

THE MOVEMENT OF CALCIUM AND MAGNESIUM IN SELECTED
VIRGINIA SOILS FROM SURFACE APPLIED DOLOMITIC LIMESTONE

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE
in
Agronomy

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August, 1982
Blacksburg, Virginia

ACKNOWLEDGEMENTS

In the two years that I have been at Virginia Tech my knowledge of agriculture has expanded greatly. My acquisition of this knowledge has not only grown but the ability to integrate and apply it has been an important step for me. There are several individuals to whom I am indebted for this experience and it is my pleasure to mention their contributions in the lines that follow.

It has been my experience in academia that several attributes are necessary in a person leading them towards excellence in their field. Initially, the individual must have an understanding of the subject matter. In addition, that person should have the ability to apply that understanding. Finally, there is something that I see as most important and that is a person should have the capacity to pass on his knowledge to others. I have been most fortunate to have a committee chairman that has a rewarding combination of all these attributes. Dr. Marcus Alley has consistently been an asset to my education. On several occasions he has shown me how to take the classroom experience and apply it to the field. His patience has been unbounded throughout the period that we have worked together. Furthermore, his support and guidance have been encouraging when the work level ap-

peared overwhelming. My sincere gratitude is extended to my major professor for his numerous contributions to my education.

I am also appreciative of Drs. T. B. Hutcheson, Jr., D. C. Martens, and L. W. Zelazny for serving on my committee. The years of experience that these gentlemen have were a benefit to my research efforts. Dr. Martens was especially helpful with his timely laboratory suggestions, effective classroom instruction, and critiquing of written materials and seminars. Dr. Zelazny's outstanding research abilities were instrumental in my research. Discussions with him were very directive to my work.

I would like to express the greatest appreciation to specialists and technicians, Phyllis Hypes, Jim Hammons, Ronnie Alls, Jim Harris, Ted Ellmore, Bill Davis, Kathy Molten, and Joe Wade. Their help in the laboratory and the field allowed my sample collection and analysis to progress smoothly. I am especially grateful to Phyllis Hypes and Jim Hammons. Their technical assistance and friendship were invaluable.

Often one hears the expression, "Behind every man there is a good secretary." I have had the fortune of having the assistance of three excellent secretaries, Kathy Haden, Carolyn Rahnema, and Linda Holden. The three of them have con-

sistently given me assistance and helped to keep me updated on policies, guidelines, and information. I am particularly grateful to Kathy Haden. She has unselfishly worked in order to meet deadlines for me. Her attitude as a professional cannot be surpassed. Without Kathy's devotion and perfectionism this thesis would not have been completed on time.

I would like to thank my fellow graduate students for their resourcefulness. I am particularly thankful for the friendship, support, and suggestions that I have received from Mike Wilson, Lynn Wilson, Steve Nagle and Bill Gravelle. It is obvious to anyone that has known me for the last two years that I have left somebody out thus far. Ken Hylton has been a sincere companion of mine throughout graduate school. We have sweated out exams together, cursed over research problems together and even visited establishments downtown together. Ken has consistently illustrated the difference between an acquaintance and a friend to me. I am looking forward to our continuing friendship even as we both leave Tech. Thank you, buddy!

I could not conclude this acknowledgement without extending my sincere thanks to my parents. They have consistently given me support and understanding throughout my college career. They have given a lot of themselves so that I may achieve what they never had the opportunity to even attempt. God bless them! They are very special people to me.

Finally, gratitude is expressed to the Virginia Agricultural Foundation for their financial assistance during my graduate study.

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Chapter I

INTRODUCTION

Much of America's land that is considered to be well suited for crop production is found in the humid region. These soils are commonly acidic and the soils of Virginia are no exception. Liming has been practiced to neutralize this acidity since the early 1800's when Edmund Ruffin first applied marl to his field. Another benefit of liming is that Ca and Mg availability are increased. Research has been conducted which has consistently verified these benefits.

Regardless of the amount of time since Ruffin first made his observations and the multitude of articles in the literature, many researchers disagree on the philosophy of how much liming material should be added to surface soils. Some researchers contend that limestone application rates should be determined based upon the level of acidity or exchangeable Al in the plow layer. On the other hand, there are those researchers who are of the philosophy that increasing the rate of applied liming materials will serve as an asset to plant production. The theory argues that an increased rate of liming material will increase the depth to which neutralizing ions and basic cations move into the solum and

thereby increase the potential for root development. The corollary to this statement is that, if root development is stimulated, increased root exploration will increase nutrient uptake and plant growth will occur. With this effect, plant yields could be maximized. The present work will examine the short term effect of this latter theory as it applies to seven acid soils from different locations in Virginia.

The objectives of this study are:

1. To measure the movement of Ca and Mg into the subsoil from various rates of surface applied dolomitic limestone.
2. To document the degree of neutralization and changes in exchangeable Al levels at various depths from the surface applied liming materials.
3. To evaluate the potential for increasing surface application rates of limestone to improve the subsurface rooting environment in soils of Virginia.

Chapter II

LITERATURE REVIEW

Highly weathered soils of the humid temperate regions are commonly acidic. Liming of these acid soils is a well-established agricultural practice, the beneficial effects having been recognized for many years. Despite extensive research in the area of soil acidity and liming, a great deal of information, particularly with respect to lime movement and neutralization of acidity, remains unknown. The discussion that follows will overview the historical development and current concepts on soil acidity, neutralization of acidity, and lime movement in soils.

2.1 SOIL ACIDITY

2.1.1 Historical Development

T. B. Veitch worked for the U.S.D.A. at the turn of the 20th century. He is credited with the initiation of Al chemistry as applied to soil acidity. Results from his work suggested that the mineral fraction of the soil caused acidity and a possible reaction involved the replacement of Al by Na (Jenny, 1961). This idea opened a debate that would last over half a century.

Two schools of thought developed concerning soil acidity. Some researchers were of the opinion that exchangeable acidity was due to the presence of exchangeable H (Page, 1926) while others followed Veitch's suggestion concerning Al. The work of V. A. Chernov (1947) figured prominently with the Al theory. He ascertained that Al-oxide-hydroxy ions are more strongly held than trivalent Al and they are more tightly held than H ions. However, this theory was not readily accepted.

In 1950, E. W. Russell added support to the Al-clay theory when he concluded that acid mineral soils and clays are Al and not H soils. This finding converted many of the British scientists of the time, but the modern theory did not come into focus in the United States until two of Adolf Mehlich's students in North Carolina made their contributions. N. T. Coleman and M. E. Harward determined that H-clays behave like strong acids and their model of an "acid clay" was an Al clay which resembled a weak acid (Harward and Coleman, 1954).

Shortly thereafter, P. F. Low (1955) published on the role of Al and H in the titration of bentonite. He showed that H saturated clays rapidly convert to Al saturated clays (Low, 1955). Moreover, protons in the system are capable of attacking the crystal lattice and releasing cations, namely

Al, from the octahedral layer which are subsequently bound tightly to the soil clays. (Bohn et al., 1979; Coleman and Craig, 1961; Coleman and Thomas, 1967; Low, 1955).

The work of Low (1955) and Harward and Coleman (1954) had a large impact on the modern Al theory. These researchers used conductometric titrations in their work to distinguish between H and Al (Harward and Coleman, 1954; Low, 1955). The conductivity of an Al-clay increases as a base is added in titration; however, the conductivity of H-clay decreases as the H ions are neutralized by the base (Coleman and Thomas, 1967).

Rich and Obenshain (1955) identified exchangeable Al and large quantities of nonexchangeable Al in Virginia soils. The nonexchangeable Al blocked exchange sites, thus preventing the collapse of vermiculite-like clay in soil formed from mica schist. These researchers determined that many soils of Virginia contained this interlayer Al. Further understanding of this concept came with the work of Hsu and Rich (1960). They illustrated that hydrolysis occurred, followed by fixation of exchangeable Al.

The concensus of these papers can be summarized as follows:

1. Exchangeable Al is the major cation displaced from acid soils by neutral salt solutions (Bhumbla and

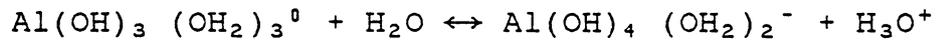
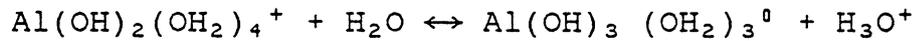
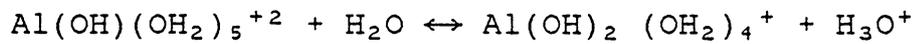
McLean, 1965; Coleman and Thomas, 1967; Heddleson et al., 1960).

2. Monomeric trivalent Al is believed to dominate in very acid soils as the primary exchangeable specie (Bloom et al. 1977; Coleman et al. 1959b; Low 1955; Thomas 1960), often as the aluminohexahydronium species (Jackson, 1963).
3. Nonexchangeable Al exists in certain clay mineral interlayers and its stability is dependent on pH. (Coleman and Thomas, 1967). This form of Al is titratable and replaceable by a buffered salt and is found to predominate in most soils above pH 5.5 (Coleman et al. 1959b; Coleman and Thomas, 1967; Pratt and Bair, 1962).
4. Little if any exchangeable H is present in soils (Bloom et al. 1977; Carlisle and Fiskell, 1962; Coleman and Craig, 1961; Coleman and Thomas, 1967), with the exception of "cat clays" and soils with salt pH's <3.7 (Dewan and Rich, 1970; Yuan, 1963).

2.1.2 Hydrolysis

Discussion of Al chemistry is not complete without the topic of hydrolysis. In such a reaction, monomeric Al ions are displaced from clay minerals by cations, and the Al spe-

Al³⁺ reacts with a H₂O molecule to release a proton. Many researchers are of the opinion that the hydrolysis products can be reabsorbed and cause further hydrolysis (Frink and Peech, 1963; Jackson, 1963; Ragland and Coleman, 1960). The generally accepted monomeric hydrolysis reactions are as follows:



The Al(OH₂)₆⁺³ form is predominant below pH 4.7, Al(OH)₂(OH₂)₄⁺² between pH 4.7 and pH 6.5, Al(OH)₃(OH₂)₃⁰ between pH 6.5 and pH 8, and Al(OH)₄⁻ above pH 8 (Bohn et al., 1979). The hydronium ions that are produced in these reactions can react with clay to decompose soil minerals (Coleman and Thomas, 1967).

2.1.3 Soil Organic Matter

Soil organic matter may contribute to acidity. Functional groups including carboxyls, phenols and, enols may affect acidity (Broadbent and Bradford, 1952, Lewis and Broadbent,

1961; Schnitzer and Gupta, 1965; Schnitzer and Skinner, 1964). In soils below pH 7 the carboxyl groups are the most appreciable donors through dissociation of H⁺ (Coleman and Thomas, 1967; Schnitzer and Gupta, 1965). Studies have indicated that organic matter can complex Al in soils and result in its immobilization (Coleman and Thomas, 1967; Schnitzer and Skinner, 1964). This may be the reason for low levels of exchangeable Al in acid soils high in organic matter (Evans and Kamprath, 1970; McLean et al. 1965).

2.2 NEUTRALIZATION OF SOIL ACIDITY

2.2.1 Reactions

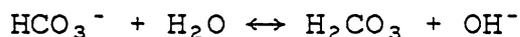
Amount of acidity, limestone particle size, degree of mixing, soil moisture levels, and specific liming material influence the reaction of limestone with soil (Coleman and Thomas, 1967; Coleman et al., 1959a; Murphy and Follett, 1979). According to Ramette (1974) the dominant acid in soil solution at pH levels less than 6.3 is H₂CO₃. This acid reacts with applied CaCO₃ according to the reaction:



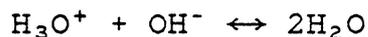
The limestone may also dissociate:



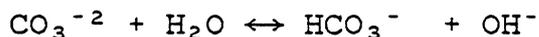
The former reaction predominates in solution since $\text{Ca}(\text{HCO}_3)_2$ is 10^3 times more dissociated than CaCO_3 . Calcium from these reactions can displace hydroxy-Al, can be adsorbed to pH dependent CEC sites created by increases in pH, or it can leach (Coleman and Thomas, 1967; McLean, 1976). The HCO_3^- by products are available to enter the reaction:



The H_2CO_3 that forms can react with more CaCO_3 while the OH^- is available for neutralization of H_3O^+ :



The CO_3^{-2} that does form from dissociation of CaCO_3 can react with H_2O :



End products of this reaction are available to enter previously discussed reactions.

2.2.2 Lime Requirements

Prior to the 1970's, lime recommendations were determined by the amount of base required to bring a soil to a given pH, usually between 6 and 7, (Adams and Evans, 1962; Shoemaker et al., 1961). Following discovery that Al often was

the predominant cation in southeastern soils (McCart and Kamprath, 1965) and its detrimental effect on plant growth (Vlams, 1953), E.J. Kamprath (1970) investigated the use of exchangeable Al levels as the basis for determining lime requirement. He found that lime additions equal to mol L⁻¹ KCl exchangeable Al levels reduced Al on the exchange to less than 30%. Furthermore, Kamprath developed an empirical formula for determining levels of calcite needed to reduce Al saturation to 15% or less on four Ultisols:

$$\text{cmol(p}^+\text{)kg}^{-1} \text{ CaCO}_3 = \text{cmol(p}^+\text{)kg}^{-1} \text{ exchangeable Al} \times 1.5$$

This factor was deemed sufficient for most crops, however, a factor of 2 was suggested for highly sensitive crops. Even with the factor of 2, none of the four soils studied had a final pH value above 6, contrary to the conventional method of liming to achieve pH values greater than 6.

E. O. McLean (1970) in Ohio, concluded that Kamprath's empirical formula is suitable for Ultisols and Oxisols but still advocates liming of mid-western soils, predominantly Alfisols and Mollisols, to pH values of approximately 6.5. He contends that additional lime would increase Ca and Mg activities for plant nutrition in the soil surface and promote their leaching into lower horizons for deeper roots.

Besides Ca and Mg, soil K, P, S, and B would also be more available at the higher pH levels. In addition, N fixation and decomposition of plant residues would increase; thereby, increasing the availability of nutrients associated with these processes.

Studies on acid soils in western Washington led A. S. Baker (1970) to state that Kamprath's novel idea of liming to reduce monomeric exchangeable Al is feasible for Mollicsols and Ultisols in his region. However, he disagrees with Kamprath's formula for that region. It is his opinion that the amount of lime needed according to Kamprath's formula is not sufficient to neutralize exchangeable Al in these soils. The objective is not accomplished because of nonuniform mixing of lime under field conditions and the higher CEC values of these soils as compared to Kamprath's experimental soils. The absolute amounts of additional lime depends on a specific crop. Results of his research show optimum yields of peas (Pisum sativum L.), corn (Zea mays L.), and alfalfa (Medicago sativum) at 0.01 mol L⁻¹ CaCl₂ soil pH values of 5.4, 5.4, and 5.9, respectively. Thus, he maintains that the concept of liming to a specific pH is most successful for soils of that region.

McLean (1970) and Baker (1970) have overlooked some important research findings in their editorial comments of

Kamprath's (1970) work. McLean states that the availability of soil Cu and Zn is greater at higher pH values. This conflicts with other researchers who found the opposite relationship (Peech, 1941; Viets et al., 1957).

Baker (1970) stated that the degree of soil-lime mixing is important. Therefore, rates of application should be greater than that prescribed by Kamprath's formula. However, he neglected levels of mixing for specific cropping systems. Low CEC soils of the Virginia Coastal Plain are predominantly cropped in peanuts (Arachis hypogaea), corn, and soybeans (Glycine max L.). Plowing and disking each growing season on these soils would increase mixing as opposed to an alfalfa crop. This is a crop on which Baker basis his conclusion.

Neither McLean (1970) nor Baker (1970) comment on Mo availability or triazine herbicide activity. Both Mo and triazine herbicide activity increase as pH increases.

In conclusion, soils in Virginia, not cropped in continuous legumes, should be limed to a pH between 6.0 and 6.2 for the following reasons:

1. All exchangeable Al will be neutralized at pH levels greater than 5.5; Ca and Mg activities will be sufficient for high crop yields.

2. Micronutrient availability will be maintained and toxicities prevented.
3. Soil microbial activity will be favored.
4. Triazine herbicide activity should be adequate.
5. Generally, at these pH values P availability is at a maximum for most agronomic crops.

Overliming is detrimental to crop yields (Brady, 1974; Tisdale and Nelson, 1976). E. J. Kamprath (1971) identified these possible detriments in liming Ultisols and Oxisols to pH 7:

1. "Infiltration is decreased and erosion susceptibility is increased due to formation of smaller aggregates."
2. "P deficiency results in certain soils as insoluble Ca phosphates form."
3. "Availability of B decreases as it is adsorbed by hydroxy Al and hydroxy Fe."
4. "Mn precipitates at lower pH values in the presence of Al and Fe compounds."
5. "Zn availability decreases."

2.2.3 Liming Materials

Materials containing Ca and Mg compounds that are capable of neutralizing soil acidity may be called liming materials (Barber, 1967). Examples of these materials include marl

(unconsolidated CaCO_3), burned lime (CaO), hydrated lime [$\text{Ca}(\text{OH})_2$], calcitic limestone (CaCO_3), and dolomitic limestone ($\text{CaCO}_3 \cdot \text{MgCO}_3$). The latter two are used most commonly in modern agriculture. When these materials are applied to the soil they react with water and then with the acidity in solution, usually termed "active acidity" (Coleman and Thomas, 1967). Secondly, lime materials react with soil acidity produced by hydrolysis of Al that has been released in weathering processes (Jackson, 1963; Schofield and Taylor, 1954). Finally the amendments can react with soil acidity produced by nonexchangeable Al that may contribute protons with pH increases. In addition to correction of Al toxicities, liming corrects Mn toxicities, increases P and Mo availability, improves soil microbial activity, and improves structure (Chapman, 1973; McLean, 1971).

2.3 MOVEMENT OF LIMING MATERIAL

The relationship between liming and increased Ca and Mg availability and reduced toxic Al and Mn levels is well documented for soil areas that receive direct lime applications, generally the surface horizons (Brady, 1974). Only limited data exists regarding movement of liming materials and subsequent changes in soil chemical properties.

The movement of Ca from surface applications of calcitic limestone has been reported by Juo and Ballaux (1977) and Mahilum et al. (1970). The former researchers conducted a greenhouse experiment in which corn was cropped in an Oxic Paleudult from Nigeria treated with limestone rates from 0 to 6.5 Mg ha⁻¹. Exchangeable Ca levels increased in the 15-30 cm increment which was immediately below the treated layer (0-15 cm). Also, the magnitude of exchangeable Ca increased (15-30 cm) with increasing rate of surface (0-15 cm) applied limestone.

Mahilum et al. (1970) performed a field study on a clayey volcanic ash derived soil (Typic Hydrandept) in Hawaii and found that five years following calcite additions at moderate or high rates (up to 38.08 Mg ha⁻¹), exchangeable Ca and soil pH increased to a depth of 120 cm. The appreciable movement of Ca was attributed to high infiltration rates and accelerated leaching with the 450 cm mean annual rainfall for this area.

Pearson et al. (1962) also showed changes in subsoil base status with high rates of limestone. These researchers applied calcite at rates up to 15.6 Mg ha⁻¹ to two clay soils in Puerto Rico. This region receives 175-200 cm mean annual rainfall. Although these soils received less than half the rainfall as the previous study, movement of Ca was detected

at 60 cm in a short period of time (2.5 to 3 years). These researchers concluded that high rates of N fertilizers coupled with relatively high rainfall caused an appreciable downward transfer of bases. The most lengthy examination of changes in subsoil reaction was done by Brown et al. (1956). These researchers applied dolomitic limestone to the surface of a sandy loam grassland soil in Connecticut at rates up to 35.84 Mg ha⁻¹. Soil pH increased to a depth of 60 cm for the highest treatment rate nine years after limestone application. Twenty-three years following the application, soil pH increased to a depth of 75 cm at the highest rate despite low amounts of rainfall (112 cm mean annual).

Referring to Virginia soils explicitly, two studies have examined lime effects on soil reaction and base content. The earliest study was performed by Moschler et al., 1962. These researchers evaluated changes in pH and base status in the surface (0-15 cm) on eleven different soil types, seven years after application of dolomitic limestone. Rates of application varied from 0 to 17.92 Mg ha⁻¹. Their research indicated that increases in pH were rate dependent. Also, increases in exchangeable Ca and Mg were rate dependent. Coarser-textured soils in the Coastal Plain contained less exchangeable bases, at a given pH, in comparison to Piedmont and Ridge and Valley soils.

The other study in Virginia on soil pH and base status changes from long-term limestone additions was completed by Sampath (1972). This researcher performed an in-depth analysis of the changes in soil chemical properties on the Nason silt loam from the Piedmont Region. Rates of dolomitic limestone application were from 0 to 35.84 Mg ha⁻¹. Twenty years following these applications, rates of less than 8.96 Mg ha⁻¹ did not increase the soil pH or increase exchangeable Ca and Mg levels of the soil in the surface (0-15.2 cm) or subsurface (15.2-30.5 cm). Furthermore, decreases in exchangeable Al did not occur. Rates above 8.96 Mg ha⁻¹ did substantially increase soil pH, exchangeable Ca and Mg content and decrease exchangeable Al content in the soil.

Chapter III

MATERIALS AND METHODS

3.1 FIELD EXPERIMENTS

3.1.1 Treatments

Seven acid soils that were representative of the state of Virginia were chosen from different locations for a series of limestone rate studies. Selected chemical properties of these soils are presented in Table 1. The Emporia loamy sand was located in Essex County and a corn-wheat (Triticum aestivum) double crop soybean rotation was utilized for the period of study. The other Coastal Plain soils, the Goldsboro sandy loam from Isle of Wight County and the Tomotley loam from the City of Chesapeake, were cropped in a corn-soybean rotation. Continuous barley (Hordeum vulgare) -double crop corn, both crops harvested as silage, was the crop rotation on the Masada loam, Orange County. A corn-barley-double crop soybean rotation was utilized on the Pacolet sandy clay loam soil, Halifax County. The Frederick silt loam, Montgomery County was cropped in continuous alfalfa while the Duffield silt loam, Wythe County, was cropped in continuous corn.

In the spring of 1978, all sites received treatments of dolomitic limestone. This high grade material contained 54

Table 1. Classification and selected chemical properties of soils used in field studies.

Soil Type	Physiographic Region	Soil Taxonomic Classification	Soil Water pH	CEC cmol(p ⁺)Kg ⁻¹
Goldsboro sandy loam	Coastal Plain	Aquic Paleudult; fine loamy, siliceous, thermic	4.3	2.4
Tomotley loam	Coastal Plain	Typic Ochraquult; fine loamy, mixed, thermic	4.5	3.9
Emporia loamy sand	Coastal Plain	Typic Hapludult; fine loamy, siliceous, thermic	4.2	1.7
Masada loam	Piedmont	Typic Hapludult; clayey, mixed, thermic	5.3	3.9
Pacolet sandy clay loam	Piedmont	Typic Hapludult; clayey, kaolinitic, thermic	5.0	2.9
Duffield silt loam	Ridge and Valley	Ultic Hapludalf; fine-loamy, mixed, mesic	5.2	3.5
Frederick silt loam	Ridge and Valley	Typic Paleudult; clayey, mixed, mesic	5.2	1.9

and 43% Ca and Mg carbonate, respectively. Treatments were applied at rates of 0, 4.48, 8.96, and 13.44 Mg ha⁻¹ for soils of the Coastal Plain. The heavier textured soils of the other two provinces received treatments up to 17.92 Mg ha⁻¹. The dolomite limestone was applied in split applications with half being applied, disked-in, and plowed down. The remainder was applied and then disked-in. Randomized complete block experimental designs with four replications were employed at all locations.

3.1.2 Sampling

Samples were taken between April and October of 1981. Samples were collected at the Goldsboro and Tomotley sites in April, 1981. The other sites were sampled in the fall immediately following crop harvest. Samples consisted of six randomly selected soil cores per plot taken to a 60 cm depth. Soils located in the Coastal Plain were sampled with a 60-cm Hoffer tube while the remaining sites in the study were sampled with a hydraulically driven 5-cm diameter sampling tube. The Masada soil was sampled uniquely due to unfavorable subsoil moisture conditions. Trenches were dug in each plot with a backhoe. Faces of the pits were cleaned and samples were taken at the seven appropriate depths.

Each sample core was subdivided in 10 cm increments. The 20-30 cm increment was further subdivided into 2-5 cm increments. All soil samples were air dried and crushed to pass through a 2 mm sieve.

3.2 LABORATORY ANALYSES

3.2.1 Acidity

Soil pH measurements were made on 1:1 soil:water and 1:1 soil:mol L⁻¹ KCl slurries for soils of the Coastal Plain. Soils from the Piedmont and Ridge and Valley regions contained greater amounts of clay and soil pH measurements were made on 1:2.5 soil:water and 1:2.5 soil:mol L⁻¹ KCl slurries. Following a 1-hour equilibration period for all samples, measurements were made with an Orion Model 901 Ionalyzer equipped with a glass electrode assembly.

3.2.2 Exchangeable Cations

Exchangeable Ca, Mg, Na, and K were extracted with mol L⁻¹ NH₄OAC (pH 7.0) according to the procedure described by Jackson (1958). Cations from the higher clay containing soils of the Piedmont and Ridge and Valley regions were extracted by a modification of this procedure. A 5-gram soil sample was shaken with 50 ml of the mol L⁻¹ NH₄OAC for 30 minutes. Samples were then centrifuged for 5 minutes at

2000 rpm and filtered. All determinations of exchangeable Ca, Mg, K, and Na were completed with a Perkin-Elmer Model 306 atomic absorption spectrophotometer.

Exchangeable Al was extracted with mol L⁻¹ KCl in a 1:10 soil:solution ratio with a 48-hour shaking period. Extracts were analyzed for Al by the aluminon procedure described by Jayman and Sivasubramiam (1974). Colorimetric analysis was performed with an Technicon Auto Analyzer II (Bertsch et al., 1981) or a Beckman Spectronic 20.

3.2.3 Statistical Analysis

Analysis of variance procedures were utilized for all data. Duncan's Multiple Range Test at the 5% level of significance was utilized for mean separations for that data with analysis of variance F test significance less than 5%. In the text, "no differences" indicate that the means being discussed were not statistically different at the 5% level for either the analysis of variance F test or the Duncan's Multiple Range Test. Mean values for a given lime rate within a specific increment are plotted at the cm values midrange to that depth (e.g. the 0-10 cm mean value is plotted at the 5 cm position). The Statistical Analysis System (SAS Institute Staff, 1979) procedures were utilized for the statistical evaluation.

