USE OF LIME-STABILIZED PRODUCT
AS AN AGRICULTURAL LIMING AGENT

by

W. J. Rogers and F. R. Cox

Soil Science Department
North Carolina State University
Raleigh, North Carolina 27695-7619

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Thanks are expressed to the staffs of both The Piedmont Research Station near Salisbury, N.C. and the Upper Coastal Plain Research Station near Rocky Mount, N.C. Their help conducting the field experiments was invaluable to the total research project.
Municipalities need efficient, economical means of sludge disposal. When sludge is stabilized with lime it may be applied safely to land and be beneficial to agriculture by reducing soil acidity. However, proper rates of application must be determined. These application rates should be based on the calcium carbonate equivalence (CCE) of the material and lime requirement of the soil. Rates of lime-stabilized sludge (LSS) were compared with those of dolomitic agricultural lime in incubation, greenhouse, and field experiments on soils from North Carolina that varied in clay and organic matter content. The materials neutralized soil acidity similarly at the same CCE rates with only slight differences noted among the types of studies. The LSS reacted more quickly in the greenhouse and field experiments, whereas the agricultural lime reacted more quickly in the incubation experiment. These effects were maintained for three crops in the greenhouse and three years in the field experiments. The LSS supplied more Ca and less Mg to plants than agricultural lime. Therefore, the soil Mg status should be considered in addition to soil pH when determining the correct type and rate of material to apply.
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SUMMARY AND CONCLUSIONS

With increased regulations, sludge disposal is becoming more expensive. Lime stabilization of sludge has the potential of being somewhat economical as a means of disposal. Lime-stabilized sludge (LSS) may be able to serve as a replacement for agricultural lime; however, the effectiveness of LSS must first be known. The objectives of this study were to compare LSS and agricultural lime in regard to contents, effects on soil chemical properties, plant uptake of elements, and crop yield.

The two materials were applied to several North Carolina soils at varying rates in incubation, greenhouse, and field experiments. The soils used varied in clay and organic matter content. LSS had a calcium carbonate equivalence (CCE) of 84% whereas the agricultural lime had a CCE of 96%. The rates applied, in terms of 100% CCE, were up to 8960 kg ha\(^{-1}\) in the incubation and greenhouse and 4480 kg ha\(^{-1}\) in the field experiments. At these application rates, contributions of heavy metals from LSS were within safe limits.

The change in soil acidity, as measured by pH, was the most important soil property considered. Soil pH increased with increasing application rate of either LSS or agricultural lime. The agricultural lime seemed more effective than LSS in increasing pH in the incubation study, whereas the LSS tended to be more effective than agricultural lime in the greenhouse and field studies.

The reactions occurred very rapidly with both materials, but especially so with LSS. After application the pH remained elevated during growth of the three crops in the greenhouse experiments and three years in the field experiments. Although soil pH would be expected to decrease more rapidly with LSS than agricultural lime due to the finer particle size, this was not consistently shown in either the third crop in the greenhouse or the third year in the field. As a consequence, both materials should be considered equally effective in decreasing soil acidity for at least two years, and perhaps longer.

There were consistent differences due to the material applied in soil and plant Ca. The LSS contained more Ca than agricultural lime, and this was reflected in both the soil and plant analysis. On the other hand, agricultural lime contained more Mg than LSS. Also, this was again reflected by the soil and plant analysis. The smaller amount of Mg in the LSS is of concern, since agricultural lime has been the major source of Mg applied to soils in the past. In addition to soil pH the Mg status of the soil should be considered to determine if LSS is an appropriate
liming material. A routine soil test will show if there is a particular need for Mg.

Applications of both LSS and agricultural lime decreased the uptake of Mn. This effect must be monitored to avoid inducing a Mn deficiency. Again, a routine soil test will disclose a potential Mn deficiency.
RECOMMENDATIONS

Lime-stabilized sludge (LSS) has the potential to be used as an agricultural liming agent. LSS neutralizes soil acidity as well as standard agricultural lime when applied at the same CCE rates. Each batch of LSS should be evaluated for CCE and nutrient composition before land application since the composition of sludge can vary widely. Both the CCE and soil liming requirement need to be determined before an application rate is decided on. There was concern that LSS would not have the longevity in neutralizing soil acidity as well as standard agricultural lime, but this was not confirmed in the three years of this study. For agriculture producers that are looking for a fast reacting lime, LSS will often be a viable product.

LSS supplies more Ca, but less Mg at the same CCE application rate than agricultural lime. The lesser amounts of Mg will be of more concern in the Coastal Plain where soil Mg is naturally low than in the Piedmont. Piedmont soils are higher in Mg and may not need the added Mg from dolomitic agricultural lime. Nevertheless, soil Mg should also be considered in addition to soil pH when determining the type and amount of a liming material to apply. If LSS is applied and Mg is needed, an outside source of Mg should be included.

The LSS used in our studies was extremely low in metal and other micronutrient concentrations. Concerns about heavy metal loading rates will need to be evaluated with each batch of LSS produced. Application rates need to be calculated correctly, since an over application of LSS could raise soil pH to a level that may induce Mn and other micronutrient deficiencies.
INTRODUCTION

Traditionally, municipal waste water treatment plant personnel have disposed of sludge either by incineration, landfilling, or land application. Land application is often one of the most cost-effective disposal options available to municipalities. Passage of 40 CFR Part 503, Standards for the use or Disposal of Sewage Sludge, in 1993 limits concentrations of ten heavy metals: As, Cd, Cr, Pb, Ni, Cu, Zn, Hg, Mo, and Se in sludge being applied (USEPA 1993). Maximum cumulative metal loading limits for the soil are also established in Part 503. Once a site has reached regulated levels, sludge may no longer be applied. Municipalities will need to either purchase or rent more land to apply their sludge. Over the last few years land application has become increasingly costly due to increased rental or purchasing cost. Therefore, municipalities are experimenting with new methods of disposal.

One new method of sewage sludge utilization is to stabilize the sludge with some form of liming material: wood ash, Ca(OH)₂, dolomitic lime, or CaO. The liming agent is added to the sludge after it has been dewatered. Two main sources of lime used are quicklime, CaO, and hydrated lime, Ca(OH)₂. With the addition of quicklime there is an increase in both the temperature and pH of the sludge. These changes cause pathogens and odor-causing organisms within the sludge to be killed by raising the temperature above 70°C and giving the final product a pH above 11.5.

Many methods of utilization for this lime-stabilized material have been proposed. They include use as a daily and final landfill cover, fill, soil conditioner, and as an agricultural liming agent. The calcium carbonate equivalence (CCE) of LSS can vary according to the liming material being used in the stabilization process. When quicklime is used as the liming material LSS can have a CCE of 75-85%, just slightly less than traditionally used agricultural lime, 90-95%. The reason for this is that quicklime has a CCE of 160% and is then diluted approximately in half with the addition of sludge. With this relatively high CCE, LSS is potentially an adequate liming material for use by the agronomic community. The LSS can supply small quantities of phosphorus and potassium for crop production. However, only a limited quantity of nitrogen would be available due to ammonia volatilization caused by the increased pH and temperature within the product.

Land application of sewage sludge has traditionally been based on the availability of nitrogen from the sludge. Due to the limited
amount of nitrogen present a new method of determining application rates needs to be evaluated. Applications of LSS based on the nitrogen content would raise soil pH to a level that would be detrimental to plant growth. Since the CCE of LSS is the limiting factor, application rates should be based on the CCE of the material.

It has been reported that the addition of sewage sludge to corn, small grains, and grasses can significantly increase yields (Hinesly et al. 1972, Lunt 1953, Evans 1968, Kelling et al. 1976). In these studies the yield increases correlated with increased soil nitrogen and phosphorus. Lutrick et al. (1986) also found an increase in the growth of young pines with applications of sewage sludge up to 60 Mg ha$^{-1}$. Soon et al. (1978a) found that with either Fe- or Ca-sludge applications up to 800 kg total N ha$^{-1}$ there was an increase in bromegrass yield. These yields were equivalent to 200 kg N ha$^{-1}$ from NH$_4$NO$_3$. In a second study with corn, Soon et al. (1978a) found that application of 200 kg total N ha$^{-1}$ from sludge increased yields as much as an application of 100 kg N ha$^{-1}$ from NH$_4$NO$_3$. Nitrogen from sewage sludge is not completely available for plant production. Much of the nitrogen is tied in organic forms. This is why a higher application of nitrogen from sewage sludge had to be applied to obtain the same yields as a lower application of nitrogen from NH$_4$NO$_3$.

