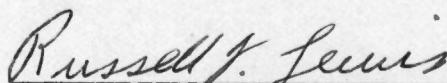


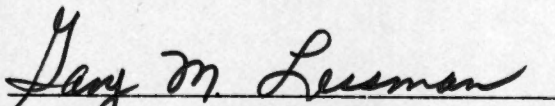
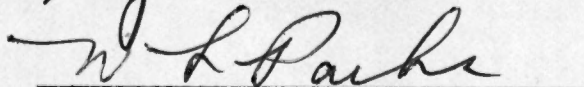
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I am submitting herewith a thesis written by Engku Ismail bin Engku-Ahmad entitled "The Effects of Addition of Wheat Straw, Corn Stalks, and Alfalfa in Reducing Aluminum Toxicity of Acid Soils." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant and Soil Science.

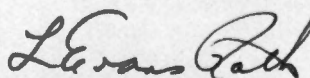


Russell J. Lewis, Major Professor

We have read this thesis
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Vice Chancellor
Graduate Studies and Research

THE EFFECTS OF ADDITION OF WHEAT STRAW,
CORN STALKS, AND ALFALFA IN REDUCING
ALUMINUM TOXICITY OF ACID SOILS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Engku Ismail bin Engku Ahmad

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ABSTRACT

Two experiments were conducted to study the effects of adding wheat straw, corn stalks, and alfalfa to acid Sequoia (Typic Hapludult) and Tellico (Typic Rhodudult) soils on chemical changes occurring in the soils, growth of the Harrison variety of barley (*Hordeum vulgare* L.), and the accumulation of selected nutrients in barley tops. The effects on root growth were studied in a soil slurry experiment, and the effects on growth, ion uptake, and soil properties were studied in a greenhouse pot experiment. In both experiments, the plant materials were added at 0, 3, and 6% rates (soil weight basis). In the greenhouse pot experiment, the effects of mixed and surface application methods were also compared. The surface application method provided greater concentration of plant materials in sampling zone than did the mixed application method.

The Sequoia soil contained a high level of Al whereas the Tellico soil contained a high level of Mn. There were no differences in the root lengths among the rates and plant materials in the Sequoia soil. The root lengths in the Tellico soil treated with wheat straw or corn stalks were longer than those of the untreated, though the differences between 3 and 6% rates were not significant. However, there were no differences in the root lengths measured in the Tellico soil treated with different rates of alfalfa. In both soils, pH values in solution and sediment of the slurries increased with increasing amounts of plant materials added, though not consistently. Root weights were not responsive to the various treatments.

In the greenhouse pot experiment, pH and exchangeable Mn of both soils increased with increasing amounts of plant materials applied. The reverse effect was observed on exchangeable Al. Among the plant materials, only alfalfa reduced the Al and Mn toxicities suffered by barley plants. Plants receiving this treatment grew vigorously and their heights and weights were the greatest. However, the greater amount of alfalfa applied to the Tellico soil caused Mn toxicity. The accumulation of Al in barley tops was without a pattern. Contrastingly, large amounts of Mn was present in the tops of plants suffering Mn toxicity. Adding wheat straw, corn stalks, or alfalfa to Sequoia soil increased the K and P contents but decreased the Ca and Mg contents measured in barley tops. Adding these materials to Tellico soil increased the Mg, K, and P contents but had no effect on the Ca content measured in barley tops.

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CHAPTER I

INTRODUCTION

Toxic effects of Al and Mn are often responsible for acid soil problems with many crops. Aluminum tends to cause more damage to plants than does Mn since many plants tolerate high concentration of Mn but not Al. Plant available Al in an acid soil is strongly pH dependent and is minimal at about pH 7.0; however, plant available Mn is affected by soil Eh as well as by soil pH.

Liming is traditionally practiced to raise the pH of acid soils thus minimizing the toxic levels of Al and Mn in those soils. Swenson et al. (1949); Schnitzer and Skinner (1963); and Bartlett and Riego (1972) discovered that organic acids extracted from soil organic matter are capable of forming complexes with polyvalent metals such as Al and Mn. It has been observed that on the fields where no-tillage to minimum-tillage operations are practiced, the surface soil was highly acid due to nitrogen fertilizer applications and yet plants grew vigorously. It is postulated that Al^{3+} activity in this acid surface soil was depressed by high soil organic matter content. The surface soil received large amounts of organic materials regularly from crop residues.

Hoyt and Turner (1975) found that applying alfalfa meal, sucrose, and peat moss to an acid soil increased the soil pH values and decreased the soil exchangeable Al which in turn increased the plant growth. They also observed that the pH values increased with increasing amounts of organic materials added. Asghar and Kanehiro (1980) treated an acid soil with sugarcane trash and pineapple residue and found that the soil

pH did increase and the soil extractable Al did decrease but the soil exchangeable Mn increased.

This research was undertaken to study:

(a) The effects of adding different kinds of plant materials to acid soils on chemical changes occurring in the soils, plant growth, and the accumulation of Al, Mn, and major nutrients in the plant tops.

(b) The differences in the effects among the plant materials, rates and methods of application.

CHAPTER II

LITERATURE REVIEW

It has long been reported that the poor growth of many crop plants in acid soils was due to the injurious effects of Al and Mn which were usually present in toxic levels (Johnson and Jackson, 1964; Adams and Lund, 1966; Evans and Kamprath, 1970).

Aluminum is a major component of most mineral soils, whereas Mn occurs in smaller amounts. Both are present in the soil as elements of clay-silicates and oxide minerals (Coleman and Thomas, 1967; McLean, 1976). Aluminum released in weathering processes undergoes hydrolysis with a resultant increase in acidity through the release of protons (Schofield and Taylor, 1954; Jackson, 1963; McLean, 1976).

Furthermore, with increasing weathering most of the basic elements such as Ca, Mg, K, and Na are leached out since they are more soluble, thus, leaving the soil in more acidic conditions. In contrast, Al and Mn are increased in their proportions since they are highly resistant to weathering processes (Jackson, 1963; McLean, 1976).

Hartwell and Pember (1918), Magistad (1925), and McLean and Gilbert (1927) are among the pioneers in reporting the excesses of Al to be a factor of substantial importance in acid soil infertility, whereas, Funchess (1919), Bortner (1935), and Morris (1948) are among the earliest workers who reported that Mn, as well as Al, was found responsible for the poor growth of many plants in acid soils.

Hartwell and Pember (1918) reported that Al was of much greater

significance as a toxic factor affecting the growth of barley in acid soils than was the hydrogen ion concentration. Vlamis (1953) measured the dry matter yields of barley growth in nutrient solution at two different pH values with different levels of Al added. His results clearly indicated that the concentration of Al rather than the low pH of the nutrient solution was the growth limiting factor. More recently, Moschler et al. (1960) found that the increases in alfalfa yields resulting from lime added at several rates to a soil were closely related to the decreases in exchangeable soil Al. Adams and Lund (1966) observed that the rate of cotton root penetration into acid subsoils appeared to decrease as the molar activity of Al in the soil solution increases. Later, Kamprath (1970) reported that for several soils the growth of corn was not decreased when the Al saturation of the exchange capacity was less than 44%. However, soybean and cotton required less than 20% Al saturation for optimum growth.

