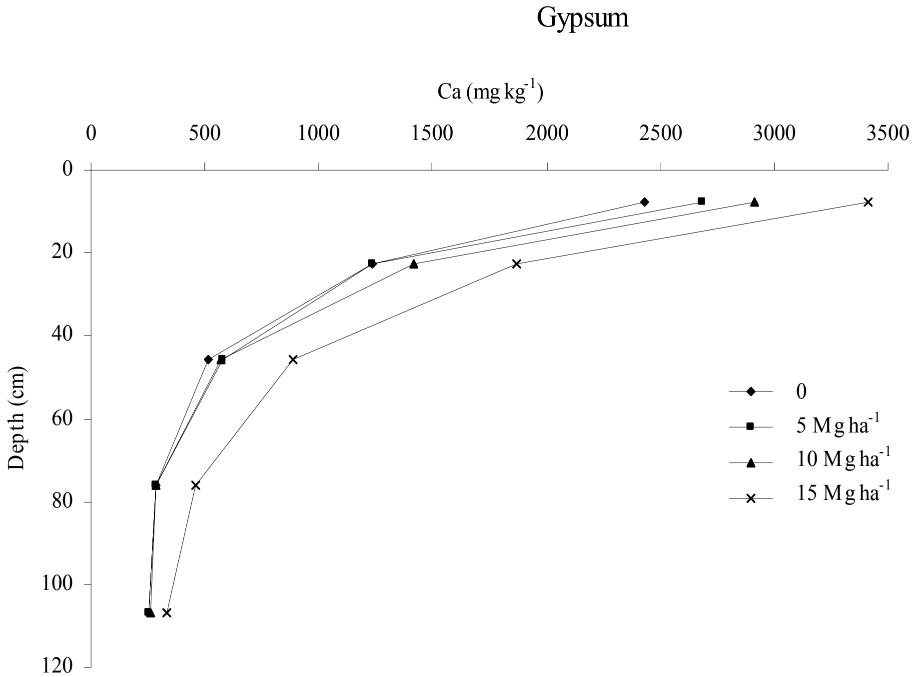
Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		Mean Squares														
			x 10^3	x 10^5	x 10^4	x 10^3	x 10^4	x 10^1	x 10^{-1}			x 10^2	x 10^5	x 10^{-1}	x 10^{-1}	
Material (M)	1	2.13	0.26	1.17	0.15	1.41	0.82	0.34	1.97	1.78	0.14	4.56	1.72	0.29	0.25	0.37
Rate (R)	3	3.99	21.58	8.46	8.14	118.10^{***}	0.84	1.30	5.70	1.28	0.32	3.67	11.92	1.63	1.73	14.88^{***}
M x R	3	11.22	3.71	4.84	3.32	3.82	0.29	0.23	0.72	1.31	0.13	1.13	1.84	0.62	0.62	0.64
Block	3	8.09	1.35	2.97	18.00	16.17	1.63	0.85	2.19	8.90	0.83	2.56	5.12	5.08	5.15	3.72
Error (a)	21	5.90	13.57	4.05	14.92	7.59	0.65	1.84	5.38	7.20	0.61	2.14	4.65	1.45^{*}	1.91	1.89
Depth (D)	4	36.57^{***}	16.38^{***}	53.69^{***}	79.96^{***}	42.63^{***}	19.08^{***}	38.60^{***}	79.80^{***}	47.77^{***}	34.98^{***}	83.17^{***}	70.72^{***}	98.45^{***}	112.16^{***}	28.59^{***}
M x D	4	0.63	0.17	0.37	0.64	0.59	0.89^{*}	0.19	0.33	0.17	0.34	0.23	0.27	0.31	0.14	0.10
R x D	12	10.34^{**}	0.92	2.88^{*}	2.45	29.63^{***}	0.18	0.56	0.83	2.94	0.18	0.83	1.53	0.27	0.52	4.34^{***}
M x R x D	12	7.38^{*}	1.08	0.60	1.25	0.94	0.18	0.22	0.31	0.68	0.74	0.31	0.31	0.12	0.20	0.21
Error (b)	96	3.72	2.30	1.17	2.55	4.58	0.35	0.79	0.61	2.08	0.26	0.80	1.27	0.49	0.44	0.69

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 13. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Sacul fine sandy loam, Nacogdoches Co. TX, sampled in Mar. 2003.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		Mg kg^{-1}														dS m^{-1}
Material	Gypsum	6.9	248	1108	736	95	210	7.9	1.80	3.40	1.21	39.9	982	3.78	4.40	0.20
	Sludge	7.1	248	1050	736	95	200	7.6	1.87	3.61	1.19	36.6	921	3.80	4.43	0.20
Rate (Mg ha^{-1})	0	6.6	218	940^{b}	701	42^{c}	210	8.5	1.71	3.40	1.28	35.5	752	3.82	4.48	0.14^{b}
	5	7.5	272	1077^{ab}	794	65^{c}	198	7.8	1.91	3.66	1.14	36.0	1044	3.80	4.43	0.17^{b}
	10	6.9	258	1061^{ab}	749	106^{b}	219	7.3	1.96	3.31	1.26	41.9	1060	3.70	4.33	0.21^{b}
	15	7.0	244	1237^{a}	700	166^{a}	192	7.3	1.76	3.66	1.10	39.6	951	3.84	4.42	0.28^{a}
Depth (cm)	0-15	23.7^{a}	284^{a}	2793^{a}	437^{d}	157^{a}	305^{a}	22.2^{a}	1.31^{d}	3.00^{b}	2.62^{a}	3.4^{d}	14^{e}	5.04^{a}	5.38^{a}	0.33^{a}
	15-30	4.1^{b}	226^{b}	1401^{b}	684^{c}	168^{a}	123^{d}	9.0^{b}	1.42^{d}	2.21^{c}	1.95^{b}	24.2^{c}	573^{d}	3.74^{b}	4.22^{b}	0.27^{b}
	30-60	2.7^{c}	233^{b}	610^{c}	772^{b}	89^{b}	146^{d}	3.7^{c}	1.79^{c}	3.10^{b}	0.81^{c}	47.6^{b}	1081^{c}	3.53^{c}	3.96^{c}	0.18^{c}
	60-90	2.3^{c}	246^{b}	314^{d}	835^{b}	35^{c}	185^{c}	1.9^{d}	2.17^{b}	3.77^{b}	0.33^{d}	56.1^{a}	1443^{b}	3.38^{d}	4.27^{b}	0.12^{d}
	90-120	2.2^{c}	251^{b}	276^{d}	951^{a}	25^{c}	267^{b}	1.7^{d}	2.50^{a}	5.45^{a}	0.27^{d}	60.0^{a}	1648^{a}	3.27^{e}	4.25^{b}	0.11^{d}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.



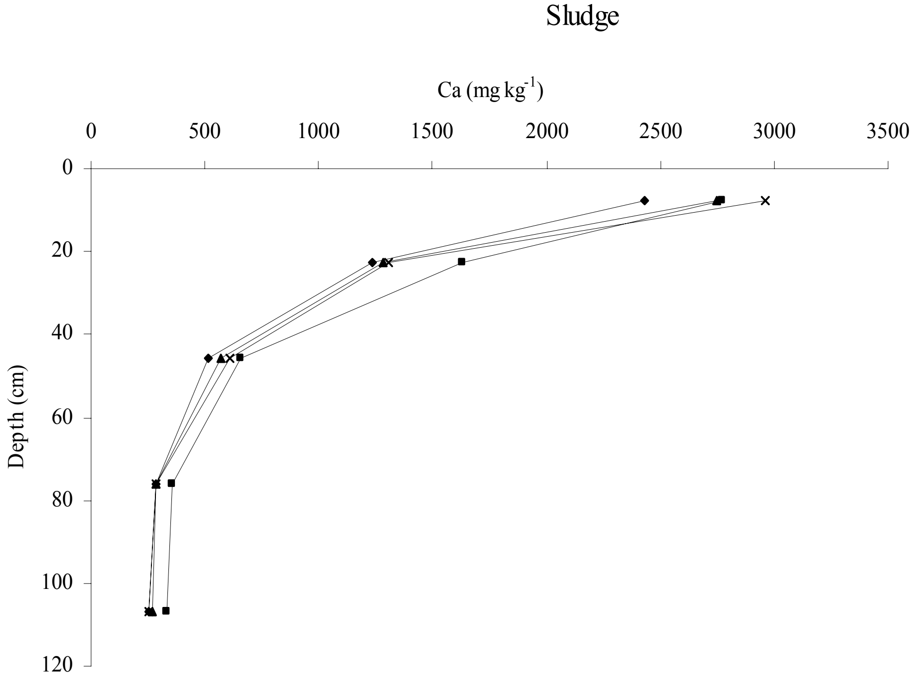
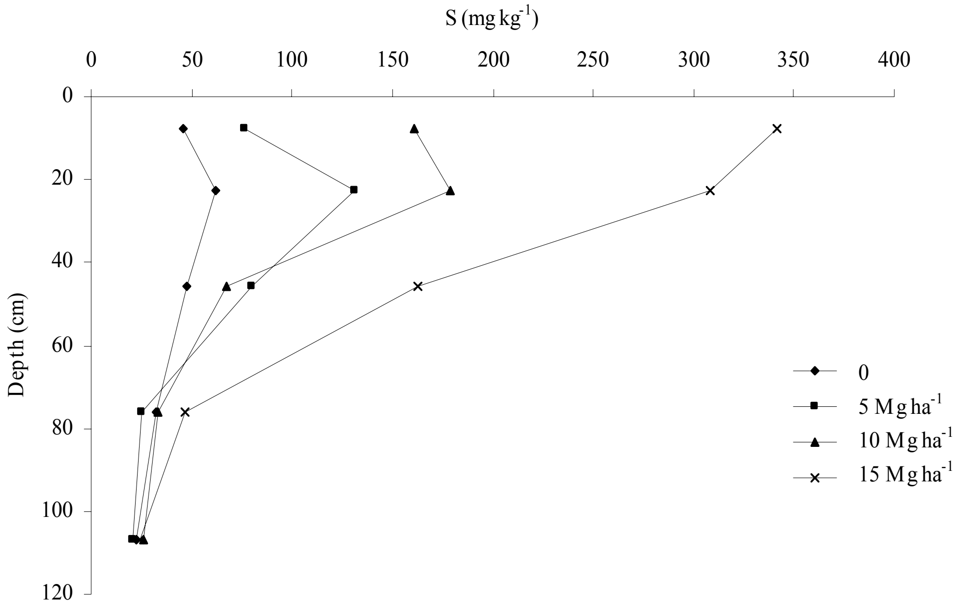


Figure 11. Mehlich-3 extractable calcium in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.

Gypsum



Sludge

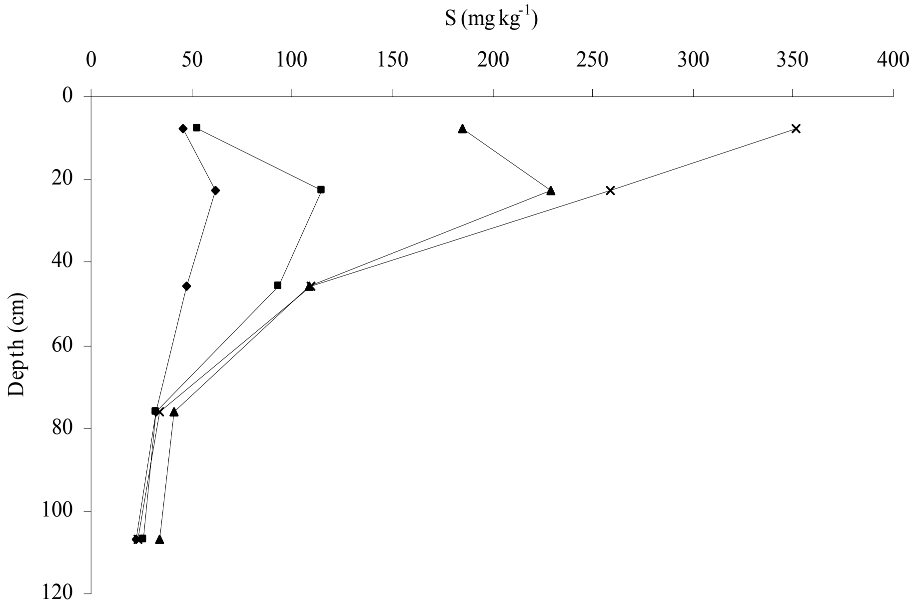
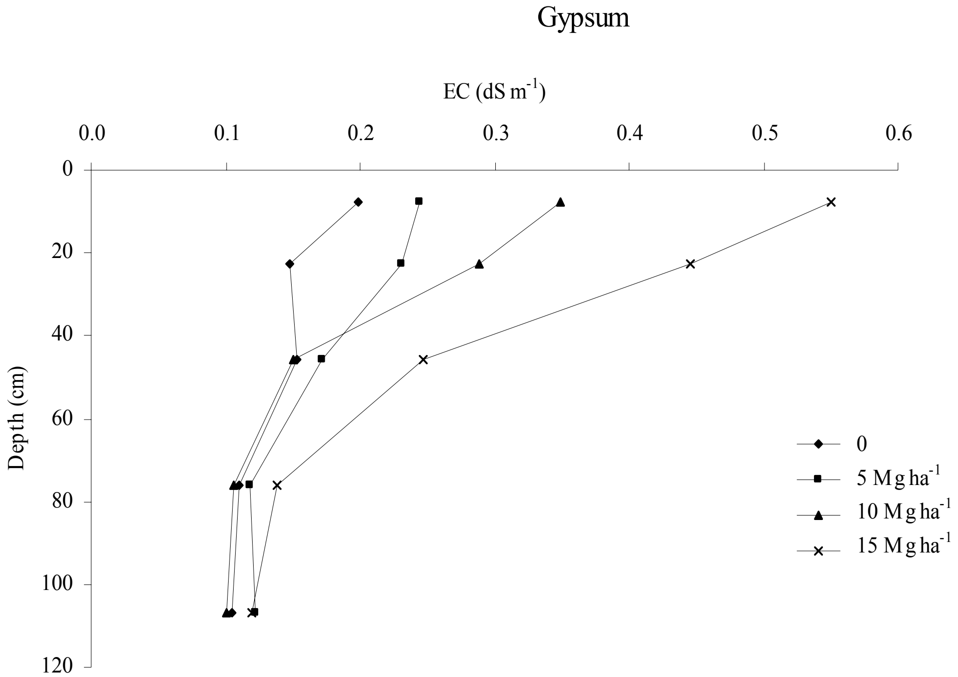
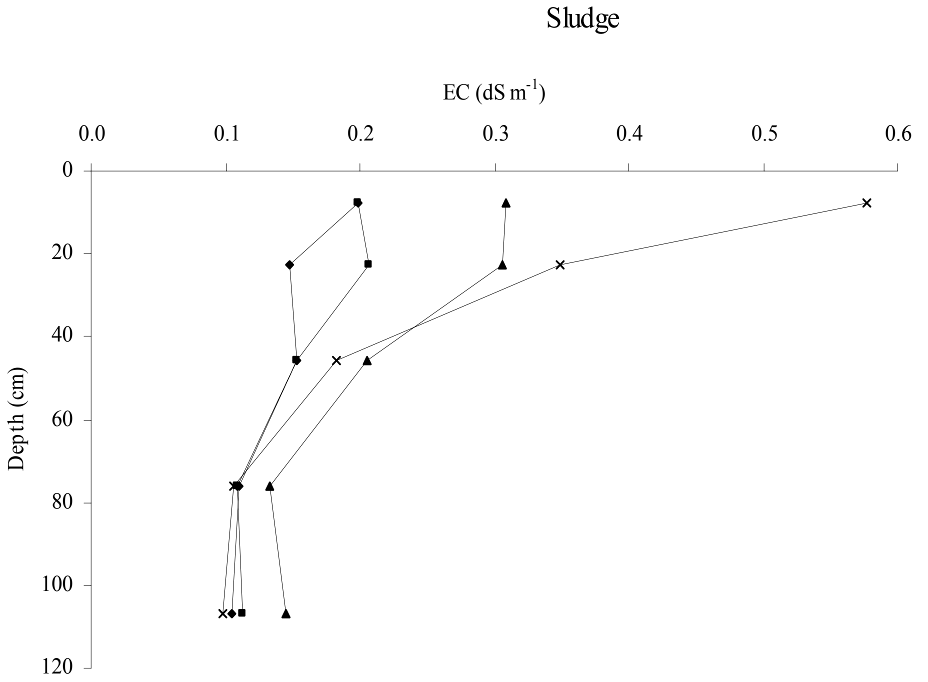


Figure 12. Mehlich-3 extractable sulfur in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.



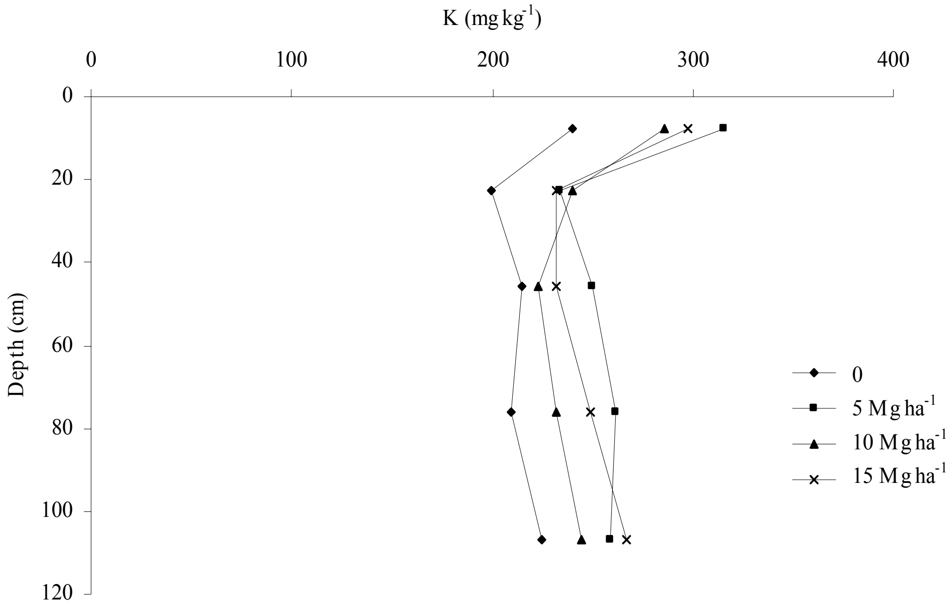
Gypsum



Sludge

Figure 13. Electrical conductivity in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.

Gypsum



Sludge

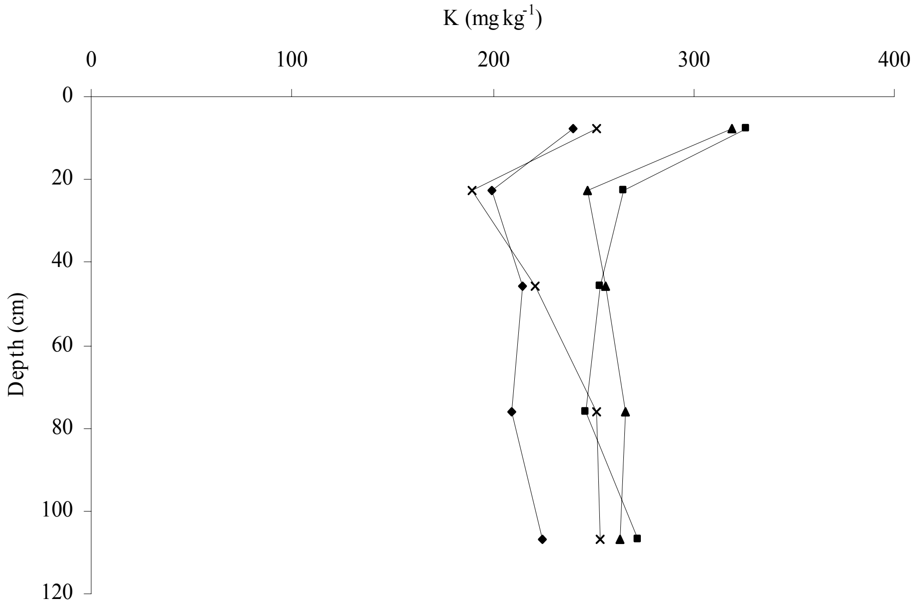
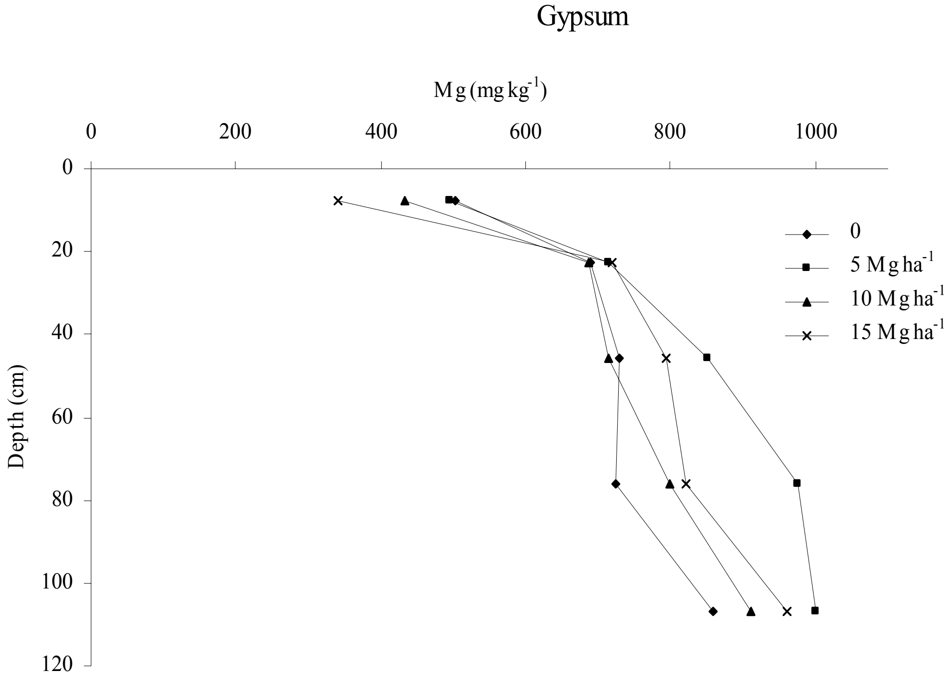


Figure 14. Mehlich-3 extractable potassium in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.



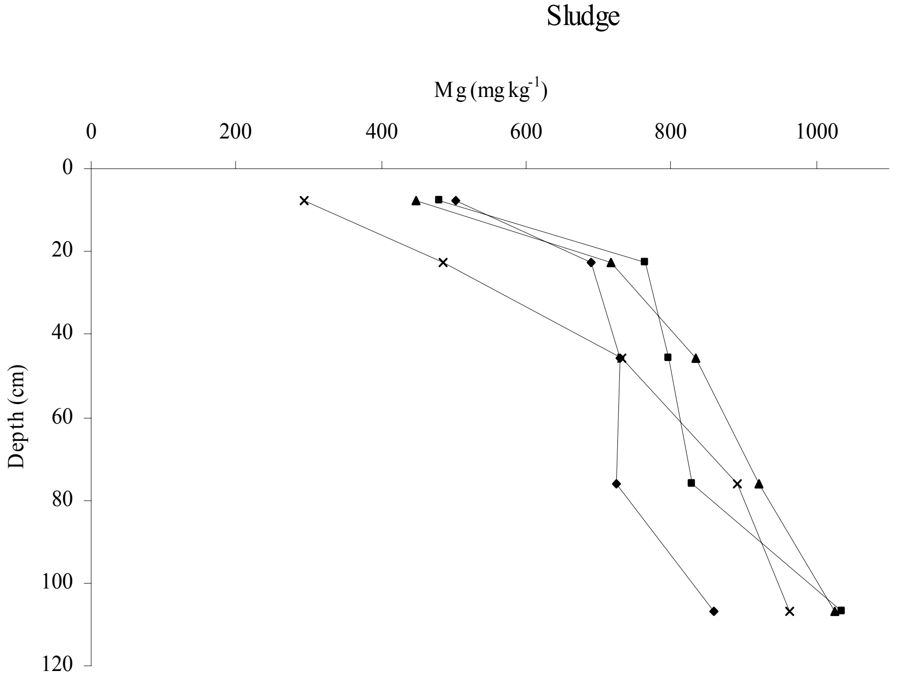


Figure 15. Mehlich-3 extractable magnesium in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.

rate affected the distribution of Mg except for the high rate of sludge (Figure 15). However, Mg levels in the high sludge plots were significantly lower than the other treatments down to 30 cm which could indicate leaching of exchangeable Mg, but below 30 cm levels were the same as the low and medium plots. Syed-Omar and Sumner (1991) observed significant leaching of exchangeable Mg from the surface 50 cm and K from the surface 22 cm of Davidson and Tifton series soils that had received increasing rates up to 10 Mg of gypsum ha^{-1}. The movement of Mg and K deeper in the soil corresponded to increased exchangeable Ca higher in the profile. They speculated that the low clay content soils in their study had exchange sites demonstrating a preference for K^+ and Ca^{2+}, particularly when K levels were naturally low. It is expected that if Mg is being moved through the soil, lower Mg levels at 0 to 30 cm would result in accumulation of Mg below 30 cm.

A stated objective of the study was to determine if surface-applied Ca amendments would reduce subsoil Al^{3+}. In theory, as exchangeable Ca increases, exchangeable Al should decrease. Much evidence exists for decreased exchangeable Al resulting from increased exchangeable Ca in subsoils (Alva et al., 1990; Farina et al., 2000b; Hammel et al., 1985; Pavan et al., 1984; Ritchey et al., 1995). Figure 16 indicates that the observed effect of treatments on *N* KCl extractable Al is apparently contrary to what is expected. Others have reported similar results. McCray et al. (1991) surface-incorporated 10 Mg ha^{-1} of phosphogypsum in an acidic soil, transitional between a Cecil and Appling series. Seventeen mo after treatment, exchangeable Ca had increased significantly to 0.8 m, but extractable Al was not lowered below 0.2 m. In fact, total Al in the surface 0.2 m had increased. They attributed the high Al levels to increased ionic strength resulting from gypsum movement into the soil. Similarly, Rechcigl et al. (1993) did not see reductions in extractable Al below 15 cm 41 mo after surface application of 2.2 and 4.4 Mg ha^{-1} of phosphogypsum in an Ona fine sand, even though Ca was increased to 90 cm. In an earlier field experiment on a different soil, Rechcigl et al. (1988) reported that gypsum at 13 Mg ha^{-1} lowered surface pH by 0.4 units, decreased soil solution Al, but did not

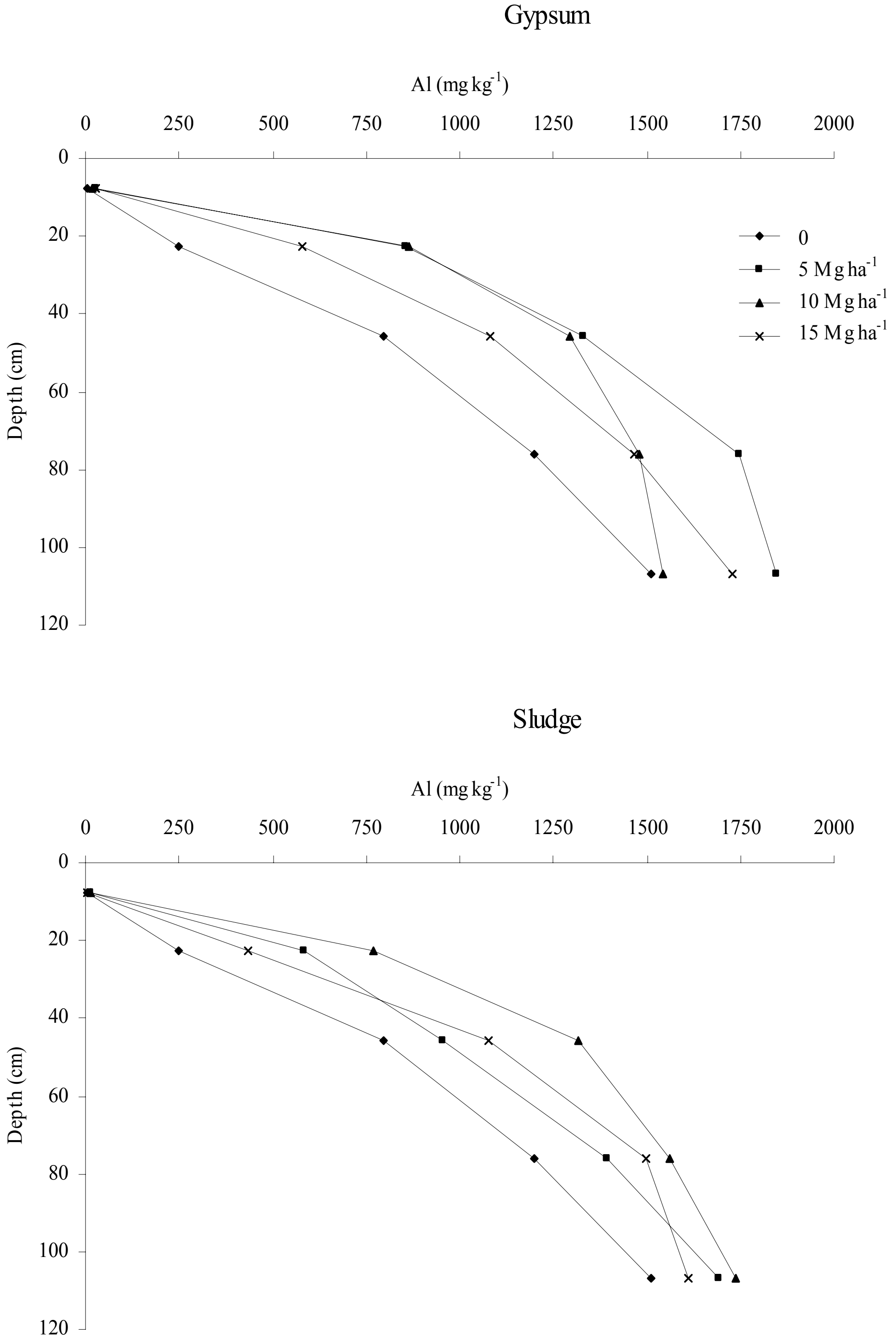


Figure 16. *N* KCl extractable aluminum in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.

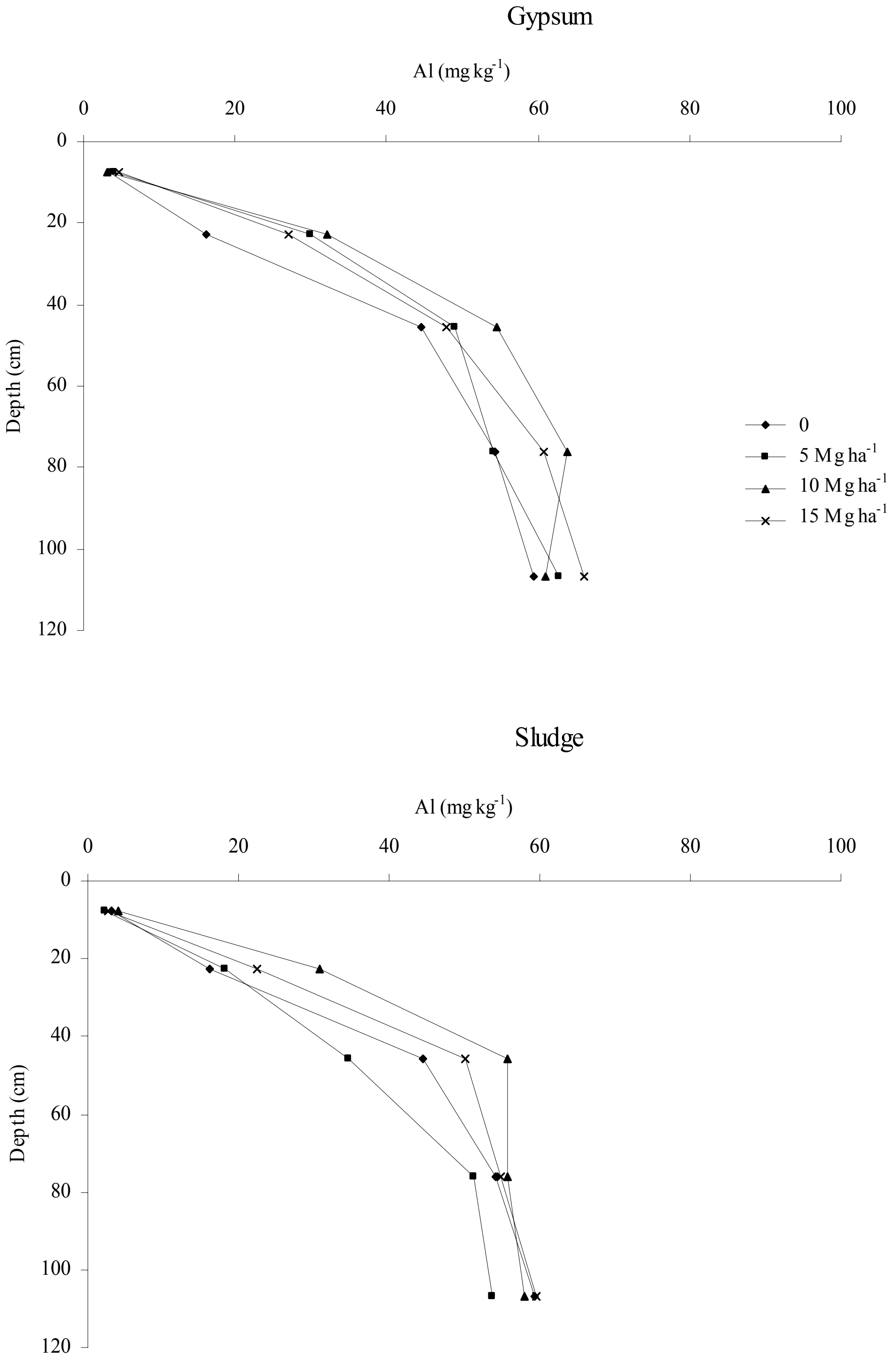
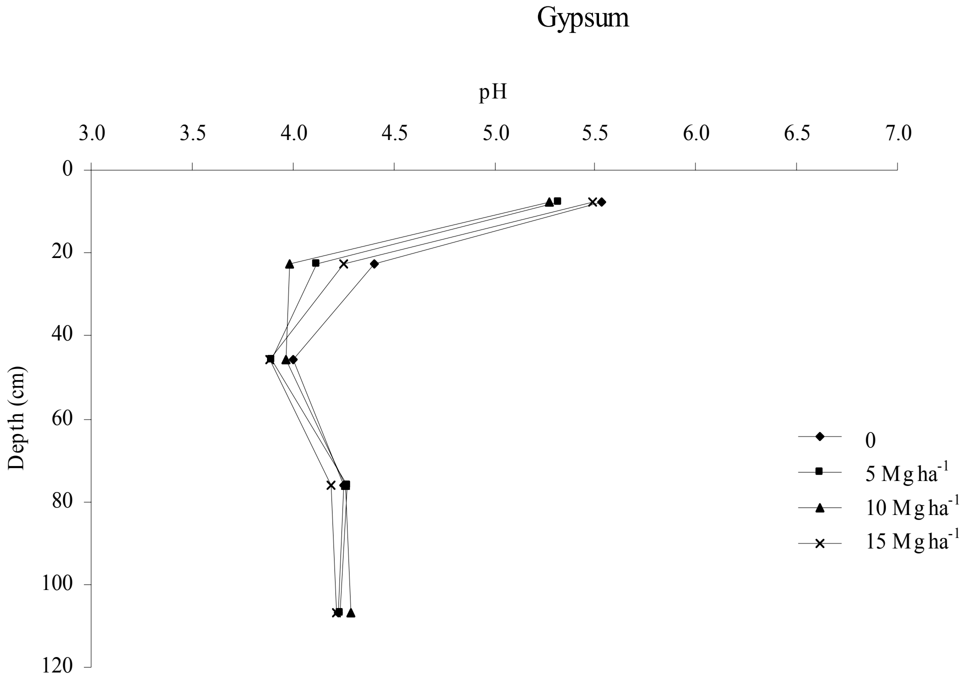


Figure 17. 0.01 *M* $CaCl_2$ exchangeable aluminum in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.

reduce extractable Al in the subsoil. They refer to high extractable Al levels in the soil as being >50 mg kg^{-1}. Both sites in the present research have levels far exceeding 50 mg kg^{-1} at depths as shallow as 15 to 30 cm (Table 1). It is possible that Al levels were higher than can be ameliorated during the time of the current study. Subsoil extractable Al is higher from 15 to 120 cm in the low, medium, and high treatments than in the check plots. High variability in the data prevented differences from being significant. Also, rate effect for Ca was not significant (Table 12), and although there appears to be a trend for higher subsoil Ca levels in the high rate plots (Figure 11), the relationship was not consistent or significant. Therefore, it is difficult to say anything unequivocal regarding treatment effect on extractable Al. Similarly, rate effect on 0.01 *M* $CaCl_2$ exchangeable Al was not apparent (Figure 17). Although rate effect was not significant, at 15 to 30 cm in the gypsum treatments exchangeable Al was lower in the check plots than in the low, medium and high rates. As Ca^{2+} replaces Al^{3+} on exchange sites more Al would be in solution. So, although treatments did not reduce subsoil Al, at least initially, a temporary increase in 0.01 *M* $CaCl_2$ exchangeable Al could be expected to result from increased exchangeable Ca. Surface pH remained relatively low throughout the experiment (Figure 18). The salt effect on pH is observable when Figures 18 and 19 are compared. Water pH decreased from the surface to 60 cm then increased, whereas $pHCaCl_2$ decreased with increasing depth in the profile. Some separation of pH related to rate was observable at 15 to 30 cm in the gypsum treatments (Figure 19), but generally there was not a rate effect on pH_{H_2O} or pH_{CaCl_2}.

Plots were sampled to 60 cm in Aug. 1999, one MAT. Measured parameters in the surface layer confounded sampling differences between the other sampling times when data from Aug. 1999 were included in the ANOVA used to determine the effect of treatments on soil depths over time. In view of this and since all other samplings were to 120 cm, the Aug. 1999 data were not included in comparisons between sample times, or when evaluating changes at each soil depth during the duration of the study.

Amendment material did not have a significant effect on any of the measured parameters at any of the depths throughout the study (Tables 14 to 18). Table 14



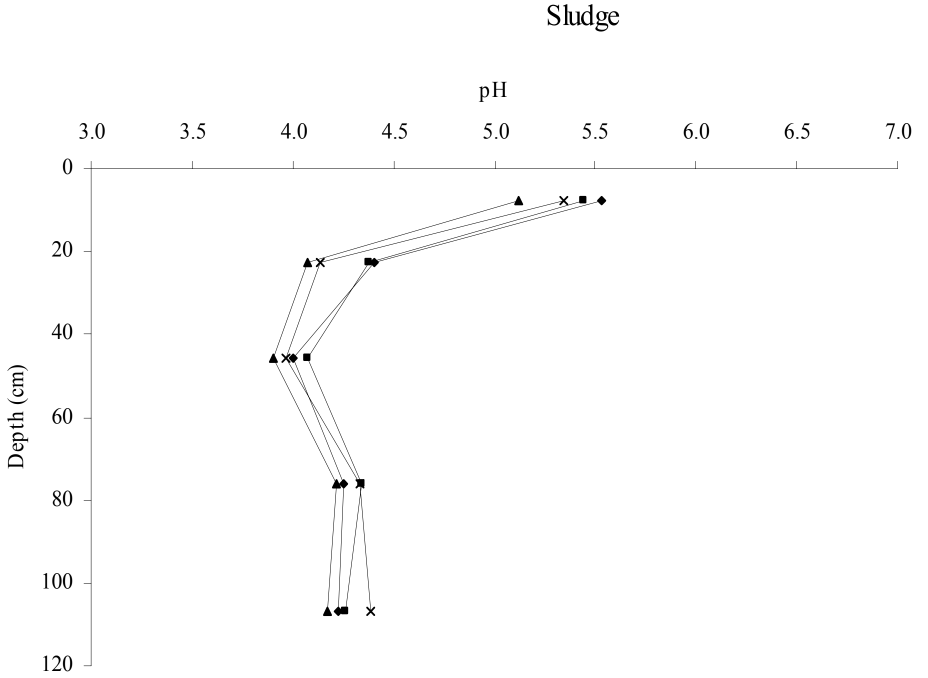


Figure 18. 2:1 water to soil pH in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.

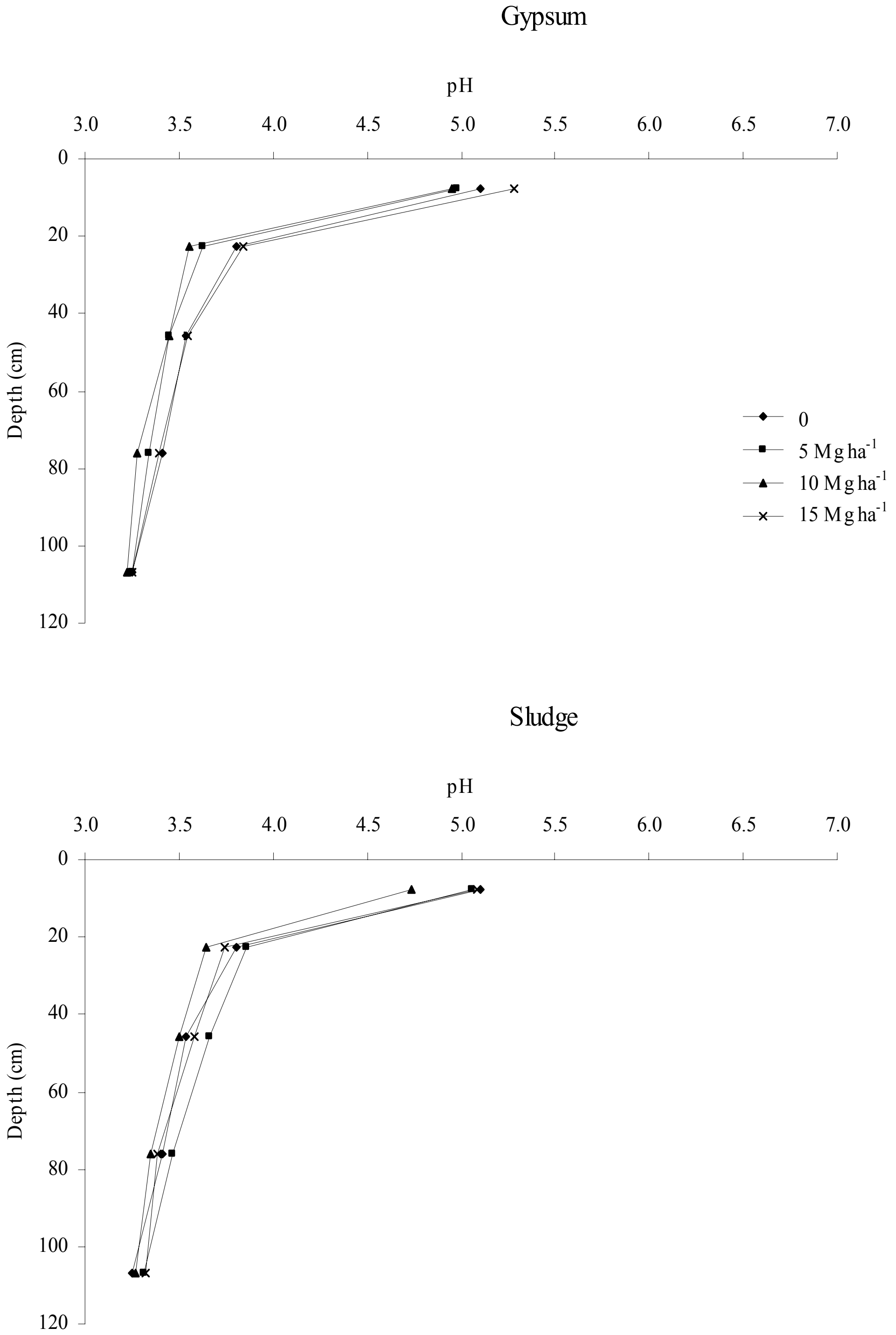


Figure 19. 2:1 0.01 *M* $CaCl_2$ to soil pH in the Sacul soil, Nacogdoches Co. TX, sampled in Mar. 2003, 45 mo after treatment with four rates of gypsum or sludge.

Table 14. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, May 2000, Apr. 2001, and Mar. 2003 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Sacul fine sandy loam, Nacogdoches Co. TX, at a soil depth of 0 to 15 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
		x 10^1	x 10^3	x 10^5	x 10^4	x 10^5	x 10^4	x 10^2	x 10^{-1}		x 10^1		x 10^3	x 10^{-1}	x 10^{-1}
Material (M)	1	10.25	7.32	0.94	9.55	0.25	3.38	0.78	0.66	3.86	0.72	26.57	7.87	3.62	1.90
Rate (R)	3	0.89	9.69	37.51^{***}	8.32	22.14^{***}	0.67	1.70	2.52	3.76	0.37	15.23	3.61	3.63	4.64
M x R	3	5.93	4.22	8.20	1.37	0.47	0.41	1.05	4.23	2.63	0.24	31.16	2.50	1.36	0.82
Block	3	7.31	1.69	9.94	1.47	0.12	1.02	2.41	17.74	3.67	1.21	18.94	1.57	8.78	7.76
Error (a)	21	2.90	9.52	3.36	2.96	0.32	0.49	1.04	3.80	2.92	0.56	19.01	2.74	6.22	4.97
Sampling (S)	3	27.50^{***}	75.89^{***}	119.64^{***}	24.73^{***}	20.35^{***}	1.75^{***}	4.23^{***}	27.38^{**}	8.22	1.44^{***}	36.96^{**}	2.00	4.62^{**}	14.99^{***}
M x S	3	0.82	0.87	2.72	1.00	0.29	0.13	0.25	4.28	4.52	0.18	0.99	0.52	1.58	1.04
R x S	9	3.70	11.71^{***}	4.90^{**}	0.80	4.71^{***}	0.26	0.32	7.14	4.16	0.25	8.05	0.80	0.99	1.16
M x R x S	9	1.93	0.88	1.25	0.26	0.80	0.11	0.32	2.79	1.54	0.10	8.58	0.50	0.57	0.43
Error (b)	72	3.06	2.56	1.64	0.49	0.26	0.26	0.32	5.65	3.83	0.13	6.97	0.97	0.90	0.62

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 15. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, May 2000, Apr. 2001, and Mar. 2003 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* CaCl$_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* CaCl$_2$ to soil and 2:1 water to soil, in a Sacul fine sandy loam, Nacogdoches Co. TX, at a soil depth of 15 to 30 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	CaCl$_2$ Mn	CaCl$_2$ Al	KCl Al	pH$_{CaCl_2}$	pH$_{H_2O}$
		Mean Squares													
			x 10^3	x 10^5	x 10^4	x 10^4	x 10^3	x 10^1	x 10^{-1}		x 10^{-1}	x 10^2	x 10^5	x 10^{-2}	x 10^{-2}
Material (M)	1	1.88	10.53	1.01	12.46	0.14	1.05	0.51	0.37	1.15	0.10	3.93	9.79	4.13	10.64
Rate (R)	3	1.62	8.56	3.24	3.87	8.03^{***}	0.22	2.54	5.87	0.70	5.02	3.49	1.65	7.86	19.86
M x R	3	5.68	5.03	4.92	7.51	0.12	3.21	0.19	2.95	0.75	0.66	0.97	1.66	1.29	2.74
Block	3	13.18^{*}	3.77	5.58	11.52	0.21	0.59	1.86	7.58	1.47	24.64	9.41	0.73	10.71	11.31
Error (a)	21	2.73	7.63	3.41	5.78	0.17	2.01	4.26	5.30	2.04	26.03	4.83	4.18	10.99	14.15
Sampling (S)	3	24.82^{***}	41.34^{***}	19.70^{***}	8.74^{**}	12.63^{***}	5.75^{***}	3.73^{**}	26.37^{***}	3.76	46.89^{***}	0.28	2.74	42.06^{***}	87.85^{***}
M x S	3	0.21	1.22	0.40	0.64	0.02	0.68	0.33	2.85	0.65	1.52	0.40	0.78	0.88	0.10
R x S	9	4.52	1.95	1.10	1.14	1.34^{***}	0.72	1.31	2.67	0.91	7.12	0.99	2.42^{*}	2.51	4.89
M x R x S	9	1.70	0.38	0.42	0.47	0.14	0.40	0.17	3.12	0.35	1.24	0.51	0.41	1.66	1.43
Error (b)	72	2.20	1.95	0.56	1.82	0.17	0.48	0.82	4.25	1.48	4.05	0.82	1.20	1.95	3.35

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 16. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, May 2000, Apr. 2001, and Mar. 2003 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Sacul fine sandy loam, Nacogdoches Co. TX, at a soil depth of 30 to 60 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
			x 10^3	x 10^5	x 10^4	x 10^2	x 10^3		x 10^{-1}		x 10^{-1}	x 10^2	x 10^5	x 10^{-2}	x 10^{-2}
Material (M)	1	0.75	1.52	0.57	2.23	1.32	32.40	0.52	2.84	0.37	0.52	2.89	7.91	15.06	7.46
Rate (R)	3	0.67	2.11	1.02	1.10	73.98***	4.58	1.64	1.27	6.00	1.07	1.46	0.27	1.82	5.42
M x R	3	0.18	3.66	0.76	2.66	11.83*	4.59	0.17	1.00	0.21	0.33	0.66	1.17	2.03	1.57
Block	3	13.32***	3.43	0.68	7.27	0.85	2.11	2.20	3.42	5.94	4.95	22.90**	2.35	6.10	0.42
Error (a)	21	1.05	6.53	0.91	9.51	3.28	4.38	1.97	2.51	6.70	1.80	3.64	4.32	4.08	5.22
Sampling (S)	3	6.64**	52.03***	4.56***	22.49***	74.58***	9.76**	26.97***	41.82***	14.17*	11.49***	3.21	2.17	18.03***	85.68***
M x S	3	0.52	0.63	0.17	0.32	0.33	0.18	0.82	0.25	0.55	0.27	0.26	0.21	0.21	0.32
R x S	9	2.64	1.03	0.28	1.16	20.49***	0.85	1.20	1.48	2.86	2.15**	1.08	2.10	0.81	1.91
M x R x S	9	0.51	0.81	0.19	0.58	9.78**	0.10	0.73	0.45	1.33	0.37	0.56	0.86	0.51	2.19
Error (b)	72	1.25	1.98	0.17	1.95	2.90	1.68	0.54	1.62	4.23	0.65	2.19	1.85	1.62	2.35

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 17. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, May 2000, Apr. 2001, and Mar. 2003 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Sacul fine sandy loam, Nacogdoches Co. TX, at a soil depth of 60 to 90 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
			x 10^3	x 10^4	x 10^4	x 10^2	x 10^3		x 10^{-1}	x 10^1	x 10^{-2}	x 10^2	x 10^4	x 10^{-2}	x 10^{-1}
Material (M)	1	0.32	0.27	1.82	0.11	0.15	63.91^*	1.03	0.63	0.63	7.02	2.64	18.90	6.89	2.72
Rate (R)	3	1.96	2.54	1.48	4.95	2.51	6.65	3.19	6.30	0.91	17.19	1.15	30.55	3.39	1.44
M x R	3	0.21	0.73	2.15	2.52	3.13	8.48	0.36	0.72	0.71	1.47	0.57	13.35	1.11	0.67
Block	3	6.35^{***}	6.81	0.27	14.65	1.27	22.62	1.51	15.88	0.86	41.71^{***}	18.60	28.68	7.17	0.24
Error (a)	21	0.44	9.99	1.81	16.45	1.15	9.98	1.30	4.60	1.08	18.37	2.36	42.56	2.64	0.76
Sampling (S)	3	6.87^{***}	47.04^{***}	8.72^{***}	19.79^{***}	34.35^{***}	15.75^{***}	5.84^{***}	55.80^{***}	1.77^*	21.61^{**}	11.11^*	29.43	18.58^{***}	17.35^{***}
M x S	3	0.61	0.25	0.12	1.08	0.12	0.73	0.16	1.67	0.54	1.11	0.19	0.57	0.04	0.50
R x S	9	0.30	2.19	0.92	0.99	0.79	0.75	0.32	1.33	0.41	2.56	0.62	6.31	0.81	0.37
M x R x S	9	0.40	1.21	0.62	0.75	0.27	0.43	0.43	0.41	0.60	0.51	0.16	3.05	0.27	0.50
Error (b)	72	0.79	1.71	0.47	2.06	0.56	1.76	0.33	1.61	0.57	4.61	2.24	11.87	1.17	0.46

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 18. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, May 2000, Apr. 2001, and Mar. 2003 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Sacul fine sandy loam, Nacogdoches Co. TX, at a soil depth of 90 to 120 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
			x 10^3	x 10^3	x 10^4	x 10^2	x 10^3	x 10^2	x 10^{-1}	x 10^1	x 10^{-2}	x 10^2	x 10^4	x 10^{-2}	x 10^{-1}
Material (M)	1	0.56	5.14	0.12	6.73	0.17	9.50	0.22	0.72	1.18	6.71	2.87	0.32	0.75	0.15
Rate (R)	3	8.10	5.39	19.94	17.12	0.32	1.97	0.98^{**}	13.22^{*}	0.26	36.02	1.09	33.32^{*}	0.33	0.45
M x R	3	0.70	2.08	13.25	2.98	0.15	1.91	0.25	0.33	0.31	4.26	3.39	6.09	0.14	0.48
Block	3	17.13^{*}	1.40	9.04	0.36	0.64	6.40	1.98^{***}	2.92	0.58	31.80	15.60^{***}	9.83	4.73^{*}	0.73^{*}
Error (a)	21	3.53	3.49	6.95	7.58	0.46	4.30	0.19	2.73	0.36	18.64	1.70	9.90	1.04	0.19
Sampling (S)	3	20.83	60.93	60.11	20.73	14.45	8.62	1.70	76.90	3.21	26.04	9.96	43.17	8.00	16.85
M x S	3	0.96	0.80	0.29	0.35	0.48	0.74	0.14	0.31	0.15	0.80	0.40	1.92	1.30	0.13
R x S	9	7.08	0.78	6.15^{*}	1.36	0.39	2.50	0.31	0.89	0.38	25.33^{**}	1.98	2.01	0.39	0.49
M x R x S	9	1.98	1.04	2.20	0.63	0.47	0.57	0.32	0.95	0.11	1.31	1.33	2.49	0.31	0.30
Error (b)	72	5.67	0.75	2.96	1.61	0.52	1.93	0.60	1.71	0.34	9.13	1.79	11.02	1.06	0.26

*, **, *** Significant at 0.05, 0.01, and 0.00,1 respectively.

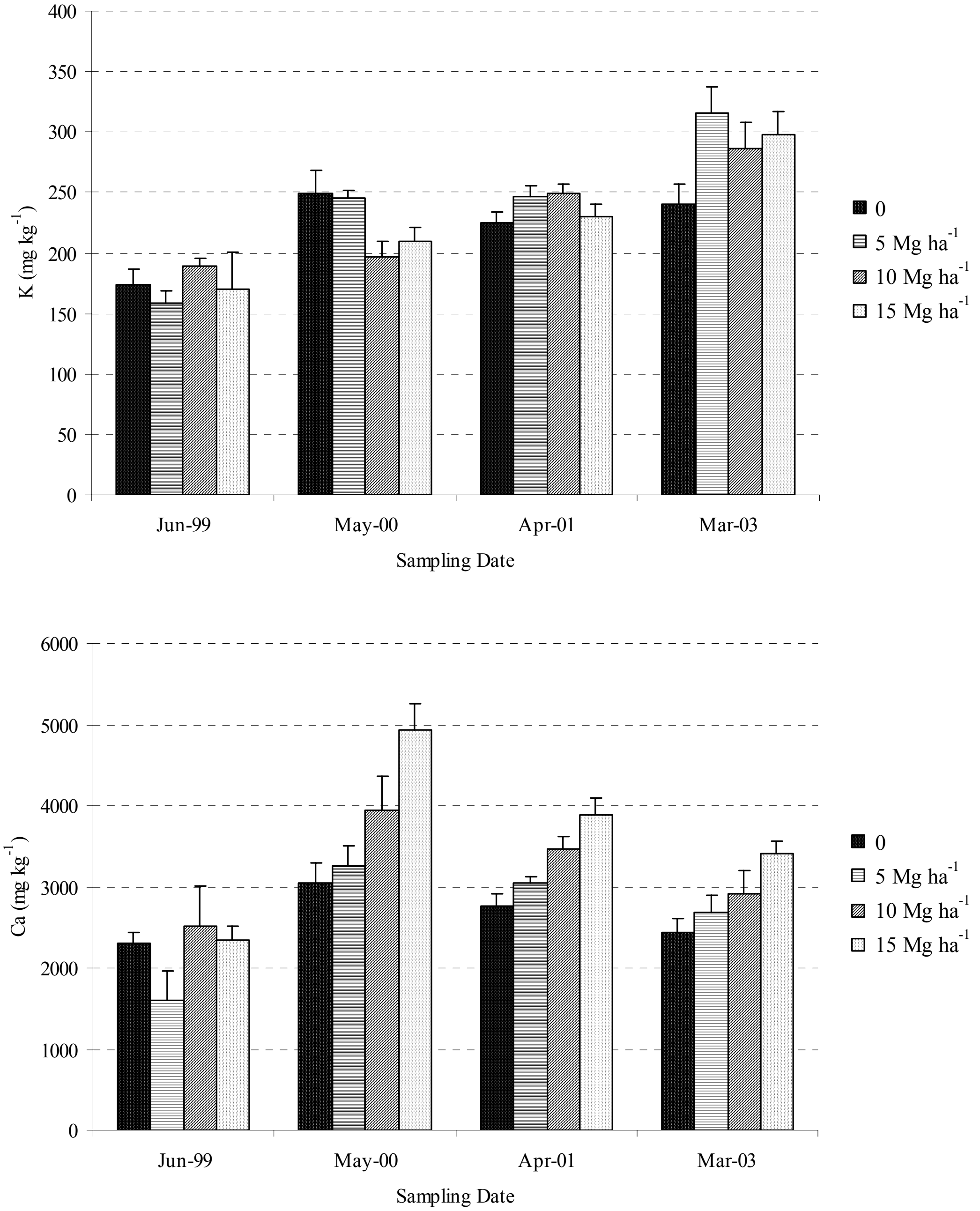


Figure 20. Mehlich-3 extractable potassium and calcium and standard errors at 0-15 cm on four sampling dates with four rates of surface-applied gypsum on the Sacul soil, Nacogdoches Co. TX.

shows mean squares for the effect of material, rate, and time of sampling on measured parameters at 0 to 15 cm. Rate effects were significant only for Ca and S. Significant rate by time of sampling effects are noted for Mehlich-3 extractable K, Ca, and S. Potassium levels generally increased in the top 15 cm throughout the study due to applied K without regard to rate of amendment applied (Figure 20). Moreover, means averaged across materials and rates show that K levels continued to increase with time down to 120 cm throughout the experiment (Table 19). The trend for Mg was similar. From Oct. 1999 to Aug. 2002, approximately 975 and 125 kg ha^{-1} of actual K and Mg, respectively, were applied to the plots (Table 3). The high K fertilizer application rate exceeded plant requirements leading to the increased levels, and also would probably confound any treatment effect, if present. Extractable calcium levels in the surface soil were highest at the May 2000 sampling and declined throughout the study as the materials continued to solubilize and move down in the soil (Figure 20). In addition to the highly significant rate by sampling effect on S in the surface soil, highly significant rate by sampling effects on S also were observed at the 15 to 30 and 30- to 60-cm depths (Tables 15 and 16). Sulfur in the surface soil decreased throughout the study for all rates of gypsum except the medium rate between May 2000 and Apr. 2001 (Figure 21). By May 2000, S at 15 to 30 cm had increased for all rates of gypsum, and some indication of higher S levels at 30 to 60 cm at this sampling could be seen. Sulfur continued to move from the surface as levels in subsoil depths increased for all gypsum rates at both the 2001 and 2003 samplings. No significant rate, or rate-by-sampling effects were observed below 60 cm (Tables 17 and 18). Ritchey et al. (1995) reported rapid downward movement of SO_4 after surface application of gypsum to a Brazilian soil. They found SO_4 below 1 m 2 yr after applying 6 Mg ha^{-1}. However, 10 yr after incorporation of 10 Mg gypsum ha^{-1}, Farina et al. (2000b) did not find evidence of SO_4 resulting from treatment below 75 cm.