Coker (1966a, 1966b) reported that sewage sludge increased dry matter production as well as equivalent amounts of commercial fertilizer. In these same studies Coker also found there was more phosphorus taken up by plants with applications of sewage sludge than with equal applications of inorganic fertilizers. Cavallaro et al. (1993) reported a significant increase in soil extractable phosphorus with applications of sewage sludge. Soil pH was slightly increased with a sludge application rate of 24 metric tons ha$^{-1}$. Lastly, there were significant increases in soil Ca and K and a significant decrease in soil Mg with sludge applications. Hue (1988) reported that three years after the application of 180 Mg sludge ha$^{-1}$ there were significant increases in soil pH, Ca, P, and K.

Sewage sludge has also been used to add organic matter to soils high in sand content and to aid in revegetation of coal mine spoils. Sewage sludge at a rate less than 83 Mg ha$^{-1}$ was found to benefit seeded grass growth on coal mine spoils (Topper and Sabey 1986). The investigators attributed the additional growth to measured increases in nutrient availability, improved physical condition of the spoil, and a possible stimulation of microbial activity. Pietz et al. (1989) applied sludge, on a dry weight basis, at 542 Mg ha$^{-1}$ with an additional 89.6 Mg ha$^{-1}$ of lime to
establish vegetative growth on acidic coal refuse material. It was concluded that the sludge could supply growing plants needed N and P along with most of their K. It was also reported that repeated applications of sewage sludge increased soil Cd, Cu, Ni, Zn, and other metals (King and Hajjar 1990, King and Giordano 1986).

Various studies in the past have used LSS to increase soil pH, soil Ca, and yields. It was reported that the application of a lime-stabilized manure to a low pH soil increased yields and soil pH (Vivekananden et al. 1991, Soon et al. 1978b). Brown and Brush (1992) found that the application of lime-stabilized sludge increased soil pH but also decreased Cd uptake in red clover and radish. Ritter et al. (1992) reported that applications of lime-stabilized sludge increased soil pH without affecting ground water quality on a 70% sand soil. In these studies the authors did not consider the CCE liming potential of the material and adjust their application rates accordingly. Little et al. (1991) compared LSS and CaCO₃ at the same CCE rates and reported that both materials reacted at the same rates. Also, yields decreased more rapidly with CaCO₃ than with the LSS at applications over the recommended liming rates.

Lime applications to agriculture fields have been shown to increase yields (Alley 1981, Kuo 1993, Buerkert et al. 1990, and Palazzo and Duell 1974). The chemistry of soils is also affected by the applications of lime. Hutcheson and Freeman (1964) and Bhumbla and Mclean (1965) found that hydrated lime applications increased soil pH, Ca, and Mg while decreasing soil Al. Kamprath (1970) reported that maximum growth occurs after a certain amount of exchangeable Al has been neutralized and that dolomitic lime applied to do this supplies Ca and Mg.

Excessive lime rates may be harmful to crop production. An increase in soil pH from 5.6 to 6.8 can decrease yields (Carran 1991). Carran also reported that excessively high applications of Ca from calcareous limestones can damage white clover growth. This damage to white clover was attributed to a high Ca:Mg ratio causing a Mg deficiency. Lime applications need to be based not only on soil acidity, but also Ca and Mg needs for plant growth.

According to the North Carolina Liming Materials and Landplaster Act (Chapter 106, Article 8A of the General Statutes, North Carolina Agricultural Liming Materials and Landplaster Act), there are two types of limestone; calcitic, which contains less than 6% magnesium (Mg), and dolomitic which contains greater than 6% Mg. With calcitic limestone, at least 90% of the material must pass through a 20 mesh screen and at least 25% must pass
through a 100 mesh screen. With dolomitic limestone, 90% of the material must pass through a 20 mesh screen and 35% must pass through a 100 mesh screen. The size differences reflect the hardness of the parent rock. Most agricultural lime is ground just enough to meet these specifications. Therefore, there is a range in particle size that affects the rate of reaction in the soil. Smaller particles react more quickly than larger particles (Pierre 1930, Meyer and Volk 1952, Leda and Wright 1991). Therefore, there is not only an immediate response to liming but also a prolonged effect that ordinarily lasts over several years due to the slower reaction of the coarser particles.

It is very important that any new material, such as LSS, be evaluated as to how quickly it will react and over how long a period it will continue to neutralize soil acidity. It will also be important to evaluate the availability of other elements such as Ca, Mg, N, P, K, and heavy metals to see how they may affect soil properties and plant growth. In this study we compared LSS to a standard agricultural lime to determine how quickly acidity is reduced, how long that effect will last, and how plant nutrition may be affected.
OBJECTIVES

The objectives of this study were to determine:
(1) the chemical and physical properties of LSS and an agricultural (dolomitic) lime,
(2) how, over time, these materials affect acidity and other properties of several North Carolina soils, and
(3) how the resulting soil properties affect nutrient uptake and growth of several crops.
PROCEDURES

Three types of studies were conducted to compare the effects of LSS and agricultural lime: incubation, greenhouse, and field. The incubation experiment was conducted with four soils. Evaluations of soil properties were made soon after application. Two greenhouse studies were conducted using three soils. Effects of application on soil properties, plant uptake of elements, and dry weight production were monitored. Three field experiments, at two locations, were conducted evaluating the effects listed above, but under natural environmental conditions.

The LSS used in all three types of studies was provided by the Charlotte-Mecklenburg Utility Department (CMUD), a member of the Urban Water Consortium. At their pilot facility quicklime is blended with dewatered sludge, 20% total solids, using a Leopold Plowblender at an approximate ratio of 1.4:1.0, quicklime to sludge, on a dry weight basis. After blending, LSS is allowed to sit for a minimum of three days to promote cooling and allow for the volatilization of ammonia. The final product has a total solid concentration of 40 to 55 percent. Calcium carbonate equivalency was determined by adding an excess of acid to react with the material, then back titrating to determine the amount of acid neutralized. This standard method is published in the latest edition of the Journal of the Association of Official Analytical Chemists.

Incubation Study

Four soils, Hiwassee, Cecil, Goldsboro, and Portsmouth, with low initial pH values and a range in clay and organic matter contents were selected (Tables 1 and 2). Hiwassee and Cecil soils are from the Piedmont region of North Carolina and contain a greater clay content than the other two soils. The Hiwassee soil was collected from the north end of field C38 on the Piedmont Research Station near Salisbury, N.C. The Cecil soil was collected from the south end of field A1hn located on the Camp Dan Allen section of the Upper Piedmont Research Station near Reidsville, N.C. The Goldsboro and Portsmouth soils are from the Coastal Plain region of North Carolina and vary in organic matter due to differences in drainage. The Goldsboro soil was collected from the north end of field G4a on the Peanut Belt Research Station near Lewiston, N.C. The Portsmouth soil was collected from the south end of field N2 on the Tidewater Research Station near Plymouth, N.C. All soils were allowed to air dry and then were ground to pass a 2-mm sieve.
Agricultural lime and LSS were applied at calcium carbonate equivalent (CCE) rates of 0, 2240, 4480, and 8960 kg ha\(^{-1}\). The composition of the two materials is given in Table 3. Soils were then wet to field capacity (0.1 bar) (Klute 1986) and placed in plastic bags on a laboratory bench at room temperature. Subsamples were taken at 1, 2, 4, 8, and 16 weeks after application of the materials.

Table 1. Taxonomic names of soils used in all experiments

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<tr>
<td>Cecil</td>
<td>clayey, kaolinitic, thermic Typic Kanhapludult</td>
</tr>
<tr>
<td>Goldsboro</td>
<td>fine-loamy, siliceous, thermic Aquic Paleudult</td>
</tr>
<tr>
<td>Hiwassee</td>
<td>clayey, kaolinitic, thermic Typic Rhodudult</td>
</tr>
<tr>
<td>Portsmouth</td>
<td>Fine-loamy over sandy or sandy skeletal, mixed, thermic Typic Umbraquult</td>
</tr>
<tr>
<td>Roanoke</td>
<td>clayey, mixed, thermic Typic Ochraquult</td>
</tr>
<tr>
<td>Wilkes</td>
<td>loamy, mixed, thermic, shallow Typic Hapludalf</td>
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</table>

Each sample was analyzed for soil pH, Ca, Mg, K, P, Cu, Zn, and Mn. Soil pH was measured in a 1:1 soil-water ratio suspension. Calcium, Mg, K, Cu, Zn, and Mn were extracted with the Mehlich-3 solution (Mehlich 1984) and were read by Atomic Absorption Spectrophotometry (AAS). Phosphorus was extracted with Mehlich-3 and analyzed colorimetrically following the methods of Murphy and Riley (1962).