Usually, Al toxicity symptoms are observed for many crops when the pH value of the soil is less than 5.0. Generally, at pH values lower than 5.0, Al in the soil is present almost entirely as Al^{3+} (McLean, 1976; Marion et al., 1976). As the pH rises, it is generally precipitated as hydroxides but appears again in solution as aluminate ions under alkaline conditions (Magistad, 1925; McLean, 1976; Marion et al., 1976). It was first suggested by Magistad (1925) that Al injury to plant growth may occur under high-pH soils, as well as under low-pH soils, if Al is present at toxic levels. The total concentration of soluble Al is strongly pH dependent and is minimal at about pH 7.0 (McLean, 1976; Marion et al., 1976).

When lime is added to neutralize the acidity of acid soils, Al

toxicity is essentially eliminated since almost all the exchangeable Al is precipitated at pH 5.5 (Ragland and Coleman, 1959; Coleman and Thomas, 1967; Evans and Kamprath, 1970; Reeve and Sumner, 1970; Foy, 1974). Toxic levels of plant available Mn also reportedly have been found to be significantly reduced upon liming of acid soils (Bortner, 1935; Fujimoto and Sherman, 1948; Morris, 1948; Christensen et al., 1950; Sanchez and Kamprath, 1959). Conversely, adding acidifying materials lowers the pH and increases the content of exchangeable Al (Ragland and Coleman, 1959; Foy and Brown, 1964) and plant available Mn (Fujimoto and Sherman, 1948; Morris, 1948) in the soil which then become toxic to the plant.

The solubility of Al in the soil is not solely determined by soil pH but also by types of clay minerals, concentration of other cations, total salt concentrations, and organic matter content (Foy, 1974; Marion et al., 1976; McLean, 1976). Thus the level of Al required to be toxic varies with soils as well as with plant species or varieties (Foy and Brown, 1964; Rios and Pearson, 1964; Adams and Lund, 1966). From a study on several mineral and organic soils, Evans and Kamprath (1970) reported that for all soils, there was not a consistent relationship between soil pH or exchangeable Al and the response of corn and soybean to liming. These values varied for the different soils at the point of maximum response especially among soils with large differences in organic matter contents. These workers also noted that the concentration of soil solution Al in mineral soils was related to the percent of Al saturation of the effective CEC, whereas in organic soils, concentration of Al was more related to the amount of exchangeable Al than to the percent of Al saturation.

A strong relationship has been reported between levels of soil exchangeable Al and toxic effects on plant growth. Ragland and Coleman (1959) reported that growth of grain sorghum roots into unlimed subsoil was inversely related to soil exchangeable Al. Similar relationships have been reported such as on the rates of cotton root penetration (Adams and Lund, 1966), yields of soybean varieties (Armiger et al., 1968), and yields of alfalfa and barley (Hoyt and Turner, 1975).

Plants are most sensitive to Al injury in the early stages of growth. The toxic effects of Al are local rather than systemic and induced rapidly in the young meristematic tissue (Clarkson, 1965; Jackson, 1967; Foy, 1974).

Aluminum toxicity produces a combination of effects. Roots usually are first affected when plants are exposed to toxic Al concentrations, with damage to the tops occurring later. Similarly, at low concentrations root injury may be noted without damage to the shoots (Foy and Brown, 1964; Clarkson, 1965; Jackson, 1967; Bartlett and Riego, 1972; Foy, 1974). Typical symptoms of Al-injured roots are the development of a brownish cast on the root and a loss of turgidity. Also main roots fail to elongate rapidly and become thick, swollen, and distorted. Laterals may be initiated but their development is limited and they largely remain as short and abortive stubs (McLean and Gilbert, 1927; Jackson, 1967; Foy, 1974).

Bortner (1935) studied the effect of Al on the root growth of tobacco seedlings in culture solutions. He observed that six days after addition of Al the root tips were blackened. Three days later, he found that the roots no longer lengthened but thickened to twice their normal size and numerous new roots were formed above the level of the culture

solution but died upon reaching the solution.

Matsumoto and Hirasawa (1979) reported that the root elongation of pea seedling (cv. Alaska) was inhibited at pH 4.5 and at Al concentrations greater than 10^{-4} M. Little or no recovery of elongation occurred when the roots were transferred to water after three hours in a 10^{-3} M Al solution. These workers also noted that shoot elongation was less affected than root elongation. Similar results of root injury due to toxic levels of Al were reported on spinach and on a weed member of the Atriplex genus (Rees and Sidrak, 1961); Corn, tomato, buckwheat, soybean, and rice (Bartlett and Riego, 1972); cotton (Adams and Lund, 1966; Rios and Pearson, 1974); and barley (Rees and Sidrak, 1961; Bartlett and Riego, 1972).

The effects of Al toxicity are not confined to the roots. Aluminum toxicity also causes damage to the tops by affecting the uptake and accumulation of nutrients. Indeed, Al-treated plants accumulate large amounts of Al in their foliage, which in barley produces stiffening of laminae which causes an upright growth habit (Rees and Sidrak, 1961; Bartlett and Riego, 1972).

Toxic Al conditions usually result in overall reduction in growth; smaller leaves with thickened and shortened internodes; dark green leaves; purpling of stems, leaves and veins; chlorosis and dieback of leaf tips. In general those symptoms of Al toxicity in plant tops resemble those of acute P deficiency (Foy and Brown, 1964; Jackson, 1967; Foy, 1974). The aboveground visual symptoms of Al toxicity can also resemble those of Ca deficiency. These include rolling of young leaves and collapse of plant apex or petioles (Jackson, 1967; Foy, 1974).

It is usually true that soil P availability is depressed under high acidity as Al reacts readily with P converting it to relatively insoluble and plant-unavailable forms (McLean, 1976). However, typical P deficiency symptoms noted in acid soils are often accounted for by precipitation of P within the root tissue by Al. Reports of histological studies on the inhibition of root growth by Al have indicated the accumulation of P and Al in the root epidermal and cortical tissues with much smaller amounts within the endodermis (McLean and Gilbert, 1927; Wright and Donahue, 1953; Jackson, 1967).

In contrast to Al, Mn injury in acid soils is largely confined to the plant tops (Funchess, 1919; Bortner, 1935). Plant uptake of Mn increases as the plant available Mn in the medium increases (Bortner, 1935; Fujimoto and Sherman, 1948; Rees and Sidrak, 1961). It has been shown that Al in solution culture depressed the uptake of Mn but not vice versa (Rees and Sidrak, 1961; Jackson, 1967). Manganese toxicity symptoms in plant tops have been described as ranging from the yellowing of leaf tips and margins to brown chlorotic areas and leaf distortion such as in tobacco (Bortner, 1935) and barley and spinach (Rees and Sidrak, 1961).

Organic matter has been found to alleviate Al toxicity in acid soils by reducing the availability of Al to plant roots (Swenson et al., 1949; Jones, 1961; Mortensen, 1963; Schnitzer and Skinner, 1963; Clark, 1964; Pionke and Corey, 1967; McLean and Owen, 1969; Evans and Kamprath, 1970; Thomas, 1975; Hoyt and Turner, 1975; Hoyt, 1977). Soil organic matter forms complexes with metals, such as Al and Mn, by ion-exchange, surface adsorption, and chelation-reaction mechanisms (Mortensen, 1963; Schnitzer and Skinner, 1965).