Although there were no significant differences related to material, Figures 22 to 30 are presented to allow comparison of the materials, and to show changes in selected parameters during the experiment in both the high gypsum and high sludge plots.

Table 19. Influence of time of sampling on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC, at each depth in a Sacul fine sandy loam, Nacogdoches Co. TX.

Depth (cm)	Sampling Date	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		mg kg^{-1}														dS m^{-1}
0-15	7 June 1999	12.0^{c}	165^{c}	2264^{d}	479^{a}	22^{d}	311^{a}	30.57^{a}	0.61^{b}	3.30^{a}	3.33^{b}	1.5^{b}	31^{a}	5.00^{b}	5.80^{a}	—
	5 May 2000	18.8^{b}	230^{b}	3662^{a}	449^{ab}	583^{a}	264^{b}	25.84^{b}	1.06^{a}	2.20^{a}	3.13^{bc}	1.2^{b}	16^{a}	5.14^{ab}	5.32^{c}	$.85^{a}$
	30 Apr 2001	26.3^{a}	228^{b}	3316^{b}	387^{c}	415^{b}	273^{b}	23.73^{bc}	1.09^{a}	3.24^{a}	4.23^{a}	3.0^{a}	18^{a}	5.26^{a}	5.55^{b}	$.60^{b}$
	5 Mar 2003	23.7^{a}	284^{a}	2793^{c}	437^{b}	157^{c}	305^{a}	22.23^{c}	1.31^{a}	3.00^{a}	2.62^{c}	3.4^{a}	14^{a}	5.04^{b}	5.38^{c}	$.33^{c}$
15-30	7 June 1999	2.9^{b}	156^{c}	827^{d}	596^{b}	20^{d}	102^{b}	6.71^{b}	0.74^{b}	2.21^{a}	1.64^{b}	22.9^{a}	532^{a}	3.87^{b}	5.02^{a}	—
	5 May 2000	2.6^{b}	149^{c}	1132^{c}	586^{b}	87^{c}	101^{b}	6.83^{b}	1.20^{a}	1.48^{a}	1.86^{b}	24.7^{a}	742^{a}	3.91^{b}	4.45^{b}	$.18^{c}$
	30 Apr 2001	4.4^{a}	195^{b}	1282^{b}	565^{b}	126^{b}	127^{a}	7.17^{b}	1.05^{ab}	1.95^{a}	2.54^{a}	25.1^{a}	581^{a}	4.01^{a}	4.53^{b}	$.23^{b}$
	5 Mar 2003	4.1^{a}	226^{a}	1401^{a}	684^{a}	168^{a}	123^{a}	9.03^{a}	1.42^{a}	2.21^{a}	1.95^{b}	24.2^{a}	573^{a}	3.74^{c}	4.22^{c}	$.27^{a}$
30-60	7 June 1999	1.9^{b}	163^{b}	343^{c}	635^{b}	18^{d}	116^{bc}	1.68^{c}	0.95^{c}	3.40^{a}	0.47^{b}	48.4^{a}	951^{a}	3.61^{b}	4.90^{a}	—
	5 May 2000	1.6^{b}	150^{b}	426^{b}	592^{b}	28^{c}	107^{c}	1.77^{c}	1.14^{bc}	1.87^{b}	0.53^{b}	48.4^{a}	1114^{a}	3.70^{a}	4.59^{b}	$.06^{c}$
	30 Apr 2001	1.9^{b}	217^{a}	545^{a}	600^{b}	51^{b}	135^{ab}	2.25^{b}	1.33^{b}	2.65^{ab}	0.83^{a}	54.4^{a}	1134^{a}	3.66^{ab}	4.40^{c}	$.12^{b}$
	5 Mar 2003	2.7^{a}	233^{a}	610^{a}	772^{a}	89^{a}	146^{a}	3.66^{a}	1.79^{a}	3.10^{a}	0.81^{a}	47.6^{a}	1081^{a}	3.53^{c}	3.96^{d}	$.18^{a}$
60-90	7 June 1999	1.3^{b}	200^{b}	202^{b}	798^{a}	12^{c}	198^{a}	0.93^{b}	1.22^{c}	4.13^{a}	0.26^{b}	60.1^{b}	1240^{a}	3.45^{b}	4.82^{a}	—
	5 May 2000	1.4^{b}	166^{c}	228^{b}	670^{b}	14^{c}	149^{b}	1.18^{b}	1.36^{c}	2.42^{b}	0.34^{b}	64.6^{ab}	1389^{a}	3.57^{a}	4.59^{b}	$.06^{c}$
	30 Apr 2001	1.3^{b}	244^{a}	291^{a}	700^{b}	24^{b}	192^{a}	1.16^{b}	1.61^{b}	3.65^{ab}	0.46^{a}	69.8^{a}	1273^{a}	3.47^{b}	4.47^{c}	$.13^{a}$
	5 Mar 2003	2.3^{a}	246^{a}	314^{a}	835^{a}	35^{a}	185^{a}	1.91^{a}	2.17^{a}	3.77^{ab}	0.33^{b}	56.1^{b}	1443^{a}	3.38^{c}	4.27^{d}	$.12^{b}$
90-120	7 June 1999	3.0^{a}	199^{c}	188^{b}	809^{bc}	11^{c}	274^{b}	2.34^{a}	1.37^{d}	3.96^{b}	0.25^{a}	62.3^{b}	1411^{b}	3.32^{b}	4.75^{a}	—
	5 May 2000	2.2^{ab}	190^{c}	205^{b}	763^{c}	11^{c}	268^{b}	2.64^{a}	1.61^{c}	3.23^{b}	0.38^{a}	70.3^{a}	1661^{a}	3.39^{a}	4.37^{b}	$.11^{a}$
	30 Apr 2001	1.1^{b}	283^{a}	264^{a}	855^{b}	17^{b}	302^{a}	1.25^{a}	1.97^{b}	4.96^{a}	0.43^{a}	71.1^{a}	1540^{ab}	3.30^{b}	4.30^{bc}	$.10^{a}$
	5 Mar 2003	2.2^{ab}	251^{b}	276^{a}	951^{a}	25^{a}	267^{b}	1.72^{a}	2.50^{a}	5.45^{a}	0.27^{a}	60.0^{b}	1648^{a}	3.27^{b}	4.25^{c}	$.11^{a}$

Means within a class followed by the same letter are not different at the 0.05 significance level.

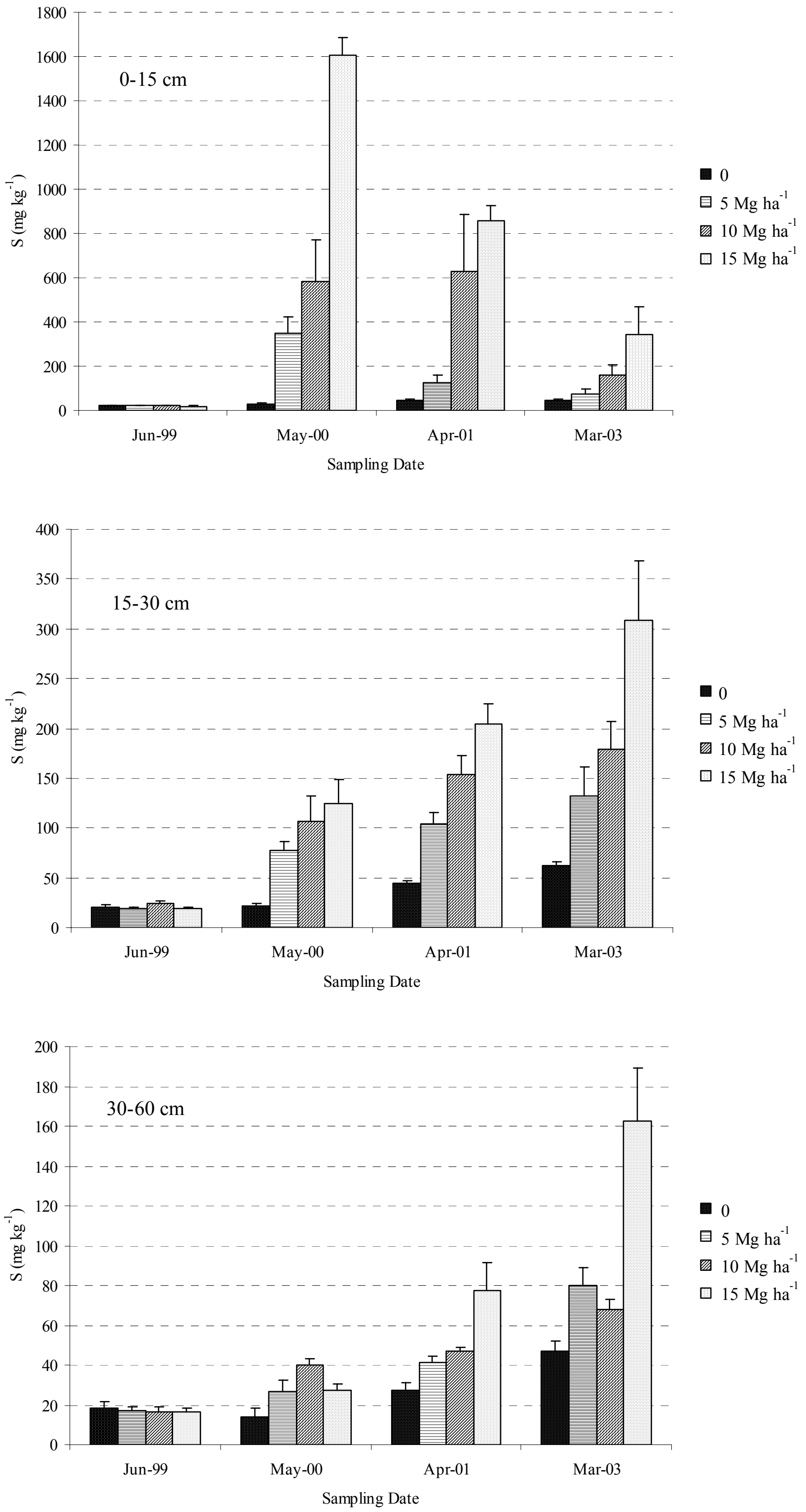
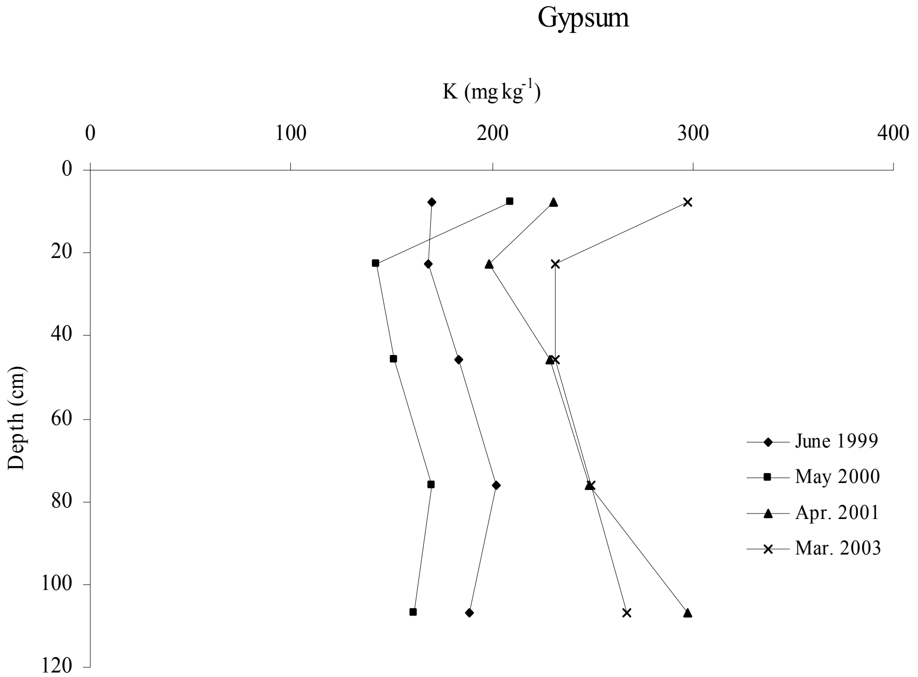


Figure 21. Mehlich-3 extractable sulfur and standard errors at 0-15, 15-30 and 30-60 cm on four sampling dates with four rates of gypsum on the Sacul soil, Nacogdoches Co. TX.



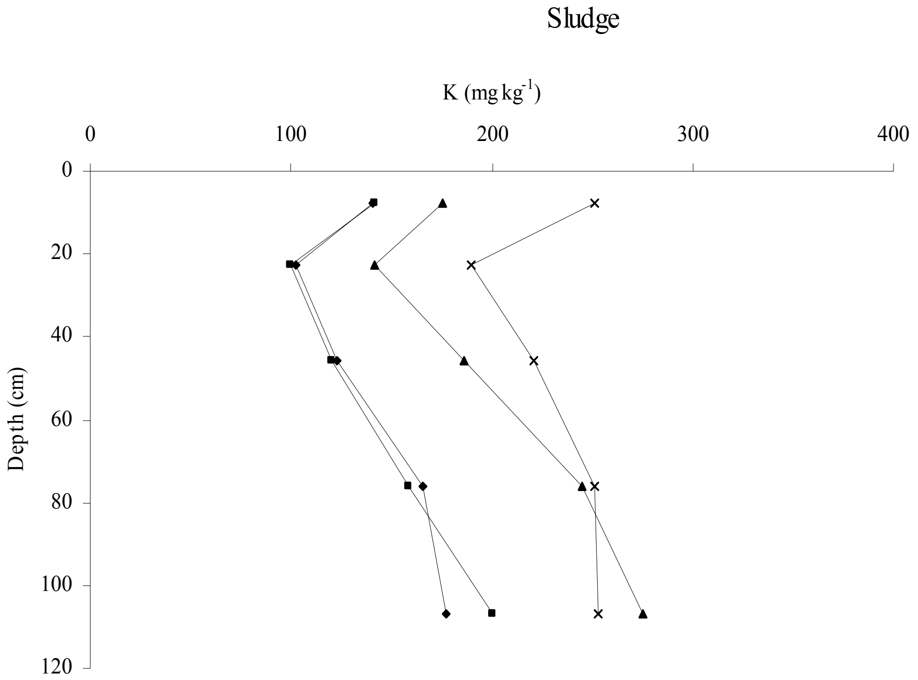


Figure 22. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable potassium at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.

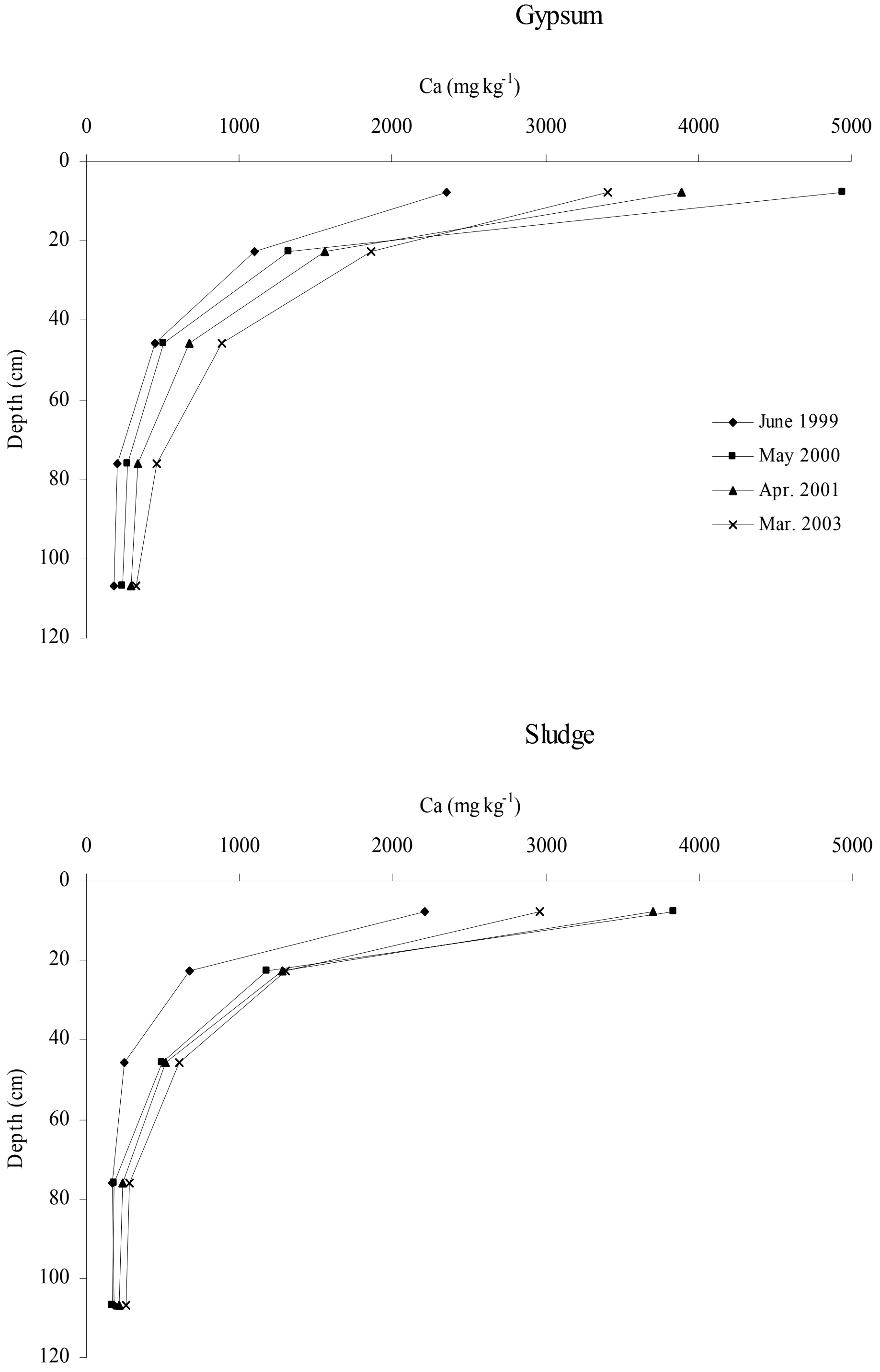
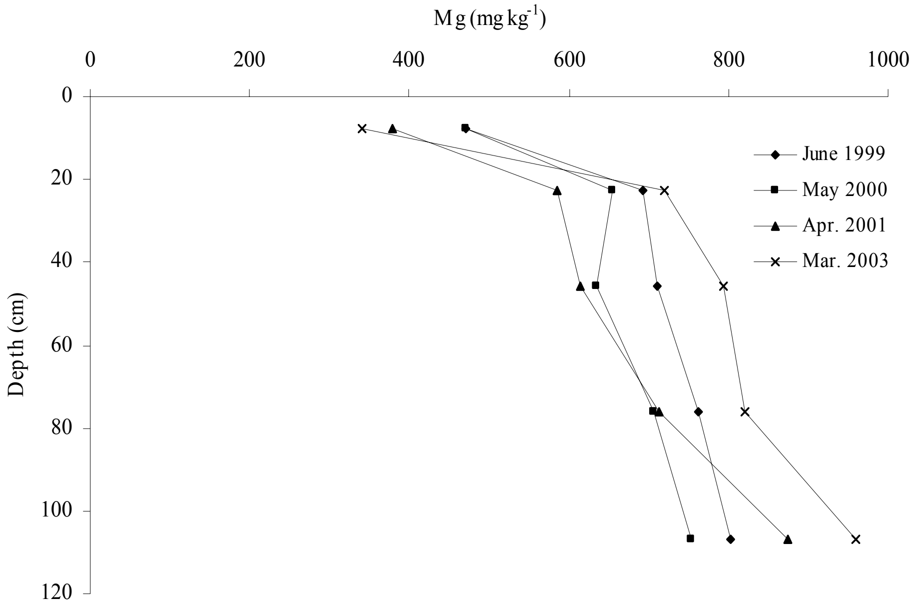


Figure 23. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable calcium at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.

Gypsum



Sludge

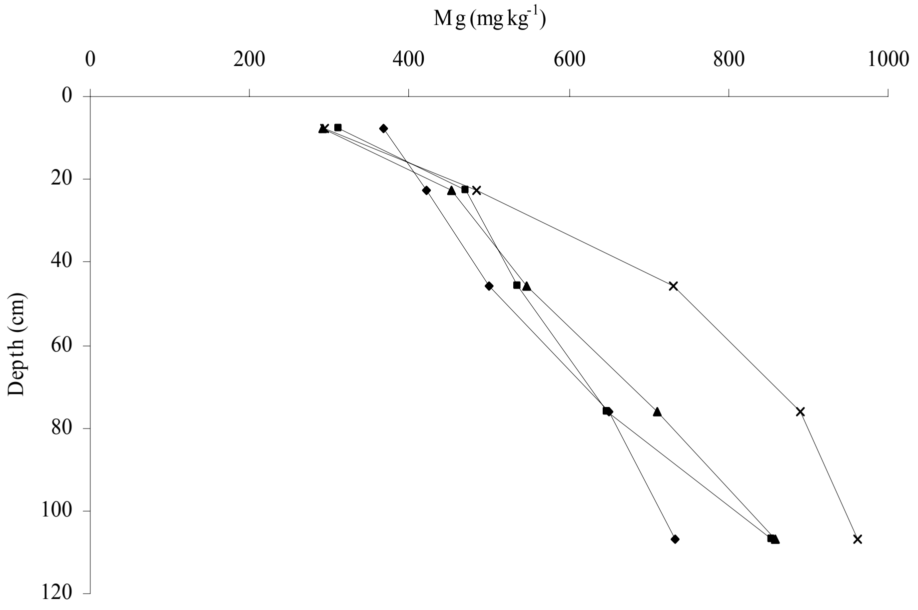
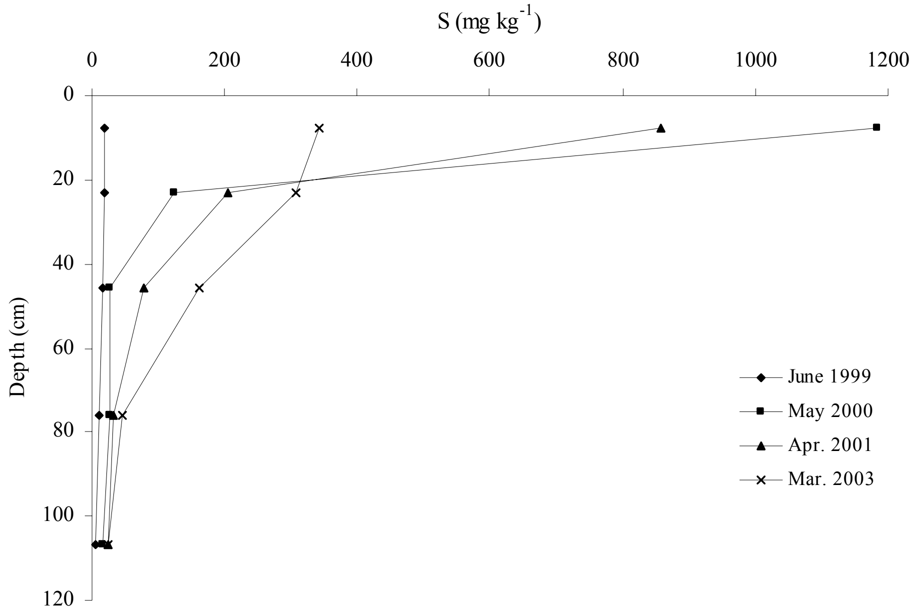


Figure 24. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable magnesium at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.

Gypsum



Sludge

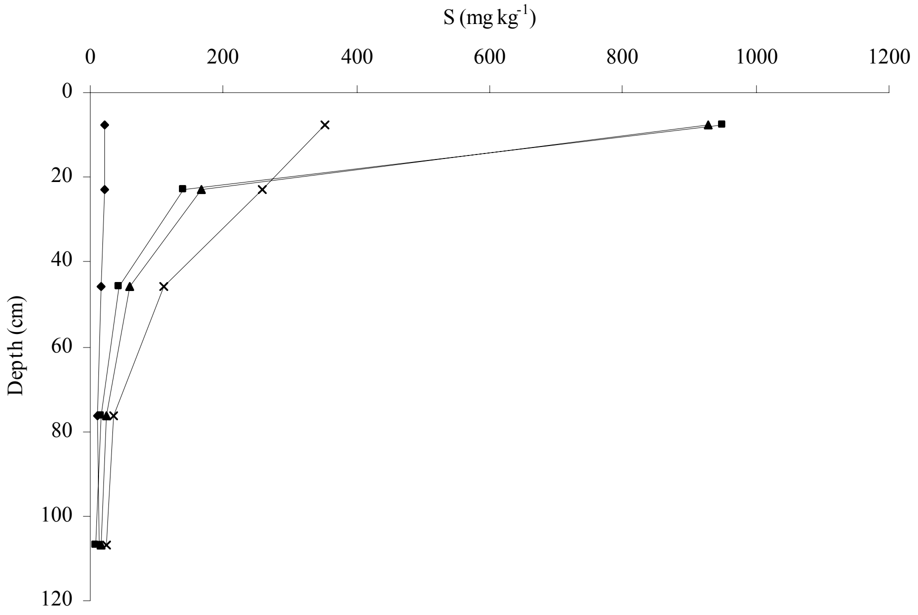


Figure 25. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable sulfur at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.

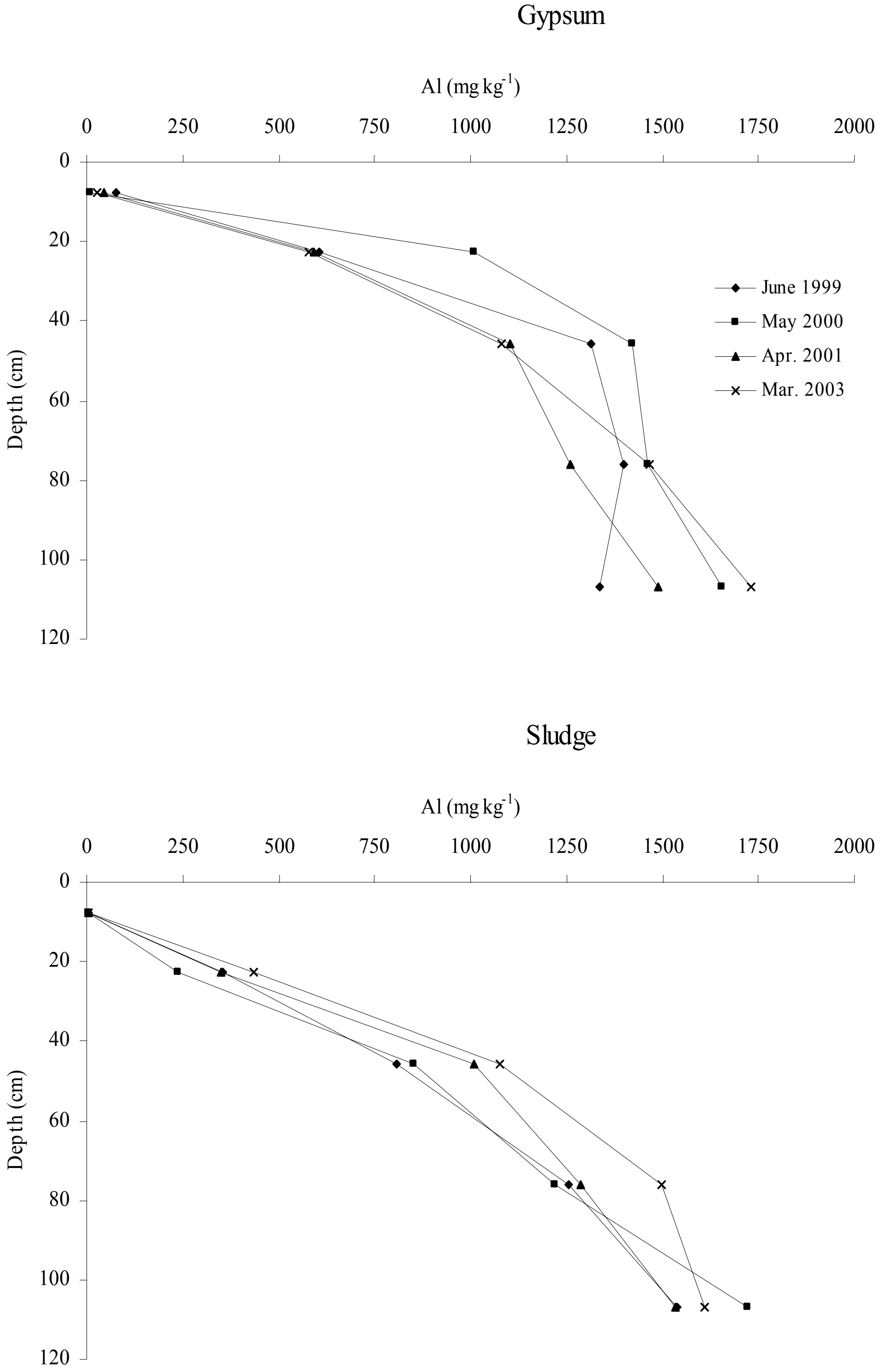


Figure 26. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on *N* KCl extractable Al at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.

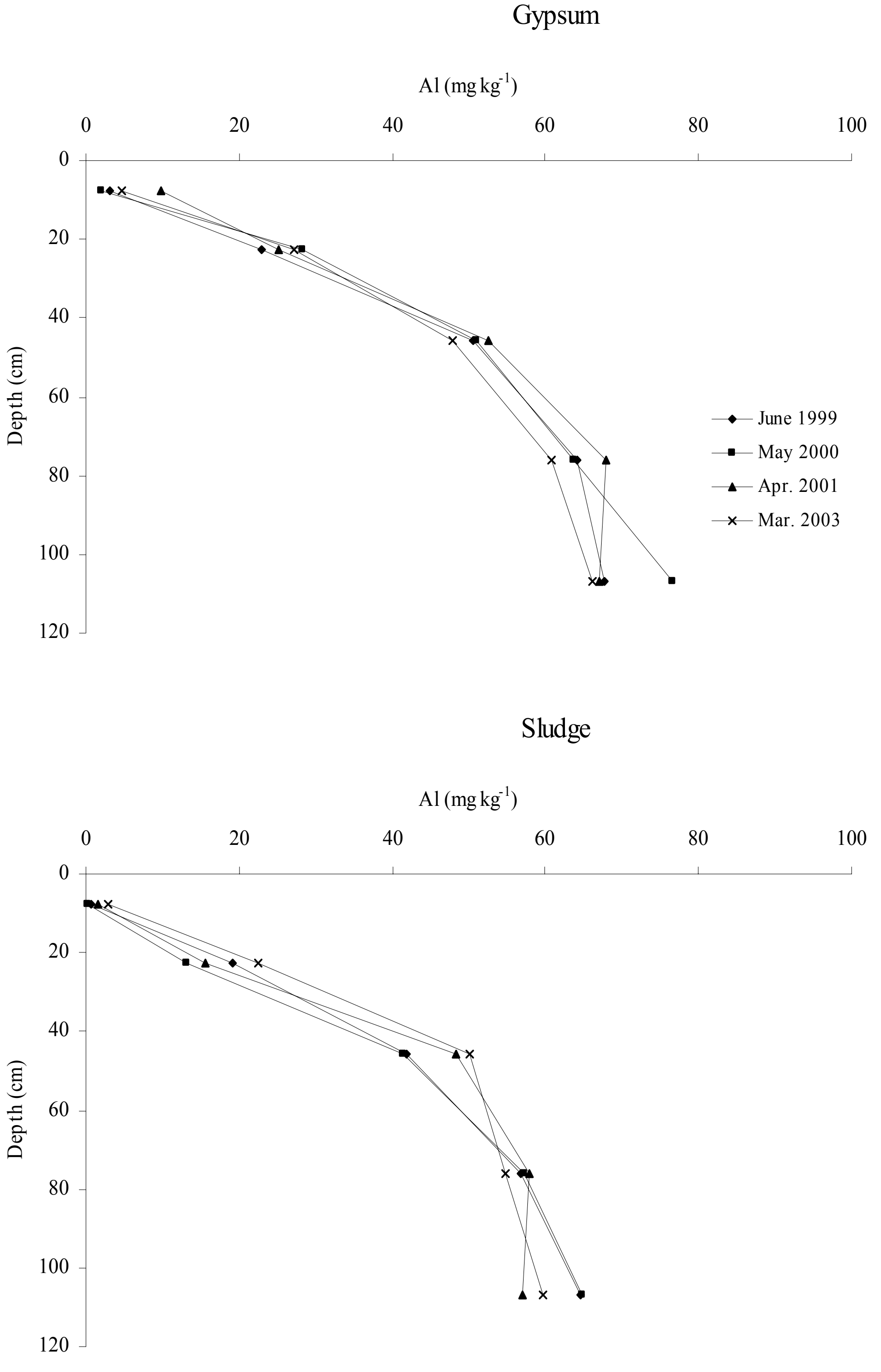
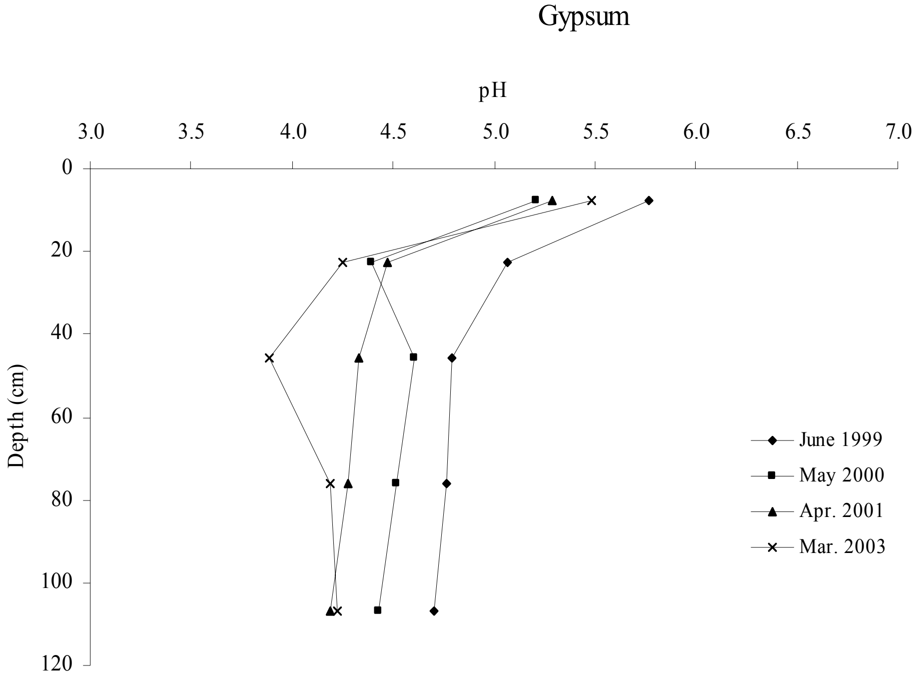


Figure 27. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on 0.01 *M* $CaCl_2$ exchangeable aluminum at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.



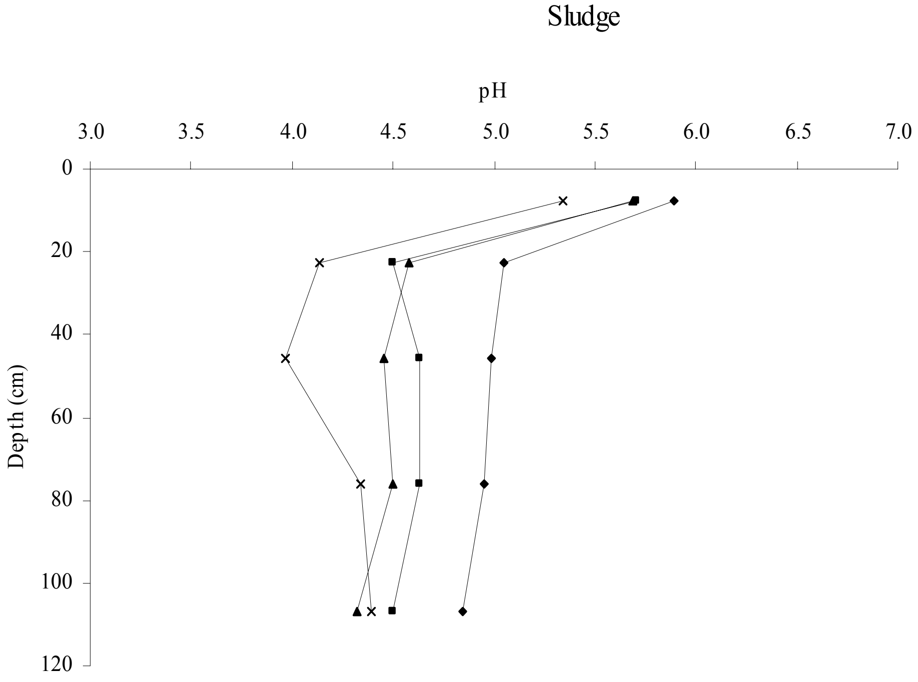


Figure 28. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on 2:1 water to soil pH at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.

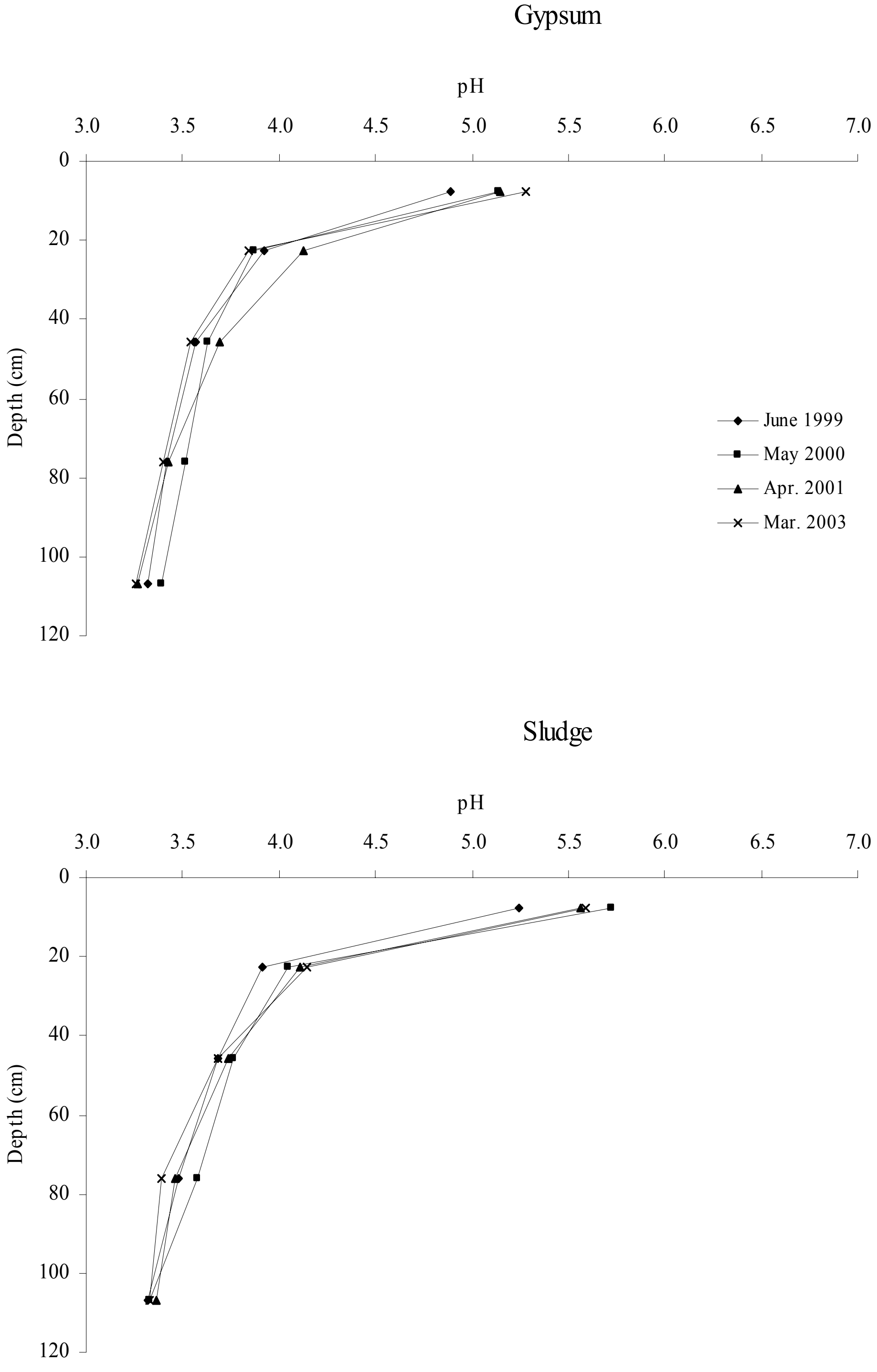


Figure 29. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on 2:1 .01 *M* $CaCl_2$ to soil pH at different depths on four sampling dates on the Sacul soil, Nacogdoches Co. TX. June 1999 sampling was prior to treatment.

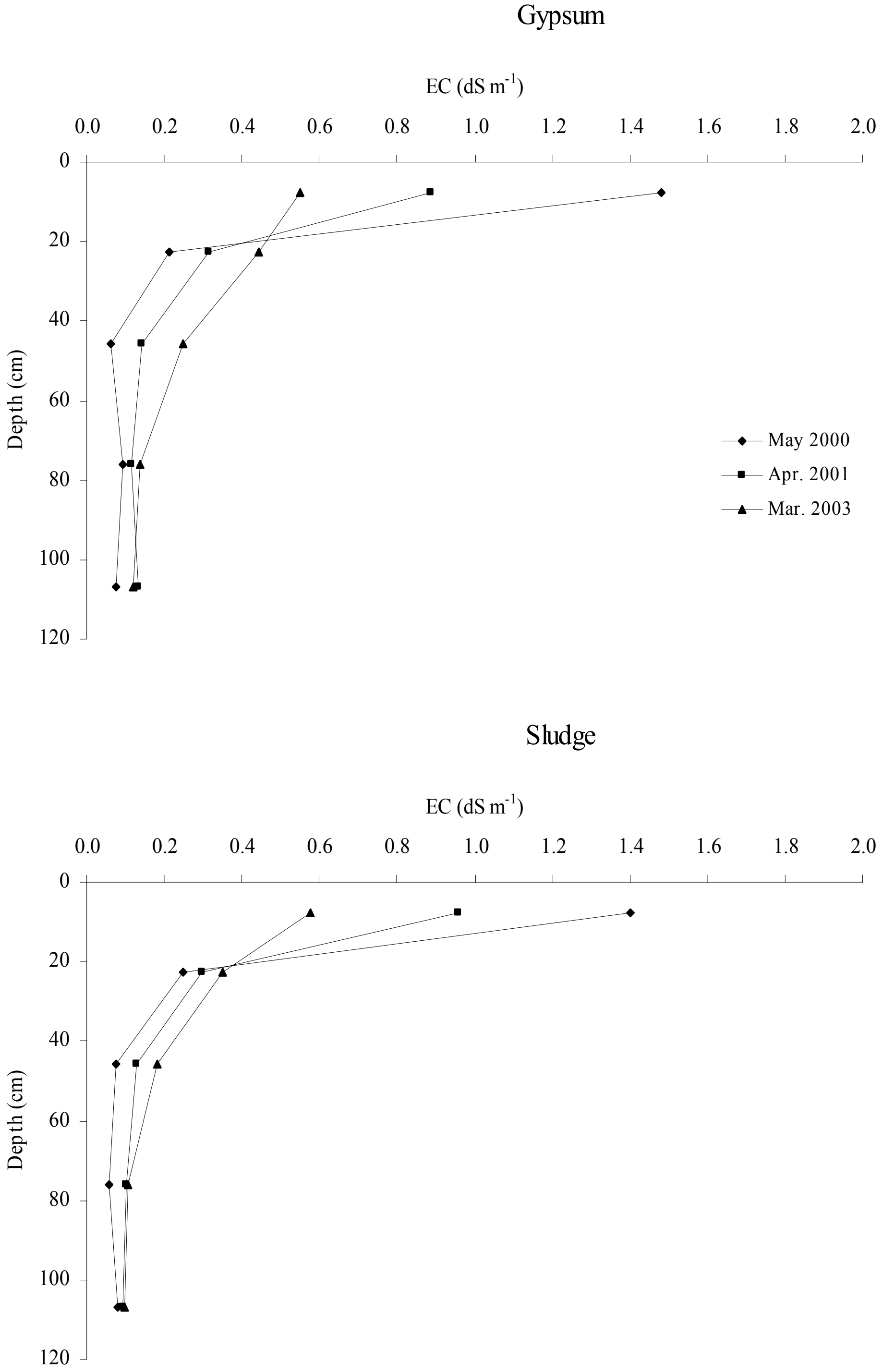


Figure 30. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on electrical conductivity at different depths on three sampling dates on the Sacul soil, Nacogdoches Co. TX.

Potassium levels varied considerably without any discernible trend related to time of sampling (Figure 22). Exchangeable Ca at the surface in the high rate gypsum plots decreased from about 5000 to about 3500 mg kg^{-1}, while levels increased at each sampling at each depth from 15 to 90 cm (Figure 23). Magnesium in the subsoil depths was highest at the Mar. 2003 sampling and increased with depth for both materials (Figure 24). Sulfur from both materials had moved into the subsoil to 60 cm (Figure 25). Extractable Al (Figure 26) and exchangeable Al (Figure 27) did not change in any consistent way at any depth. Water pH was lowest at 30 to 60 cm for both materials and lower in all samplings after treatment application (Figure 28). However, pH_{CaCl_2} was relatively unchanged at all subsoil depths (Figure 29). Electrical conductivity was not measured on the initial soil samples. Surface EC decreased throughout the study with a corresponding increase in subsurface conductivity down to 60 cm (Figure 30). The differences in EC over time were similar to the response noted for S, and were more evident in the gypsum than sludge plots.

Cuthbert Soil, Rusk County. As with the Sacul soil, significant depth effects that are not related to material or rate will not be discussed. In the 1999 sampling (1 MAT), there were significant rate effects for Ca, S, and Zn, significant material by depth interactions for Mehlich-3 extractable and 0.01 *M* $CaCl_2$ exchangeable Mn, and significant rate by depth interactions for K, Ca, and S (Table 20). Separations for Ca and S were similar, with the only difference seen between the high rate and all the others (Table 21). Potassium levels at 15 to 30 and 30 to 60 cm were higher for the check plots than for plots that received the low, medium, and high gypsum rates (Figure 31). Surface soil Ca levels increased with increasing gypsum rate, but plots receiving gypsum had lower levels of Ca at 15-30 cm than the check plots (Figure 32). Sulfur increased in the surface soil with increasing gypsum rate (Figure 33).

At the 2000 sampling, rate and rate by depth interactions were highly significant for Ca, S, and EC (Table 22). Calcium was not different for the zero and low rate plots (Table 23), but S increased significantly with increasing rate. Electrical

Table 20. Analysis of variance for the effects of gypsum and scrubber sludge at three soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Aug. 1999.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
		x 10^2	x 10^4	x 10^5	x 10^3	x 10^6	x 10^4	x 10^1	x 10^{-2}	x 10^{-1}	x 10^{-1}	x 10^2	x 10^3	x 10^{-2}	x 10^{-2}
Material (M)	1	0.18	0.86	0.23	0.23	1.05	0.13	0.43	5.43	4.41	5.40^{*}	0.13	0.25	0.29	0.35
Rate (R)	3	0.52	1.12	6.42^{**}	52.89	2.36^{**}	0.09	0.21	4.87	27.20^{*}	2.08	2.40	17.76	0.77	12.10
M x R	3	0.43	0.77	0.40	14.85	0.52	0.15	0.19	4.59	4.35	1.24	0.33	34.76	0.23	0.62
Block	3	0.47	0.23	0.69	14.79	0.23	0.37	1.08	27.78^{**}	57.60	3.87^{*}	1.27	42.69	4.66	11.87
Error (a)	21	0.69	0.64	1.03	20.25	0.41	0.29	0.47	5.26	6.87	0.85	2.00	62.84	27.23	27.23
Depth (D)	2	45.87^{***}	12.24^{***}	43.02^{***}	30.73	3.36^{***}	2.36^{***}	11.19^{***}	5.46	10.17	0.97	56.45^{***}	89.45^{***}	90.09^{***}	99.31^{***}
M x D	2	0.16	0.18	0.23	3.90	0.38	0.08	0.56^{*}	0.33	0.11	3.30^{*}	0.17	0.12	0.69	0.47
R x D	6	0.70	0.69^{**}	8.92^{***}	10.36	1.20^{***}	0.11	0.33	2.47	4.63	0.76	1.03	10.87	1.97	5.95
M x R x D	6	0.23	0.31	0.42	7.45	0.13	0.05	0.33	4.35	7.81	0.82	0.89	12.76	5.77	1.81
Error (b)	48	0.59	0.20	1.11	10.97	0.15	0.12	0.15	3.64	4.15	0.90	0.55	19.34	8.38	7.86

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 21. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Aug. 1999.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		mg kg^{-1}													
Material	Gypsum	13.5	167	1510	257	234	51.2	2.64	0.57	0.86	0.40^{b}	14.4	255	4.56	4.94
	Sludge	12.7	186	1541	257	443	44.0	3.07	0.53	1.00	0.55^{a}	14.6	255	4.56	4.93
Rate (Mg ha^{-1})	0	10.9	173	1308^{b}	324	65^{b}	48.9	2.65	0.51	0.77^{ab}	0.37	11.2	259	4.58	5.01
	5	13.8	162	1388^{b}	240	160^{b}	55.0	2.63	0.56	1.03^{ab}	0.43	12.6	284	4.55	4.92
	10	13.7	208	1612^{ab}	250	359^{b}	40.3	3.26	0.61	1.35^{a}	0.56	18.0	258	4.57	4.96
	15	14.0	163	1713^{a}	215	772^{a}	46.2	2.89	0.52	0.57^{b}	0.55	16.3	218	4.54	4.84
Depth (cm)	0-15	26.9^{a}	246^{a}	2779^{a}	224	712^{a}	79.0^{a}	5.02^{a}	0.52	1.11	0.54	1.3^{c}	2^{c}	5.53^{a}	5.77^{a}
	15-30	6.7^{b}	157^{b}	1183^{b}	285	137^{b}	33.0^{b}	1.76^{b}	0.54	0.76	0.45	14.5^{b}	310^{b}	4.14^{b}	4.61^{b}
	30-60	5.7^{b}	127^{c}	614^{c}	262	167^{b}	30.8^{b}	1.79^{b}	0.60	0.92	0.44	27.8^{a}	452^{a}	4.00^{b}	4.42^{c}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

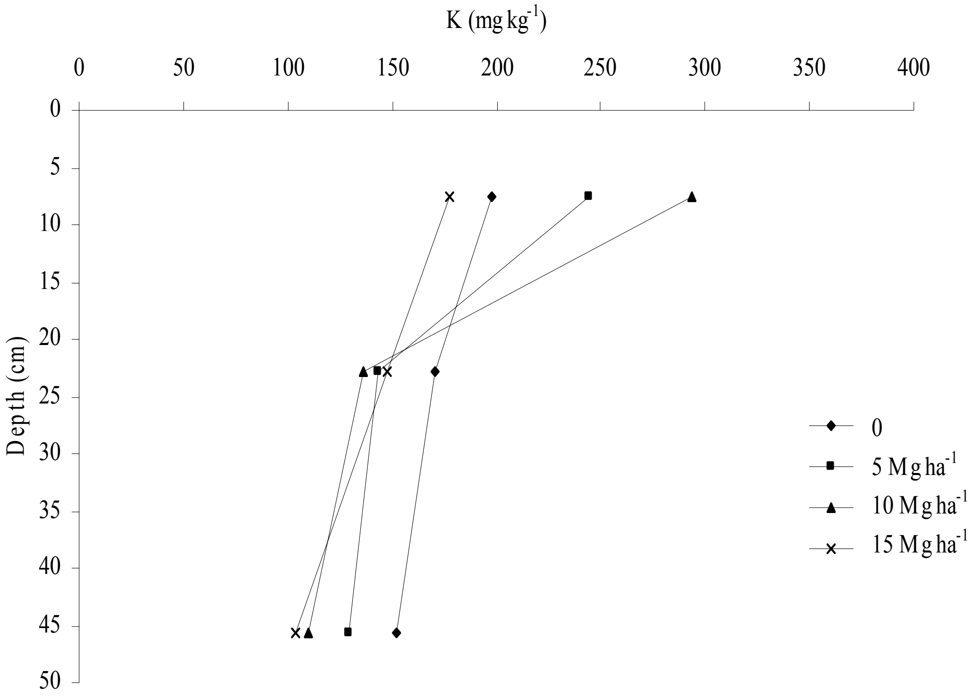


Figure 31. Mehlich-3 extractable potassium at different depths in the Cuthbert soil, Rusk Co. TX, sampled in Aug. 1999, 1 mo after treatment with four rates of gypsum.

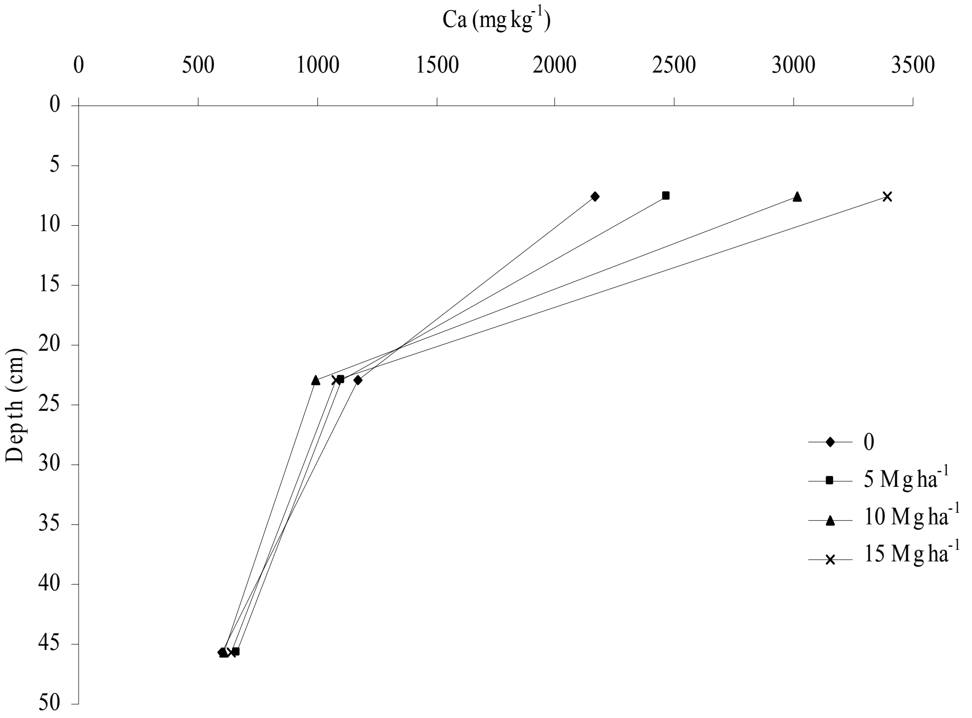


Figure 32. Mehlich-3 extractable calcium at different depths in the Cuthbert soil, Rusk Co. TX, sampled in Aug. 1999, 1 mo after treatment with four rates of gypsum.

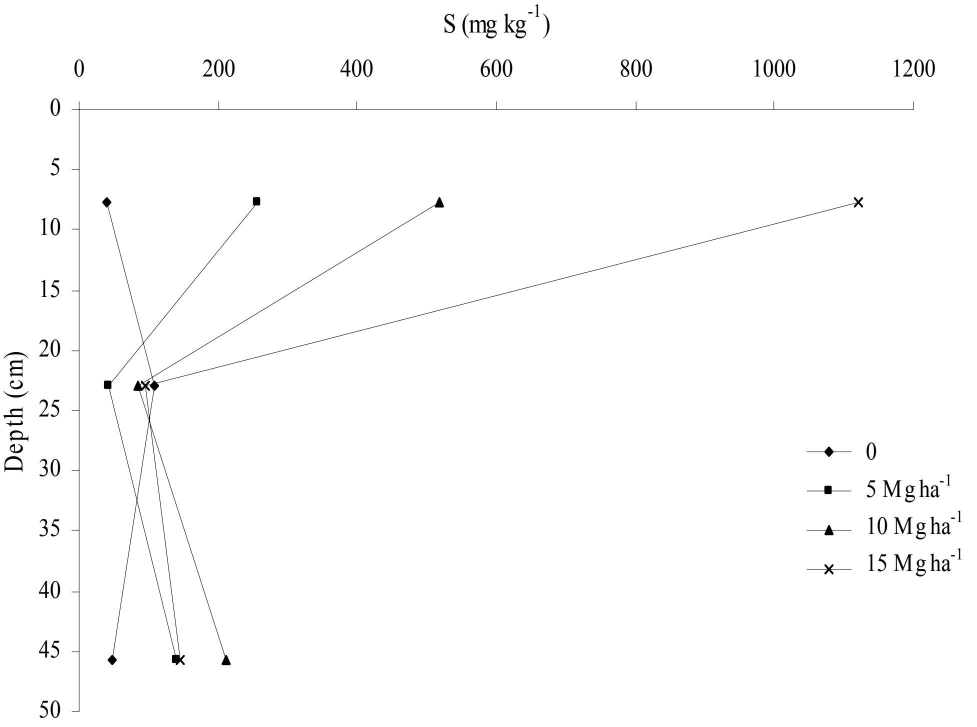


Figure 33. Mehlich-3 extractable sulfur at different depths in the Cuthbert soil, Rusk Co. TX, sampled in Aug. 1999, 1 mo after treatment with four rates of gypsum.

Table 22. Analysis of variance for the effects of gypsum and scrubber sludge at five soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Apr. 2000.