The experimental design was a randomized complete block with three replications. Treatment variables included soil, liming material, and application rate, arranged factorially. Statistical analysis was conducted using analysis of variance procedures in PC-SAS. (SAS Institute 1987). Effects were considered significant if the F-test was significant at a probability of 0.05 or less.
Table 2. Initial pH, organic matter content, and clay content of the soils used in all three types of experiments

<table>
<thead>
<tr>
<th>Soil</th>
<th>Initial pH</th>
<th>Organic Matter</th>
<th>Clay Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cecil</td>
<td>4.4</td>
<td>2.0</td>
<td>36.0</td>
</tr>
<tr>
<td>Goldsboro</td>
<td>4.4</td>
<td>1.9</td>
<td>6.5</td>
</tr>
<tr>
<td>Hiwassee</td>
<td>5.2</td>
<td>1.3</td>
<td>50.6</td>
</tr>
<tr>
<td>Portsmouth</td>
<td>4.3</td>
<td>8.8</td>
<td>15.5</td>
</tr>
<tr>
<td>Roanoke</td>
<td>5.2</td>
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</tr>
<tr>
<td>Wilkes</td>
<td>6.0</td>
<td>2.9</td>
<td>16.8</td>
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</table>

Table 3. Calcium carbonate equivalency and elemental composition of LSS and agricultural lime

<table>
<thead>
<tr>
<th>CCE</th>
<th>N</th>
<th>Ca</th>
<th>Mg</th>
<th>P&lt;sup&gt;1&lt;/sup&gt;</th>
<th>K&lt;sup&gt;2&lt;/sup&gt;</th>
<th>S</th>
<th>Fe</th>
<th>Mn</th>
<th>Zn</th>
<th>Cu</th>
<th>B</th>
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<tr>
<td>---</td>
<td>84</td>
<td>12</td>
<td>320</td>
<td>3</td>
<td>6</td>
<td>1.2</td>
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<td>3568</td>
<td>152</td>
<td>21</td>
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</tbody>
</table>

<sup>1</sup> P x 2.29 = P<sub>2</sub>O<sub>5</sub>
<sup>2</sup> K x 1.21 = K<sub>2</sub>O
na = not analyzed
Greenhouse Studies

Two greenhouse studies were initiated to examine the rate of reaction and elemental uptake by different crops from soils treated with LSS in comparison to an agricultural lime. In both experiments, three soils: Cecil, Goldsboro, and Portsmouth were selected with low initial soil pH values and a range in clay and organic matter contents (Table 2).

Experiment 1:
Four rates of agricultural lime and LSS were incorporated into 72 pots; the other 72 pots did not receive any application at this time. Both materials were applied at CCE rates of 0, 2240, 4480, and 8960 kg ha\(^{-1}\). All pots were seeded with fescue (\textit{Festuca arundinacea} Schreb 'K31'). After six weeks the untreated pots received a surface application of agricultural lime or LSS with the same application rates as the incorporated treatments.

The experimental design was split split split plot. The whole plot was soil type, the first split was application method, the second split was source of liming material applied, and the third split was application rate. Each treatment was replicated three times.

Fescue was harvested every six weeks for a total of five cuttings for the incorporated treatments and four cuttings for the surface application treatments. Yields were determined at each harvest. Plant samples were dried at 70°C for 72 hours, ground to pass a 20-mesh screen, dry ashed for 12 hours at 500°C in a muffle furnace, and dissolved in 6 M HCl. Phosphorus, Ca, Mg, K, Cu, Fe, Al, B, S, Cd, Cr, Pd, and Ni were determined by ICP (Inductively Coupled Plasma Spectrophotometer). After the last harvest, soil samples were collected and analyzed for soil pH, P, K, Ca, Mg, Cu, Zn, and Mn with the same methods used in the incubation study. Statistical analysis was conducted using PC-SAS as in the incubation study.

Experiment 2:
In the second greenhouse experiment corn (\textit{Zea mays} L. 'Dekalb 689'), wheat (\textit{Triticum aestivum} L. 'Coker 9803') and soybeans (\textit{Glycine max} L. 'Delta Pine 417') were grown. Agricultural lime and lime-stabilized sludge were applied to three soils: Cecil, Goldsboro, and Portsmouth. Four CCE rates of 0, 2240, 4480, and 8960 kg ha\(^{-1}\) were incorporated into the soil. The pots were wet to field capacity and allowed to sit for two weeks. Corn was then seeded into the pots and allowed to grow for six weeks.
After six weeks the corn was harvested and soil and plant samples collected. Wheat was then planted into the pots and allowed to grow for six weeks. Soybeans were then planted and allowed to grow for eight weeks. At harvest yield, soil, and plant samples were collected.

All soil and plant samples were analyzed using the previously cited methods in the incubation and greenhouse studies. The design of this study was a split split plot. The whole plot was the soil type, materials applied was the first split, and the rate of application was the second split. All statistics were completed using PC-SAS and differences were significant at $P = 0.05$.

Field studies

Three field experiments were conducted to examine the viability of using lime-stabilized sludge as an agricultural liming material. Each of the three experiments was designed as a randomized complete block with a split plot arrangement of treatments; the material applied being the whole plot and the rate of application being the split plot. Four CCE rates of 0, 1120, 2240, and 4480 kg ha$^{-1}$ were applied. Each treatment was replicated four times.

Rocky Mount

The first experiment was conducted on the Fountain Farm of the Upper Coastal Plain Research Station near Rocky Mount, N.C. The study was in a continuous corn rotation on a Roanoke loam for three years (Table 1 and 2).

The material was applied on February 1, 1993, and lightly disked. Due to wet weather the material was not incorporated more thoroughly until April 29 when a deep rotovator was used for complete mixing of the liming materials into the plow layer (20 cm). Corn ('Dekalb 689') was planted on April 30. Six weeks after planting, whole corn plant and soil samples were collected on June 11. Soil samples were taken of the top 20 cm; ten cores were collected from each plot, mixed, and subsampled. Twenty corn ear leaf samples were collected at anthesis on July 8. At harvest yield, grain, and soil samples were collected on September 20. Soil and plant samples were analyzed as in the incubation and greenhouse studies.

On April 18, 1994, corn ('Pioneer 3245') was planted for a second year. Whole plant and soil samples were collected on May 27. On
July 5 ear leaf samples were collected. The corn was harvested on October 12; soil and grain samples were also collected at this time. Soil and plant samples were analyzed using earlier-stated procedures.

Corn ('Pioneer 3394') was again planted on April 5, 1995. Soil samples were collected in the spring on May 23. Ear-leaf samples were collected at anthesis on July 5. Corn was harvested on August 30.

**Salisbury fescue**

Two other experiments were initiated on the Piedmont Research Station near Salisbury, N.C. These studies were conducted on a Wilkes sandy loam (Table 1 and 2).

The first experiment was conducted on an established pasture planted in fescue (Festuca arundinacea 'AU Triumph') in October 1988. LSS and agricultural lime were surface-applied on December 16, 1992. The first harvest was on May 10, 1993, when plant and soil samples were collected. Other fescue harvests were on December 13, 1993; May 12, 1994; November 15, 1994; May 9, 1995; and July 14, 1995. At each harvest, plant and soil samples were collected and analyzed using previously stated procedures. Soil samples at the first five samplings consisted of ten 10 cm cores mixed to create one subsample. On July 14, 1995, soil samples were collected to two depths, 0-10 cm and 10-20 cm. The sampling with depth was to evaluate the movement of cations through the soil profile.

**Salisbury row crop**

The second experiment was planted in a corn, wheat/soybean rotation. After the initial incorporation of the materials this study was in a continuous no-till system. LSS and agricultural lime were applied on December 16, 1992, and lightly disked. Due to wet weather the materials were not completely incorporated in the top 20 cm with a rotovator until May 3, 1993. Corn ('Dekalb 689') was planted on May 4. Whole corn plant and soil samples were collected on June 15. Soil samples were taken of the top 20 cm; ten cores were collected from each plot, mixed, and subsampled. Corn ear leaf samples were collected at anthesis on July 13. The corn was harvested on September 28, and at this time soil and grain samples were also collected.