Swenson et al. (1949) reported that the organic acids produced from the decomposing mulch reacted with Al. Schnitzer and Skinner (1963) reported that the organic matter extracted from soil of a podzol Bh horizon reacted with Al forming water-soluble and water-insoluble complexes. The formation of insoluble Al-organic matter complexes has also been suggested by Clark and Nichol (1966) as they found less lime was required to neutralize the acidity of organic soils compared to mineral soils. This observation was supported by Reeve and Sumner (1970), who also stressed that less lime should be required for soils with higher organic matter contents. Working with solution culture, Bartlett and Riego (1972) reported that the injury of Al toxicity was alleviated by organic acids which was similar to the effects of other chelating agents.

McLean and Owen (1969), using twelve unlimed soils, found that the destruction of the soil organic matter with H_2O_2 released Al causing the KCl-extracted exchangeable Al to be doubled. Aluminum ions are strongly adsorbed to the organic exchange sites and are not displaceable by KCl (Clark, 1964). Thomas (1975) measured the exchangeable Al and organic matter content of Maury silt loam soil at various depths. He found that the exchangeable Al was highest when the organic matter content was lowest. He observed that the effect of organic matter on exchangeable Al at any given pH was strongest from 0.8% up to 2.5% organic matter with smaller effect at higher organic matter contents. He also found that the influence of organic matter on exchangeable Al was greater at lower pH values. Similar relationships between soil exchangeable Al and organic matter content at a particular pH have been reported by Evans and Kamprath (1970) and by Hoyt (1977).

The intensity of interaction of Al differs with different organic fractions. Schnitzer and Skinner (1965) reported that the organo-metallic reaction very likely takes place via the functional groups of organic acids which are mainly carboxyls, hydroxyls, and carbonyls. Earlier, Jones (1961) compared the chelating ability of several organic acids commonly found in soil organic matter. He discovered that the most active acids in complexing Al were citric and oxalic, followed by malic and tartaric, whereas succinic, maleic, and lactic acids were ineffective. This observation was supported by Ng Kee Kwong and Huang (1979) as they found that the affinity of organic acids for Al decreased in the order citric acid > malic acid > tannic acid > aspartic acid > p-hydroxybenzoic acid.

It was suggested by Schnitzer and Desjardins (1962), based on the reactions of humic and fulvic acids fractions of soil organic matter, that most of the complexed Fe and Al in soils should be associated with the fulvic acid fraction. The work of Rodriguez and Schaefer (1971) showed that fulvic acids were the most active fraction in complexing Al and the stability of the complex decreased with decreasing proportion of Al.

The effectiveness of organic matter in reducing the activity of Al^{3+} depends on the soil pH and the base saturation of organic matter. Bloom et al. (1979) found that the addition of organic matter may lower the apparent solubility of aluminum hydroxides without lowering Al^{3+} activity if the degree of neutralization of the added organic matter is low. These researchers stressed that such an effect is most important at higher soil pH values as the release of protons from the organic matter may result in a decrease in pH without a decrease in Al^{3+} .

activity. These findings are in agreement with those of Hoyt (1977) who reported that the soil exchangeable Al decreased while pH-dependent acidity increased with increasing amount of organic matter content. For that reason, he suggested that very acid mineral soils of high organic matter content should require less lime to precipitate the Al^{3+} for the purpose of growing grain crops but more lime is likely required to raise the pH to 6 for the purpose of growing alfalfa.

Adding organic matter, such as mulches of wheat straw, saw dust, and partially decomposed forest litter to acid soils, particularly those low in organic matter contents, has been found beneficial for crop yields and nutrient uptake in many crops (Swenson et al., 1949; Robinson and Hosegood, 1965; McLean and Owen, 1969; Othieno, 1973). Researchers have attributed such effects to physical and chemical factors.

With the rising prices of agricultural limestone, research has been done to study the possibility of adding crop residues to acid soils in order to reduce the toxic levels of Al as well as a way of disposing of the crop residues. Hoyt and Turner (1975) treated an acid soil with alfalfa meal, sucrose, and peat moss using barley and alfalfa as indicator crops. They found that the soil pH values increased with increasing amounts of organic materials added and among those organic materials, alfalfa meal was the most effective in complexing exchangeable Al since the yields of barley and alfalfa were highest while exchangeable Al was lowest from alfalfa treated pots. They also found that the decrease in exchangeable Al had taken place before there was an increase in exchangeable NH_4^+ .

Asghar and Kanehiro (1980) reported that besides the reduction of extractable Al, adding sugarcane trash and pineapple residue at 0,

5, and 10% rates (soil weight basis) to an acid soil caused an increase in soil pH and water-soluble and exchangeable Mn but a decrease in soil Eh. These researchers suggested that the addition of those plant materials had a liming effect as well as a chelating effect which had depressed the toxic concentration of Al in the soil.

Upon adding plant materials, the high activity of microorganisms in the soil causes the depression of Eh which in turn causes the increase in water-soluble and exchangeable Mn (Fujimoto and Sherman, 1948; Christensen et al., 1950; Sanchez and Kamprath, 1959; Asghar and Kanehiro, 1980).

Plant species and even cultivars within a species differ widely in their tolerance to Al toxicity (Jones, 1961; Foy and Brown, 1964; Foy et al., 1965; Foy et al., 1967; Mugwira and Elgawhary, 1979). Tolerance of a specific plant to Al toxicity in a nutrient culture or in an acid soil is associated with many factors such as root CEC, root pH, and Ca and P levels in the medium (Foy, 1974). Plant tolerance to toxic levels of Al has been attributed to its capability of absorbing and utilizing P in the presence of excess Al (Foy and Brown, 1964). Aluminum tolerant plants are also found to have low root CEC thus less Al^{3+} is absorbed compared to Al-sensitive plants (Foy et al., 1967; Mugwira and Elgawhary, 1979). Foy et al. (1965, 1967) found that the pH values around the root of Al-sensitive plants were lower than those of Al-tolerant plants. Decreasing Ca levels in a medium increases the effect of Al toxicity to an Al-sensitive plant (Foy, 1974).

Besides the reduction of top and root yields, toxic levels of Al in plant growth media strongly affects the uptake and accumulation of other mineral elements. Depressions in the uptake of Mn, Ca, K, and

B in cotton (Foy and Brown, 1963); Mn, Ca, and P in corn (Bartlett and Riego, 1972); Mn and Ca in barley and spinach (Rees and Sidrak, 1961); Na, K, Mg, Ca, and P in Harding grass (Helyar and Anderson, 1974); and Ca in wheat, corn, and soybean (Johnson and Jackson, 1964; Evans and Kamprath, 1970) have often been described. However, it also has been reported that Al increased the uptake of Ca (MacLeod and Jackson, 1965), Mg (Andrew et al., 1973), and K (MacLeod and Jackson, 1965; Andrew et al., 1973); but most often the reverse occurs.