Chapter IV

RESULTS

4.1 COASTAL PLAIN REGION

4.1.1 Goldsboro sandy loam

Changes in Ca levels of the limed plots as compared to the unlimed plots for the Goldsboro sandy loam soil are shown in Figure 1. Increases in Ca levels occurred with increasing lime rate in the plow layer (0-20 cm). Only small variations in Ca levels were detected for a given lime rate within the plow layer indicating thorough mixing in the Ap over the course of the study. Immediately below the plow layer there is a sharp decrease in Ca levels. The magnitude of this decrease is greater as the rate of application increases. This substantial increase in Ca retention in the surface layers was also observed by Juo and Ballaux (1977), and is attributed to increasing negative charges, i.e. pH dependent, from liming.

Increases in Ca levels as compared to the unlimed plots were observed to a depth of 30 cm for all rates of application (Figure 1). Increases with increasing lime rate occurred to a depth of 25 cm. However, the 4.48 Mg ha⁻¹ lime rate samples did not differ from any other subsurface sample at this depth (Table 2). The higher two rates of applica-

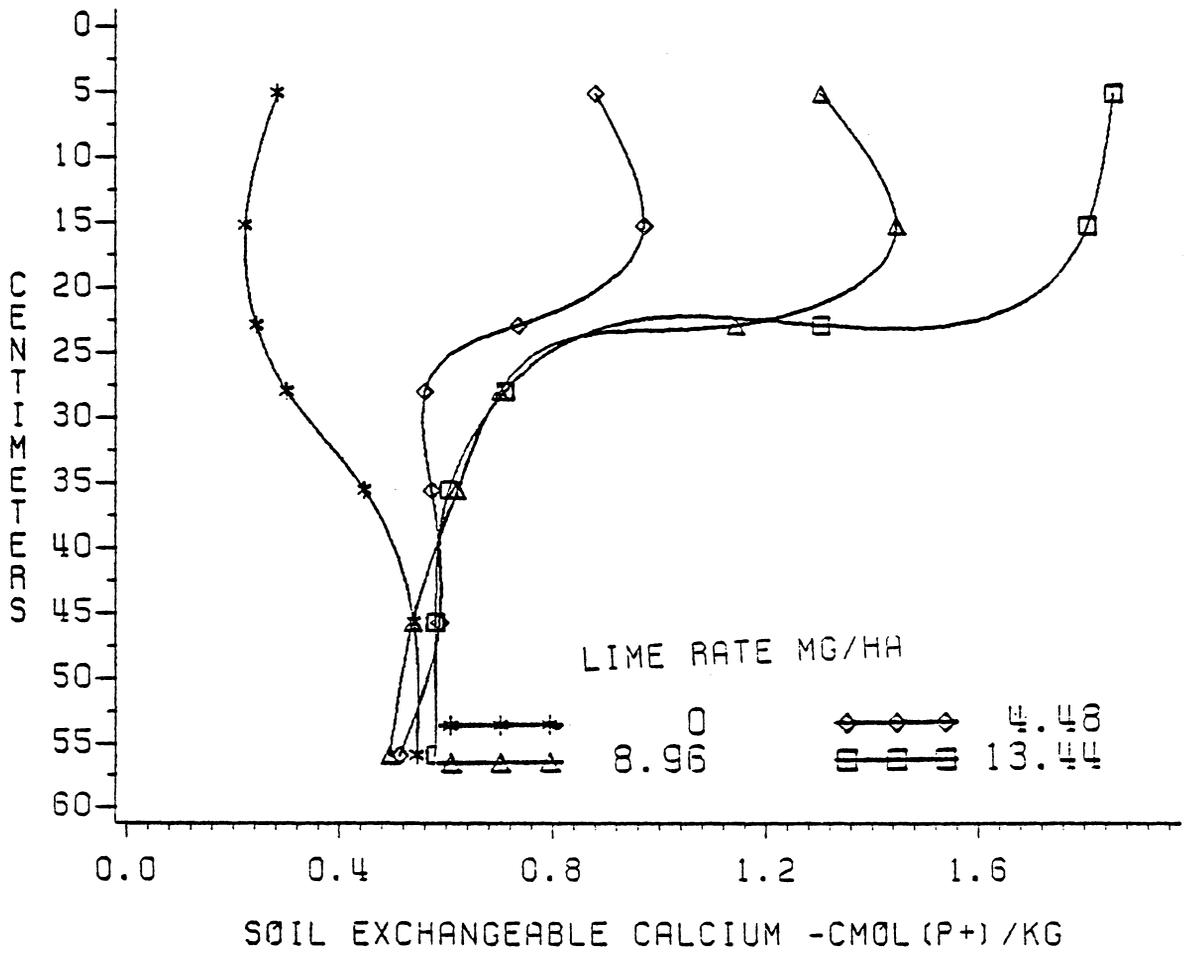


FIG. 1-EXCHANGEABLE SOIL CA FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A GOLDSBORO SANDY LOAM SOIL.

tion did not vary from the other subsurface samples below the 25-30 cm depth. Therefore, movement of Ca occurred at a greater magnitude with increasing lime rate.

As observed with Ca, increases in Mg were detected with increasing lime rate in the plow layer with little or no variation for a given lime rate (Figure 2). Below the plow layer Mg levels increased as compared to the unlimed plots at all rates of application, and at all depths sampled with exception of the 50-60 cm sample of the 4.48 Mg ha⁻¹ rate (Figure 2). Decreases in Mg levels are detectable from layer to layer to the 30, 40, and 40 cm depths for the 4.48, 8.96, and 13.44 Mg ha⁻¹ lime rates, respectively (Table 2). These findings indicate that an increase in lime rate increases the amount of movement of Mg from the Ap horizon, similar to Ca. Furthermore, movement of Mg occurred to a greater degree than Ca.

Decreases in Al levels were observed with an increase in lime rate within the plow layer (Figure 3). Rates of 4.48 Mg ha⁻¹ were sufficient to decrease Al levels by 50% (Table 3). At the 13.44 Mg ha⁻¹ rate of application Al was scarcely detected in the plow layer.

Aluminum levels continued to decrease below the plow layer at all rates of application as compared to the untreated soil (Figure 3). The 4.48 Mg ha⁻¹ rate of application exhi-

Table 2. Exchangeable Ca and Mg as a function of lime rate and depth for the Goldsboro soil.

Depth	Lime Rate Mg/ha ⁻¹							
	0	4.48	8.96	13.44	0	4.48	8.96	13.44
	Ca				Mg			
cm	cmol(p ⁺)Kg ⁻¹							
0-10	0.3b*	0.9ab	1.3ab	1.9a	0.1 NS	0.5ab	0.8a	1.2a
10-20	0.2b	1.0a	1.4a	1.8a	0.1	0.6a	0.9a	1.2a
20-25	0.2b	0.7bc	1.1b	1.3b	0.1	0.5bc	0.8a	0.9b
25-30	0.3b	0.6cd	0.7c	0.7c	0.1	0.4cd	0.6b	0.7c
30-40	0.5a	0.6cd	0.6c	0.6c	0.1	0.3de	0.4bc	0.5cd
40-50	0.5a	0.6cd	0.5c	0.6c	0.1	0.2e	0.3cd	0.4de
50-60	0.6a	0.5d	0.5c	0.6c	0.1	0.2e	0.2d	0.2e

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

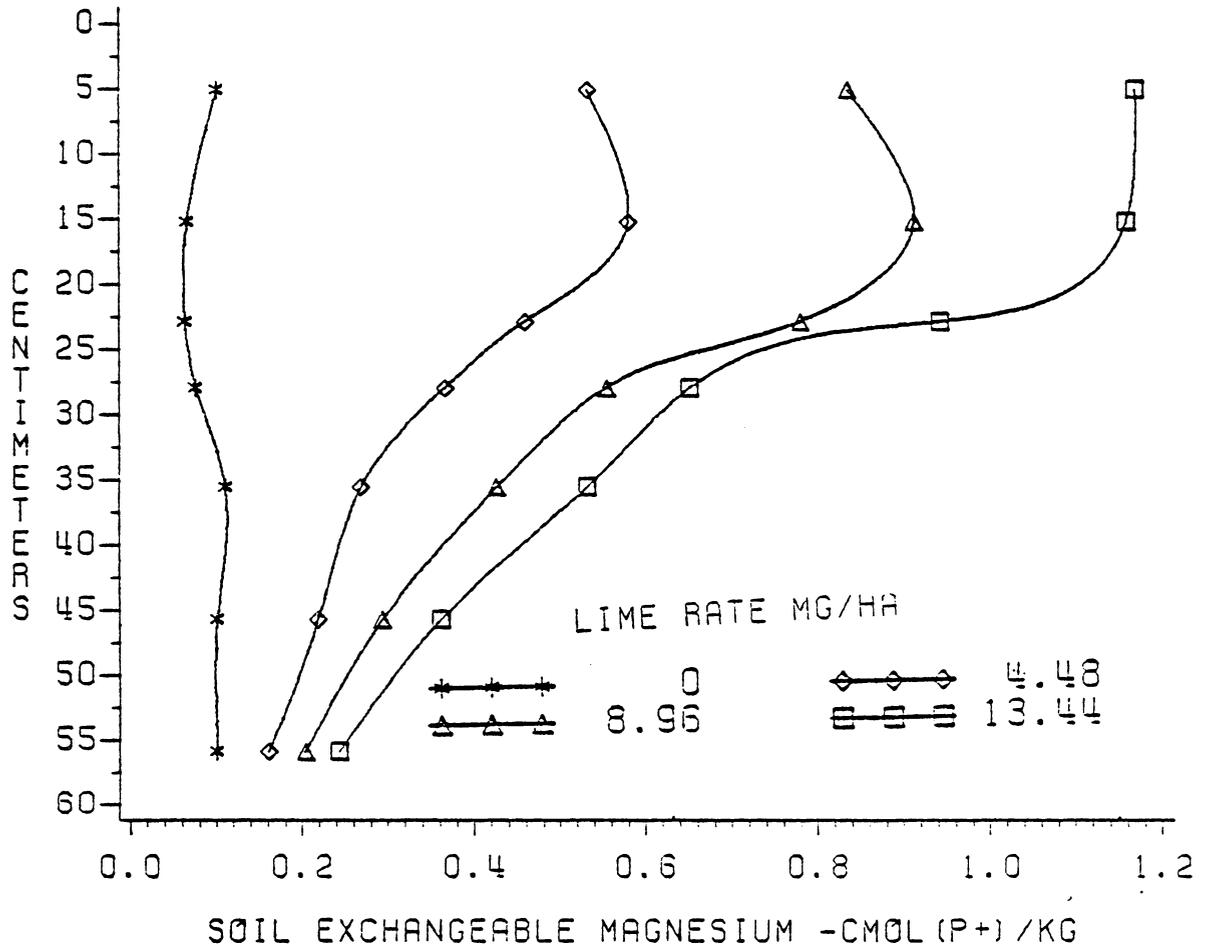


FIG. 2-EXCHANGEABLE SOIL MG FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A GOLDSBORO SANDY LOAM SOIL.

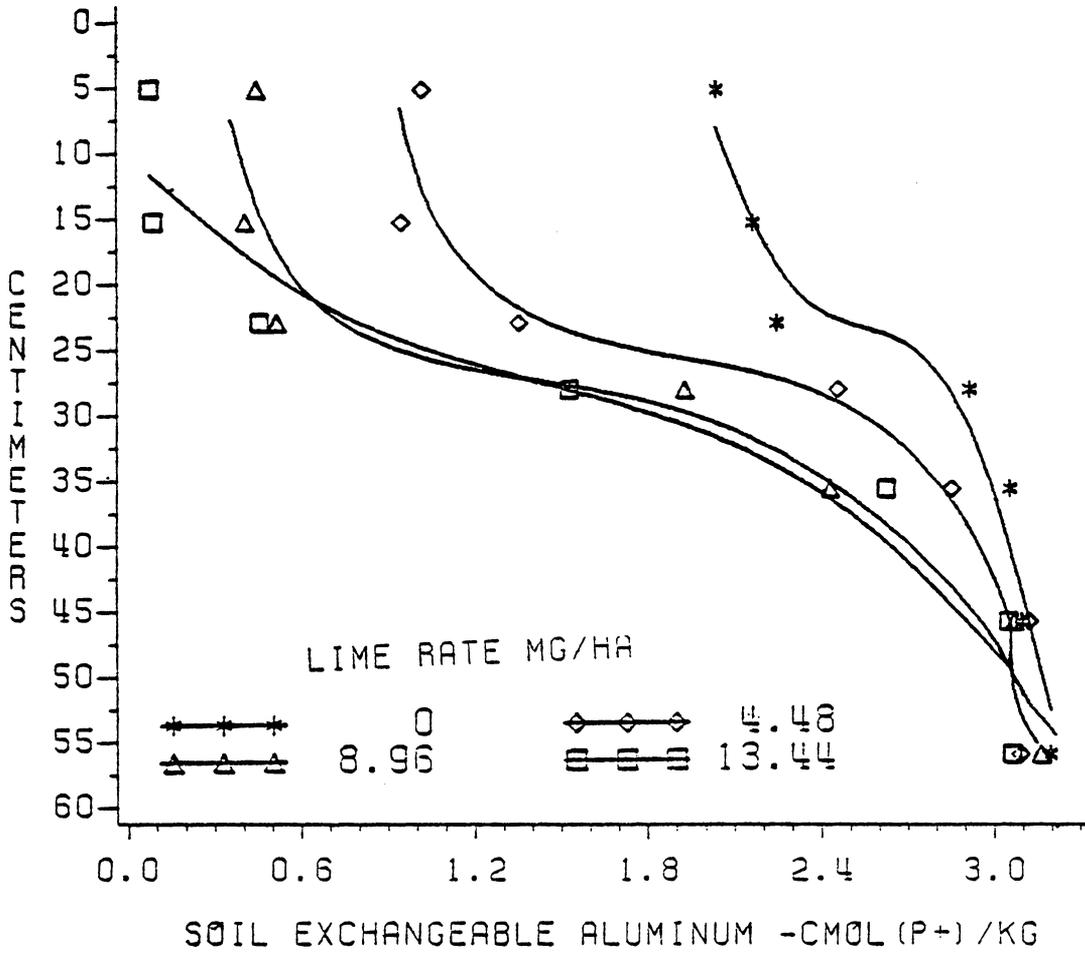


FIG. 3-EXCHANGEABLE SOIL AL FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A GOLDSBORO SANDY LOAM SOIL.

Table 3. Exchangeable Al, soil water pH, and 1 mol L⁻¹ KCl pH as a function of lime rate and depth for the Goldsboro soil.

Depth	Lime Rate Mg/ha ⁻¹											
	0	4.48	8.96	13.44	0	4.48	8.96	13.44	0	4.48	8.96	13.44
cm	Al				Water pH				KCl pH			
	cmol(p ⁺)Kg ⁻¹											
0-10	2.0a*	1.0a	0.4a	0.1a	3.8a	4.4bc	4.7b	5.1a	3.7ab	3.9b	4.1ab	4.6a
10-20	2.2a	0.9a	0.4a	0.1a	3.9ab	4.7a	5.0a	5.3a	3.6abc	4.0a	4.3a	4.6a
20-25	2.2a	1.4a	0.6a	0.5a	4.1bc	4.6b	4.9ab	5.1a	3.7a	3.9b	4.1b	4.3b
25-30	2.9b	2.5b	1.9b	1.5b	4.1bcd	4.3cd	4.5c	4.5b	3.7a	3.7c	3.8c	3.9c
30-40	3.1b	2.9bc	2.4c	2.6c	4.1bc	4.2d	4.2d	4.3b	3.6abc	3.6cd	3.7cd	3.7cd
40-50	3.1b	3.1c	3.1d	3.1c	4.2cd	4.3d	4.2d	4.2b	3.6c	3.6de	3.6d	3.6d
50-60	3.2b	3.1c	3.2d	3.1c	4.3d	4.3d	4.3cd	4.3b	3.6bc	3.5e	3.5d	3.5d

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

bited a decrease in Al levels as compared to the unlimed plots to a depth of 20-25 cm. The effect of the surface applied limestone was not detected below 20-25 cm. The higher rates of application showed decreases in Al levels from layer to layer to a depth of 30 cm (Table 3). In the 30-40 cm layer decreases in native levels of Al were measured for the 8.96 Mg ha⁻¹ rate of application. The other two amendment rates tended to decrease in Al levels as compared to the values obtained in the two deepest increments (Table 3).

Since decreases in exchangeable Al occur as hydroxyl content increases, similar trends would be expected with respect to soil reaction. This expectation was verified. Soil water pH increased with increasing lime rate in the plow layer (Figure 4). Increases in soil pH were greater than in the unlimed plots for all rates of application to the 20-25 cm depth. The two higher rates of application showed further increases in the 25-30 cm increments (Figure 4). In addition, the sample pH values at this depth tended to be greater than the native subsoil reaction (Table 3).

Plow layer salt pH values increased with an increase in lime rate (Figure 5), and as expected the values were lower than the water pH values (Table 3). This decrease was evident in the surface and subsurface layers and ranged from 0.5 to 0.8 pH units lower in the salt solution. Yuan (1963)

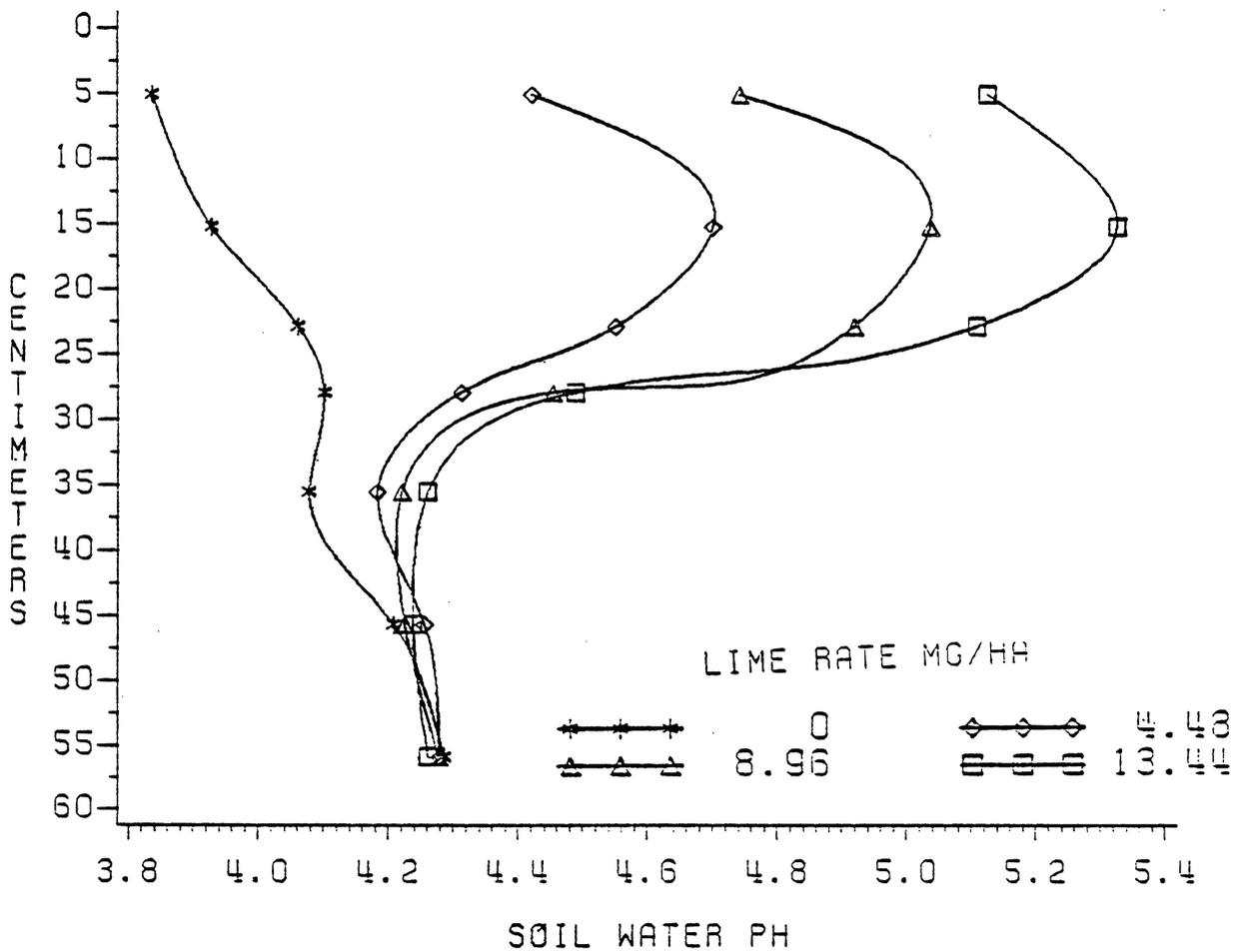


FIG. 4-SOIL WATER PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A GOLDSBORO SANDY LOAM SOIL.

observed decreases in pH values ranging from 0.6 to 1.5 units in salt solutions for 22 Florida soils. The reason for the lower values with the unbuffered salt is the result of increased hydrolysis of exchangeable Al and the junction potential.

The effect of the limestone with regard to changes in salt pH from layer to layer is evident at the 25 cm depth for all rates (Table 3). This result is similar to changes in water pH values (Table 3). Values obtained in the next 5 cm are statistically different than those pH values in the two deepest increments for all rates of application. However, those values at the 25-30 cm depth do not differ from the unlimed soil. Therefore, it cannot be concluded that the increases were due to the limestone movement.

4.1.2 Tomotley loam

Comparison of Ca levels in the Tomotley loam for each of the amendment rates and the unlimed soil are given in Figure 6. There was an increase in Ca levels with increasing lime rate within the plow layer (0-20 cm). Furthermore, adequate mixing over the period of study limited variations in Ca levels within the plow layer. Immediately below the plow layer, Ca levels decreased. This indicated more retention of Ca in the surface as a result of increased negative

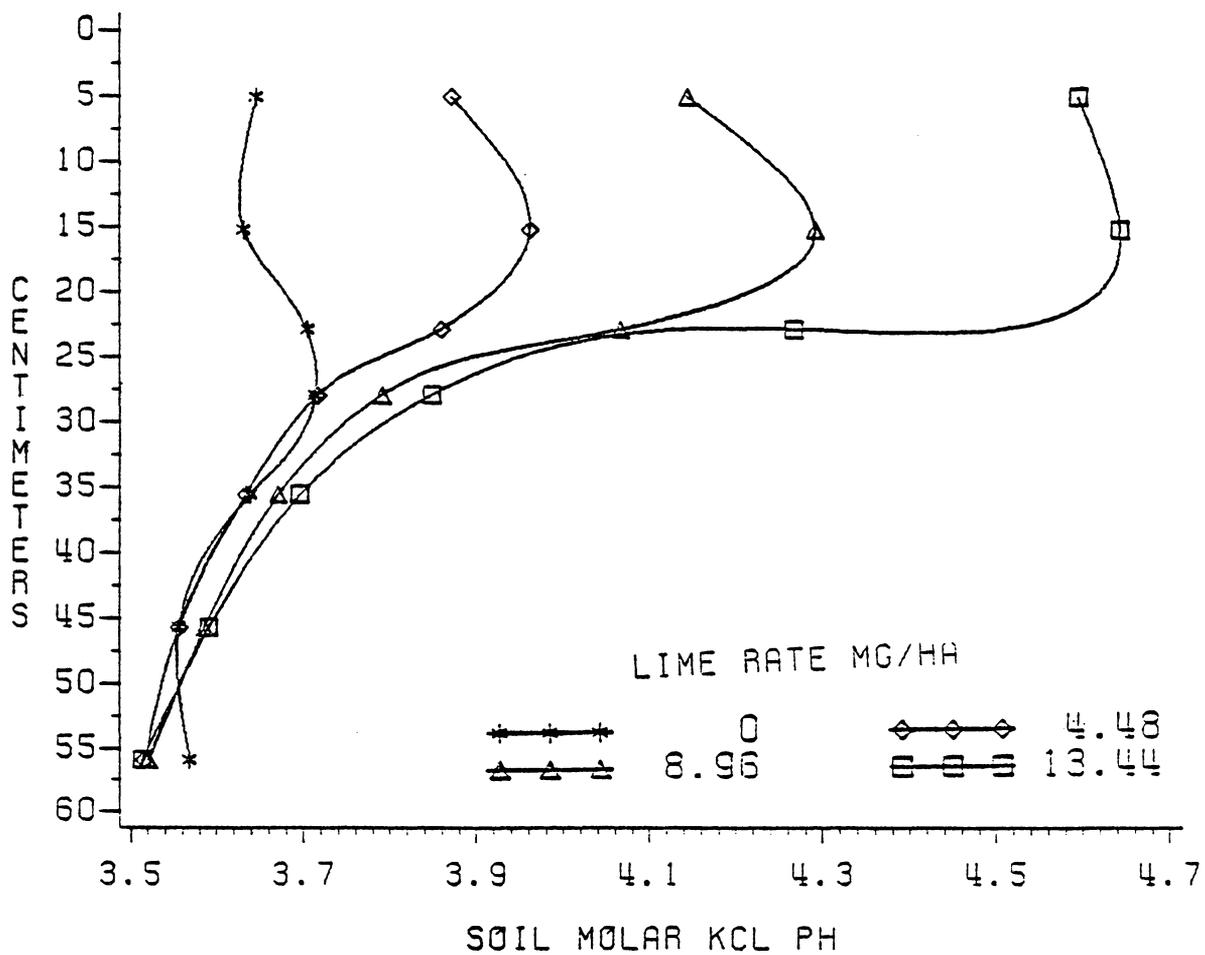


FIG. 5-SOIL MOLAR KCL PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A GOLDSBORO SANDY LOAM SOIL.

charges from liming. The observations in the surface horizon follow expected trends and correspond with the Goldsboro experiment.

Below the plow layer, Ca levels increased as compared to the unlimed plots, but no difference existed between the Ca levels for the limed plots (Figure 6). At the 20 cm depth only the 13.44 Mg ha⁻¹ plots were different from deeper subsoil samples (Table 4). The Goldsboro soil showed the above effect with the 8.96 and 13.44 Mg ha⁻¹ rates of application. This indicates that movement of Ca was more facilitated than in the Goldsboro soil.

Magnesium levels followed trends observed with the Ca (Figure 7). An increase in amount of lime increased the detected levels in the surface. These same trends existed in the Goldsboro soil; however, the absolute amounts of Mg were lower in the Goldsboro than in the Tomotley (Figures 2 and 7).