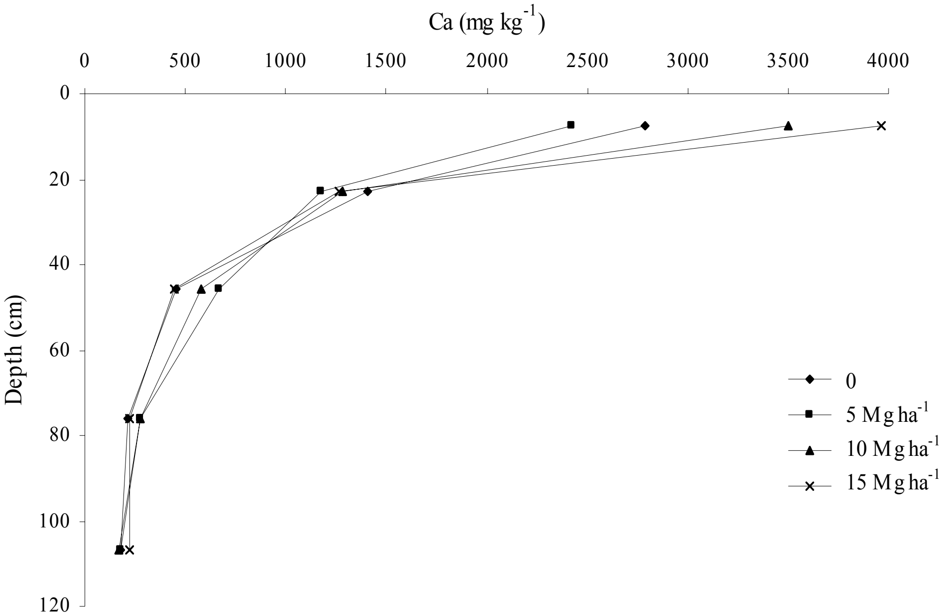
Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		Mean Squares														
		x 10^2	x 10^4	x 10^5	x 10^4	x 10^4	x 10^3		x 10^{-1}		x 10^{-2}		x 10^5	x 10^{-1}	x 10^{-1}	x 10^5
Material (M)	1	0.14	0.12	0.80	2.57	1.11	0.49	1.49	4.44	0.82	2.70	0.91	0.27	0.12	0.81	0.65
Rate (R)	3	0.41	0.21	4.73***	1.51	40.86***	1.58	0.89	1.92	2.98	13.14	0.49	0.26	0.35	2.20	4.85***
M x R	3	1.03	0.14	0.34	0.67	1.25	1.45	1.88	0.91	2.72	1.92	0.72	0.14	0.56	0.38	1.21*
Block	3	0.66	1.23***	6.91***	0.81	1.63	1.25	5.09	4.68*	8.07*	31.16	2.22	3.33**	0.44	2.74	0.93
Error (a)	21	0.69	0.11	0.35	1.56	0.94	1.19	3.61	1.50	2.62	9.16	2.46	0.53	2.36	2.49	0.37
Depth (D)	4	95.46***	8.42***	53.82***	2.70*	50.95***	23.38***	39.45***	21.81***	1.38*	28.99***	90.14***	20.62***	51.87***	68.40***	37.26***
M x D	4	0.18	1.23	0.98	1.75	0.79	0.28	0.60	1.04	0.32	0.48	0.60	0.51	0.29	0.26	0.29
R x D	12	0.25	0.12	5.85***	0.41	28.45***	0.60	0.63	0.56	0.70	3.24	0.39	0.14	1.07	1.23*	2.55***
M x R x D	12	0.54	0.24	0.81	0.85	1.40	0.69	0.90	0.23	0.47	3.49	0.29	0.14	0.43	0.16	0.52
Error (b)	96	0.33	0.20	0.87	1.09	0.90	0.64	0.98	0.67	0.44	4.40	0.74	0.36	0.90	0.62	0.42

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 23. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Apr. 2000.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		mg kg^{-1}														dS m^{-1}
Material	Gypsum	14.4	147	1084	264	154	44.6	1.75	0.62	1.21	0.30	23.3	383	4.32	4.77	0.33
	Sludge	14.0	153	1127	239	138	41.1	1.95	0.51	1.07	0.33	21.8	357	4.31	4.76	0.37
Rate (Mg ha^{-1})	0	13.2	150	1006^{b}	280	35^{d}	40.7	1.74	0.67	1.21	0.24	22.7	347	4.34	4.84	0.22^{b}
	5	15.5	143	1009^{b}	236	95^{c}	52.2	2.05	0.54	1.09	0.37	21.6	349	4.33	4.82	0.29^{b}
	10	14.4	160	1184^{a}	247	193^{b}	38.4	1.89	0.52	1.46	0.35	24.1	394	4.27	4.69	0.45^{a}
	15	13.7	147	1223^{a}	243	262^{a}	40.2	1.72	0.54	0.80	0.30	21.9	390	4.31	4.71	0.43^{a}
Depth (cm)	0-15	46.1^{a}	235^{a}	3288^{a}	202	516^{a}	89.9^{a}	5.43^{a}	0.43^{c}	1.48^{a}	0.36^{a}	0.8^{d}	2^{d}	5.87^{a}	6.06^{a}	0.92^{a}
	15-30	11.9^{b}	159^{b}	1260^{b}	272	112^{b}	38.6^{b}	1.88^{b}	0.37^{c}	1.12^{ab}	0.43^{a}	10.5^{c}	248^{c}	4.21^{b}	4.52^{b}	0.42^{b}
	30-60	5.3^{c}	126^{c}	539^{c}	274	47^{c}	24.9^{b}	1.06^{c}	0.42^{c}	1.03^{b}	0.34^{a}	25.1^{b}	435^{b}	3.95^{c}	4.42^{b}	0.19^{c}
	60-90	4.1^{c}	109^{c}	245^{d}	255	28^{c}	24.8^{b}	0.44^{d}	0.60^{b}	0.93^{b}	0.22^{b}	36.4^{a}	503^{b}	3.81^{cd}	4.43^{b}	0.13^{c}
	90-120	3.6^{c}	119^{c}	196^{d}	255	26^{c}	36.1^{b}	0.44^{d}	1.00^{a}	1.13^{ab}	0.21^{b}	40.1^{a}	662^{a}	3.73^{d}	4.38^{b}	0.09^{c}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.



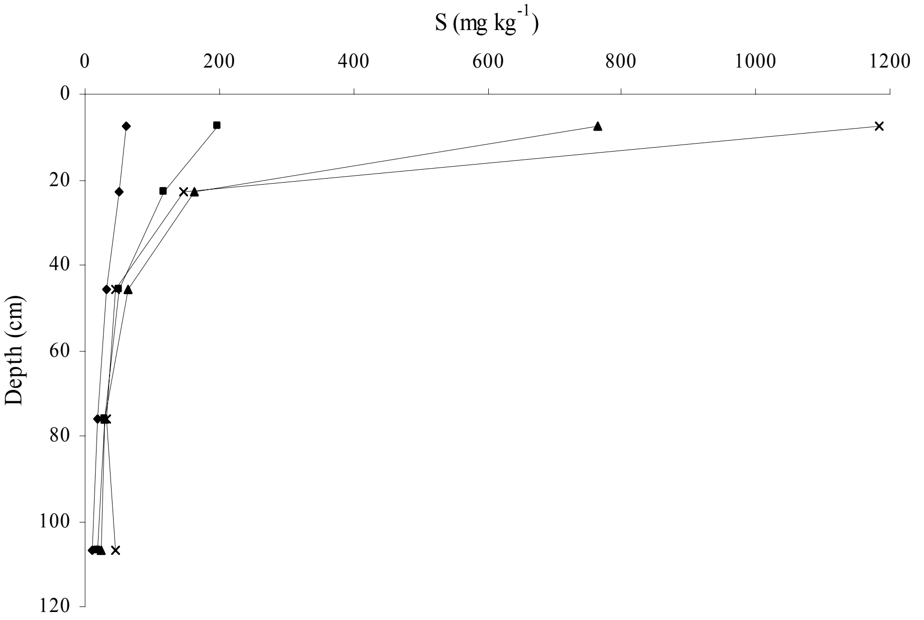
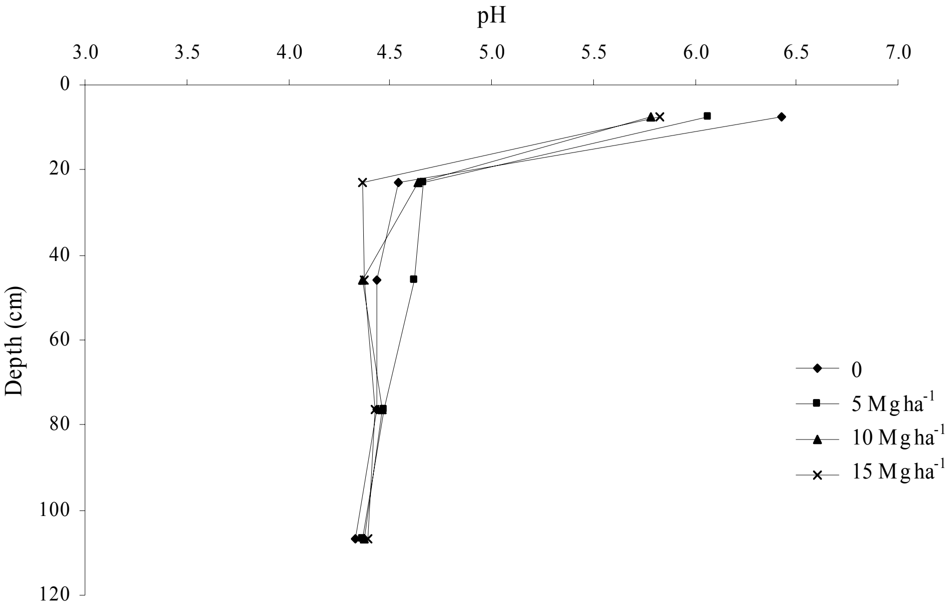


Figure 34. Mehlich-3 extractable calcium and sulfur at different depths in the Cuthbert soil, Rusk Co. TX, sampled in Apr. 2000, 11 mo after treatment with four rates of gypsum.



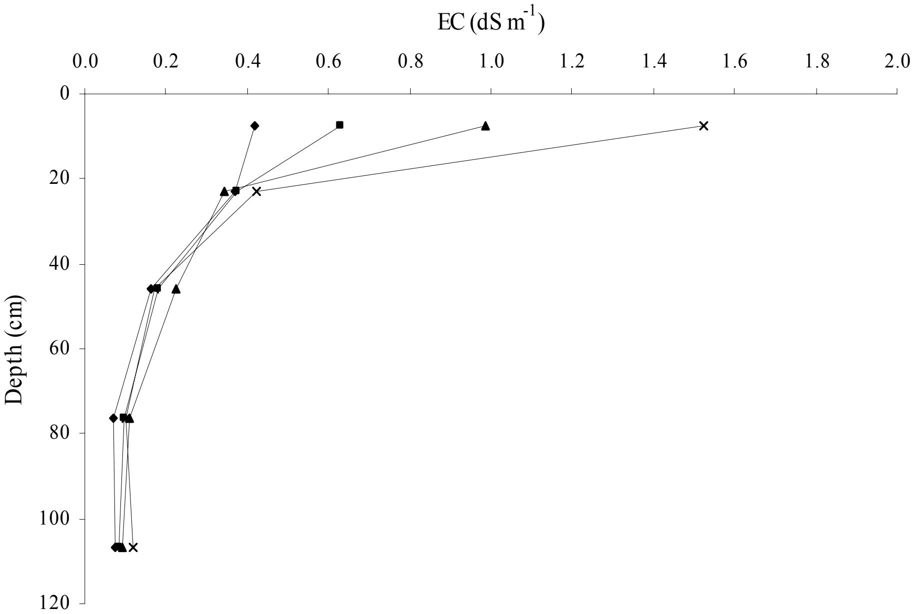


Figure 35. 2:1 water to soil pH and electrical conductivity at different depths in the Cuthbert soil, Rusk Co. TX, 11 mo after treatment with four rates of gypsum.

conductivity between the zero and low rate plots, and between the medium and high rate plots was not significantly different. Calcium in the surface soil appeared to be greater in the zero than in the low rate gypsum plots, but the difference was not significant (Figure 34). The lack of difference may be due to the high rate of limestone applied during the previous 13 mo which could mask the effect of the 5 Mg ha^{-1} treatment. As expected, S levels in the surface increased with increasing gypsum rate, and levels in the check plots changed little with depth (Figure 34). Also, there was evidence that S levels in the 5, 10, and 15 Mg ha^{-1} plots had moved to the 15- to 30-cm depth. Soil pH_{H_2O} was highest at 0 to 15 cm for the check plots and lowest at 15 to 30 cm in the high gypsum plots (Figure 35). The same trend was not noted with pH_{CaCl_2} (Table 23), and therefore is probably the result of high SO_4 in the materials. This salt effect is further implicated by increased EC in the surface soil with increasing gypsum rate (Figure 35).

During 2001, rate effect was significant only for Ca, S, and EC (Table 24). Sulfur increased significantly with increasing rate (Table 25). The relationship of Ca to rate was much less obvious. According to Figure 36, Ca levels in the surface were still higher in the check plots than the 5 Mg ha^{-1} gypsum plots, and the highest levels at 15 to 30 cm were in the 10 Mg ha^{-1} plots. Surface soil S levels corresponded to rate of gypsum, but levels were higher at 15 to 30 cm than in the surface in the medium rate plots (Figure 37). Levels of S at 30 to 60 and 60 to 90 cm increased with increasing gypsum rate. Both trends would indicate movement of S. The effect of rate on EC was seen down to the 60- to 90-cm depth (Figure 38).

By Nov. 2002 only S and EC showed significant effects due to rate (Table 26). Sulfur levels significantly increased with each amendment rate increase (Table 27).

Although the effects were not significant, data from the last soil sampling are presented in Figures 39 to 47 to show any trends related to rate for both gypsum and sludge. Extractable K decreased with soil depth down to 90 cm, and no obvious separation among the rates was observable at any depth (Figure 39). The relationship among rates was not consistent at depth for Ca in either the gypsum or sludge

Table 24. Analysis of variance for the effects of gypsum and scrubber sludge at five soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Apr. 2001.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		Mean Squares														
		x 10^2	x 10^3	x 10^6	x 10^4	x 10^3	x 10^3		x 10^{-1}		x 10^{-1}	x 10^2	x 10^6	x 10^2	x 10^{-1}	x 10^4
Material (M)	1	0.61	0.71	0.23	0.47	0.36	0.83	0.17	2.22	0.13	0.36	2.22	0.14	0.68	1.27	0.81
Rate (R)	3	2.82	4.34	0.61*	2.83	85.28***	0.39	0.33	2.39	9.39	3.14	1.82	0.20	0.63	2.09	7.80**
M x R	3	0.51	0.77	0.30	0.14	0.51	1.04	1.05	7.23	12.18	0.21	0.84	0.16	0.66	0.88	0.63
Block	3	0.84	10.13	0.85	0.72	2.82	0.68	5.39	15.01	59.37**	25.97**	0.98	0.12	0.68	1.18	6.16**
Error (a)	21	1.46	4.94	0.29	1.59	8.56	1.19	3.81	8.71	9.65	4.33	7.90	0.62	0.68	3.19	1.10
Depth (D)	4	86.21***	74.09***	27.89***	7.31***	95.92***	15.93***	64.68***	16.60***	4.98*	15.16***	93.63***	18.46***	0.58***	82.90***	17.69***
M x D	4	0.11	3.96	0.17	0.56	1.37	0.15	0.27	0.69	1.00	0.33	0.50	0.15	0.68	0.87	0.67
R x D	12	2.42**	2.55	0.20	0.79	11.78	0.22	0.18	1.33	1.42	0.69	0.78	0.11	0.67	0.87	4.92***
M x R x D	12	0.25	3.23	0.22	1.27	1.59	0.27	0.92	3.77	1.39	1.19	1.01	0.15	0.67	0.30	0.66
Error (b)	96	0.99	2.94	0.22	1.02	7.74	0.49	0.85	2.62	1.66	1.72	1.90	0.21	0.66	0.47	0.99

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 25. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Apr. 2001.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		mg kg^{-1}														dS m^{-1}
Material	Gypsum	17.5	177	990	246	111	47.0	1.71	0.91	1.93	0.55	40.8	358	4.28	4.69	0.18
	Sludge	16.2	172	1058	235	109	42.4	1.78	0.83	1.96	0.52	38.5	339	4.30	4.74	0.16
Rate (Mg ha^{-1})	0	20.0	186	892^{b}	279	63^{d}	45.2	1.65	0.83	1.45	0.44	41.4	373	4.29	4.78	0.13^{b}
	5	15.4	173	1037^{ab}	224	80^{c}	48.7	1.82	0.78	1.68	0.64	36.7	318	4.33	4.77	0.14^{b}
	10	18.0	178	1148^{a}	237	133^{b}	41.4	1.69	0.90	2.56	0.50	41.0	354	4.24	4.63	0.19^{a}
	15	14.1	161	1021^{ab}	221	163^{a}	43.4	1.82	0.96	2.08	0.58	39.3	350	4.29	4.67	0.23^{a}
Depth (cm)	0-15	59.7^{a}	281^{a}	2665^{a}	159^{b}	172^{a}	83.7^{a}	5.07^{a}	0.89^{b}	2.63^{a}	0.77^{a}	2.0^{e}	2^{e}	5.70^{a}	6.03^{a}	0.29^{a}
	15-30	11.1^{b}	177^{b}	1293^{b}	254^{a}	163^{a}	40.7^{b}	1.45^{b}	0.60^{b}	1.78^{b}	0.65^{a}	17.2^{d}	216^{d}	4.26^{b}	4.68^{b}	0.19^{b}
	30-60	5.0^{c}	142^{c}	590^{c}	286^{a}	101^{b}	30.1^{b}	1.02^{bc}	0.84^{b}	1.82^{b}	0.66^{a}	44.1^{c}	418^{c}	3.93^{c}	4.39^{c}	0.13^{cd}
	60-90	4.2^{c}	125^{c}	353^{d}	248^{a}	80^{b}	30.6^{b}	0.64^{c}	0.78^{b}	1.62^{b}	0.34^{b}	57.9^{b}	510^{b}	3.84^{d}	4.30^{c}	0.16^{bc}
	90-120	4.2^{c}	148^{c}	221^{d}	256^{a}	35^{c}	38.3^{b}	0.55^{c}	1.23^{a}	1.88^{b}	0.28^{b}	77.0^{a}	597^{a}	3.71^{e}	4.18^{d}	0.10^{d}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

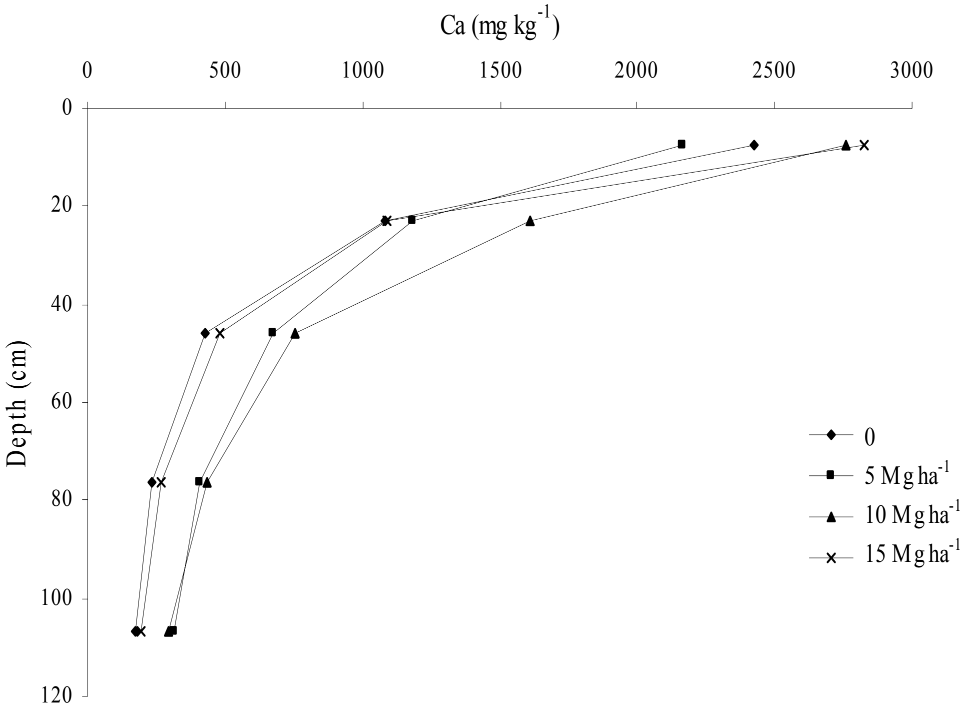


Figure 36. Mehlich-3 extractable calcium and sulfur and electrical conductivity at different depths in the Cuthbert soil, Rusk Co. TX, sampled in Apr. 2001, 22 mo after treatment with four rates of gypsum.

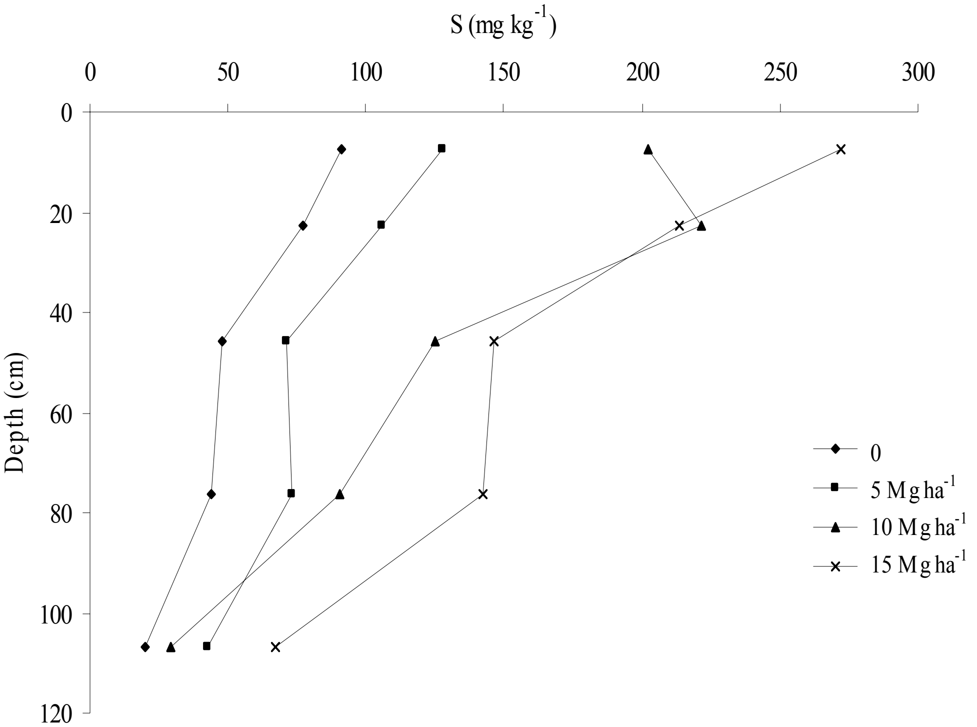


Figure 37. Mehlich-3 extractable sulfur at different depths in the Cuthbert soil, Rusk Co. TX, sampled in Apr. 2001, 22 mo after treatment with four rates of gypsum.

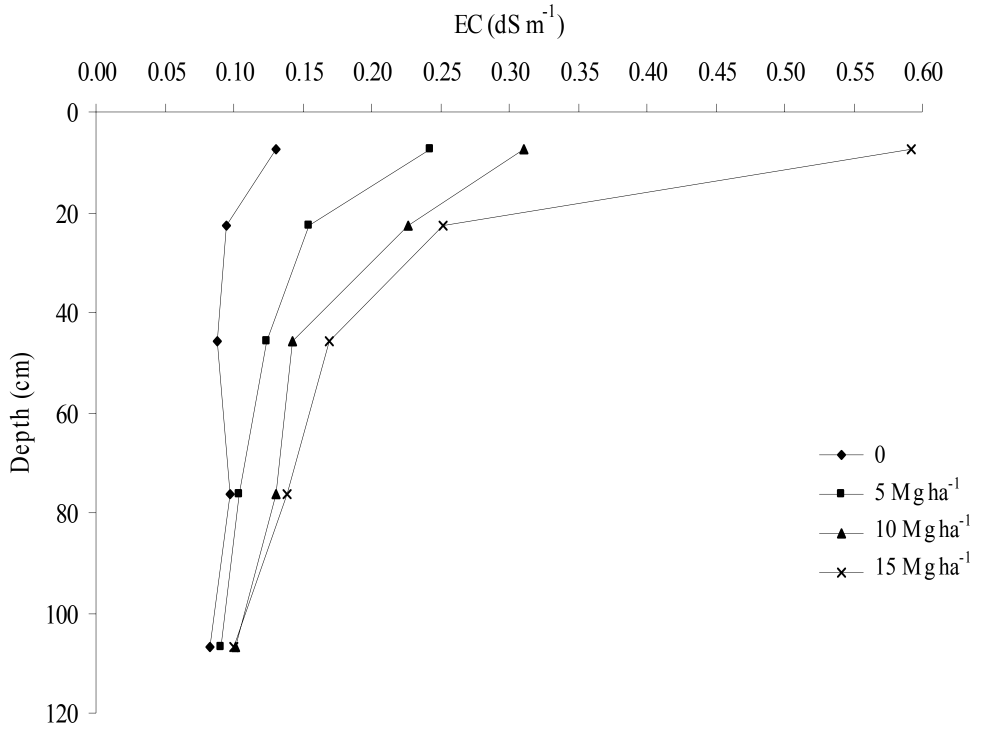


Figure 38. Electrical conductivity at different depths in the Cuthbert soil, Rusk Co. TX, sampled in Apr. 2001, 22 mo after treatment with four rates of gypsum.

Table 26. Analysis of variance for the effects of gypsum and scrubber sludge at three soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Nov. 2002.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		Mean Squares														
		x 10^1	x 10^3	x 10^5	x 10^4	x 10^3	x 10^3		x 10^{-1}	x 10^1	x 10^{-2}	x 10^3	x 10^5	x 10^{-1}	x 10^{-1}	x 10^3
Material (M)	1	0.15	0.46	0.44	4.29	0.98	0.63	0.33	14.20	0.81	0.92	0.22	2.13	0.12	0.25	1.76
Rate (R)	3	0.39	3.33	0.42	3.78	51.26***	0.42	1.11	10.79	3.85	2.37	0.58	0.80	0.40	3.94	40.30***
M x R	3	0.81	0.81	0.25	0.69	0.66	0.78	0.19	6.97	3.76	2.05	0.18	0.39	0.30	0.66	0.88
Block	3	23.64	7.41	2.10	0.45	0.64	0.80	5.86*	57.26*	10.26	12.76*	0.27	0.79	0.60	2.38	9.55*
Error (a)	21	6.70	3.38	0.96	2.93	2.14	1.12	1.51	12.77	2.96	2.65	0.76	0.89	2.88	3.86	2.53
Depth (D)	4	74.80***	36.41***	84.88***	3.45*	69.18***	17.22***	97.09***	27.80***	1.82**	19.47***	44.37***	38.93***	60.94***	93.31***	6.29**
M x D	4	0.93	3.66	0.25	1.28	0.61	0.27	0.10	0.36	0.35	0.26	0.52	0.73	0.30	0.35	0.18
R x D	12	4.02	0.63	2.08	0.38	2.70	0.19	1.49	0.21	0.52	2.14	0.42	0.26	0.57	0.44	3.04
M x R x D	12	0.82	1.70	1.16	0.74	0.45	0.36	0.76	0.22	0.38	1.07	0.29	0.32	0.70	0.41	0.40
Error (b)	96	7.82	1.61	1.35	1.01	1.86	0.75	0.95	0.98	0.40	3.72	0.28	0.55	0.84	0.80	1.69

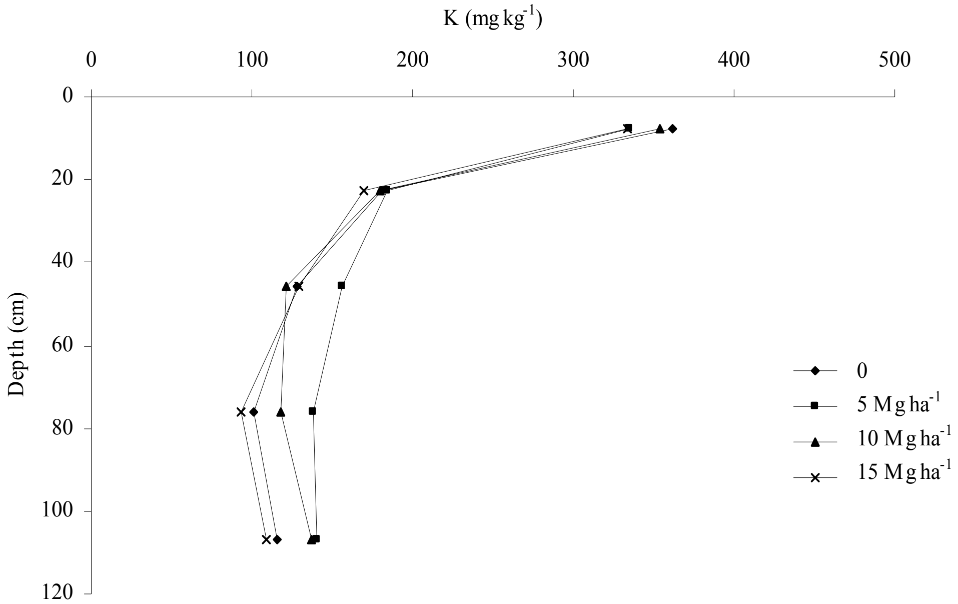
*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 27. Influence of gypsum, scrubber sludge, and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, and EC in a Cuthbert fine sandy loam, Rusk Co. TX, sampled in Nov. 2002.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
		mg kg^{-1}														dS m^{-1}
Material	Gypsum	15.8	179	999	284	94	49.5	2.13	1.17	2.09	0.30	48.1	441	4.24	4.89	0.10
	Sludge	15.5	183	996	251	99	45.5	2.21	1.06	1.82	0.31	45.8	383	4.25	4.92	0.11
Rate (Mg ha^{-1})	0	16.4	177	969	307	54^{d}	45.9	2.36	1.05	1.88	0.29	51.3	454	4.27	5.02	0.07^{c}
	5	15.5	187	1003	264	84^{c}	52.3	2.14	1.16	2.46	0.33	43.5	370	4.27	4.96	0.09^{b}
	10	15.6	189	1020	268	111^{b}	45.2	2.22	1.23	2.32	0.32	49.0	427	4.20	4.82	0.12^{a}
	15	15.2	170	999	232	137^{a}	46.6	1.96	1.02	1.15	0.28	44.1	398	4.24	4.82	0.14^{a}
Depth (cm)	0-15	59.4^{a}	363^{a}	2284^{a}	219^{b}	54^{d}	87.0^{a}	5.72^{a}	1.10^{b}	2.54^{a}	0.41^{a}	1.6^{e}	3^{d}	5.65^{a}	6.23^{a}	0.11^{a}
	15-30	8.6^{b}	187^{b}	1367^{b}	257^{ab}	131^{b}	43.6^{b}	2.13^{b}	0.96^{c}	1.97^{abc}	0.35^{ab}	19.1^{d}	293^{c}	4.21^{b}	4.94^{b}	0.11^{a}
	30-60	3.7^{b}	131^{c}	716^{c}	283^{ab}	157^{a}	29.8^{b}	1.53^{c}	0.98^{c}	1.59^{c}	0.31^{ab}	49.9^{c}	500^{b}	3.91^{c}	4.58^{c}	0.12^{a}
	60-90	3.2^{b}	107^{d}	365^{d}	272^{ab}	89^{c}	31.4^{b}	0.71^{d}	1.16^{b}	1.42^{c}	0.22^{b}	71.1^{b}	563^{b}	3.78^{cd}	4.45^{cd}	0.09^{b}
	90-120	3.4^{b}	117^{cd}	256^{d}	308^{a}	52^{d}	45.9^{b}	0.76^{d}	1.40^{a}	2.21^{ab}	0.24^{b}	93.1^{a}	703^{a}	3.68^{d}	4.32^{d}	0.09^{b}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

Gypsum



Sludge

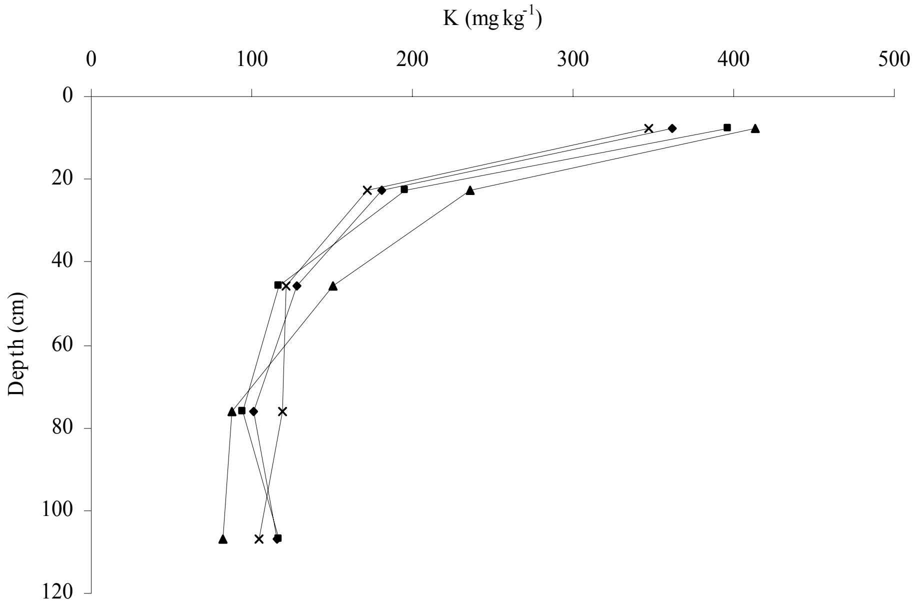
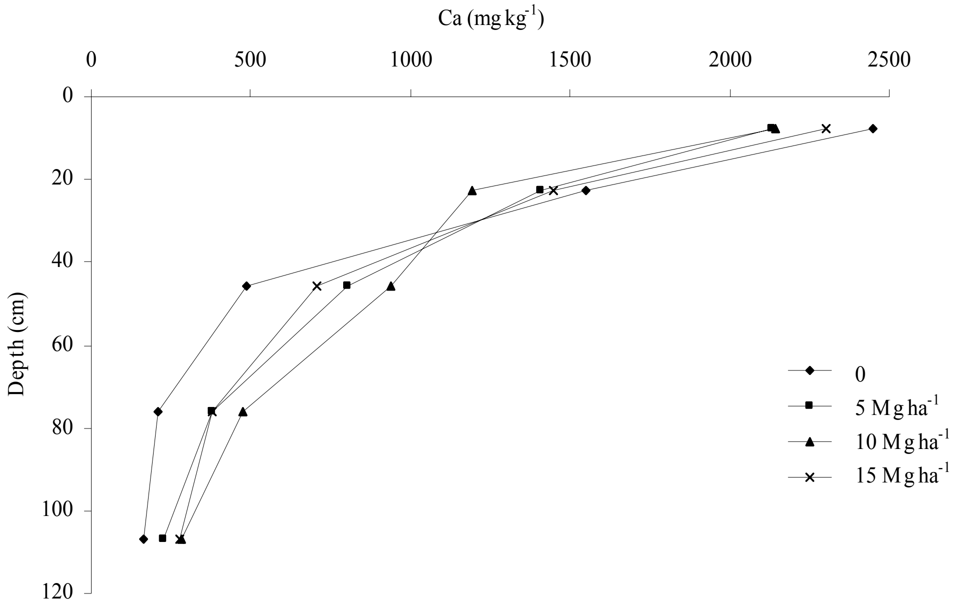


Figure 39. Mehlich-3 extractable potassium in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.

Gypsum



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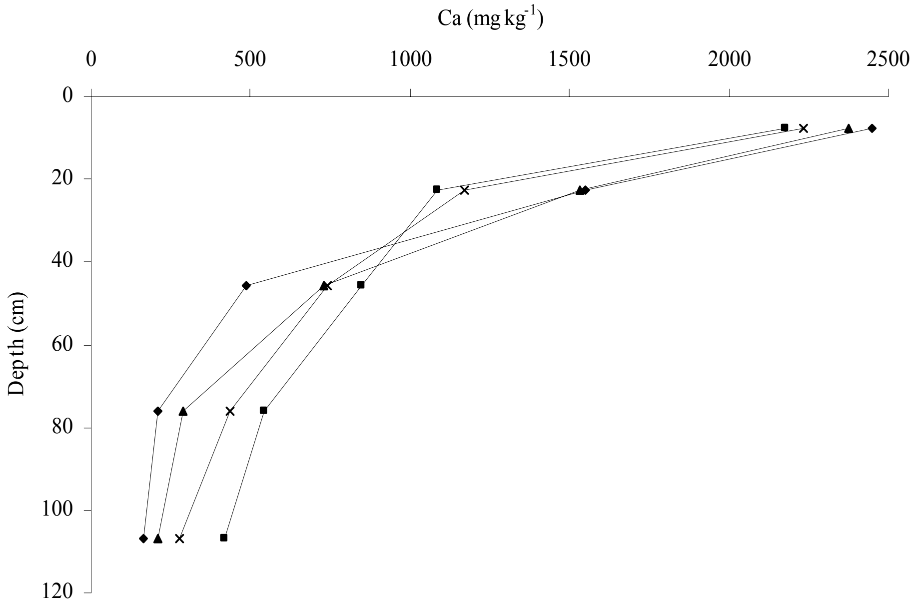


Figure 40. Mehlich-3 extractable calcium in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.

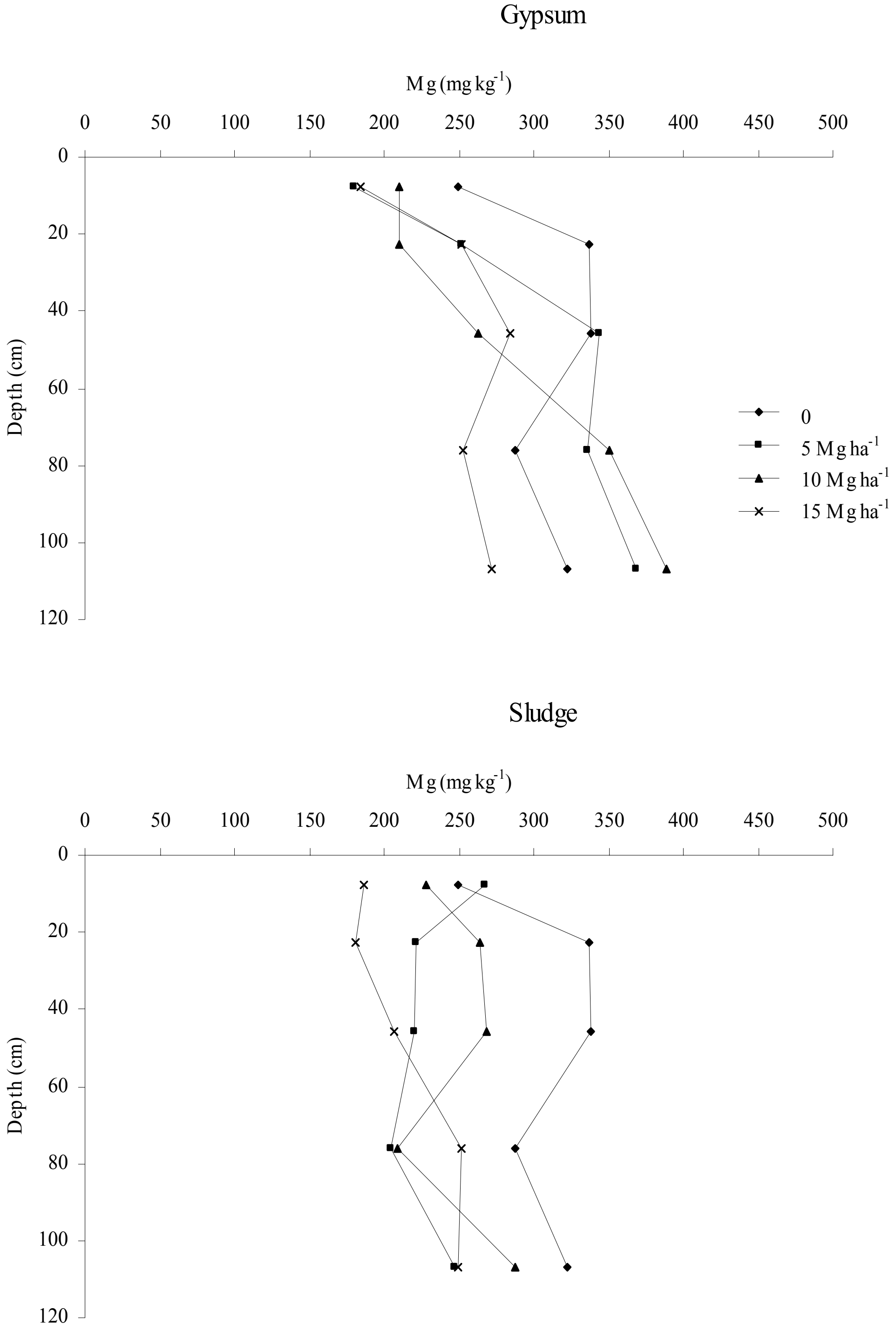
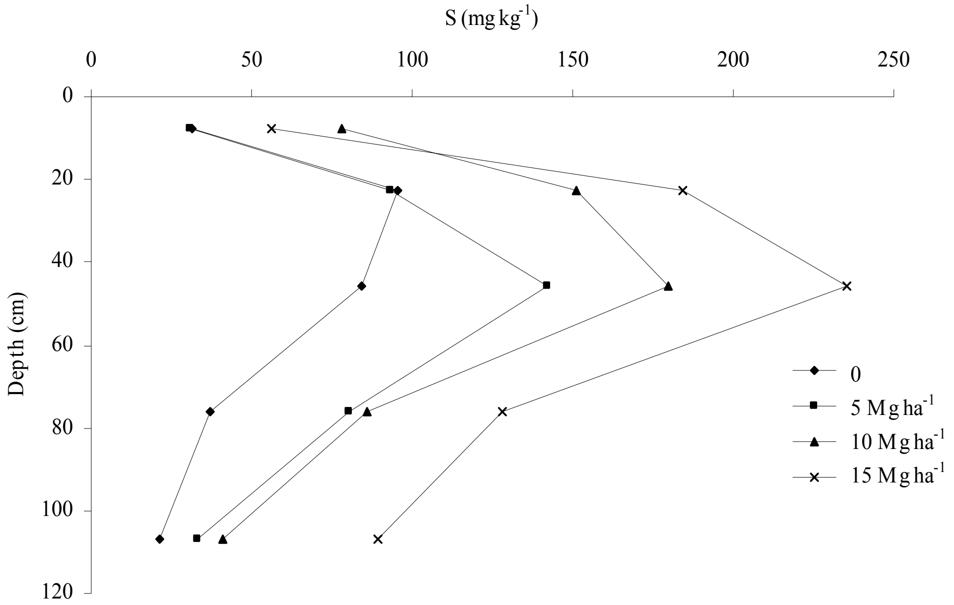


Figure 41. Mehlich-3 extractable magnesium in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.

Gypsum



Sludge

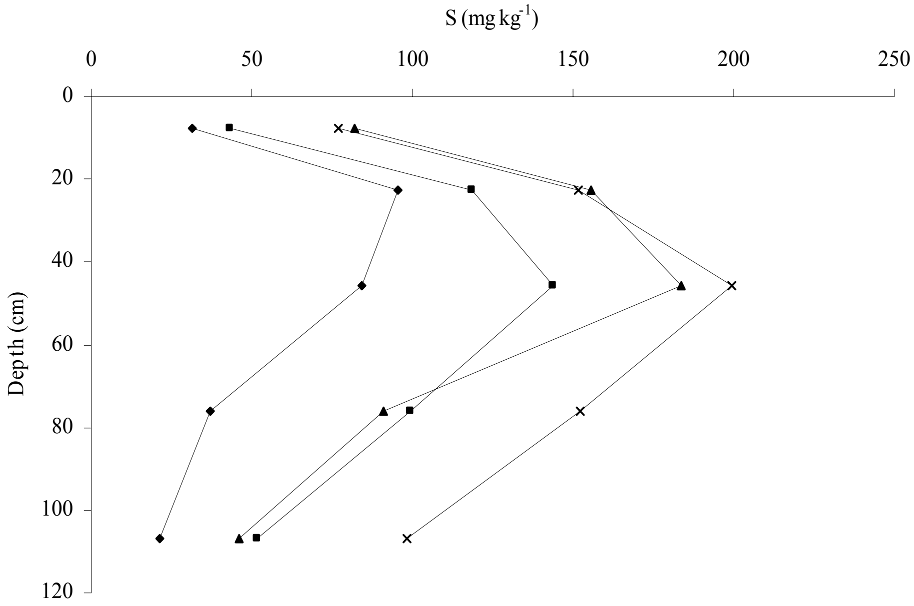
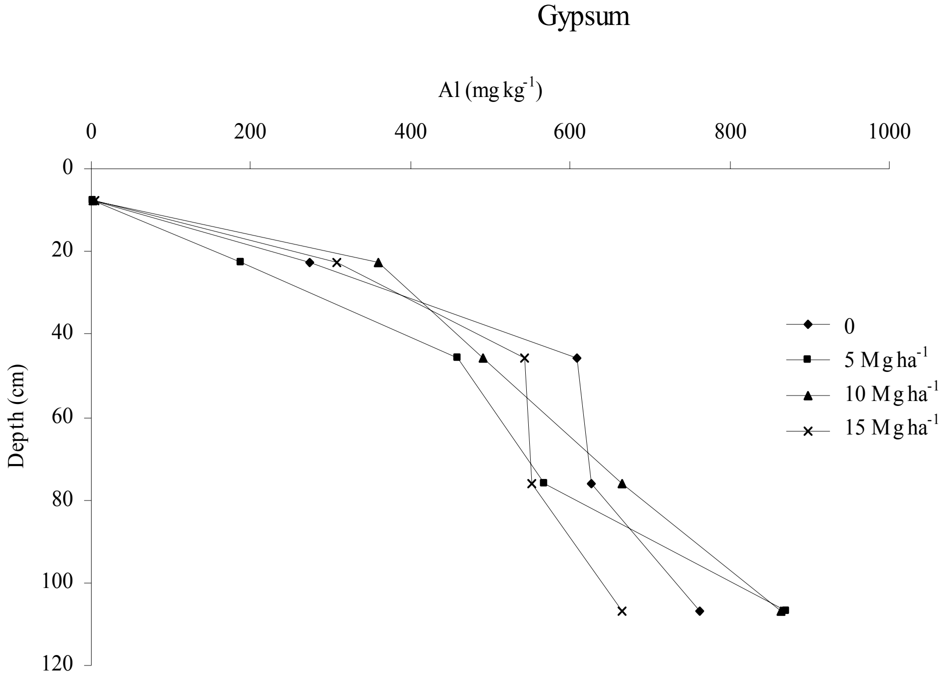


Figure 42. Mehlich-3 extractable sulfur in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.



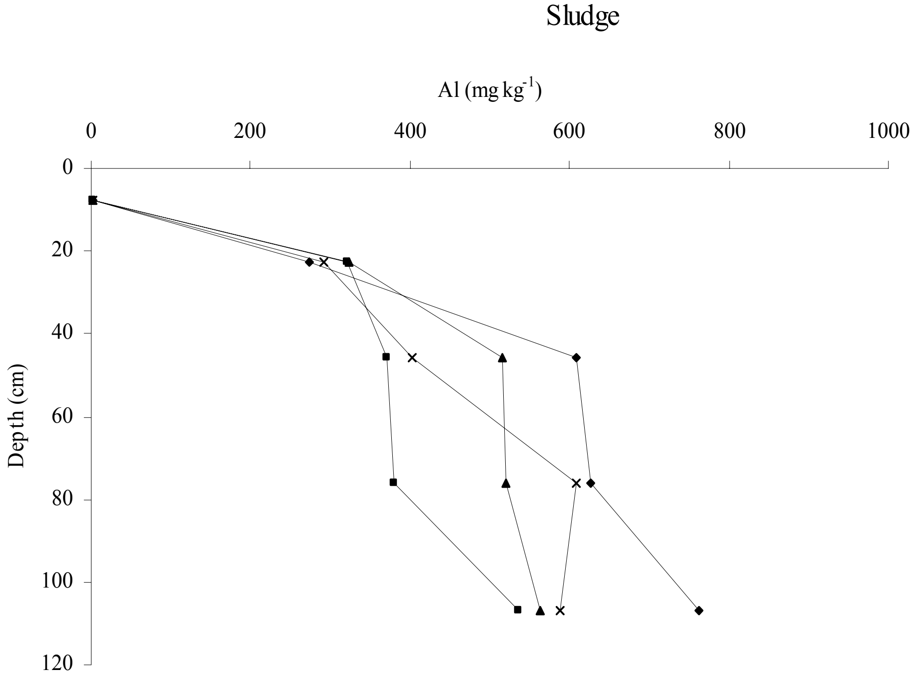
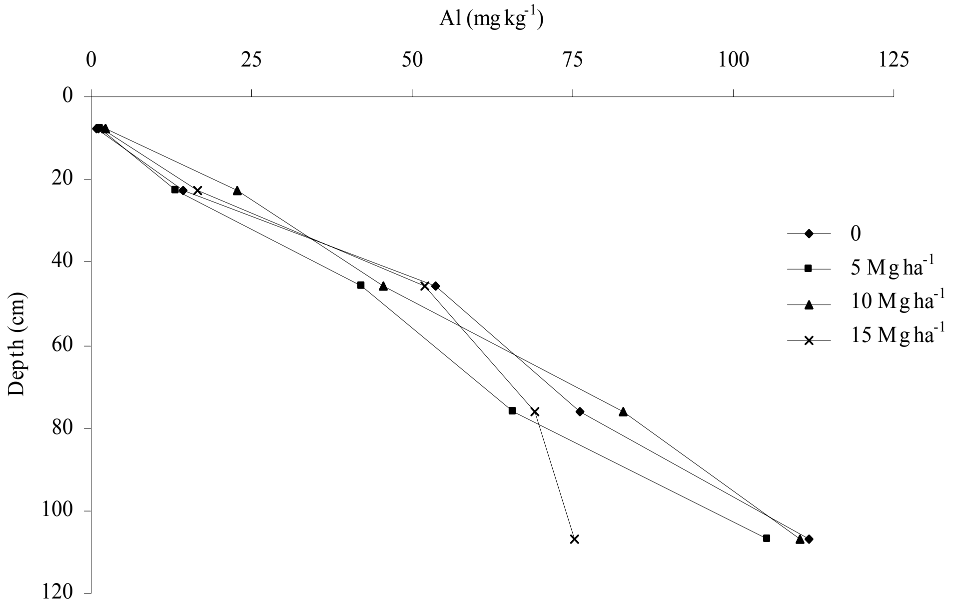


Figure 43. *N* KCl extractable aluminum in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.

Gypsum



Sludge

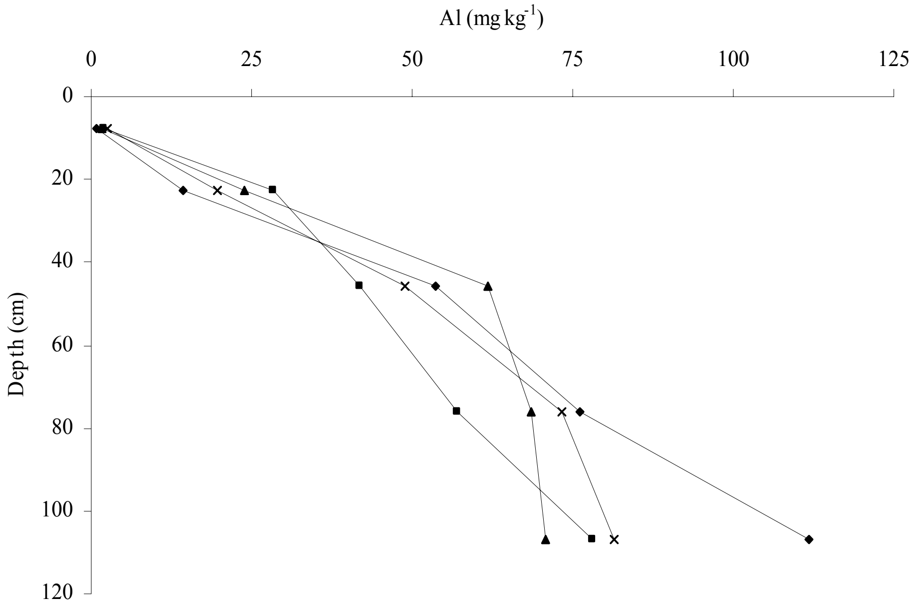
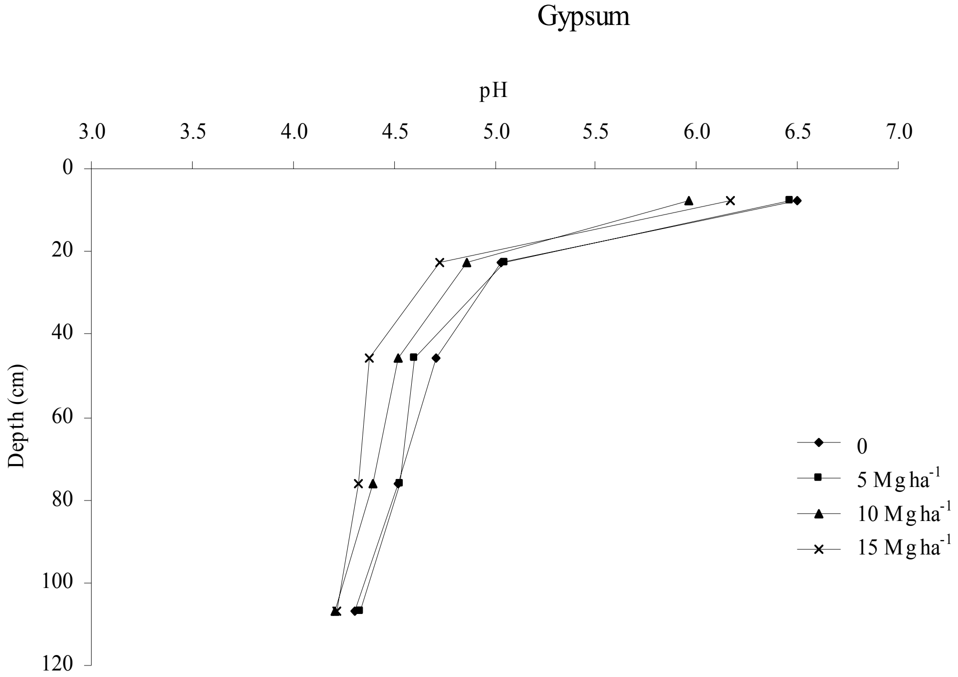


Figure 44. 0.01 *M* $CaCl_2$ exchangeable aluminum in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.



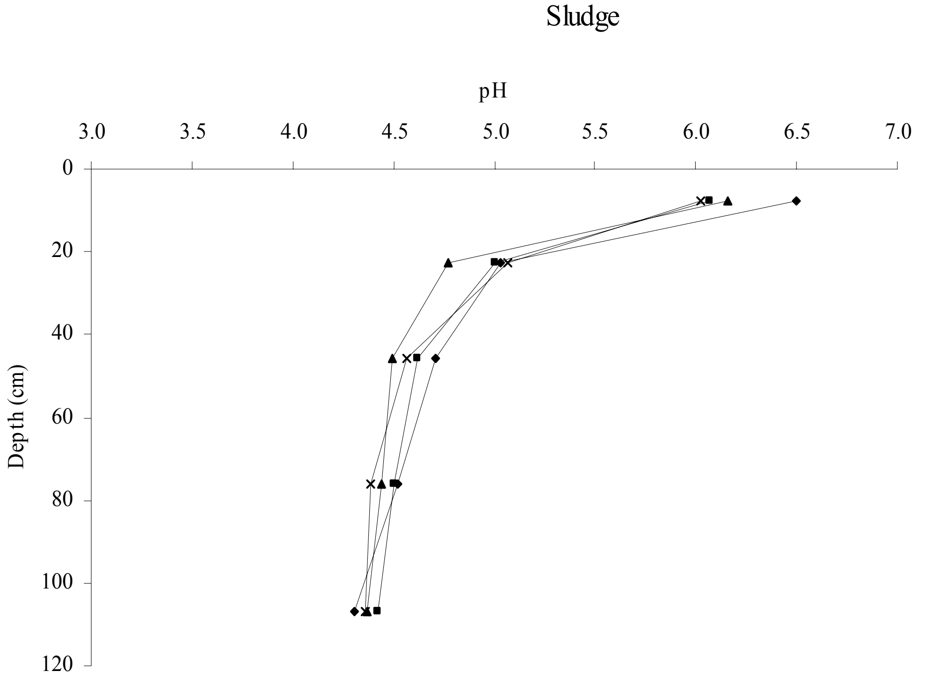


Figure 45. 2:1 water to soil pH in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.

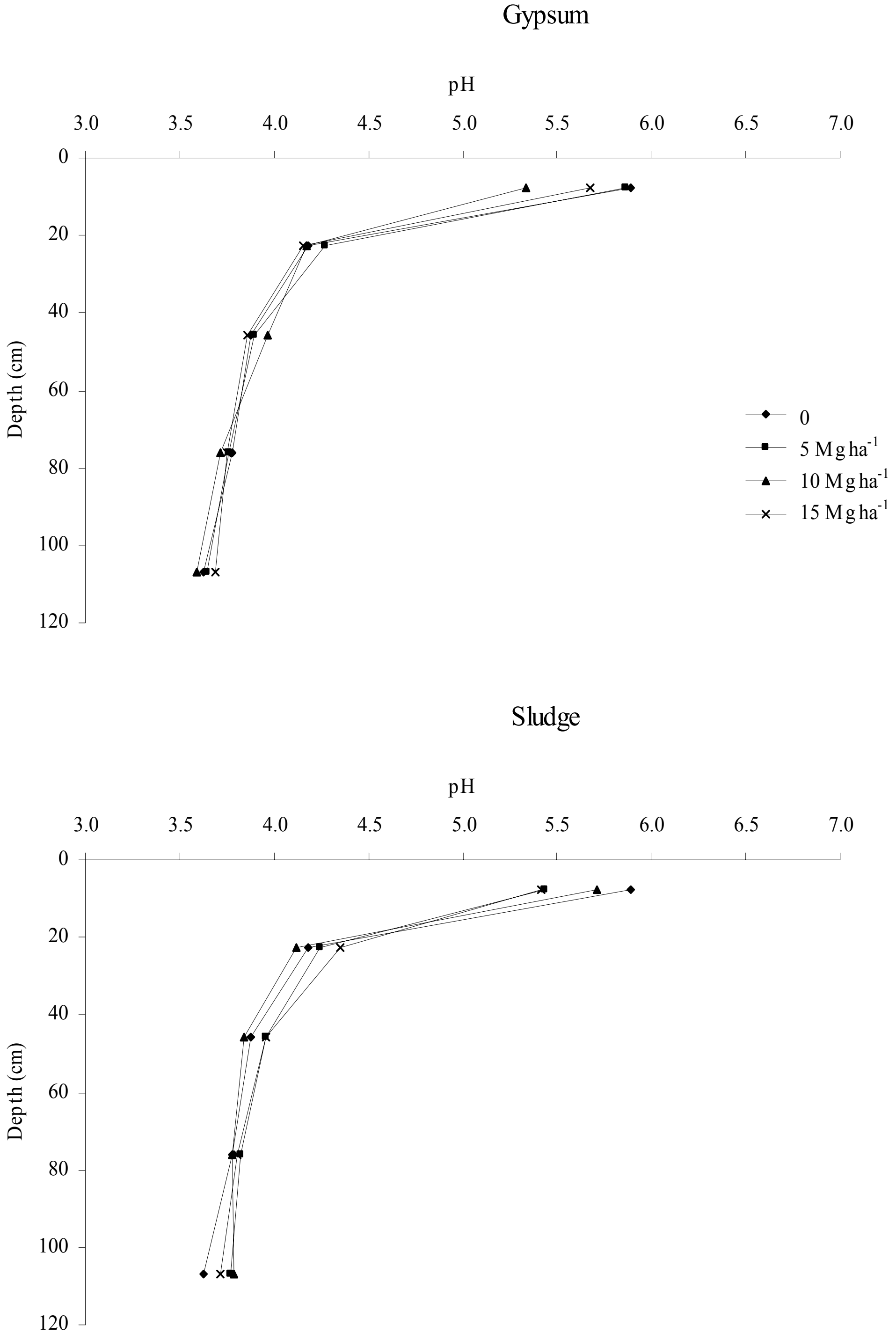
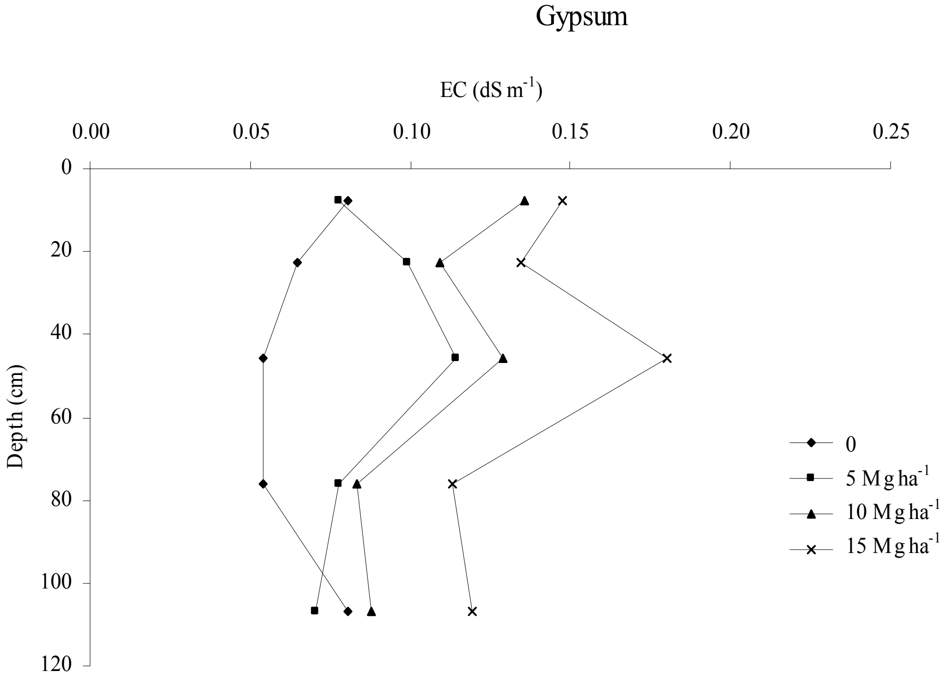


Figure 46. 2:1 0.01 *M* $CaCl_2$ to soil pH in the Cuthbert soil, Rusk Co. TX, sampled in Nov. 2002, 41 mo after treatment with four rates of gypsum or sludge.