CHAPTER III

MATERIALS AND METHODS

General

Soils

Two different acid soils were used in this study. Samples of Sequoia (Typic Hapludult) silty clay loam (12-20% slopes) and Tellico (Typic Rhodudult) loam (12-20% slopes) were collected from the Plant Sciences Field Laboratory of The University of Tennessee, Knoxville. Samples were taken from the subsurface horizons located between 10 cm and 25 cm (4 in and 10 in) in a soil profile exposed in a pit of five feet in diameter. The subsurface soil was selected because of its higher acidity (lower pH) and lower organic matter content than the surface soil.

While still moist, the samples were ground to pass through a 6mm screen, thoroughly mixed, and air dried in a greenhouse at 29-32 C (85-90°F) for one week. Then, four samples were randomly taken from each soil, ground to pass through a 2 mm screen, thoroughly mixed, and stored awaiting chemical analyses.

Plant Materials

Three different kinds of plant materials were used as treatments to the acid soils. They were wheat straw, corn stalks, and alfalfa. Wheat straw and corn stalks were taken from mature plants after their harvest. Alfalfa was taken from commercially available alfalfa hay after being separated from weeds.

The plant materials were prepared by oven drying at 70 C for 24 hours and grinding in a Wiley Mill to pass through a 2 mm screen. Then they were thoroughly mixed and stored in plastic bags.

Determination of Soil Moisture Content at Field Capacity

Approximately a 100 g air-dried soil sample was transferred into each of six 100 ml beakers and slightly compacted by gently tapping on a bench for several times. Different amounts of distilled water were added to each of the beakers so that the soil in those beakers were ranged from extremely dry to extremely wet. Three hours later, a beaker with the added water that just did wet the whole soil in it was selected. A small amount of wet soil was taken from the selected beaker, weighed, oven dried at 105 C for 24 hours and weighed again. Grams of water lost upon drying per gram of oven-dried soil was taken as the basis in calculating the soil moisture content at field capacity.

Indicator Crop

Barley (*Hordeum vulgare* L.) variety Harrison which is known to be sensitive to Al was used as an indicator crop in this study.

Experimental Procedure

Soil Slurry Experiment

This experiment was carried out in order to study the effects of adding different rates of wheat straw, corn stalks, and alfalfa to the two acid soils on root length, root weight, and pH of solution [pH(solution)] and sediment [pH(sediment)] in soil slurries. The experimental design was a randomized complete block (RCB) with a 2x3x3 (two soils x three plant materials x three rates of each plant material)

factorial treatment arrangement with three replications.

One hundred grams of air-dried soil samples (passed through a 2 mm screen) were transferred into 400 ml beakers. Plant materials at the rates of 0, 3, and 6% (soil weight basis) were added to the soil in the beakers and thoroughly mixed. The contents were watered with distilled water to field capacity and left for incubation on a laboratory bench for four weeks. Soil moisture status was examined daily by means of weighing and distilled water was added whenever necessary during the incubation period.

At the end of the incubation period, the beakers were filled with distilled water and the contents were stirred and made to 400 ml volumes. Barley seeds were pregerminated in acid-washed sand for two days prior to transplanting and only those with one centimeter root length were selected to ensure uniformity. Five seedlings were transplanted to each beaker at equal distances between cheesecloth which had been tied across the mouth of each beaker. Folded "Kimwipes" tissue papers were used to conduct soil solution to the cheesecloth. Carbon dioxide-free air was bubbled into the soil slurry of each beaker by means of glass capillary tubes connected to a system of rubber tubing in order to keep the soil slurry stirred and well aerated. The seedlings were allowed to grow for two weeks following the transplanting.

The laboratory lighting and the soil slurry aeration systems were left on throughout the growing period. The volume of the soil slurries was adjusted to 400 ml daily with distilled water.

At the end of the growing period, root length, root weight, pH (solution), and pH(sediment) were measured. Root length measurement for each treatment was taken from the average of twelve individual roots

comprised of the three longest roots of each four plants. Root weight measurement for each treatment was taken from the oven-dried weight of all roots of the four selected plants. The pH(solution) and pH(sediment) values were measured by placing the pH electrodes into the appropriate parts of the soil slurries after allowing the sediment to settle.

Greenhouse Pot Experiment

A greenhouse study was carried out in an attempt to study the effects of adding different rates of the plant materials to the acid soils by different methods of application on top yields; soil pH, soil exchangeable Al and Mn; and the absorption and accumulation of Al, Mn, Ca, Mg, K, and P in plant tops. The experimental design was a randomized complete block (RCB) with a 2x2x3x3 (two soils x two methods of plant material application x three plant materials x three rates of each plant material) factorial treatment arrangement with three replications.

Two kilograms of air-dried soil samples were transferred into black polyethylene pots which had holes at the bottom for drainage. Sixty ppm of N as NH_4NO_3 , 30 ppm of P as $\text{NH}_4\text{H}_2\text{PO}_4$ (N in this compound is counted) and 30 ppm of K as KCl (soil weight basis) were added to each pot and thoroughly mixed with the soil. Then, the plant materials at the rates of 0, 3, and 6% (soil weight basis) were added and thoroughly mixed with the whole soil of "mixed application" pots or thoroughly mixed with 5 cm surface soil of "surface application" pots. The treated pots were watered to field capacity with distilled water and left for incubation for four weeks. Soil water status was adjusted to field capacity by means of weighing every two days and distilled water

was added whenever necessary throughout the incubation period.

At the end of the four week incubation period, ten barley seeds were placed equidistant at one centimeter depths in each pot, allowed to grow ten days, and thinned to seven plants per pot. Thirty ppm of N as NH_4NO_3 (soil weight basis) was added to each pot as a top-dressing at the end of the third week. Soil moisture status was adjusted to field capacity by means of weighing every two days and distilled water was added whenever necessary throughout the growing period.

At the end of the eighth week after planting, plant heights were measured, tops harvested, and soil samples taken from each plot. Plant height for each treatment was taken by measuring the height from the soil surface to the tip of the tallest leaf. The plants were cut at the base of the stem, dipped in a dilute detergent solution, rinsed with distilled water, transferred into brown paper bags and oven dried at 70 C for 24 hours before weighing. Eight soil subsamples were taken from each pot at 7.5 - 10.0 cm (3-4 in) depths using a soil sample tube. The subsamples taken, from each plot, were composited into a single sample in a brown paper bag, air dried, ground to pass a 2 mm screen, thoroughly mixed, and stored in a refrigerator awaiting chemical analyses.

Soil Analysis

Soil Before Treatment

The four soil samples taken from each soil prior to potting were used for "soil before treatment" analyses. The samples were analyzed for pH; organic matter content; titratable acidity; and exchangeable Al, Mn, Ca, Mg, K, and Na.

Two different values of pH were measured for each soil sample. The $\text{pH}(\text{H}_2\text{O})$ was measured in saturated soil paste (U. S. Salinity Laboratory Staff, 1969a) and the $\text{pH}(\text{KCl})$ was measured after a small amount of KCl salt was added to the paste, stirred, and left for a half of an hour. Organic matter was determined by the Walkley-Black Method (U. S. Salinity Laboratory Staff, 1969b).

Methods of Evans and Kamprath (1970) were used for extracting exchangeable Al and determining titratable acidity, except that Whatman's Number 40 filter papers were used in filtering the samples. The leachate was made to 100 ml volume and mixed thoroughly before exchangeable Al was determined by a Perkin-Elmer, model 5000, atomic absorption spectrophotometer using the wavelength and other settings as described in the instrument manual. A known volume of the remaining leachate was used for determining titratable acidity by titrating with 0.1N NaOH.