Below the plow layer, changes in Mg levels did not parallel those found in the Goldsboro soil. The Tomotley soil had increases in Mg levels as compared to the unlimed plots for all rates of application to a depth of 40 cm (Figure 7). Changes in Mg from increment to increment for a given lime rate were highest in the surface and declined thereafter. With increasing lime rates, i.e. 4.48, 8.96, and 13.44 Mg

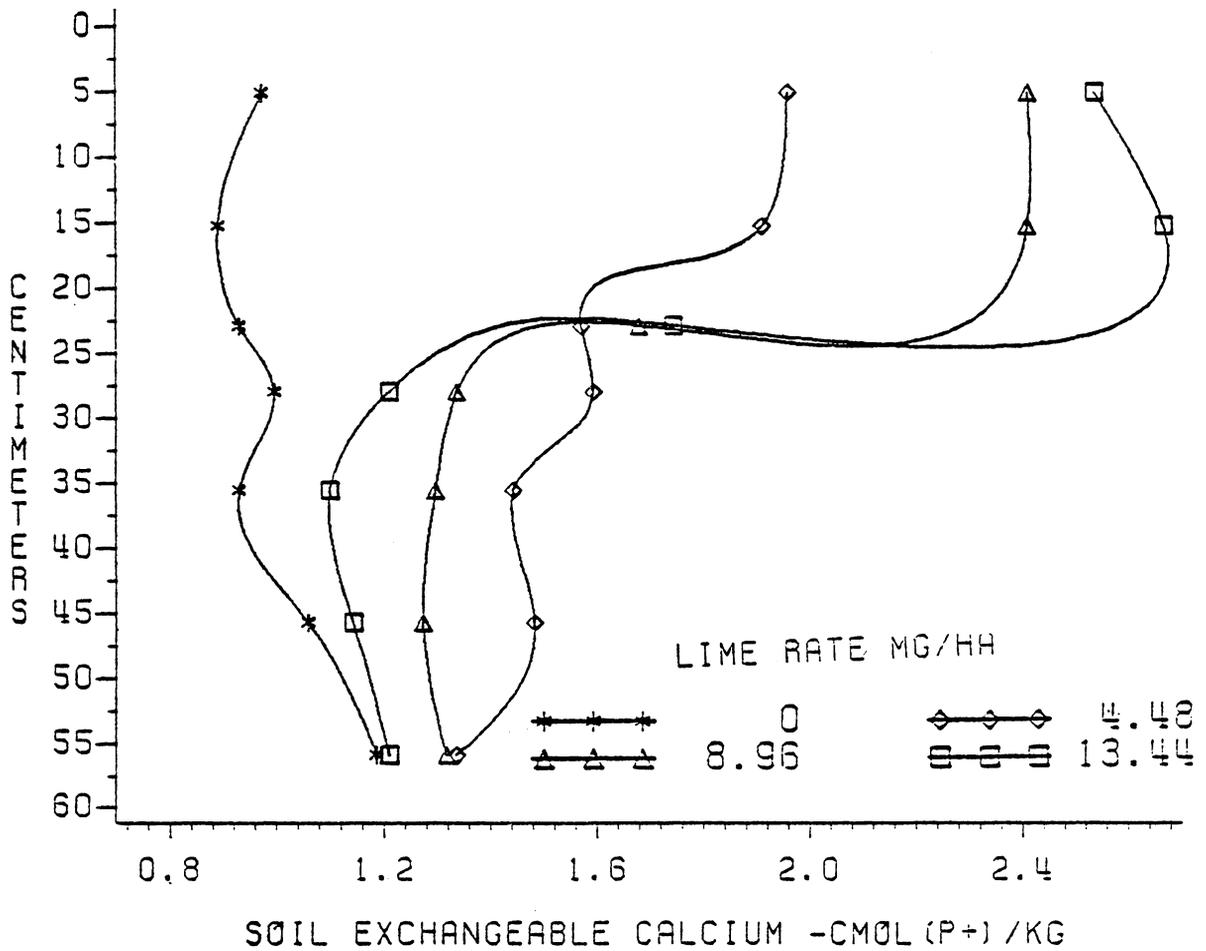


FIG. 6-EXCHANGEABLE SOIL CA FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A TOMOTLEY LOAM SOIL.

Table 4. Exchangeable Ca and Mg as a function of lime rate and depth for the Tomotley soil.

Depth	Lime Rate Mg/ha ⁻¹							
	0	4.48	8.96	13.44	0	4.48	8.96	13.44
cm	Ca				Mg			
	cmol(p ⁺)Kg ⁻¹							
0-10	1.0 NS	2.0a*	2.4a	2.5a	0.4ab	1.0a	1.4a	1.7a
10-20	0.9	1.9ab	2.4a	2.7a	0.3a	0.9ab	1.4a	1.6a
20-25	0.9	1.6abc	1.7b	1.7b	0.3a	0.8bc	1.1b	1.1b
25-30	1.0	1.6abc	1.3b	1.2c	0.4ab	0.7cd	0.8c	0.8c
30-40	0.9	1.4c	1.3b	1.1c	0.4ab	0.6d	0.7c	0.6d
40-50	1.1	1.5bc	1.3b	1.1c	0.5bc	0.7d	0.7c	0.6d
50-60	1.2	1.3c	1.3b	1.2c	0.6c	0.7cd	0.7c	0.6d

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

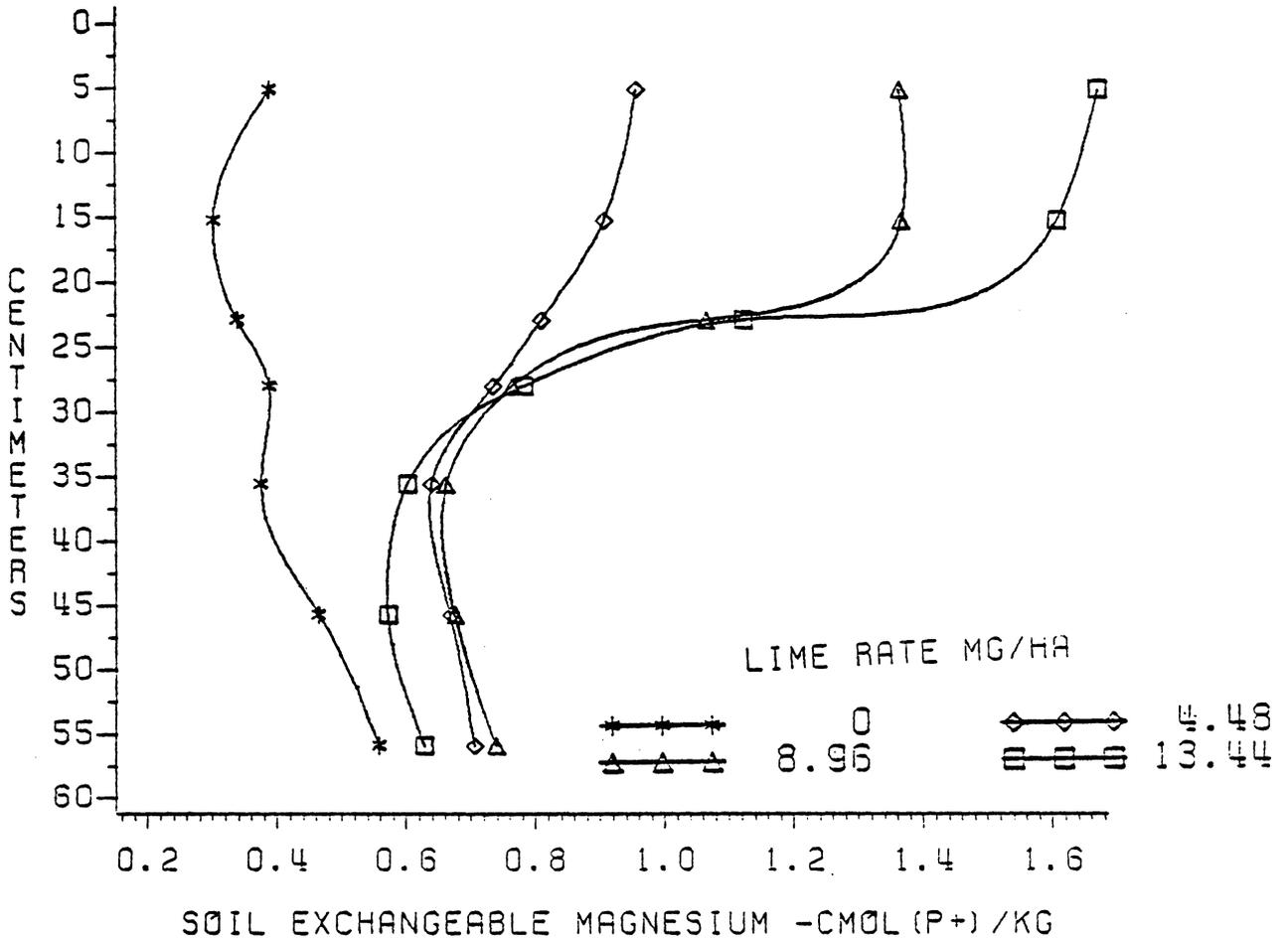


FIG. 7-EXCHANGEABLE SOIL MG FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A TOMOTLEY LOAM SOIL.

ha⁻¹, there was no variation from layer to layer beyond the 25, 25, and 30 cm depths, respectively (Table 4). As exhibited in the Goldsboro soil, movement of Mg increased with increasing lime rate and to a greater depth than Ca. However, movement of both cations was greater in the Goldsboro soil than in the Tomotley soil.

Aluminum levels in the surface decreased drastically with the addition of any rate of limestone under the experimental conditions. Moreover, application of 4.48 Mg ha⁻¹ was sufficient to reduce Al to barely detectable, i.e. 0.1 cmol(p⁺)kg⁻¹ levels (Table 5). For the highest rate of application, Al was not detected at a depth of 25 cm. Such reductions in Al outside of the plow layer did not occur on the Goldsboro soil. This trend was evident for the 8.96 Mg ha⁻¹ lime rate although not statistically different than the untreated soil. Effects of surface applied limestone were not observed below 30 cm on any of the treated soils as compared to the unlimed plots (Figure 8). Considering each individual lime rate, decreases in Al from layer to layer were evident to a depth of 40, 30, and 40 cm for the respective lime rates in ascending order (Table 5). Below these increments, subsoil Al levels existed for all rates of application.

Table 5. Exchangeable Al, soil water pH, and 1 mol L⁻¹ KCl pH as a function of lime rate and depth for the Tomotley soil.

Depth	Lime Rate Mg/ha ⁻¹											
	0	4.48	8.96	13.44	0	4.48	8.96	13.44	0	4.48	8.96	13.44
cm	Al				Water pH				KCl pH			
	cmol(p ⁺)Kg ⁻¹											
0-10	1.2 a	0.1a	0.0a	0.0a	4.9 NS	5.0cd	5.3b	5.6abc	3.7	4.4a	5.0b	5.3b
10-20	1.3ab	0.1a	0.0a	0.0a	4.9	5.3a	5.6a	6.0a	3.6	4.4a	5.1a	5.6a
20-25	2.0bc	0.8b	0.8b	0.2a	4.9	5.3a	5.6a	5.9ab	3.6	4.0b	4.0c	4.2c
25-30	2.4cd	1.5c	2.0c	1.8b	4.9	5.1ab	5.3b	5.5bcd	3.6	3.8c	3.7d	3.7d
30-40	2.8de	2.2d	2.5cd	2.1b	4.8	5.0bc	5.1c	5.2cde	3.6	3.7cd	3.7de	3.7d
40-50	3.0de	2.9e	3.1de	2.6c	4.8	4.9cd	5.0cd	5.1de	3.6	3.6d	3.6e	3.6d
50-60	3.4e	2.9e	3.3e	2.8c	4.7	4.8d	4.9d	5.0e	3.6	3.6d	3.6e	3.6d

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

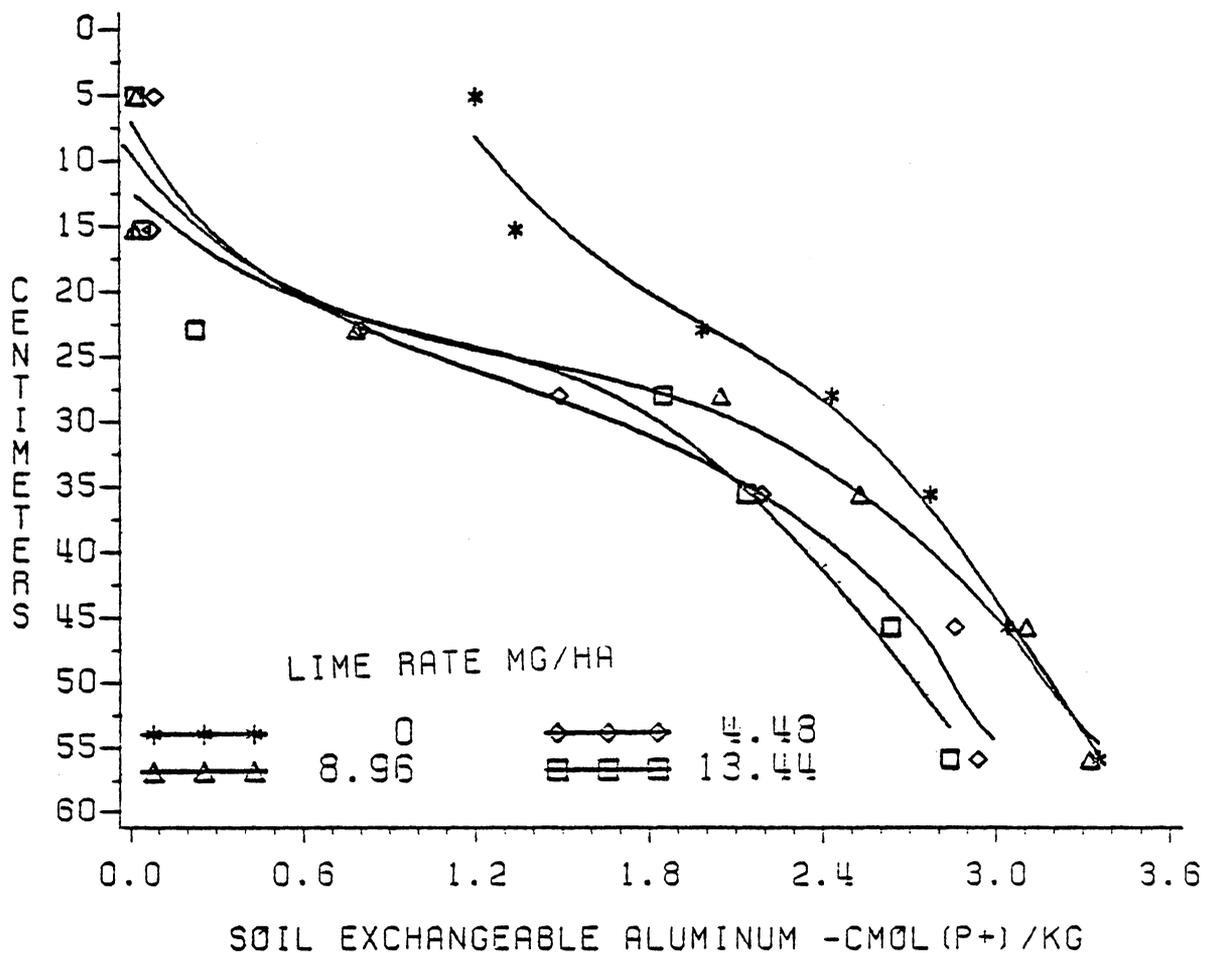


FIG. 8-EXCHANGEABLE SOIL AL FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A TOMOTLEY LOAM SOIL.

Increases in water pH levels occurred with increasing lime rate to the 25 cm depth as compared to the unlimed plots (Figure 9). The two higher rates of application showed further increases in the 25-30 cm increments. These findings generally paralleled decreases in Al (Figure 8). Samples at the 25-30 cm depths had greater soil pH values than the subsoil (Table 5). Samples below this layer for a given lime rate may consistently differ, but by little magnitude.

Dramatic increases occurred with increasing lime rate to a depth of 25 cm for the salt pH levels as compared to the unlimed sample (Figure 10). The following 5 cm had salt pH values slightly greater than the unlimed soil. Values below 30 cm for a given lime rate did not differ from layer to layer or with the unlimed soil. Results for Al and the two pH determinations parallel trends in the Goldsboro soil (Tables 3 and 5).

4.1.3 Emporia loamy sand

Calcium levels for the different limestone rates increased as compared to the unlimed plots within the plow layer (0-20 cm) (Figure 11). However, no difference existed between Ca levels for soils that received limestone amendments. No change existed in Ca levels for a given lime rate

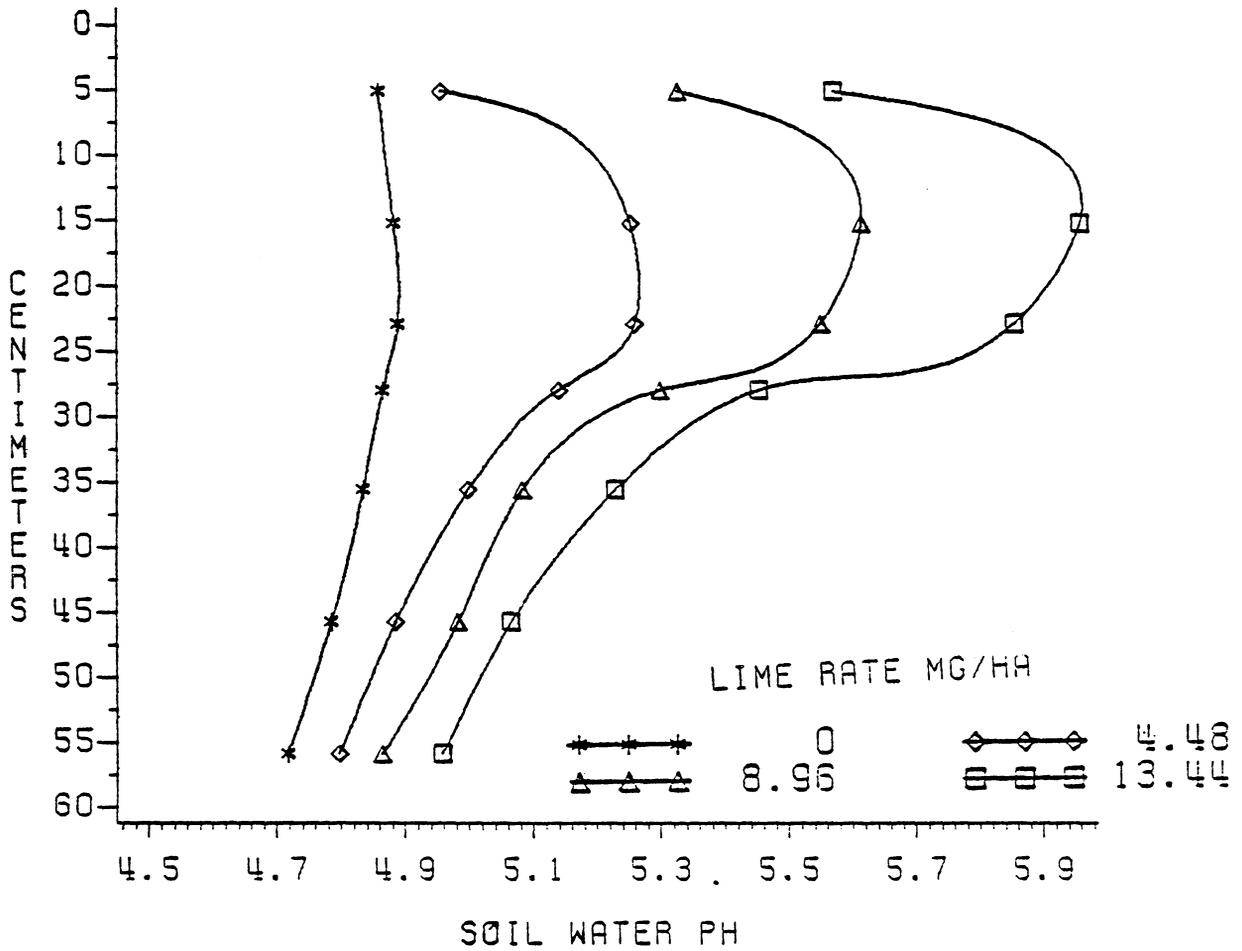


FIG. 9-SOIL WATER PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A TOMOTLEY LOAM SOIL.

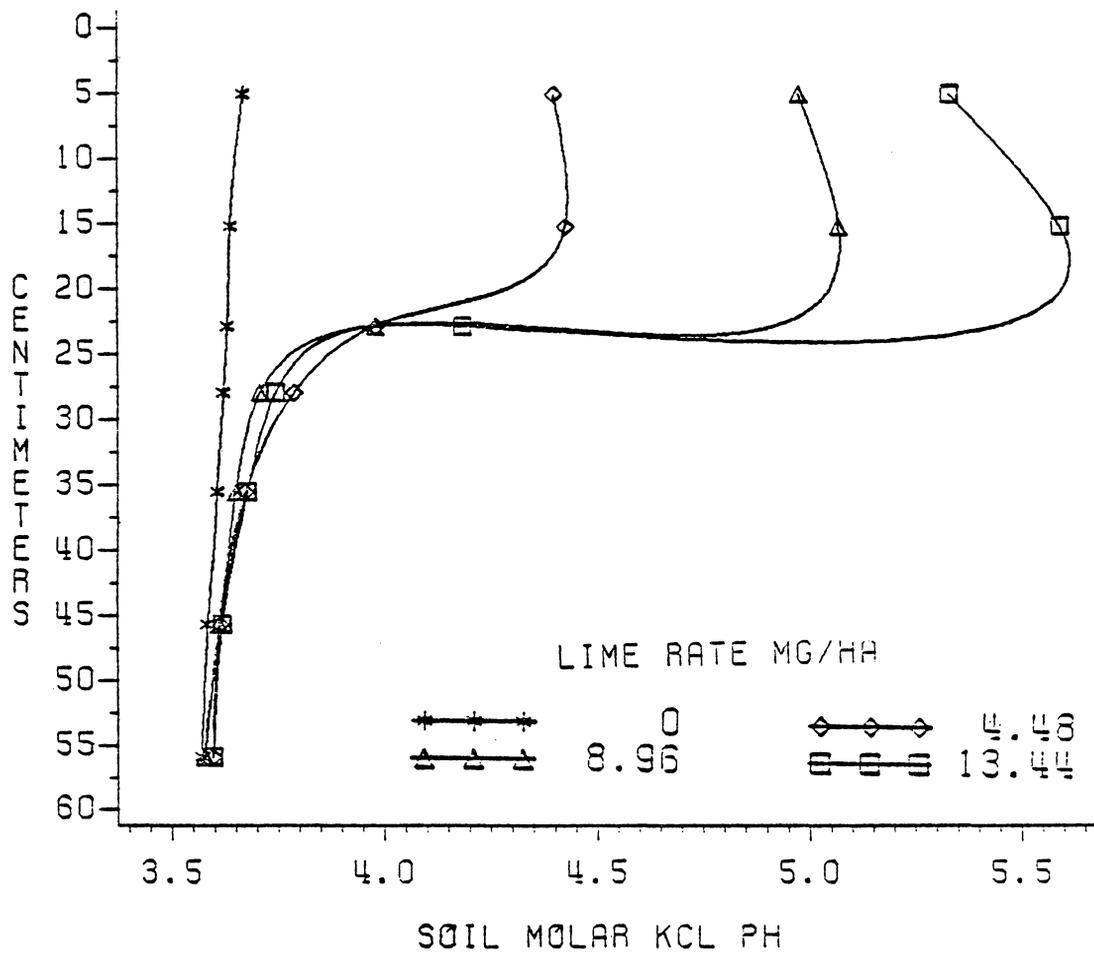


FIG. 10-SOIL MOLAR KCL PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A TOMOTLEY LOAM SOIL.

below the plow layer as compared to the unlimed soils. There does appear to be a trend towards retention of Ca in the plow layer as was exhibited in the previously discussed soils.

Below the plow layer, no difference in Ca levels existed either between the unlimed and the treated soil or between any of the three lime rates (Figure 11). For a given lime rate, no difference occurred between any depth increment and its adjacent layer whether above or below it (Table 6). These findings indicate that the Ca moved through the profile for the depths analyzed. This is considerably more movement than was observed in the Goldsboro or Tomotley soils.

Magnesium levels for soils receiving limestone additions compared to untreated soil levels are given in Figure 12. An increase in Mg as compared to the unlimed soil occurred to the 40 cm depth for all lime rates. This same result was observed in the Tomotley soil for all treatments. As detected with Ca in this Emporia soil, there were no increases in detected levels of Mg between lime rates in the plow layer or below it (Table 6).