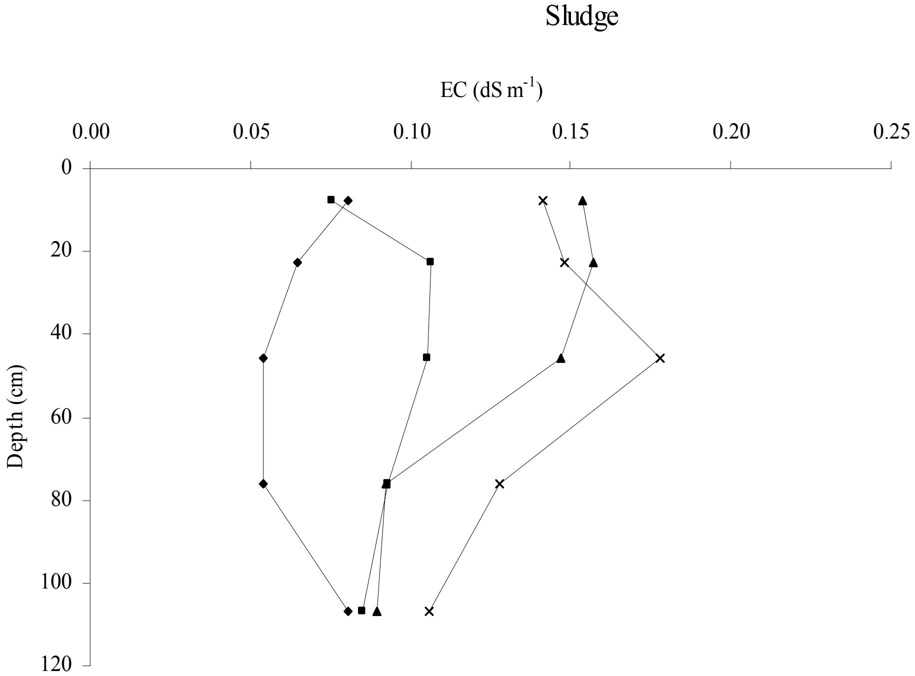


Figure 47. Electrical conductivity in the Cuthbert soil, Rusk Co. TX, 41 mo after treatment with four rates of gypsum or sludge.

treatments (Figure 40), and the high rates did not show a trend to highest subsoil Ca with either material. However, when comparing 2002 to 2000 data (Figure 34), Ca levels in subsoil of the 2002 sampling were higher than the 2000 sampling at all rates. The magnesium data presented in Figure 41 are difficult to interpret. In the gypsum treatment, levels tended to increase with depth, but in the sludge treatment there were differences from one depth to the next, but negligible change overall from the surface to 120 cm. During the study, 144 kg ha^{-1} of fertilizer Mg was applied to the plots, half of which was applied in 2002 (Table 3). A clear separation by rate was observable for S below the surface 15 cm (Figure 42). The highest S levels for the low, medium and high rates of both materials occurred at 30 to 60 cm. Levels at 15 to 30 cm were relatively high in the check plots, and significantly higher than the surface soil. This was probably due to the almost 290 kg ha^{-1} of S applied as fertilizer during the experiment (Table 3). Extractable Al below 30 cm was not consistent with rate in either amendment (Figure 43). Coefficients of variability were high for the data indicating much heterogeneity related to extractable Al, particularly in the subsoil. The difference when materials were compared further confirms this. Although treatments appeared to reduce exchangeable Al below 30 cm, the relationship was not consistent (Figure 44). The pH_{H_2O} trend observable in Figure 45 indicated a salt affect down to 90 cm. This corresponded to the increased S levels to that depth (Figure 42). When pH_{CaCl_2} was measured, differences related to rate were not evident (Figure 46). Electrical conductivity was highest at 30 to 60 cm in the gypsum plots (Figure 47). Sulfur levels were also high at that depth (Figure 42).

Tables 28 to 32 show the effect of rate, material, and sampling date on measured parameters at each depth separately. Significant sampling effects not related to material or rate were considered to be due to sampling variability and therefore will not be discussed. At 0 to 15 cm, there was a significant rate by sampling effect for Ca, Mg and S (Table 28). Calcium and S levels in the surface soil for all treatments were highest in the Apr. 2000 sampling. Calcium levels in the gypsum treatments were highest 11 MAT in the 15 Mg ha^{-1} plots (Figure 48). By 22 MAT there was essentially

Table 28. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, Apr. 2000, Apr. 2001, and Nov. 2002 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Cuthbert fine sandy loam, Rusk Co. TX, at a soil depth of 0 to 15 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
		x 10^{2}	x 10^{4}	x 10^{5}	x 10^{3}	x 10^{4}	x 10^{3}		x 10^{-1}		x 10^{-1}			x 10^{-1}	x 10^{-1}
Material (M)	1	1.23	5.29	7.91	25.00	0.82	4.80	4.30	0.20	0.11	0.14	0.33	6.70	1.96	0.34
Rate (R)	3	6.00	0.54	14.64	4.25	58.79***	4.39	4.06	0.88	1.92	1.31	3.80	33.46	6.88	13.20
M x R	3	2.04	0.87	4.93	15.93	1.17	9.09	2.95	0.43	1.30	0.44	1.70	10.23	2.61	0.71
Block	3	3.93	1.37	19.95*	6.43	3.71	8.51	8.49	6.69*	4.62	5.49*	5.06***	0.64	1.32	1.35
Error (a)	21	5.77	1.66	5.52	23.80	2.12	11.98	4.53	1.69	3.70	1.24	0.62	14.17	9.26	9.06
Sampling (S)	3	67.64***	12.60***	87.96***	22.50***	160.37***	0.23	7.88***	36.75***	13.41***	15.03***	12.77***	49.34*	8.97***	7.87***
M x S	3	0.20	0.29	0.76	0.22	1.12	0.32	0.55	1.11	0.47	0.13	0.46	13.57	0.24	0.76
R x S	9	3.04	0.18	5.89***	2.94***	33.78**	0.48	2.03	1.16	1.97	0.38	0.94	13.40	0.64	0.59
M x R x S	9	1.22	0.26	0.69	0.22	1.91	0.29	1.11	1.06	0.87	0.51	1.66	4.32	0.73	0.42
Error (b)	72	1.74	0.21	0.82	0.79	1.54	0.32	1.12	1.89	1.67	0.40	1.36	12.45	1.14	0.67

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

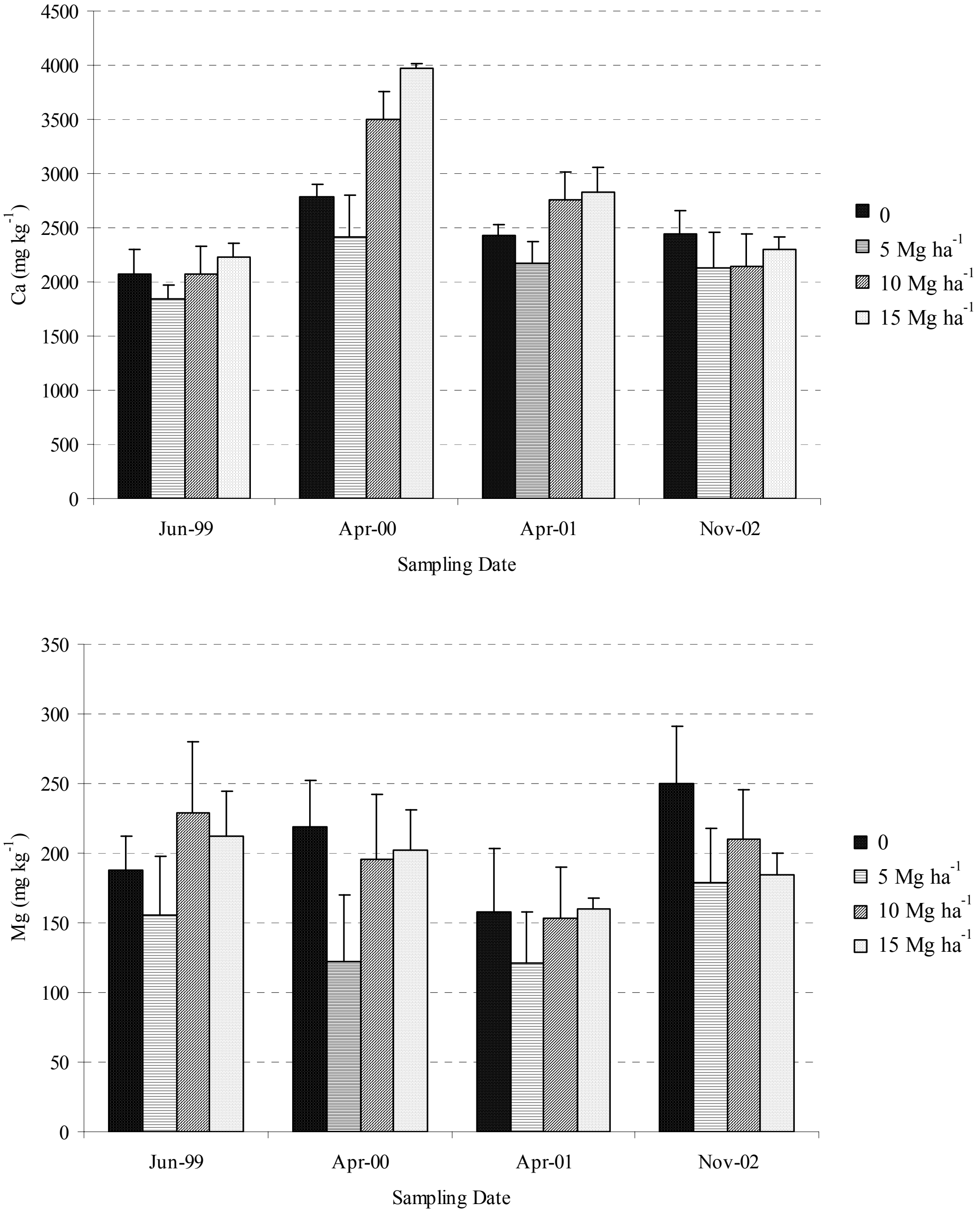


Figure 48. Mehlich-3 extractable calcium and magnesium and standard errors at 0-15 cm on four sampling dates with four rates of surface-applied gypsum on the Cuthbert soil, Rusk Co. TX.

Table 29. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, Apr. 2000, Apr. 2001, and Nov. 2002 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Cuthbert fine sandy loam, Rusk Co. TX, at a soil depth of 15 to 30 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
		x 10^1	x 10^3	x 10^4	x 10^3	x 10^3	x 10^2	x 10^{-1}	x 10^{-1}		x 10^{-2}	x 10^2	x 10^4	x 10^{-2}	x 10^{-2}
Material (M)	1	0.30	5.97	0.22	0.29	0.42	5.94	7.61	0.66	0.67	0.18	0.49	0.11	1.36	0.20
Rate (R)	3	5.53	4.32	26.61	40.79	42.93^{**}	12.42	7.35	0.25	3.66	6.68	1.94	3.70	7.14	12.76
M x R	3	2.89	5.09	19.72	25.96	1.37	10.42	73.68	0.26	7.56	3.59	0.96	0.95	18.12	26.32
Block	3	7.05	9.62	14.89	10.41	0.78	12.14	84.66	4.24^{*}	3.46	77.13	1.91	8.76	49.49	32.99
Error (a)	21	7.46	5.66	16.67	40.10	5.86	21.94	93.71	1.11	5.92	30.98	4.59	10.28	44.75	58.73
Sampling (S)	3	16.12^{***}	15.69^{***}	44.59^{***}	4.00	90.71^{***}	2.89^{*}	26.83^{***}	25.28^{***}	6.88	62.82^{***}	5.27^{***}	4.62^{*}	8.36^{*}	98.70^{***}
M x S	3	0.83	0.66	4.52	0.57	1.26	0.58	0.69	0.42	3.87	0.70	0.51	0.27	1.07	2.96
R x S	9	1.64	0.90	9.53	5.34^{**}	7.38^{**}	0.74	3.63	0.90	2.20	4.36	0.37	1.65	1.09	3.62
M x R x S	9	1.35	0.34	9.25	1.61	0.91	0.37	0.91	0.41	1.92	1.03	0.14	0.67	0.72	1.31
Error (b)	72	1.48	0.72	7.11	1.87	2.96	0.83	3.40	1.24	3.27	7.23	0.39	1.14	1.82	3.50

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 30. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, Apr. 2000, Apr. 2001, and Nov. 2002 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Cuthbert fine sandy loam, Rusk Co. TX, at a soil depth of 30 to 60 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
			$x 10^2$	$x 10^4$	$x 10^4$	$x 10^3$	$x 10^2$	$x 10^{-1}$	$x 10^{-1}$		$x 10^{-1}$	$x 10^2$	$x 10^4$	$x 10^{-2}$	$x 10^{-2}$
Material (M)	1	3.05	0.29	0.56	1.66	0.22	0.27	0.10	0.13	0.93	0.03	0.29	0.36	0.38	0.48
Rate (R)	3	0.65	11.62	42.69	5.17	24.16^{***}	0.46	15.67	0.52	3.03	2.59	3.03	10.83	2.84	8.22
M x R	3	2.49	32.36	8.58	1.21	0.17	0.78	34.43	1.95	1.74	2.91	1.10	3.06	3.35	3.16
Block	3	8.74	49.46	40.73	2.23	6.68^{**}	3.06	73.28	1.48	6.45	11.70	7.22	11.55	9.17	20.68
Error (a)	21	4.60	31.86	16.69	4.16	1.13	1.20	49.36	1.70	2.65	5.05	6.99	9.04	7.92	9.72
Sampling (S)	3	55.01^{***}	36.51^{***}	22.40^{***}	0.45	97.49^{***}	3.72^{***}	18.13^{**}	25.25^{***}	5.69	8.96^{***}	60.74^{***}	5.06^{*}	3.53^{***}	32.75^{***}
M x S	3	2.94	1.85	0.40	0.25	0.28	0.45	1.16	0.53	1.84	0.45	0.58	1.96	0.10	1.72
R x S	9	2.96	6.44	2.21	0.40	6.00^{***}	0.53	4.81	0.76	2.21	0.72	0.35	2.24	0.52	3.79
M x R x S	9	5.99	5.38	1.06	0.13	0.63	1.02	3.15	2.27	2.05	0.45	0.44	0.96	0.36	1.21
Error (b)	72	5.08	4.54	2.74	0.34	1.04	0.46	3.60	1.84	2.77	1.11	1.06	1.36	0.51	1.72

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 31. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, Apr. 2000, Apr. 2001, and Nov. 2002 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Cuthbert fine sandy loam, Rusk Co. TX, at a soil depth of 60 to 90 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
			x 10^2	x 10^4	x 10^3	x 10^3	x 10^1	x 10^{-1}	x 10^{-1}	x 10^{-1}	x 10^{-2}	x 10^2	x 10^4	x 10^{-2}	x 10^{-2}
Material (M)	1	0.54	73.99	0.70	86.33	0.21	0.18	1.65	2.34	0.48	1.30	3.21	12.42	2.73	0.89
Rate (R)	3	1.43	0.70	8.56	9.51	13.02***	8.59	0.82	1.84	15.61	5.22	3.69	6.47	1.58	2.94
M x R	3	4.60	58.77	5.81	34.11	0.21	1.00	1.16	1.14	4.39	1.31	0.64	4.22	0.62	0.99
Block	3	7.46	68.91	4.88	21.95	0.95	6.57	1.20	2.42	36.86*	24.43***	3.39	7.75	4.86	7.77
Error (a)	21	2.37	22.73	3.76	48.19	1.44	5.59	2.29	2.37	9.06	2.95	7.49	7.70	3.66	5.44
Sampling (S)	3	31.18***	36.09***	14.77***	4.63	33.99***	49.34***	4.44**	21.71***	40.97	10.76**	67.11***	10.81**	4.56***	29.53***
M x S	3	1.35	2.09	0.25	3.77	1.12	3.20	0.37	0.48	1.84	0.52	0.22	0.66	0.19	1.15
R x S	9	2.42	5.15	2.13	0.69	3.25***	9.65*	0.44	0.82	16.00	0.72	0.86	1.16	0.22	1.81
M x R x S	9	2.74	3.71	1.64	2.19	0.38	0.76	0.16	0.27	5.94	0.55	0.82	0.71	0.22	0.84
Error (b)	72	2.48	4.54	1.11	2.03	0.89	4.10	0.79	1.15	17.83	2.10	1.28	1.98	0.50	1.66

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 32. Analysis of variance for the effects of gypsum and scrubber sludge sampled in June 1999, Apr. 2000, Apr. 2001, and Nov. 2002 on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil, in a Cuthbert fine sandy loam, Rusk Co. TX, at a soil depth of 90 to 120 cm.

Source	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}
		Mean Squares													
			x 10^3	x 10^3	x 10^4	x 10^2	x 10^2	x 10^{-1}	x 10^{-1}		x 10^{-2}	x 10^3	x 10^4	x 10^{-2}	x 10^{-2}
Material (M)	1	3.13	19.30	0.24	12.66	0.97	8.63	0.93	15.91	0.23	4.77	1.83	46.88	24.41	19.38
Rate (R)	3	0.92	2.94	46.73	1.88	57.83^{**}	9.07	0.34	1.59	5.32	1.65	0.54	5.20	2.74	0.86
M x R	3	4.58	7.26	5.89	6.19	7.42	3.73	1.15	10.07	5.88	3.60	0.97	16.86	4.64	2.98
Block	3	6.25	0.39	37.87	0.25	6.67	9.64	0.27	1.84	1.26	20.27^{**}	0.33	0.70	2.79	12.53
Error (a)	21	2.53	5.58	26.35	6.69	7.44	5.33	0.99	6.88	1.77	2.94	1.31	26.86	7.17	7.28
Sampling (S)	3	35.51^{***}	9.92^{***}	55.31^{***}	2.00^{***}	72.51^{***}	10.94^{***}	6.17^{***}	10.47^{***}	9.22^{*}	3.57	23.25^{***}	28.21^{***}	3.20^{***}	36.12^{***}
M x S	3	1.97	0.43	9.87	0.15	6.22	0.24	0.47	0.22	1.18	0.70	0.23	1.60	0.10	1.17
R x S	9	0.77	1.48	7.36	0.28	13.00^{*}	0.87	0.73	0.84	2.24	1.21	0.39	2.40	0.63	1.43
M x R x S	9	3.08	0.67	9.92	0.27	3.11	0.43	0.59	1.75	3.83	1.41	0.17	0.96	0.16	0.57
Error (b)	72	2.92	1.10	9.18	0.28	5.98	1.13	0.85	1.21	2.72	1.98	0.19	3.22	0.50	1.55

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

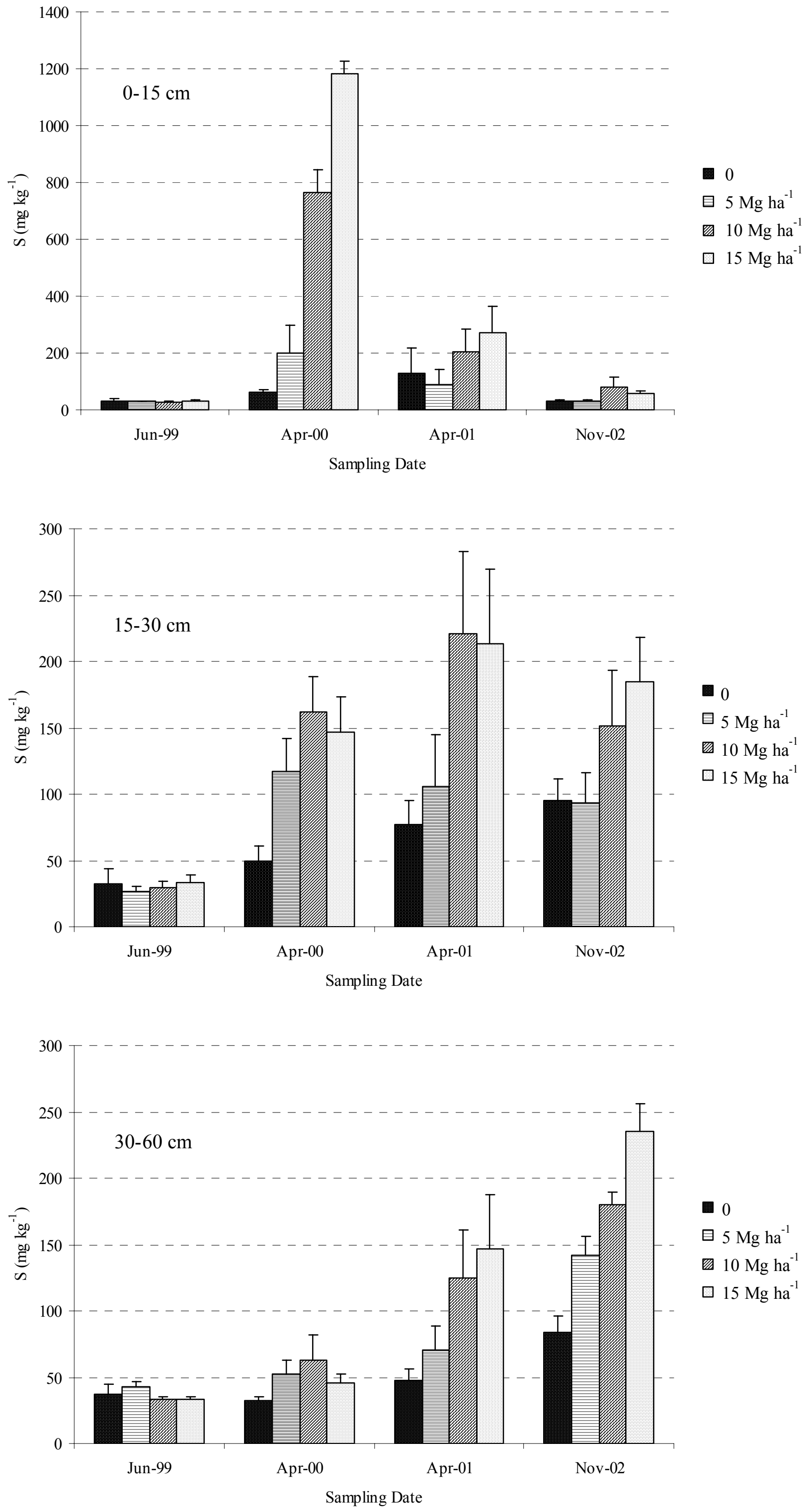


Figure 49. Mehlich-3 extractable sulfur and standard errors at 0-15, 15-30 and 30-60 cm on four sampling dates with four rates of surface-applied gypsum on the Cuthbert soil, Rusk Co. TX.

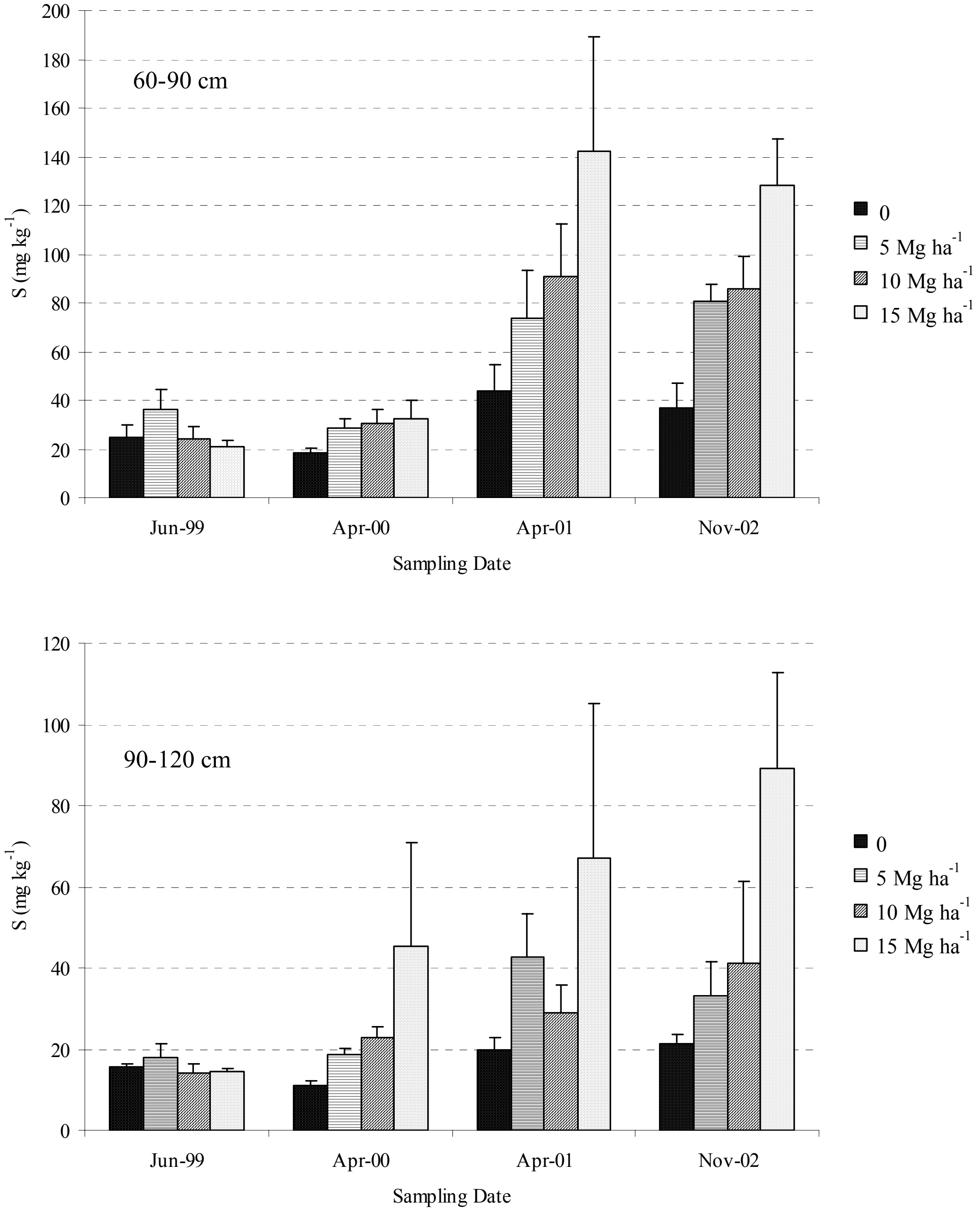


Figure 50. Mehlich-3 extractable sulfur and standard errors at 60-90 and 90-120 cm on four sampling dates with four rates of surface-applied gypsum on the Cuthbert soil, Rusk Co. TX.

no difference among rates, and by 41 MAT there was no affect of rate on Ca levels in the gypsum plots. At 15 to 30 cm there was a significant effect of rate on S, and a significant rate by sampling effect on Mg and S (Table 29). Below 30 cm, the only significant effect was on S (Tables 30, 31 and 32). Sulfur decreased dramatically in the surface 15 cm between Apr. 2000 and Apr. 2001, particularly in the high and medium gypsum plots (Figure 49). With successive samplings S had moved deeper in the profile. By the 2001 sampling there was an obvious rate effect on S level at 60 to 90 cm, and by Nov. 2002 there was an apparent rate effect on S at 90 to 120 cm (Figure 50).

Although there were no significant differences related to material, Figures 51 to 59 are presented to allow comparison of the materials, and to show any trends and changes in selected parameters during the experiment in both the high gypsum and high sludge plots. In both gypsum and sludge treatments, K in the top 15 cm was highest at the last sampling date (Figure 51). About 250 kg ha^{-1} of actual K was applied in 2002 (Table 3). At all sampling dates, K levels decreased to 60 cm and then remained relatively unchanged to 120 cm. Calcium levels in the surface soil were highest in 2000 (Figure 52). Subsoil levels in the gypsum plots show a trend for an increase with increased time, and in the sludge plots, all samplings after the initial 1999 sampling had higher levels at 15 to 30 cm. In the gypsum plots, Mg levels were highest at 15 to 30 cm during 1999, 2000, and 2001 (Figure 53). In 2002, the level was highest at 30 to 60 cm, and remained higher than the other sampling dates to 120 cm. Figure 54 indicates that S moved deeper in the profile with each successive sampling. Below 30 cm, sample variability was very high in regard to extractable Al (Figure 55). Therefore, no trends were obvious. The high rates of gypsum and sludge demonstrated similar responses with much lower Al values for 0.01 M $CaCl_2$ exchangeable Al (Figure 56). Subsoil exchangeable Al increased dramatically from 2000 to 2001, and less so from 2001 to 2002. If Al^{3+} was being moved off of exchange sites and into soil solution by Ca^{2+} and other cations, it would be expected that the increase in solution Al would manifest in higher 0.01 M $CaCl_2$ Al levels. Exchangeable Al should decrease with

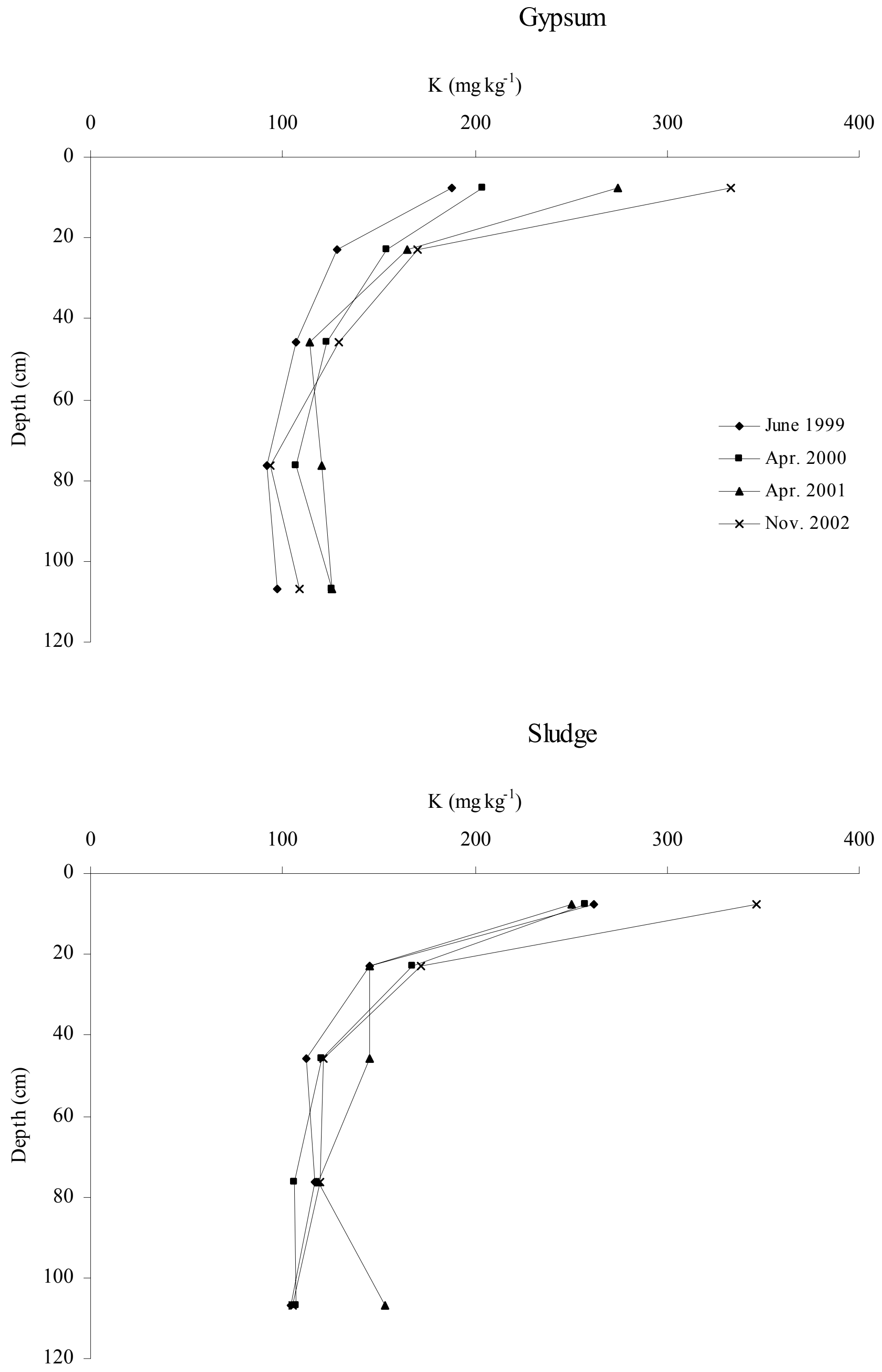
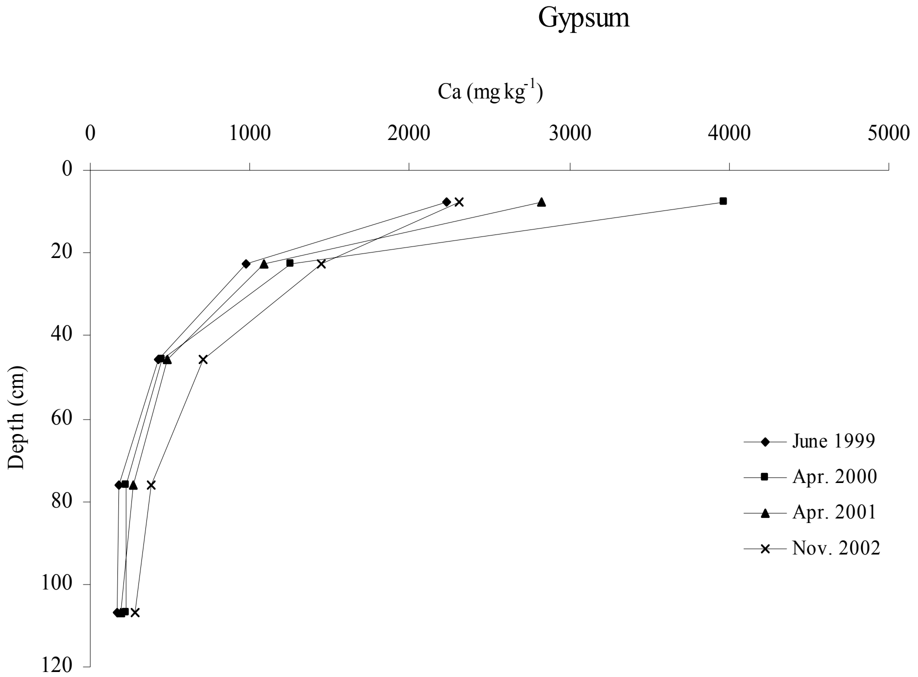


Figure 51. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable potassium at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment.



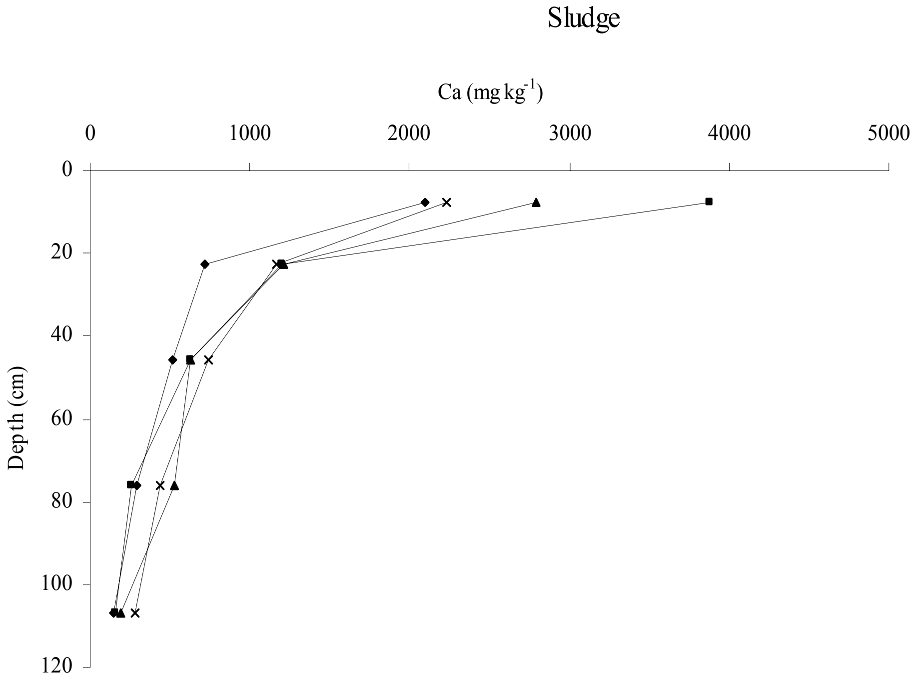


Figure 52. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable calcium at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment.

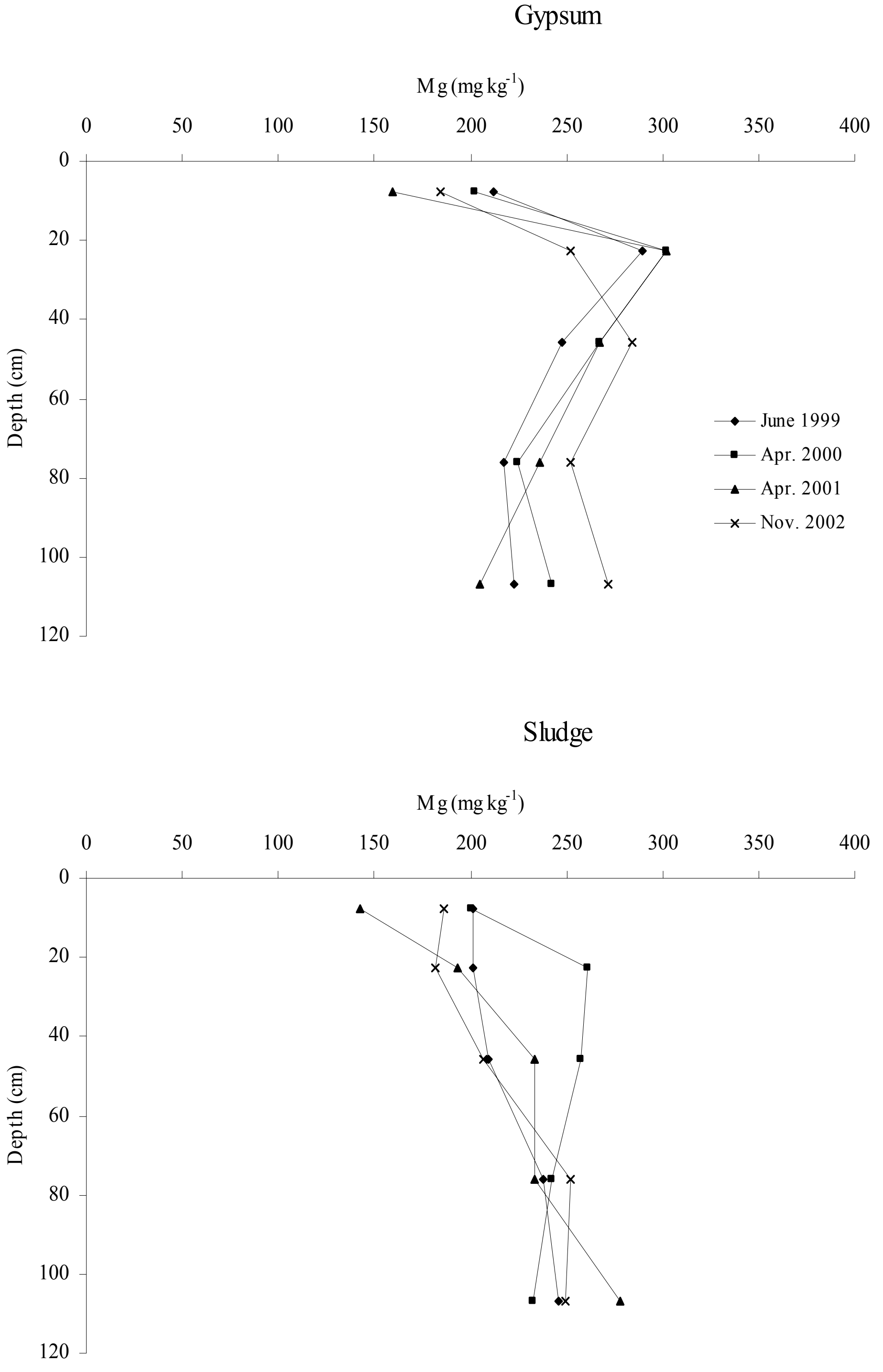
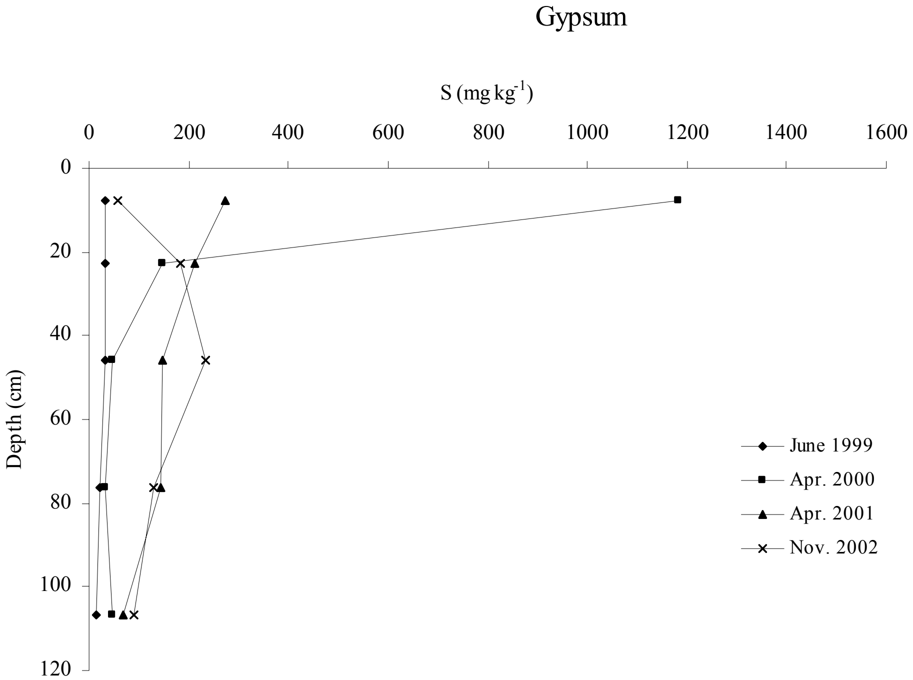


Figure 53. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable magnesium at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment.



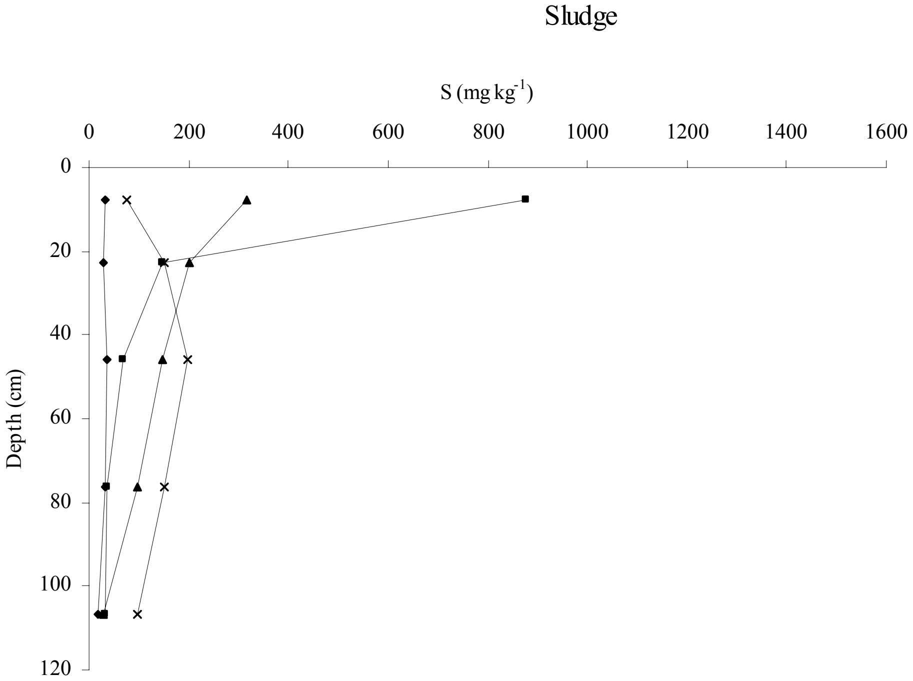
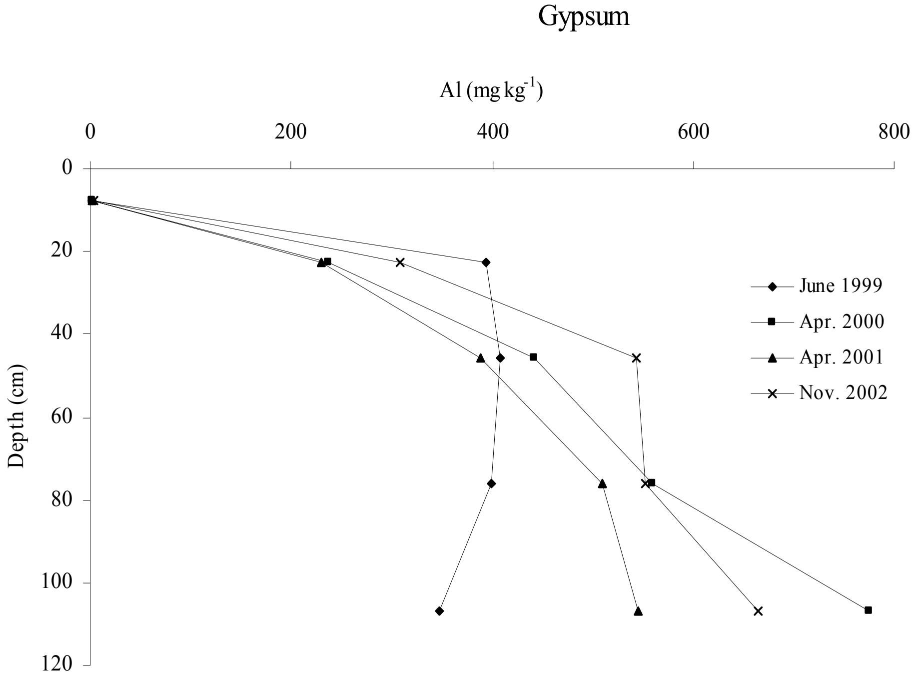


Figure 54. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on Mehlich-3 extractable sulfur at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment.



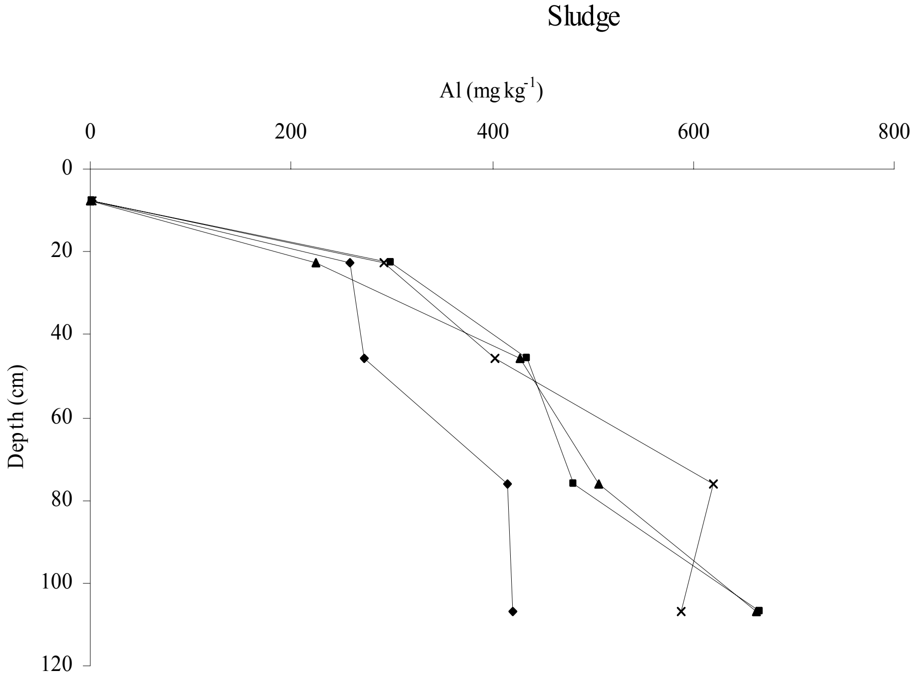
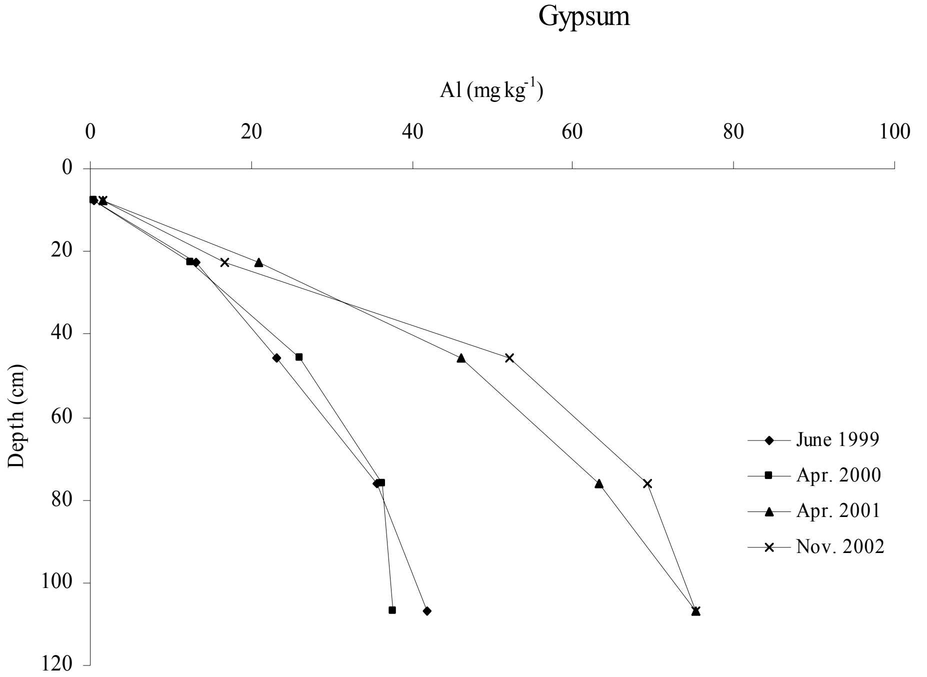


Figure 55. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on *N* KCl extractable Al at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment.



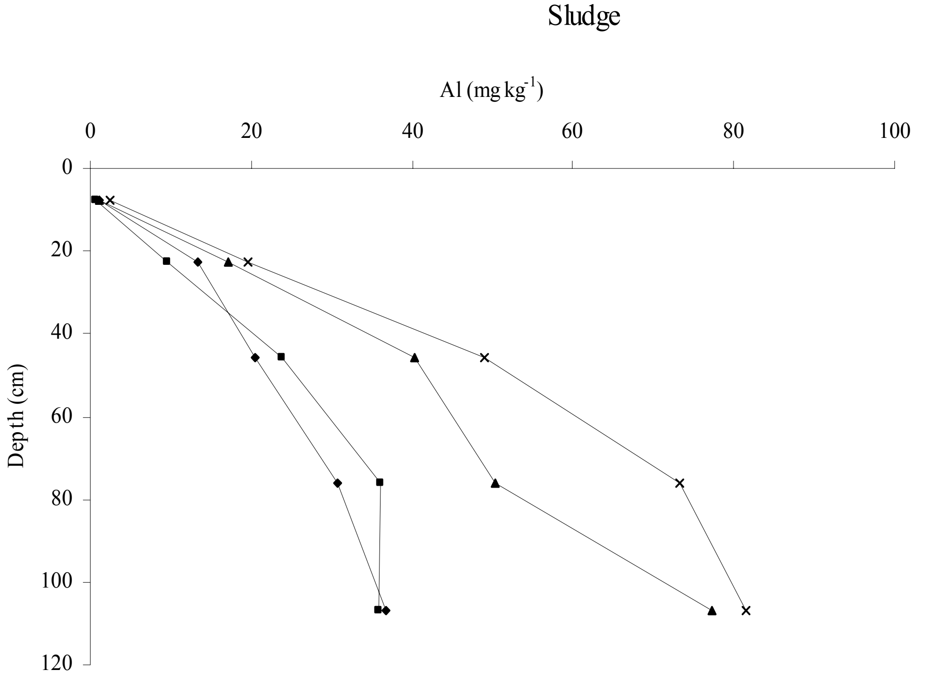
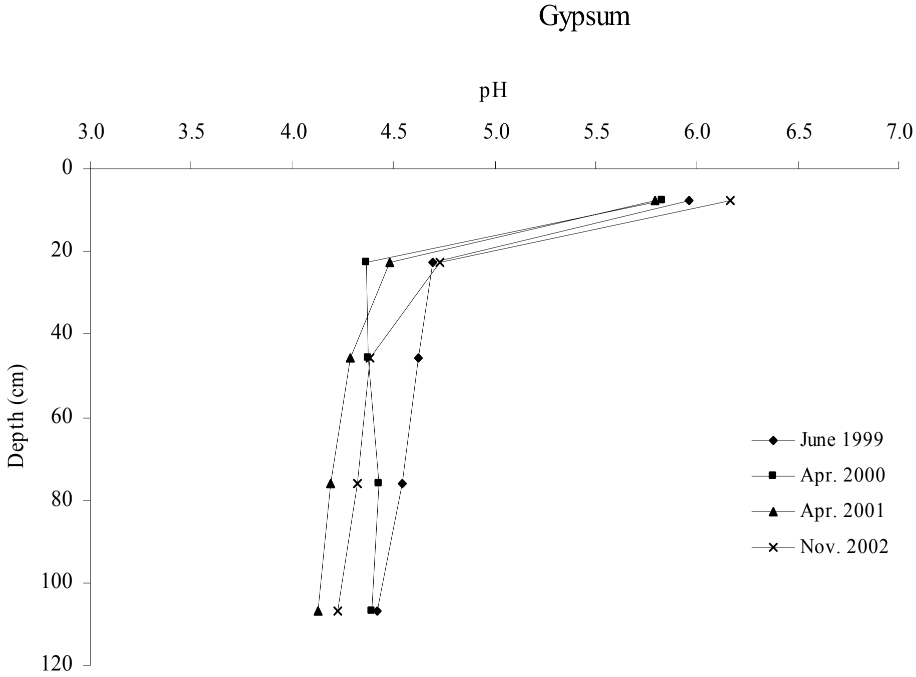


Figure 56. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on 0.01 *M* $CaCl_2$ exchangeable aluminum at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment.



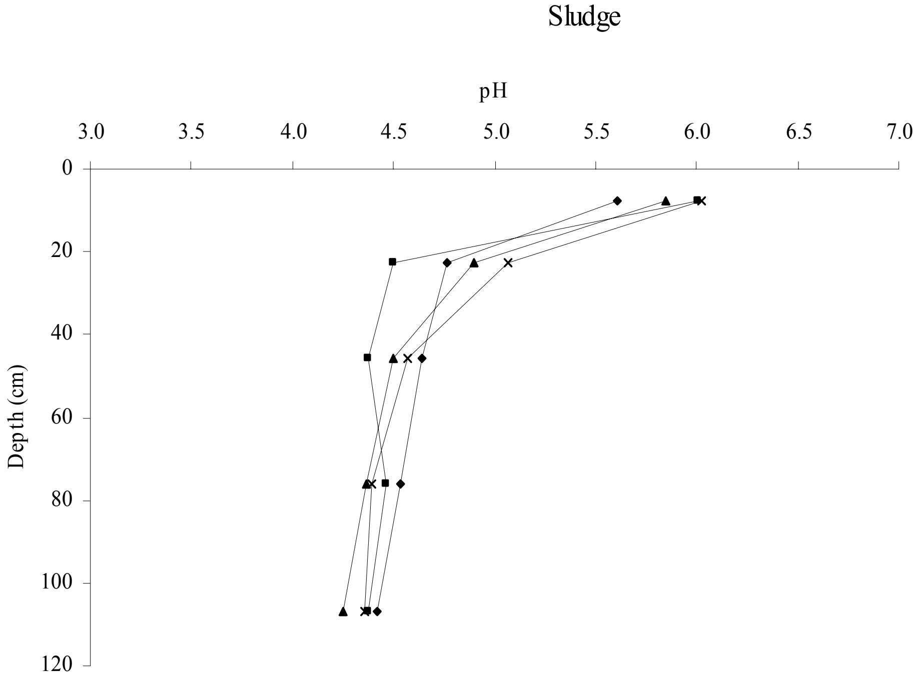
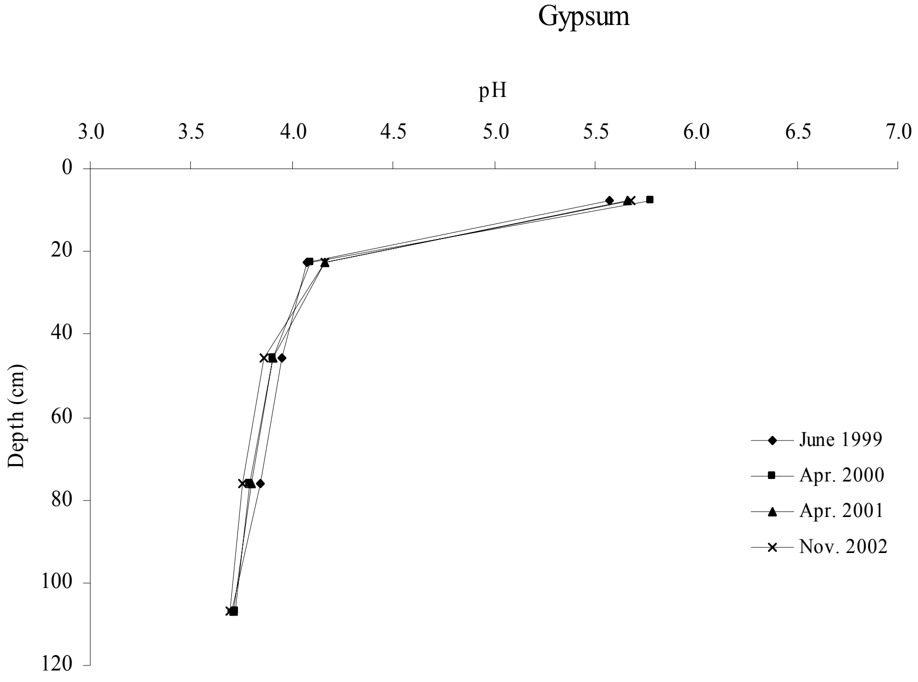


Figure 57. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on 2:1 water to soil pH at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment.