Modified methods of Chapman and Pratt (1961a) were used for extracting soil exchangeable Mn and exchangeable bases. One hundred milliliters of neutral normal NH_4OAc was added to 5.00 g soil samples in 250 ml Erlenmeyer flasks, shaken thoroughly, and left overnight. The flasks' contents were filtered through Whatman's Number 40 filter papers in Buchner funnels. Each sample was leached four times with 20 ml of the extractant while filtering. The leachate was made to 200 ml volume with the extractant and mixed thoroughly before exchangeable Mn, Ca, Mg, K, and Na were determined by a Perkin-Elmer, model 5000, atomic absorption spectrophotometer as previously described. Potassium and Na were determined on emission mode whereas other cations were determined on absorption mode. The cation exchange capacity (CEC) was calculated by summing the exchangeable Ca, Mg, K, and Na and the titratable

acidity. Data from the "soil before treatment" analyses are presented in Table 1.

Soil After Treatment

The stored soil samples taken from the greenhouse pot experiment were analyzed for $\text{pH}(\text{H}_2\text{O})$, $\text{pH}(\text{KCl})$, exchangeable Al, and exchangeable Mn only. Methods used are similar to those described under the "soil before treatment" analyses. The results and discussion are presented in the following chapter.

Plant Analysis

Due to the small amount of the plant samples, the whole plant tops were used in this analysis. The stored oven-dried plant samples were crushed, thoroughly mixed, and stored in plastic vials prior to the analysis. Samples of known weight between 0.100 g to 0.500 g were put in 25 ml porcelain cups and dry ashed in a muffle furnace at 550 C for four hours, cooled, dissolved in 10 ml 1N HCl, and filtered through Whatman's Number 42 filter papers on small Buchner funnels. Each sample was washed twice with 5 ml of hot distilled water while filtering and the leachate was made to 25 ml volume with distilled water and thoroughly mixed before total Al, Mn, Ca, Mg, K, and P were measured.

Except for P, other ions were determined similar to those described under soil analysis. Phosphorus was determined by the Molybdenum Blue Method of Fiske and Subbarow (Chapman and Pratt, 1961b) on a Baush and Lomb, model Spectronic 20, spectrophotometer.

TABLE 1. Data on Soil Before Treatment Analysis*

Soil	pH(H ₂ O)	pH(KCl)	%O.M.	meq/100 g							
				Al	Mn	Titra. acidity	Ca	Mg	K	Na	CEC
Sequoia	4.70	3.46	0.78	6.54	0.02	6.16	2.93	0.76	0.18	0.05	10.08
Tellico	4.83	3.66	1.24	1.28	0.44	2.23	1.54	0.35	0.20	0.03	4.35

* All values are means of four replications on an air-dried soil basis.

Statistical Analysis

Analysis of variance and F tests, Duncan's New Multiple Range Test, and correlation coefficient (r values) were determined by an IBM System/360 model 65 computer using the Statistical Analysis System developed by SAS Institute Inc. (SAS User's guide, 1979 Edition). F tests and Duncan's New Multiple Range Test were conducted at the 5% probability level (P.05).

CHAPTER IV

RESULTS AND DISCUSSION

Data on chemical characteristics of Sequoia and Tellico soils before treatment were presented earlier in Table 1. The soils differed considerably in their native pH values, organic matter, exchangeable Al and Mn, titratable acidity, and exchangeable base contents. The Sequoia soil was lower in pH values, organic matter, and exchangeable Mn contents but higher in exchangeable Al, titratable acidity, and CEC than was the Tellico soil. Further discussion will be limited to the changes that occurred upon treatment and all comments on significance will be at the 5% probability level (P.05).

Soil Slurry Experiment

Effects of Materials and Rates on pH(solution), pH(sediment), and Root Growth

The results of this study are presented in Table 2. With the exception of wheat straw, adding the plant materials to both soils significantly increased the pH(solution) values. Increasing the amounts of corn stalks or alfalfa in the order of 0, 3, and 6% rates significantly increased the pH(solution) values with the alfalfa giving the greatest increase at all rates. The pH(solution) values of both soils treated with wheat straw agreed with those treated with corn stalks or alfalfa but with a lesser effectiveness since the differences among the rates were not significant.

The pH(sediment) values closely followed those of the pH(solution)

TABLE 2. Effects of Materials and Rates on pH(solution), pH(sediment), and Root Yields of Soil Slurry Experiment.

Treatment	Treatment rate (%)	pH(solution) ^A		pH(sediment) ^B		Root length(cm) ^C		Root weight(mg) ^D	
		Sequoia	Tellico	Sequoia	Tellico	Sequoia	Tellico	Sequoia	Tellico
Wheat straw	0	5.27 g*	5.30 g	4.87 i	5.17 g	7.45 bcd	8.07 bc	20.33 ab	20.53 ab
	3	4.92 h	5.36 g	4.85 i	5.43 f	6.86 bcd	11.37 a	15.33 b	19.53 ab
	6	5.27 g	6.53 c	5.63 e	6.63 c	6.59 cd	10.73 a	17.87 ab	16.50 ab
Corn stalks	0	5.23 g	5.37 g	4.93 hi	5.23 g	7.53 bcd	7.67 bcd	20.00 ab	16.50 ab
	3	5.63 f	6.33 d	5.19 g	6.19 d	6.58 cd	11.54 a	16.30 ab	22.33 a
	6	5.83 e	7.17 b	5.07 gh	6.60 c	7.73 bcd	10.23 a	17.13 ab	21.73 a
Alfalfa	0	5.27 g	5.32 g	4.95 hi	5.20 g	7.31 bcd	7.51 bcd	18.20 ab	18.33 ab
	3	5.74 ef	7.03 b	4.83 i	6.79 b	6.30 d	8.37 b	15.00 b	14.50 b
	6	6.30 d	7.93 a	5.07 gh	7.10 a	8.03 bc	8.24 b	18.30 ab	14.67 b

A,B,C,D Different set of variables.

*Means of the same letter under A,B,C,D are not significantly different at P.05 level. Comparison among A,B,C,D are not valid.

but showed a greater effectiveness of wheat straw in raising pH values. Interestingly, the pH(sediment) values measured in the Tellico soil showed significant differences among the rates upon treating with any of the plant materials. In contrast, the differences in the pH(sediment) values among the rates and plant materials were generally not significant in the Sequoia soil.

The root lengths in the Tellico soil treated with wheat straw or corn stalks were significantly longer than those of the untreated, though the differences between 3 and 6% rates were not significant. However, there was no significant difference in the root lengths measured in the Tellico soil treated with different rates of alfalfa. There was no significant difference in the root lengths among the rates and plant materials in the Sequoia soil. The root weight data suggest that this variable was not responsive to the various treatments since there were no differences among the rates and plant materials in either soil.

The data of the soil slurry experiment were correlated to each other (Table 3) and to the data of the pot experiment in an attempt to see any relationship between them (Table 4). Root length gave a better correlation coefficient with pH(sediment) [$r = 0.510$] than with pH(solution) [$r = 0.374$]. Root length did correlate well with exchangeable Al ($r = -0.510$), exchangeable Mn ($r = 0.647$), and the concentration of Mn in barley tops ($r = 0.771$). Root weight did not correlate well to anything but root length.