Changes in Mg levels from increment to increment for a given lime rate did not differ below the plow layer (Table 6). The same result was present for Ca on this soil, but

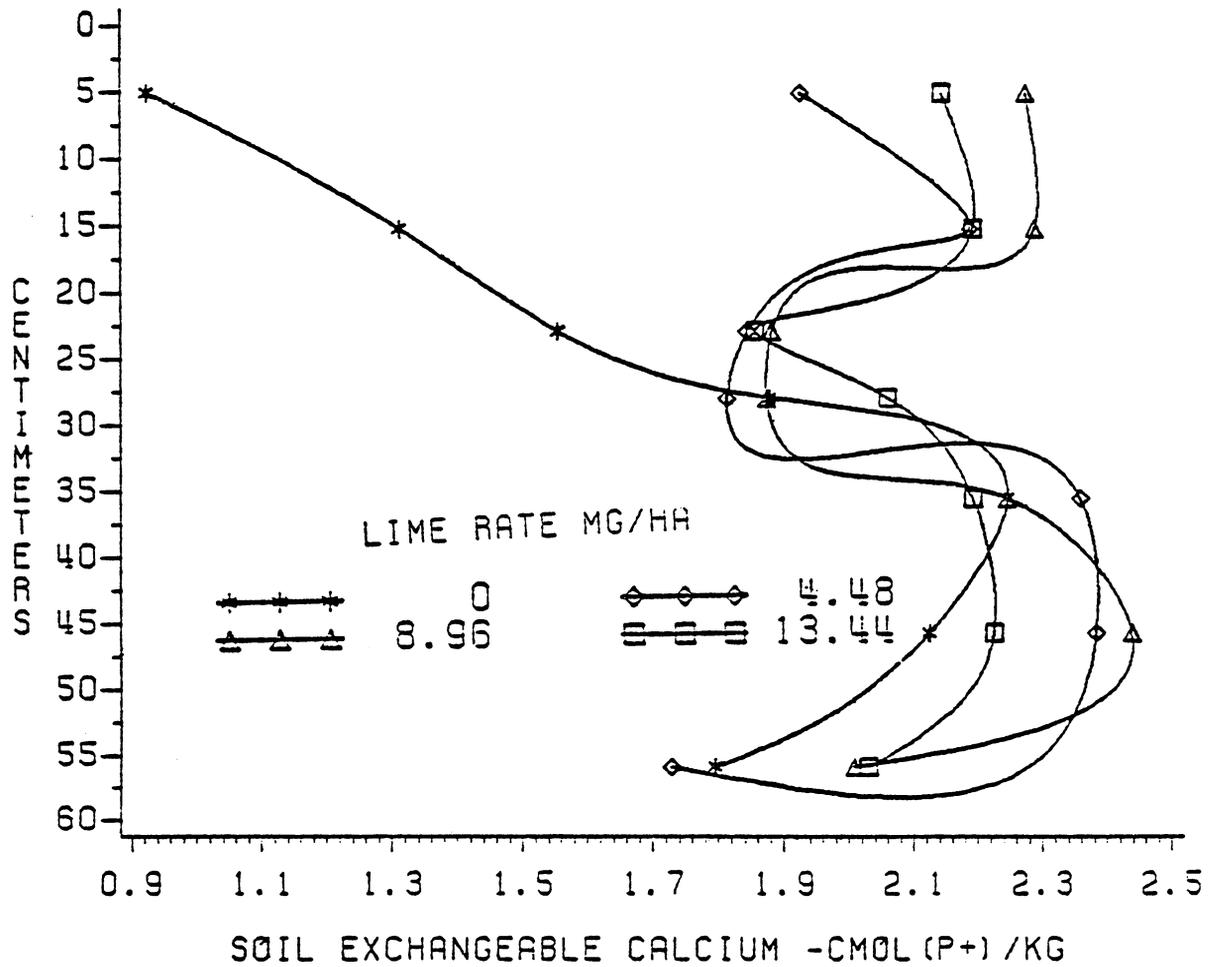


FIG. 11-EXCHANGEABLE SOIL CA FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR AN EMPORIA LOAMY SAND SOIL.

Table 6. Exchangeable Ca and Mg as a function of lime rate and depth for the Emporia soil.

Depth	Lime Rate Mg/ha ⁻¹							
	0	4.48	8.96	13.44	0	4.48	8.96	13.44
cm	Ca				Mg			
	cmol(p ⁺)Kg ⁻¹							
0-10	0.9a*	1.9 NS	2.3	2.1	0.3ab	1.1	1.5a	1.3
10-20	1.3ab	2.2	2.3	2.2	0.2a	1.2	1.3ab	1.2
20-25	1.6abc	1.8	1.9	1.9	0.3ab	1.0	1.0b	1.0
25-30	1.9bc	1.8	1.9	2.1	0.4ab	0.9	1.0b	1.0
30-40	2.2c	2.4	2.2	2.2	0.6bc	1.0	1.1b	1.1
40-50	2.1c	2.4	2.4	2.2	0.9c	1.0	1.1b	1.0
50-60	1.8bc	1.7	2.0	2.0	0.9c	1.0	1.1b	1.2

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

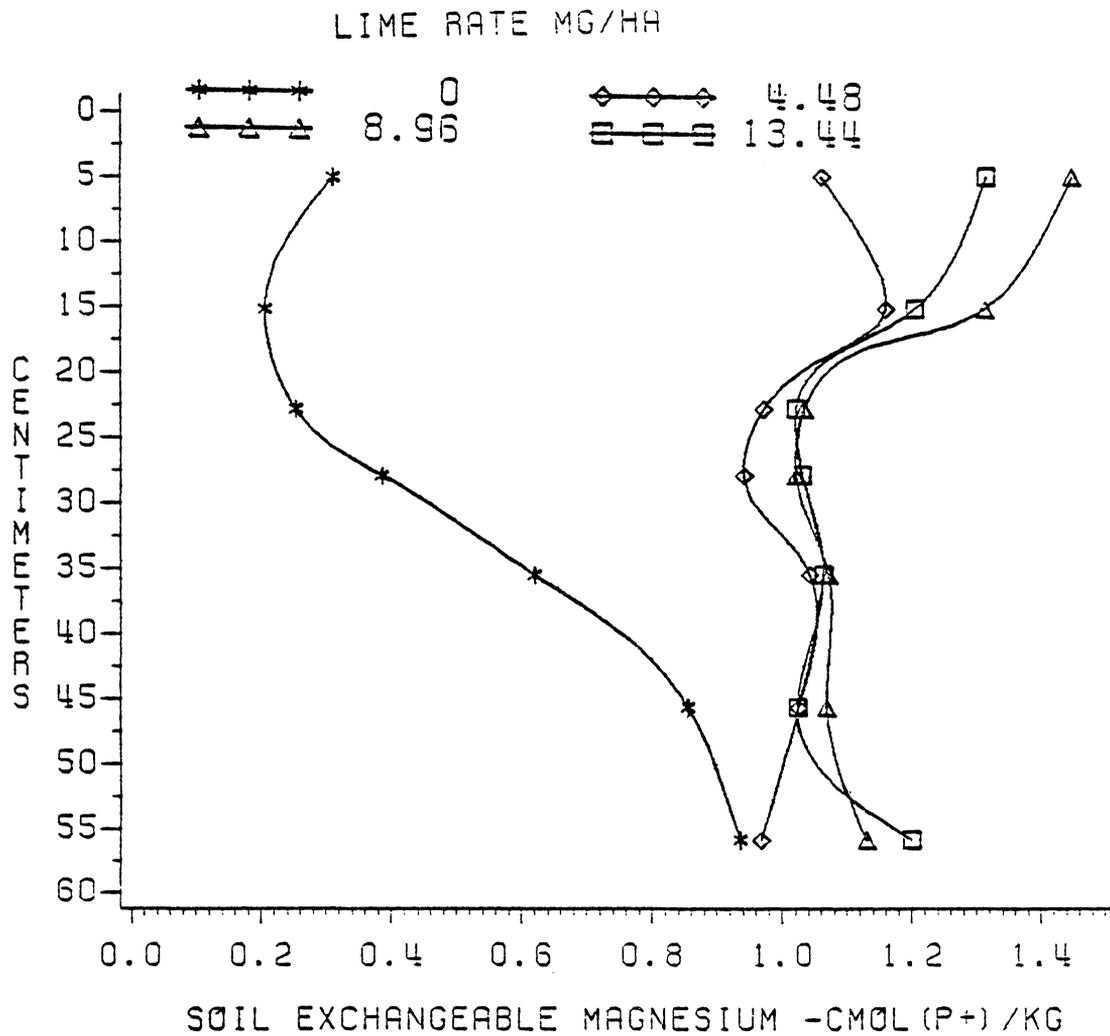


FIG. 12-EXCHANGEABLE SOIL MG FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR AN EMPORIA LOAMY SAND SOIL.

the finding did not exist on the other two Coastal Plain soils.

Results indicate that Mg moved rapidly through the profile for the depths examined. These findings illustrate that cations from the dolomitic limestone moved more rapidly from the surface and into the subsoil on the coarser textured soils, i.e. Emporia and Goldsboro, than the loam soil, i.e. Tomotley. In addition to textural differences with these soils, mineralogical properties of the clay-sized fraction support these findings. The Goldsboro and Emporia soils have predominantly chloritized vermiculite and quartz in the clay-sized fraction, while the Tomotley is predominantly chloritized vermiculite and kaolinite (L. W. Zelazny, personal communication). The presence of kaolinite as opposed to quartz would favor increased exchange capacity and cation retention which these data illustrate.

The Emporia soil has natively low levels of Al as compared to the other two soils (Figures 3, 8, and 13). As a result, small additions of limestone rapidly neutralize Al that is present. For a given lime rate, there was a decrease from the Al levels in the unlimed plots to a depth of 40 cm. Decreases greater than $0.3 \text{ cmol}(p^+)\text{kg}^{-1}$ did not occur (Table 7). In the following 10 cm, Al levels decreased as compared to the untreated soil, but were not statistical-

ly different. Reductions in Al to this depth, as compared to the unlimed soil, did not occur on either of the other soils.

The decreases in Al from layer to layer were present for all lime rates to a depth of 40 cm (Table 7). Below this, Al levels were much higher. Aluminum levels in the 40-50 cm increment were different from the values in the above increments for all lime rates. The 50-60 cm increment differed from the other layers for the two lower rates of application. The increasing trend was also present for the highest rate of application. These findings indicate neutralization of Al to the 50 cm depth.

Increases in soil water pH values were obtained for all rates of application as compared to the unlimed soils to a depth of 30 cm (Figure 14). The increases were most dramatic in the plow layer and decreased readily below this layer. Although the effect did not necessarily increase with increasing lime rate, increases in soil pH as compared to subsoil levels were evident at depths of 50 cm (Table 7). The 13.44 Mg ha⁻¹ sample at this depth did not differ from either layer above or below it. This result was present despite a decrease in 0.6 pH units from the layer above which was greater than the other rates of application. This finding was probably a result of soil heterogeneity that could be

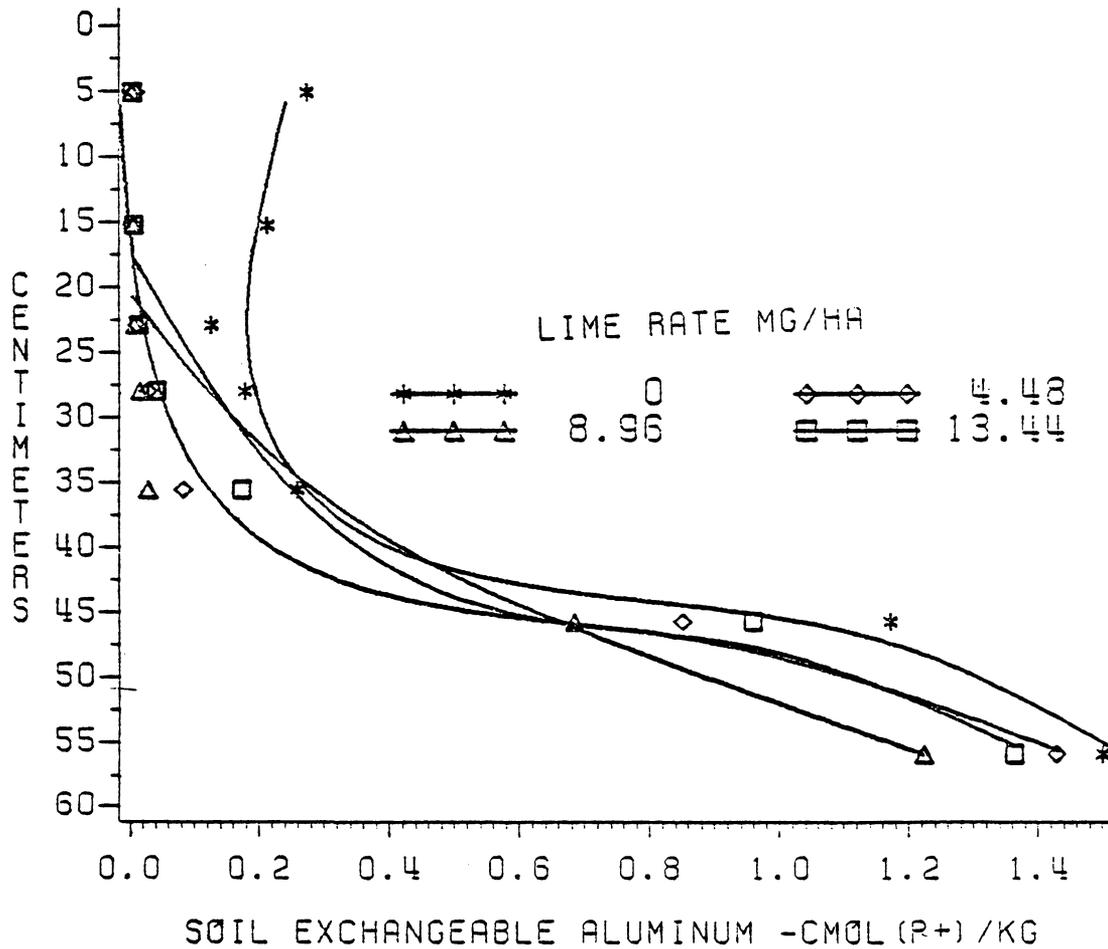


FIG. 13-EXCHANGEABLE SOIL AL FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR AN EMPORIA LOAMY SAND SOIL.

Table 7. Exchangeable Al, soil water pH, and 1 mol L⁻¹ KCl pH as a function of lime rate and depth for the Emporia soil.

Depth	Lime Rate Mg/ha ⁻¹											
	0	4.48	8.96	13.44	0	4.48	8.96	13.44	0	4.48	8.96	13.44
cm	Al cmol(p ⁺)Kg ⁻¹				Water pH				KCl pH			
0-10	0.3a*	0.0a	0.0a	0.0a	5.1bc	6.2ab	6.6a	6.5a	4.4a	5.3b	5.9a	5.7a
10-20	0.2a	0.0a	0.0a	0.0a	5.3ab	6.5a	6.7a	6.6a	4.5a	5.6a	5.9a	5.8a
20-25	0.1a	0.0a	0.0a	0.0b	5.5a	6.2ab	6.4ab	6.3ab	4.5a	5.2b	5.4b	5.3ab
25-30	0.2a	0.0a	0.0a	0.0b	5.5a	6.0bc	6.3b	6.1ab	4.4a	4.8c	5.1c	4.9bc
30-40	0.3a	0.1a	0.0a	0.2b	5.3ab	5.7c	5.9c	5.7bc	4.3a	4.6c	4.8d	4.5cd
40-50	1.2b	0.9b	0.7b	1.0c	4.9cd	5.1d	5.3d	5.1cd	3.9a	4.2d	4.1e	3.9de
50-60	1.5b	1.4c	*1.2c	1.4c	4.7d	4.7e	4.9e	4.8d	3.8b	3.8e	3.9f	3.7e

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

encountered at these depths. Neutralization at this depth for all rates of application was coupled with decreases in Al levels (Table 7). Changes in pH levels to this depth were not observed in the other two soils.

Salt pH levels increased as compared to the unlimed soils at all rates of application in the plow layer (Figure 15). Below the plow layer the effects decreased rapidly, but levels different than the unlimed plots were present at 30 cm. This finding corresponds directly with results for water pH (Table 7). Differences for a given lime rate were observed from subsoil pH values to a depth of 50 cm. The 13.44 Mg ha⁻¹ sample, once again, did not differ from either layer above or below it. Relative changes in salt pH values to this depth were not observed on the other two soils of the Coastal Plain.

4.2 PIEDMONT REGION

4.2.1 Masada loam

Alterations in Ca levels for the limed plots as compared to the unlimed plots for the Masada loam soil are shown in Figure 16. Within the plow layer (0-20 cm), there was an increase in Ca levels with increasing lime rate. Furthermore, within the plow layer, limited variations for determined values illustrate adequate mixing. As seen in the

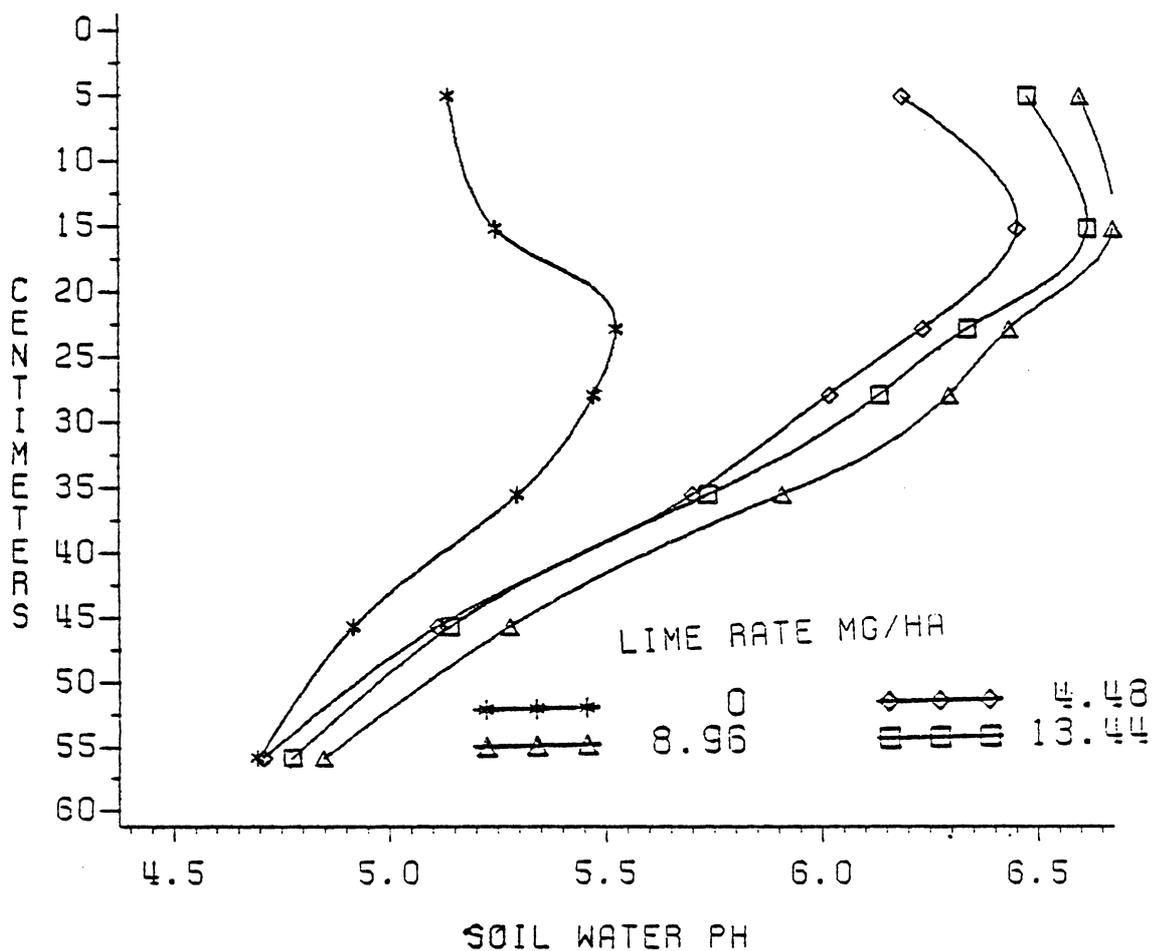


FIG. 14-SOIL WATER PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR AN EMPORIA LOAMY SAND SOIL.

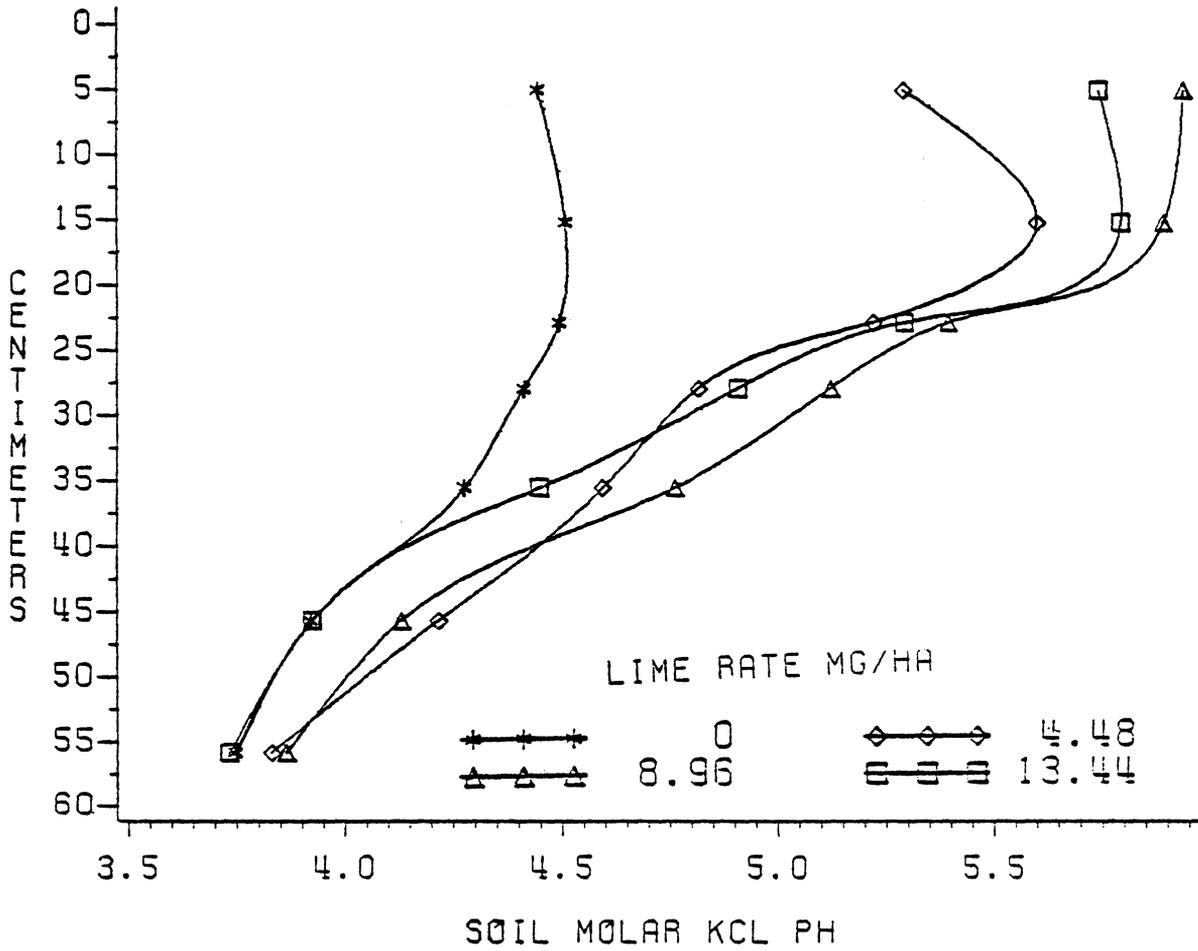


FIG. 15-SOIL MOLAR KCL PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR AN EMPORIA LOAMY SAND SOIL.

Coastal Plain soils, retention of Ca occurred in the plow layer (Figures 1,6,11, and 16). In the 5 cm below the plow layer, the trend for increasing Ca levels as compared to the unlimed soil was present. Only the 17.92 Mg ha⁻¹ sample contained increases in Ca large enough to differ from the untreated soil. The 25-30 cm increment also exhibited the same trend, although increases were not sufficient to differ from the native soil.

With regard to movement within a given rate, there was no difference between Ca levels in the surface and Ca levels in the subsoil for the 4.48 Mg ha⁻¹ rate of application (Table 8). A possible explanation for this result would include two considerations. Initially, addition of low levels of lime, i.e. 4.48 Mg ha⁻¹, increases the CEC by increasing the pH dependent charges. Since Ca can be held by these sites, expected increases as compared to the unlimed soil would be expected. Any Ca that was not retained by these sites and was in solution could move further into the profile or be utilized by plants. Since no differences existed between the surface and subsoil layers, any Ca not on the pH dependent sites may have been utilized by the plant.

The 8.96 Mg ha⁻¹ rate of application had increases in Ca levels at a depth of 25-30 cm as compared to the subsoil. Increases in Ca levels as compared to the subsoil were ob-

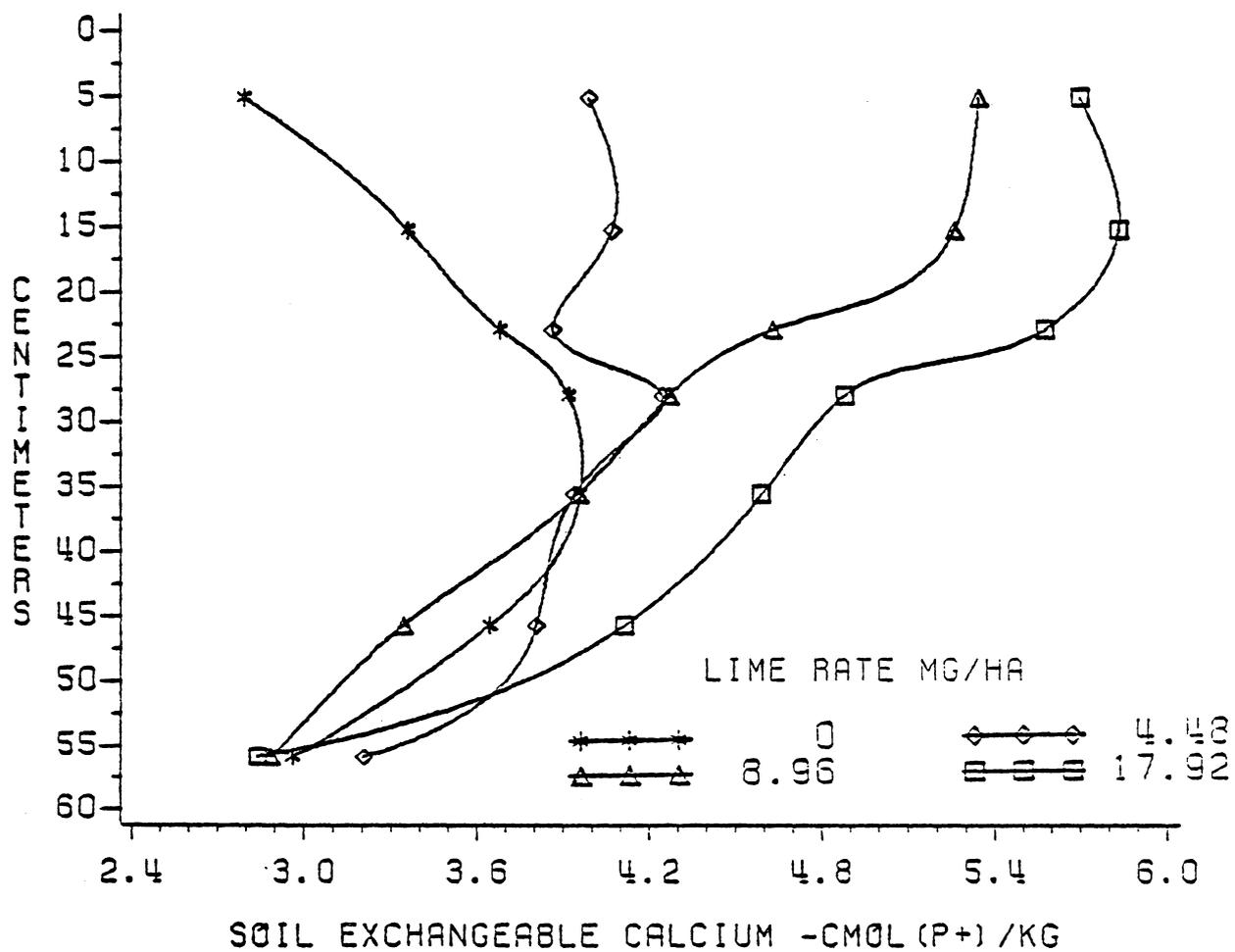


FIG. 16-EXCHANGEABLE SOIL CA FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A MASADA LOAM SOIL.

served to the 30-40 cm increment for the highest rate of application. Results indicate that movement of Ca occurred with the two higher rates of application from layer to layer (Table 8), but in no case was the movement large enough to be different than the unlimed soil at the 30-40 cm depth (Figure 16).