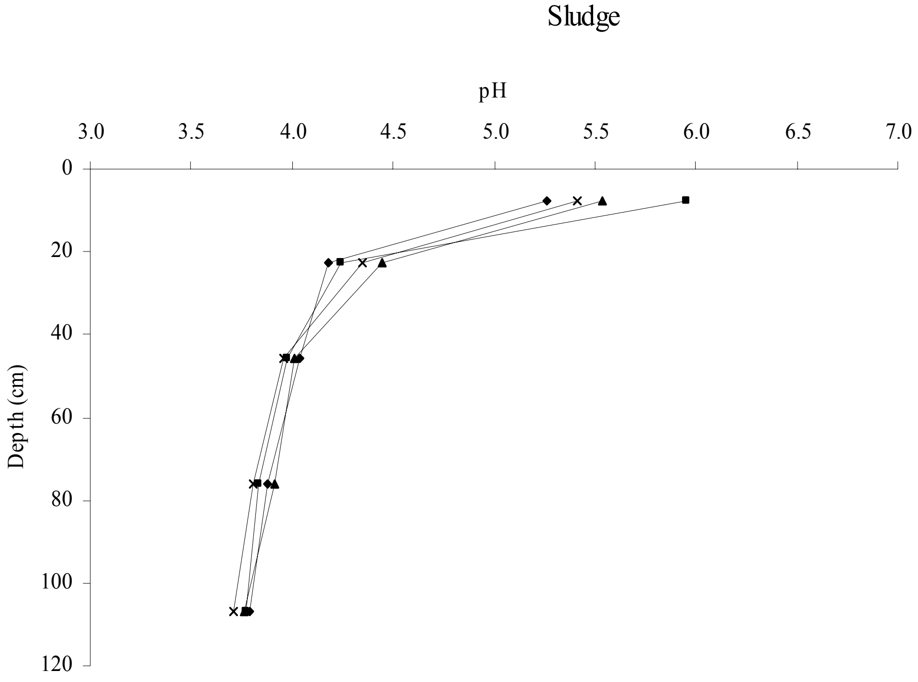


Figure 58. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on 2:1 0.01 *M* $CaCl_2$ to soil pH at different depths on four sampling dates on the Cuthbert soil, Rusk Co. TX. June 1999 sampling was prior to treatment

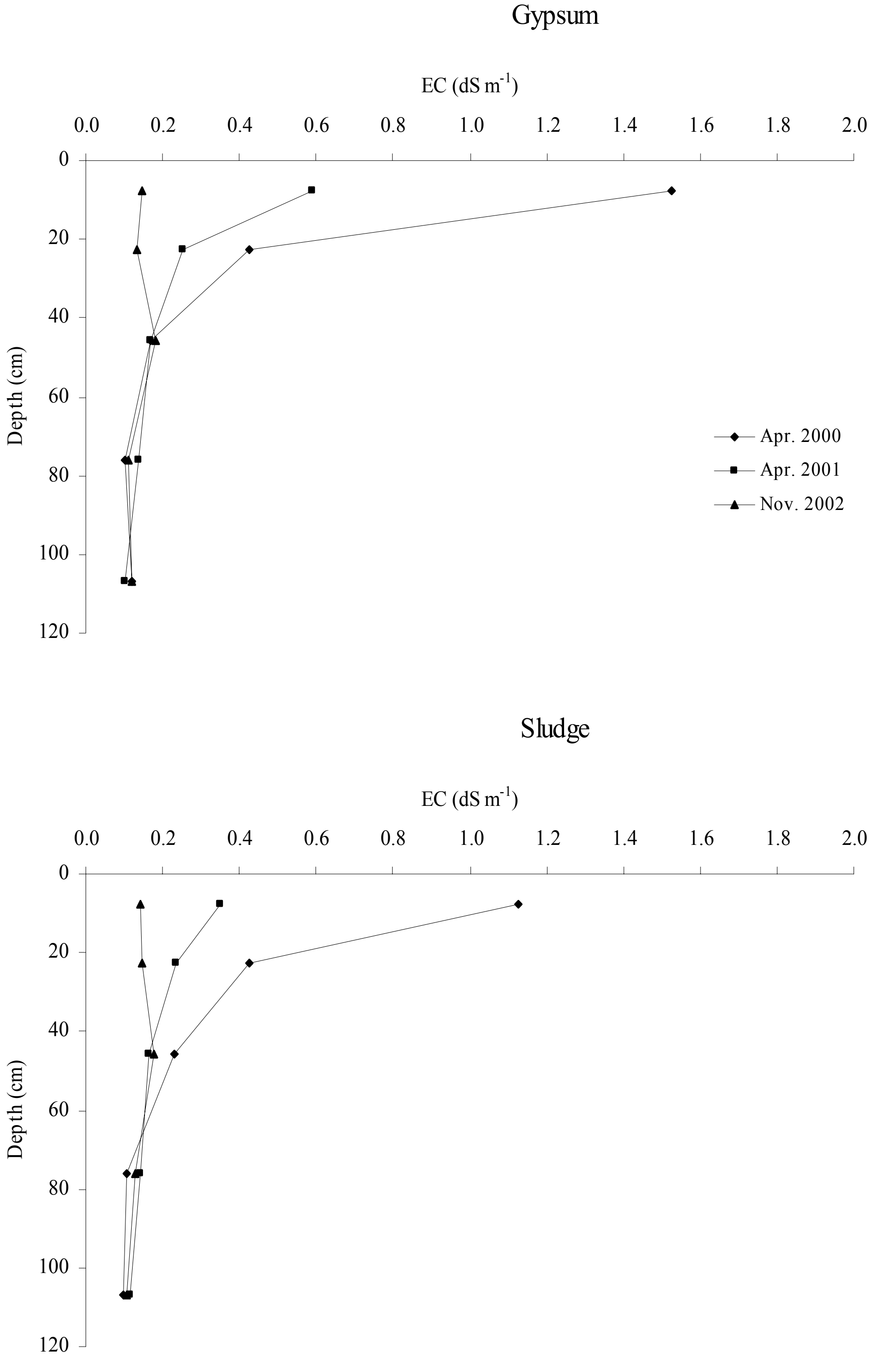


Figure 59. Effects of surface-applied gypsum and sludge at 15 Mg ha^{-1} on electrical conductivity at different depths on three sampling dates on the Cuthbert soil, Rusk Co. TX.

time as solution Al^{3+} forms $Al(OH)_3$ and various aluminum sulfate species which can be leached deeper in the soil. The trend was for pH_{H_2O} to initially decrease after treatment application, then increase so that by the 2002 sampling it was at pre-treatment levels at the 0 to 15 and 15- to 30-cm depths (Figure 57). Soil pH_{CaCl_2} did not show any discernible change throughout the study (Figure 58). Electrical conductivity decreased with time into the 30-cm depth until by 2002 there was little difference between EC at any depth (Figure 59).

Treatment Effect on Alfalfa Dry Matter Yield

Sacul Soil, Nacogdoches County. Alfalfa was harvested three times in 2000. There was not a significant material or rate effect on dry matter yield (DMY) in any of the harvests or for the total of the three harvests (Table 33). Mean DMY for the first harvest was about 1.4 Mg ha^{-1} for both materials and all rates (Table 34). Dry matter yield increased for the second and third harvests and averaged approximately 2.3 Mg ha^{-1} at each harvest. Although differences were not significant, by harvest two and continuing to harvest three a trend showed the check plots yielded slightly more than those receiving material. This was also true for the season total.

Alfalfa was harvested four times in 2001. There was not a significant material or rate effect on DMY in any of the harvests or for the total of the four harvests (Table 35). Unlike 2000, maximum DMY was obtained at the first harvest, and then steadily declined with successive harvests (Table 34). By the final harvest mean DMY for materials and rates was about 0.6 Mg ha^{-1}. Although an additional harvest was possible in 2001 compared to 2000, total DMY for the season was about 1 Mg ha^{-1} less. The trend for the check plots to yield higher than the amendment treated plots was again apparent, but only for harvests one and three. Also, the season total is slightly greater for the check plots.

Alfalfa was harvested two times in 2002. There was not a significant material or rate effect on DMY in either harvest or for the season total (Table 36). As in 2001,

Table 33. Analysis of variance for the effects of gypsum and scrubber sludge on alfalfa dry matter yield (DMY) and tissue mineral concentration of plants growing on a Sacul fine sandy loam in Nacogdoches Co. TX, harvested in 2000. Mineral analysis was not performed on harvest one samples.

Harvest	Source	df	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al
			Mean Squares											
			x 10^5											
1	Material (M)	1	0.23	—	—	—	—	—	—	—	—	—	—	—
	Rate (R)	3	0.64	—	—	—	—	—	—	—	—	—	—	—
	M x R	3	1.99	—	—	—	—	—	—	—	—	—	—	—
	Block	3	23.14***	—	—	—	—	—	—	—	—	—	—	—
	Error	21	1.96	—	—	—	—	—	—	—	—	—	—	—
			x 10^5		x 10^4	x 10^6	x 10^5	x 10^4	x 10^5	x 10^3	x 10^2	x 10^1	x 10^2	x 10^3
2	Material (M)	1	0.19	1.14	1.68	0.60	0.10	0.36	0.14	0.97	1.85	0.55	0.17	3.20
	Rate (R)	3	2.43	0.55	2.30	12.03	14.56	2.42	11.71***	1.25	2.25	0.20	0.40	0.66
	M x R	3	1.38	4.15	0.55	2.14	2.05	1.14	1.00	9.87*	0.28	0.16	0.20	1.37
	Block	3	12.63**	9.27*	6.06	8.25	12.65	18.87**	2.21	10.98*	6.32*	0.30	0.90*	0.91
	Error	21	2.15	2.85	4.25	6.61	9.17	2.92	1.08	2.94	1.80	0.12	0.25	2.05
			x 10^5		x 10^4	x 10^7	x 10^5	x 10^4	x 10^5	x 10^2	x 10^1	x 10^1	x 10^1	x 10^2
3	Material (M)	1	0.13	1.66	0.53	0.88	0.75	0.14	0.90	0.15	0.27	0.45	1.21	0.11
	Rate (R)	3	0.84	0.91	1.59	0.31	13.07	3.02	12.52***	54.18	11.22	0.16	0.23	15.00
	M x R	3	0.42	0.60	4.43	0.42	1.55	4.04	0.42	14.71	2.27	0.37	0.81	12.81
	Block	3	2.06	1.05	16.23	0.67	14.08	0.92	0.70	117.35	7.63	10.07	5.24	27.21
	Error	21	0.76	1.97	5.57	0.56	7.64	2.68	1.10	46.91	8.61	0.53***	1.90	11.22

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 34. Influence of gypsum and scrubber sludge on alfalfa dry matter yield harvested in 2000, 2001, and 2002 on a Sacul fine sandy loam in Nacogdoches Co. TX.

Year	Class		Harvest 1	Harvest 2	Harvest 3	Harvest 4	Total
			Mg ha^{-1}				
2000	Material	Gypsum	1.40	2.18	2.35	—	5.93
		Sludge	1.32	2.25	2.29	—	5.86
	Rate (Mg ha^{-1})	0	1.45	2.60	2.49	—	6.53
		5	1.36	2.27	2.42	—	6.05
		10	1.25	2.22	2.25	—	5.72
		15	1.47	2.16	2.27	—	5.90
2001	Material	Gypsum	2.02	1.43	0.71	0.58	4.74
		Sludge	2.05	1.28	0.83	0.55	4.71
	Rate (Mg ha^{-1})	0	2.42	1.26	1.02	0.66	5.36
		5	2.00	1.34	0.87	0.57	4.78
		10	2.01	1.25	0.75	0.53	4.54
		15	2.08	1.46	0.70	0.61	4.86
2002	Material	Gypsum	2.43	1.53	—	—	3.96
		Sludge	2.40	1.58	—	—	3.98
	Rate (Mg ha^{-1})	0	2.39	1.54	—	—	3.93
		5	2.26	1.56	—	—	3.82
		10	2.40	1.67	—	—	4.07
		15	2.62	1.46	—	—	4.08

Means within a class and harvest, and season total were not different at the 0.05 significance level.

Table 35. Analysis of variance for the effects of gypsum and scrubber sludge on alfalfa dry matter yield (DMY) and tissue mineral concentration of plants growing on a Sacul fine sandy loam in Nacogdoches Co. TX, harvested in 2001.

Harvest	Source	df	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al
			Mean Squares											
			x 10^4	x 10^1	x 10^5	x 10^6	x 10^5	x 10^5	x 10^5	x 10^3	x 10^2	x 10^1	x 10^3	x 10^3
1	Material (M)	1	0.48	0.87	1.73	0.92	0.15	0.16	5.92	3.65	2.40	0.12	0.79	0.24
	Rate (R)	3	24.26	0.83	0.92	11.21	60.73	0.70^{*}	6.56^{*}	3.42	7.94^{***}	1.66^{*}	1.26	1.94^{*}
	M x R	3	1.87	0.19	0.21	1.53	2.33	0.04	0.82	0.53	0.88	0.42	1.76	0.33
	Block	3	29.76	0.54	16.41^{***}	11.14	63.57	0.78^{*}	9.15^{**}	0.93	0.63	1.15	4.41^{*}	1.87^{*}
	Error	21	14.12	0.34	0.64	8.21	28.13	0.19	1.42	1.29	0.75	0.45	1.35	0.44
			x 10^5		x 10^4	x 10^6	x 10^6	x 10^4	x 10^5	x 10^3	x 10^2		x 10^2	x 10^3
2	Material (M)	1	0.82	1.28	0.12	0.70	1.25	0.21	1.50	2.20	1.33	0.17	1.25	7.18
	Rate (R)	3	0.63	0.90	4.41	2.75	0.36	19.67^{***}	0.43	0.75	1.40	2.05	0.22	0.74
	M x R	3	1.54	1.52	3.58	6.56	0.17	0.66	0.18	5.33	0.35	1.12	1.23	3.40
	Block	3	1.92	1.10	19.73^{**}	82.89^{**}	0.33	5.69^{*}	0.54	13.98	6.72	3.63	3.23^{*}	7.19
	Error	21	1.59	3.48	2.68	11.72	0.49	1.58	0.90	5.83	2.34	2.97	0.93	5.24
			x 10^5		x 10^5	x 10^6	x 10^6	x 10^4	x 10^5	x 10^3	x 10^1	x 10^1	x 10^1	x 10^4
3	Material (M)	1	0.49	0.77	2.72	2.08	0.12	0.57	0.16	0.59	0.51	1.02	0.64	0.34
	Rate (R)	3	1.32	6.44	0.17	0.99	3.72^{***}	12.87^{*}	6.27^{**}	1.96	9.84	0.79	15.89	0.30
	M x R	3	0.76	4.63	0.58	0.86	0.49	1.49	1.27	0.73	2.14	0.67	1.78	0.19
	Block	3	2.95^{**}	39.41^{***}	11.02^{***}	78.45^{***}	4.34^{***}	9.39^{*}	12.10^{***}	9.58^{**}	33.23	0.23	13.40	0.40
	Error	21	0.47	2.29	0.68	1.64	0.50	2.76	1.00	1.42	11.09	0.49	6.22	0.41
			x 10^4		x 10^5	x 10^6	x 10^6	x 10^4	x 10^5	x 10^5	x 10^2			x 10^3
4	Material (M)	1	0.36	0.76	0.14	0.68	0.19	0.18	0.29	0.13	0.95	1.91	0.70	1.83
	Rate (R)	3	2.08	1.43	0.60	1.67	3.71	2.63	8.72	0.47^{*}	0.85	0.85	14.28	1.32
	M x R	3	0.86	4.72	0.70	0.80	0.42	3.29	1.24	0.33	1.39	1.60	34.47	1.29
	Block	3	16.36^{**}	36.54^{*}	0.66	24.18^{***}	4.45	23.51^{***}	11.35^{**}	0.20	6.55^{*}	3.45	58.20	1.54^{*}
	Error	21	3.26	9.51	0.65	1.58	2.26	2.71	2.15	0.08	1.88	1.54	20.57	0.47

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 36. Analysis of variance for the effects of gypsum and scrubber sludge on alfalfa dry matter yield (DMY) and tissue mineral concentration of plants growing on a Sacul fine sandy loam in Nacogdoches Co. TX, harvested in 2002. Mineral analysis was not performed on harvest one samples.

Harvest	Source	df	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al	B	Mo
			Mean Squares													
			x 10^4													
1	Material (M)	1	0.49	—	—	—	—	—	—	—	—	—	—	—	—	—
	Rate (R)	3	14.70	—	—	—	—	—	—	—	—	—	—	—	—	—
	M x R	3	1.39	—	—	—	—	—	—	—	—	—	—	—	—	—
	Block	3	51.27*	—	—	—	—	—	—	—	—	—	—	—	—	—
	Error	21	12.69	—	—	—	—	—	—	—	—	—	—	—	—	—
			x 10^5	x 10^1	x 10^4	x 10^6	x 10^5	x 10^4	x 10^5	x 10^4	x 10^1	x 10^1		x 10^1	x 10^2	
2	Material (M)	1	0.19	0.22	1.28	2.34	0.23	0.70	0.25	0.43	0.35	0.78	0.36	0.17	0.68	0.19
	Rate (R)	3	0.49	0.17	3.33	1.38	4.83	2.79	1.03	0.52	0.52	0.12	0.85	0.16	0.17	1.65*
	M x R	3	0.16	0.11	0.28	1.75	5.52	2.26	1.39	0.46	1.15	0.11	0.25	0.26	0.36	0.34
	Block	3	2.31*	1.75***	8.33	0.99	50.65**	20.60***	11.69***	0.84	0.33	10.88***	6.57	0.91	3.67**	9.76***
	Error	21	0.70	0.18	2.83	2.34	7.46	1.67	0.87	0.40	4.41	0.60	7.42	0.45	0.61	0.38

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

maximum DMY was obtained at the first harvest. The mean of 2.4 Mg ha^{-1} was as high as any of the harvests during the two previous years (Table 34). However, DMY declined to approximately 1.6 Mg ha^{-1} in harvest two. Season total DMY was the lowest of the three years. Any previous trend indicating slightly higher yields in the check plots was no longer evident.

Cuthbert Soil, Rusk County. The same harvest schedule that was reported earlier for the Nacogdoches County site was followed for the Rusk County site. On the Rusk County site, DMY was not significantly affected by material or rate in any of the harvests during three years (Tables 37, 38 and 39). The highest total seasonal harvest was achieved in 2001, and the lowest in 2002 (Table 40). Except for harvest three in 2000, there was an apparent trend for gypsum yields to be higher than sludge yields. Although not significant, total seasonal yield is higher at the zero rate in 2001 and 2002. This is similar to the trend noticed on the Nacogdoches County site in 2000 and 2001 (Table 34).

Treatment Effect on Tissue Mineral Concentration

Sacul Soil, Nacogdoches County. Tissue mineral determination was conducted on harvests two and three during 2000. There were no significant material effects on mineral concentration in either harvest and, the only rate effect was on S which was highly significant in both harvests (Table 33). In both harvests, S in the alfalfa tissue was not significantly different between the 5, 10, and 15 Mg ha^{-1} treatments, but was significantly higher than in the zero treatment (Table 41). Differences between harvests were not compared statistically, but tissue S concentrations for both materials and all rates were higher in harvest three than in harvest two.

Tissue mineral determination was conducted on all four harvests in 2001. There were no significant material effects on mineral concentration in any of the harvests (Table 35). In harvest one there were significant rate effects on Mg, S, Mn, and Al. The highest Mg concentration was in alfalfa grown on the 10 Mg ha^{-1} amendment

Table 37. Analysis of variance for the effects of gypsum and scrubber sludge on alfalfa dry matter yield (DMY) and tissue mineral concentration of plants growing on a Cuthbert fine sandy loam in Rusk Co. TX, harvested in 2000. Mineral analysis was not performed on harvest one samples.

Harvest	Source	df	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al
			Mean Squares											
			x 10^6											
1	Material (M)	1	0.76	—	—	—	—	—	—	—	—	—	—	—
	Rate (R)	3	0.33	—	—	—	—	—	—	—	—	—	—	—
	M x R	3	0.43	—	—	—	—	—	—	—	—	—	—	—
	Block	3	1.43	—	—	—	—	—	—	—	—	—	—	—
	Error	21	0.68	—	—	—	—	—	—	—	—	—	—	—
			x 10^6	x 10^1	x 10^4	x 10^6	x 10^6	x 10^4	x 10^5	x 10^4	x 10^2	x 10^1	x 10^2	x 10^5
2	Material (M)	1	0.39	0.28	0.39	0.12	0.38	1.54	0.25	0.57	0.62	0.71	0.18	0.52
	Rate (R)	3	0.58	1.09	0.77	14.61^{*}	1.46	0.77	3.88^{*}	9.05	1.75	8.14	0.47	0.44
	M x R	3	0.25	0.32	1.60	4.25	0.29	0.48	0.04	0.72	0.57	1.22	0.10	0.19
	Block	3	0.63	1.71	12.25^{*}	15.01^{*}	3.16	11.91^{**}	1.31^{*}	10.38^{*}	2.41	3.24	0.41	0.69
	Error	21	0.66	0.59	2.75	4.57	2.15	1.94	1.04	3.22	0.99	6.61	0.18	0.36
			x 10^4		x 10^4	x 10^7	x 10^6	x 10^5	x 10^4	x 10^3	x 10^2		x 10^1	x 10^4
3	Material (M)	1	0.49	0.53	0.12	0.38	0.35	0.11	0.65	0.98	0.12	0.14	0.14	0.18
	Rate (R)	3	23.20	0.91	0.67	0.79	0.12	1.03	2.67	3.67	0.45	3.60	1.71	0.35
	M x R	3	8.40	3.35	0.89	0.13	0.40	0.21	4.08	4.59	0.14	0.39	0.45	0.29
	Block	3	41.09	6.64	2.98	2.54^{**}	2.60	0.41	9.31^{*}	14.43^{*}	0.34	1.75	2.16	1.53
	Error	21	35.92	2.93	2.36	0.40	1.02	0.39	3.91	4.31	0.39	0.92	1.08	0.67

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 38. Analysis of variance for the effects of gypsum and scrubber sludge on alfalfa dry matter yield (DMY) and tissue mineral concentration of plants growing on a Cuthbert fine sandy loam in Rusk Co. TX, harvested in 2001.

Harvest	Source	df	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al
			Mean Squares											
			x 10^5		x 10^5	x 10^6	x 10^5	x 10^4	x 10^5	x 10^2		x 10^1		x 10^3
1	Material (M)	1	0.26	0.39	0.38	0.48	3.09	1.86	1.41	0.99	0.29	0.41	0.90	0.22
	Rate (R)	3	4.14	9.89^{*}	4.46	1.10	0.58	13.95^{***}	7.49^{*}	22.96	9.18	0.13	8.82	1.05
	M x R	3	1.87	4.67	1.66	1.22	9.66	0.22	0.82	20.50	29.51	0.22	3.18	1.29
	Block	3	3.75	7.22^{*}	25.83^{***}	21.56^{***}	36.46	0.83	3.06	46.64^{*}	40.06	1.83	75.59	1.99
	Error	21	2.98	2.33	2.65	1.65	27.32	1.31	1.85	11.68	32.67	0.41	25.00	1.71
			x 10^6		x 10^4	x 10^7	x 10^5	x 10^4	x 10^4	x 10^3	x 10^2	x 10^{-1}		x 10^3
2	Material (M)	1	0.38	2.57	0.21	0.91	0.90	0.12	0.29	0.82	0.43	0.91	0.64	0.14
	Rate (R)	3	0.11	0.92	6.15	0.86	9.39	7.36^{*}	116.53^{***}	3.13	0.59	9.34	2.75	0.19
	M x R	3	0.18	3.55	2.11	0.76	4.22	2.91	4.98	1.21	1.05	3.68	0.74	0.45
	Block	3	0.46	7.23^{*}	4.00	1.51	0.64	0.53	15.44^{*}	2.69	0.34	22.67	1.34	3.37^{**}
	Error	21	0.37	1.84	4.62	0.79	8.74	2.24	4.84	4.14	0.48	29.64	2.09	0.62
			x 10^6		x 10^5	x 10^7	x 10^5	x 10^4	x 10^5	x 10^3	x 10^1		x 10^1	x 10^3
3	Material (M)	1	0.89	0.16	0.21	0.41	0.11	0.22	0.32	1.38	0.94	0.15	3.23	1.75
	Rate (R)	3	1.20	8.92	0.19	0.55	90.24^{***}	0.47	30.44^{***}	1.68	4.18	14.80	0.18	0.72
	M x R	3	0.12	0.45	0.17	0.29	7.87	1.30	0.68	0.44	5.35	0.31	0.58	0.24
	Block	3	0.46	1.18	0.28	3.55^{**}	8.26	0.43	0.90	5.35	4.48	14.86	1.26	1.43
	Error	21	0.44	4.26	0.25	0.58	6.00	1.63	1.45	2.02	2.84	5.37	1.69	2.11
			x 10^5	x 10^1	x 10^5	x 10^5	x 10^6	x 10^4	x 10^5	x 10^4	x 10^2		x 10^1	x 10^4
4	Material (M)	1	1.61	0.26	0.81	0.17	0.87	4.88	1.26	0.38	0.63	0.23	1.10	1.02
	Rate (R)	3	0.93	0.60	1.02	21.78	1.29	4.88	3.03	0.85	0.18	0.43	0.17	0.47
	M x R	3	0.20	0.14	0.40	9.25	0.98	1.40	0.44	0.21	0.36	0.21	0.30	0.20
	Block	3	1.11	0.47	15.75^{***}	16.19	2.67	0.73	2.71	1.91	2.11^{***}	2.55^{*}	0.82	1.32
	Error	21	1.61	0.26	0.66	19.65	3.15	2.83	1.38	0.81	0.26	0.63	0.56	1.56

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 39. Analysis of variance for the effects of gypsum and scrubber sludge on alfalfa dry matter yield (DMY) and tissue mineral concentration of plants growing on a Cuthbert fine sandy loam in Rusk Co. TX, harvested in 2002. Mineral analysis was not performed on harvest one samples.

Harvest	Source	df	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al	B	Mo
			Mean Squares													
			x 10^5													
1	Material (M)	1	0.57	—	—	—	—	—	—	—	—	—	—	—	—	—
	Rate (R)	3	1.13	—	—	—	—	—	—	—	—	—	—	—	—	—
	M x R	3	0.35	—	—	—	—	—	—	—	—	—	—	—	—	—
	Block	3	2.31	—	—	—	—	—	—	—	—	—	—	—	—	—
	Error	21	2.14	—	—	—	—	—	—	—	—	—	—	—	—	—
			x 10^5		x 10^5	x 10^7	x 10^6	x 10^5	x 10^4	x 10^4	x 10^1		x 10^1	x 10^1	x 10^1	
2	Material (M)	1	3.15	0.15	0.47	0.36	0.70	0.70	0.13	0.19	0.98	0.43	0.29	0.47	0.61	0.57
	Rate (R)	3	1.33	0.11	0.69	0.24	0.99	1.06	6.39	0.27	0.90	0.53	1.06	80.71	2.29	0.14
	M x R	3	0.90	1.34	1.07	0.15	0.52	0.57	7.83	0.31	0.23	0.61	0.12	48.34	1.17	0.27
	Block	3	3.35	1.11	7.77^{***}	1.15^{**}	0.70	0.59	9.46	0.53^{*}	2.11	0.67	1.01	47.82	4.44	1.50
	Error	21	3.10	0.83	0.59	0.23	2.32	0.71	4.95	0.15	1.51	0.58	0.96	97.20	3.91	0.72

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 40. Influence of gypsum and scrubber sludge on alfalfa dry matter yield harvested in 2000, 2001, and 2002 on a Cuthbert fine sandy loam in Rusk Co. TX.

Year	Class		Harvest 1	Harvest 2	Harvest 3	Harvest 4	Total
			Mg ha^{-1}				
2000	Material	Gypsum	1.72	1.84	1.20	—	4.76
		Sludge	1.26	1.51	1.23	—	4.01
	Rate (Mg ha^{-1})	0	1.69	2.08	1.11	—	4.88
		5	1.72	1.97	1.43	—	5.12
		10	1.23	1.45	0.98	—	3.65
		15	1.53	1.60	1.24	—	4.37
2001	Material	Gypsum	1.88	1.05	2.13	1.37	6.43
		Sludge	1.79	0.73	1.63	1.15	5.31
	Rate (Mg ha^{-1})	0	2.21	0.74	2.57	1.46	6.99
		5	2.07	0.89	2.26	1.30	6.52
		10	1.77	0.76	1.70	1.17	5.40
		15	1.67	1.02	1.68	1.31	5.69
2002	Material	Gypsum	0.95	1.21	—	—	2.16
		Sludge	0.86	0.96	—	—	1.82
	Rate (Mg ha^{-1})	0	1.07	1.32	—	—	2.39
		5	0.95	1.09	—	—	2.04
		10	0.83	0.95	—	—	1.78
		15	0.77	1.00	—	—	1.77

Means within a class and harvest, and season total were not different at the 0.05 significance level.

Table 41. Influence of gypsum and scrubber sludge on alfalfa tissue mineral concentration harvested in 2000 on a Sacul fine sandy loam in Nacogdoches Co. TX.

Harvest	Class		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
			g kg^{-1}						mg kg^{-1}			
2	Material	Gypsum	36.1	2.37	29.8	10.83	1.84	3.67	113	53.9	7.11	34.5
		Sludge	36.9	2.43	29.4	10.78	1.81	3.64	99	47.5	8.22	32.5
	Rate (Mg ha^{-1})	0	36.7	2.48	28.6	9.98	1.80	2.90^{b}	82	40.2	7.77	31.6
		5	37.0	2.45	30.9	10.75	1.79	3.65^{a}	103	50.8	8.10	36.3
		10	36.1	2.39	29.6	10.72	1.90	3.62^{a}	109	51.4	7.94	32.6
		15	36.4	2.36	28.2	10.95	1.79	3.72^{a}	107	49.8	6.96	31.5
3	Material	Gypsum	38.5	2.73	27.3	9.83	1.81	3.90	114	51.0	4.62	32.0
		Sludge	37.6	2.76	25.9	9.70	1.80	4.04	115	50.2	5.62	30.3
	Rate (Mg ha^{-1})	0	37.7	2.77	27.5	9.16	1.91	3.22^{b}	150	45.9	4.89	32.0
		5	38.4	2.70	27.0	9.47	1.81	3.80^{a}	107	51.5	4.53	30.7
		10	38.4	2.81	26.8	9.70	1.83	4.05^{a}	141	53.7	5.56	31.5
		15	37.3	2.74	26.0	10.12	1.77	4.06^{a}	95	46.7	5.26	31.2

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

plots which were significantly higher than in the 15 Mg ha^{-1} treatment alfalfa (Table 42). Rate effect on S concentration was not consistent. The highest S concentration was in the 10 Mg ha^{-1} plots which were significantly higher than the 5 Mg ha^{-1} treatment. Manganese concentration was highest at 10 Mg ha^{-1}. The other three treatments were not significantly different from each other. Magnesium concentration in harvest two was significantly higher in the check plots. This response would be expected if the high Ca levels in the treatments resulted in exchange and movement of Mg down in the soil therefore making it less available to plant roots, or if Ca^{2+} simply competed with Mg^{2+} for uptake. Treatments receiving gypsum or sludge were not different from each other. In harvest three, Ca, Mg, and S were significantly affected by treatment rate. Calcium in plant tissue was highest in the 15 Mg ha^{-1} treatments while S was highest in the 10 and 15 Mg ha^{-1} amendment treated plots. By harvest four Mg, Ca, and S concentrations were similar for all rates. Iron was the only element showing a significant increase due to higher amendment rates in harvest four.

In 2002, tissue mineral concentration was determined only on samples from harvest two. As in previous years, there was not a significant material effect on any plant element (Table 36). Rate was significant only for Mo, and the relationship was not consistent with rate (Table 43).

Cuthbert Soil, Rusk County. In 2000, harvests two and three were analyzed for tissue mineral concentration. There were no significant material effects in either harvest (Table 37). In harvest two, the only significant effects from rate were on K and S, and in harvest three there were no significant effects. Potassium was significantly lower in the 15 Mg ha^{-1} treatment than in the other three treatments (Table 44). Lower K levels were probably due to increased soil Ca^{2+} levels and the resulting exclusion of K^+ from roots, even though there was no apparent difference in plant Ca concentrations between rates. Tissue S concentrations increased with increasing rate, but only the high rate was significantly different than the check.

Tissue mineral concentration was analyzed on all four harvests in 2001. There were no significant material effects on mineral concentration in any of the

Table 42. Influence of gypsum and scrubber sludge on alfalfa tissue mineral concentration harvested in 2001 on a Sacul fine sandy loam in Nacogdoches Co. TX.

Harvest	Class		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
			g kg^{-1}						mg kg^{-1}			
1	Material	Gypsum	42.4	3.10	27.3	13.56	1.81	4.21	176	43.1	12.19	37.7
		Sludge	44.6	3.29	26.8	13.59	1.87	4.57	204	50.4	12.71	50.9
	Rate (Mg ha^{-1})	0	44.0	3.41	27.8	12.70	1.88^{ab}	4.25^{ab}	187	33.8^{b}	12.65	24.5
		5	42.2	3.18	28.5	12.53	1.82^{ab}	4.05^{b}	185	40.5^{b}	14.48	54.9
		10	45.8	3.19	25.8	14.28	1.97^{a}	4.73^{a}	218	57.4^{a}	11.36	36.8
		15	42.5	3.21	26.7	13.92	1.75^{b}	4.38^{ab}	168	42.5^{b}	11.51	41.2
2	Material	Gypsum	48.2	3.18	29.0	12.18	1.97	4.26	235	55.2	9.80	36.7
		Sludge	47.3	3.17	29.4	11.65	1.97	4.07	213	49.8	9.68	31.5
	Rate (Mg ha^{-1})	0	48.4	3.24	28.7	12.24	2.28^{a}	4.05	207	50.6	9.91	35.5
		5	47.2	3.09	29.9	11.85	2.02^{b}	4.11	221	56.8	9.27	32.7
		10	48.2	3.20	28.8	11.79	1.97^{b}	4.17	230	53.7	10.43	33.4
		15	47.8	3.25	29.0	12.10	1.93^{b}	4.21	222	47.0	9.52	36.2
3	Material	Gypsum	37.6	2.65	26.6	11.42	1.84	3.89	180	54.3	12.33	23.5
		Sludge	38.3	2.89	27.2	10.74	1.87	3.95	191	55.4	10.83	22.3
	Rate (Mg ha^{-1})	0	36.8	2.84	27.4	10.74^{b}	2.10^{a}	3.61^{b}	169	48.8	10.14	31.6
		5	37.3	2.78	27.1	10.58^{b}	1.82^{b}	3.59^{b}	167	53.0	10.87	22.0
		10	36.7	2.73	27.1	11.35^{ab}	1.87^{ab}	4.09^{a}	196	54.4	12.50	24.1
		15	39.8	2.80	26.5	12.08^{a}	1.88^{ab}	4.11^{a}	194	57.2	11.36	22.6
4	Material	Gypsum	40.7	3.52	30.9	13.40	2.00	4.42	336	57.1	5.48	20.8
		Sludge	40.0	3.46	30.5	13.19	1.99	4.34	282	52.5	6.13	20.4
	Rate (Mg ha^{-1})	0	41.7	3.35	30.8	12.92	2.10	3.86	244^{b}	56.4	6.14	19.1
		5	40.3	3.45	31.2	12.55	2.00	4.12	246^{b}	52.2	6.10	19.1
		10	40.4	3.46	30.8	13.18	1.97	4.43	277^{b}	53.0	5.43	21.1
		15	40.4	3.57	30.1	14.14	2.02	4.61	406^{a}	59.2	5.87	21.7

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

Table 43. Influence of gypsum and scrubber sludge on alfalfa tissue mineral concentration in harvest two in 2002 on a Sacul fine sandy loam in Nacogdoches Co. TX.

Class		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B	Mo
		g kg^{-1}						mg kg^{-1}					
Material	Gypsum	29.7	2.84	30.8	9.49	1.61	2.93	44	27.7	10.94	24.8	47.5	2.08
	Sludge	30.9	2.89	30.1	9.56	1.65	3.01	75	26.8	9.62	25.0	51.4	1.88
Rate (Mg ha^{-1})	0	29.1	2.76	29.8	9.38	1.72	2.76	44	27.0	9.71	24.6	47.9	1.80^{ab}
	5	30.9	2.82	30.6	9.19	1.68	2.92	93	27.8	10.07	25.3	50.3	1.39^{b}
	10	29.8	2.87	30.7	9.70	1.63	2.96	46	27.9	10.66	24.8	50.3	2.47^{a}
	15	30.3	2.91	30.1	9.67	1.58	3.03	38	26.2	10.12	24.6	47.8	2.07^{ab}

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

Table 44. Influence of gypsum and scrubber sludge on alfalfa tissue mineral concentration harvested in 2000 on a Cuthbert fine sandy loam in Rusk Co. TX.

Harvest	Class		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
			g kg^{-1}						mg kg^{-1}			
2	Material	Gypsum	42.2	2.50	26.0	13.1	1.75	3.26	245	44.4	1.23	22.2
		Sludge	43.4	2.53	26.2	13.4	1.81	3.34	280	48.1	1.35	24.2
	Rate (Mg ha^{-1})	0	39.3	2.46	26.5^{a}	12.6	1.80	2.91^{b}	128	37.6	1.00	18.4
		5	42.2	2.51	26.6^{a}	13.0	1.80	3.21^{ab}	165	44.0	0.93	23.0
		10	42.5	2.53	27.4^{a}	13.2	1.74	3.25^{ab}	366	48.1	1.63	23.3
		15	43.7	2.49	24.2^{b}	13.6	1.80	3.44^{a}	256	46.8	1.31	23.3
3	Material	Gypsum	36.0	2.22	30.2	10.9	2.02	2.90	99	33.2	2.14	26.5
		Sludge	36.5	2.23	31.1	10.7	1.97	2.86	114	34.8	2.32	27.0
	Rate (Mg ha^{-1})	0	36.1	2.18	29.4	11.0	2.20	2.77	83	32.4	1.19	25.2
		5	36.4	2.23	31.0	10.9	2.04	2.90	81	35.9	1.67	26.5
		10	36.8	2.20	31.3	10.8	1.94	2.85	122	35.3	2.68	28.3
		15	35.5	2.24	29.6	10.7	2.00	2.88	116	30.8	2.34	25.3

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

Table 45. Influence of gypsum and scrubber sludge on alfalfa tissue mineral concentration harvested in 2001 on a Cuthbert fine sandy loam in Rusk Co. TX.

Harvest	Class		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
			g kg^{-1}						mg kg^{-1}			
1	Material	Gypsum	43.3	3.76	27.3	14.5	1.63	4.30^{a}	169	25.7	5.81	20.8
		Sludge	42.8	3.67	27.0	14.3	1.56	4.12^{b}	164	25.4	4.86	20.3
	Rate (Mg ha^{-1})	0	45.4^{a}	4.08	27.4	14.3	1.84^{a}	3.69^{b}	157	26.3	4.64	20.1
		5	44.8^{a}	3.71	27.1	14.4	1.65^{b}	4.02^{ab}	144	24.3	5.59	21.9
		10	41.8^{b}	3.90	27.6	14.3	1.59^{b}	4.20^{ab}	177	26.7	5.30	20.5
		15	42.5^{b}	3.53	26.8	14.5	1.54^{b}	4.41^{a}	179	25.6	5.12	19.3
2	Material	Gypsum	40.6	2.66	28.2	12.5	2.01	4.02	84	29.3	4.51	46.0
		Sludge	39.4	2.64	29.7	12.3	2.03	3.99	97	32.4	4.65	57.9
	Rate (Mg ha^{-1})	0	39.7	2.82	30.5	11.8	2.15^{a}	3.31^{c}	97	26.8	4.52	71.9
		5	40.6	2.67	28.2	12.3	2.07^{a}	3.79^{b}	79	29.3	4.93	60.0
		10	40.0	2.66	29.8	12.4	2.06^{a}	4.04^{ab}	118	33.3	4.70	65.7
		15	39.4	2.62	28.9	12.6	1.92^{b}	4.18^{a}	75	30.0	4.12	30.1
3	Material	Gypsum	39.7	2.68	28.5	12.1	1.61	0.26	115	28.5	7.96	16.0
		Sludge	40.0	2.75	29.5	12.0	1.58	0.31	133	30.0	7.98	18.7
	Rate (Mg ha^{-1})	0	36.9	2.81	30.5	10.3^{c}	1.59	2.82^{c}	145	25.1	9.72	16.4
		5	39.4	2.73	28.6	11.6^{b}	1.61	3.52^{b}	115	27.8	9.19	17.2
		10	39.3	2.70	29.4	11.7^{b}	1.56	3.80^{b}	119	29.7	6.65	17.2
		15	41.0	2.71	29.0	12.9^{a}	1.61	4.29^{a}	138	30.1	8.09	17.5
4	Material	Gypsum	43.5	3.70	29.3	11.6	1.48	3.73	229	29.6	2.84	11.9
		Sludge	44.8	3.70	29.3	12.1	1.58	3.90	258	33.3	3.07	13.4
	Rate (Mg ha^{-1})	0	45.3	3.77	29.1	11.3	1.65	3.53	181	28.8	2.65	12.3
		5	44.6	3.79	29.3	11.8	1.59	3.72	231	31.6	3.20	13.2
		10	42.4	3.55	28.7	11.5	1.51	3.72	250	32.3	2.84	12.4
		15	45.4	3.77	29.9	12.2	1.48	4.00	249	30.5	2.83	12.2

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

Table 46. Influence of gypsum and scrubber sludge on alfalfa tissue mineral concentration in harvest two in 2002 on a Cuthbert fine sandy loam in Rusk Co. TX.

Class		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B	Mo
		g kg^{-1}						mg kg^{-1}					
Material	Gypsum	29.1	3.33	28.2	11.1	1.64	2.61	47	17.1	2.50	24.6	47.8	1.33
	Sludge	29.0	3.23	27.2	10.8	1.77	2.60	70	18.6	2.85	25.3	49.5	0.96
Rate (Mg ha^{-1})	0	28.6	3.26	26.8	10.2	1.81	2.45	29	16.3	2.50	23.5	44.8	1.32
	5	29.1	3.41	27.5	10.8	1.78	2.60	75	17.6	3.03	25.1	49.4	1.21
	10	28.9	3.21	27.6	11.1	1.77	2.62	50	18.8	2.50	25.8	48.8	1.18
	15	29.0	3.23	28.0	11.0	1.57	2.59	50	17.1	2.50	23.9	47.8	1.05

Means within a class followed by the same letter or unlettered are not different at the 0.05 significance level.

harvests (Table 38). Rate effect was significant for N in harvest one, Mg in harvests one and two, S in harvests one, two, and three, and Ca in harvest three. There were no significant rate effects in harvest four. Nitrogen was significantly higher in the 0 and 5 Mg ha^{-1} treatments than in the 10 and 15 Mg ha^{-1} treatments in harvest one (Table 45). No similar trend was noticed in any other harvest during 2001 or the other two years of the study (Tables 44 and 46). Magnesium was significantly higher in harvest one at the zero rate than where gypsum or sludge were applied. Increased soil Ca probably resulted in increased Ca^{2+} uptake in preference to Mg^{2+}. Also, S concentration increased with higher amendment rate. In harvest two, Mg concentrations were higher than harvest one, and the 0, 5, and 10 Mg ha^{-1} treatments were not different but were significantly higher than the 15 Mg ha^{-1} rate. Sulfur concentrations increased significantly with increasing amendment rate. Calcium concentration increased with increasing rate in harvest three. However, there was not a corresponding inverse relationship with K or Mg. As in harvests one and two, tissue S increased with increasing amendment rate.

In 2002, only harvest two was analyzed for tissue mineral concentration. There were no significant material or rate effects on any of the measure elements (Table 39). The trends related to rate that were observed in previous harvests were not evident in means for rates in 2002 (Table 46).

Correlations of Soil Analysis Data and Dry Matter Yield

Sacul Soil, Nacogdoches County. Mehlich-3 extractable K at the 0 to 15 and 30- to 60-cm depth was negatively correlated with DMY for harvest one in 2000 (Table 47). A similar relationship occurred with K in the 0 to 15 and 15- to 30-cm depths in harvests one, two and total yield in 2001 (Table 48). Extractable K in the 0- to 15-cm depth was significantly related to DMY in harvest one, and total yield in 2002 (Table 49). Dry matter yield was also negatively correlated with 0.01 *M* $CaCl_2$ exchangeable Al at 0 to 15 or 15 to 30 cm for harvest one, two and total yield in 2000, harvest one, three and total yield in 2001, and both harvests and total yield in 2002. In 2000, KCl extractable Al was not significantly correlated with DMY. However, in 2001 there was a significant negative correlation between DMY for harvest one, two and total seasonal yield and extractable Al at 0-15 or 15-30 cm. In 2002, there was significant correlation between DMY and extractable Al from the surface to 60 cm in harvest one and from the surface to 120 cm for total seasonal yield. Also in 2002, pH_{H_2O} and pH_{CaCl_2} were closely associated. At all harvests except the last one each year, there was a positive correlation between DMY and both pH measures in the surface 30 cm. This was particularly true for pH_{CaCl_2} from the surface to 60 cm and DMY for harvest two in 2000 and 2001, and to 90 cm for total yield in 2001 and 2002.

Cuthbert Soil, Rusk County. Exchangeable cation levels in the surface 15 cm were negatively to highly negatively correlated with DMY for season totals and all harvests except soil K and harvests one and three in 2001 (Tables 50, 51, and 52). In 2000 and 2002, there was a high negative correlation between soil K in the surface 30 cm and DMY of all harvests and the season totals, and a high positive correlation between Ca at 30 to 60 cm and DMY of all harvests. There was also a high negative correlation between both 0.01 M $CaCl_2$ exchangeable and N KCl extractable Al at 15 to 60 cm and DMY of all harvests in 2000 (Table 50). Also in 2000, extractable Al at 60 to 90 cm was negatively correlated with DMY in all harvests. There was a negative to highly negative correlation in 2001 and 2002 between exchangeable Al at 15 to 90 cm and DMY for all harvests except harvest three in 2001 (Table 51). Also in 2001 and 2002, there was an association between yield and KCl extractable Al at 15 to 90 cm. The negative relationship is particularly strong with extractable Al at 15 to 30 cm in both years. Although ANOVA did not identify significant rate effects on DMY or differences in exchangeable or extractable soil Al, the correlation indicates that increased soil Al levels are related to decreased DMY. The relationship between increased yields and increased pH_{H_2O} and pH_{CaCl_2} from the surface to 90 cm is apparent in all harvests in all years. Except for three harvests in 2001, the association is strongest with pH at 15 to 30 cm. Increased pH_{H_2O} to 75 cm from surface incorporation

Table 47. Simple correlations (r) between alfalfa dry matter yield from year 2000 harvests and soil parameters at five depths sampled in May 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Soil Parameter								
		K	Ca	Mg	S	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
1	0-15	-0.483**	0.124	0.016	0.005	-0.232	-0.028	0.365*	0.462**	0.011
	15-30	-0.161	0.402*	-0.081	0.117	-0.393*	0.244	0.410*	0.367*	-0.064
	30-60	-0.419*	0.358*	-0.416*	0.195	-0.257	0.128	0.133	-0.021	-0.341
	60-90	-0.274	0.146	-0.253	0.038	-0.330	-0.204	0.110	-0.059	-0.13
	90-120	0.187	-0.290	0.254	0.497**	-0.271	0.052	0.189	-0.239	0.104
2	0-15	-0.238	-0.123	-0.034	-0.238	-0.460**	-0.238	0.522**	0.609***	-0.193
	15-30	-0.261	0.264	-0.234	-0.102	-0.569***	-0.026	0.615***	0.526**	-0.118
	30-60	-0.240	0.198	-0.213	0.036	-0.234	-0.131	0.402*	0.150	-0.287
	60-90	-0.116	0.149	-0.160	-0.137	-0.242	-0.394*	0.310	0.082	0.005
	90-120	0.172	0.106	0.053	0.351*	-0.069	-0.236	0.219	-0.254	0.230
3	0-15	0.147	-0.186	0.003	-0.301	-0.313	-0.035	0.279	0.299	-0.290
	15-30	0.091	0.061	0.025	-0.046	-0.268	-0.191	0.203	0.017	-0.009
	30-60	0.057	-0.012	-0.002	0.002	-0.065	-0.197	0.105	-0.138	0.115
	60-90	0.174	0.284	0.012	-0.277	-0.111	-0.139	0.079	0.098	0.163
	90-120	0.018	0.299	-0.181	-0.307	0.127	-0.288	0.070	-0.152	0.331
Total	0-15	-0.324	-0.037	-0.005	-0.181	-0.407*	-0.131	0.495**	0.591***	-0.155
	15-30	-0.180	0.345	-0.142	0.002	-0.530**	0.068	0.542***	0.436**	-0.091
	30-60	-0.314	0.273	-0.314	0.117	-0.255	-0.040	0.277	0.026	-0.280
	60-90	-0.153	0.214	-0.202	-0.111	-0.309	-0.319	0.217	0.033	-0.026
	90-120	0.181	-0.031	0.113	0.343	-0.142	-0.151	0.215	-0.279	0.241

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 48. Simple correlations (r) between alfalfa dry matter yield from year 2001 harvests and soil parameters at five depths sampled in Apr. 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Soil Parameter								
		K	Ca	Mg	S	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
1	0-15	-0.501**	-0.105	-0.265	-0.244	-0.421*	-0.516**	0.594***	0.667***	-0.308
	15-30	-0.400*	0.053	-0.278	-0.215	-0.493**	-0.460**	0.498**	0.539**	-0.220
	30-60	-0.242	0.053	-0.222	-0.159	-0.166	-0.170	0.347	0.348	-0.348
	60-90	0.030	0.391*	0.011	-0.035	-0.214	-0.106	0.402*	-0.085	-0.412*
	90-120	0.185	0.270	0.245	-0.142	-0.048	-0.008	0.100	0.089	-0.087
2	0-15	-0.472**	0.076	-0.307	-0.019	-0.188	-0.302	0.459**	0.410*	0.018
	15-30	-0.393*	0.146	-0.231	0.122	-0.321	-0.393*	0.539***	0.340	0.109
	30-60	-0.230	0.147	-0.143	0.110	-0.098	-0.188	0.421*	0.368*	-0.136
	60-90	0.121	0.160	0.135	0.040	-0.076	0.062	0.260	-0.107	-0.195
	90-120	0.350*	0.027	0.401	-0.005	-0.110	0.203	-0.049	-0.149	0.146
3	0-15	-0.322	-0.133	-0.026	-0.330	-0.396*	-0.293	0.377*	0.475**	-0.269
	15-30	-0.161	0.090	-0.128	-0.283	-0.271	-0.204	0.294	0.359*	-0.223
	30-60	0.061	0.172	-0.068	-0.272	0.079	0.092	0.225	0.331	-0.267
	60-90	0.070	0.366*	-0.045	-0.145	0.111	0.133	0.365*	0.215	-0.345
	90-120	0.149	0.285	0.179	-0.160	0.370*	0.248	0.153	0.093	0.010
4	0-15	-0.180	-0.141	-0.011	-0.119	0.126	0.009	0.202	0.299	-0.090
	15-30	-0.281	-0.120	-0.236	-0.185	-0.135	-0.138	0.300	0.326	-0.131
	30-60	-0.136	0.142	-0.122	-0.165	-0.006	0.055	0.548***	0.453**	0.019
	60-90	-0.080	0.082	-0.049	-0.267	0.351	0.288	0.212	-0.038	0.187
	90-120	-0.055	0.133	0.042	0.144	0.449**	0.308	0.368*	0.020	0.200
Total	0-15	-0.459**	-0.150	-0.152	-0.301	-0.328	-0.380*	0.515**	0.614***	-0.281
	15-30	-0.379*	0.026	-0.259	-0.276	-0.398*	-0.389*	0.478**	0.530**	-0.255
	30-60	-0.191	0.089	-0.196	-0.223	-0.073	-0.088	0.422*	0.455**	-0.340
	60-90	0.018	0.372*	-0.004	-0.097	-0.001	0.050	0.415*	-0.024	-0.294
	90-120	0.178	0.269	0.253	-0.082	0.163	0.183	0.150	0.040	-0.002

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 49. Simple correlations (r) between alfalfa dry matter yield from year 2002 harvests and soil parameters at five depths sampled in Mar 2003 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Soil Parameter								
		K	Ca	Mg	S	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
1	0-15	-0.526**	-0.219	-0.405*	-0.333	0.122	-0.506**	0.690***	0.731***	-0.228
	15-30	-0.280	0.233	-0.225	-0.253	-0.692***	-0.748***	0.656***	0.650***	-0.200
	30-60	-0.174	0.656***	-0.172	0.112	-0.442*	-0.546***	0.436*	0.318	0.041
	60-90	0.057	0.182	-0.094	0.175	-0.139	-0.243	0.251	0.100	-0.105
	90-120	-0.121	0.064	-0.101	-0.072	-0.199	-0.297	0.133	0.112	-0.144
2	0-15	-0.221	-0.108	0.078	-0.108	-0.452**	-0.323	0.102	0.110	-0.019
	15-30	0.180	0.210	0.277	-0.021	-0.183	-0.202	-0.029	-0.013	0.089
	30-60	0.009	-0.029	0.020	-0.023	-0.047	-0.173	0.133	0.067	0.150
	60-90	-0.030	-0.139	-0.038	-0.210	-0.083	-0.057	0.157	0.131	-0.043
	90-120	-0.141	-0.121	-0.075	-0.072	-0.228	-0.207	0.036	0.056	0.031
Total	0-15	-0.582***	-0.247	-0.310	-0.303	-0.015	-0.495**	0.575***	0.624***	-0.216
	15-30	-0.223	0.138	-0.199	-0.210	-0.619***	-0.653***	0.524**	0.520**	-0.154
	30-60	-0.253	0.524**	-0.313	0.014	-0.417*	-0.571***	0.472**	0.416*	-0.055
	60-90	-0.055	-0.048	-0.233	-0.032	-0.273	-0.365*	0.447**	0.348	-0.290
	90-120	-0.211	-0.099	-0.196	-0.086	-0.292	-0.445*	0.263	0.212	-0.185

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 50. Simple correlations (r) between alfalfa dry matter yield from year 2000 harvests and soil parameters at five depths sampled in May 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Soil Parameter								
		K	Ca	Mg	S	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
1	0-15	-0.746***	-0.539**	-0.782***	-0.226	-0.226	-0.292	0.592***	0.599***	-0.647***
	15-30	-0.696***	-0.004	-0.298	0.198	-0.674***	-0.634***	0.787***	0.801***	-0.053
	30-60	0.095	0.456**	0.266	0.377*	-0.548***	-0.456**	0.428*	0.753***	-0.075
	60-90	0.261	0.074	0.428**	0.160	-0.394*	-0.355*	0.484**	0.660***	-0.315
	90-120	0.319	-0.256	0.586***	-0.316	-0.108	-0.134	0.151	0.422*	-0.366*
2	0-15	-0.743***	-0.680***	-0.847***	-0.293	-0.096	-0.375*	0.591***	0.669***	-0.678***
	15-30	-0.567***	0.139	-0.232	0.184	-0.789***	-0.753***	0.767***	0.761***	-0.236
	30-60	0.095	0.604***	0.274	0.389*	-0.666***	-0.520**	0.538**	0.583***	0.094
	60-90	0.287	0.232	0.417*	0.182	-0.398*	-0.313	0.494**	0.651***	-0.128
	90-120	0.340	-0.231	0.576***	-0.406*	-0.101	-0.079	0.110	0.322	-0.303
3	0-15	-0.674***	-0.544***	-0.799***	-0.185	-0.102	-0.328	0.572***	0.588***	-0.566***
	15-30	-0.707***	-0.085	-0.454**	0.299	-0.776***	-0.746***	0.849***	0.830***	-0.002
	30-60	0.031	0.671***	0.154	0.554***	-0.732***	-0.538**	0.602***	0.659***	0.192
	60-90	0.287	0.297	0.429*	0.351*	-0.487**	-0.249	0.484**	0.468**	-0.113
	90-120	0.395*	-0.260	0.634***	-0.225	-0.103	-0.056	0.171	0.311	-0.264
Total	0-15	-0.772***	-0.628***	-0.861***	-0.255	-0.157	-0.352*	0.624***	0.661***	-0.678***
	15-30	-0.695***	0.027	-0.335	0.233	-0.788***	-0.750***	0.846***	0.844***	-0.111
	30-60	0.083	0.599***	0.255	0.454**	-0.677***	-0.532**	0.544***	0.710***	0.058
	60-90	0.295	0.199	0.452**	0.230	-0.446*	-0.332	0.518**	0.646***	-0.209
	90-120	0.368*	-0.264	0.632***	-0.345	-0.111	-0.100	0.150	0.380*	-0.337

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 51. Simple correlations (r) between alfalfa dry matter yield from year 2001 harvests and soil parameters at five depths sampled in Apr. 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Soil Parameter								
		K	Ca	Mg	S	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
1	0-15	-0.310	-0.541***	-0.413*	-0.531**	-0.366*	-0.116	0.662***	0.744***	-0.387*
	15-30	-0.048	-0.087	-0.245	-0.678***	-0.675***	-0.655***	0.605***	0.668***	-0.615***
	30-60	0.131	-0.096	0.125	-0.431*	-0.504**	-0.496**	0.523**	0.440*	-0.152
	60-90	0.459**	0.396*	0.450**	0.166	-0.499**	-0.272	0.395*	0.433*	0.318
	90-120	0.088	0.094	0.389*	0.174	-0.281	-0.064	0.260	0.256	-0.280
2	0-15	-0.665***	-0.570***	-0.645***	-0.250	0.029	0.213	0.473**	0.459**	-0.140
	15-30	-0.531**	-0.085	-0.361	-0.515**	-0.597***	-0.646***	0.841***	0.707***	-0.459**
	30-60	-0.195	0.155	0.038	0.092	-0.781***	-0.590***	0.742***	0.584***	0.212
	60-90	0.015	0.307	0.379*	0.158	-0.557***	-0.575***	0.449**	0.359*	-0.095
	90-120	0.114	0.261	0.406*	0.278	-0.289	-0.039	-0.081	0.125	-0.186
3	0-15	-0.322	-0.556***	-0.400*	-0.371*	-0.264	-0.076	0.593***	0.649***	-0.318
	15-30	0.163	0.051	-0.038	-0.613***	-0.613***	-0.608***	0.403*	0.524**	-0.551**
	30-60	0.504**	-0.202	0.511**	-0.322	-0.328	-0.090	0.141	0.035	-0.062
	60-90	0.603***	0.351*	0.490**	0.030	-0.442*	-0.143	0.284	0.459**	0.602***
	90-120	0.200	0.003	0.554***	0.054	-0.226	0.007	-0.054	0.190	-0.173
4	0-15	-0.632***	-0.481**	-0.730***	-0.047	-0.173	-0.155	0.731***	0.681***	-0.212
	15-30	-0.272	-0.198	-0.111	-0.511**	-0.530**	-0.636***	0.528**	0.560**	-0.419*
	30-60	-0.141	-0.200	0.301	-0.281	-0.465**	-0.477**	0.442*	0.408*	-0.249
	60-90	0.316	0.465**	0.276	0.303	-0.467**	-0.376*	0.543**	0.551**	0.236
	90-120	0.215	0.175	0.328	0.135	-0.521**	-0.213	0.166	0.423*	-0.369*
Total	0-15	-0.576***	-0.679***	-0.654***	-0.405*	-0.247	-0.029	0.752***	0.784***	-0.338
	15-30	-0.180	-0.077	-0.233	-0.732***	-0.762***	-0.793***	0.736***	0.767***	-0.651***
	30-60	0.149	-0.102	0.319	-0.292	-0.642***	-0.484**	0.555***	0.428*	-0.055
	60-90	0.456**	0.462**	0.519**	0.179	-0.612***	-0.409*	0.497**	0.551***	0.359*
	90-120	0.190	0.153	0.545***	0.196	-0.382*	-0.075	0.067	0.285	-0.295

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 52. Simple correlations (r) between alfalfa dry matter yield from year 2002 harvests and soil parameters at five depths sampled in Nov. 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Soil Parameter								
		K	Ca	Mg	S	$CaCl_2$ Al	KCl Al	pH_{CaCl_2}	pH_{H_2O}	EC
1	0-15	-0.798***	-0.610***	-0.654***	-0.437*	-0.004	-0.045	0.522**	0.590***	-0.544***
	15-30	-0.511**	-0.082	-0.162	-0.716***	-0.631***	-0.680***	0.730***	0.747***	-0.633***
	30-60	0.095	0.730***	0.369*	-0.155	-0.541***	-0.148	0.539**	0.512**	-0.250
	60-90	0.160	-0.057	0.566***	0.242	-0.371*	0.012	0.452**	0.660***	-0.078
	90-120	0.326	-0.058	0.788***	0.135	0.059	0.205	0.051	0.407*	-0.386*
2	0-15	-0.720***	-0.610***	-0.684***	-0.609***	-0.167	-0.340	0.644***	0.717***	-0.662***
	15-30	-0.627***	-0.188	-0.260	-0.800***	-0.727***	-0.751***	0.796***	0.832***	-0.734***
	30-60	-0.116	0.796***	0.159	-0.241	-0.674***	-0.338	0.679***	0.639***	-0.188
	60-90	0.129	-0.144	0.418*	0.262	-0.459**	-0.110	0.577***	0.721***	-0.065
	90-120	0.354*	-0.107	0.704***	0.276	-0.035	0.155	0.121	0.423*	-0.214
Total	0-15	-0.787***	-0.641***	-0.685***	-0.500**	-0.077	-0.159	0.567***	0.633***	-0.545***
	15-30	-0.594***	-0.092	-0.164	-0.730***	-0.725***	-0.741***	0.763***	0.774***	-0.649***
	30-60	0.041	0.763***	0.339	-0.159	-0.606***	-0.171	0.574***	0.547***	-0.233
	60-90	0.140	-0.111	0.529**	0.232	-0.391*	-0.006	0.477**	0.670***	-0.091
	90-120	0.339	-0.090	0.775***	0.168	0.002	0.203	0.068	0.379*	-0.274

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

of gypsum resulted in dramatic improvement in maize rooting (Farina et al., 2000a). Rechcigl et al. (1991) had similar results with alfalfa growing in acid soils where lime had been deep plowed to 30 cm. They found that increased pH_{H_2O} in the zone of incorporation resulted in improved rooting and yield. The suppression of pH in the surface 15 cm resulting from amendments probably caused this higher degree of correlation at 15 to 30 cm than in the surface soil. This was substantiated by the negative relationship between yield and EC at 0-15 cm in 2000, and 0-30 cm in 2001 and 2002. Although the association with the surface 15 cm in 2001 was only significant for harvest one, it was highly significant at 0 to 15 and 15 to 30 cm for both harvests in 2002 (Table 52).