TABLE 3. Correlation of Root Yields, pH(solution), and pH(sediment) of Soil Slurry Experiment and Top Yields, pH(H₂O), and pH(KCl) of Pot Experiment (r Values).

Variable	Slurry experiment			Pot experiment			
	Root weight	pH(solution)	pH(sediment)	Plant height	Plant weight	Soil pH H ₂ O	KCl
Root length	0.502*	0.374*	0.510*	-0.123	-0.090	0.361*	0.259
Root weight	-	-0.136	-0.085	-0.217	-0.279*	-0.172	-0.185
pH(solution)	-	-	0.872*	0.481*	0.606*	0.862*	0.862*
pH(sediment)	-	-	-	0.253	0.334*	0.731*	0.691*
Plant height	-	-	-	-	0.853*	0.463*	0.616*
Plant weight	-	-	-	-	-	0.498*	0.601*
pH(H ₂ O)	-	-	-	-	-	-	0.958*

*Significant at P.05 level.

TABLE 4. Correlation of Root Yields, pH(solution), and pH(sediment) of Soil Slurry Experiment and pH Values, Soil Exchangeable Al and Mn, and Selected Nutrient Concentrations in Barley Tops of Pot Experiment (r Values).

Variable	Soil exch. Al	Soil exch. Mn	Concentration in barley tops					
			Al	Mn	Ca	Mg	K	P
Root length	-0.510*	0.647*	-0.236	0.771*	0.016	0.421*	0.199	0.074
Root weight	0.014	0.036	0.065	0.193	0.066	0.281*	-0.224	-0.334*
pH(solution)	-0.664*	0.520*	-0.448*	0.384*	-0.172	0.289*	0.700*	0.404*
pH(sediment)	-0.611*	0.728*	-0.242	0.599*	-0.178	0.262	0.480*	0.268
Plant height	-0.565*	0.353*	-0.491*	0.097	-0.300*	-0.351*	0.766*	0.343*
Plant weight	-0.442*	0.136	-0.374*	-0.083	-0.210*	-0.249*	0.812*	0.468*
pH(H ₂ O)	-0.732*	0.566*	-0.501*	0.364*	-0.333*	-0.062	0.682*	0.221*
pH(KCl)	-0.724*	0.590*	-0.510*	0.307*	-0.279*	-0.074	0.708*	0.246*

*Significant at P.05 level.

Greenhouse Pot Experiment

Effects of Materials, Rates, and Methods of Application on Soil pH(H₂O) and pH(KCl)

As shown in Table 5 and Table 6, pH(H₂O) and pH(KCl) responded similarly to the various combinations of treatments, in which their values increased with increasing amounts of plant materials applied. For any given treatment, the pH(H₂O) or pH(KCl) value was higher in the Tellico soil than in the Sequoia soil. This is most likely due to the higher native acidity (lower pH) in Sequoia soil than in Tellico soil. Similarly, for each soil, the value was higher under surface application than under mixed application. This is caused by the higher concentration of a plant material within the sampling depth under surface application than under mixed application.

Although there were no consistent significant differences, alfalfa was the most effective in increasing both the pH(H₂O) and pH(KCl) values, followed by corn stalks and wheat straw. For each soil, either under mixed or surface application, the alfalfa treated pots produced significantly higher pH(H₂O) or pH(KCl) values over the untreated pot with the 6% rate giving significantly greater values over the 3% rate. However, these effects were not consistently obtained from treating with corn stalks or wheat straw.

The increase in soil pH after adding plant materials to acid soils has been similarly observed by Asghar and Kanehiro (1980) and Hoyt and Turner (1975). The superiority of alfalfa over the higher C/N ratio plant materials in raising the soil pH of acid soils is in agreement with those reported by Hoyt and Turner (1975).

TABLE 5. Effects of Materials, Rates, and Methods of Application on Soil pH(H₂O) Value.

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	4.51 m*	4.54 lm	4.77 ijk1	4.80 ijk
	3	4.66 klm	4.76 ijk1	4.95 ghij	4.97 ghi
	6	4.74 ijk1m	4.80 ijk	5.06 fgh	5.17 efg
Corn stalks	0	4.53 lm	4.50 m	4.77 ijk1	4.76 ijk1
	3	4.72 jklm	4.79 ijk	5.05 fgh	5.09 fgh
	6	4.74 ijk1m	4.91 hijk	5.18 efg	5.49 c
Alfalfa	0	4.51 m	4.53 lm	4.71 jklm	4.76 ijk1
	3	4.81 ijk	4.82 ijk	5.42 cd	5.21 def
	6	5.51 c	5.34 cde	5.75 b	6.09 a

*Means with the same letter are not significantly different at P.05 level.

TABLE 6. Effects of Materials, Rates, and Methods of Application on Soil pH(KCl) Value.

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	3.57 n*	3.67 lmn	3.93 ghijk	3.91 ghijkl
	3	3.60 n	3.70 klmn	3.97 ghi	3.97 ghi
	6	3.66 mn	3.72 jklmn	4.10 fgh	4.23 ef
Corn stalks	0	3.65 n	3.63 n	3.94 ghijk	3.91 ghijkl
	3	3.66 mn	3.81 ijklmn	4.12 fgh	4.14 fg
	6	3.78 ijklmn	3.89 hijklm	4.39 e	4.70 d
Alfalfa	0	3.65 mn	3.63 n	3.92 ghijkl	3.92 ghijkl
	3	3.96 ghij	3.91 ghijkl	4.94 c	4.82 cd
	6	4.97 c	4.86 cd	5.49 b	5.76 a

*Means with the same letter are not significantly different at P.05 level.

Table 3, page 26, shows $\text{pH}(\text{H}_2\text{O})$ and $\text{pH}(\text{KCl})$ highly correlated to each other ($r = 0.958$) [hereafter any comparison to soil pH will be made only to soil $\text{pH}(\text{H}_2\text{O})$].

Effects of Materials, Rates, and Methods of Application on Soil

Exchangeable Al Content

The effects on exchangeable Al are presented in Table 7. Generally, exchangeable Al was lower in the Tellico soil than in the Sequoia soil and for each soil, surface application depressed soil exchangeable Al more than did the mixed application method. In the Sequoia soil, increasing the amounts of corn stalks or alfalfa in the order of 0, 3, and 5% rates by mixed application significantly reduced the soil exchangeable Al levels. Interestingly, under surface application, wheat straw as well as corn stalks and alfalfa produced these effects. It suggests that wheat straw should produce a greater effectiveness when applied at higher concentration into the soil.

Adding corn stalks or alfalfa to the Tellico soil at the 6% rate, either by mixed or by surface application, did not decrease the soil exchangeable Al more than did the 3% rate. This is possibly due to the lower native exchangeable Al content in this soil. Nonetheless, the soil exchangeable Al in the treated pots significantly decreased compared to the untreated pots. Wheat straw also showed its limited effectiveness in this soil since there was no significant decrease in the exchangeable Al among the rates under either method except when treated with the 6% rate by surface application.