Wheat ('Coker 9803') was planted on October 31, 1993. Whole wheat plant and soil samples were collected on April 14, 1994.
On June 20, the wheat was harvested; yield, soil, and grain samples were collected. All soil and plant samples were analyzed using previously stated procedures.

Soybeans ('Holladay') were planted on June 22, 1994, and due to a weak stand were replanted on July 13. Soybean leaf samples were collected during flowering on August 23. Yield data and grain samples were collected at harvest on November 15. Soil samples were collected on December 14. All soil and plant samples were analyzed using previously stated procedures.

Corn ('Dekalb 683') was planted on April 18, 1995. Soil samples were collected on June 15. Corn ear leaf samples were collected on July 6. The corn was harvested on September 30. All plant and soil samples were analyzed as earlier stated.
RESULTS AND DISCUSSION

Material analyses

LSS has higher concentrations of Ca, P, K, S, Fe, Mn, Zn, and Cu than agricultural lime (Table 3). However, agricultural lime contains a greater concentration of Mg. LSS metal concentrations are consistently well below the limits of 40 CFR Part 503 regulations for metal concentrations (Table 4). LSS is also well below the high quality limits of 40 CFR Part 503. McBride (1995) has stated concerns that the metal concentration limits of 40 CFR Part 503 may have been set too high and that applications within these standards may be toxic to plants. Since metal concentrations of LSS are well below the high quality limits, there should be no concern about toxicities with normal application rates.

Table 4. Metal composition of LSS and 40 CFR Part 503 regulations

<table>
<thead>
<tr>
<th></th>
<th>As</th>
<th>Cd</th>
<th>Cr</th>
<th>Cu</th>
<th>Hg</th>
<th>Mo</th>
<th>Ni</th>
<th>Pb</th>
<th>Se</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;0.5</td>
<td>&lt;0.8</td>
<td>37</td>
<td>114</td>
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<td>3.8</td>
<td>6</td>
<td>19</td>
<td>&lt;5.0</td>
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<td>40 CFR Part 503 Maximum Limits</td>
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<td>85</td>
<td>3000</td>
<td>4300</td>
<td>57</td>
<td>75</td>
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<td>840</td>
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<td>7500</td>
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<td>40 CFR Part 503 High Quality Limits</td>
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<td>39</td>
<td>1200</td>
<td>1500</td>
<td>17</td>
<td>na</td>
<td>420</td>
<td>300</td>
<td>100</td>
<td>2800</td>
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</tbody>
</table>

na = not applicable

Agricultural lime and LSS had different calcium carbonate equivalence (CCE). Agricultural lime had a CCE of 96% while the LSS had a CCE of 84%. Due to the different CCE's the materials had to be applied at different total rates to achieve the same CCE application. Since the materials were applied at different total rates and contents, there were differing amounts of macro
and micronutrients applied. The CCE application rates, total application rates, and rates of selected macro and micronutrients applied are presented in Table 5.

Table 5. Total application rates along with selected total nutrients of LSS and agricultural lime applied for all incubation, greenhouse, and field experiments

<table>
<thead>
<tr>
<th>CCE rate</th>
<th>Total application rate kg ha⁻¹</th>
<th>Ca</th>
<th>Mg</th>
<th>P</th>
<th>Zn</th>
<th>Mn</th>
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<td>1120</td>
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<td>427</td>
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<td>0.79</td>
</tr>
<tr>
<td>2240</td>
<td>2666</td>
<td>854</td>
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<td>16</td>
<td>0.54</td>
<td>1.58</td>
</tr>
<tr>
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<td>5333</td>
<td>1708</td>
<td>16</td>
<td>32</td>
<td>1.08</td>
<td>3.16</td>
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<td>Agricultural lime</td>
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<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

Incubation Study

Soil pH increased during the 16-week period with the addition of LSS and agricultural lime (Table 6). The largest percentage of the total reaction occurred in the first week after application. After one week, the pH increase was linear in all soils except the Hiwassee, in which it did not continue to increase after the 4480 kg ha⁻¹ application rate of agricultural lime (Figure 1). The pH increase after one week tended to be greater for agricultural lime than LSS for three of the soils, but the effect was significant only when applied at 8690 kg ha⁻¹ to the Portsmouth soil.

There were minor fluctuations in the pH increase during the 1- to 16-week period for all soils. Examples of the change in pH for the two sources applied at 8960 kg ha⁻¹ are shown for the four soils in Figure 2. In the Cecil soil there was a rapid increase the first week and then a gradual increase through the sixteenth
week, while in the Hiwassee, the soil pH increased slightly from the first week to the fourth week and then plateaued. In the Goldsboro soil, pH increased to a plateau in the first week and then changed little thereafter. With the Portsmouth soil there was an increase in soil pH for two to four weeks and then a plateau. As previously indicated, agricultural lime increased soil pH higher than LSS when the sources were applied at 8960 kg ha\(^{-1}\) on the Portsmouth soil.

With the applications of either liming material there were additions of other nutrients. A significant difference in P, Ca, Mg, Zn, and Mn existed between the two materials. LSS contains more P, Ca, Zn, and Mn, however, agricultural lime contains more Mg. LSS had a lower concentration of Mg than did agricultural lime (Table 3).

Both materials increased soil Ca with increasing application rates on all soils (Table 6). However, applications of LSS increased soil Ca significantly higher than did the application of agricultural lime. There were large increases in soil Mg with the application of agricultural lime, but only a slight increase in soil Mg with the application of agricultural lime, but only a slight increase in soil Mg with the application of LSS.

Soil P increased with increasing application rate of LSS, but not with agricultural lime (Table 7). This increase was consistent from the first through the sixteenth week. With the application of LSS at a rate of 8960 kg ha\(^{-1}\) there was a phosphorus recovery of 98% for Cecil, 76% for Hiwassee, 389% for Goldsboro, and 186% for Portsmouth soils. Cox (1994) predicted a recovery of 24% for Cecil, 13% for Hiwassee, 77% for Goldsboro, and 54% for Portsmouth based on the clay percentage of the soils. Cox's work was conducted in the field with the application of inorganic fertilizer. The differences may be attributed to the change in type of fertilizer and other changes induced in the soil. The recoveries of greater than 100% may be due to P becoming available that was formerly fixed and not readily extractable with a routine soil test.

Both LSS and agricultural lime increased soil Zn with increased applications (Table 7). LSS has a larger concentration of Zn than does agricultural lime (Table 3). Therefore, LSS was expected to raise soil Zn significantly higher than agricultural lime. However, there were no significant differences between the materials' ability to increase soil Zn with increased rate of application for all soils except the Goldsboro. The Cecil and Hiwassee soils are higher in clay content than the Goldsboro (Table 2). Clays and organic matter adsorb Zn quite strongly (Farrah and Pickering 1977, Wada and Abd-Elfattah 1978, Shuman
Table 6. Effect of LSS and agricultural lime at four CCE rates on soil pH, calcium, and magnesium of four soils for 1 to 16 weeks after application in the incubation study

<table>
<thead>
<tr>
<th>Src</th>
<th>CCE Rate</th>
<th>Weeks after application</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>Lime</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cecil</td>
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</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>4480</td>
<td>5.5 3.3 2.5</td>
</tr>
<tr>
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<td>8960</td>
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</tr>
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<td>6.6 9.2 3.8</td>
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<tr>
<td></td>
<td>8960</td>
<td>6.0 5.9 1.7</td>
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† Units of Ca and Mg are in cmol dm⁻³

- Continued -
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<thead>
<tr>
<th>Source</th>
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<td>Ca</td>
<td>Mg</td>
<td>pH</td>
<td>Ca</td>
</tr>
<tr>
<td></td>
<td>kg ha⁻¹</td>
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<td></td>
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**Statistical Analysis**

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<th>Soil(L)</th>
<th>Source(S)</th>
<th>Rate(R)</th>
<th>L*S</th>
<th>L*R</th>
<th>S*R</th>
<th>L<em>S</em>R</th>
<th>CV (%)</th>
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<tbody>
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<td><strong>NS</strong></td>
<td><strong>NS</strong></td>
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† Units of Ca and Mg are in cmol dm⁻³

NS = Not Significant

* p = .05

** p = .01
Figure 1. Changes in soil acidity one week after application of four rates of lime-stabilized sludge [closed squares] and dolomitic lime [open squares] on (A) Cecil, (B) Hiwassee, (C) Goldsboro, and (D) Portsmouth soils.
Figure 2. Effects of lime-stabilized sludge [closed squares] and dolomitic lime [open squares] at CCE rates of 8960 and zero [open circles] kg/ha over a 16-week period on (A) Cecil, (B) Hiwassee, (C) Goldsboro, and (D) Portsmouth soils.
The Portsmouth soil has almost the same clay content as the Goldsboro soil but is higher in organic matter. The additional organic matter adsorbs the additional Zn added with LSS. The Goldsboro soil is the lowest in clay and organic matter, therefore it is unable to adsorb the additional Zn added with LSS. After the initial applications of the liming materials there was no mineralization of Zn. Zinc applied by either material increased the level of extractable Zn at the first week and did not increase soil Zn with time thereafter.