Correlations of Soil Analysis Data and Tissue Mineral Concentration

Sacul Soil, Nacogdoches County. Mineral concentrations were determined for seven harvests during the course of the experiment. Mehlich-3 extractable K was not consistently associated with any of the measured plant elements throughout the study (Tables 53, 54, and 55). The correlation with plant K was significant in only four harvests, and at more than one depth only in harvest two in 2002. Extractable Ca was not consistently associated with any measured plant element (Tables 56, 57, and 58). Significant correlations with plant Ca were observed in four harvests, and none of those were highly significant. Also, increased soil Ca corresponded with increased plant S, but the correlation was significant in only in three harvests. There was a trend for soil Mg to be negatively correlated with plant Ca and S, however the relationship was never significant (Tables 59, 60, and 61). Plant S was significantly correlated with Mehlich-3 extractable S in the 0- to 60-cm depths in both harvests of 2000, but the association was only significant in one harvest during the following two seasons (Tables 62, 63, and 64). Plant Mn was positively correlated with 0.01 *M* $CaCl_2$ exchangeable Al at the 0 to 15 or 15- to 30-cm depths in six of the seven harvests analyzed (Tables 65, 66, and 67). The same association with plant Mn is observed

Table 53. Simple correlations (r) between Mehlich-3 extractable K determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.359*	0.164	0.178	-0.180	0.002	-0.314	0.117	0.045	-0.053	0.403*
	15-30	-0.040	0.378*	0.562***	-0.362*	-0.265	-0.381*	0.308	-0.276	0.076	0.462**
	30-60	0.167	0.165	0.346	-0.080	-0.109	-0.265	0.195	-0.269	-0.108	0.503**
	60-90	0.016	0.111	0.110	0.300	0.047	0.090	0.247	-0.085	-0.178	0.173
	90-120	-0.220	0.090	0.204	0.004	-0.335	-0.163	0.049	-0.454**	0.328	-0.107
3	0-15	0.253	-0.117	0.294	-0.111	0.233	-0.350*	0.522**	0.254	0.124	0.586***
	15-30	0.306	-0.032	0.288	0.036	0.165	-0.246	0.138	-0.009	-0.225	0.154
	30-60	0.363*	-0.084	0.367*	0.223	0.189	-0.071	0.228	-0.086	-0.070	0.436*
	60-90	0.159	-0.079	0.322	0.140	-0.192	0.013	0.084	-0.094	0.032	0.209
	90-120	-0.024	0.177	0.138	0.242	-0.086	0.133	-0.221	-0.219	-0.287	-0.314

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 54. Simple correlations (r) between Mehlich-3 extractable K determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.339	-0.013	0.548***	-0.417*	-0.068	-0.270	-0.096	0.080	0.190	-0.018
	15-30	-0.180	-0.056	0.258	-0.072	0.061	-0.128	0.070	0.075	-0.006	0.006
	30-60	-0.144	0.036	0.214	-0.032	0.059	-0.131	0.049	0.042	0.190	-0.125
	60-90	0.083	0.078	0.086	-0.014	-0.104	-0.044	0.011	-0.013	0.336	-0.186
	90-120	0.318	0.208	-0.059	-0.049	-0.334	0.081	-0.086	-0.161	0.524	-0.136
2	0-15	0.196	-0.007	0.264	-0.144	0.015	0.214	0.531**	0.498**	0.160	0.064
	15-30	0.235	-0.005	0.226	-0.155	0.069	0.161	0.553***	0.286	-0.040	0.033
	30-60	0.319	-0.086	0.173	0.018	0.058	0.221	0.453**	0.213	0.046	-0.065
	60-90	0.324	0.226	0.263	0.079	0.025	0.421	0.252	0.046	-0.049	-0.202
	90-120	0.004	0.038	-0.129	-0.156	-0.176	-0.359	-0.176	-0.331	-0.035	0.034
3	0-15	-0.293	-0.099	0.189	-0.286	-0.093	-0.534**	0.468**	0.419*	-0.139	0.229
	15-30	-0.091	-0.099	0.161	-0.078	0.012	0.223	0.005	0.046	0.132	-0.030
	30-60	0.163	0.031	0.199	-0.002	-0.062	0.177	-0.242	0.008	0.133	0.033
	60-90	0.273	0.236	0.285	0.251	-0.084	0.251	-0.336	-0.066	-0.044	-0.259
	90-120	0.335	0.490	0.319	0.390*	-0.060	0.124	-0.389*	-0.144	-0.168	-0.394*
4	0-15	-0.053	0.139	0.154	-0.049	-0.004	0.122	-0.140	0.294	-0.106	0.220
	15-30	0.132	0.260	0.032	0.178	0.186	0.379*	-0.089	0.129	-0.159	0.291
	30-60	0.167	0.253	0.003	0.248	0.265	0.280	-0.010	0.007	0.084	0.369*
	60-90	-0.014	0.249	-0.001	0.213	0.162	0.057	0.076	-0.147	0.061	0.478**
	90-120	0.252	0.297	0.206	0.176	-0.067	-0.205	0.164	-0.211	0.017	0.383*

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 55. Simple correlations (r) between Mehlich-3 extractable K determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.194	-0.126	0.418*	-0.032	0.041	0.060	0.409*	0.450**	0.000	0.457**
	15-30	0.087	-0.021	0.374*	-0.077	0.112	0.046	0.288	0.303	0.088	0.364*
	30-60	0.148	0.017	0.387*	-0.022	0.037	0.053	0.410*	0.237	-0.051	0.405*
	60-90	-0.047	0.096	0.385*	-0.177	-0.298	-0.091	0.178	-0.178	-0.199	-0.028
	90-120	0.139	0.087	0.022	-0.151	-0.317	0.095	0.201	-0.253	-0.146	-0.115

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 56. Simple correlations (r) between Mehlich-3 extractable Ca determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.004	0.000	0.173	0.065	-0.347	0.200	0.238	-0.163	-0.099	0.027
	15-30	-0.227	0.184	-0.052	-0.058	-0.339	-0.183	0.099	-0.347	0.172	-0.299
	30-60	-0.290	-0.107	0.140	-0.088	-0.649***	0.112	-0.039	-0.187	0.314	-0.105
	60-90	-0.084	-0.398*	-0.245	-0.125	0.070	-0.146	0.007	-0.018	-0.205	-0.286
	90-120	0.257	0.026	-0.073	-0.106	0.074	-0.304	-0.085	-0.096	-0.165	0.117
3	0-15	0.032	-0.019	0.000	0.384*	0.085	0.326	-0.363*	-0.250	-0.358*	-0.157
	15-30	-0.214	0.051	-0.101	0.118	0.195	-0.168	-0.297	-0.399*	-0.364*	-0.364*
	30-60	-0.210	0.151	0.116	0.009	-0.336	0.146	-0.149	-0.160	-0.164	-0.179
	60-90	-0.168	-0.194	-0.225	0.077	0.221	-0.035	-0.171	-0.133	-0.001	-0.034
	90-120	0.174	-0.083	0.109	-0.141	0.139	-0.311	0.614***	0.077	0.294	0.629***

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 57. Simple correlations (r) between Mehlich-3 extractable Ca determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.039	-0.213	-0.261	0.371*	-0.066	0.078	-0.045	0.280	-0.495	0.077
	15-30	0.171	0.170	-0.204	0.226	-0.168	0.118	-0.045	0.062	-0.281	0.009
	30-60	0.145	0.145	-0.064	0.030	-0.275	0.018	-0.164	0.080	-0.145	0.055
	60-90	0.182	0.079	-0.356	0.223*	0.053	0.007	-0.028	-0.096	-0.081	-0.075
	90-120	0.289	0.374	-0.186	-0.040	-0.134	0.097	-0.180	-0.082	-0.051	-0.104
2	0-15	0.134	-0.142	-0.201	0.089	-0.415*	0.103	0.253	0.014	0.181	-0.036
	15-30	0.213	0.098	0.147	-0.134	-0.196	0.151	0.226	-0.175	-0.235	-0.211
	30-60	0.096	0.087	0.203	-0.163	-0.200	0.147	0.233	0.041	0.023	-0.093
	60-90	0.226	-0.262	-0.272	0.189	0.195	-0.042	0.044	0.027	0.264	-0.043
	90-120	0.077	0.045	-0.117	0.136	-0.080	0.343	0.081	0.166	0.071	0.100
3	0-15	0.315	-0.176	-0.211	0.376*	-0.359*	0.429*	0.250	0.277	0.262	-0.332
	15-30	0.467**	0.155	0.264	0.475**	0.143	0.535**	-0.186	-0.158	0.150	-0.108
	30-60	0.429*	0.212	0.220	0.337	-0.038	0.418*	-0.166	0.081	0.077	-0.209
	60-90	0.089	-0.032	-0.088	-0.209	0.041	-0.153	-0.156	-0.180	0.252	0.539***
	90-120	0.167	0.258	0.244	0.056	0.173	0.142	-0.140	-0.145	0.138	0.277
4	0-15	-0.158	0.178	-0.246	0.273	0.146	0.536**	0.294	-0.122	-0.120	0.211
	15-30	-0.001	0.289	0.087	0.161	0.166	0.302	0.165	-0.255	-0.112	0.498**
	30-60	-0.043	0.266	0.200	0.075	0.002	0.160	0.135	-0.108	-0.084	0.492**
	60-90	0.088	-0.150	0.018	0.096	0.248	0.043	0.188	0.039	0.247	0.116
	90-120	0.243	-0.108	0.361*	-0.076	-0.005	-0.080	0.003	-0.003	0.134	0.130

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 58. Simple correlations (r) between Mehlich-3 extractable Ca determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.251	0.113	0.191	0.249	0.049	0.295	0.079	0.144	0.016	0.099
	15-30	0.244	0.141	0.075	0.314	0.210	0.352*	0.099	0.146	-0.067	0.071
	30-60	0.400*	-0.098	-0.501**	0.383*	0.286	0.466**	0.072	-0.289	-0.236	-0.361*
	60-90	0.243	0.001	-0.160	0.324	0.172	0.294	0.022	0.394*	0.091	0.181
	90-120	0.449**	0.056	-0.138	0.369*	0.308	0.475**	0.282	0.466**	0.191	0.380*

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 59. Simple correlations (r) between Mehlich-3 extractable Mg determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.087	0.306	0.069	-0.145	0.124	-0.278	0.099	-0.028	0.064	0.129
	15-30	-0.006	0.399*	0.126	-0.100	0.010	-0.228	0.293	-0.164	-0.041	0.153
	30-60	0.363*	0.281	0.186	0.089	0.007	-0.162	0.166	-0.181	-0.129	0.502**
	60-90	0.182	0.266	0.202	0.325	0.030	0.166	0.165	-0.133	-0.118	0.258
	90-120	-0.209	-0.004	0.301	0.097	-0.360*	0.171	0.017	-0.291	0.220	-0.035
3	0-15	0.061	-0.050	0.276	-0.143	0.393*	-0.422*	-0.305	-0.225	-0.319	-0.220
	15-30	0.160	-0.079	0.146	0.120	0.399*	-0.260	-0.291	-0.258	-0.336	-0.176
	30-60	0.352*	-0.039	0.238	0.329	0.334	0.001	0.199	-0.094	-0.097	0.410*
	60-90	0.368*	0.105	0.354*	0.374*	0.043	0.239	-0.101	-0.105	-0.175	0.117
	90-120	0.052	0.203	0.012	0.400*	-0.088	0.433*	-0.431*	-0.178	-0.366*	-0.420*

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 60. Simple correlations (r) between Mehlich-3 extractable Mg determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.363*	-0.149	0.443*	-0.260	0.245	-0.312	0.017	-0.092	-0.055	0.087
	15-30	-0.308	-0.321	0.215	-0.019	0.144	-0.282	0.078	0.061	-0.224	0.143
	30-60	-0.258	-0.312	0.219	-0.071	-0.036	-0.355*	0.013	0.048	0.068	-0.085
	60-90	-0.091	-0.171	0.105	-0.051	-0.161	-0.235	-0.007	-0.045	0.186	-0.120
	90-120	0.249	0.009	-0.100	-0.032	-0.315	-0.063	-0.056	-0.206	0.309	-0.082
2	0-15	0.218	-0.141	-0.039	-0.020	0.338	0.025	0.506**	0.501**	0.130	0.245
	15-30	0.174	-0.147	0.016	-0.217	0.053	-0.028	0.630***	0.350*	-0.083	0.195
	30-60	0.233	-0.118	0.050	0.009	-0.019	0.151	0.559***	0.286	0.034	0.018
	60-90	0.212	0.178	0.149	0.068	-0.044	0.351*	0.311	0.100	-0.019	-0.099
	90-120	0.315	0.320	-0.204	-0.256	-0.243	-0.165	0.266	-0.266	-0.118	0.207
3	0-15	-0.250	-0.393*	-0.157	-0.451*	0.066	0.045	0.094	0.037	-0.250	-0.053
	15-30	-0.192	-0.427*	-0.115	-0.231	0.068	-0.056	0.101	0.107	0.166	0.177
	30-60	-0.075	-0.160	-0.033	-0.131	-0.221	-0.098	-0.124	0.080	0.104	0.090
	60-90	0.040	0.076	0.068	0.073	-0.244	-0.022	-0.158	0.000	-0.058	-0.177
	90-120	0.215	0.362*	0.109	0.282	-0.093	-0.054	-0.304	-0.139	-0.200	-0.299
4	0-15	0.061	-0.114	-0.154	-0.044	0.246	0.210	-0.281	0.267	-0.207	-0.171
	15-30	-0.007	0.176	-0.229	0.152	0.374*	0.383*	-0.033	0.154	-0.099	0.131
	30-60	-0.045	0.394*	-0.208	0.324	0.399*	0.214	0.149	0.097	0.207	0.399*
	60-90	-0.199	0.282	-0.129	0.218	0.188	-0.015	0.201	-0.011	0.168	0.409*
	90-120	0.038	0.264	0.016	0.149	-0.014	-0.291	0.186	-0.212	0.094	0.270

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 61. Simple correlations (r) between Mehlich-3 extractable Mg determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.203	-0.177	0.316	-0.213	0.162	-0.256	0.308	0.512**	0.308	0.545***
	15-30	-0.180	0.068	0.388*	-0.235	0.014	-0.240	0.212	0.302	0.170	0.391*
	30-60	-0.113	0.028	0.421*	-0.259	-0.210	-0.264	0.295	0.132	-0.093	0.340
	60-90	-0.147	0.062	0.417*	-0.333	-0.423*	-0.275	0.187	-0.148	-0.221	0.061
	90-120	-0.054	0.084	0.142	-0.366*	-0.425*	-0.152	0.205	-0.319	-0.163	-0.128

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 62. Simple correlations (r) between Mehlich-3 extractable S determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.041	-0.109	-0.022	0.331	-0.019	0.483**	0.310	0.180	-0.262	0.003
	15-30	-0.221	-0.224	0.116	0.336	-0.138	0.561***	0.123	0.037	-0.028	-0.130
	30-60	-0.458**	-0.289	0.041	0.197	-0.144	0.471**	-0.120	0.093	0.023	-0.256
	60-90	0.097	-0.224	-0.301	0.064	0.104	0.186	0.167	0.479**	0.143	-0.056
	90-120	-0.244	-0.158	0.066	-0.229	-0.254	-0.199	-0.141	-0.174	0.074	-0.308
3	0-15	-0.073	-0.125	-0.149	0.407*	-0.191	0.520**	-0.229	-0.130	-0.057	-0.041
	15-30	0.082	0.121	-0.090	0.533**	-0.182	0.684***	-0.244	0.047	-0.138	-0.115
	30-60	-0.108	0.043	-0.186	0.157	-0.521**	0.436*	0.013	0.137	0.139	-0.077
	60-90	-0.241	-0.352*	-0.451*	0.034	-0.014	0.121	0.087	0.249	0.232	0.082
	90-120	-0.208	0.049	-0.045	-0.153	-0.091	-0.121	0.062	-0.272	-0.009	-0.081

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 63. Simple correlations (r) between Mehlich-3 extractable S determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.023	-0.184	-0.233	0.351	-0.149	0.246	-0.031	0.442*	-0.324	0.124
	15-30	0.064	-0.041	-0.162	0.218	-0.302	0.171	-0.164	0.296	-0.071	0.001
	30-60	0.287	0.063	-0.266	0.174	-0.415	0.257	-0.089	0.296	0.116	-0.054
	60-90	0.210	-0.110	-0.516**	0.454**	0.125	0.306	0.219	0.340	-0.208	0.013
	90-120	0.010	0.054	-0.048	0.058	-0.061	0.121	-0.198	0.252	-0.119	0.001
2	0-15	-0.004	0.006	-0.047	0.011	-0.493**	0.180	0.252	0.091	0.345	0.050
	15-30	0.109	0.057	0.115	-0.127	-0.623***	0.262	0.120	-0.039	-0.005	0.000
	30-60	-0.047	0.109	0.216	-0.134	-0.539**	0.220	-0.014	-0.127	0.004	-0.047
	60-90	0.153	-0.268	-0.388*	-0.036	-0.195	0.000	0.132	0.020	0.304	0.115
	90-120	0.074	0.231	0.031	0.154	-0.339	0.458**	-0.220	-0.088	-0.132	-0.033
3	0-15	0.236	-0.024	-0.150	0.445*	0.501**	0.177	-0.401*	-0.306	-0.019	0.231
	15-30	0.286	0.034	0.093	0.453**	-0.402*	0.383*	0.011	0.187	0.362	-0.326
	30-60	0.184	0.336*	0.244	0.448**	-0.468**	0.291	0.045	0.156	0.274	-0.417*
	60-90	-0.107	-0.093	-0.219	0.030	-0.228	-0.024	0.283	0.074	0.474	0.343
	90-120	-0.132	-0.049	-0.075	0.027	-0.240	0.023	0.266	0.308	0.259	0.010
4	0-15	-0.177	0.266	-0.142	0.288	-0.082	0.486**	0.388*	0.087	-0.165	0.274
	15-30	0.046	0.337	-0.051	0.322	-0.060	0.455**	0.394*	0.000	-0.087	0.362*
	30-60	0.108	0.490**	0.230	0.307	-0.131	0.117	0.520**	0.112	0.139	0.528**
	60-90	0.241	0.046	-0.089	0.281	0.074	0.293	0.399*	0.216	0.114	0.063
	90-120	0.342	0.219	0.119	0.270	-0.032	0.206	0.416*	0.498**	0.023	0.169

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 64. Simple correlations (r) between Mehlich-3 extractable S determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.090	0.383*	0.156	0.083	-0.139	0.068	-0.076	0.182	0.377*	0.193
	15-30	0.015	0.523**	0.181	0.132	-0.126	0.120	-0.126	0.086	0.263	0.200
	30-60	0.209	0.403*	-0.088	0.199	-0.023	0.239	-0.062	0.017	0.078	0.040
	60-90	0.084	0.050	-0.295	0.128	0.082	0.161	-0.170	0.248	0.222	0.039
	90-120	0.088	0.173	0.025	-0.019	-0.056	0.047	-0.036	0.042	0.007	0.095

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 65. Simple correlations (r) between 0.01 *M* $CaCl_2$ exchangeable Al determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.225	0.167	0.217	0.110	0.231	0.273	0.366*	0.529**	0.156	0.515**
	15-30	0.201	0.210	0.248	-0.069	0.257	0.017	0.324	0.221	-0.107	0.332
	30-60	0.221	0.114	-0.192	0.023	0.529**	-0.152	0.172	0.131	-0.259	0.089
	60-90	0.318	0.331	-0.023	0.146	0.405*	0.048	0.212	0.221	-0.168	0.333
	90-120	0.203	-0.051	-0.282	0.006	0.313	-0.050	0.055	0.242	-0.056	0.028
3	0-15	-0.013	-0.268	-0.009	0.003	-0.009	0.186	0.006	0.328	0.057	0.030
	15-30	0.305	-0.180	0.071	0.137	0.239	0.094	0.071	0.265	0.027	0.212
	30-60	0.050	-0.120	-0.008	-0.051	0.260	-0.145	-0.189	-0.067	0.059	-0.061
	60-90	-0.020	-0.261	0.095	-0.208	-0.024	-0.191	-0.037	-0.145	0.181	0.033
	90-120	-0.050	-0.075	0.123	-0.230	-0.046	-0.183	0.178	0.058	0.274	0.260

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 66. Simple correlations (r) between 0.01 *M* $CaCl_2$ exchangeable Al determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.283	-0.213	0.083	0.016	0.018	-0.027	-0.053	0.442*	-0.249	0.289
	15-30	-0.196	-0.505**	0.085	0.079	0.382*	-0.115	0.216	0.371*	-0.004	0.094
	30-60	0.003	-0.322	-0.048	0.223	0.489**	0.028	0.216	0.224	-0.112	0.123
	60-90	-0.127	-0.314	0.133	0.019	0.246	-0.168	0.046	0.056	-0.337	0.160
	90-120	0.065	-0.011	0.134	-0.072	0.196	-0.059	-0.072	-0.057	-0.103	0.255
2	0-15	-0.145	-0.224	-0.155	-0.175	-0.163	0.074	0.420*	0.482**	0.328	0.384*
	15-30	0.095	-0.307	-0.230	0.086	0.065	0.103	0.359*	0.570***	0.328	0.457**
	30-60	0.329	-0.302	-0.366*	0.295	0.265	0.156	0.091	0.317	0.252	0.405*
	60-90	0.173	-0.204	-0.328	0.143	0.262	0.011	0.214	0.167	-0.021	0.392*
	90-120	-0.120	-0.222	-0.020	-0.145	0.271	-0.126	-0.302	0.117	0.149	-0.001
3	0-15	-0.360*	-0.197	-0.269	-0.200	-0.284	-0.283	0.228	0.279	-0.018	-0.110
	15-30	-0.528**	-0.556***	-0.493**	-0.516**	-0.300	-0.330	0.363*	0.392*	0.166	0.113
	30-60	-0.219	-0.441*	-0.540**	-0.381*	-0.009	-0.260	0.183	0.183	0.054	0.240
	60-90	-0.153	-0.327	-0.453**	-0.294	0.101	-0.131	0.171	0.158	-0.229	0.056
	90-120	0.012	-0.021	-0.196	-0.187	0.293	0.014	0.121	0.272	-0.125	0.027
4	0-15	-0.013	0.223	0.072	0.150	-0.103	0.219	0.408*	0.711***	0.019	0.079
	15-30	0.203	0.118	-0.385*	0.336	0.194	0.424*	0.104	0.550***	-0.127	-0.211
	30-60	0.248	-0.055	-0.531**	0.340	0.232	0.460**	-0.041	0.251	-0.275	-0.382
	60-90	0.325	0.292	-0.436*	0.484**	0.313	0.523**	0.098	0.347	-0.177	-0.158
	90-120	0.368*	0.109	-0.032	0.171	0.113	0.236	-0.142	0.327	-0.221	-0.122

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 67. Simple correlations (r) between 0.01 *M* $CaCl_2$ exchangeable Al determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.086	-0.037	0.129	0.511**	0.243	0.436*	0.069	0.423*	0.056	0.101
	15-30	-0.271	0.095	0.398*	-0.272	-0.266	-0.299	0.012	0.348	0.345	0.339
	30-60	-0.430*	0.149	0.483**	-0.370*	-0.384*	-0.390*	-0.103	0.024	0.147	0.179
	60-90	-0.115	-0.030	0.123	-0.078	-0.285	-0.080	-0.280	-0.075	-0.139	-0.169
	90-120	-0.078	-0.016	0.408*	-0.044	-0.126	-0.021	-0.262	0.246	0.044	0.181

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 68. Simple correlations (r) between *N* KCl extractable Al determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.004	0.111	0.325	-0.143	-0.025	0.011	0.053	0.145	0.001	0.637***
	15-30	-0.273	0.136	0.349*	-0.391*	-0.356*	-0.332	0.031	-0.263	0.071	0.116
	30-60	-0.157	0.217	0.209	-0.219	-0.166	-0.304	0.197	-0.266	0.000	0.166
	60-90	0.176	0.455**	0.403*	0.137	0.017	0.008	0.419*	0.034	0.084	0.383*
	90-120	-0.048	0.139	0.535**	-0.030	-0.296	0.058	0.157	0.007	0.147	0.284
3	0-15	-0.038	-0.099	-0.041	-0.128	-0.152	-0.014	-0.048	0.071	-0.050	-0.125
	15-30	-0.052	0.078	0.247	-0.117	0.034	-0.245	-0.191	-0.312	-0.344	-0.308
	30-60	-0.069	0.086	0.180	0.046	0.145	-0.178	-0.408*	-0.406*	-0.445*	-0.479**
	60-90	-0.049	-0.052	0.224	0.271	0.182	0.012	-0.449**	-0.079	-0.412*	-0.393*
	90-120	-0.124	-0.015	-0.035	0.290	-0.037	0.157	-0.209	0.050	-0.302	-0.285

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 69. Simple correlations (r) between *N* KCL extractable Al determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.283	-0.213	0.083	0.016	0.018	-0.027	-0.053	0.442*	-0.249	0.289
	15-30	-0.196	-0.505**	0.085	0.079	0.382*	-0.115	0.216	0.371*	-0.004	0.094
	30-60	0.003	-0.322	-0.048	0.223	0.489**	0.028	0.216	0.224	-0.112	0.123
	60-90	-0.127	-0.314	0.133	0.019	0.246	-0.168	0.046	0.056	-0.337	0.160
	90-120	0.065	-0.011	0.134	-0.072	0.196	-0.059	-0.072	-0.057	-0.103	0.255
2	0-15	-0.145	-0.224	-0.155	-0.175	-0.163	0.074	0.420*	0.482**	0.328	0.384*
	15-30	0.095	-0.307	-0.230	0.086	0.065	0.103	0.359*	0.570***	0.328	0.457**
	30-60	0.329	-0.302	-0.366*	0.295	0.265	0.156	0.091	0.317	0.252	0.405*
	60-90	0.173	-0.204	-0.328	0.143	0.262	0.011	0.214	0.167	-0.021	0.392*
	90-120	-0.120	-0.222	-0.020	-0.145	0.271	-0.126	-0.302	0.117	0.149	-0.001
3	0-15	-0.360*	-0.197	-0.269	-0.200	-0.284	-0.283	0.228	0.279	-0.018	-0.110
	15-30	-0.528**	-0.556***	-0.493**	-0.516**	-0.300	-0.330	0.363*	0.392*	0.166	0.113
	30-60	-0.219	-0.441*	-0.540**	-0.381*	-0.009	-0.260	0.183	0.183	0.054	0.240
	60-90	-0.153	-0.327	-0.453**	-0.294	0.101	-0.131	0.171	0.158	-0.229	0.056
	90-120	0.012	-0.021	-0.196	-0.187	0.293	0.014	0.121	0.272	-0.125	0.027
4	0-15	-0.013	0.223	0.072	0.150	-0.103	0.219	0.408*	0.711***	0.019	0.079
	15-30	0.203	0.118	-0.385*	0.336	0.194	0.424*	0.104	0.550***	-0.127	-0.211
	30-60	0.248	-0.055	-0.531**	0.340	0.232	0.460**	-0.041	0.251	-0.275	-0.382
	60-90	0.325	0.292	-0.436*	0.484**	0.313	0.523**	0.098	0.347	-0.177	-0.158
	90-120	0.368*	0.109	-0.032	0.171	0.113	0.236	-0.142	0.327	-0.221	-0.122

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 70. Simple correlations (r) between *N* KCl extractable Al determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.193	0.080	0.230	-0.082	-0.097	-0.116	0.151	0.536**	0.547***	0.497**
	15-30	-0.078	-0.068	0.372*	-0.079	-0.086	-0.136	0.245	0.461**	0.214	0.407*
	30-60	-0.087	0.010	0.478**	-0.084	-0.183	-0.189	0.267	0.319	0.014	0.444*
	60-90	-0.169	0.014	0.492**	-0.310	-0.428*	-0.297	0.156	0.001	-0.199	0.154
	90-120	-0.169	-0.064	0.196	-0.468**	-0.551***	-0.287	0.005	-0.038	-0.123	-0.026

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 71. Simple correlations (r) between 2:1 water to soil pH determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.204	-0.110	-0.350*	-0.078	-0.275	-0.217	-0.407*	-0.468**	0.014	-0.545***
	15-30	-0.149	0.064	-0.323	-0.009	0.069	-0.244	-0.273	-0.190	0.126	-0.425*
	30-60	0.324	0.282	-0.264	0.167	0.207	-0.189	0.205	-0.017	0.190	-0.039
	60-90	0.126	0.226	0.173	-0.014	0.022	-0.246	0.001	-0.259	0.118	0.080
	90-120	0.251	-0.013	0.076	0.326	0.101	0.540***	0.073	0.396	-0.057	0.349
3	0-15	-0.138	0.229	-0.131	-0.103	0.062	-0.206	-0.128	-0.376*	-0.089	-0.126
	15-30	-0.481**	-0.084	-0.329	-0.352*	0.042	-0.403*	-0.055	-0.429*	0.065	-0.346
	30-60	-0.326	-0.055	-0.141	-0.117	0.222	-0.297	-0.125	-0.327	-0.097	-0.297
	60-90	-0.237	0.147	0.095	0.061	0.323	-0.194	-0.372*	-0.296	-0.361*	-0.452**
	90-120	0.119	-0.170	-0.154	0.107	-0.217	0.358*	0.257	0.341	0.198	0.354*

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 72. Simple correlations (r) between 2:1 water to soil pH determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	0.270	0.332	-0.184	0.004	-0.148	0.069	-0.181	-0.502**	-0.001	-0.197
	15-30	0.165	0.354*	-0.125	-0.041	-0.129	0.035	-0.074	-0.402*	0.045	-0.032
	30-60	0.105	0.356*	0.047	-0.195	0.022	0.061	-0.029	-0.336	0.000	0.101
	60-90	-0.050	-0.150	0.071	-0.058	0.068	-0.136	0.106	-0.055	-0.123	0.821***
	90-120	-0.114	0.198	0.321	-0.266	-0.114	-0.072	-0.115	-0.442*	0.208	-0.160
2	0-15	-0.089	0.113	-0.017	0.264	0.285	-0.195	-0.575***	-0.554**	-0.347	-0.194
	15-30	-0.021	0.131	-0.038	0.240	0.270	-0.047	-0.342	-0.442*	-0.226	-0.341
	30-60	-0.180	0.100	-0.123	0.049	0.158	-0.168	-0.527**	-0.456**	-0.342	-0.216
	60-90	-0.121	-0.272	-0.145	-0.144	0.010	-0.192	0.019	-0.078	0.051	-0.156
	90-120	-0.078	-0.004	0.092	0.273	-0.109	0.008	0.372*	-0.057	-0.168	-0.097
3	0-15	0.359*	0.325	0.195	0.201	-0.424*	-0.074	0.656***	0.578***	0.101	-0.055
	15-30	0.279	0.439*	0.242	0.144	0.345	-0.009	-0.229	-0.401*	-0.295	0.068
	30-60	0.216	0.243	0.107	0.088	0.386*	0.001	-0.156	-0.319	-0.440*	-0.206
	60-90	-0.025	0.100	-0.173	0.041	0.166	-0.025	0.323	0.204	-0.131	0.099
	90-120	0.075	0.168	0.308	0.064	0.335	-0.043	-0.298	-0.233	-0.129	-0.093
4	0-15	0.105	-0.117	0.194	-0.177	0.068	-0.389*	-0.167	-0.452**	0.140	-0.114
	15-30	-0.137	-0.098	0.318	-0.286	0.007	-0.552***	-0.050	-0.282	0.274	0.078
	30-60	-0.008	-0.311	0.206	-0.451**	-0.230	-0.463**	-0.279	-0.329	-0.001	-0.356*
	60-90	-0.440*	-0.306	-0.117	-0.421*	-0.289	-0.285	-0.245	-0.223	0.049	-0.291
	90-120	0.109	-0.025	0.224	-0.161	-0.038	-0.234	-0.291	-0.256	0.125	-0.068

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 73. Simple correlations (r) between 2:1 water to soil pH determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.350*	-0.103	-0.335	0.321	0.289	0.391*	-0.055	-0.466**	-0.342	-0.499**
	15-30	0.336	-0.197	-0.512**	0.318	0.284	0.366*	0.088	-0.270	-0.261	-0.370*
	30-60	0.323	-0.078	-0.571***	0.234	0.336	0.345	0.030	-0.258	0.019	-0.366*
	60-90	0.251	0.213	-0.374*	0.176	0.342	0.329	0.012	-0.236	0.265	-0.169
	90-120	0.166	0.201	-0.337	0.298	0.242	0.278	-0.084	-0.007	0.258	-0.062

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 74. Simple correlations (r) between 2:1 0.01 *M* CaCl$_2$ to soil pH determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.169	-0.141	-0.349*	0.094	-0.209	0.024	-0.353*	-0.372*	-0.032	-0.472**
	15-30	-0.244	-0.127	-0.369*	0.165	-0.065	0.131	-0.433*	-0.173	0.055	-0.534**
	30-60	-0.047	-0.053	-0.135	0.039	-0.125	0.102	-0.401*	-0.103	0.259	-0.384*
	60-90	0.112	-0.197	-0.287	-0.098	0.068	0.006	-0.449**	0.079	0.283	-0.286
	90-120	-0.115	-0.399*	-0.163	-0.245	0.117	0.047	-0.413*	0.154	-0.241	-0.190
3	0-15	-0.089	0.173	-0.233	0.043	-0.046	0.047	-0.082	-0.307	-0.011	-0.056
	15-30	-0.357*	-0.002	-0.259	-0.244	-0.238	-0.060	0.063	-0.317	0.248	-0.037
	30-60	-0.163	0.040	-0.179	-0.214	-0.126	0.039	0.374*	0.034	0.326	0.235
	60-90	-0.003	0.032	-0.347	-0.131	0.205	0.105	0.307	0.309	0.257	0.243
	90-120	0.008	-0.176	-0.318	-0.356*	0.024	-0.082	0.218	0.109	0.378*	0.268

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 75. Simple correlations (r) between 2:1 0.01 M $CaCl_2$ to soil pH determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	0.319	0.158	-0.350*	0.175	-0.166	0.108	-0.166	-0.303	-0.116	-0.150
	15-30	0.169	0.139	-0.230	0.125	-0.312	-0.005	-0.318	-0.265	-0.040	-0.012
	30-60	0.115	0.194	0.036	-0.172	-0.239	0.059	-0.267	-0.232	0.024	0.065
	60-90	0.112	0.036	-0.205	0.056	0.152	0.041	-0.051	-0.177	0.082	-0.017
	90-120	-0.165	0.026	0.126	0.028	0.237	0.057	-0.122	0.010	-0.177	0.015
2	0-15	-0.091	-0.025	-0.162	0.260	0.061	-0.204	-0.520**	-0.552***	-0.275	-0.198
	15-30	0.084	0.029	-0.110	0.314	0.001	0.094	-0.262	-0.358	-0.205	-0.154
	30-60	-0.203	0.221	0.036	0.022	0.066	-0.069	-0.367*	-0.232	-0.209	0.150
	60-90	-0.198	-0.361*	-0.367*	0.123	0.221	-0.421*	-0.446*	-0.126	-0.023	0.177
	90-120	-0.045	-0.182	0.022	0.175	0.059	0.065	0.117	0.118	0.060	0.218
3	0-15	0.371	0.238	0.060	0.314	-0.318	-0.057	0.403	0.566***	0.103	-0.046
	15-30	0.435*	0.266	0.071	0.356*	0.134	0.055	-0.292	-0.207	-0.051	-0.001
	30-60	0.218	0.195	0.056	0.183	0.186	-0.058	-0.057	0.037	-0.314	-0.357
	60-90	-0.074	-0.190	-0.284	-0.333	0.165	-0.540***	-0.124	-0.134	0.059	0.374*
	90-120	-0.013	-0.263	-0.217	-0.223	0.301	-0.211	0.071	0.157	-0.103	0.172
4	0-15	0.094	-0.004	0.046	0.003	0.127	-0.196	0.036	-0.454**	0.201	-0.044
	15-30	-0.036	0.202	0.105	0.082	0.159	-0.179	0.300	-0.242	0.212	0.274
	30-60	0.099	0.079	0.192	-0.126	-0.127	-0.293	0.062	0.011	0.003	-0.028
	60-90	0.310	-0.257	-0.033	-0.087	0.151	-0.162	-0.023	-0.022	0.245	-0.427*
	90-120	0.243	0.024	-0.021	0.099	0.248	0.190	-0.015	0.196	0.097	-0.272

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 76. Simple correlations (r) between 2:1 0.01 *M* $CaCl_2$ to soil pH determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.387*	-0.030	-0.328	0.358*	0.249	0.421*	-0.093	-0.456**	-0.307	-0.489**
	15-30	0.400*	-0.098	-0.501**	0.383*	0.286	0.466**	0.072	-0.289	-0.236	-0.361*
	30-60	0.313	-0.015	-0.618***	0.185	0.236	0.303	-0.061	-0.298	-0.058	-0.393*
	60-90	0.296	0.121	-0.535**	0.293	0.422*	0.376*	-0.015	-0.123	0.183	-0.113
	90-120	0.440*	0.115	-0.531**	0.447**	0.370*	0.464**	0.188	-0.013	0.029	-0.002

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 77. Simple correlations (r) between electrical conductivity determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.026	-0.045	-0.246	0.499**	0.202	0.651***	0.108	0.325	-0.145	-0.085
	15-30	-0.098	-0.120	0.073	0.316	-0.105	0.416*	0.139	-0.070	-0.035	-0.051
	30-60	-0.136	-0.253	0.122	0.215	0.087	0.426*	0.059	0.235	-0.078	0.058
	60-90	-0.003	-0.342	-0.337	0.290	0.192	0.297	0.038	0.230	-0.167	-0.127
	90-120	-0.095	-0.176	-0.258	-0.317	0.117	-0.462**	-0.157	-0.264	-0.226	-0.314
3	0-15	-0.017	0.002	-0.184	0.342	-0.277	0.585***	-0.201	0.005	0.102	-0.018
	15-30	0.204	0.195	0.009	0.495**	-0.170	0.635***	-0.018	0.089	-0.015	0.157
	30-60	-0.024	-0.091	0.156	0.142	-0.367*	0.375*	0.040	0.244	0.288	0.217
	60-90	-0.047	-0.258	-0.059	0.142	-0.099	0.215	-0.001	-0.061	0.209	0.211
	90-120	0.042	0.120	0.034	-0.129	0.254	-0.337	-0.173	-0.181	-0.032	-0.134

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 78. Simple correlations (r) between electrical conductivity determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.047	-0.485**	-0.202	0.117	-0.233	-0.118	0.009	0.409*	-0.380*	0.223
	15-30	0.019	-0.236	-0.248	0.305	-0.173	0.105	-0.048	0.428*	-0.262	0.117
	30-60	-0.111	-0.312	-0.012	0.065	-0.237	-0.024	-0.076	0.437*	-0.134	0.209
	60-90	-0.378	-0.300	0.079	-0.026	-0.134	-0.194	-0.113	0.222	-0.331	0.290
	90-120	-0.027	-0.086	-0.050	0.131	0.226	0.088	0.074	0.407*	-0.196	0.351*
2	0-15	0.023	-0.167	-0.264	-0.101	-0.503**	0.083	0.417*	0.210	0.340	0.097
	15-30	0.056	-0.066	-0.023	-0.241	-0.621***	0.122	0.241	0.062	0.031	0.064
	30-60	-0.063	-0.065	0.086	-0.431*	-0.469**	-0.015	0.372*	0.286	0.180	0.333
	60-90	-0.205	-0.175	-0.147	-0.224	-0.280	-0.030	0.401*	0.309	0.249	0.392*
	90-120	-0.279	-0.066	0.067	0.059	-0.175	0.276	-0.121	0.161	-0.170	-0.117
3	0-15	-0.044	-0.184	-0.336	0.278	-0.125	0.138	0.217	0.403*	0.128	0.014
	15-30	0.192	-0.146	-0.121	0.295	-0.425*	0.274	0.127	0.251	0.310	-0.201
	30-60	-0.091	-0.073	-0.114	0.027	-0.562***	0.017	0.333	0.495**	0.174	-0.212
	60-90	-0.333	-0.185	-0.237	-0.173	-0.430*	-0.140	0.595***	0.500**	0.146	-0.022
	90-120	-0.167	-0.217	-0.386	-0.252	-0.391*	-0.185	0.423*	0.378*	0.142	-0.101
4	0-15	-0.268	0.369*	-0.301	0.280	-0.006	0.324*	0.479**	0.166	0.062	0.354*
	15-30	-0.040	0.347	-0.227	0.388*	0.042	0.577***	0.425*	0.063	-0.059	0.333
	30-60	0.022	0.456**	-0.107	0.402*	-0.073	0.424*	0.405*	0.416*	0.041	0.358*
	60-90	0.016	0.266	0.037	0.231	-0.105	0.216	0.510**	0.714***	0.197	0.111
	90-120	-0.134	-0.030	-0.132	-0.018	-0.043	0.139	0.201	0.363*	-0.046	-0.068

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 79. Simple correlations (r) between electrical conductivity determined at five depths in Mar. 2003 and tissue mineral concentration of alfalfa harvested during 2002 in Nacogdoches Co. TX on a Sacul soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.069	0.410*	0.140	0.076	-0.114	0.043	-0.124	0.126	0.373*	0.170
	15-30	-0.006	0.521**	0.234	0.100	-0.070	0.071	-0.112	0.122	0.296	0.256
	30-60	-0.130	0.414*	0.220	-0.040	-0.167	-0.124	-0.114	0.092	0.095	0.236
	60-90	-0.186	0.049	0.284	-0.193	-0.376*	-0.307	-0.063	0.164	-0.135	0.220
	90-120	-0.067	0.043	0.201	-0.318	-0.352*	-0.273	-0.038	-0.060	-0.206	0.102

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

with *N* KCl extractable Al in the surface 30 cm, but only in four harvests (Tables 68, 69, and 70). The only consistent relationship of a plant element with pH_{H_2O} was with Mn. There was a significant negative correlation between plant Mn and pH_{H_2O} at 0 to 15 or 15 to 30 cm in six harvests (Tables 71, 72, and 73). Although the same trend was seen with $pHCaCl_2$, the association was significant in only four of the seven harvests analyzed (Tables 74, 75, and 76). As noted earlier, when EC at each soil depth was plotted, it appeared to be closely related to Mehlich-3 extractable S at each soil sampling. The positive correlation between EC and plant S was significant only in the two harvests in 2000, and the last harvest in 2001 (Tables 77, 78, and 79). Interestingly, extractable S was correlated with tissue S for the same harvests.

Cuthbert Soil, Rusk County. Extractable K in the top 30 cm was positively correlated with plant Mg and Fe in three harvests during the study, but there were no other consistent relationships with plant elements (Tables 80, 81, and 82). Extractable Ca was significantly associated with plant Ca in three harvests and plant S in four harvests, but the relationships were not always positive (Tables 83, 84, and 85). Soil Mg at 0 to 15 or 15 to 30 cm was significantly correlated to plant Mg in five harvests. There were no other significant associations between soil and plant Mg (Tables 86, 87, and 88). Plant Ca, Mn, and Zn were also positively correlated with Mg in the surface 15 cm in four harvests. There was a significant positive correlation between Mehlich-3 extractable S at 0 to 15 or 15 to 30 cm in most harvests (Tables 89, 90, and 91). In harvests two and three in 2001, the correlation was seen between plant S and soil S at 30 to 60 cm. Sulfur in the surface 30 cm was also significantly correlated with plant Fe in five harvests. Plant Fe in five of the harvests analyzed also significantly increased with increasing 0.01 *M* $CaCl_2$ exchangeable Al in the surface 30 cm (Tables 92, 93, and 94). The increase in plant Fe is probably soil pH related, as is the level of exchangeable Al. The solubility of Fe and Al increase with decreasing pH, so that plant Fe in affect is responding to changes in pH, not changes in soluble Al. Also, plant Ca in four harvests was significantly correlated with exchangeable Al, especially at 15 to 60 cm, and on two occasions at 15 to 90 cm. Increased extractable Al at either

Table 80. Simple correlations (r) between Mehlich-3 extractable K determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.083	-0.016	0.283	-0.365*	-0.228	-0.191	0.506**	0.229	-0.14	0.183
	15-30	-0.063	-0.078	0.058	-0.281	-0.253	-0.102	0.578***	0.393	-0.116	-0.144
	30-60	-0.335	0.099	0.011	-0.077	-0.269	-0.114	0.098	-0.03	-0.117	-0.451**
	60-90	-0.201	0.149	-0.107	-0.038	-0.348	-0.083	0.006	-0.087	0.113	-0.296
	90-120	-0.154	-0.006	-0.214	-0.198	-0.358*	-0.222	-0.178	-0.202	0.077	-0.328
3	0-15	0.617***	-0.334	0.544***	0.209	0.006	0.067	0.652***	0.387*	-0.121	0.402*
	15-30	0.567***	-0.542***	0.639***	0.333	0.013	0.101	0.541***	0.366*	-0.262	0.325
	30-60	-0.041	0.125	0.221	0.293	0.086	0.165	-0.034	0.141	-0.107	-0.034
	60-90	-0.242	0.114	-0.141	0.102	-0.058	0.011	-0.112	0.072	0.106	-0.052
	90-120	-0.217	0.114	-0.163	-0.246	-0.221	-0.186	-0.233	-0.184	-0.038	-0.229

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 81. Simple correlations (r) between Mehlich-3 extractable K determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.094	-0.267	-0.022	0.405*	0.308	0.255	0.275	0.336	0.066	0.435*
	15-30	-0.007	-0.260	0.174	0.121	0.284	0.069	-0.049	0.170	-0.189	0.210
	30-60	0.124	-0.021	0.223	-0.152	0.386*	-0.218	-0.156	0.116	0.072	0.179
	60-90	0.015	-0.397*	0.201	-0.140	0.125	-0.220	-0.066	0.018	0.020	-0.150
	90-120	0.442*	0.109	-0.026	-0.080	0.260	-0.239	0.048	-0.230	0.418*	-0.149
2	0-15	-0.293	-0.218	0.319	0.027	0.452**	0.047	0.055	0.455**	0.404*	-0.283
	15-30	-0.331	-0.048	0.485**	-0.157	0.410*	-0.041	0.234	0.235	0.166	-0.263
	30-60	-0.116	0.354*	0.432*	-0.344	0.292	-0.210	0.107	0.003	0.089	-0.004
	60-90	-0.078	0.360*	0.304	-0.146	-0.138	-0.067	0.324	-0.083	0.165	-0.087
	90-120	0.004	0.038	-0.129	-0.156	-0.176	-0.359*	-0.176	-0.331	-0.035	0.034
3	0-15	-0.205	0.035	0.117	0.027	0.054	0.211	0.207	0.307	-0.067	0.421*
	15-30	-0.058	0.089	0.185	-0.151	0.076	-0.008	0.328	0.126	0.142	0.166
	30-60	-0.161	0.124	0.203	-0.202	0.172	-0.257	0.266	0.019	0.241	0.070
	60-90	-0.256	0.206	0.455**	-0.208	-0.080	-0.271	0.379*	-0.139	0.311	-0.131
	90-120	-0.052	-0.340	-0.405*	-0.159	-0.201	-0.260	-0.145	-0.278	0.126	-0.442*
4	0-15	-0.021	0.136	-0.206	0.631***	0.505**	0.404*	0.340	0.292	-0.019	0.250
	15-30	-0.035	-0.021	0.047	0.321	0.349*	0.105	0.021	0.212	0.004	0.284
	30-60	0.179	0.032	0.303	0.101	0.108	-0.101	-0.324	0.070	-0.154	0.170
	60-90	0.115	-0.233	0.274	-0.035	-0.160	-0.219	-0.326	-0.043	-0.079	0.027
	90-120	0.039	0.159	-0.039	-0.410*	-0.313	-0.262	-0.299	-0.385*	-0.022	-0.477**

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 82. Simple correlations (r) between Mehlich-3 extractable K determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.345	0.052	-0.043	0.549***	0.586***	0.165	0.521**	0.592***	0.246	0.597***
	15-30	0.428*	-0.005	0.119	0.425*	0.489**	0.289	0.270	0.506**	-0.006	0.492**
	30-60	0.131	-0.025	0.555***	0.002	-0.126	0.143	-0.053	-0.085	-0.094	0.175
	60-90	-0.001	0.005	0.571***	-0.012	-0.212	0.189	-0.180	-0.174	-0.222	0.087
	90-120	0.047	-0.029	0.189	-0.154	-0.157	0.052	-0.299	-0.302	-0.044	-0.294

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 83. Simple correlations (r) between Mehlich-3 extractable Ca determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.116	0.138	-0.064	-0.039	-0.246	0.265	0.580***	0.307	-0.079	0.177
	15-30	-0.564***	-0.19	0.062	-0.386*	-0.375*	-0.439*	0.136	-0.163	0.109	-0.451**
	30-60	-0.217	0.033	-0.042	0.132	-0.222	0.026	-0.165	-0.103	0.393	-0.081
	60-90	-0.185	0.036	0.053	-0.059	-0.419*	-0.024	0.055	0.012	0.499**	0.083
	90-120	-0.202	0.081	0.202	-0.291	-0.556***	-0.203	0.204	-0.026	-0.038	-0.065
3	0-15	0.422*	-0.035	0.401*	0.274	-0.129	0.261	0.565***	0.143	0.142	0.371*
	15-30	0.065	-0.131	0.272	0.093	0.082	0.068	0.184	0.044	-0.383*	-0.189
	30-60	-0.459**	0.224	-0.103	-0.283	-0.353*	-0.028	-0.295	0.009	-0.006	-0.255
	60-90	-0.236	-0.122	0.175	-0.355	-0.617***	-0.207	-0.045	0.076	0.043	-0.152
	90-120	0.322	-0.112	0.653***	0.145	-0.395*	-0.054	0.384*	0.155	-0.221	0.066

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 84. Simple correlations (r) between Mehlich-3 extractable Ca determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.297	-0.385*	-0.168	0.392*	-0.037	0.406*	0.286	0.128	0.012	0.127
	15-30	-0.103	-0.061	0.311	-0.252	-0.177	-0.136	0.126	-0.068	0.049	0.178
	30-60	-0.037	-0.133	-0.108	0.101	-0.322	0.028	0.240	0.287	-0.114	-0.078
	60-90	-0.198	-0.125	-0.312	0.127	0.004	0.027	-0.024	0.122	-0.385*	-0.496**
	90-120	-0.156	0.010	-0.315	0.084	-0.288	0.122	0.001	0.201	-0.359	-0.497**
2	0-15	-0.487**	-0.427*	0.358*	0.037	0.140	0.161	0.008	0.189	0.039	-0.315
	15-30	0.102	0.033	-0.057	0.229	0.219	0.338	0.521**	0.241	0.242	-0.415*
	30-60	0.202	-0.121	-0.350*	0.156	-0.075	0.470**	0.154	0.356	0.223	0.034
	60-90	-0.022	0.124	0.089	0.059	-0.145	-0.102	0.201	-0.205	-0.188	0.132
	90-120	0.077	0.045	-0.117	0.136	-0.080	0.343	0.081	0.166	0.071	0.100
3	0-15	-0.065	-0.160	0.226	0.261	-0.120	0.430*	0.107	0.075	-0.247	0.348
	15-30	-0.182	0.002	0.070	0.017	0.001	0.128	0.422*	0.259	-0.122	0.411*
	30-60	0.166	-0.025	-0.210	0.139	-0.042	0.191	0.264	0.460**	0.186	0.144
	60-90	-0.032	0.108	0.509**	-0.094	0.184	-0.247	0.300	-0.133	0.417*	-0.179
	90-120	0.225	-0.036	-0.081	0.163	0.060	0.108	0.122	0.302	0.259	-0.203
4	0-15	0.167	-0.151	-0.100	0.538**	0.216	0.415*	0.336	0.116	-0.009	0.250
	15-30	-0.295	-0.121	0.029	0.204	0.082	0.095	0.132	0.187	0.427*	0.436*
	30-60	-0.174	0.005	0.009	0.065	-0.019	0.182	0.344	0.320	-0.049	0.237
	60-90	-0.139	-0.639***	-0.085	-0.400*	-0.150	-0.563***	-0.118	-0.171	-0.391*	-0.187
	90-120	-0.435*	-0.336	-0.120	-0.209	-0.256	-0.220	0.200	0.056	-0.487**	-0.277

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 85. Simple correlations (r) between Mehlich-3 extractable Ca determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.298	0.264	-0.030	0.505**	0.507**	0.202	0.268	0.337	0.173	0.538**
	15-30	0.362*	0.502**	0.230	0.205	0.279	0.364*	-0.205	-0.073	-0.123	0.315
	30-60	-0.385*	0.052	0.136	-0.714***	-0.643***	-0.133	-0.524**	-0.520**	-0.124	-0.437*
	60-90	0.223	0.483**	0.216	0.195	0.222	0.426*	-0.093	0.085	-0.124	0.479**
	90-120	0.272	0.567***	0.052	0.078	0.206	0.203	-0.080	-0.023	0.045	0.085

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 86. Simple correlations (r) between Mehlich-3 extractable Mg determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.026	0.127	0.221	-0.345	0.022	-0.124	0.383*	0.164	-0.334	0.172
	15-30	-0.146	-0.197	0.076	-0.271	0.128	-0.223	-0.008	-0.012	-0.116	-0.155
	30-60	-0.421*	0.049	0.066	-0.078	0.013	-0.192	-0.125	-0.217	-0.084	-0.299
	60-90	-0.362*	0.053	0.016	-0.063	-0.309	-0.197	-0.143	-0.224	0.204	-0.224
	90-120	-0.374*	-0.123	-0.104	-0.137	-0.389*	-0.293	-0.277	-0.311	0.262	-0.32
3	0-15	0.741***	-0.324	0.322	0.454**	0.381*	0.141	0.557***	0.324	-0.097	0.533**
	15-30	0.242	-0.323	0.192	0.176	0.346	0.067	0.066	-0.068	-0.232	0.043
	30-60	-0.203	0.181	-0.017	0.234	0.335	0.147	-0.168	0.029	-0.116	-0.169
	60-90	-0.422*	0.196	-0.188	-0.007	-0.059	-0.004	-0.254	0.058	0.095	-0.179
	90-120	-0.526**	0.213	-0.245	-0.365*	-0.291	-0.183	-0.386*	-0.161	-0.001	-0.417