As observed with Ca, Mg increased with increasing lime rate in the plow layer as compared to the unlimed soils (Figure 17). Increases in Mg levels with increasing lime rate were different than the unlimed soils to a depth of 30 cm. The highest rate of application exhibited an increase in Mg levels as compared to the unlimed soil to the 40 cm depth.

The 4.48 Mg ha⁻¹ lime rate had no differences in Mg levels among the seven increments analyzed (Table 8). The 8.96 Mg ha⁻¹ lime rate showed decreases in Mg levels as depth increased to a depth of 25 cm. The following 5 cm exhibited a trend of increase in Mg, but did not differ statistically from the subsoil. The highest rate of application showed changes from increment to increment to a depth of 30 cm. The following 20 cm showed evidence of differences as compared to the subsoil. These findings parallel Ca for this soil (Table 8).

Table 8. Exchangeable Ca and Mg as a function of lime rate and depth for the Masada soil.

Depth	Lime Rate Mg/ha ⁻¹							
	0	4.48	8.96	17.92	0	4.48	8.96	17.92
	Ca				Mg			
	cmol (p ⁺) Kg ⁻¹							
0-10	2.8 NS	4.0	5.3a*	5.7a	0.8a	2.0	3.4a	3.8a
10-20	3.4	4.1	5.3ab	5.8a	0.9ab	2.1	3.3a	4.0a
20-25	3.7	3.9	4.6abc	5.6ab	1.3abc	2.3	3.0a	4.1a
25-30	3.9	4.2	4.3abc	4.9abc	1.5abc	2.5	2.7ab	3.6ab
30-40	4.0	3.9	4.0bcd	4.6bc	1.6bc	2.0	2.1b	3.1bc
40-50	3.6	3.8	3.3cd	4.1c	1.8c	2.0	2.0b	2.6cd
50-60	3.0	3.2	2.9d	2.8d	1.9c	2.1	2.0b	2.3d

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

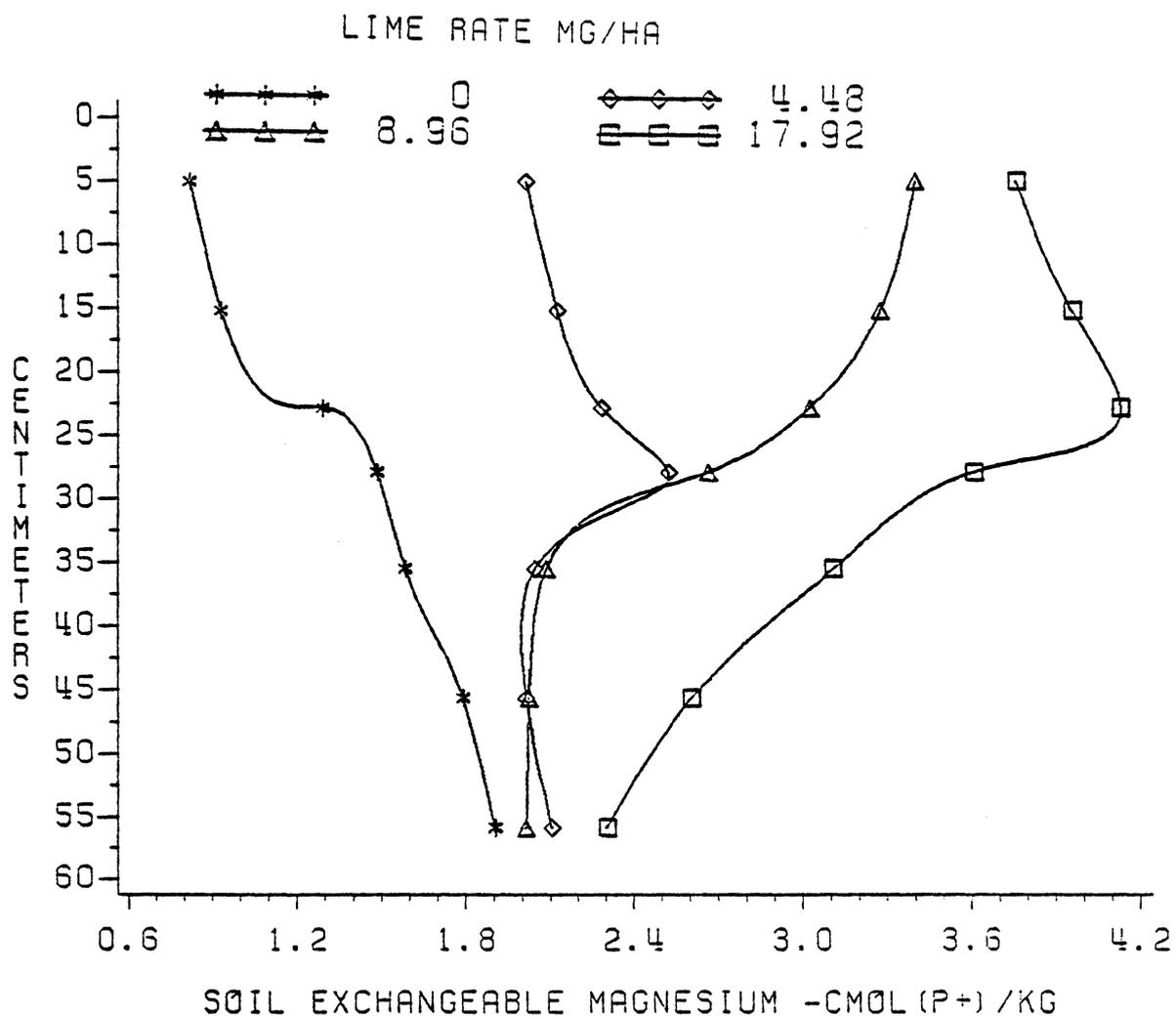


FIG. 17-EXCHANGEABLE SOIL MG FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A MASADA LOAM SOIL.

Aluminum levels decreased rapidly in the surface as compared to the unlimed soil with the addition of any of the rates of limestone (Figure 18). This decrease was to the point where Al was barely detectable in the surface. A trend for reduction of Al levels at the highest rate of application existed at the 20-25 cm depth (Table 9). This value of $0.4 \text{ cmol(p}^+)\text{kg}^{-1}$ was not statistically different from the unlimed soil. These findings are similar to the Tomotley loam where reduction of Al was large in the surface layer, but neutralization was not observed below the plow layer (Tables 5 and 9).

The marked increase in Al levels in the subsoil must be considered when discussing these data (Table 9). The increase occurs starting at the 25-30 cm increment. There is another large increase in Al levels below 40 cm. At depths greater than 40 cm, no value determined was different than the unlimed sample or the other sample within that lime rate. At depths above 40 cm, none of the samples for any given lime rate differed from the unlimed sample except in the plow layer. For the 20-40 cm layer only the highest rate of application showed any trend towards reduction of Al in comparison with the increment above or below it. This occurred at the 20-25 cm depth as mentioned previously.

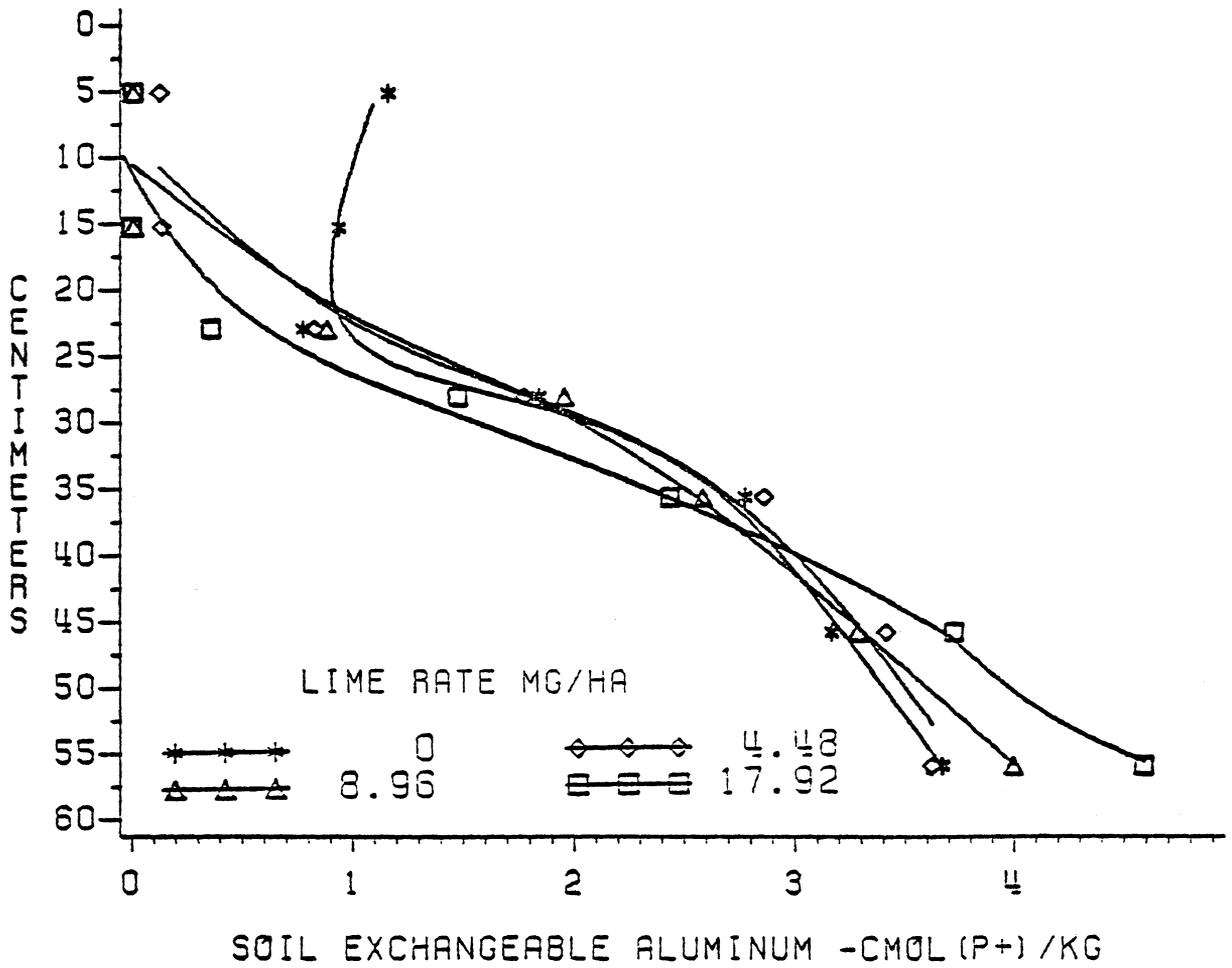


FIG. 18-EXCHANGERABLE SOIL AL FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A MASADA LOAM SOIL.

Table 9. Exchangeable Al, soil water pH, and 1 mol L⁻¹ KCl pH as a function of lime rate and depth for the Masada loam.

Depth	Lime Rate Mg/ha ⁻¹											
	0	4.48	8.96	17.92	0	4.48	8.96	17.92	0	4.48	8.96	17.92
	Al				Water pH				KCl pH			
cm	cmol(p ⁺)Kg ⁻¹											
0-10	1.2a*	0.1a	0.0a	0.0a	4.6 NS	5.3ab	5.9a	6.4ab	4.0a	4.5a	5.1a	5.6a
10-20	0.9a	0.1a	0.0a	0.0a	4.7	5.3a	6.0a	6.7a	4.1a	4.5a	5.0a	5.8a
20-25	0.8a	0.8a	0.9b	0.4a	4.7	5.1ab	5.2b	6.1b	4.0a	4.2b	4.1b	4.8b
25-30	1.8b	1.8b	2.0c	1.5b	4.7	4.9bc	4.9bc	5.3c	3.8b	3.9bc	3.9bc	4.2c
30-40	2.8c	2.9c	2.6cd	2.4c	4.5	4.6c	4.7cd	4.8d	3.7bc	3.7c	3.7c	3.8cd
40-50	3.2cd	3.4c	3.3de	3.7d	4.4	4.5c	4.5d	4.6d	3.7c	3.7c	3.7c	3.6d
50-60	3.7d	3.6c	4.0e	4.6d	4.4	4.4c	4.4d	4.4d	3.6c	3.7c	3.6c	3.6d

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

Water pH levels increased to the 30 cm depth as compared to the unlimed soils for all rates of application (Figure 19). Samples at the 25-30 cm depths had greater soil pH values than the subsoil although only the value at the highest lime rate was statistically different (Table 9). Samples at the 20-25 cm level were all higher than the subsoil values for a given rate of application. Results for soil water pH on this soil are similar to findings in the Tomotley despite differences in neutralization of Al (Tables 5 and 9).

Increases in salt pH as compared to the unlimed soils occurred in the plow layer for all rates of application (Figure 20). The highest rate of application showed this effect for an additional 5 cm. This finding follows the trend observed with Al results. In this high rate of application the trend exists for this effect on pH to be present in the 25-30 cm depth, but it is not statistically different than the subsoil values (Table 9).

4.2.2 Pacolet sandy clay loam

Calcium levels determined in the unlimed and limed soils for the Pacolet sandy clay loam soil are shown in Figure 21. Plow layer (0-20 cm) Ca levels increase with increasing lime rate. Variations within the plow layer were limited due to mixing of this layer during the period of study. Calcium

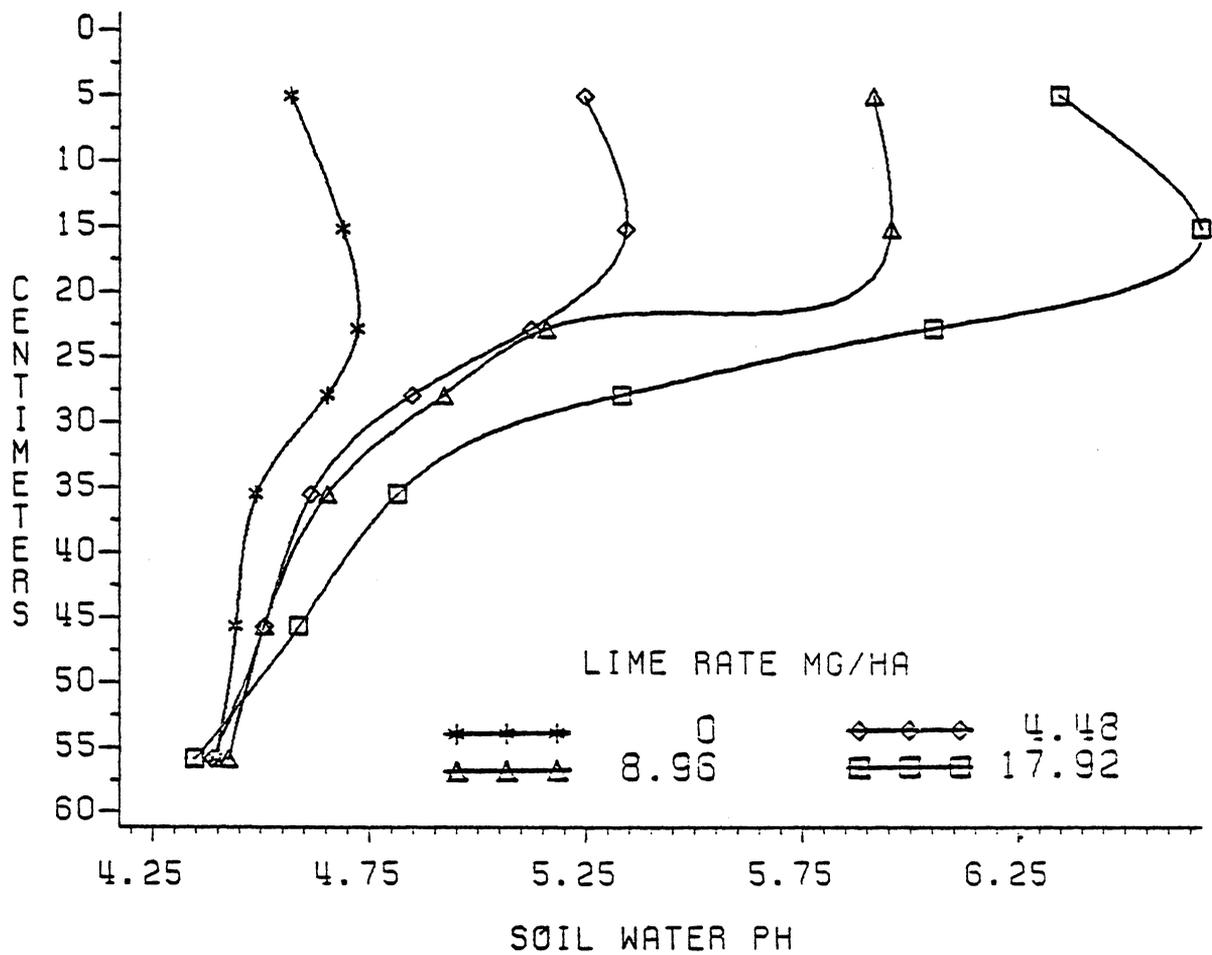


FIG. 19-SOIL WATER PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A MASADA LOAM SOIL.

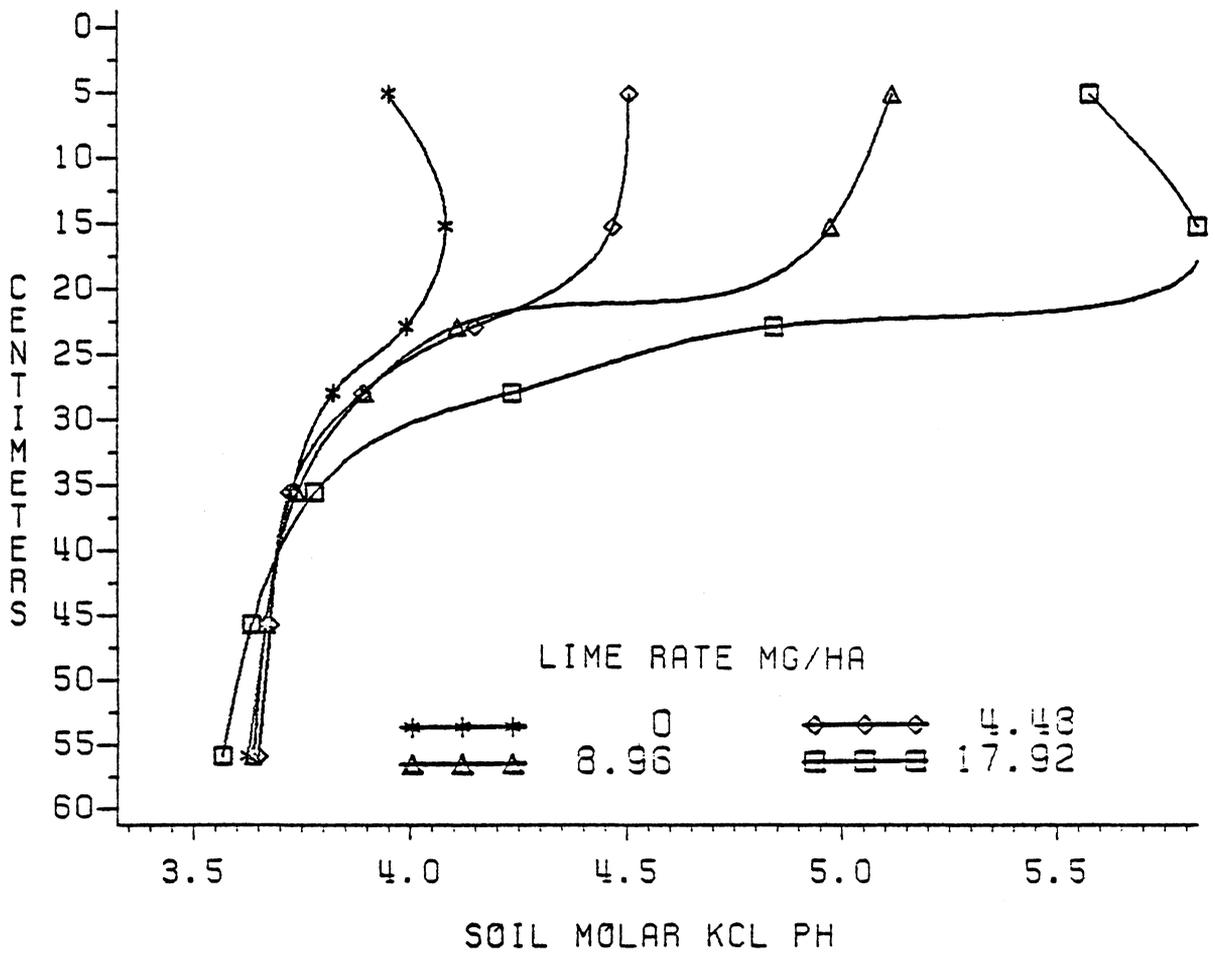


FIG. 20-SOIL MOLAR KCL PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A MASADA LOAM SOIL.

levels 5 cm below the plow layer increased with increasing lime rate, but were not statistically different ($\alpha = .14$) from that value for the area that did not receive limestone additions.

As observed in the Masada soil there is considerable variation in Ca levels within the profile of the untreated soils (Tables 8 and 10). The highest values were detected at the 25-30 and 30-40 cm depths as was the case with the Masada. The increase is attributed to an increase in effective negative charges with an increase in clay content. Clay content averages 35 to 50 % in this subsoil as opposed to 20 to 35 % in the surface (Lietzke, 1979a). Higher Ca levels at the 25-40 cm depths held by these sites may have come from past liming additions.

The subsequent decrease below 40 cm is coupled with an increase in Mg and Al content (Tables 10 and 11). In other words, effective CEC does not decrease, but the exchange contains more Al and Mg in the deeper increments. The presence of increased Mg in the deeper increments could be from two sources. Past liming amendments may have been with dolomitic limestone. Magnesium from this material quite possibly moved to these depths preferentially to the Ca. This explanation is consistent with data reported in limed plots most recently analyzed (Table 10). An alternate or contri-

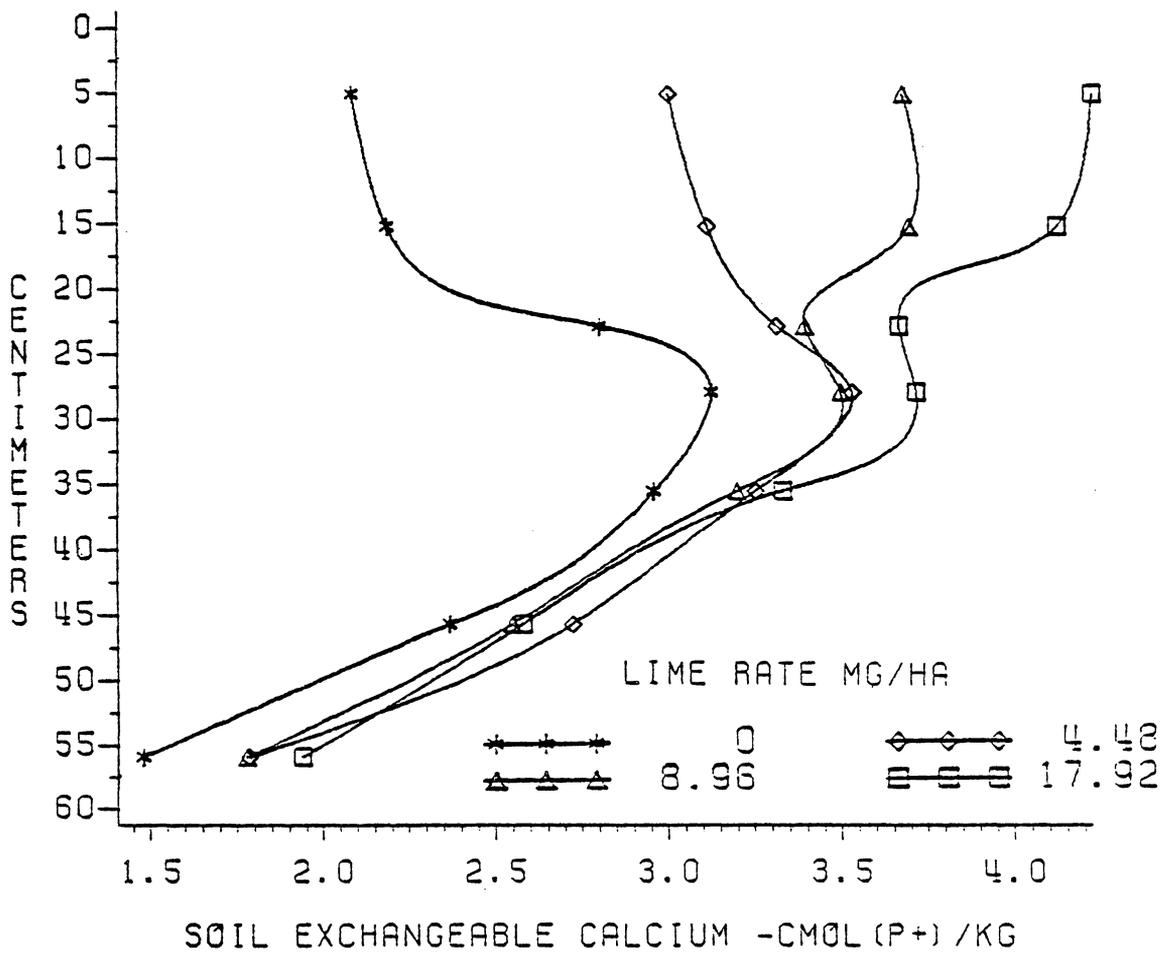


FIG. 21-EXCHANGEABLE SOIL CA FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A PACOLET SANDY CLAY LOAM SOIL.

Table 10. Exchangeable Ca and Mg as a function of lime rate and depth for the Pacolet soil.