Applications of agricultural lime had no significant effect on soil Mn in the Hiwassee soil. There was an increase in soil Mn with increased applications of LSS in the Goldsboro and Portsmouth soils. The Cecil soil showed the same trend but was not consistent over the entire 16-week period. At the highest application rate of agricultural lime there was only an application of 1.44 kg ha\(^{-1}\) of Mn. This was lower than the lowest application of Mn with LSS. Again, soil Mn increased within the first week and there was no further increase in soil Mn from the first to the sixteenth week. The increases in soil Mn tend to be related to the clay percentage of the different soils. Applications of LSS tended to increase soil Mn in the lower clay percentage soils, but had much less effect on soil Mn in the higher clay soils.

Greenhouse fescue study: Materials incorporated

Soil analysis
Both materials increased soil pH with increased application rates (Table 8). LSS increased soil pH more than agricultural lime at the highest application rate of 8960 kg ha\(^{-1}\) with both soils. The increase in soil pH was slightly higher in the Goldsboro soil than with the Cecil soil (statistical analysis not shown). This was again due to the higher clay content and cation exchange capacity of the Cecil soil.

There was increased soil Ca with increased application of either liming material. The increase with application rate was larger with the application of LSS than with agricultural lime when sampled after the fifth fescue cutting for both soils (Table 8). Soil Ca from the LSS was twice as high as that from agricultural lime. It was noted previously that LSS supplied 50% more Ca than agricultural lime (Table 4).
Table 7. Effects of agricultural lime and LSS at four CCE rates on phosphorus, zinc and manganese soil test levels during a 16-week incubation experiment

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Table 7. Continued

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Statistical Analysis

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NS = Not Significant
* p = .05
** p = .01
Table 8. Effects of LSS and agricultural lime incorporated at four CCE rates on soil calcium, magnesium, zinc, and pH after the fifth cutting of fescue grown in the greenhouse on Cecil and Goldsboro soils

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NS = Not Significant
* p = .05
** p = .01
Agricultural lime increased soil Mg with increased application rates after the fifth cutting of fescue in both the Cecil and the Goldsboro soils (Table 8). LSS did not increase soil Mg in the Goldsboro and seemed to decrease soil Mg in the Cecil soil. The decrease in soil Mg may be due in part to crop removal of Mg in the five cuttings. LSS supplied only 6 kg ha\(^{-1}\) of Mg at the highest application rate of 8960 kg ha\(^{-1}\). In contrast, agricultural lime supplied 206 kg ha\(^{-1}\) of Mg at this same application rate.

The fact that LSS supplies little Mg os of concern. Magnesium is an essential nutrient and must be present in sufficient amounts for optimum crop production. It has been supplied primarily by dolomitic lime in the past. The need for Mg can be determined with a routine soil test. There are two sets of conditions in which there is a recommendation for Mg to be applied. If soil Mg is less than 0.50 cmol dm\(^{-3}\) and Mg occupies less than 10% of the cation exchange capacity, or if soil Mg is less than 0.25 cmol dm\(^{-3}\), then Mg should be applied.

Applications of agricultural lime increased extractable Zn more than the same rate of LSS. It seems as if the Zn in the LSS is not readily extractable with a routine soil test, and is most likely tied in the organic matter of the sludge. LSS had a higher concentration of Zn than agricultural lime. Differences between the two liming materials were not significant for the Cecil soil but were for the Goldsboro soil. These results contrast with those of the incubation study in which increasing rates of either liming material increased the soil Zn level slightly.

**Plant analysis**

Incorporated LSS increased fescue plant concentrations of Ca more than agricultural lime (Table 9). At the largest application of 8960 kg ha\(^{-1}\), fescue grown on LSS had a Ca concentration of 12 g kg\(^{-1}\) for the Cecil soil and 10 g kg\(^{-1}\) for the Goldsboro soil after the first cutting. There was a significant increase in fescue Ca concentrations with increased applications of LSS, whereas, with the application of agricultural lime there was only a slight increase. The increased fescue Ca due to rate of application was consistent from the second to the fifth cuttings. LSS supplied 1.7 times more total Ca than agricultural lime. Therefore, it would be expected that plant Ca concentrations for the LSS treatments would be almost double that of the fescue grown on agricultural lime. On the average over the second to fifth cuttings LSS fescue Ca was double that of agricultural lime.
Table 9. Calcium, magnesium, and manganese concentrations of five cuttings of fescue grown in the greenhouse on Cecil and Goldsboro soils after the incorporation of LSS and agricultural lime

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† Units of Ca and Mg are g kg$^{-1}$ Units of Mn are mg kg$^{-1}$
In contrast to Ca, fescue took up more Mg from agricultural lime than from LSS (Table 9). The agricultural lime supplied more Mg than LSS (Table 3). Although there was an increase in plant Mg with the increased application of agricultural lime, there was not a significant increase in plant Mg from the application of LSS. These trends of increased plant Mg from application of agricultural lime with application rate were present at all cutting periods. Agricultural lime only slightly increased fescue Mg in the Cecil soil but significantly increased fescue Mg in the Goldsboro soil. The Cecil soil was naturally higher in Mg and gave a high initial level of plant Mg. Since the Cecil soil had a higher initial level of Mg, that supplied by agricultural lime was less effective. The Goldsboro soil was low in Mg and plants grown on the check plots were very close to the deficiency range for forage crops of 2 g kg\(^{-1}\) (Chapman 1967, Jones 1967, Kelling 1982, and Cornforth and Sinclair 1982).

Although there was not a difference in plant Mn due to the type of liming material applied, there was a significant decrease in plant Mn due to increasing application rate for the Cecil soil (Table 9). The reduction in plant Mn was due to the increase in soil pH. As soil pH increased, Mn became less available to the plant. Over time there is a trend for plant Mn to decrease. Soil samples were not collected until after the fifth cutting, but it can be assumed that soil pH continued to rise as the reactions of materials continued. For the fourth and fifth cutting of fescue on the Goldsboro soil there is a trend for there to be an increase in plant Mn with increased application rate. This may be due to increased mineralization of Mn from the LSS and a reduced buffering capacity of the low clay content Goldsboro soil. There was a trend for LSS to have slightly higher plant Mn than agricultural lime. This trend was perhaps due to a greater amount of Mn applied with the LSS.

There is a soil test interpretation for Mn that includes soil pH as an additional contributing factor to nutrient availability. Increasing the pH decreases the availability of Mn, so the maximum amount the pH can be increased before inducing a Mn deficiency may be predicted.

Greenhouse fescue study: Materials topdressed

Soil analysis
Soil pH was increased with increased application rate by both sources of liming materials in all three soils (Table 10). LSS
Table 10. Effects of LSS and agricultural lime after topdressing four CCE rates on soil calcium, magnesium, phosphorus, and pH after the fourth cutting of fescue on Cecil, Goldsboro, and Portsmouth soils in the greenhouse

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**Statistical Analysis**

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NS = Not Significant
* p = .05
** p = .01
neutralized a greater amount of soil acidity than agricultural lime. This is most likely due to the finer particle size of the LSS. The finer particle size dissolves more rapidly causing LSS to have a faster reaction time. Agricultural lime is a coarser material with a slower reaction time. The highest rate of the topdress treatment increased the average soil pH of the three soils by 0.6; in contrast, the increase was 2.0 when the materials were incorporated into the two soils (Table 8).