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 87. Simple correlations (r) between Mehlich-3 extractable Mg determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	0.045	-0.161	-0.072	0.403*	0.348	0.290	0.281	0.311	0.023	0.440*
	15-30	-0.018	0.167	0.058	0.076	0.352*	0.094	-0.110	-0.086	-0.122	0.005
	30-60	0.062	0.208	0.090	-0.286	0.271	-0.282	-0.144	-0.206	0.065	-0.220
	60-90	0.174	-0.010	0.312	-0.273	-0.038	-0.225	-0.029	-0.048	0.157	-0.258
	90-120	0.226	-0.064	0.109	-0.284	0.032	-0.374*	-0.069	-0.083	0.210	-0.153
2	0-15	-0.372*	-0.199	0.262	0.035	0.469**	0.011	0.053	0.406*	0.302	-0.443*
	15-30	-0.373*	-0.157	0.520**	-0.245	0.398*	-0.219	-0.175	-0.114	0.096	-0.027
	30-60	-0.157	0.295	0.414*	-0.419*	0.154	-0.395*	0.160	-0.351*	-0.041	0.154
	60-90	0.175	0.491**	0.043	-0.092	-0.258	0.081	0.411*	-0.062	0.124	0.026
	90-120	0.315	0.320	-0.204	-0.256	-0.243	-0.165	0.266	-0.266	-0.118	0.207
3	0-15	-0.301	0.034	0.034	0.047	-0.015	0.245	0.175	0.333	-0.171	0.387*
	15-30	0.005	-0.125	0.070	-0.211	-0.036	-0.132	-0.065	-0.323	0.174	0.054
	30-60	-0.175	-0.027	0.312	-0.421*	-0.035	-0.498**	0.216	-0.497**	0.520**	-0.074
	60-90	-0.278	0.144	0.224	-0.310	-0.300	-0.349*	0.243	-0.122	0.193	-0.055
	90-120	-0.076	-0.014	0.126	-0.144	0.060	-0.321	0.184	-0.164	0.298	-0.123
4	0-15	0.077	0.144	-0.183	0.655***	0.513**	0.457**	0.450**	0.285	0.019	0.247
	15-30	-0.039	0.100	-0.110	0.024	0.177	0.091	-0.105	-0.270	-0.274	-0.246
	30-60	0.023	-0.087	0.265	-0.352*	-0.178	-0.322	-0.372*	-0.430*	-0.100	-0.203
	60-90	-0.039	-0.116	0.304	-0.320	-0.353*	-0.219	-0.171	-0.042	0.140	0.038
	90-120	-0.022	-0.142	0.315	-0.514**	-0.371*	-0.472**	-0.390*	-0.208	0.085	-0.068

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 88. Simple correlations (r) between Mehlich-3 extractable Mg determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.298	0.264	-0.030	0.505**	0.507**	0.202	0.268	0.337	0.173	0.538**
	15-30	0.362*	0.502**	0.230	0.205	0.279	0.364*	-0.205	-0.073	-0.123	0.315
	30-60	-0.385*	0.052	0.136	-0.714***	-0.643***	-0.133	-0.524**	-0.520**	-0.124	-0.437*
	60-90	0.223	0.483**	0.216	0.195	0.222	0.426*	-0.093	0.085	-0.124	0.479**
	90-120	0.272	0.567***	0.052	0.078	0.206	0.203	-0.080	-0.023	0.045	0.085

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 89. Simple correlations (r) between Mehlich-3 extractable S determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.293	0.015	-0.416*	0.214	-0.037	0.445*	0.491**	0.426*	0.142	0.143
	15-30	0.154	0.012	-0.24	0.196	-0.118	0.346	0.217	0.125	0.418*	0.205
	30-60	0.281	-0.075	-0.249	0.298	-0.029	0.301	-0.12	0.094	0.464**	0.268
	60-90	0.263	-0.033	-0.267	0.264	-0.102	0.361*	0.195	0.226	0.241	0.122
	90-120	0.267	0.281	-0.112	-0.037	-0.152	0.256	0.193	0.113	-0.013	0.272
3	0-15	0.142	0.009	0.073	0.147	-0.141	0.241	0.383*	0.088	0.252	0.107
	15-30	-0.243	0.166	-0.069	-0.159	-0.407	0.154	0.033	-0.108	0.305	0.001
	30-60	-0.472**	0.117	-0.294	-0.445*	-0.474**	-0.093	-0.299	-0.178	0.295	-0.101
	60-90	-0.155	0.165	-0.039	-0.312	-0.474**	0.053	0.067	-0.033	0.197	-0.057
	90-120	0.352*	0.131	0.229	0.298	-0.103	0.251	0.371*	0.158	0.337	0.311

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 90. Simple correlations (r) between Mehlich-3 extractable S determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.313	-0.253	-0.146	0.233	-0.184	0.324	0.171	0.125	0.082	-0.128
	15-30	-0.398*	-0.300	-0.079	0.265	-0.264	0.418*	0.390*	0.193	0.066	0.235
	30-60	-0.006	0.166	0.240	-0.144	-0.519**	0.312	0.039	-0.030	-0.137	0.048
	60-90	-0.293	-0.382*	-0.248	0.116	-0.367*	0.347	0.028	-0.207	-0.037	-0.389*
	90-120	-0.049	0.156	0.068	-0.137	-0.307	0.247	-0.230	-0.186	-0.153	-0.334
2	0-15	-0.320	-0.538**	0.250	-0.095	-0.065	0.119	-0.080	0.062	-0.127	-0.038
	15-30	-0.376*	-0.552**	0.208	0.114	0.173	0.391*	0.099	0.426*	0.184	-0.391*
	30-60	0.043	-0.177	-0.089	0.047	-0.114	0.670***	-0.004	0.301	0.194	-0.172
	60-90	-0.285	-0.079	0.143	0.240	-0.586***	0.270	-0.220	-0.300	-0.420*	-0.262
	90-120	0.074	0.231	0.031	0.154	-0.339	0.458**	-0.220	-0.088	-0.132	-0.033
3	0-15	0.098	-0.471**	0.024	0.230	-0.199	0.291	-0.177	-0.090	-0.222	-0.100
	15-30	0.044	-0.304	-0.014	0.378	-0.132	0.605***	0.059	0.301	-0.344	0.246
	30-60	0.447**	-0.237	-0.449**	0.273	-0.169	0.468**	-0.076	0.341	-0.218	0.212
	60-90	0.444*	-0.056	0.164	0.601***	0.138	0.464**	0.036	-0.105	-0.006	-0.320
	90-120	0.519**	0.108	-0.249	0.300	0.040	0.273	-0.149	0.045	0.047	-0.155
4	0-15	0.101	-0.078	0.029	0.207	-0.152	0.228	0.045	0.018	-0.157	0.031
	15-30	-0.127	-0.013	-0.141	0.564***	0.051	0.497**	0.435*	0.217	0.057	0.156
	30-60	-0.294	0.288	0.194	0.038	-0.256	0.386	0.241	0.212	0.194	0.067
	60-90	0.143	-0.474**	0.020	-0.153	-0.506**	-0.177	-0.091	-0.307	-0.288	-0.487**
	90-120	-0.184	-0.009	0.141	-0.259	-0.356	0.002	-0.007	-0.130	-0.265	-0.430

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 91. Simple correlations (r) between Mehlich-3 extractable S determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.220	-0.057	0.164	0.544***	0.204	0.123	0.294	0.341	0.001	0.372*
	15-30	0.544***	0.199	0.126	0.757***	0.375*	0.318	0.357*	0.524**	0.076	0.471**
	30-60	0.229	0.080	0.365*	0.247	-0.279	0.275	0.062	0.063	-0.015	0.192
	60-90	-0.058	-0.073	0.192	-0.195	-0.497**	0.143	-0.201	-0.246	-0.132	-0.216
	90-120	-0.211	-0.045	0.069	-0.221	-0.485**	-0.137	-0.123	-0.213	-0.025	-0.172

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 92. Simple correlations (r) between 0.01 *M* $CaCl_2$ exchangeable Al determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.073	0.181	-0.051	-0.111	-0.195	-0.02	0.316	0.219	0.139	-0.044
	15-30	0.245	0.337	0.072	-0.096	-0.076	0.127	0.570***	0.349	-0.402*	0.111
	30-60	0.114	0.358	-0.003	-0.064	-0.015	0.059	0.407*	0.081	-0.318	-0.202
	60-90	0.057	0.227	-0.185	-0.081	-0.188	0.006	0.303	0.104	-0.398*	-0.413*
	90-120	-0.063	0.062	-0.039	-0.279	-0.115	-0.219	0.024	-0.061	-0.04	-0.122
3	0-15	0.141	-0.062	0.303	0.169	-0.138	0.018	0.223	0.291	0.189	0.172
	15-30	0.649***	-0.273	0.469**	0.525**	0.069	0.025	0.508**	0.305	0.018	0.549***
	30-60	0.532**	-0.249	0.244	0.553***	0.228	-0.049	0.335	0.092	-0.001	0.368*
	60-90	0.447**	-0.101	0.089	0.504**	0.297	0.107	0.288	0.101	-0.128	0.323
	90-120	0.214	-0.152	0.022	0.173	0.147	-0.058	-0.014	0.087	0.056	0.212

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 93. Simple correlations (r) between 0.01 *M* $CaCl_2$ exchangeable Al determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	0.081	0.157	-0.424*	0.367*	-0.011	0.515**	0.073	0.132	-0.345	-0.141
	15-30	-0.259	-0.284	-0.388*	0.551***	0.018	0.447**	0.474**	0.433*	-0.110	0.177
	30-60	-0.255	-0.400*	-0.206	0.433*	0.244	0.216	0.335	0.283	0.216	0.303
	60-90	0.133	0.006	0.093	0.262	0.232	0.049	0.055	0.242	0.006	0.242
	90-120	0.111	-0.067	-0.115	0.373*	0.393*	0.188	0.142	0.315	0.013	0.381*
2	0-15	-0.158	-0.364*	-0.213	0.162	0.052	0.056	0.099	-0.010	-0.147	-0.130
	15-30	-0.338	-0.489**	0.032	0.144	0.226	0.118	0.062	0.379*	0.014	-0.300
	30-60	-0.518**	-0.378*	0.371*	-0.044	0.279	-0.175	-0.099	0.189	0.084	-0.238
	60-90	-0.244	-0.289	0.132	-0.223	0.367*	-0.089	-0.222	0.294	0.368*	0.108
	90-120	-0.120	-0.222	-0.020	-0.145	0.271	-0.126	-0.302	0.117	0.149	-0.001
3	0-15	-0.017	-0.294	-0.172	-0.057	-0.085	0.073	-0.178	0.012	0.001	-0.171
	15-30	-0.106	-0.263	-0.034	0.293	0.068	0.464**	0.111	0.455**	-0.344	0.180
	30-60	-0.201	-0.259	0.118	0.206	-0.007	0.269	0.114	0.116	-0.121	0.029
	60-90	-0.174	-0.163	-0.349	-0.220	-0.401*	-0.012	-0.240	0.095	-0.118	0.027
	90-120	-0.077	-0.137	-0.156	0.115	0.203	0.163	-0.108	0.249	-0.099	0.139
4	0-15	-0.250	-0.311	-0.252	-0.202	0.032	-0.135	0.432*	0.001	0.021	-0.059
	15-30	-0.169	-0.196	-0.399*	0.528**	0.274	0.223	0.576***	0.353*	-0.145	0.153
	30-60	0.054	-0.092	-0.255	0.478**	0.107	0.180	0.250	0.102	-0.246	-0.116
	60-90	-0.061	0.450	-0.222	0.343	0.235	0.470**	0.345	0.268	-0.153	0.024
	90-120	-0.038	0.143	-0.269	0.172	0.210	0.123	0.114	0.091	-0.315	-0.080

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 94. Simple correlations (r) between 0.01 *M* CaCl$_2$ exchangeable Al determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.031	-0.031	0.090	0.265	0.048	0.043	0.090	0.132	-0.161	0.181
	15-30	0.305	-0.022	-0.299	0.632***	0.622***	0.150	0.531**	0.705***	0.179	0.443*
	30-60	0.241	-0.077	0.155	0.426*	0.260	0.016	0.459**	0.366*	0.173	0.353*
	60-90	0.245	0.236	0.524**	0.392*	0.106	0.202	-0.020	0.109	-0.120	0.293
	90-120	0.150	0.107	0.015	0.114	0.287	0.161	-0.439*	0.010	-0.428*	-0.093

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 95. Simple correlations (r) between *N* KCl extractable Al determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.173	0.129	-0.032	0.064	-0.274	0.215	0.377*	0.383*	-0.252	0.153
	15-30	0.204	0.047	-0.008	-0.112	-0.168	0.072	0.610***	0.523**	-0.397*	0.104
	30-60	-0.105	0.03	-0.105	-0.273	-0.394*	-0.144	0.439*	0.296	-0.278	-0.259
	60-90	-0.221	0.099	-0.118	-0.493**	-0.676***	-0.296	0.216	0.054	0.022	-0.142
	90-120	-0.138	0.083	-0.186	-0.369*	-0.337	-0.287	-0.016	-0.104	-0.023	-0.201
3	0-15	0.337	0.006	0.488**	0.214	-0.258	0.153	0.241	0.248	-0.096	0.409*
	15-30	0.512**	-0.446**	0.533**	0.383*	-0.046	-0.022	0.444*	0.372*	-0.085	0.492**
	30-60	0.459**	-0.074	0.546***	0.525**	0.114	0.239	0.388*	0.336	-0.028	0.377*
	60-90	0.266	-0.077	0.282	0.274	-0.106	0.109	0.306	0.294	0.151	0.299
	90-120	0.067	-0.111	0.074	-0.102	-0.152	-0.278	0.012	-0.074	-0.056	-0.078

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 96. Simple correlations (r) between *N* KCL extractable Al determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	0.091	0.273	-0.093	0.110	-0.160	0.210	-0.080	0.267	-0.288	-0.090
	15-30	-0.162	-0.221	-0.270	0.565***	0.183	0.397*	0.406*	0.466**	-0.041	0.312
	30-60	-0.121	-0.149	0.009	0.061	0.171	0.031	0.289	0.155	0.403*	0.259
	60-90	-0.006	-0.245	0.063	0.136	0.273	-0.080	0.141	0.339	0.137	0.077
	90-120	0.288	-0.117	-0.112	0.170	0.271	-0.014	0.193	0.110	0.391*	0.151
2	0-15	0.105	-0.112	-0.270	0.100	0.152	0.122	0.386*	0.228	-0.254	0.064
	15-30	-0.341	-0.487**	0.129	0.117	0.383*	0.056	-0.007	0.443*	0.107	-0.321
	30-60	-0.426*	-0.145	0.382*	-0.143	0.313	-0.085	0.230	0.211	0.085	-0.323
	60-90	-0.453**	0.022	0.461**	-0.367*	0.265	-0.175	0.144	0.325	0.320	-0.030
	90-120	-0.004	-0.092	-0.174	-0.230	-0.083	-0.186	-0.180	-0.083	-0.004	0.072
3	0-15	-0.202	-0.205	-0.024	-0.041	-0.052	-0.053	-0.227	0.241	-0.392*	-0.082
	15-30	-0.131	-0.208	-0.083	0.222	0.049	0.397*	0.034	0.434*	-0.387*	0.189
	30-60	-0.317	-0.273	0.053	0.063	-0.102	0.140	0.226	0.089	-0.055	0.081
	60-90	-0.479**	0.016	0.075	-0.217	-0.439*	-0.052	0.100	0.113	-0.005	-0.064
	90-120	-0.048	-0.241	-0.257	0.062	-0.016	0.002	-0.093	-0.010	0.126	-0.174
4	0-15	-0.335	-0.394*	-0.258	-0.247	-0.060	-0.309	0.376*	0.345	0.082	0.139
	15-30	-0.070	-0.030	-0.411*	0.634***	0.416*	0.333	0.506**	0.373*	-0.136	0.190
	30-60	0.036	-0.014	0.020	0.365*	-0.013	0.186	0.196	0.082	0.027	0.028
	60-90	0.094	0.176	0.041	0.404*	0.058	0.351*	0.228	0.240	-0.241	0.044
	90-120	0.114	0.185	0.020	-0.150	-0.167	-0.025	-0.054	-0.165	-0.140	-0.292

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 97. Simple correlations (r) between *N* KCl extractable Al determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.186	0.028	0.059	0.379*	0.250	0.106	0.050	0.107	-0.086	0.114
	15-30	0.289	-0.112	-0.235	0.659***	0.582***	0.058	0.474**	0.643***	0.141	0.390*
	30-60	0.193	0.010	0.416*	0.144	0.015	-0.038	0.053	-0.006	0.001	0.065
	60-90	0.058	0.176	0.637***	0.157	-0.178	0.189	-0.238	-0.002	-0.218	0.210
	90-120	0.060	0.109	0.072	0.040	0.008	0.164	-0.394*	-0.091	-0.339	-0.219

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 98. Simple correlations (r) between 2:1 water to soil pH determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.518**	-0.052	0.113	-0.117	-0.212	-0.383*	-0.469**	-0.577***	0.139	-0.431*
	15-30	-0.151	-0.179	0.028	0.262	0.043	0.008	-0.444*	-0.308	0.401*	0.001
	30-60	-0.041	-0.185	0.053	0.276	0.309	0.043	-0.431*	-0.336	0.088	0.028
	60-90	-0.021	-0.088	0.049	0.481**	0.295	0.203	-0.304	-0.212	0.191	-0.021
	90-120	-0.241	-0.081	0.392	0.198	0.191	0.124	-0.143	-0.315	0.308	0.236
3	0-15	-0.589***	0.352*	-0.161	-0.391*	-0.197	-0.276	-0.433*	-0.438*	-0.257	-0.642***
	15-30	-0.692***	0.356*	-0.472**	-0.543***	-0.252	-0.109	-0.563***	-0.266	0.133	-0.422*
	30-60	-0.535**	0.321	-0.515**	-0.464**	-0.03	-0.127	-0.489**	-0.347	0.044	-0.461**
	60-90	-0.635***	0.126	-0.191	-0.467**	-0.348	-0.384*	-0.481**	-0.548***	-0.13	-0.589***
	90-120	-0.382*	0.137	0.018	-0.333	-0.263	-0.009	-0.201	-0.274	-0.107	-0.351*

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 99. Simple correlations (r) between 2:1 water to soil pH determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	0.226	0.159	0.181	-0.500**	0.046	-0.606***	-0.392*	-0.479**	-0.022	-0.328
	15-30	0.010	0.271	0.087	-0.386*	-0.152	-0.295	-0.108	-0.213	-0.083	-0.169
	30-60	-0.071	0.119	-0.202	-0.080	-0.265	-0.144	-0.152	-0.068	-0.125	-0.252
	60-90	-0.085	-0.221	-0.244	-0.136	-0.139	-0.230	-0.066	-0.242	-0.075	-0.321
	90-120	-0.315	-0.140	-0.083	-0.139	-0.305	-0.161	-0.010	-0.106	-0.252	-0.307
2	0-15	0.311	0.584***	-0.073	-0.110	-0.214	-0.317	0.035	-0.517**	-0.096	0.326
	15-30	0.373*	0.443*	-0.231	0.196	-0.317	-0.040	0.053	-0.271	-0.158	0.120
	30-60	0.426*	0.056	-0.528**	0.342	-0.293	0.082	-0.125	-0.101	-0.222	0.360*
	60-90	0.120	0.095	-0.198	0.153	-0.328	-0.174	0.225	-0.439*	-0.395*	0.035
	90-120	-0.078	-0.004	0.092	0.273	-0.109	0.008	0.372*	-0.057	-0.168	-0.097
3	0-15	-0.019	0.348	0.228	-0.366*	0.026	-0.590***	0.133	-0.484**	0.447*	-0.126
	15-30	0.013	0.289	0.219	-0.119	0.223	-0.313	0.170	-0.079	0.208	-0.085
	30-60	0.172	0.176	-0.114	0.073	0.169	-0.082	-0.227	0.032	-0.031	-0.254
	60-90	0.084	0.085	0.405*	0.061	0.335	-0.185	0.351*	-0.290	0.396*	-0.123
	90-120	-0.051	0.148	0.462**	-0.059	0.020	-0.132	0.394*	-0.113	0.190	-0.020
4	0-15	0.136	-0.087	0.249	-0.542**	-0.155	-0.473**	-0.548**	-0.392*	0.079	-0.140
	15-30	0.094	-0.155	0.134	-0.412*	-0.162	-0.394*	-0.345	-0.124	0.089	0.014
	30-60	0.065	-0.152	-0.157	-0.237	-0.019	-0.200	-0.096	0.026	-0.004	0.091
	60-90	0.118	-0.570***	0.074	-0.430*	-0.166	-0.592***	-0.293	-0.306	0.122	-0.038
	90-120	0.011	-0.478**	-0.029	-0.090	-0.013	-0.256	-0.007	0.032	0.153	0.183

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 100. Simple correlations (r) between 2:1 water to soil pH determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.362*	-0.171	0.008	-0.668***	-0.441*	-0.197	-0.393*	-0.517**	-0.003	-0.351*
	15-30	-0.450**	0.039	0.071	-0.748***	-0.561**	-0.191	-0.552***	-0.518**	-0.133	-0.427*
	30-60	-0.378*	0.162	-0.186	-0.529**	-0.158	-0.236	-0.511**	-0.351*	-0.121	-0.310
	60-90	-0.406*	0.041	-0.326	-0.656***	-0.144	-0.283	-0.332	-0.340	-0.035	-0.339
	90-120	-0.359*	-0.086	-0.011	-0.592***	-0.465**	-0.352*	0.137	-0.402*	0.459**	-0.308

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 101. Simple correlations (r) between 2:1 0.01 *M* $CaCl_2$ to soil pH determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.311	-0.154	0.016	-0.125	-0.251	-0.347	-0.332	-0.388*	0.081	-0.277
	15-30	-0.095	-0.158	-0.043	0.289	0.042	0.08	-0.421*	-0.295	0.452**	0.021
	30-60	-0.049	0.086	0.106	0.356	0.229	0.275	-0.376*	-0.227	0.485**	0.241
	60-90	-0.093	0.029	0.296	0.243	0.105	0.133	-0.255	-0.268	0.313	0.229
	90-120	-0.083	0.081	0.279	0.157	-0.154	0.19	0.071	-0.076	0.221	0.171
3	0-15	-0.582***	0.348	-0.187	-0.368*	-0.204	-0.196	-0.293	-0.289	-0.04	-0.477**
	15-30	-0.681***	0.379*	-0.494**	-0.537**	-0.272	-0.056	-0.531**	-0.298	0.161	-0.406*
	30-60	-0.487**	0.208	-0.288	-0.478**	-0.312	-0.111	-0.434*	-0.295	0.021	-0.377*
	60-90	-0.468**	0.268	0.051	-0.497**	-0.503**	-0.216	-0.298	-0.444*	-0.048	-0.431*
	90-120	-0.121	0.266	0.338	-0.072	-0.396*	0.191	0.088	-0.059	0.008	-0.094

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 102. Simple correlations (r) between 2:1 0.01 *M* $CaCl_2$ to soil pH determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	0.179	0.152	0.193	-0.503**	-0.045	-0.485**	-0.350*	-0.610***	0.043	-0.421*
	15-30	0.094	0.296	0.136	-0.404*	-0.199	-0.241	-0.083	-0.281	0.128	-0.099
	30-60	0.015	0.283	-0.023	-0.217	-0.231	-0.114	-0.065	-0.201	-0.117	-0.140
	60-90	-0.233	-0.176	-0.358*	-0.030	-0.176	-0.032	0.109	-0.188	-0.104	-0.273
	90-120	-0.164	-0.253	-0.115	0.174	0.042	-0.007	0.006	0.043	-0.164	-0.254
2	0-15	0.229	0.512**	0.000	-0.122	-0.343	-0.229	-0.047	-0.618***	-0.157	0.278
	15-30	0.658***	0.383*	-0.522**	0.220	-0.456**	0.107	-0.018	-0.306	-0.169	0.207
	30-60	0.541***	0.227	-0.559***	0.375*	-0.357*	0.172	-0.122	-0.180	-0.145	0.197
	60-90	0.194	0.025	-0.242	0.270	-0.374*	-0.035	0.073	-0.384*	-0.399*	-0.013
	90-120	-0.045	-0.182	0.022	0.175	0.059	0.065	0.117	0.118	0.060	0.218
3	0-15	0.139	0.229	0.165	-0.289	-0.030	-0.481**	0.089	-0.593***	0.445**	-0.157
	15-30	0.189	0.236	-0.022	-0.017	0.236	-0.204	-0.042	-0.144	0.133	-0.059
	30-60	0.241	0.290	-0.118	0.026	0.245	-0.082	-0.086	0.010	0.039	-0.070
	60-90	0.272	0.093	0.384*	0.269	0.531**	0.035	0.285	-0.162	0.247	-0.078
	90-120	0.091	0.018	0.056	-0.045	0.081	-0.031	0.042	-0.038	0.055	-0.118
4	0-15	0.119	-0.082	0.272	-0.606***	-0.302	-0.437*	-0.580***	-0.542**	0.086	-0.259
	15-30	0.078	0.067	0.244	-0.476**	-0.200	-0.277	-0.402*	-0.246	0.242	-0.037
	30-60	0.045	0.023	-0.013	-0.294	0.018	-0.146	-0.189	-0.118	0.163	0.065
	60-90	0.080	-0.548**	-0.021	-0.326	-0.113	-0.534**	-0.328	-0.380*	0.005	-0.140
	90-120	-0.120	-0.242	-0.341	-0.031	0.243	-0.098	-0.125	-0.066	-0.122	0.007

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 103. Simple correlations (r) between 2:1 0.01 *M* $CaCl_2$ to soil pH determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.331	-0.185	0.025	-0.621***	-0.435*	-0.183	-0.337	-0.500**	0.040	-0.304
	15-30	-0.385*	0.052	0.136	-0.714***	-0.643***	-0.133	-0.524**	-0.520**	-0.124	-0.437*
	30-60	-0.405*	-0.086	-0.283	-0.471**	-0.297	-0.185	-0.391*	-0.338	-0.097	-0.420*
	60-90	-0.360*	-0.440*	-0.543***	-0.605***	-0.275	-0.452**	-0.037	-0.352*	0.186	-0.587***
	90-120	-0.164	-0.137	-0.075	-0.337	-0.351*	-0.239	0.384*	-0.103	0.573***	-0.046

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 104. Simple correlations (r) between electrical conductivity determined at five depths in May 2000 and tissue mineral concentration of alfalfa harvested during 2000 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	0.222	0.137	-0.118	-0.119	-0.138	0.235	0.587***	0.394*	-0.078	0.166
	15-30	-0.324	-0.156	0.362*	-0.325	-0.341	-0.202	-0.016	-0.206	0.276	0.312
	30-60	0.047	-0.001	-0.051	0.067	-0.324	0.137	0.241	0.227	0.413*	0.161
	60-90	0.121	0.204	0.202	0.095	-0.013	0.151	0.405*	0.132	0.173	-0.082
	90-120	0.322	0.039	-0.313	-0.063	-0.206	0.113	0.238	0.197	0.015	0.021
3	0-15	0.524**	-0.165	0.423*	0.316	-0.051	0.268	0.635***	0.299	0.196	0.335
	15-30	-0.164	0.106	0.136	-0.428*	-0.353*	0.018	0.036	-0.041	0.401*	0.017
	30-60	-0.099	-0.101	0.115	-0.165	-0.478**	0.012	0.139	0.188	0.094	0.096
	60-90	0.226	-0.181	0.214	-0.049	-0.262	-0.103	0.473**	0.141	-0.081	-0.121
	90-120	0.325	-0.119	0.125	0.083	-0.204	0.032	0.341	0.082	0.141	0.187

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 105. Simple correlations (r) between electrical conductivity determined at five depths in Apr. 2001 and tissue mineral concentration of alfalfa harvested during 2001 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
1	0-15	-0.384*	-0.323	-0.205	0.305	-0.328	0.587***	0.311	0.172	0.116	-0.154
	15-30	-0.493**	-0.478**	-0.266	0.324	-0.446*	0.566***	0.293	0.260	-0.128	-0.031
	30-60	-0.227	-0.156	-0.122	0.139	-0.425*	0.571***	0.167	0.276	-0.136	-0.025
	60-90	-0.020	-0.218	0.171	-0.266	0.171	-0.326	-0.031	0.044	-0.216	-0.074
	90-120	-0.249	-0.328	-0.267	0.251	-0.245	0.378*	-0.116	0.354*	-0.361*	0.005
2	0-15	-0.384*	-0.391*	0.162	0.139	-0.227	0.468**	0.038	0.166	-0.338	-0.364*
	15-30	-0.383*	-0.573***	0.114	0.217	-0.085	0.583***	0.131	0.402*	0.030	-0.342
	30-60	0.080	-0.043	-0.243	0.401*	-0.390*	0.764***	0.101	0.256	-0.130	-0.347
	60-90	-0.098	0.468**	0.361*	-0.202	0.084	-0.204	0.559**	-0.065	0.066	-0.289
	90-120	-0.279	-0.066	0.067	0.059	-0.175	0.276	-0.121	0.161	-0.170	-0.117
3	0-15	0.269	-0.270	-0.027	0.557***	0.010	0.636***	0.040	0.183	-0.147	-0.113
	15-30	0.182	-0.291	-0.022	0.547**	-0.043	0.739***	0.047	0.385*	-0.240	0.096
	30-60	0.314	0.032	-0.125	0.551**	0.258	0.597***	0.110	0.503**	-0.064	0.044
	60-90	-0.357*	0.413*	0.662***	-0.280	0.100	-0.309	0.763***	-0.042	0.484**	0.239
	90-120	0.068	0.105	0.084	0.451**	0.148	0.484**	-0.010	0.452**	-0.163	0.009
4	0-15	0.027	-0.226	0.018	0.254	-0.276	0.282	0.375*	0.034	-0.129	-0.067
	15-30	-0.192	-0.263	0.141	0.438*	-0.045	0.395*	0.540**	0.324	-0.159	0.064
	30-60	-0.093	-0.185	0.139	0.141	-0.173	0.200	0.402*	0.333	-0.081	0.060
	60-90	0.033	-0.218	0.432*	0.015	0.052	-0.222	-0.140	0.023	0.066	0.198
	90-120	0.087	-0313	0.035	0.286	-0.070	0.140	0.406*	0.499**	-0.356	0.171

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 106. Simple correlations (r) between electrical conductivity determined at five depths in Nov. 2002 and tissue mineral concentration of alfalfa harvested during 2002 in Rusk Co. TX on a Cuthbert soil.

Harvest	Depth (cm)	Plant Element									
		N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn
2	0-15	-0.362*	-0.171	0.008	-0.668***	-0.441*	-0.197	-0.393*	-0.517**	-0.003	-0.351*
	15-30	-0.450**	0.039	0.071	-0.748***	-0.561**	-0.191	-0.552***	-0.518**	-0.133	-0.427*
	30-60	-0.378*	0.162	-0.186	-0.529**	-0.158	-0.236	-0.511**	-0.351*	-0.121	-0.310
	60-90	-0.406*	0.041	-0.326	-0.656***	-0.144	-0.283	-0.332	-0.340	-0.035	-0.339
	90-120	-0.359*	-0.086	-0.011	-0.592***	-0.465**	-0.352*	0.137	-0.402*	0.459**	-0.308

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

0 to 15 or 15 to 30 cm was closely associated with increased plant Fe and Mn in all harvests (Tables 95, 96, and 97). There was also some positive relationship between extractable Al and plant K and Ca, however it was not consistent. There was a frequent significant negative correlation between pH_{H_2O} and many of the plant elements in all harvests (Tables 98, 99, and 100). This association most often occurred in relation to the surface 15 cm, but did extend from the surface to 120 cm for some elements in harvest two in 2000 and the 2002 harvest. The negative association was apparent with plant Mn in every harvest, but also with Ca, Fe, and S in most harvests. Soil effects, when observed, occurred in the surface 30 cm. Like Fe, Mn solubility increases significantly at pH_{H_2O} below 5.5 (Lindsay, 1991). The relationship with pH is probably the result of increased mineral solubility as pH decreased. Therefore mineral availability increased leading to increased accumulation in plant tissue. The association with other plant elements was not consistent or consistently significant. The same associations were frequently noted for pH_{CaCl_2}, however they were not as consistent as with pH_{H_2O} (Tables 101, 102, and 103). Electrical conductivity was not consistently associated with any measured plant element in all three seasons. However, in 2001 there was a highly significant positive correlation between plant S and EC at each of the top three soil depths (Tables 104, 105, and 106).

CHAPTER IV

SOIL AND ALFALFA RESPONSE TO SURFACE-APPLIED GYPSUM: A GLASSHOUSE STUDY

Many of the highly weathered soils of the southeastern United States are typical of those with characteristics that inhibit alfalfa growth, namely, acid subsoils that are high in exchangeable Al. Gypsum has been shown to ameliorate the negative effects of acid subsoils by decreasing soluble Al, particularly Al^{3+}. The trivalent ion is thought to be the primary phytotoxic Al species. To determine the effectiveness of gypsum for alleviating the toxic effects of Al^{3+} on a representative east Texas soil, a glasshouse experiment was conducted. The objectives of the experiment were 1) to evaluate the effects of surface-applied gypsum on an acid soil by determining the ability of treatments to ameliorate the negative effects associated with subsoil acidity thereby improving alfalfa growth, and, 2) to observe the potential movement of elements from soil by monitoring their concentrations in leachate at the bottom of soil columns.

Materials and Methods

A Kirvin very fine sandy loam (clayey, mixed, thermic Typic Hapludult) located on property leased to the Texas A&M University Agricultural Research and Extension Center at Overton was excavated to 120 cm with depths separated as follows: 0 to 15, 15 to 30, 30 to 60, 60 to 90, and 90 to 120 cm. The soil was selected because it had subsoil pH_{H_2O} below 5.5, and what were believed to be phytotoxic levels of 0.01 *M* $CaCl_2$ exchangeable Al. After excavation, soil depths were air dried and homogenized. Polyvinyl chloride (PVC) pipe with an inside diameter of 10.3 cm was cut into 132-cm lengths and capped on one end. The capped pipes functioned as pots for the experiment. Approximately 5 cm of fine gravel were placed in the bottom of each pot. A 6-mm plastic tube was inserted through a hole drilled in the cap at the bottom of each pipe. The other end of the tube was inserted through a hole drilled in the lid of a 500-ml glass canning jar. Silicon was used to seal tubing connections in the PVC and jar lids.

The excavated soil was placed by depth into the PVC pipe to achieve a final soil depth of 120 cm. The equivalent of 6.7 Mg of super fine limestone ha^{-1} was mixed into the surface 15 cm of all pots. The pots were arranged in a glasshouse in a completely randomized design with four replications. Approximately one month after pots were filled, gypsum treatments of 0, 5, and 10 Mg ha^{-1} were applied to the soil surface. After treatments were applied, 400 ml of deionized water was applied to the soil surface every day until water was observed leaching from the tube in each pot. Jars were emptied and representative samples taken when 500 ml of leachate were collected in each jar. A leachate sample was taken from each pot when 500 ml of leachate were collected. Twelve leachate samples were taken during the experiment, with the last one being after the second alfalfa harvest. Leachate was analyzed for Ca, Mg, K, Na, Al, Mn, B, and S using an ICAP.

Fertilizer was applied according to Table 107. On 22 Oct. 1999, after 3 L of leachate were collected, fifteen pre-inoculated Amerigraze 702 alfalfa seeds were planted in each pot. Plants emerged within six d and were thinned to eight equally spaced plants per pot. Pots were watered when plants showed signs of wilting. Alfalfa was harvested by cutting the plants 5 cm above the soil surface. Harvests were made in 2000 on 14 Jan., 2 Mar., 31 Mar., 18 May, 20 June, and 24 July. All of the harvested plant material was dried in a forced-air oven at 60° C for 72 h. Dried samples were weighed to determine DMY, and the entire sample was ground in a Udy cyclone mill to pass a 1-mm screen. Ground samples were digested with nitric acid and analyzed for P, K, Mg, Ca, S, Mn, Na, Fe, Cu, Al and Zn using an ICAP (Havlin and Soltanpour, 1980). Also, plant tissue nitrogen was determined on a 200-mg sample using a Leco CN-2000 combustion analyzer that was calibrated using an alfalfa standard.

After the final harvest, a chop saw with a 38-cm circular, composite blade was used to section the pots and soil. Soil was separated every 7.5 cm from the surface to 30 cm, and every 15 cm from 30 to 120 cm. A representative soil sample was obtained from each depth, air-dried and ground to pass through a 2-mm sieve. The Mehlich-3 extraction procedure was used to remove exchangeable bases in addition to P, S, Al, Fe, Mn, Cu, and Zn (Mehlich, 1984). Extractable Al was determined using normal KCl (Bertsch and Bloom, 1996). Aluminum and manganese exchangeable in 0.01 M $CaCl_2$ were also determined (Hoyt and Nyborg, 1972). Filtrates of all extractions were analyzed using ICAP. In addition, pH in a 1:2 soil to water suspension (pH_{H_2O}), and 1:2 soil to 0.01 M $CaCl_2$ (pH_{CaCl_2}) were measured on all samples. Electrical conductivity in a 1:2 soil to water suspension was also determined.

Large roots were removed from each soil section. The remainder of the soil was washed with water through two stacked sieves with openings of 2.36 and 0.85 mm. Root material not removed initially was retrained by the sieves and collected. All root material from each section was then dried in a forced-air oven at 60° C for 72 h and weighed.

Table 107. Plant nutrients added to the Kirvin soil in the glasshouse column experiment.

Date	Plant Nutrients			
	P	K	Mg	S
	Kg ha^{-1}			
18 Oct. 1999	50	140	23	45
20 Jan. 2000	—	70	—	—
6 Mar. 2000	50	70	12	22
12 Apr. 2000	—	70	—	—
2 May 2000	50	70	12	22
7 July 2000	—	70	—	—

Analysis of variance for the effects of rate on leachate mineral concentration, alfalfa yield, root growth, tissue mineral concentrations and soil parameters was performed using the General Linear Models procedure in SAS (1994). Response differences between treatment means were evaluated using the Student-Newman-Keuls (SNK) multiple comparison procedure. Soil data were analyzed to determine differences by depth. Simple correlations of soil parameters with root mass at the corresponding depth were determined using PROC CORR in SAS.

Results and Discussion

Treatment Effect on Extractable Soil Elements

The effect of depth was highly significant for all soil parameters analyzed (Table 108). Soil chemistry changes with depth. Therefore, only significant rate and rate by depth effects will be discussed. Significant gypsum rate effects were observed for Mehlich-3 extractable Ca and S, and EC. Sulfur and EC increased with increasing rate, but Ca levels were not significantly different between the 5 and 10 Mg ha^{-1} rates (Table 109). These results are similar to field data where Ca, S, and EC increased with increasing treatment rate. The salt effect associated with the dissolution of gypsum resulted in high electrolyte concentration and therefore high EC. There were significant to highly significant rate by depth interactions for all measured soil parameters except Mehlich-3 extractable Cu, and 0.01 *M* $CaCl_2$ exchangeable Al and Mn (Table 108). Measured cations indicated movement through the profile, and separation in the subsoil based on treatment rate (Figures 60, 61, and 62). At 30 to 45 cm, soil K was highest in the zero rate cylinders, but at both 45 to 60 and 60- to 75-cm depths, levels were significantly higher in the high rate cylinders (Figure 60). The Ca in the gypsum had apparently displaced K^+, particularly at the 22.5- to 45-cm depths, allowing it to move down in the profile. This is substantiated by the plot of Ca by depth (Figure 61). At all rates, Ca levels were highest at 15 to 22.5 cm, and from that depth to 75 cm soil Ca levels increased with increasing rate. Magnesium (Mg^{2+}) was also being displaced from exchange sites by Ca^{2+} and moving similar to K^+ (Figure 62). As with K, Mg levels were highest at 60 to 75 cm in all treatments. From 45 to 90 cm, treatments were significantly different, with the highest Mg levels in the 10 Mg ha^{-1} cylinders and the lowest in the zero cylinders. However, from 15 to 45 cm the 10 Mg ha^{-1} gypsum treated soil had the lowest Mg levels, indicating movement of exchangeable Mg from those depths initiated by increased Ca levels. Ritchey et al. (1980) applied gypsum and limestone treatments to columns filled with an Oxisol that were then leached with 1500 mm of water. Significant amounts of Mg and K were

Table 108. Analysis of variance for the effects of gypsum at twelve soil depths on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil in a Kirvin very fine sandy loam in a glasshouse column experiment.

Class	df	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl2}	pH_{H2O}	EC
		Mean Squares														
		x 10^2	x 10^3	x 10^5	x 10^4	x 10^3	x 10^4			x 10^1		x 10^2	x 10^4	x 10^{-1}	x 10^{-1}	x 10^4
Rate (R)	2	4.69	0.19	6.87*	0.52	87.92***	1.70	3.29	2.33	0.24	4.85	1.50	9.44	2.91	5.70	10.68**
Rep	3	2.49	13.74	3.68	0.52	1.97	0.39	0.46	4.66	0.33	0.88	2.42	8.87	1.34	4.16	0.95
Error (a)	6	1.00	3.19	1.06	0.60	0.47	0.51	1.76	1.78	1.18	7.41	2.89	7.80	1.00	2.02	0.56
Depth (D)	9	63.87***	86.22***	56.84***	69.06***	98.99***	25.15***	60.42***	41.96***	5.77***	36.45***	51.76***	86.82***	98.94***	99.32***	8.02***
R x D	18	2.51***	8.14***	0.59**	1.89***	34.53***	0.31*	3.79***	1.22	0.52**	3.29	0.88	1.27*	0.63*	2.07***	3.45***
Error (b)	441	0.66	1.61	0.27	0.23	0.70	0.16	1.11	0.89	0.25	2.55	1.02	0.69	0.33	0.45	0.85

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 109. Influence of gypsum rate and sample depth on Mehlich-3 extractable P, K, Ca, Mg, S, Fe, Mn, Cu and Zn, 0.01 *M* $CaCl_2$ exchangeable Mn and Al, *N* KCl extractable Al, pH measured in 2:1 0.01 *M* $CaCl_2$ to soil and 2:1 water to soil in a Kirvin very fine sandy loam in a glasshouse column experiment.

Class		P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	$CaCl_2$ Mn	$CaCl_2$ Al	KCl Al	pH_{CaCl2}	pH_{H2O}	EC
		mg kg^{-1}														dS m^{-1}
Rate (Mg ha^{-1})	0	13.2^{a}	158^{a}	499^{b}	183^{a}	47^{c}	87^{a}	2.52^{a}	1.05^{a}	2.66^{a}	1.16^{a}	20.3^{a}	302^{a}	4.17^{a}	5.02^{a}	0.05^{c}
	5	13.9^{a}	160^{a}	596^{a}	190^{a}	78^{b}	72^{a}	2.58^{a}	1.23^{a}	2.58^{a}	0.84^{a}	20.6^{a}	325^{a}	4.24^{a}	4.97^{a}	0.08^{b}
	10	16.5^{a}	159^{a}	624^{a}	179^{a}	115^{a}	92^{a}	2.79^{a}	1.28^{a}	2.42^{a}	1.10^{a}	22.1^{a}	277^{a}	4.24^{a}	4.90^{a}	0.11^{a}
Depth (cm)	0-7.5	61.3^{a}	53^{f}	313^{f}	58^{f}	45^{e}	190^{b}	6.54^{a}	3.83^{a}	5.53^{a}	2.85^{a}	3.6^{d}	13^{f}	4.24^{d}	5.22^{c}	0.03^{e}
	7.5-15	56.3^{b}	33^{g}	651^{c}	16^{g}	16^{f}	234^{a}	6.44^{a}	1.05^{b}	2.87^{b}	2.35^{a}	2.7^{d}	1^{f}	4.92^{b}	5.78^{b}	0.03^{de}
	15-22.5	7.5^{c}	46^{fg}	1284^{a}	49^{f}	14^{f}	107^{c}	3.96^{b}	0.91	2.44^{bc}	0.88^{b}	4.9^{d}	4^{f}	5.06^{a}	5.88^{a}	0.05^{cde}
	22.5-30	7.4^{c}	92^{e}	972^{b}	136^{e}	23^{f}	83^{d}	2.86^{c}	0.79^{b}	2.19^{bc}	0.95^{b}	5.1^{d}	38^{f}	4.41^{c}	5.15^{c}	0.07^{cde}
	30-45	2.8^{d}	217^{c}	695^{c}	209^{d}	54^{e}	36^{e}	2.39^{d}	0.80^{b}	1.88^{c}	0.91^{b}	13.6^{c}	183^{e}	4.11^{e}	4.78^{d}	0.10^{bc}
	45-60	2.5^{d}	302^{a}	572^{d}	289^{c}	171^{b}	36^{e}	1.57^{e}	0.68^{b}	1.84^{c}	0.66^{b}	17.1^{c}	285^{d}	4.04^{f}	4.68^{e}	0.13^{ab}
	60-75	1.7^{d}	305^{a}	448^{e}	372^{a}	202^{a}	36^{e}	0.88^{f}	0.86^{b}	2.47^{bc}	0.34^{b}	35.9^{b}	721^{a}	3.88^{g}	4.55^{f}	0.16^{a}
	75-90	1.5^{d}	243^{b}	355^{f}	316^{b}	151^{c}	35^{e}	0.59^{f}	0.91^{b}	2.44^{bc}	0.78^{b}	37.9^{b}	673^{b}	3.88^{g}	4.57^{f}	0.08^{cd}
	90-105	2.8^{d}	153^{d}	232^{g}	199^{d}	73^{d}	39^{e}	0.53^{f}	1.02^{b}	1.89^{c}	0.18^{b}	46.1^{a}	542^{c}	3.80^{g}	4.53^{f}	0.07^{cde}
	105-120	1.8^{d}	143^{d}	208^{g}	197^{d}	48^{e}	43^{e}	0.54^{f}	1.01^{b}	1.98^{bc}	0.45^{b}	43.1^{a}	554^{c}	3.82^{g}	4.53^{f}	0.07^{cde}

Means within a class followed by the same letter are not different at the 0.05 significance level.

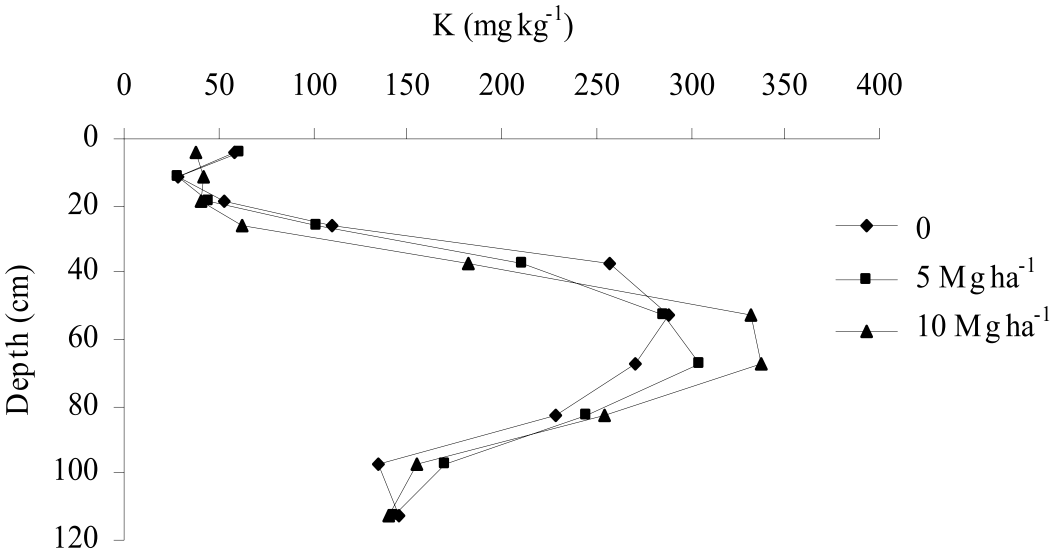


Figure 60. Mehlich-3 extractable potassium by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

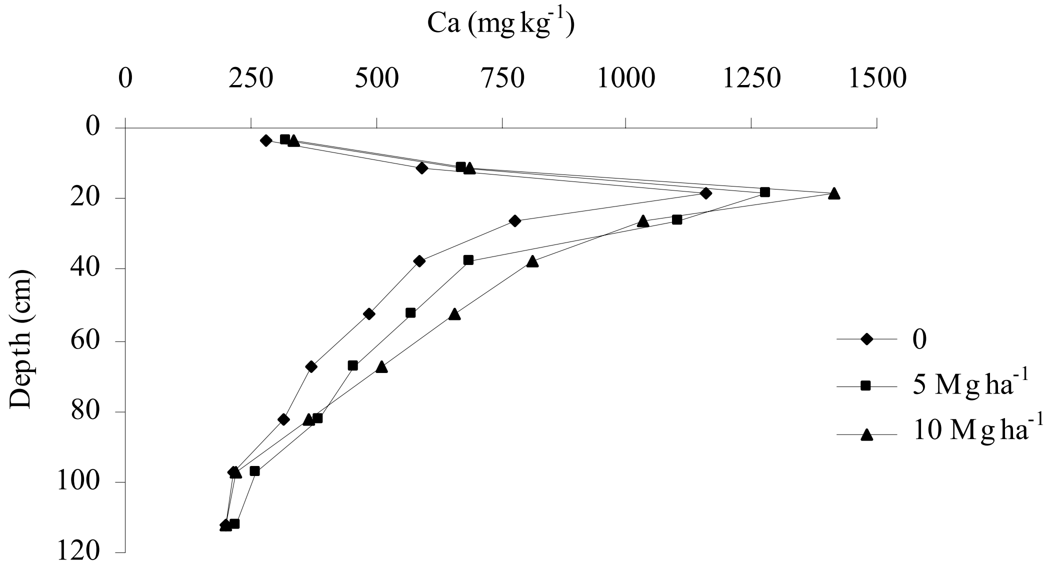


Figure 61. Mehlich-3 extractable calcium by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

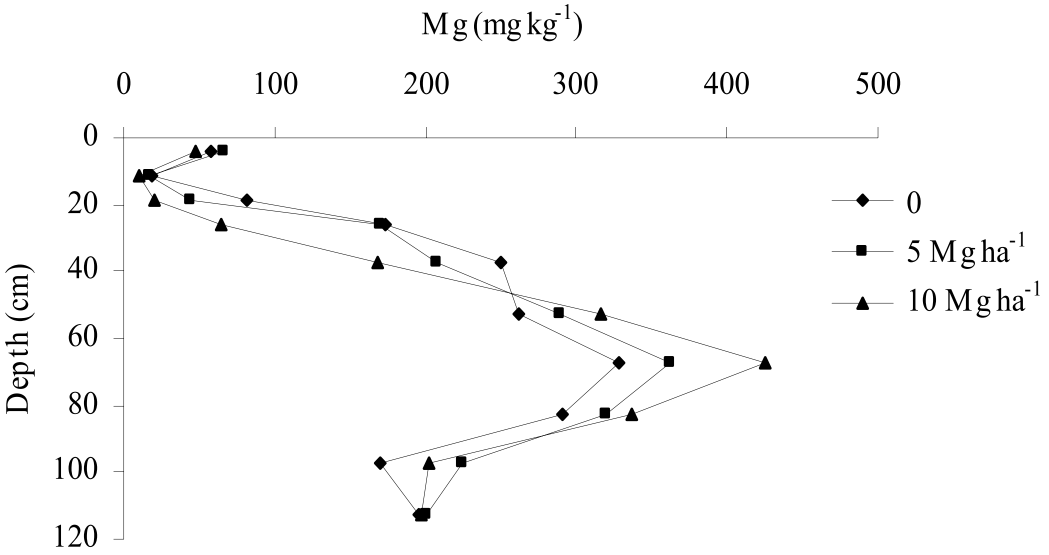


Figure 62. Mehlich-3 extractable magnesium by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

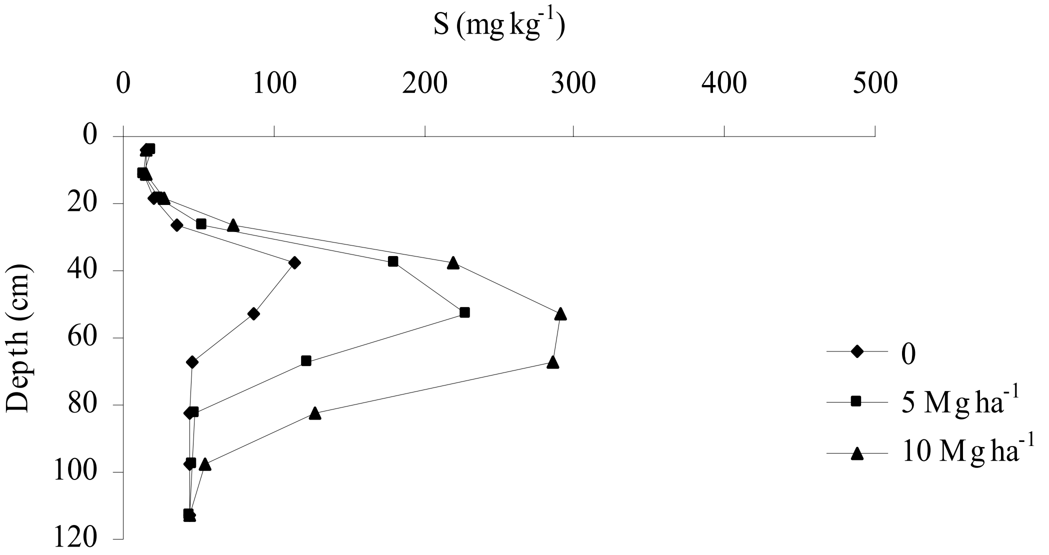


Figure 63. Mehlich-3 extractable sulfur by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

removed from the surface 15 cm of soil as a result of gypsum applications of approximately 7 Mg ha^{-1}, leading them to conclude that supplemental Mg and K should be applied when using high rates of gypsum as a soil amendment. Similar results were reported by Liu and Hue (2001) from mixing gypsum in the surface 15 cm of an acid Hawaiian soil. In their study, exchangeable K and Mg were reduced in the subsoil layers as was exchangeable Al. Figure 63 shows that the depth of the highest level of Mehlich-3 extractable S corresponded positively to treatment rate. From 30 to 90 cm, the high rate treatment had significantly more extractable S, with the highest levels at 45 to 75 cm. The relationship of soil Mn with depth was not consistent, although there appeared to be a trend at 30 to 75 cm for increased Mn with increasing rate (Figure 64). However there was not a corresponding inverse relationship at depths above 30 cm except for the significantly lower level of Mn at 22.5 to 30 cm in the soil treated with 10 Mg gypsum ha^{-1}. It is difficult to draw any conclusions based on the weakness of the apparent effects and the inconsistency of the relationships. Both *N* KCl extractable Al (Figure 65) and 0.01 *M* $CaCl_2$ exchangeable Al (Figure 66) did not demonstrate any consistency or pattern with depth related to rate. Extractable Al was significant at the 0.05 level, but exchangeable Al levels were not significant in regard to either rate or rate by depth (Table 108). The salt effect on pH_{H_2O} was apparent from 30 to 60 cm in both the 5 and 10 Mg ha^{-1} gypsum treatments, and continued to 90 cm in the 10 Mg ha^{-1} treatment (Figure 67). Mathews and Joost (1990) decreased pH_{H_2O} down to 45 cm in soil columns where 2.5 Mg of gypsum ha^{-1} had been mixed in the surface 10 cm. This follows the pattern indicated by increased soil S levels (Figure 63). The treatment difference was not seen in pH_{CaCl_2} (Figure 68), but was apparent in EC (Figure 69). However, pH_{CaCl_2} was lower at the 7 to 15 and 15- to 22.5-cm depths in the high treatment soils compared to the other two treatments. The 15- to 22.5-cm depth is where Ca levels were highest (Figure 61). The higher pH_{CaCl_2} and Ca levels did not result in lower Al levels. Electrical conductivity was closely associated with Mehlich-3 extractable S. The highest S levels (Figure 63) corresponded to the highest EC

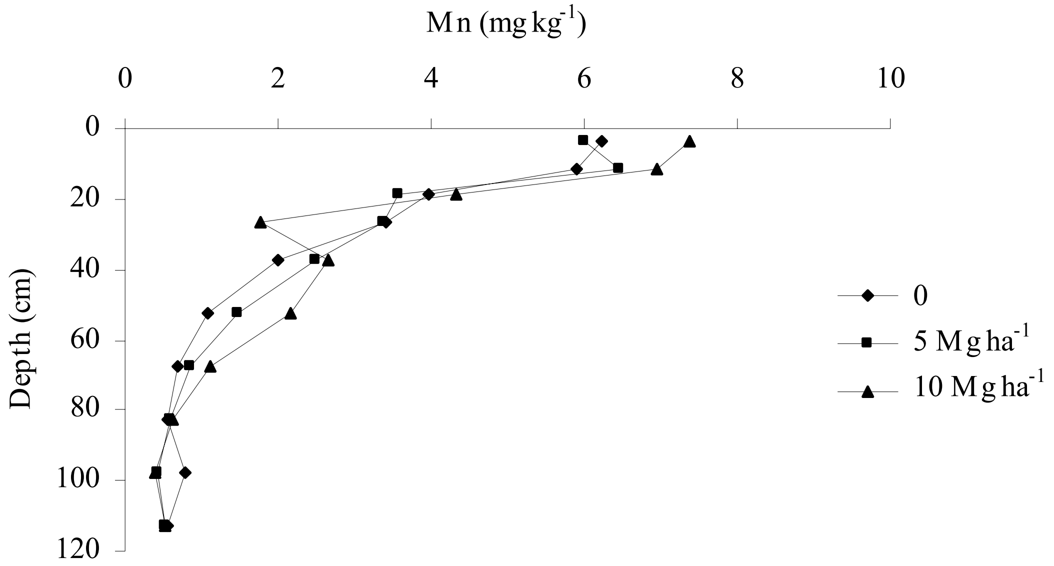


Figure 64. Mehlich-3 extractable manganese by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

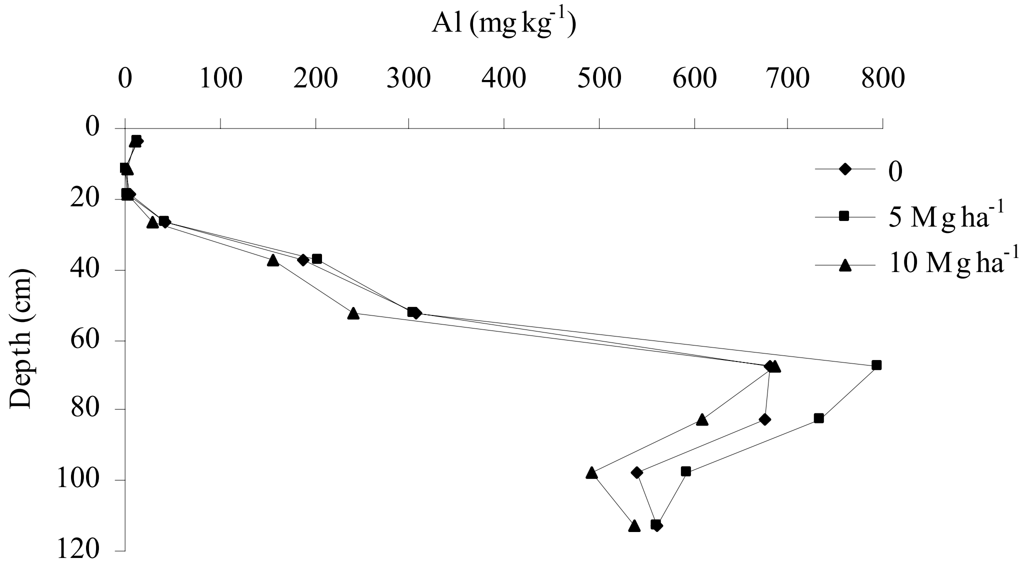


Figure 65. *N* KCl extractable aluminum by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

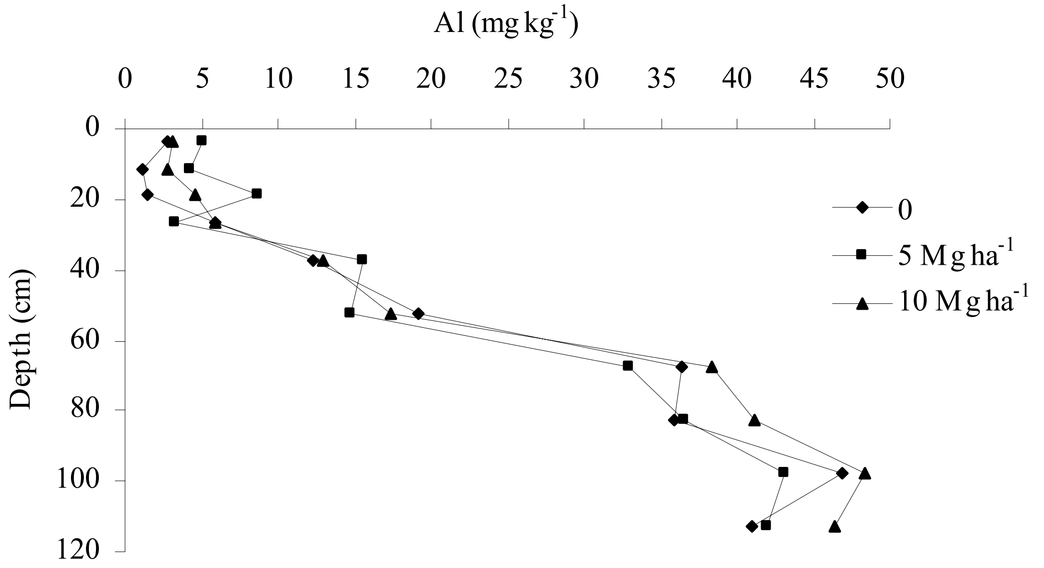


Figure 66. 0.01 *M* $CaCl_2$ exchangeable aluminum by depth in a Kirvin soil as influenced by rate of surface- applied gypsum in a glasshouse column experiment.