Depth	Lime Rate Mg/ha ⁻¹							
	0	4.48	8.96	17.92	0	4.48	8.96	17.92
	Ca				Mg			
	cmol(p ⁺)Kg ⁻¹							
0-10	2.1cd*	3.0ab	3.7a	4.2a	1.3a	2.2 NS	3.0	3.6a
10-20	2.2bcd	3.1ab	3.7a	4.1ab	1.4a	2.4	3.2	3.6a
20-25	2.8abc	3.3a	3.4a	3.7bc	2.0ab	2.6	3.2	3.5a
25-30	3.1a	3.5a	3.5a	3.7bc	2.5ab	3.0	3.2	3.4a
30-40	3.0ab	3.3a	3.2ab	3.3c	2.8b	2.9	3.0	2.9b
40-50	2.4abc	2.7b	2.6b	2.6d	3.4b	3.0	3.0	2.7bc
50-60	1.5d	1.8c	1.8c	1.9c	2.8b	2.8	3.1	2.5c

*Column means followed by the same letter do not differ significantly at the 5% level

NS = not significant.

buting thought is related to the parent material. This soil is derived from a granite gneiss (Lietzke, 1979a). Source rocks of this type from the Piedmont Region of Virginia have been documented to contain traces of Mg but no Ca (Plaster and Sherwood, 1971). Also these researchers found that percent Al was second to percent Si in composition of this rock.

The 4.48 Mg ha⁻¹ rate of application exhibited no change in Ca levels that was statistically different from the one above it until a depth of 40-50 cm was reached (Table 10). This is also the depths where Ca levels in the unlimed soils decreased. Therefore, lime additions of this rate were not effective at facilitating Ca movement into the subsoil. The 8.96 and 17.92 Mg ha⁻¹ rates of application showed the same results as observed in the lower rate. This soil had the least amount of Ca movement of any of the soils in either the Coastal Plain or the Piedmont Regions (Tables 2,4,6,8 and 10).

Magnesium levels increased with increasing lime rate in the plow layer as compared with the unlimed soils (Figure 22). Increases in Mg levels with increasing lime rate occurred in the 20-25 cm increment; however, the 4.48 Mg ha⁻¹ rate of application increase was not statistically different from the unlimed soil. The following 5 cm exhibited the

Table 11. Exchangeable Al, soil water pH, and 1 mol L⁻¹ KCl pH as a function of lime rate and depth for the Pacolet soil.

Depth	Lime Rate Mg/ha ⁻¹											
	0	4.48	8.96	17.92	0	4.48	8.96	17.92	0	4.48	8.96	17.92
cm	Al cmol(p ⁺)Kg ⁻¹				Water pH				KCl pH			
0-10	0.1 NS	0.0a*	0.0a	0.0a	5.0	5.4bc	6.1b	6.5a	4.2	4.7b	5.4a	5.9a
10-20	0.1	0.0a	0.0a	0.0a	5.3	5.8a	6.5a	6.8a	4.3	4.9a	5.5a	6.0a
20-25	0.1	0.0a	0.0a	0.0a	5.2	5.5b	5.7c	6.1b	4.2	4.6b	4.8b	5.1b
25-30	0.1	0.1a	0.1a	0.1a	5.1	5.2cd	5.3d	5.5c	4.1	4.2c	4.1c	4.5c
30-40	1.0	0.5a	1.1ab	0.4ab	5.1	5.1cd	5.2d	5.1d	4.0	4.1cd	4.0c	4.1cd
40-50	1.3	0.6ab	1.6b	0.9bc	5.0	5.1cd	5.1d	5.1d	4.0	4.0cd	4.0c	4.0d
50-60	1.4	1.5b	1.8b	1.6c	5.0	5.0d	5.1d	5.0d	4.0	4.0d	4.0c	4.0d

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

trend but did not differ from the unlimed soil (Table 10). These findings demonstrate again that Mg moves preferentially to Ca.

Aluminum levels were low in the unamended soil (Figure 23). In the first 30 cm, Al levels did not exceed $0.1 \text{ cmol(p}^+)\text{kg}^{-1}$. The addition of any limestone readily neutralized those low levels of Al in the upper 25 cm. There was no statistical difference between the unlimed soils and the limed soils below the 25 cm depth. Within a given lime rate, there was no evidence of neutralization of Al below the 25 cm depth (Table 11).

Soil pH values increased with increasing lime rate within the plow layer in comparison to the untreated soil (Figure 24). Below the plow layer, the trend for increases in pH with an increase in lime rate occurred to a depth of 30 cm. In the 20-25 cm increment, the two higher rates of application had values different from the native soil. The 5 cm depth below this had no values differing from the unlimed soil although the trend was present.

The untreated soil showed variations no greater than 0.3 pH units throughout the profile (Table 11). Movement of hydroxyls below the plow layer did occur in the limed soils. Both the 4.48 and 8.96 Mg ha^{-1} treatments exhibited increases in pH as compared to native subsoil levels. The highest

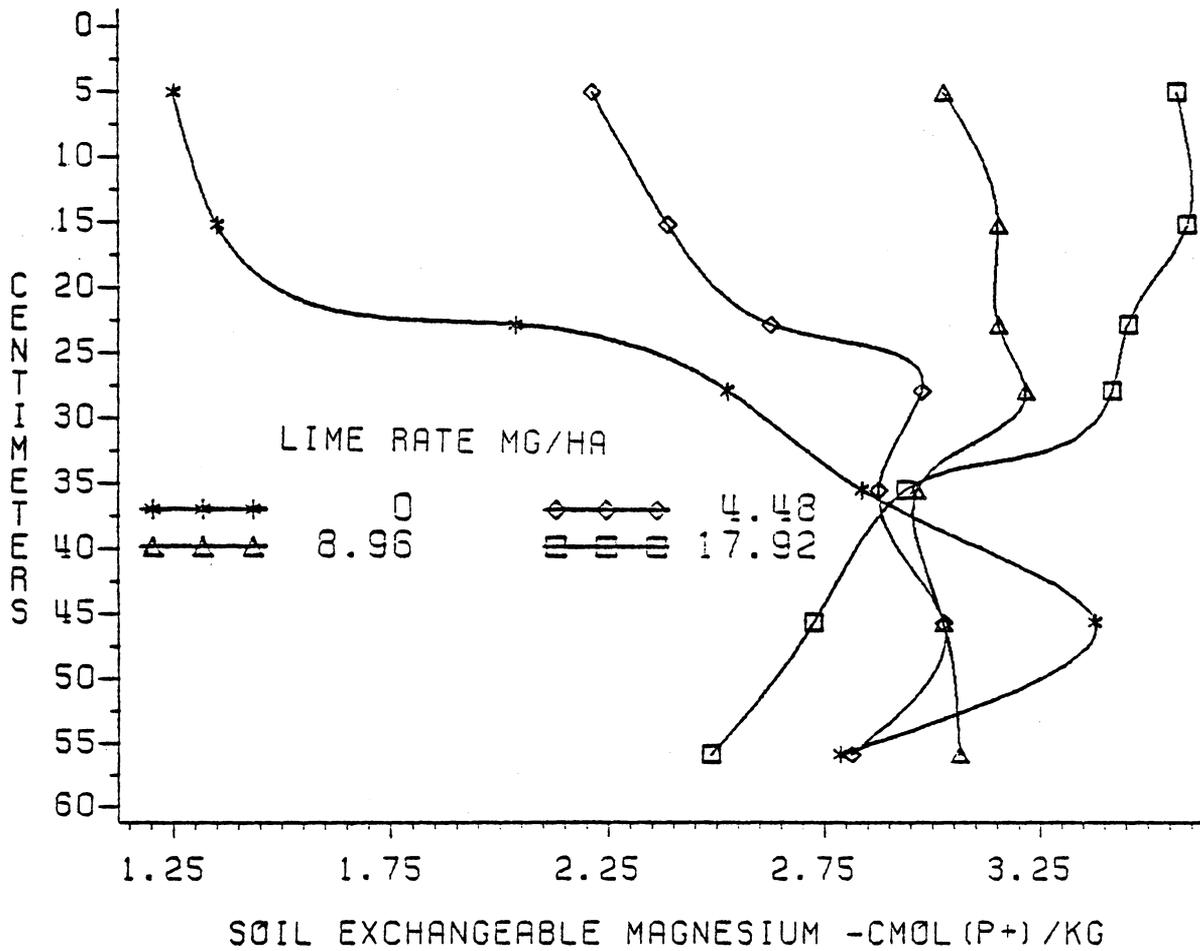


FIG. 22-EXCHANGEABLE SOIL MG FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A PACOLET SANDY CLAY LOAM SOIL.

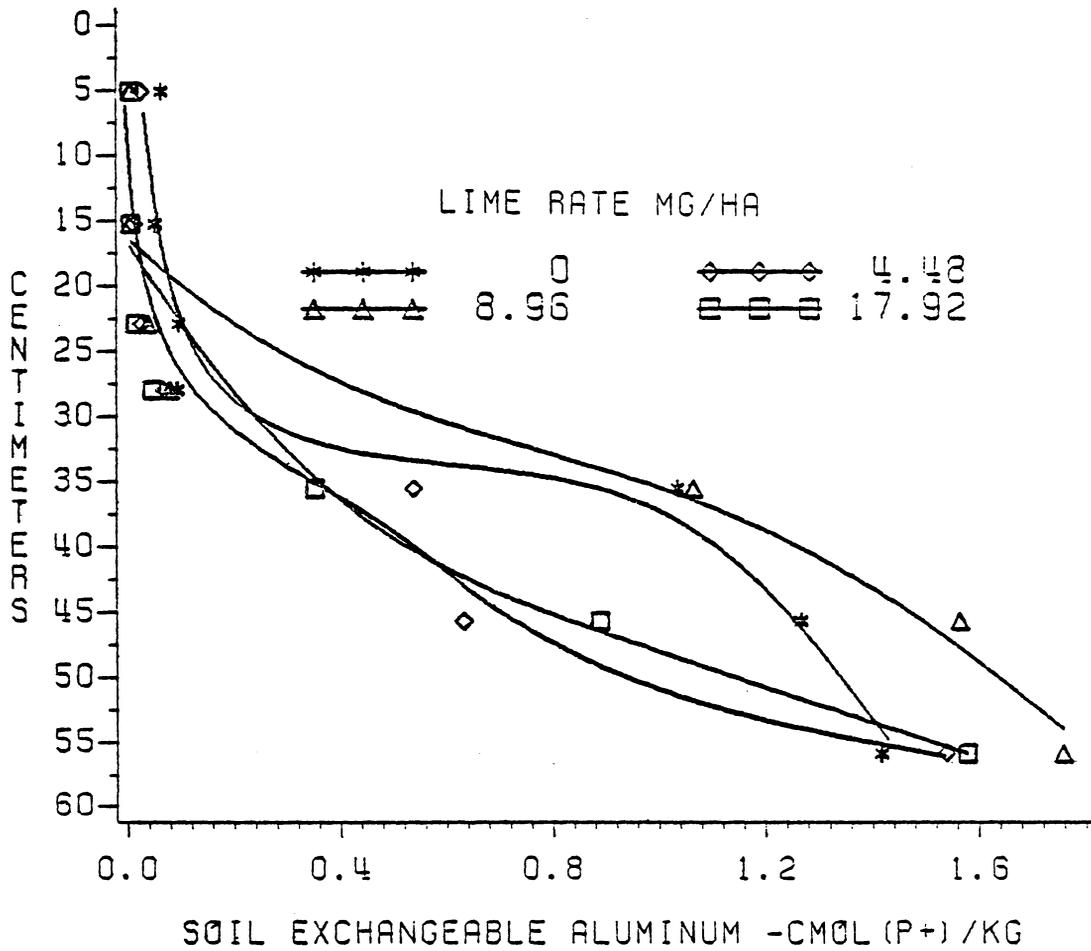


FIG. 23-EXCHANGEABLE SOIL AL FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A PACOLET SANDY CLAY LOAM SOIL.

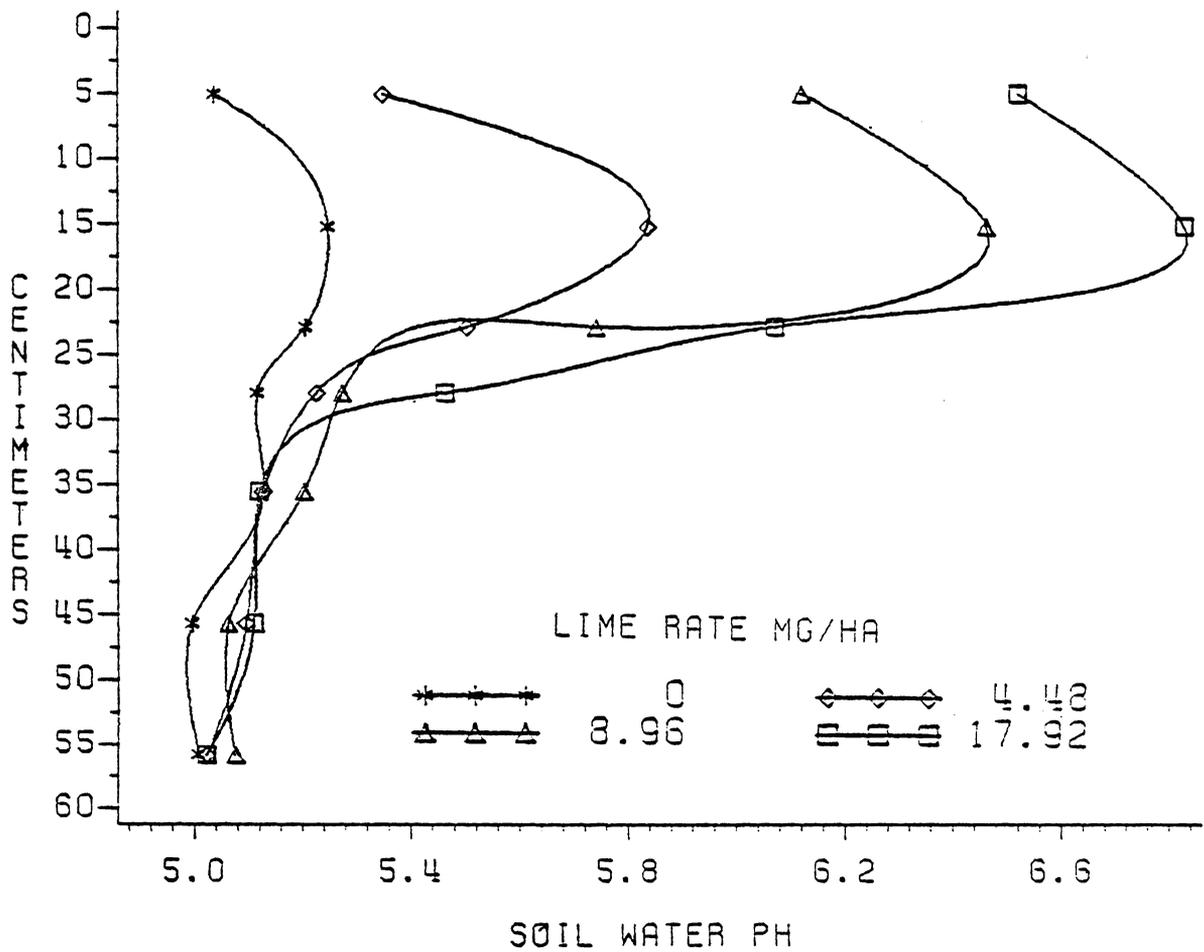


FIG. 24-SOIL WATER PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A PACOLET SANDY CLAY LOAM SOIL.

rate of application not only showed movement of hydroxyls to the 20-25 cm depth, but the increase in pH occurred in the next 5 cm as well. This change was not accompanied by a decrease in Al as expected; however, the level was already very low, i.e. $0.1 \text{ cmol(p}^+\text{)kg}^{-1}$ (Table 11).

Salt pH values increased with increasing lime rate as compared to the untreated soils in the plow layer (Figure 25). In the 5 cm below the plow layer, increases in pH were observed at the two highest rates of application. The value obtained at the 4.48 Mg ha^{-1} rate of application followed the trend, but was not statistically different than the unlimed value.

The salt pH values in the native soil varied by the same amount as seen in the water pH determinations (Table 11). Soil salt pH levels increased and were different than the subsoil values 5 cm below the plow layer for a given lime rate. Furthermore, in the highest rate of application hydroxyl movement was detected in the 25-30 cm increments. None of the values obtained below this depth illustrated differences from subsoil soil reaction. Results for the salt pH levels directly parallel findings for soil water pH levels (Table 11). This soil had the least amount of neutralization of subsoil acidity for the two pH determinations than was observed in the Coastal Plain or the Piedmont Regions (Tables 3,5,7, 9, and 11).

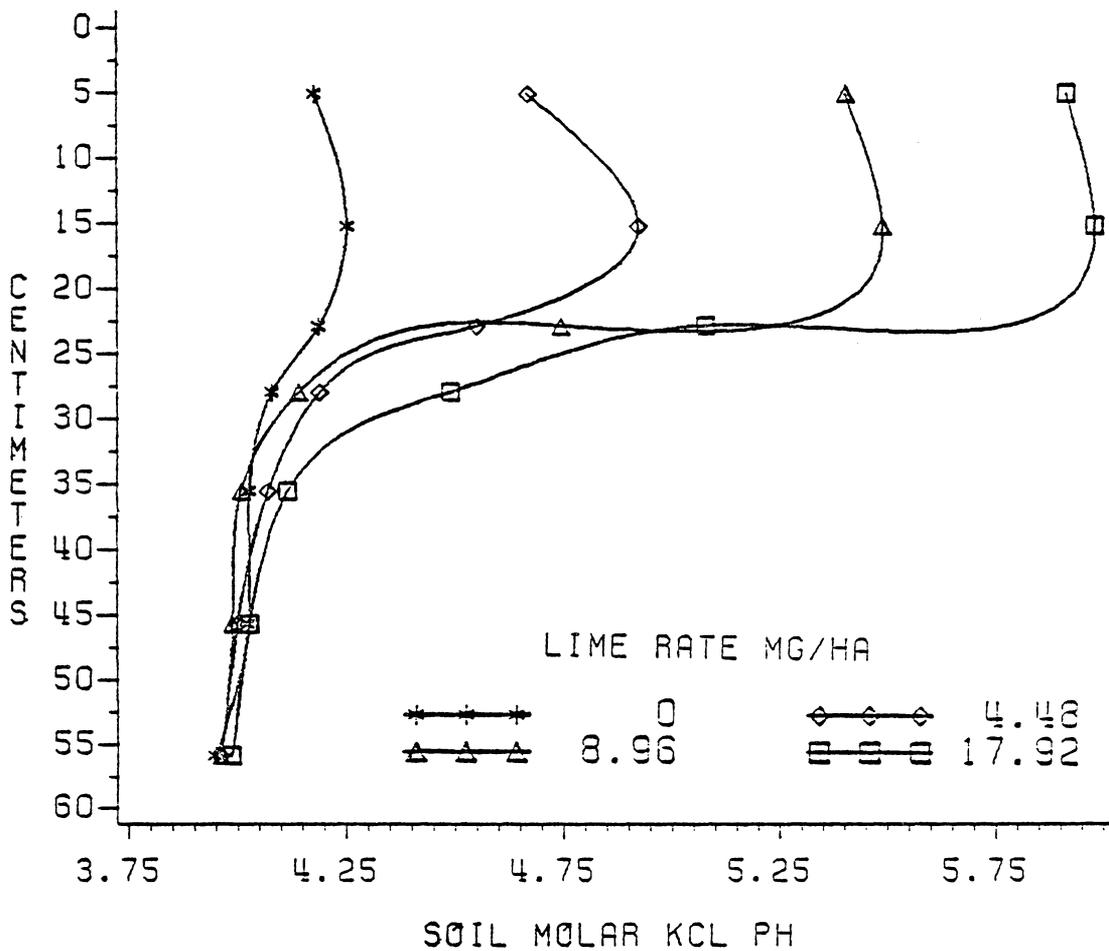


FIG. 25-SOIL MOLAR KCL PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A PACOLET SANDY CLAY LOAM SOIL.

One contributing factor to this finding would be surface texture. This soil has the greatest amount of clay of the soils studied in the Coastal Plain or the Piedmont Regions (Table 1). As a result of liming, the pH increases in the plow layer and the CEC increases due to pH-dependent charges. The rate of increase is proportional to the amount of clay and therefore, Ca and Mg retention is favored. With retention of cations increased, there is a decrease in their movement and movement of an accompanying anion (ie. OH^-) to increase subsoil pH.

4.3 RIDGE AND VALLEY REGION

4.3.1 Duffield silt loam

Calcium levels for the experimental conditions and the unlimed soil are given in Figure 26. Plow layer (0-20 cm) Ca levels increase with increasing lime rate on this Duffield silt loam. The 5 cm below the plow layer also exhibited this trend.

Considerable variation exists in Ca levels within the profile of the untreated soil, as was seen in the Piedmont soils (Table 8, 10, and 12). High values for Ca were detected at the 40-50 and 50-60 cm depths. This soil is derived from calcareous shale and limestone and such a climb in measured Ca would be anticipated (Lietzke, 1979b). Another

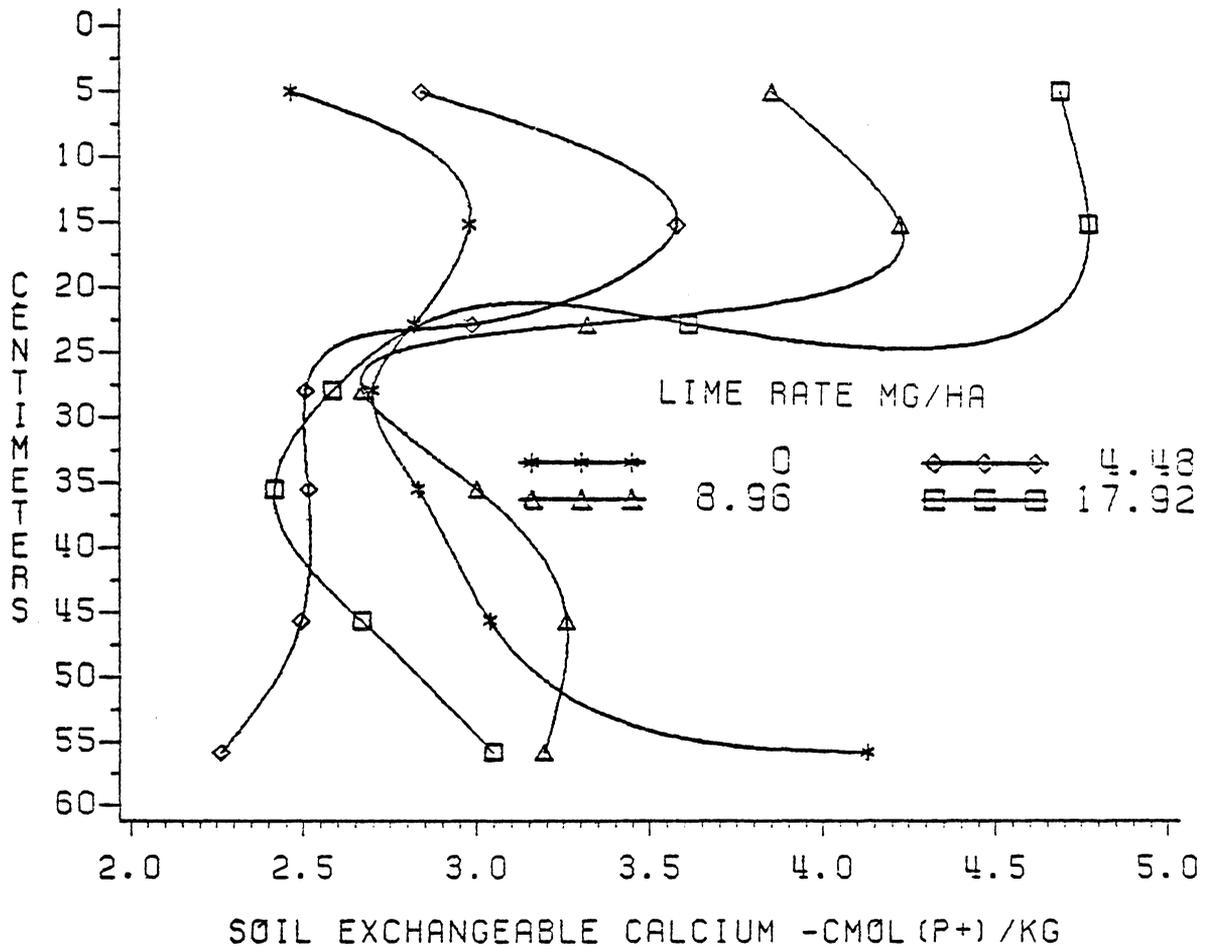


FIG. 26-EXCHANGEABLE SOIL CA FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A DUFFIELD SILT LOAM SOIL.

Ca source would be from limestone applied in past years that has moved into the subsoil.

The 4.48 Mg ha⁻¹ rate of application exhibited no change in Ca levels between any of the values determined. Therefore, addition of limestone to the surface at this rate did not cause movement of Ca. The 8.96 and 17.92 Mg ha⁻¹ rates of application showed trends of Ca movement from the plow layer. The highest rate of application showed an increase over subsoil values immediately below the 20 cm depth which would indicate movement from the surface. Although slight, this soil showed more movement of Ca than observed in the Pacolet soil (Tables 10 and 12).

Magnesium levels increased with increasing lime rate in the surface as compared to the untreated soils (Figure 27). This same trend existed in the 10 cm below the plow layer. Within this 10 cm layer values obtained at the two higher rates of application were statistically different than the unlimed soil (Figure 27). The value obtained for the 4.48 Mg ha⁻¹ rate was higher than the unlimed soil ($\alpha = .10$) in the 20-25 cm increment. The value in the next 5 cm for the same lime rate tended to be higher than the unlimed soil.

There was no difference between any of the Mg levels determined in the untreated soil profile except the 50-60 cm increment which exhibited an increasing trend as was seen

Table 12. Exchangeable Ca and Mg as a function of lime rate and depth for the Duffield soil.