Soil Ca was increased with increasing application rates for both materials on all three soils (Table 10). LSS increased soil Ca higher than agricultural lime, more than doubling the increase in Ca due to agricultural lime. This again is due to the higher solubility of the LSS over the agricultural lime. Agricultural lime increased soil Mg with increased application rates for all three soils (Table 10). However, LSS did not increase soil Mg in any of the soils used for this study.

LSS increased soil P in the Cecil soil with increased application rates. With the Goldsboro and Portsmouth soils LSS did not increase soil P with increased application rate. There was no increase in soil P with agricultural lime applications in any of the soils.

Plant analysis
Fescue Ca concentrations were increased over the check with applications of either liming material (Table 11). The trend was to increase Ca concentrations with increased application rates, but most of the increase occurred with 2240 kg ha⁻¹. Applications of LSS increased fescue Ca concentrations more than applications of agricultural lime.

Over time there was an increase in fescue Ca concentrations. Since both materials were topdressed onto the soil after the establishment of the fescue, the increase over time was due to the movement of Ca slowly into the rooting zone. These increases were somewhat similar for all soils.

More Ca was taken up by the first cutting of fescue when the liming materials were incorporated (Table 9) versus when they were topdressed (Table 10). This is most likely due to the Ca being readily available in the root zone when the materials were incorporated. With a topdress application the nutrients must move into the soil profile to be absorbed by roots.

Fescue Mg was increased with application of agricultural lime, but not with the application of LSS (Table 11). Agricultural lime increased plant Mg continually through the period of the study at the same application rates. Plants grown on the Cecil
Table 11. Calcium and magnesium concentrations of four cuttings of fescue grown in the greenhouse on Cecil, Goldsboro, and Portsmouth soils after the top dressing of LSS and agricultural lime

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<tr>
<td></td>
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<td>g kg⁻¹</td>
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<tr>
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</tr>
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</tr>
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Table 11. Continued

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Statistical Analysis

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NS = Not Significant
* p = .05
** p = .01
and Goldsboro soils had Mg concentrations above the critical value of 2.0 g kg\(^{-1}\), but the Mg concentrations of the plants grown on the Portsmouth soil were below this critical value.

Greenhouse field crops: Materials incorporated

**Soil analysis**

Soil pH was increased with increasing applications of either liming material in the samples taken after each corn, wheat, and soybean harvests (Figures 3, 4, and 5). LSS increased soil pH slightly higher than agricultural lime. The pH increase due to application rate was similar after the three crops. The average increase in pH with an application rate of 8960 kg ha\(^{-1}\) over the three soils was 1.5 for corn, 1.8 for wheat, and 1.0 for soybeans (Figure 6).

The soil pH of the checks, or no application, seemed to increase with each step of the cropping system (Tables 12, 13, and 14). This may be due to less salt concentration in the soil solution as cropping progressed. When determining pH in water, the results are dependent on the salt content of the solution.

Increased application rates of either liming material increased soil Ca in all three soils. LSS increased soil Ca twice as high as agricultural lime at the same CCE application rate. Soil Ca levels were similar after each crop, so the reaction occurred within the first six weeks and conditions remained stable thereafter.

Agricultural lime increased soil Mg with increased application rate (Tables 12, 13, and 14). LSS was unable to increase soil Mg. Soil Mg levels were similar after each of the three crops.
Figure 3. Effects of LSS [closed squares] and agricultural lime [open squares] on soil pH after growing corn in the greenhouse for 6 weeks on (A) Cecil, (B) Goldsboro, and (C) Portsmouth soils.

(A)

(B)

(C)
Figure 4. Effects of LSS [closed squares] and agricultural lime [open squares] on soil pH after growing wheat in the greenhouse for 6 weeks on (A) Cecil, (B) Goldsboro, and (C) Portsmouth soils.
Figure 5. Effects of LSS [closed squares] and agricultural lime [open squares] on soil pH after growing soybeans in the greenhouse for 8 weeks on (A) Cecil, (B) Goldsboro, and (C) Portsmouth soils.

(A) 

(B) 

(C)
Figure 6. Effects of LSS [closed squares] and agricultural lime [open squares] applied at 8960 and zero [open circles] kg/ha over the 20-week period of the field crop greenhouse study on (A) Cecil, (B) Goldsboro, and (C) Portsmouth soils.
Table 12. Effects of LSS and agricultural lime at four CCE rates on soil calcium, magnesium, and pH after corn was grown in the greenhouse for six weeks on Cecil, Goldsboro, and Portsmouth soils

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<th>Mg</th>
<th>pH</th>
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Statistical Analysis

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Goldsboro

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Statistical Analysis

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**Statistical Analysis**

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Table 13. Effects of LSS and agricultural lime at four CCE rates on soil calcium, magnesium, and pH after wheat was grown in the greenhouse for six weeks on Cecil, Goldsboro, and Portsmouth soils

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Statistical Analysis

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Table 13. Continued

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NS = Not Significant
* p = .05
** p = .01
Table 14. Effects of LSS and agricultural lime at four CCE rates on soil calcium, magnesium, and pH after soybeans was grown in the greenhouse for eight weeks on Cecil, Goldsboro, and Portsmouth soils

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Statistical Analysis

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Table 14. Continued

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NS = Not Significant
* p = .05
** p = .01
Plant analysis

Plant Ca increased in corn, wheat, and soybeans with increased application rates of both materials (Tables 15, 16, 17). LSS increased plant Ca significantly higher than agricultural lime at the same application rates for all three crops. These results are similar to those in the fescue study in which LSS increased plant Ca double that of agricultural lime. For all three crops on the three soils of this study LSS increased plant Ca greater than agricultural lime. In some instances LSS increased plant Ca three times that of agricultural lime at the same application rate.

Agricultural lime increased plant Mg with increased application rate for all three crops (Tables 15, 16, and 17). LSS did not increase plant Mg. Critical values of 1.5 and 2.5 g kg\(^{-1}\) have been reported for corn ear leaf samples at anthesis (Melsted et al 1969, Peaslee and Moss 1966). Using these values as a comparison, the Cecil soil supplied sufficient Mg for corn with no additions from the liming agents. The Goldsboro soil was marginal and the Portsmouth was unable to supply sufficient Mg. Agricultural lime added sufficient Mg for optimal corn growth, but the LSS did not.

With increased applications of both materials there was a significant decrease in plant Mn for all three crops on the Cecil and Goldsboro soils (Tables 15, 16, and 17). However, plant Mn increased with increasing application rates in the Portsmouth soil for corn and wheat, but not for soybeans. With increased soil pH there is normally a decrease in plant available Mn, so there is really no reason for this observation. The Portsmouth soil was quite high in organic matter. With the Portsmouth soil there may be some release of Mn from the organic matter with the increase in soil pH. It should be noted that the original pH of this soil was extremely low (3.8). There were no differences between the two materials in their ability to affect plant Mn.
Table 15. Effects of LSS and agricultural lime at four CCE rates on plant calcium, magnesium, manganese, and dry matter of corn grown in the greenhouse for six weeks on Cecil, Goldsboro, and Portsmouth soils

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<td>mg kg⁻¹</td>
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* p = .05
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Table 16. Effects of LSS and agricultural lime at four CCE rates on plant calcium, magnesium, manganese, and dry matter of wheat grown in the greenhouse for six weeks on Cecil, Goldsboro, and Portsmouth soils

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</tr>
<tr>
<td>CV (%)</td>
<td>10</td>
<td>15</td>
<td>35</td>
<td>28</td>
<td></td>
</tr>
</tbody>
</table>

- Continued -
Yields of all three crops were increased with increasing application rates for the Goldsboro and Portsmouth soils (Tables 15, 16, and 17). There was not an increase in yield due to increased application rates with the Cecil soil. The Cecil soil was the lowest in soil Al (data not shown), and a primary purpose of liming is to overcome Al toxicity at low soil pH. The increase in soil pH is needed to lower the amount of exchangeable Al causing toxicity to plant roots. Since the Cecil soil was low in exchangeable Al there was not as large a need to increase soil pH to overcome the Al toxicity. Both the Goldsboro and Portsmouth soils were higher in exchangeable Al (data not shown).
Soil analysis
Increased applications of both liming materials increased soil pH (Table 18). LSS consistently tended to increase soil pH to a greater extent than agricultural lime, but the effect was significant only for the Fall, 1994 samples. As the study progressed the agricultural lime treatments were expected to neutralize the same amount of soil acidity as the LSS due to the coarser particles in the agricultural lime beginning to react. This was not apparent with the 4480 kg ha\(^{-1}\) application rate (Figure 7). Also, there was not a decrease in pH in time. It was believed that the LSS would decrease in its ability to neutralize soil acidity over time. More time would be required to show this trend. The decrease in all soil pH at the 1.4 year mark is due most likely to a very dry period just previous to the soil sampling (data not shown). van der Paauw (1962) found that pH increases during periods of high rainfall and decreases during periods of low rainfall.