In general, the exchangeable Al in each soil was lowest when any of the plant materials were added at the highest rates. This observation

TABLE 7. Effects of Materials, Rates, and Methods of Application on Soil Exchangeable Al Content (meq/100g).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	5.86 ab*	5.90 ab	1.24 ghi	1.33 gh
	3	5.47 bc	5.22 c	1.15 ghijk	1.17 ghij
	6	5.18 c	4.48 d	0.85 hijkl	0.60 klmn
Corn stalks	0	5.99 ab	5.52 bc	1.30 gh	1.38 gh
	3	5.14 c	3.85 e	0.73 ijklm	0.64 jklm
	6	3.70 e	2.81 f	0.34 lmn	0.18 mn
Alfalfa	0	5.87 ab	6.11 a	1.37 gh	1.31 gh
	3	1.63 g	1.50 g	0.03 n	0.04 n
	6	0.18 mn	0.33 lmn	0.02 n	0.02 n

*Means with the same letter are not significantly different at P.05 level.

is in agreement with those of Hoyt and Turner (1975) and Asghar and Kanehiro (1980).

Among the plant materials, alfalfa was the most effective in reducing soil exchangeable Al, followed by corn stalks and wheat straw respectively. The higher concentration of any of the plant materials within the sampling depth under the surface application method than under the mixed application method could explain the better effectiveness shown by the former method. The effects of the plant materials on soil exchangeable Al closely followed the $\text{pH}(\text{H}_2\text{O})$ values. Table 4, page 27, shows exchangeable Al was significantly correlated with $\text{pH}(\text{H}_2\text{O})$ as expected ($r = -0.732$).

Effects of Materials, Rates, and Methods of Application on Soil

Exchangeable Mn Content

There were no changes in exchangeable Mn in the Sequoia soil regardless of the rates, plant materials, and methods of application (Table 8). This is obviously due to the lower native exchangeable Mn in this soil.

Tellico soil produced greater increases in exchangeable Mn than did the Sequoia soil after treating with plant materials. Only the values in the Tellico soil treated with the 6% rate of wheat straw by mixed application and those treated with 3 and 6% rates of alfalfa by surface application were significantly greater than those of the untreated.

Treating Tellico soil with alfalfa by surface application caused the highest increases in the soil exchangeable Mn contents compared to treating with corn stalks or wheat straw. However, under mixed

TABLE 8. Effects of Materials, Rates, and Methods of Application on Soil Exchangeable Mn Content (meq/100g).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	0.006 e*	0.006 e	0.427 cd	0.370 d
	3	0.015 e	0.021 e	0.460 cd	0.436 cd
	6	0.025 e	0.036 e	0.623 b	0.409 cd
Corn stalks	0	0.004 e	0.005 e	0.400 cd	0.363 d
	3	0.011 e	0.013 e	0.497 bcd	0.499 bcd
	6	0.018 e	0.016 e	0.400 cd	0.445 cd
Alfalfa	0	0.005 e	0.004 e	0.420 cd	0.402 cd
	3	0.015 e	0.009 e	0.459 cd	1.107 a
	6	0.015 e	0.009 e	0.521 bc	1.011 a

*Means with the same letter are not significantly different at P.05 level.

application the effects in this soil differed, whereby the wheat straw treatments tended to cause the highest increases in the soil exchangeable Mn, followed by the alfalfa and corn stalks treatments respectively.

The increases in exchangeable Mn content upon treating with either plant material regardless of the increases in pH (H_2O) values are in agreement with the results of Fujimoto and Sherman (1948), Christensen et al. (1950), Sanchez and Kamprath (1959), and Asghar and Kanehiro (1980). These workers attributed such an effect to the depression of soil Eh as a consequence of high microbial activity in the soil. This could explain the observed positive correlation of exchangeable Mn with pH(H_2O) [$r = 0.566$] in this study as shown in Table 4, page 27. Soil exchangeable Mn negatively correlated with soil exchangeable Al ($r = -0.704$) [Table 9].

Effects of Materials, Rates, and Methods of Application on Plant Height and Weight

As shown in Table 3, page 26, pH(H_2O) significantly correlated with plant height ($r = 0.463$) and plant weight ($r = 0.498$). As expected, exchangeable Al showed a significant negative correlation with plant height ($r = -0.565$) and plant weight ($r = -0.442$) as shown in Table 4, page 27. However, exchangeable Mn significantly correlated with plant height ($r = 0.353$) but not plant weight ($r = 0.136$).

Treating Sequoia or Tellico soil with wheat straw or corn stalks by either method of application generally depressed the plant heights, but not consistently (Table 10). In contrast, the barley plants grown on the alfalfa treated pots of both soils and methods of application, produced greater heights over the plants grown on the untreated pots

TABLE 9. Correlation of Soil Exchangeable Al and Mn, and Selected Nutrient Concentrations in Barley Tops of Pot Experiment (r Values).

Variable	Soil exch. Mn	Concentration in barley tops					
		Al	Mn	Ca	Mg	K	P
Soil exch. Al	-0.704*	0.557*	-0.727*	0.540*	0.207*	-0.788*	-0.182
Soil exch. Mn	-	-0.412*	0.763*	-0.357*	-0.121	0.402*	0.121
Al in tops	-	-	-0.321*	0.243*	0.046	-0.543*	-0.277*
Mn in tops	-	-	-	-0.351*	-0.075	0.292*	-0.037
Ca in tops	-	-	-	-	0.524*	-0.453*	0.074
Mg in tops	-	-	-	-	-	-0.248*	0.023
K in tops	-	-	-	-	-	-	0.495*

*Significant at P.05 level.

TABLE 10. Effects of Materials, Rates, and Methods of Application on Plant Height (cm).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	16.0 fghi*	14.2 ijkl	20.0 ef	19.2 efgh
	3	10.3 lm	10.6 lm	12.1 jklm	21.1 e
	6	9.3 m	10.2 lm	10.4 lm	18.7 efgh
Corn stalks	0	15.9 ghij	15.2 hijk	21.6 e	18.1 efghi
	3	9.3 m	11.3 klm	14.0 jkl	18.3 efgh
	6	9.0 m	10.3 lm	12.8 jklm	18.6 efgh
Alfalfa	0	14.3 ijkl	15.3 hij	19.6 efg	20.3 e
	3	26.1 d	31.5 bc	30.1 bc	35.3 a
	6	28.9 cd	30.2 bc	33.1 ab	21.6 e

*Means with the same letter are not significantly different at P.05 level.

except the 6% rate surface applied to the Tellico soil. In both cases, there was no significant difference in the plant heights between 3 and 6% rates. The effects on plant weights were approximately the same as for the plant heights (Table 11). Data on plant height and plant weight suggest that even alfalfa, when applied to the soils in excessive amounts, such as the 6% rate surface applied to the Tellico soil, was unfavorable to barley growth.

There were no aboveground visual symptoms of Al toxicity observed from the plants grown on the Tellico soil regardless of treatments nor on the Sequoia soil treated with alfalfa. The reduced growth of barley plants grown on the Sequoia soil treated with wheat straw or corn stalks was most likely due to the toxic effects of Al. The plants of these treatments were observed to be stunted; purpling of stems, leaves and veins; and chlorosis and dieback of leaf tips. It can be concluded that this particular variety of barley tolerated the soil exchangeable Al up to 1.63 meq/100 g since there were no such symptoms noted from the plants of this pot (Table 7, page 32). In addition to that, the results of soil exchangeable Al analysis (Table 3, page 26) clearly indicate that the soil exchangeable Al levels in the pots where those symptoms were observed were still very high and toxic to the plants.