Depth	Lime Rate Mg/ha ⁻¹							
	0	4.48	8.96	17.92	0	4.48	8.96	17.92
	Ca				Mg			
	cmol(p ⁺)Kg ⁻¹							
0-10	2.5a*	2.8 NS	3.9ab	4.7a	1.3	1.6bc	2.5b	3.3ab
10-20	3.0a	3.6	4.2a	4.8a	1.6	2.3a	3.1a	3.8a
20-25	2.8a	3.0	3.3bc	3.6b	1.4	1.9ab	2.5b	3.2b
25-30	2.7a	2.5	2.7c	2.6c	1.2	1.5bcd	2.0c	2.2c
30-40	2.8a	2.5	3.0c	2.4c	1.2	1.8cd	1.5d	1.6d
40-50	3.0a	2.5	3.3bc	2.7c	1.2	0.9d	1.2de	1.3d
50-60	4.1b	2.3	3.2bc	3.1bc	1.9	0.7d	1.1e	1.7cd

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

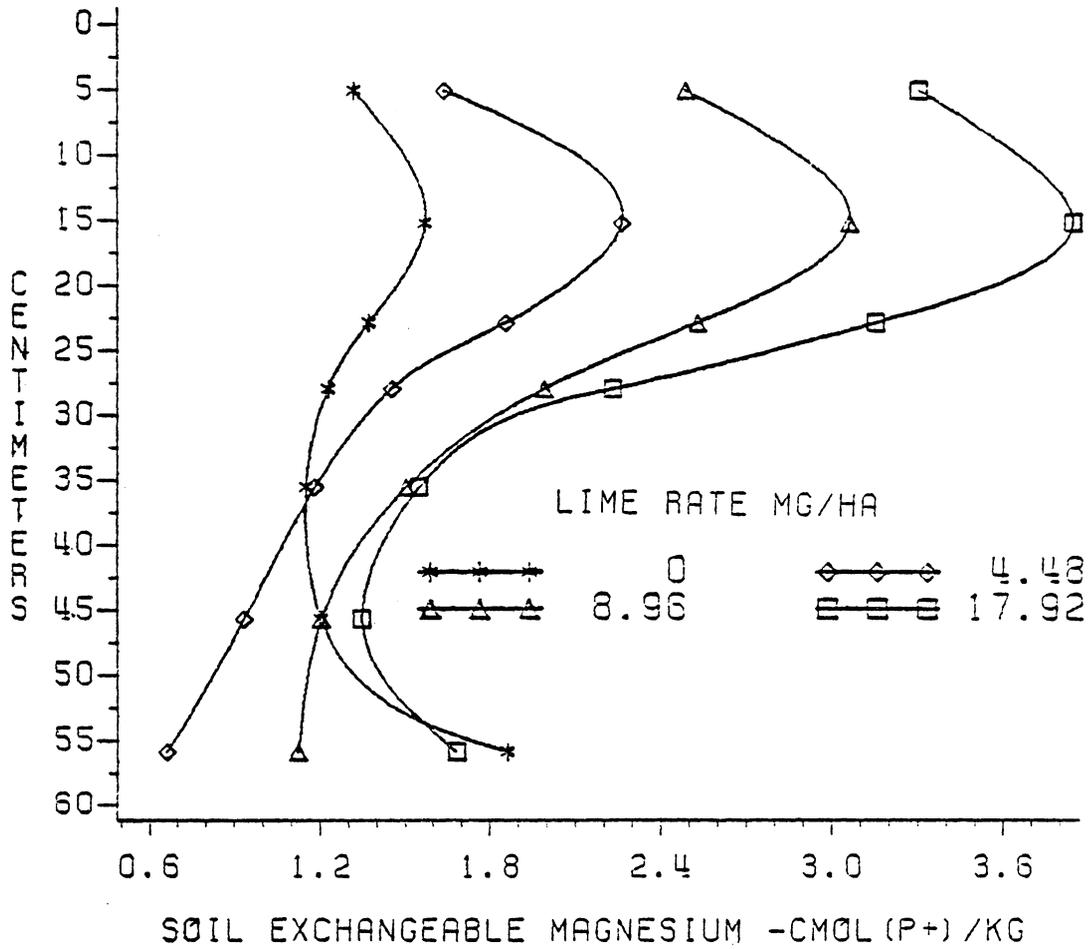


FIG. 27-EXCHANGEABLE SOIL MG FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A DUFFIELD SILT LOAM SOIL.

with Ca (Table 12). In the 4.48 Mg ha⁻¹ treatment, movement of Mg occurred into the 20-25 cm increment as compared to the subsoil (Table 12). The 8.96 and 17.92 Mg ha⁻¹ rates of application exhibited movement to a depth of 30 cm as compared to untreated values. Movement of Mg from the surface horizon was more pronounced in this soil as compared to the Pacolet soil, however it occurred to a greater degree than Ca movement, which has been observed on the previously discussed soils (Tables 2,4,6,8,10 and 12).

Aluminum levels of this soil are natively low (Figure 28). Additions of limestone to the surface readily neutralize Al that is present. The trend towards decreasing Al with increasing lime rate is observed to a depth of 25 cm (Table 13). The value obtained for the lowest rate of application is not statistically different than the untreated soil. Since native Al levels are so low and limestone additions readily alter these values, the plotted curves (Figure 28) show what appears to be large variations, but these variations occur only in the range of 0 to 0.4 cmol(p⁺)kg⁻¹.

Soil water pH values increased with increasing lime rate in the plow layer as compared to the unlimed soil (Figure 29). The 5 cm below the plow layer exhibited this same trend. The lowest rate of application was not statistically different than the untreated soil.

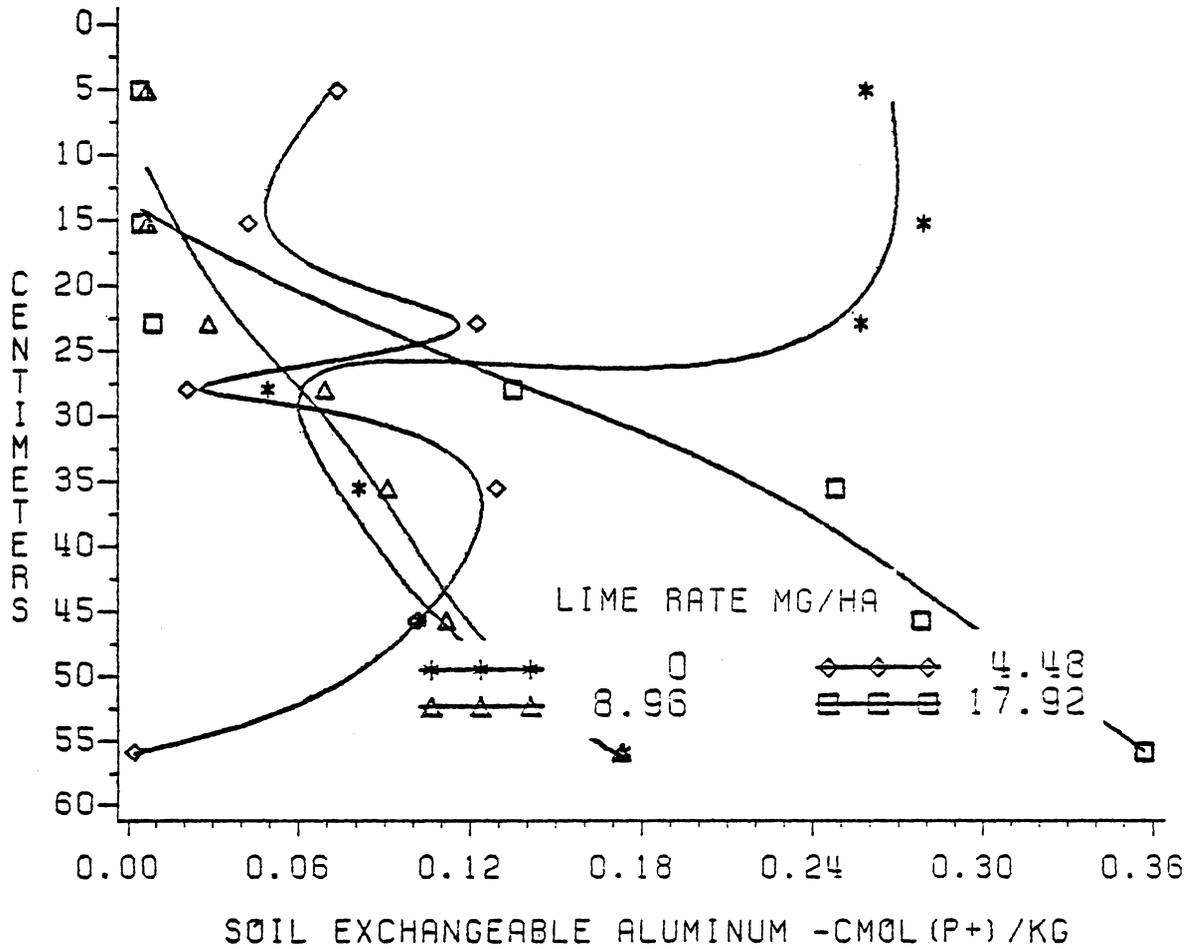


FIG. 28-EXCHANGEABLE SOIL AL FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A DUFFIELD SILT LOAM SOIL.

The unlimed soil showed no significant variations in soil water pH in its profile (Table 13). The maximum difference in pH was 0.4 units. For the lowest lime rate, similar results were observed. No statistical difference existed between any of the values. The variation was nearly the same magnitude. Movement of hydroxyls below the plow layer was observed in the two higher rates of application. The 20-25 cm increment in the 8.96 Mg ha⁻¹ lime rate was different than the 50-60 cm depth and illustrated a trend of increasing pH in relation to the other subsoil pH values (Table 13). The highest rate of application showed an increasing trend to the 30 cm depth. The value at 20-25 cm differed from the plow layer and the subsoil pH levels. Also, the 25-30 cm increment differed from the plow layer and subsoil values at depths greater than 40 cm. Changes in Al did not correspond to these pH changes (Table 13).

Salt pH values increased with increasing lime rate as compared to the unlimed soils in the plow layer (Figure 30). In the 5 cm increment below the surface, this trend was present, but the value for the 4.48 Mg ha⁻¹ lime rate did not differ from native levels. This same trend was observed with values for soil water pH (Figure 29).

No statistical differences existed between the salt pH values obtained in the untreated profile (Table 13). This

Table 13. Exchangeable Al, soil water pH, and 1 mol L⁻¹ KCl pH as a function of lime rate and depth for the Duffield soil.

Depth	Lime Rate Mg/ha ⁻¹											
	0	4.48	8.96	17.92	0	4.48	8.96	17.92	0	4.48	8.96	17.92
cm	Al cmol(p ⁺)Kg ⁻¹				Water pH				KCl pH			
0-10	0.3 NS	0.1	0.0	0.0a*	5.1	5.5	6.1ab	6.6a	4.3	4.5	5.1a	5.7a
10-20	0.3	0.0	0.0	0.0a	5.2	5.6	6.1a	6.4a	4.4	4.8	5.3a	5.6a
20-25	0.3	0.1	0.0	0.0a	5.1	5.4	5.8bc	6.0b	4.4	4.6	4.9ab	5.2b
25-30	0.1	0.0	0.1	0.1b	5.3	5.5	5.6cd	5.6c	4.5	4.6	4.7bc	4.7c
30-40	0.1	0.1	0.1	0.3bc	5.5	5.5	5.6cd	5.3cd	4.5	4.5	4.6bc	4.3d
40-50	0.1	0.1	0.1	0.3c	5.4	5.4	5.5cd	5.1d	4.4	4.5	4.5bc	4.1d
50-60	0.2	0.0	0.2	0.4c	5.4	5.7	5.4d	5.0d	4.4	4.8	4.3c	4.0d

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

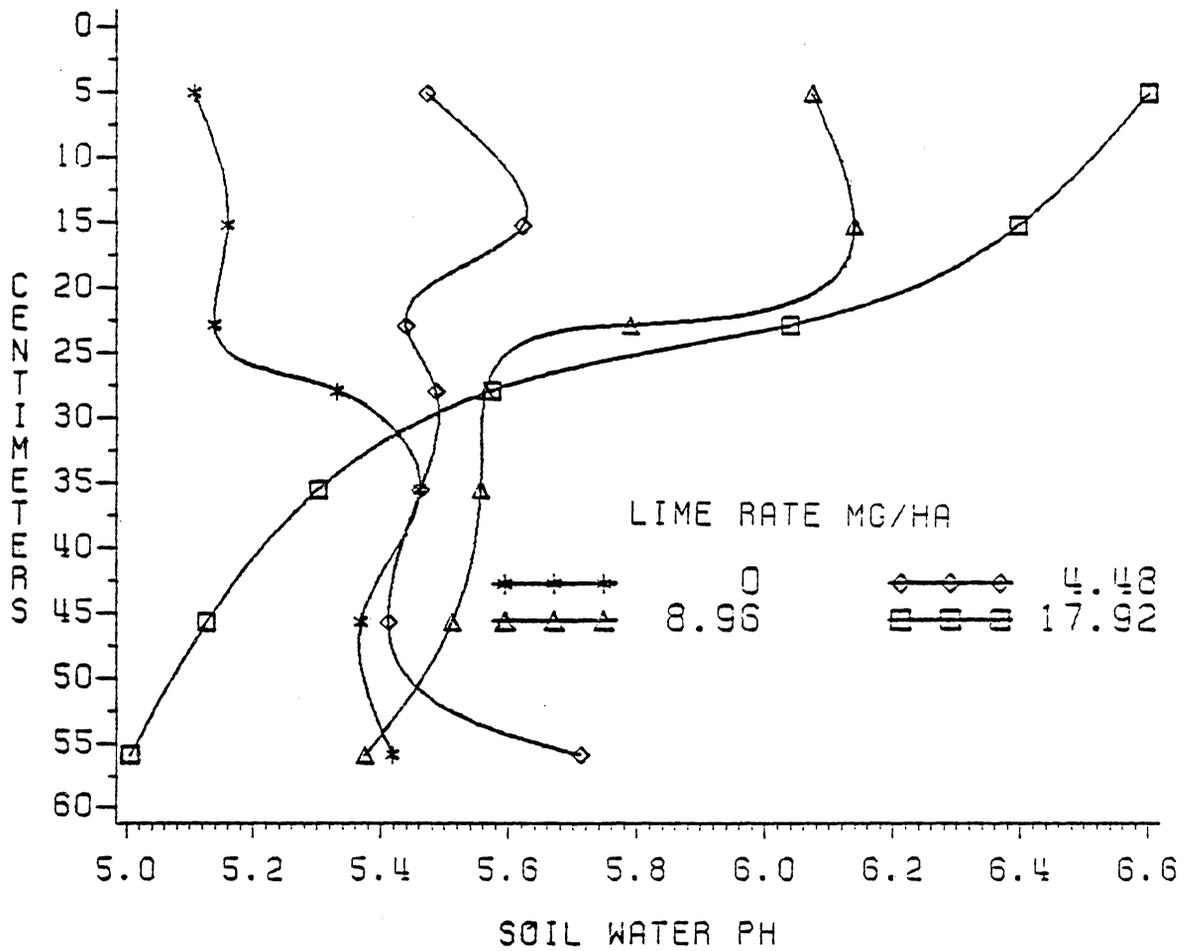


FIG. 29-SOIL WATER PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A DUFFIELD SILT LOAM SOIL.

same result was obtained at the lowest rate of application. Movement of hydroxyls as indicated by salt pH values was present with the two higher lime rates. Findings here were very similar to the water pH values (Table 13). The 8.96 Mg ha⁻¹ rate of application had a value statistically different from that value at 50-60 cm in the 5 cm immediately below the plow layer. The highest rate of application had values statistically different from any other in the profile at depths of 20-25 cm and 25-30 cm. Neutralization of soil acidity as indicated by both pH determinations followed observations in the Pacolet soil (Tables 11 and 13).

4.3.2 Frederick silt loam

Calcium levels obtained for the treated and untreated soils are given in Figure 31. Increases in Ca occur with an increase in lime rate in the plow layer (0-20 cm). Only the surface 10 cm in the highest rate of application had values statistically different than the unlimed soil. Variations between the values for the untreated soil or for a given lime rate were noticeably great in this soil (Table 14). A major reason for this was the limited degree of mixing that occurred over the period of study. In the other soils, plowing and disking during each growing season was part of the management. This soil was cropped in alfalfa and only an initial plowing and disking provided mixing.

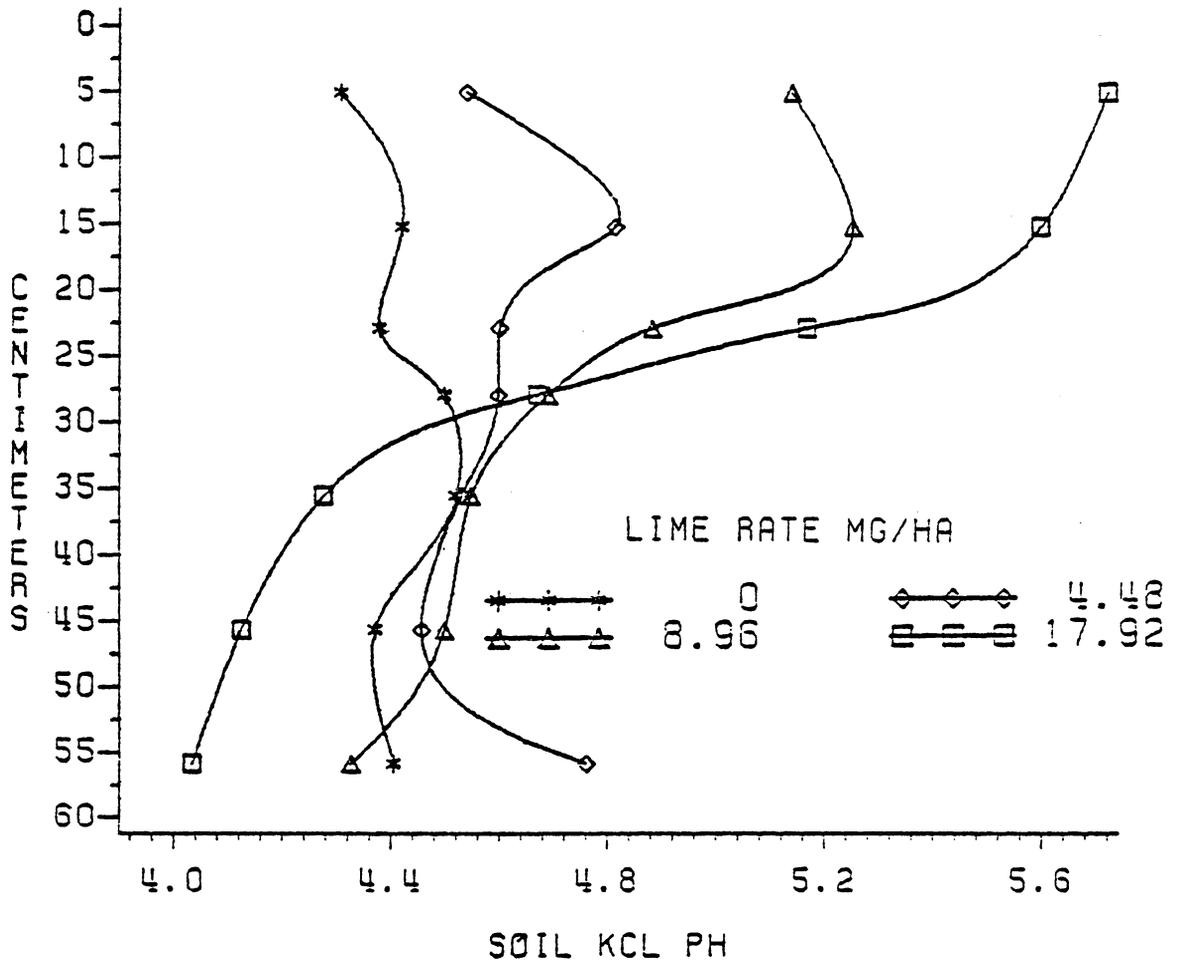


FIG. 30-SOIL MOLAR KCL PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A DUFFIELD SILT LOAM SOIL.

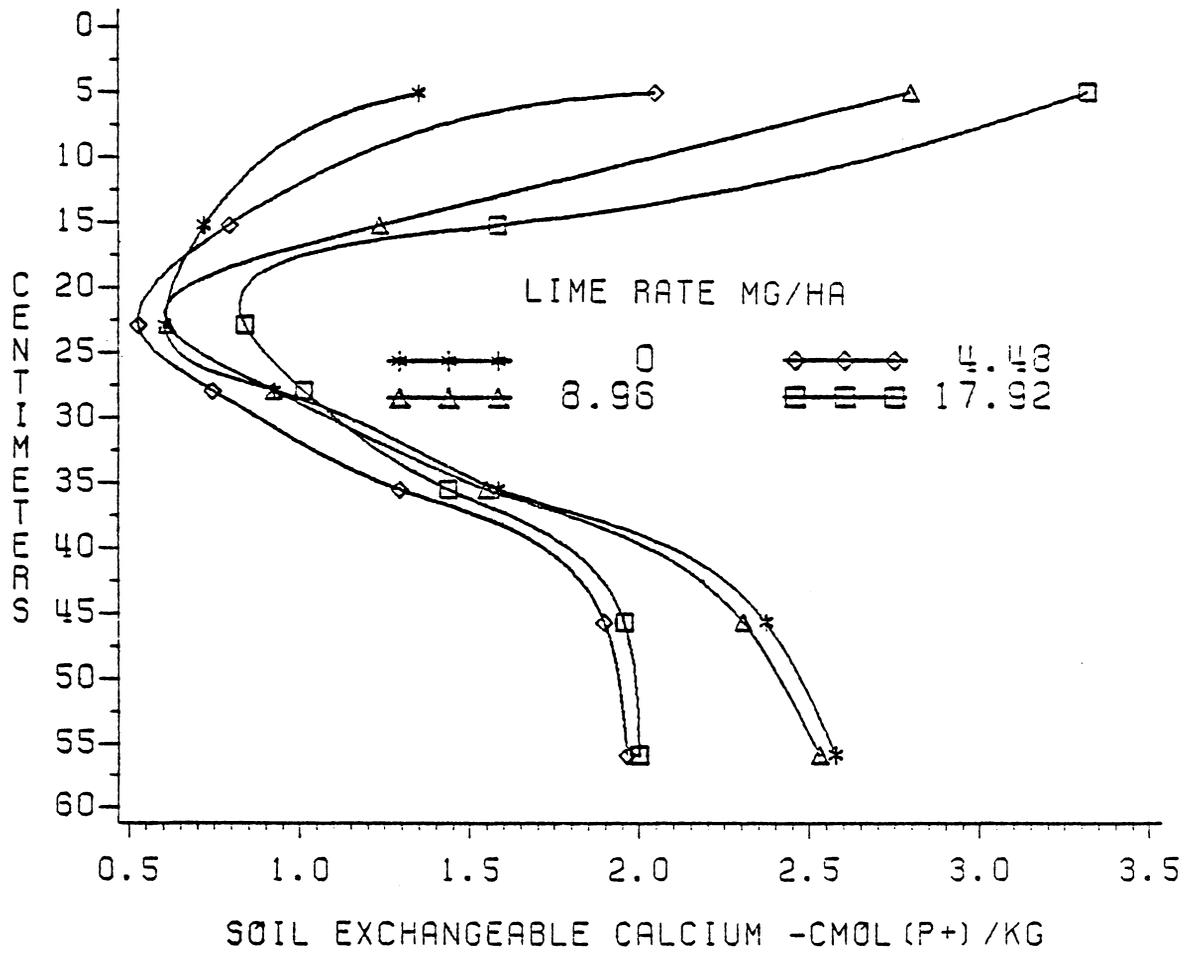


FIG. 31-EXCHANGEABLE SOIL CA FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A FREDERICK SILT LOAM SOIL.

As observed in the Piedmont and other Ridge and Valley soils, there is considerable variation in Ca levels within the untreated soil (Tables 8, 10, 12, and 14). Values obtained at the 40-50 and 50-60 cm depth were high. This increase could be attributed to Ca from past liming that has moved to this depth. A more probable reason would be with regard to parent material. The substratum of this soil is clayey and has weathered from limestone or dolomite both serving as a Ca source (Lietzke, 1979b).

The 4.48 Mg ha⁻¹ rate of application exhibited an initially high value for Ca from the surface applied limestone (Table 14). The level declined rapidly below the surface 10 cm and then began to climb at values greater than 25 cm. It reached the same values as observed in the surface 10 cm where clay content increased, i.e. the 40-50 cm increment.

The 8.96 and 17.92 Mg ha⁻¹ rates of application showed similar results (Table 14). Calcium values determined were highest in the surface 10 cm then declined rapidly. Below the 25 cm increment measured values began to increase again and at depths greater than 40 cm these levels did not differ statistically from the surface layer. This soil had the least amount of movement of Ca from limestone additions in comparison to all soils examined.

Table 14. Exchangeable Ca and Mg as a function of lime rate and depth for the Frederick soil.

Depth	Lime Rate Mg/ha ⁻¹							
	0	4.48	8.96	17.92	0	4.48	8.96	17.92
	Ca				Mg			
cm	cmol(p ⁺)Kg ⁻¹							
0-10	1.4ab*	2.0a	2.8a	3.3a	0.6a	1.7a	2.2a	2.8a
10-20	0.7b	0.8bc	1.2cd	1.6bc	0.4a	1.1b	1.6ab	2.2abc
20-25	0.6b	0.5c	0.6d	0.8c	0.3a	0.6c	0.7bc	1.0cd
25-30	0.9b	0.7c	0.9cd	1.0bc	0.4a	0.5c	0.6c	0.8d
30-40	1.6ab	1.3b	1.6bc	1.4bc	0.8a	0.6c	0.8bc	0.8d
40-50	2.4a	1.9a	2.3ab	2.0bc	1.7b	1.1b	1.6ab	1.6bcd
50-60	2.6a	2.0a	2.5a	2.0b	2.8c	1.8a	2.3a	2.4c

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

Soil Mg levels increased with increasing lime rate to a depth of 30 cm (Figure 32). The values determined did not always differ statistically with the untreated soil. In the surface 10 cm increases were of the greatest magnitude. The two higher rates of application had values statistically different than the unlimed soil at this depth. The 10-20 cm increment showed the same results. Magnesium levels increased in this layer, but not at the magnitude present in the surface 10 cm. The lack of mixing within the plow layer is readily observed with Mg levels as well as with the Ca (Figures 31 and 32). Below the plow layer, the highest rate of application illustrated statistically different results than the unlimed soil. Despite the limited degree of mixing observed in the plow layer, Mg still exhibited more relative movement than Ca (Table 14). This result has been observed on all the soils.