Soil Ca increased slightly with increased rate of agricultural lime and was increased markedly with increased rates of LSS (Table 18). Agricultural lime increased soil Mg with increased application rates. LSS did not increase soil Mg significantly with increased application rate.

Plant analysis
Six-week-old corn plant samples were not collected in 1995 due to excessive rain. While there tended to be an increase in Ca concentrations of all plant samples with increased applications of agricultural lime, it was not consistent (Table 19). However, increasing rates of LSS increased both whole plant and ear leaf Ca.

Just the opposite was true for Mg. Agricultural lime increased plant Mg with increased applications in all plant samples (Table 19). LSS did not increase plant Mg in any of the plant samples taken. The Mg concentrations were close to the 1.5 g kg\(^{-1}\) critical value for corn in 1993 and 1994. Plant Mg concentrations fell below the critical value for Mg in 1995. A very large amount of rainfall was received from the time of harvest in 1994 until anthesis in 1995. This rainfall may have leached considerable Mg out of the root zone for corn. Soil Mg appeared lower in 1995 than in previous years (Table 19). The Roanoke soil at this site is a Coastal Plain soil that is naturally lower in plant available Mg than soils in the Piedmont.
Table 18. Effects of LSS and agricultural lime at four CCE rates on spring and fall soil calcium, magnesium, and pH at Rocky Mount for 1993, 1994, and 1995 in a continuous corn rotation

<table>
<thead>
<tr>
<th>Source</th>
<th>CCE Rate</th>
<th>Spring Samples</th>
<th>Fall Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ca (cmol dm$^{-3}$)</td>
<td>Mg (cmol dm$^{-3}$)</td>
</tr>
<tr>
<td>Ag Lime</td>
<td>0</td>
<td>2.3 .60 5.2</td>
<td>2.5 0.9 5.4</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>2.5 .77 5.2</td>
<td>2.7 1.1 5.3</td>
</tr>
<tr>
<td></td>
<td>2240</td>
<td>2.4 .86 5.3</td>
<td>2.8 1.2 5.6</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>2.6 .96 5.7</td>
<td>2.8 1.3 5.9</td>
</tr>
<tr>
<td>LSS</td>
<td>0</td>
<td>2.0 .50 5.1</td>
<td>2.1 0.7 5.4</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>3.2 .68 5.4</td>
<td>3.4 0.8 5.6</td>
</tr>
<tr>
<td></td>
<td>2240</td>
<td>3.8 .73 5.9</td>
<td>4.2 1.0 6.0</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>4.3 .62 5.8</td>
<td>5.8 0.8 6.4</td>
</tr>
<tr>
<td>Statistical Analysis</td>
<td>Source</td>
<td>* * NS</td>
<td>* ** NS</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>30 40 5</td>
<td>28 31 7</td>
</tr>
<tr>
<td>Source</td>
<td>CCE Rate</td>
<td><strong>Spring Samples</strong></td>
<td><strong>Fall Samples</strong></td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>-------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td></td>
<td>kg ha⁻¹</td>
<td>cmol dm⁻³</td>
<td>cmol dm⁻³</td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag Lime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>1.4</td>
<td>0.42</td>
</tr>
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<td>0.51</td>
</tr>
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<td>2240</td>
<td></td>
<td>1.4</td>
<td>0.52</td>
</tr>
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<td>4480</td>
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<td>1.6</td>
<td>0.63</td>
</tr>
<tr>
<td>LSS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td>1.4</td>
<td>0.39</td>
</tr>
<tr>
<td>1120</td>
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<td>2.0</td>
<td>0.56</td>
</tr>
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<td>2240</td>
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<td>0.61</td>
</tr>
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<td>4480</td>
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<td>2.5</td>
<td>0.43</td>
</tr>
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<td><strong>Statistical Analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source</td>
<td>*</td>
<td>*</td>
<td>NS</td>
</tr>
<tr>
<td>Rate</td>
<td>*</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>Source*Rate</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>CV (%)</td>
<td>28</td>
<td>37</td>
<td>4</td>
</tr>
</tbody>
</table>

**NS** = Not Significant
* p = .05
** p = .01
Figure 7. Changes in soil pH with the application of LSS (closed squares) and agricultural lime (open squares) at 4480 and zero (open circles) kg/ha at Rocky Mount over time.
Table 19. Six-week-old whole corn plant and corn ear leaf calcium, magnesium, and manganese concentrations for 1993, 1994, and 1995 at Rocky Mount

<table>
<thead>
<tr>
<th>Source</th>
<th>CCE Rate</th>
<th>Whole Corn Plant</th>
<th>Ear Leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ca</td>
<td>Mg</td>
</tr>
<tr>
<td></td>
<td>kg ha⁻¹</td>
<td>g kg⁻¹</td>
<td>mg kg⁻¹</td>
</tr>
<tr>
<td></td>
<td>1993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag Lime</td>
<td>0</td>
<td>.34</td>
<td>.25</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>.39</td>
<td>.28</td>
</tr>
<tr>
<td></td>
<td>2240</td>
<td>.35</td>
<td>.28</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>.40</td>
<td>.29</td>
</tr>
<tr>
<td>LSS</td>
<td>0</td>
<td>.35</td>
<td>.26</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>.39</td>
<td>.22</td>
</tr>
<tr>
<td></td>
<td>2240</td>
<td>.41</td>
<td>.24</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>.46</td>
<td>.24</td>
</tr>
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<td>Source</td>
<td>NS</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rate</td>
<td>NS</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Source*Rate</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Ag Lime</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>.34</td>
<td>.24</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>.37</td>
<td>.26</td>
</tr>
<tr>
<td></td>
<td>2240</td>
<td>.33</td>
<td>.28</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>.37</td>
<td>.33</td>
</tr>
<tr>
<td>LSS</td>
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<td>.25</td>
</tr>
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<td></td>
<td>1120</td>
<td>.38</td>
<td>.23</td>
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<td></td>
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<td>.23</td>
</tr>
<tr>
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<td>4480</td>
<td>.43</td>
<td>.23</td>
</tr>
<tr>
<td>Statistical Analysis</td>
<td>Source</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>Rate</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>Source*Rate</td>
<td>NS</td>
<td>**</td>
</tr>
<tr>
<td></td>
<td>CV (%)</td>
<td>9</td>
<td>12</td>
</tr>
</tbody>
</table>

- Continued -
Table 19. Continued

<table>
<thead>
<tr>
<th>Source</th>
<th>CCE Rate kg ha(^{-1})</th>
<th>Whole Corn Plant</th>
<th>Ear Leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ca g kg(^{-1})</td>
<td>Mg mg kg(^{-1})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1995</td>
<td></td>
</tr>
<tr>
<td>Ag Lime</td>
<td>0</td>
<td>-- -- --</td>
<td>.24 .13</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>-- -- --</td>
<td>.25 .14</td>
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<td>2240</td>
<td>-- -- --</td>
<td>.26 .16</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>-- -- --</td>
<td>.26 .18</td>
</tr>
<tr>
<td>LSS</td>
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<td>-- -- --</td>
<td>.24 .13</td>
</tr>
<tr>
<td></td>
<td>1120</td>
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</tr>
<tr>
<td></td>
<td>4480</td>
<td>-- -- --</td>
<td>.30 .14</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Source</td>
<td>-- -- --</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Rate</td>
<td>-- -- --</td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>Source*Rate</td>
<td>-- -- --</td>
<td></td>
<td>NS</td>
</tr>
<tr>
<td>CV (%)</td>
<td>-- -- --</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

NS = Not Significant
* p = .05
** p = .01

With increased applications of either liming material there is a decrease in plant Mn (Table 19). At tassel a value of 15 mg kg\(^{-1}\) is considered to be critical (Melsted et al. 1969). At the largest application rate this critical value was not reached, so there was always sufficient Mn. Increased application of either material had no significant effect on the yield of corn (data not shown).