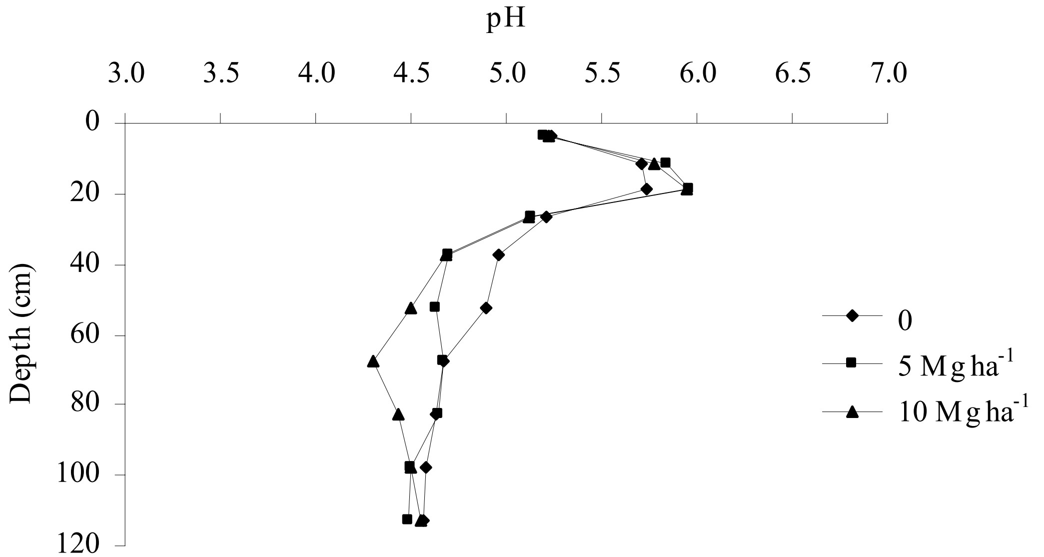


Figure 67. pH_{H_2O} by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

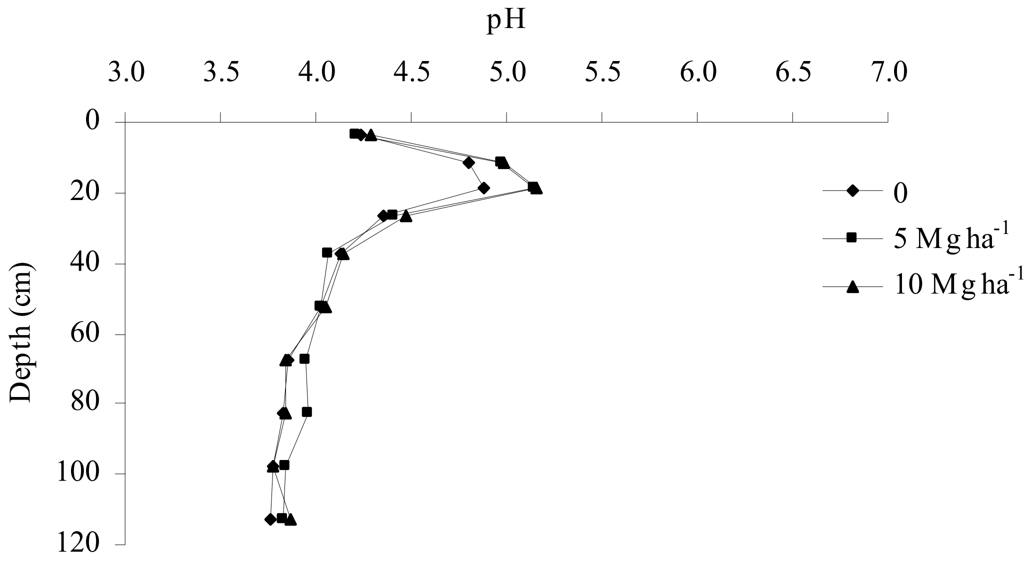


Figure 68. pH$_{CaCl2}$ by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

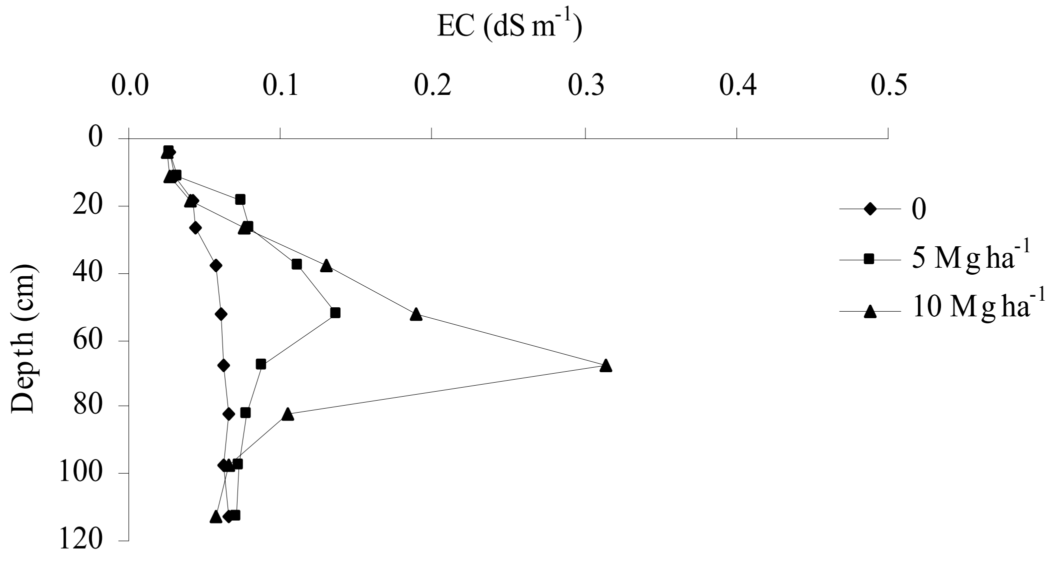


Figure 69. Electrical conductivity by depth in a Kirvin soil as influenced by rate of surface-applied gypsum in a glasshouse column experiment.

(Figure 69). These results are similar to those observed in data from the field experiments.

Treatment Effect on Alfalfa Dry Matter Yield

There were six harvests during the experiment, and gypsum rate did not significantly affect DMY in any of them (Table 110). Yields were highest during the second and third harvests, and steadily declined (Table 111). The lack of difference in yields is in keeping with the non-significant effects observed in root growth (Figure 70). Also, significant soil differences attributed to rate primarily occurred below 15 cm. Seventy-eight percent of the root mass was in the top 15 cm of soil. Lack of differences in the surface soil which contained the majority of the root mass probably contributed to the lack of yield difference. Keerthisinghe et al. (1991) indicated similar results in a potted subterranean clover (*Trifolium subterraneum*) study using gypsum-amended acid soils. Rates of gypsum up to 10 Mg ha^{-1} were incorporated into the surface 10 mm. Plants were harvested after 80 d, and there was no significant effect of gypsum on yield. Similar to the current study, they found that 0.01 M $CaCl_2$ exchangeable Al was not affected by gypsum rate. They did not speculate about the absence of yield response related to gypsum. In a field experiment, Rechcigl et al. (1993) did not see a yield response in bahiagrass (*Paspalum notatum* Fluegge) to 4.4 Mg of phosphogypsum ha^{-1} applied to the surface of an acidic soil. These authors noted that exchangeable Al in this same soil was not decreased 41 mo after treatment even though exchangeable Ca had increased to 90 cm as a result of treatment.

Treatment Effect on Tissue Mineral Concentration

Plant tissue from all six harvests was analyzed for mineral concentrations. There was a significant plant N effect only in harvests two and six (Table 110). Only plants growing in the 10 Mg ha^{-1} gypsum treatments had higher N concentrations than

Table 110. Analysis of variance for the effects of gypsum on alfalfa dry matter yield (DMY) and tissue mineral concentration of plants growing on a Kirvin very fine sandy loam in a glasshouse column experiment.

Harvest	Source	df	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al
			Mean Squares											
					x 10^5	x 10^7	x 10^7	x 10^5	x 10^5	x 10^3	x 10^2		x 10^2	x 10^2
1	Rate	2	0.12	2.93	0.80*	4.50***	14.41***	9.08***	91.14***	1.45	0.13	20.65**	0.11	8.49
	Rep	3	0.14	5.98**	1.16**	0.34*	0.25	0.17	0.53	7.56***	0.29	62.40***	0.13**	5.85
	Error	42	0.12	1.23	0.22	0.12	0.46	0.16	1.16	0.70	0.48	4.04	0.11	3.42
2	Rate	2	2.51	8.84**	1.40**	2.85***	1.93***	9.63***	27.46***	2.08	1.33*	1.26	0.22	0.75
	Rep	3	0.43	4.90*	0.44	0.76***	0.31	0.31*	0.34	3.30	0.65	0.99	1.19*	1.72
	Error	42	0.84	1.63	0.18	0.10	0.20	0.18	0.50	1.39	0.31	2.23	0.39	0.86
3	Rate	2	5.47	1.26	0.18	0.77*	1.27***	12.85***	2.33	11.84*	16.95*	29.77*	0.26	9.24
	Rep	3	1.58	2.61	0.66	0.20	0.78***	0.18	0.64	11.28*	2.28	131.97***	0.37	15.15
	Error	42	2.96	1.69	0.71	0.24	0.14	0.18	1.33	3.26	3.41	7.83	0.17	8.88
4	Rate	2	10.82	2.86	3.21	4.27***	1.92	13.85***	0.19	8.98	23.65	7.50	12.31	2.34
	Rep	3	31.79	7.28	6.33**	0.50	0.31	0.59	1.68	4.28	24.43	76.74	14.71	10.07*
	Error	42	13.28	5.78	1.20	0.27	0.63	0.68	0.69	5.13	17.09	53.17	6.71	3.35
5	Rate	2	4.13	4.72	0.39	3.60	2.87**	12.41***	14.91***	23.09	2.31	125.97*	21.83	13.03
	Rep	3	10.73	1.19	4.31	1.68	0.51	1.14	3.35	76.25**	24.08	259.79***	43.91**	21.56
	Error	42	4.26	2.26	2.00	1.55	0.42	1.05	3.44	17.04	12.40	30.86	8.59	13.58
6	Rate	2	0.31	6.28*	0.19	2.65	4.05**	14.38***	13.54***	257.01	8.79	0.15	1.41	1.15
	Rep	3	1.95**	2.23	3.69	1.41	0.21	4.89*	1.72	448.82*	12.61	2.79	12.99***	1.12
	Error	42	0.40	1.79	1.53	1.46	0.75	1.21	1.42	112.90	13.82	2.65	1.59	1.68

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 111. Influence of surface-applied gypsum on alfalfa DMY and tissue mineral concentration of plants growing on a Kirvin very fine sandy loam in a glasshouse column experiment.

Harvest	Gypsum Rate	DMY	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	Al
	Mg ha^{-1}	g pot^{-1}				——— g kg^{-1} ———					——— mg kg^{-1} ———		
1	0	4.09^{a}	35.5^{a}	2.11^{a}	24.5^{a}	26.4^{c}	2.29^{a}	3.11^{c}	64^{a}	55^{a}	8^{a}	23^{a}	59^{a}
	5	4.05^{a}	36.4^{a}	2.04^{ab}	22.5^{b}	30.1^{b}	1.97^{b}	4.15^{b}	55^{a}	56^{a}	7^{ab}	21^{b}	48^{a}
	10	4.21^{a}	36.8^{a}	1.97^{b}	21.1^{c}	32.3^{a}	1.83^{c}	4.98^{a}	45^{a}	56^{a}	6^{b}	22^{ab}	46^{a}
2	0	10.37^{a}	29.2^{b}	1.75^{b}	23.0^{a}	15.3^{b}	1.66^{a}	1.78^{c}	51^{a}	43^{a}	8^{a}	21^{a}	40^{a}
	5	9.63^{a}	31.4^{a}	1.93^{a}	21.5^{b}	17.4^{a}	1.47^{b}	2.35^{b}	48^{a}	42^{ab}	7^{a}	19^{a}	36^{a}
	10	10.24^{a}	31.1^{a}	1.81^{b}	20.3^{c}	16.6^{a}	1.17^{c}	2.58^{a}	30^{a}	38^{b}	7^{a}	19^{a}	36^{a}
3	0	10.13^{a}	29.6^{a}	2.07^{a}	16.8^{a}	13.9^{b}	1.97^{a}	2.80^{a}	125^{a}	73^{a}	6^{a}	24^{a}	47^{a}
	5	10.99^{a}	29.9^{a}	2.08^{a}	15.7^{a}	15.4^{a}	1.68^{b}	2.99^{a}	76^{a}	61^{ab}	5^{ab}	22^{a}	39^{a}
	10	11.24^{a}	30.5^{a}	2.02^{a}	15.5^{a}	15.5^{a}	1.40^{c}	2.77^{a}	80^{a}	52^{b}	3^{b}	23^{a}	31^{a}
4	0	7.22^{a}	32.3^{a}	2.60^{a}	17.6^{a}	14.3^{a}	2.58^{a}	2.23^{a}	121^{a}	154^{a}	10^{a}	50^{a}	62^{a}
	5	8.78^{a}	32.4^{a}	2.79^{a}	16.4^{a}	16.2^{a}	2.37^{b}	2.29^{a}	81^{a}	136^{a}	11^{a}	37^{a}	60^{a}
	10	8.45^{a}	31.2^{a}	2.52^{a}	14.4^{b}	16.1^{a}	2.00^{c}	2.25^{a}	80^{a}	131^{a}	9^{a}	54^{a}	55^{a}
5	0	4.29^{a}	31.5^{a}	3.00^{a}	18.8^{a}	12.7^{b}	2.61^{a}	2.01^{c}	220^{a}	146^{a}	11^{a}	59^{a}	59^{a}
	5	5.10^{a}	32.4^{a}	2.98^{a}	16.3^{a}	15.3^{a}	2.26^{b}	2.30^{b}	152^{a}	151^{a}	5^{b}	41^{a}	43^{a}
	10	4.16^{a}	33.3^{a}	3.08^{a}	16.0^{a}	14.5^{a}	2.06^{b}	2.62^{a}	156^{a}	153^{a}	6^{b}	62^{a}	44^{a}
6	0	2.70^{a}	25.4^{b}	2.88^{a}	16.4^{a}	13.4^{b}	2.74^{a}	2.74^{c}	471^{a}	164^{a}	10^{a}	61^{a}	30^{a}
	5	2.91^{a}	26.0^{ab}	2.93^{a}	13.9^{a}	16.3^{a}	2.26^{b}	3.02^{b}	269^{a}	178^{a}	9^{a}	57^{a}	32^{a}
	10	2.64^{a}	27.4^{a}	2.94^{a}	14.9^{a}	15.9^{a}	2.19^{b}	3.32^{a}	237^{a}	175^{a}	10^{a}	62^{a}	36^{a}

Means within a class followed by the same letter are not different at the 0.05 significance level.

the control (Table 111). However, the trend in three of the other four harvests was for higher N concentrations in the gypsum treatments. No attempt was made to quantify root nodulation. Although plant P was significantly affected by rate in harvests one and two, the relationship between the harvests was not consistent. In the first four harvests, the highest plant K levels occurred in the plants grown in the control soils (Table 111). The trend, even when not significant, was for K concentrations to be lowest in the high rate treatment. Effects of gypsum on plant Ca were significant in all but the fourth harvest (Table 110). The 5 and 10 Mg ha^{-1} treatments were consistently higher than the control, but different from each other only during harvest one. In every harvest, Mg in the control plants was significantly higher than in plants receiving both gypsum treatments, and in the first four harvests, Mg significantly decreased with increasing rate. The lower Mg concentrations that correspond to increasing gypsum rates and higher plant Ca, demonstrate the probable competition and/or exclusion of Mg^{2+} from uptake sites on roots by Ca^{2+}. This relationship between Ca and Mg uptake resulting from gypsum application has been demonstrated by other researchers (Stehouwer et al., 1995; Rechcigl et al., 1988). A similar but less obvious relationship was seen between Ca^{2+} and K^{+}. Plant S concentration significantly increased with increasing rate in all harvests except three and four. Increasing soil S has led to higher plant S concentrations in other research (Clark et al., 2001). Barney et al., (1984) demonstrated the propensity for alfalfa to absorb high amounts of S at high solution S levels. Plant Mn was significantly affected by gypsum rate only in harvests two and three, and only the high rate was significantly different than the control. Others have shown decreasing plant Mn with increasing levels of gypsum and lime (Rechcigl et al., 1988). However, they also reported increased soil pH and higher yields from the low Mn plants. Soil pH has a significant effect on Mn solubility, with solubility greatly decreased at pH_{H2O} above 6.0 (Lindsay, 1991). Soil pH in the columns was low enough to expect that the activity of Mn species in soil solution would be high. Plant Cu was significantly affected by rate in three of the six harvests, with the high rate having significantly lower concentrations than the control. Soil Cu behaves similar to Mn in regard to pH. However, plant Cu may better reflect minor changes in soil pH than plant Mn. Plant Al concentrations were highly variable and therefore treatment means were not significantly different even though the trend was for Al in plant tissue to decrease with increasing rate in all but the last harvest.

Treatment Effect on Root Growth

No roots were found growing below 60 cm in any pots. There were no significant treatment effects on root weight at any of the soil depths (Figure 70). Root mass decreased significantly with depth, with 78% of the roots in the top 15 cm, and 54% in the top 7.5 cm. Much of the literature reports improvement of root growth following gypsum, lime, or by-product application to acid soils. However, many of the positive results were seen when amendments were incorporated throughout the profile, and not simply surface-applied (Ritchey and deSousa, 1997; Ritchey et al., 1996). Clark et al. (1997) increased root mass of maize (*Zea maize*) grown on acid soils which had been mixed with high $CaSO_4$ flue gas desulfurization by-products. Wright et al. (1987) saw similar effects in *Phaseolus vulgaris* L. growing in Appalachian region acid subsoils mixed with dolomitic limestone. However, other researchers have reported only minor or no effect on root growth from amendment of acid soils. Matthews and Joost (1990) grew alfalfa in columns filled with a Toula silt loam treated with 2.5 Mg of gypsum ha^{-1} in the surface 10 cm and leached. Alfalfa was grown for one harvest, and the soil was sectioned by depth. Differences in root growth were not significant between the control and gypsum treatment. Even when treatments are mixed throughout the profile, root growth may not be improved. In a glasshouse experiment, Simpson et al. (1979) mixed Ca sources, including gypsum, at rates up to the equivalent of 1250 mg kg^{-1} $CaCO_3$ in subsoils to 85 cm. Gypsum did not improve alfalfa root growth compared to the control, and was not as effective as the other Ca sources considered. It has been demonstrated that root growth is often correlated with

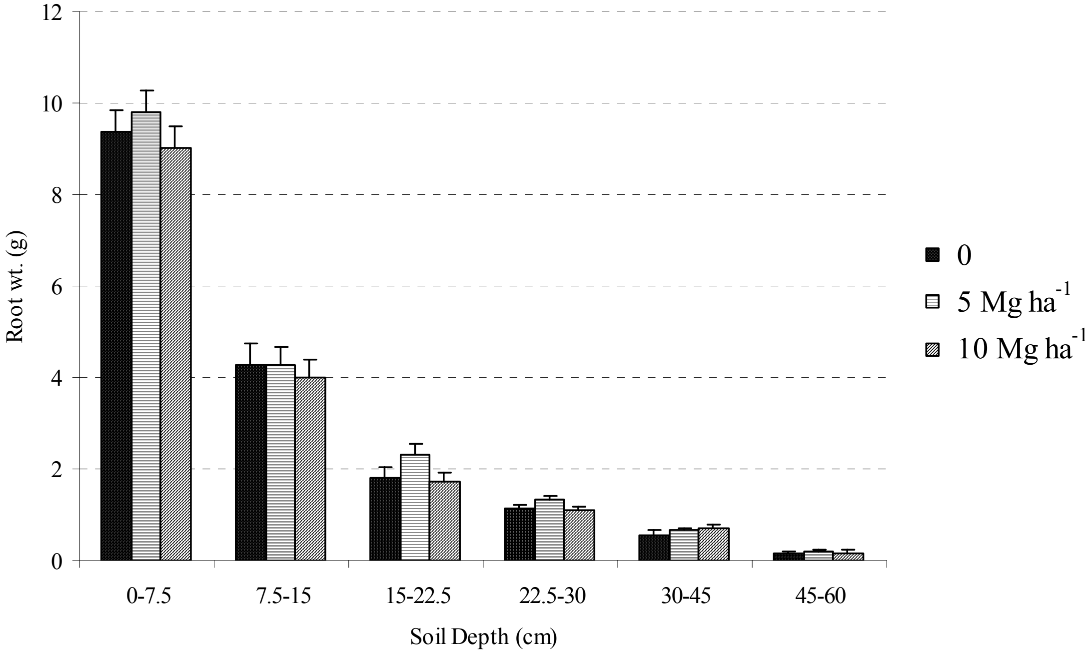


Figure 70. Alfalfa root mass and standard errors by depth as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam in a glasshouse column experiment.

Table 112. Simple correlations (r) between alfalfa root weight by depth and soil parameters at six depths in a Kirvin very fine sandy loam from a glasshouse column experiment.

Depth (cm)	Soil Parameter														
	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	CaCl$_2$ Mn	CaCl$_2$ Al	KCl Al	pH$_{CaCl2}$	pH$_{H2O}$	EC
0-7.5	-0.223	0.190	0.190	0.005	0.000	-0.227	0.025	-0.265	0.017	0.189	-0.007	0.061	-0.156	-0.186	-0.152
7.5-15	-0.089	-0.026	0.058	-0.152	0.063	-0.500***	0.196	-0.076	-0.177	-0.267	0.172	-0.221	0.239	0.130	0.056
15-22.5	0.266	-0.296	0.056	-0.018	-0.130	-0.434**	-0.224	-0.049	0.069	-0.485***	0.022	-0.087	0.332*	0.354*	0.168
22.5-30	0.259	-0.011	0.136	0.197	-0.049	-0.432**	-0.073	0.059	0.202	-0.427**	0.101	0.305*	-0.281	-0.124	0.276
30-45	0.042	-0.233	0.138	-0.213	0.031	-0.108	-0.058	0.133	0.004	-0.023	-0.065	0.119	-0.124	0.056	0.099
45-60	0.239	-0.518***	-0.194	-0.168	0.090	-0.172	-0.174	-0.195	0.043	-0.151	0.100	-0.018	-0.046	0.109	0.103

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

exchangeable Al, and also dependent on the predominant soil Al species (Brady et al., 1993; Cameron et al., 1986; Noble et al., 1988a; Wright et al., 1989). Even when subsoil exchangeable Al is decreased through surface-applied gypsum, root growth may not be improved (Wright et al., 1985). Since extractable and exchangeable Al were not significantly affected by gypsum treatment in this experiment (Table 108), it would be difficult to say anything conclusive about the effect of Al on root growth. Few soil parameters were correlated with root growth, and there was no consistent relationship between soil Al and root mass (Table 112). Although there was a positive relationship with soil Ca, it was not significant at any depth. The only relationships of note were the negative correlations with Mehlich-3 extractable Fe and 0.01 *M* $CaCl_2$ exchangeable Mn. The solubility of Fe and Mn decrease when pH_{H_2O} increases above 5.5 (Lindsay, 1991). The relationship of root mass to Fe may reflect pH_{H_20} differences not detected when comparing pH_{H_2O} to root mass. Soil Mn can be toxic to plant roots (Hue et al., 2001; Vega et al., 1992).

Treatment Effect on Mineral Concentration in Leachate

Leachate was sampled twelve times. The effect of time of sampling was highly significant for all elements measured (Table 113). Gypsum rate was significant only for Na and Ca. Highly significant rate by sampling effects occurred for Na, Mg, Ca, and K. Means of Na and Ca for all twelve samplings indicated that the 5 and 10 Mg ha^{-1} rates had higher concentrations than the control cylinders, but were not significantly different from each other (Table 114). Although the differences were not significant, the trend was for Mg and K concentrations in the leachate to increase with increasing gypsum rate. Concentrations of all elements initially decreased in leachate samples and then increased after approximately 3 L were leached (Figures 71, 72, 73, and 74). This initial decrease can be accounted for by the movement of elements that were in soil solution after the initial wetting of the columns. The subsequent increase in cation concentration with additional water leached probably resulted from

Table 113. Analysis of variance for the effects of gypsum on leachate mineral concentration from a Kirvin very fine sandy loam in a glasshouse column experiment.

Source	df	Na	Mg	Ca	K	S	Mn	Al	B
		Mean Squares							
			x 10^1	x 10^1	x 10^1		x 10^{-1}		x 10^{-3}
Rate (R)	2	20.08**	20.77	10.30*	8.92	0.62	2.05	1.39	0.71
Rep	3	0.27	1.46	0.35	0.50	0.31	0.27	0.36	3.91*
Error (a)	6	1.65	5.53	2.00	2.12	0.15	2.22	0.75	0.66
Sample (S)	11	50.93***	72.13***	22.42***	48.04***	15.22***	93.41***	2.51***	71.33***
R x S	22	3.55***	3.05***	1.55***	1.37***	0.15	0.60	0.15	0.37
Error (b)	531	1.09	0.69	0.27	0.37	0.20	0.63	0.12	0.69

*, **, *** Significant at 0.05, 0.01, and 0.001, respectively.

Table 114. Influence of gypsum on alfalfa leachate mineral concentration from a Kirvin very fine sandy loam in a glasshouse column experiment.

Class		Na	Mg	Ca	K	S	Mn	Al	B	pH
		mg L^{-1}								
Rate (Mg ha^{-1})	0	3.94^{b}	4.72^{a}	4.94^{b}	7.78^{a}	0.93^{a}	0.91^{a}	0.14^{a}	0.06^{a}	5.15^{a}
	5	4.38^{a}	5.97^{a}	5.90^{ab}	8.62^{a}	0.83^{a}	0.92^{a}	0.19^{a}	0.05^{a}	4.90^{b}
	10	4.57^{a}	6.79^{a}	6.38^{a}	9.13^{a}	0.85^{a}	0.85^{a}	0.30^{a}	0.06^{a}	4.82^{b}
Sample	1	4.68^{bc}	4.29^{d}	5.61^{c}	5.86^{de}	2.12^{a}	2.01^{a}	0.22^{c}	0.06^{c}	—
	2	4.58^{c}	2.95^{e}	5.61^{c}	6.21^{d}	1.42^{b}	1.45^{b}	0.01^{d}	0.06^{c}	—
	3	3.54^{d}	2.22^{e}	4.01^{d}	5.37^{de}	1.34^{b}	1.02^{c}	0.02^{d}	0.05^{d}	—
	4	3.07^{e}	1.83^{e}	3.09^{e}	4.94^{e}	1.11^{c}	0.80^{de}	0.01^{d}	0.14^{a}	—
	5	2.81^{e}	1.88^{e}	2.73^{e}	5.44^{de}	1.06^{c}	0.71^{e}	0.01^{d}	0.12^{b}	—
	6	2.88^{e}	2.30^{e}	3.32^{e}	5.98^{de}	0.85^{d}	0.81^{de}	0.01^{d}	0.07^{c}	—
	7	3.87^{d}	4.94^{d}	5.18^{c}	9.40^{c}	0.56^{e}	0.92^{cd}	0.15^{cd}	0.05^{d}	—
	8	5.59^{a}	8.03^{c}	7.05^{b}	12.04^{ab}	0.65^{e}	0.82^{de}	0.28^{c}	0.03^{de}	—
	9	5.13^{abc}	8.37^{c}	7.19^{b}	11.53^{b}	0.38^{f}	0.69^{e}	0.24^{c}	0.03^{e}	—
	10	4.68^{bc}	9.49^{b}	7.39^{b}	10.03^{c}	0.32^{f}	0.54^{f}	0.33^{c}	0.02^{e}	5.30^{a}
	11	5.57^{a}	11.35^{a}	8.58^{a}	12.62^{a}	0.30^{f}	0.53^{f}	0.52^{b}	0.03^{e}	4.84^{b}
	12	5.19^{ab}	12.28^{a}	9.13^{a}	12.73^{a}	0.32^{f}	0.42^{g}	0.71^{a}	0.02^{e}	4.74^{b}

Means within a class followed by the same letter are not different at the 0.05 significance level.

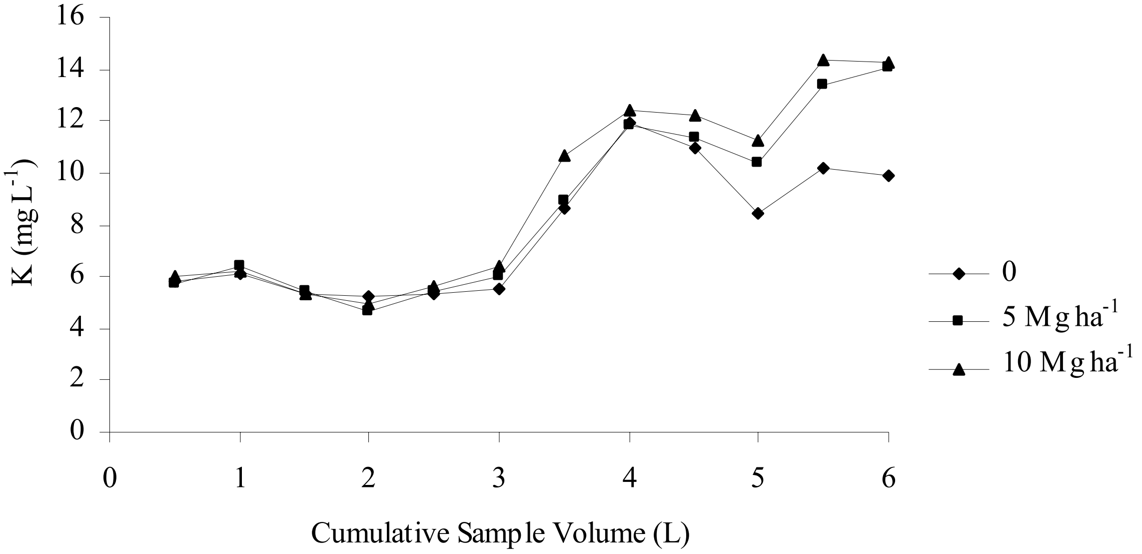


Figure 71. Potassium in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

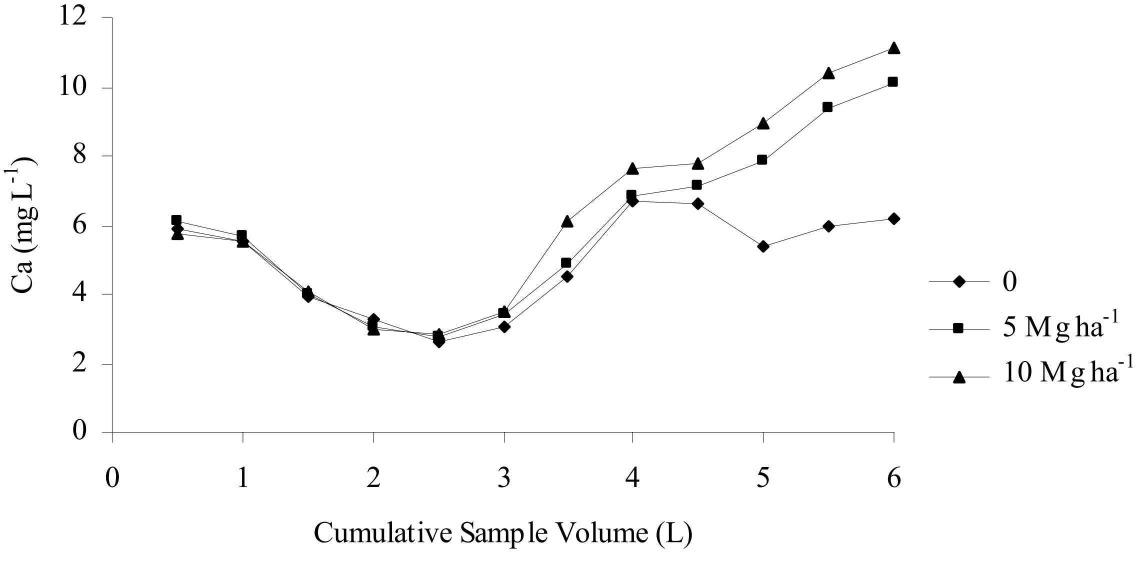


Figure 72. Calcium in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

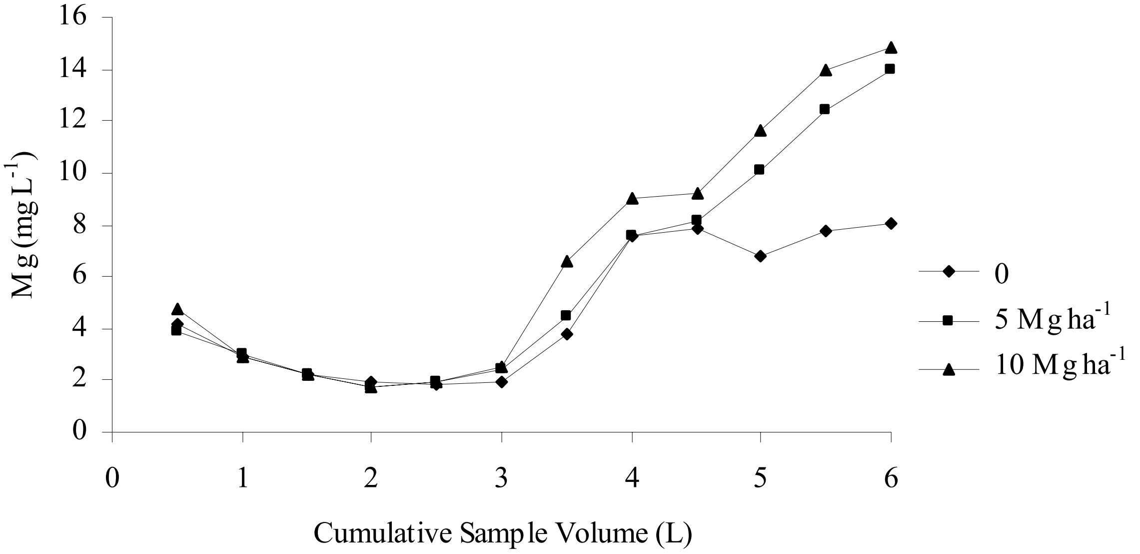


Figure 73. Magnesium in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

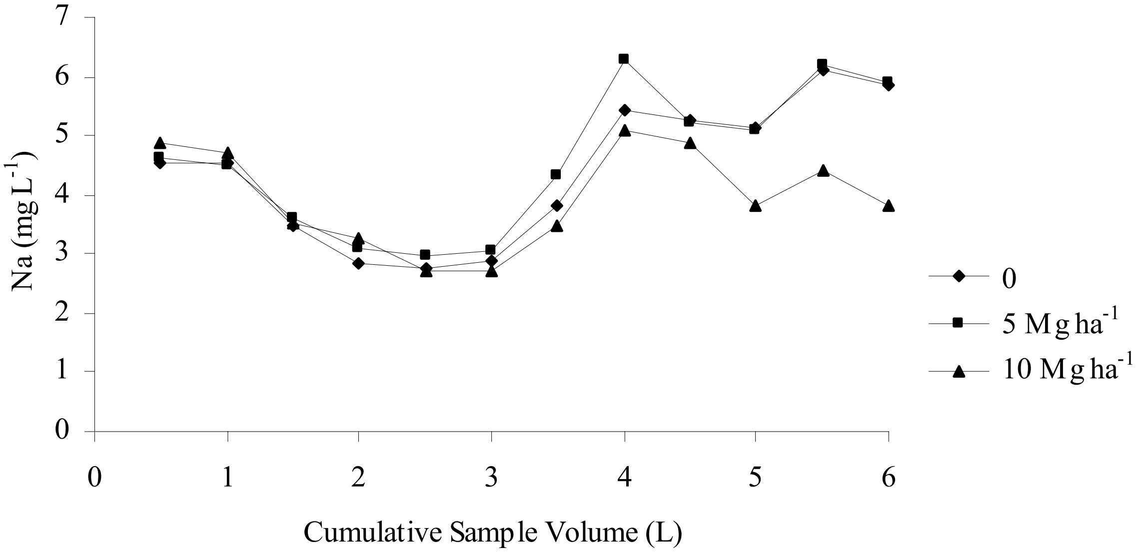


Figure 74. Sodium in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

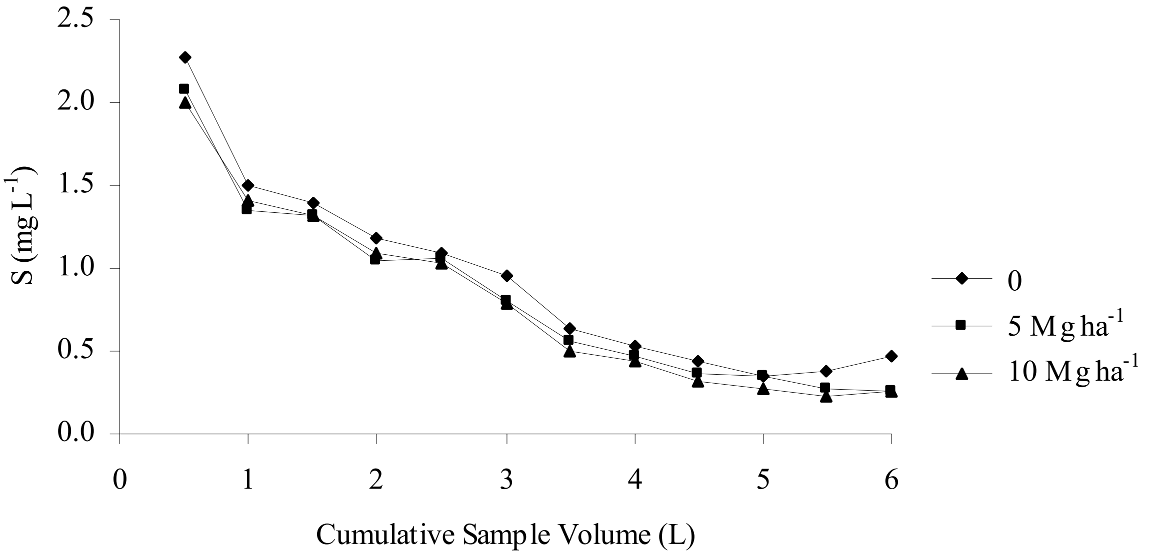


Figure 75. Sulfur in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

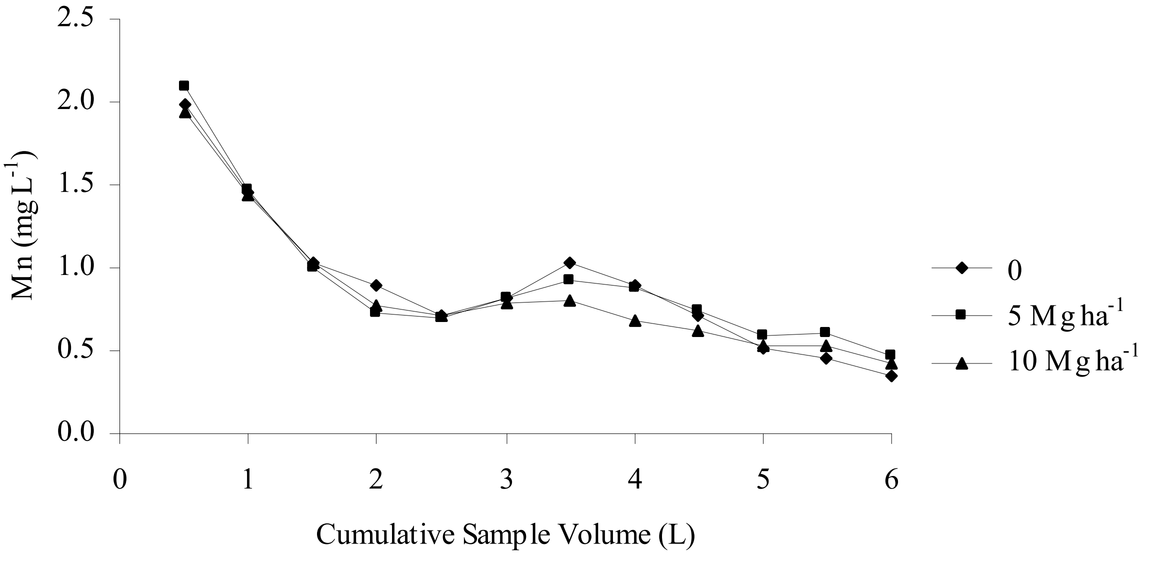


Figure 76. Manganese in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

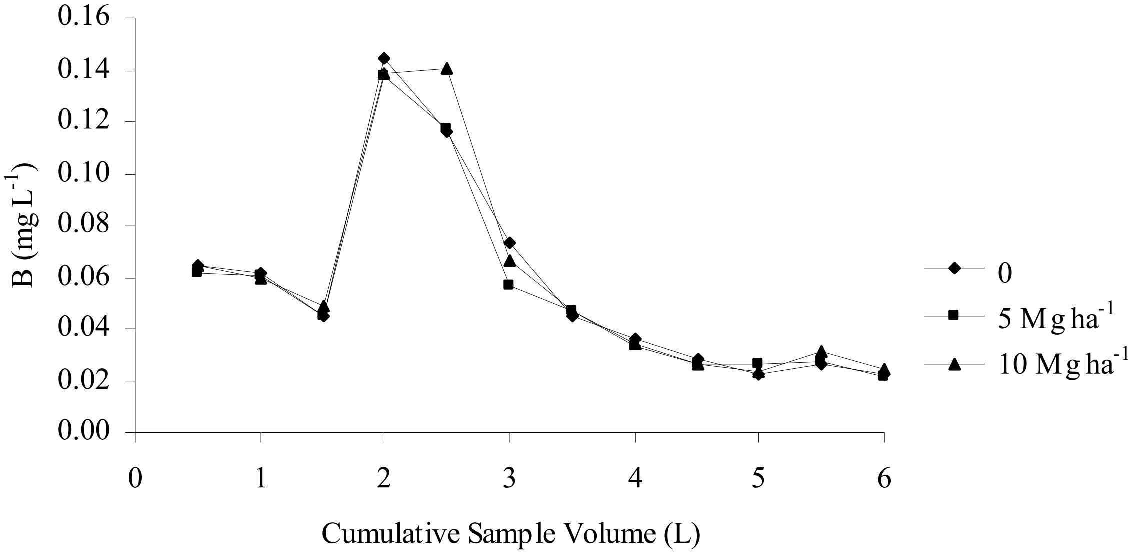


Figure 77. Boron in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

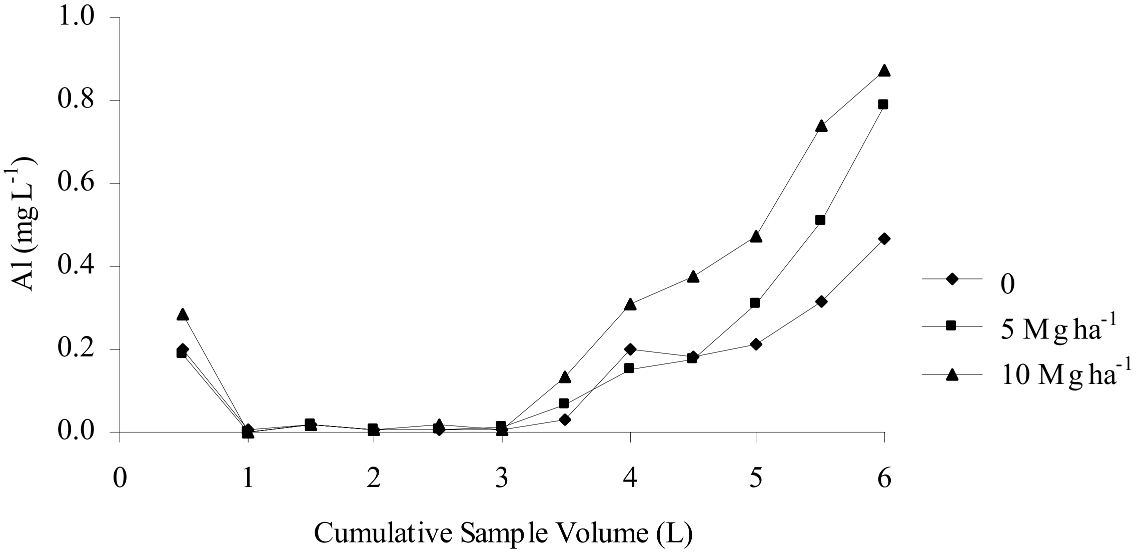


Figure 78. Aluminum in leachate as influenced by rate of surface-applied gypsum on a Kirvin very fine sandy loam soil in a glasshouse column experiment.

displacement of cations from exchange sites by Ca^{2+} solubilized from the gypsum. By the time 4.5 L were leached, the concentration of K, Ca, and Mg in the control decreases compared to the 5 and 10 Mg ha^{-1} cylinders. Increased leachate cation concentration resulting from $CaSO_4$ treatment of acidic soils has been reported by other authors (Alva et al., 1998; Liu and Hue, 2001; Wendell and Ritchey, 1996; Zhu and Alva, 1993). In each case the increases were attributed to Ca^{2+}-mediated exchange reactions resulting in K^+ and Mg^{2+} entering soil solution and moving with the water. However, Na in the high rate cylinders is significantly less than in the control or low gypsum rate. This may be due to the soils ability to retain more Na^{2+} on exchange sites because of the greater removal of other cations from the high rate cylinders. Similar results were observed by Vizcayno et al. (2001) in a leaching column study, in which they surface-incorporated gypsum at rates up to 40 Mg ha^{-1}. They found that Na in the leachate peaked at 10 Mg ha^{-1}, and then declined as rate increased above that. This was contrary to leachate concentrations of the other cations, particularly Ca and Mg, which continued to increase with increasing rate. By the time sampling was terminated after harvest two, K, Ca, and Mg concentrations were still increasing. No differences between treatments were observed for leachate concentrations of S (Figure 75), Mn (Figure 76), and B (Figure 78). Apparently, S from the gypsum had not arrived at the bottom of the columns by the conclusion of sampling. By the termination of the experiment, Mehlich-3 extractable S attributed to treatments was concentrated at about 60 cm, and levels at 120 cm were low in all treatments (Figure 63). Aluminum in all treatments began to increase significantly after 3 L were leached (Figure 77). These results conflict somewhat with those observed by Zaifnejad et al. (1996b). They evaluated the effect of surface application of several coal combustion by-products on the subsoil characteristics of an acid soil. One of the materials in the column study was a high $CaSO_4$ flue gas desulfurization by-product. After leaching 138 cm of water through the 105 cm columns, leachates were extremely high in K, Ca, Mg, Mn, S, and Al. It should be noted that the volume leached was almost twice that used in the current experiment. Their conclusion was that the high levels of Mg, K, Mn, and Al in the leachates were the result of displacement or solubilization of the elements and their movement as sulfate salts. Syed-Omar et al. (1991) reported similar results from using various ratios of gypsum and lime in a pot experiment with a highly-weathered soil. They observed increases in leachate Ca, Mg, K, and Al from mixing equivalents of 1 Mg Ca ha^{-1} throughout the soil. It is possible that significant increases in these elements could have been observed in the current study if leachate had been collected until there was indication of S reaching the bottoms of the columns, or if treatments had been mixed throughout the profile.

CHAPTER V

SUMMARY AND CONCLUSIONS

Highly weathered soils of the Coastal Plain often have acid subsoils and associated high soluble Al. Both characteristics are impediments to the growth of legumes such as alfalfa. Gypsum and various coal combustion by-products have been shown to ameliorate the negative effects of acid subsoils. Field and glasshouse studies were conducted between 1999 and 2002 to determine the effects of surface-applied gypsum and a flue gas desulfurization by-product on acid, east Texas soils representing three soil series.

Field Study

Gypsum and coal desulfurization scrubber sludge were surface-applied in July 1999 at 0, 5, 10, and 15 Mg ha^{-1} in a randomized complete block experimental design at two sites in east Texas. The sites were in Nacogdoches County on a Sacul fine sandy loam (clayey, mixed, thermic Aquic Hapludult), and Rusk County on a Cuthbert fine sandy loam (clayey, mixed thermic Typic Hapludult). Amerigraze 702 alfalfa was planted at both locations in Oct. 1999 and harvested as necessary beginning in 2000. Soil was sampled by depth to 120 cm before treatment application, and periodically throughout the experiment. Plant and soil samples were subjected to analysis appropriate to the objectives of determining the effects of treatments on soil characteristics and alfalfa growth.

Throughout the study, there were not any significant effects on any measured soil or plant variable due to differences between gypsum and scrubber sludge. At both locations, application of the materials produced an initial reduction in pH_{H_2O} by as much as 0.4 units compared to the zero rate plots. This lowering of pH_{H_2O} is attributed to the salt effect associated with high electrolyte concentrations in the soil solution resulting from the high $CaSO_4$ materials. The benefit of measuring pH in a dilute salt such as 0.01 M $CaCl_2$ was observed, in that the variability associated with relatively low concentrations of salts in the soil was negated. On the Sacul soil, rate effects on pH_{H_2O} and Mehlich-3 extractable S were observed from the surface to 60 cm one MAT. Plots receiving 15 Mg ha^{-1} had significantly higher S levels to that depth, and pH_{H_2O} in the check plots was significantly higher than in those receiving material. The same trend was not observed on the Cuthbert soil. Sulfur levels in the subsoil continued to increase, and by the conclusion of the study, had increased related to rate to 90 cm in the Sacul soil, and to 120 cm in the Cuthbert soil. There was indication of increased Ca at 15 to 30 cm in the high rate plots on the Sacul soil one MAT. Mehlich-3 extractable Ca in the subsoil continued to increase related to rate throughout the study. High rates of limestone applied to the surface soil confounded treatment effects on Ca in the surface 30 cm, but by the final sampling, there was evidence of a trend for higher Ca attributed to rate to 120 cm at both sites. However, high sample variability prevented changes in Ca level at depth during the study from being statistically significant below 15 cm on the Sacul soil, even though rate by depth effects were significant at every sampling. Treatment effects on K and Mg were inconsistent and difficult to interpret, and any conclusion regarding the movement of K^+ and Mg^{2+} as a result of exchange with Ca^{2+} would not be warranted. These results are at least partly due to high rates of fertilizer K applied during the study.

Subsoil *N* KCl extractable Al, and 0.01 *M* $CaCl_2$ exchangeable Al were not significantly reduced as a result of treatments, even though subsoil extractable Ca was increased in both soils. There was indication of increased exchangeable Al at 15 to 30 cm in the Sacul soil that might suggest Al being moved from exchange sites to solution. However, there was not a corresponding decrease in extractable Al. Several explanations are possible to explain this lack of treatment response. Subsoil Al levels were so high at both sites that they may not be good candidates for amelioration with surface-applied $CaSO_4$. Related to this, more time may be necessary for benefit to be realized. If this is the case, question would need to be raised concerning the practicality of such practices for short-term agronomic use. No attempt was made to determine if there were any changes in Al species as a result of treatments. With suspected differences in phytotoxicity, even among soluble species, perhaps there were effects not revealed by the two extraction procedures utilized. The other observation of note was that increased treatment rate resulted in increased EC. In addition to the response to rate, EC values closely tracked differences in extractable S at both sites. Electrical conductivity is a fairly easy determination that can be made in the field, and can potentially offer insight regarding soil conditions beyond simply determining levels of soluble salts. Further work is probably warranted to correlate EC with other soil parameters.

There was no observed significant response in DMY to any treatment during any harvest at either site. There were however differences between yields in a year, attributed primarily to soil moisture. Yields typically decreased at both sites as the season progressed and entered the relatively dry months of July and August. The summer of 2000 was drier than normal, especially at the Rusk Co. site. However, early 2001 growth at both locations was exceptional, and the previous year's drought seemed to have little effect. Yields and overall stand vigor had decreased by the third harvest season. Insect and weed pressure although regular, were managed, and therefore are believed to have contributed little to yield reduction. Overall, yields were lower than what would be expected for alfalfa. The inability of treatments to modify undesirable soil conditions appeared to be the primary cause of this poor overall performance.

The effect of treatment rate on alfalfa tissue mineral concentration was of little note. Differences in soil minerals related to treatment did not usually translate into differences when means of plant elements were compared. Sulfur was most often the element demonstrating difference with rate, but only in about half of the harvests, and only significant between the 5, 10, and 15 Mg ha^{-1} plots and the check, or the 15 Mg ha^{-1} plots and the other rates. So, although plant S tended to increase with increasing treatment rate, there was not a consistent significant relationship. Other trends of note were increasing plant Ca and decreasing plant Mg with increasing treatment rate. However, these differences were seldom significant.

When DMY and plant minerals were correlated with soil parameters, some interesting relationships emerged. Both pH_{H_2O} and pH_{CaCl_2} were positively correlated with yield at both sites. The association was strongest for pH at 15 to 30 cm, but extended to 60 and 90 cm for several harvests at both locations. Although soil pH throughout the study remained below that which is considered desirable for alfalfa growth, increased pH did correspond to increased yield. Also, exchangeable and/or extractable Al were negatively correlated with DMY in most harvests at both sites. Even though there were no significant treatment effects on soil Al or DMY, there was an apparent relationship between decreasing soil Al levels and increasing yield. Both measures of soil pH were negatively correlated with a number of plant elements at both sites, but especially on the Cuthbert soil. Even though yields were not affected by treatment, there is indication that on some soils, the benefits of increased soil pH may warrant efforts to modify acid subsoils for Al-sensitive crops such as alfalfa.

Since the area of highly weathered soils is vast, and many important crop plants are Al-sensitive, further research on the use of surface applied and incorporated amendments to ameliorate the negative affects of subsoil acidity is probably warranted. In the current study, the particular flue gas desulfurization scrubber sludge used, and gypsum did not produce different results. If by-products are investigated further, use of a different CCP is suggested, and then only if economical compared to gypsum. Some researchers have used rates as high a 70 Mg ha^{-1}. Increasing application rates may produce soil and plant treatment effects not observed in the work reported here. Several questions arise related to the current study. How would incorporation to 30 cm influence amendment effect? Can subsoils with extractable Al levels > 1000 mg kg^{-1}, such as the Sacul soil in the current study, realistically be ameliorated via surface applications at any rate? What is the level at which Al becomes phytotoxic, particularly as levels relate to the various extraction procedures? Which Al analysis procedure best correlates to response in sensitive plants?

Glasshouse Study

Three rates of gypsum (0, 5, and 10 Mg ha^{-1}) were surface applied to a Kirvin soil (clayey, mixed, thermic Typic Hapludult) that had been excavated by depth and placed in 10.3 by 132 cm PVC pots in a glasshouse. After a period of leaching with deionized water, Amerigraze 702 alfalfa was planted. Leachate was collected and analyzed for elemental concentration. Alfalfa was harvested six times, DMY determined, and tissue mineral concentrations analyzed. At the conclusion of the experiment, pots and soil were separated by depth to determine (i) movement of elements through the profile, (ii) the effect of gypsum rate on subsoil Al, and (iii) the effect of gypsum rate on root growth and distribution by depth.

Gypsum rate did not have a significant effect on DMY. The highest yields occurred during harvests two and three, and then declined to the conclusion of the study. Trends were for plant Ca and S to increase and K and Mg to decrease with increasing gypsum rate. Rate differences in regard to plant Mg were significant in every harvest. Although the differences for the other three elements were not always significant, the same trends were nonetheless evident. Calcium and S in the gypsum accounted for the increases in plant tissue. At least two factors are probably combining to cause these reduced K and Mg concentrations with increased gypsum rate. First, high levels of soil Ca^{2+} arising from the gypsum could have interfered with uptake of the two cations, K^+ and especially Mg^{2+}, even though uptake of cations by roots is believed to be fairly selective. A second consideration would be decreased exchangeable K^+ and Mg^{2+} levels resulting from their replacement by high levels of Ca^{2+}. Therefore, the decrease of the nutrients in the root zone would mean that less was available to enter the plants.

Rate by depth effects were significant for all measured soil parameters except Mehlich-3 extractable Cu, and 0.01 *M* $CaCl_2$ exchangeable Al and Mn. The movement of Mehlich-3 extractable cations and S into the soil, and the effect of rate on levels at depth was evident. Sulfur had moved deeper in the profile than Ca. In the soils that received 10 Mg gypsum ha^{-1} the highest S levels were at 45 to 75 cm, while at all gypsum rates, Ca was concentrated at 15 to 22.5 cm. Electrical conductivity was highest and pH$_{H_2O}$ was lowest in the high gypsum rate soils at 45 to 75 cm, the zone of highest extractable S. The Kirvin soil was used in this study because it contains high levels of subsoil Al. As in the field study, no consistent effect on Al was observed. Both exchangeable and extractable Al increased dramatically between 45 to 60, and 60 to75 cm in all treatments. Levels of exchangeable and extractable Al below 60 cm are well above what is considered phytotoxic for alfalfa roots. Interestingly, no roots were found below 60 cm, and gypsum rate did not significantly affect root mass or root mass by depth. Correlation of all soil parameters with root mass indicated that only Mehlich-3 extractable Fe and 0.01 *M* $CaCl_2$ exchangeable Mn were somewhat associated with root mass. There was a consistent negative relationship between both parameters and root mass at all depths to 60 cm. However, the correlation was not always significant.

Analysis of leachate showed that all cations were leached from the soil as the total volume of water moving through the soil increased, and that increasing gypsum rates resulted in higher concentrations of all the cations in the leachate. Aluminum was still increasing in the leachate at the termination of sample collection, and although the differences were not significant, the trend was for higher concentrations of Al in leachate from soils with higher gypsum rates. Leachate sample collection was probably terminated too soon. Differences attributed to rate were just beginning to develop, and Al concentration was increasing.

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