Aluminum levels are low in the surface of the native soil (Figure 33). The addition of limestone to the surface readily neutralized native Al levels to where they were barely detectable in the surface 10 cm. Below the first 10 cm Al levels decreased in comparison to the unlimed soil. In the highest rate of application Al levels were scarcely detected as in the uppermost increment. At levels greater than 20 cm Al levels increased readily. None of the values for a given

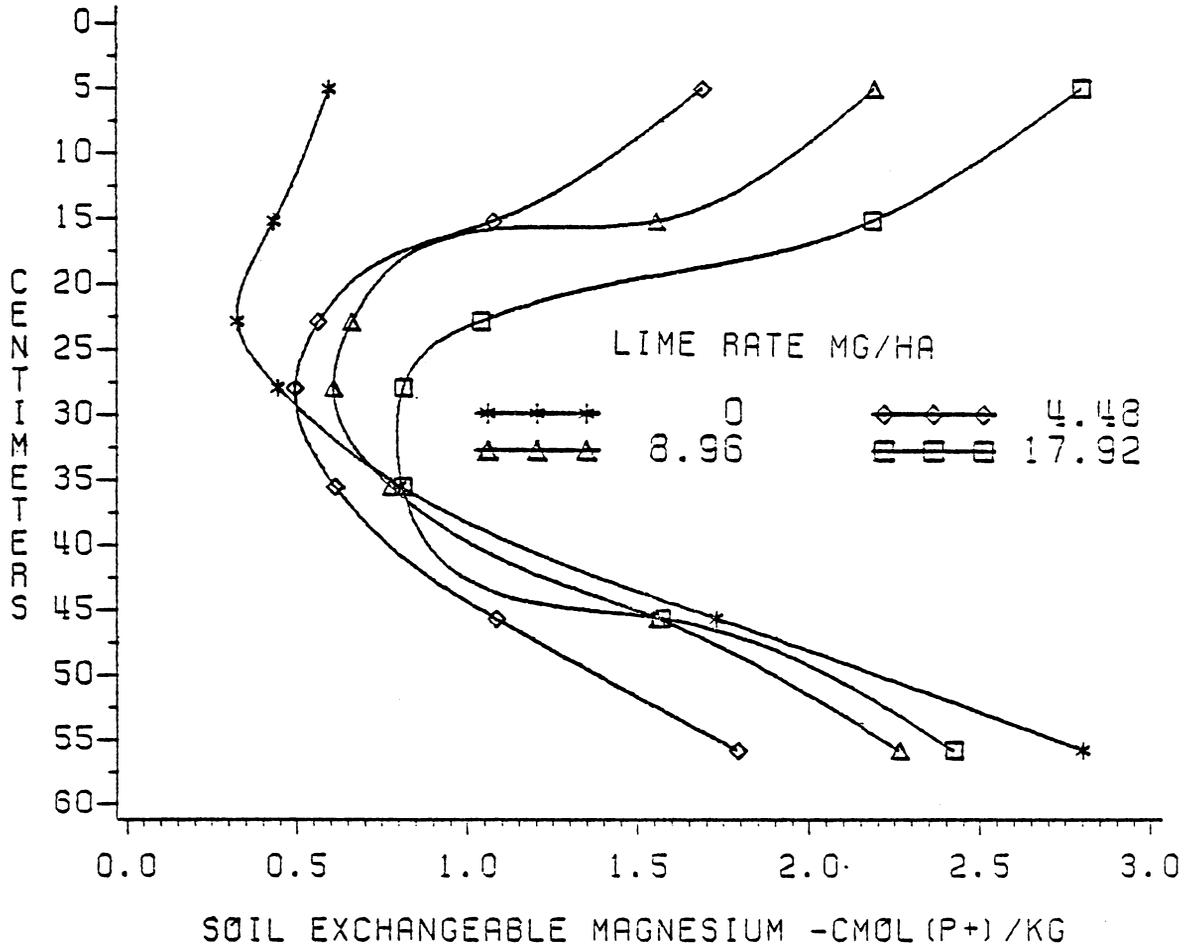


FIG. 32-EXCHANGEABLE SOIL MG FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A FREDERICK SILT LOAM SOIL.

depth below 20 cm had Al levels statistically different from the untreated soil.

The unlimed soil showed great increases in Al levels between the surface and the subsoil (Table 15). Levels were highest in the depths greater than 40 cm where clay content and CEC increase. Between 20 and 40 cm, values determined are intermediate to levels in the surface and levels at the deeper increments. Neutralization of Al did not occur for any lime rate at depths greater than 20 cm.

Soil pH values increased with an increase in lime rate in the surface 20 cm (Figure 34). The values for the two highest lime rates were different than the pH levels in the untreated soil. These findings are similar to those observed with neutralization of Al in this soil (Table 15).

The soil that did not receive limestone additions showed little variation in soil reaction from increment to increment (Table 15). All of the soils receiving limestone exhibited changes in pH levels in the 10-20 cm increment as compared to subsoil values. This indicates that hydroxyl movement from the surface occurred because lime was primarily mixed in the 0-10 cm increment. Below the 20 cm level no differences were detected between subsoil pH values.

Salt pH values increased with increasing lime rate as compared with the unlimed soil in the surface 20 cm (Figure

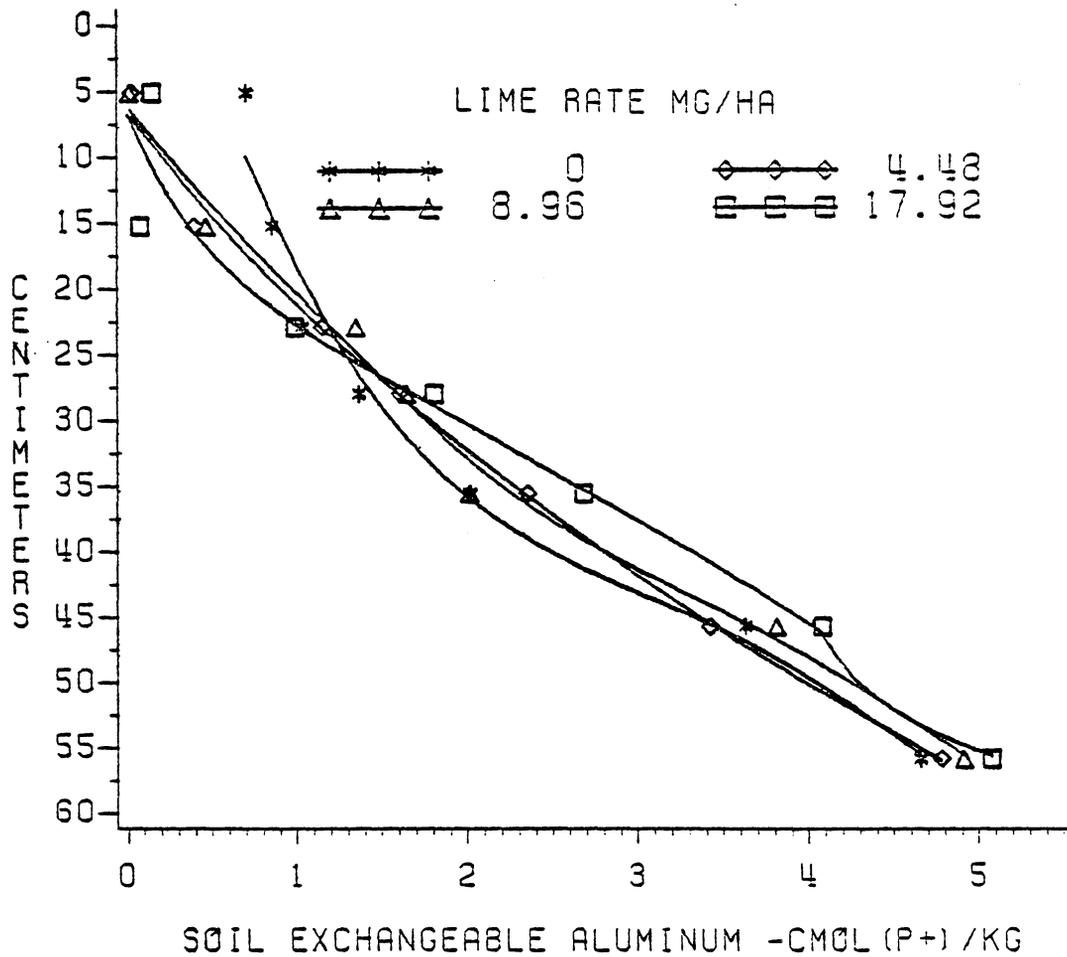


FIG. 33-EXCHANGEABLE SOIL AL FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A FREDERICK SILT LOAM SOIL.

Table 15. Exchangeable Al, soil water pH, and 1 mol L⁻¹ KCl pH as a function of lime rate and depth for the Frederick soil.

Depth	Lime Rate Mg/ha ⁻¹											
	0	4.48	8.96	17.92	0	4.48	8.96	17.92	0	4.48	8.96	17.92
cm	Al				Water pH				KCl pH			
	cmol(p ⁺)Kg ⁻¹											
0-10	0.7a*	0.0a	0.0a	0.1a	5.1a	5.6a	5.9a	6.2a	4.2a	4.7a	5.2a	5.6a
10-20	0.9a	0.4a	0.5a	0.1a	4.8b	5.0b	5.4b	5.7b	4.1ab	4.2b	4.5b	4.8b
20-25	1.0a	1.2b	1.3b	1.0b	4.6b	4.7c	4.7c	4.8c	4.0b	4.0c	4.0c	4.0c
25-30	1.4ab	1.6b	1.6bc	1.8b	4.6b	4.6c	4.7c	4.7c	3.9c	3.8d	3.8cd	3.7c
30-40	2.0b	2.4c	2.0c	2.7c	4.6b	4.6c	4.6c	4.6c	3.6d	3.6e	3.6de	3.6c
40-50	3.6c	3.4d	3.8d	4.1d	4.6b	4.6c	4.6c	4.6c	3.5d	3.5f	3.5e	3.5c
50-60	4.7d	4.8e	4.9e	5.1e	4.6b	4.6c	4.5e	4.6c	3.5d	3.5f	3.5e	3.5c

*Column means followed by the same letter do not differ significantly at the 5% level.

NS = not significant.

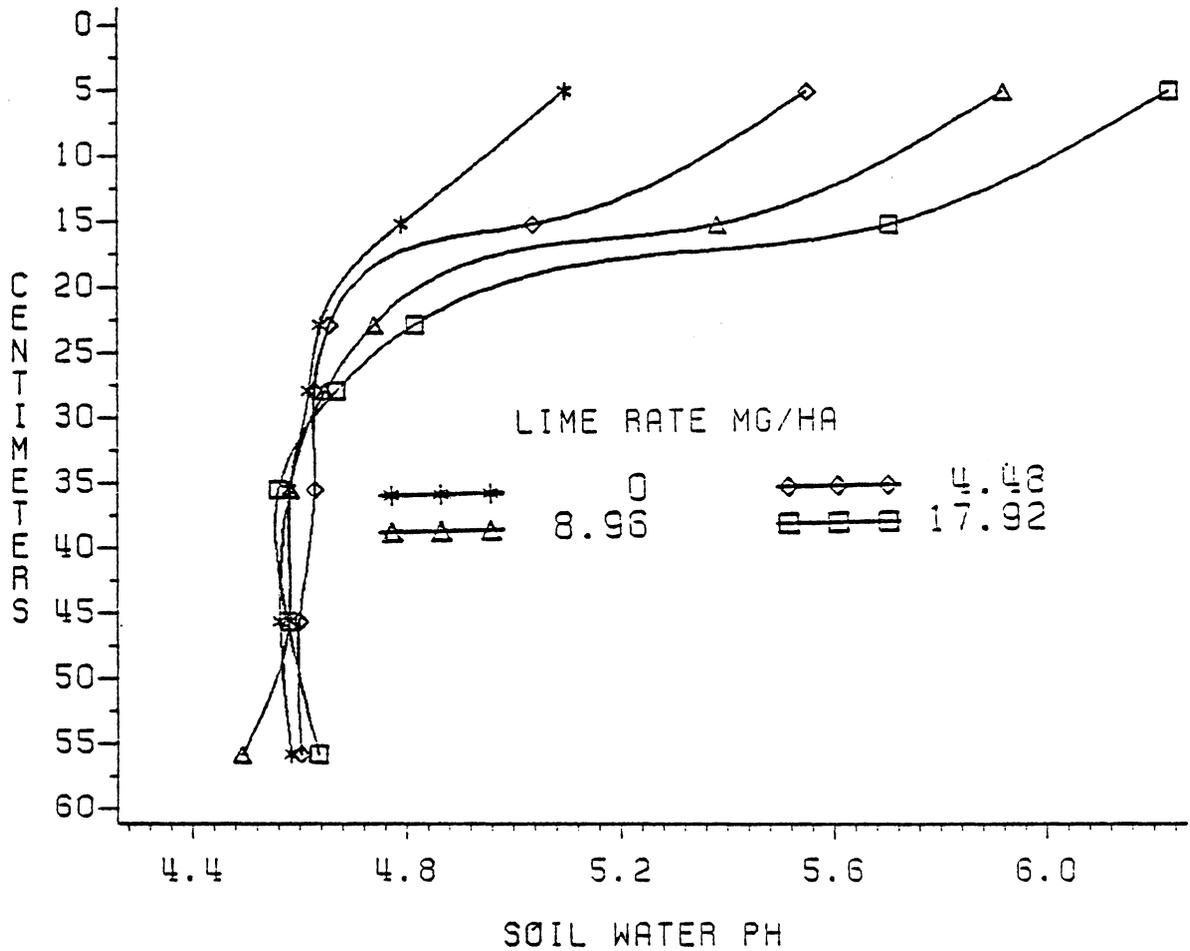


FIG. 34-SOIL WATER PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A FREDERICK SILT LOAM SOIL.

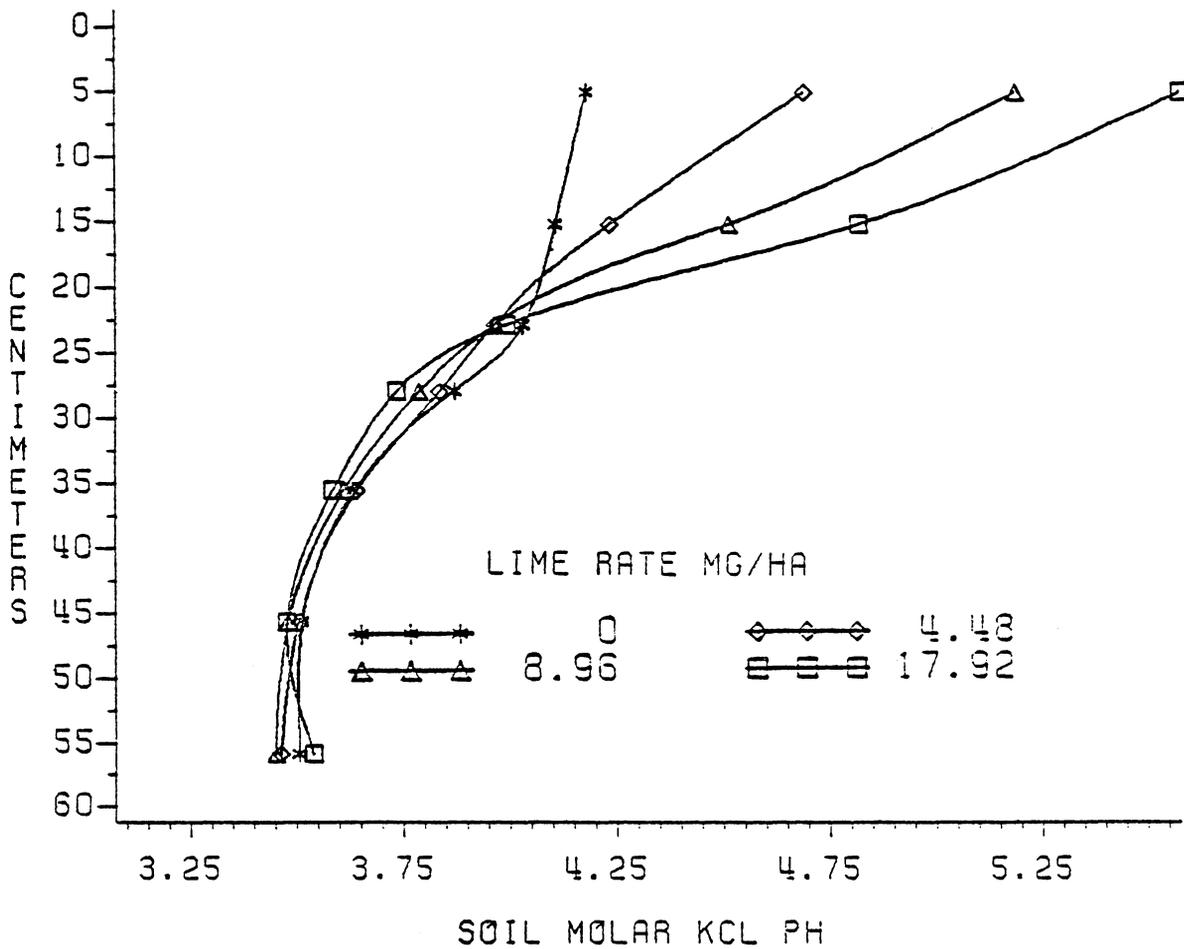


FIG. 35-SOIL MOLAR KCL PH FROM 0-60 CM AS A FUNCTION OF LIME RATE FOR A FREDERICK SILT LOAM SOIL.

35). Although the increase occurred, only the values obtained in the 17.92 Mg ha⁻¹ lime rate were statistically different than the unlimed soil. For this unlimed soil small variations, i.e. 0.7 unit, in salt pH values were determined in the profile (Table 15). These values decreased with increasing depth. In the 5 cm below the plow layer, the pH values obtained were the same regardless of lime rate. The 10 cm above this had a statistically higher value if it had received limestone. Therefore for a given lime rate, hydroxyl movement occurred to a depth of 20 cm. This finding is similar to soil water pH determinations (Table 15).

Chapter V

DISCUSSION

Many differences in the exchangeable cations (Ca, Mg, and Al) and soil pH (water and mol L⁻¹ KCl) resulted from limestone additions and were still detected after three years. These differences were soil and limestone rate dependent.

The field experiments in the Coastal Plain exhibited the greatest changes in soil chemical properties to the greatest depth from limestone applications. The three soils from this region all had different surface textures. Surface texture was an important factor relating to movement. As soil clay content increased, Ca and Mg movement and depth of neutralization was decreased. The Tomotley loam had the highest amount of clay in the surface of these Coastal Plain soils and also had the least amount of cation movement and neutralization. Another contributing factor in this soil was clay type. The Tomotley soil had greater amounts of kaolinite in its clay size fraction which has predominantly pH dependent charges. With the addition of lime, pH dependent CEC would increase and cation retention would be favored. This finding concurs with Juo and Ballaux, (1977).

The Emporia loamy sand had the least amount of clay in the surface. Only slight differences existed between layers

within a given lime rate for Ca and Mg contents. This result indicates that these cations moved readily through the profile. Aluminum was scarcely detected at 40 cm but soil pH determinations did not increase to this extent.

The Goldsboro sandy loam was intermediate to the other two Coastal Plain soils in clay content and intermediate to these soils in Ca and Mg movement as well as Al neutralization. This soil exhibited movement of Mg to greater depths than Ca as seen in the Tomotley. This finding was also observed by Pleysier and Juo (1981). These researchers suggested that Ca may be retained by organic exchange sites previously blocked by polymeric- Al^{+3} ions. An additional possibility for preferential Ca retention would be with regard to clay affinities. The smaller the hydrated radii of an ion the greater it is tightly bound to a clay micelle (Gast, 1977). Calcium has a smaller hydrated radii than Mg, i.e. 4.12×10^{-8} and 4.28×10^{-8} cm, respectively. Therefore, it would be expected to be more attracted to the clay particle.

Another important observation on these Coastal Plain soils was that movement of Mg or Ca was not accompanied by acidity neutralization. Therefore, the cations must be moving as neutral salts and without hydroxyls to reduce acidity. This finding concurs with Pleysier and Juo (1981). If

the Ca or Mg had moved with the hydroxyls, changes in Al and pH would be expected to coincide with increases in Ca and Mg. Since the cations did not leach with hydroxyls, they quite possibly moved with surface applied nitrate from N fertilizers. All of the soils in the Coastal Plain received nitrogen applications during the course of the study. Nitrate has been shown to facilitate cation movement through the soil (Juo and Ballaux, 1977; Pleyzier and Juo, 1981).

The three soils outside of the Coastal Plain that received N fertilization were the Masada loam, the Pacolet sandy clay loam and the Duffield silt loam. In these soils, the movement of Ca and Mg was dependent on surface texture as illustrated in the Coastal Plain. Once again as clay content in the surface increased the movement of cations decreased. Therefore, the Pacolet sandy clay loam had the least amount of cation movement for these three soils. The Duffield silt loam and the Masada loam exhibited more cation movement than observed in the Pacolet sandy clay loam. Regardless, all soils exhibited greater movement of Mg in comparison to Ca.

Variations in neutralization did not differ to any great extent in these soils. All of these soils had a subsoil increase in clay content which further limits cation movement or neutralization.

The Frederick silt loam located in the Ridge and Valley Region did not receive N fertilization since it was cropped in alfalfa. The soil exhibited the least amount of cation movement and level of acidity neutralization of all the soils in the study. The other soil in this region, the Duffield silt loam, had cation movement to a greater degree. The Duffield soil was cropped in corn and received yearly N fertilizer applications. All of the soils in the study, except the Frederick silt loam, received these blanket N applications. The finding that cation movement was greater in all the soils except the Frederick silt loam, supports the thought that the nitrate anion was the predominant anion that made cation movement possible.

Another observation can be made with regard to addition of N fertilizers. These acid producing nitrogenous fertilizers can effectively reduce surface pH values. The soils that received the N showed a slight decrease in pH in the surface 10 cm as a result; however, the Frederick silt loam exhibited no decrease. Furthermore, it had higher values of Ca and Mg in the upper 10 cm since the limestone was not mixed to the degree that it was in the other soils.

Chapter VI

SUMMARY AND CONCLUSIONS

Surface (0-20 cm) applications of dolomitic limestone at rates of 0, 4.48, 8.96, and 13.44 Mg ha⁻¹ on the Coastal Plain and up to 17.92 Mg ha⁻¹ on the Piedmont and Ridge and Valley soils were made to seven acid Virginia soils. Chemical properties of the soils were determined at 5 to 10 cm increments to a depth of 60 cm. Sampling occurred three years following the limestone applications.

Coarser surface textured soils of the Coastal Plain exhibited the most dramatic changes in surface and subsoil chemical properties from the limestone amendment. Movement of Ca was observed from the plow layer (0-20 cm) on all Coastal Plain soils. Magnesium movement was in each case greater than that of Ca. Reasoning for differences in selective ion movement in the soils is attributed to differences in hydrated radii for these two cations. Calcium has a smaller hydrated radii and is more tightly held than Mg. Neutralization of soil acidity as measured by decreases in exchangeable Al, and increases in both soil water pH and soil mol L⁻¹ KCl pH were measured below the plow layer in all soils of the Coastal Plain. Acidity neutralization did not coincide with cation movement in a given soil suggesting that

the cations moved as neutral salts. Surface additions of nitrate producing N fertilizers are suggested as a major source for accompanying anions. It was also observed that addition of these fertilizers increased the active acidity in the surface.

Results for soils cropped in continuous corn, corn-barley, or corn-barley- soybean rotations in the Piedmont and Ridge and Valley physiographic provinces illustrate that similar factors affect movement in all regions. Initially, surface texture is important. Generally, these soils had a greater amount of clay in the surface than the Coastal Plain soils. The result of this was less cation movement and neutralization of acidity to a lesser degree. Calcium movement into the profile was repeatedly less than Mg movement. These soils received N fertilization which supplied potentially accompanying anions. Cation movement and acidity neutralization below the plow layer were not only soil dependent, but limestone rate dependent. In some instances, movement of cations or decreases in acidity were not detected below the plow layer.

One soil located in the Ridge and Valley physiographic province was in alfalfa during the period of study. This soil did not receive yearly plowing, disking, and applications of N. The differences in management coupled with

higher clay contents in the surface of this soil as compared to the Coastal Plain soils greatly restricted cation movement and acidity neutralization. Of the parameters measured only Mg at the highest rate of application showed a change from the unlimed soil below the original plow layer.

Based on this research the following conclusions can be made:

1. Movement of cations and depth of acidity neutralization is dependent on the amount of clay present in the soil and the amount of limestone applied.
2. Magnesium moves more readily through the profile than Ca, most likely with surface applied nitrates.
3. Increased surface loading of liming materials to decrease subsoil acidity in the upper 50 cm did not occur over a short period of time in these seven acid soils of Virginia.

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THE MOVEMENT OF CALCIUM AND MAGNESIUM IN SELECTED VIRGINIA
SOILS FROM SURFACE APPLIED DOLOMITIC LIMESTONE

by

Donald Lee Messick

(ABSTRACT)

Surface (0-20 cm) dolomitic limestone treatments of 0, 4.48, 8.96, and 13.44 Mg ha⁻¹ on the Coastal Plain and up to 17.92 Mg ha⁻¹ on the Piedmont and Ridge and Valley soils were made to seven acid Virginia soils. These amendments were made to document movement of Ca and Mg as well as neutralization of soil acidity within these soil profiles. During the fourth growing season following application, samples in 5 or 10 cm increments were taken to a depth of 60 cm. Soil chemical properties (soil water pH, soil mol L⁻¹ KCl pH, exchangeable Ca, Mg, and Al) were determined.

Calcium and Mg movement and depth of neutralization decreased as soil clay content increased. These cations moved through the sampling depth in the coarse-textured Emporia loamy sand, but neutralization was only evident to the 50 cm depth. The Pacolet sandy clay loam, with the high percentage of clay in the surface horizon, showed no movement of Ca from the surface layer and Mg movement was limited to 25 cm. Liming increased pH dependent CEC which increased cation retention in the horizons receiving direct lime application. Depth of neutralization was lime rate dependent

with higher rates resulting in greater acidity neutralized. The Pacolet soil illustrated increasing water pH values to the 25 cm depth, in comparison to the subsoil at the 8.96 and 17.92 Mg ha⁻¹ rates of lime application.

Magnesium movement was detected at greater depths than Ca in all soils. Neutralization of acidity did not accompany Mg movement, demonstrating that the cation moved as a neutral salt.

Results indicate that subsurface chemical properties will be affected in soils cropped in continuous corn or corn-soybean rotations as opposed to crops of continuous alfalfa. Despite cation movement in the profile, neutralization of acidity may not occur beyond the plow layer, i.e. the Frederick silt loam or may occur to a depth of 50 cm, i.e. the Emporia loamy sand, with the other soils being intermediate.