Salisbury Fescue Study

Soil Analysis
Increased rates of application increased soil pH and Ca (Table 20). LSS initially increased soil pH to a greater extent than agricultural lime (Figure 8). This trend was also present for soil Ca. In 1994 there was not a significant difference between the two liming materials' ability to reduce soil acidity. However, the trend toward greater effectiveness of LSS remained. The coarser particles of the agriculture lime continued to react
Table 20. Effects of LSS and agricultural lime at four CCE rates on soil calcium and pH in the spring and fall of 1993 and 1994 on the pasture study at Salisbury

<table>
<thead>
<tr>
<th>Source</th>
<th>CCE Rate kg ha(^{-1})</th>
<th>Spring Ca cmol dm(^{-3})</th>
<th>Spring pH</th>
<th>Fall Ca cmol dm(^{-3})</th>
<th>Fall pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag lime</td>
<td>0</td>
<td>7.4</td>
<td>5.9</td>
<td>6.0</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>8.5</td>
<td>6.0</td>
<td>5.4</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>2240</td>
<td>8.1</td>
<td>6.2</td>
<td>5.9</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>8.2</td>
<td>6.3</td>
<td>6.2</td>
<td>6.4</td>
</tr>
<tr>
<td>LSS</td>
<td>0</td>
<td>7.7</td>
<td>6.0</td>
<td>5.8</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>9.4</td>
<td>6.2</td>
<td>6.5</td>
<td>6.2</td>
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<td>4480</td>
<td>14.4</td>
<td>6.6</td>
<td>10.4</td>
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</table>

Statistical Analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate</th>
<th>Source*Rate</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1993</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Ag lime</td>
<td>*</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>LSS</td>
<td></td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

1994

<table>
<thead>
<tr>
<th>Source</th>
<th>Rate</th>
<th>Source*Rate</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1994</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>Ag lime</td>
<td></td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>LSS</td>
<td></td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

NS = Not Significant
* p = .05
** p = .01
Figure 8. Increase in soil pH with rate of LSS [closed squares] and agricultural lime [open squares] six months after application on fescue at Salisbury.

Figure 9. Changes in soil pH with the application of lime-stabilized sludge [closed squares] and dolomitic lime [open squares] at 4480 and zero [open circles] kg/ha over time on fescue at Salisbury.
Table 21. Soil calcium and pH in 1995 for the fescue study at Salisbury sampled to two depths

<table>
<thead>
<tr>
<th>Source</th>
<th>CCE Rate</th>
<th>0-10 cm Ca</th>
<th>0-10 cm pH</th>
<th>10-20 cm Ca</th>
<th>10-20 cm pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kg ha⁻¹</td>
<td>cmol dm⁻³</td>
<td>cmol dm⁻³</td>
<td></td>
</tr>
<tr>
<td>Ag lime</td>
<td>0</td>
<td>3.5</td>
<td>6.0</td>
<td>3.4</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>3.7</td>
<td>6.4</td>
<td>3.6</td>
<td>6.6</td>
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<td>2240</td>
<td>3.8</td>
<td>6.5</td>
<td>4.0</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>3.8</td>
<td>6.7</td>
<td>3.6</td>
<td>6.6</td>
</tr>
<tr>
<td>LSS</td>
<td>0</td>
<td>3.5</td>
<td>6.2</td>
<td>3.8</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>1120</td>
<td>4.2</td>
<td>6.3</td>
<td>3.8</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>2240</td>
<td>4.9</td>
<td>6.6</td>
<td>4.2</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>4480</td>
<td>5.9</td>
<td>6.8</td>
<td>4.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Statistical Analysis

Source | * | NS | NS | NS
Rate   | ** | ** | * |
Source*Rate | ** | NS | NS | *
CV (%)  | 12 | 4  | 9  | 1

NS = Not Significant
* p = .05
** p = .01

with soil acidity over the period of the study, whereas the LSS did not continue to react (Figure 9). At the last sampling period there was no significant difference in the two materials ability to neutralize soil acidity.

LSS increased soil Ca and pH slightly in the 10-20 cm depth of soil in 1995 (Table 21). Agricultural lime did not affect these properties as much at this sampling depth. It is possible that the finer particles of the LSS moved into the second soil depth. This would have to be through macropores or some channel in the soil. It is perhaps more likely that the greater solubility of Ca(OH)₂ in LSS over the CaCO₃ in agricultural lime would allow this movement of Ca.

Plant analysis

The fescue in the Salisbury study was harvested six times over the three-year period. There were no significant differences in plant elemental composition for the first cutting taken four
months after the application of the liming materials. However, LSS increased fescue Ca concentrations with increased application rates for the second through the sixth cutting (Table 22). Agricultural lime had little to no effect on fescue Ca concentrations.

With increased application rates of both materials there was a decrease in plant Mn (Table 22). The decrease in plant Mn was consistent for all cuttings except the first. This effect is a typical response to increasing soil pH. At the highest rate of liming material applied, the plant Mn is still quite sufficient, so the effect noted is of little concern.

There was no effect on yield by application of either liming material or the increased application rate (data not shown). The lack of a response to increased application rate is due to the already elevated soil pH of the check. A soil pH of 5.5 is considered to be optimum for crop production. The lowest soil pH that was observed was 5.9 (Tables 20 and 21).

Table 22. Fescue calcium and manganese concentrations from five cuttings of hay at Salisbury

<table>
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<tr>
<th>Source</th>
<th>CCE Rate</th>
<th>Cutting number</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca</td>
</tr>
<tr>
<td>kg ha⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag lime</td>
<td>0</td>
<td>3.6 90</td>
</tr>
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Statistical Analysis

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<th>Source*Rate</th>
<th>CV (%)</th>
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</thead>
<tbody>
<tr>
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<td>**</td>
<td>**</td>
<td>7 14</td>
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</table>

Units on Ca are g kg⁻¹ and on Mn are mg kg⁻¹
NS = Not Significant
* p = .05
** p = .01
Salisbury Rowcrop Study

Soil analysis
At all sampling dates there was an increase in soil pH due to increased rate of application (Table 23). However, the overall effect was less than that observed in the prior two studies. For this reason no differences were noted between the two materials.

Both liming materials increased soil Ca with increased application rates. LSS again increased soil Ca more effectively than agricultural lime.

Plant analysis
Both liming materials only tended to increase plant Ca with increased application rates in all crops except the soybeans (Table 23). LSS seemed to increase plant Ca slightly higher than did agricultural lime. There was no effect of treatments on plant Mg. The general lack of effects on plant concentrations in this study is most likely associated with the fact that the field did not need liming to begin with. The pH on the control was greater than 6.0, and the soil contained an abundance of Ca and Mg.
Table 23. Effects of LSS and agricultural lime at four CCE rates on plant calcium, soil calcium, and soil pH of the crops grown for three years at Salisbury

<table>
<thead>
<tr>
<th>Source</th>
<th>CCE Rate</th>
<th>Plant Ca</th>
<th>Soil Ca</th>
<th>Soil pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha⁻¹</td>
<td>- g kg⁻¹ -</td>
<td>cmol dm⁻³</td>
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<td>5.4</td>
<td>6.4</td>
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<td>6.0</td>
<td>7.4</td>
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Statistical Analysis

<table>
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<th>Source</th>
<th>Rate</th>
<th>Source*Rate</th>
<th>CV (%)</th>
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</thead>
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</tr>
<tr>
<td></td>
<td>2240</td>
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</tr>
</tbody>
</table>

1994 Wheat

| Ag lime | 0      | 2.2    | 9.2    | 6.3    |
|         | 1120   | 2.4    | 8.9    | 6.3    |
|         | 2240   | 2.4    | 9.6    | 6.3    |
|         | 4480   | 2.5    | 9.4    | 6.3    |
| LSS     | 0      | 2.3    | 11.6   | 6.1    |
|         | 1120   | 2.6    | 10.4   | 6.2    |
|         | 2240   | 2.8    | 10.5   | 6.3    |
|         | 4480   | 2.6    | 11.9   | 6.4    |

Statistical Analysis

<table>
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<th>Source</th>
<th>Rate</th>
<th>Source*Rate</th>
<th>CV (%)</th>
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- Continued -
Table 23. Continued

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<th>Soil pH</th>
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Statistical Analysis

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Statistical Analysis

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NS = Not Significant
* p = .05
** p = .01
REFERENCES


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