There were no aboveground visual symptoms of Mn toxicity observed from the plants grown on the Sequoia soil regardless of treatment. The reduced growth of barley plants grown on the Tellico soil treated with corn stalks or wheat straw and the one treated with 6% rate of alfalfa by surface application method was most likely due to the toxic effects of Mn. Table 7, page 32, shows that the soil exchangeable Al in these pots were well below the 1.63 meq/100 g level, which is known to be

TABLE 11. Effects of Materials, Rates, and Methods of Application on Plant Weight (g).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	0.246 ghi*	0.198 ghi	0.340 fghi	0.322 fghi
	3	0.159 hi	0.216 ghi	0.174 hi	0.400 fghi
	6	0.158 hi	0.170 hi	0.147 i	0.398 fghi
Corn stalks	0	0.226 ghi	0.251 ghi	0.372 fghi	0.272 ghi
	3	0.133 i	0.226 ghi	0.213 ghi	0.516 fg
	6	0.179 hi	0.202 ghi	0.213 ghi	0.609 f
Alfalfa	0	0.216 ghi	0.241 ghi	0.295 ghi	0.291 ghi
	3	0.988	2.473 a	1.690 cd	1.801 c
	6	2.305 ab	1.499 d	2.165 b	0.479 fgh

*Means with the same letter are not significantly different at P.05 level.

nontoxic to barley growth. This observation is also supported by the results of the soil exchangeable Mn in those pots (Table 8, page 34). Although the threshold level of toxicity could not be identified from these results, the Mn concentrations in the tops of plants suffering Mn toxicity were the largest in this experiment. Barley plants suffering Mn toxicity were observed to be stunted and their leaves were dark green in color with a lot of brown spot areas.

The observed aboveground visual symptoms of Al toxicity were similar to those reported by Rees and Sidrak (1961), Foy and Brown (1964), Jackson (1967), and Foy (1974); whereas the symptoms of Mn toxicity were similar to those reported by Bortner (1935) and Rees and Sidrak (1961).

Effects of Materials, Rates, and Methods of Application on the Concentration of Al in Barley Tops

The concentration of Al in barley tops (Table 12) showed the highest correlations with exchangeable Al ($r = 0.557$), $\text{pH}(\text{H}_2\text{O})$ [$r = -0.501$], and plant height ($r = -0.491$) followed by somewhat lower correlation values with exchangeable Mn ($r = -0.412$) and plant weight ($r = -0.374$) as shown in Table 4, page 27, and Table 9, page 36.

Apparently, the absorption and accumulation of Al by the plants of each treatment followed the trend of the exchangeable Al contents in the soils. The Al concentrations in the plant tops tended to decrease with the increasing amounts of plant materials applied to the soils. However, most of the treatments were not significantly different.

These results are considerably in agreement with those of Rees and Sidrak (1961) and Bartlett and Riego (1972) who reported that the

TABLE 12. Effects of Materials, Rates, and Methods of Application on the Concentration of Al in Barley Tops (ppm).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	81 bcdefgh*	96 bcde	68 cdefgh	80 bcdefgh
	3	91 bcdefg	85 bcdefgh	76 bcdefgh	48 efgh
	6	175 a	98 bcde	104 bc	52 defgh
Corn stalks	0	121 b	88 bcdefgh	81 bcdefgh	70 cdefgh
	3	91 bcdefg	85 bcdefgh	57 cdefgh	63 cdefgh
	6	93 bcdef	80 bcdefgh	55 cdefgh	37 h
Alfalfa	0	122 b	102 bcd	73 bcdefgh	76 bcdefgh
	3	53 defgh	64 cdefgh	50 efgh	40 gh
	6	62 cdefgh	52 defgh	41 fgh	41 fgh

*Means with the same letter are not significantly different at P.05 level.

Al-treated plants in culture solution accumulated large amounts of Al in their foliage. Most Al absorbed by a plant is precipitated with P within the root tissues (McLean and Gilbert, 1927; Wright and Donahue, 1953; Jackson, 1967) and this could explain the poor consistency of the measured Al in the barley tops regarding the various treatments.

Effects of Materials, Rates, and Methods of Application on the Concentration of Mn in Barley Tops

As was previously noted, Sequoia and Tellico soils differed considerably in their native and after treatment exchangeable Mn levels. This is reflected by the Mn concentrations measured in the plant tops (Table 13). Barley plants grown on the Tellico soil accumulated larger amounts of Mn in their tops as compared to those grown on the Sequoia soil. This is most likely due to the higher native exchangeable Mn and Mn^{2+} released by the reducing effect of the decomposing plant materials in the Tellico soil than in the Sequoia soil. The results show a trend that the Mn concentrations in barley tops increased with the increasing amounts of wheat straw, corn stalks, or alfalfa applied to the soils. The results also suggest that alfalfa treatment caused a lower accumulation of Mn in the plant tops but the effects of corn stalks and wheat straw treatments varied.

It was mentioned earlier that no aboveground visual symptoms of Mn toxicity were observed from the plants grown on the Sequoia soil regardless of treatments nor on the Tellico soil treated with alfalfa except the one treated with 6% rate of alfalfa by surface application. This observation is in agreement with the data of Mn concentrations in barley tops. It can be concluded that this particular variety of barley

TABLE 13. Effects of Materials, Rates, and Methods of Application on the Concentration of Mn in Barley Tops (ppm).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	128 i*	129 i	515 ef	511 ef
	3	105 i	181 hi	760 ab	528 ef
	6	138 i	273 gh	821 a	596 cde
Corn stalks	0	99 i	113 i	532 ef	621 cde
	3	110 i	199 hi	664 bc	650 cd
	6	186 hi	308 g	607 cde	527 ef
Alfalfa	0	123 i	94 i	517 ef	605 cde
	3	155 i	139 i	431 f	450 f
	6	154 i	125 i	449 f	510 ef

*Means with the same letter are not significantly different at P.05 level.

tolerated a relatively high concentration of Mn since with an average concentration of about 450 ppm Mn in the tops, the plants still did not show any Mn toxicity symptoms and still produced significantly greater yields than the untreated. However, with higher Mn concentrations in the plant tops, such as on the Tellico soil treated with 6% rate of alfalfa by surface application which contained 510 ppm Mn, the plants did show Mn toxicity symptoms.

The concentration of Mn in barley tops correlated significantly with exchangeable Mn ($r = 0.763$), exchangeable Al ($r = -0.727$), $\text{pH}(\text{H}_2\text{O})$ [$r = 0.364$], and Al in barley tops ($r = -0.321$). Correlation coefficients were presented earlier in Table 4, page 27, and Table 9, page 36.

Effects of Materials, Rates, and Methods of Application on the Concentration of Ca in Barley Tops

Unexpectedly, the concentration of Ca in barley tops positively correlated with exchangeable Al ($r = 0.540$) as shown in Table 9, page 36. This effect is in agreement with the results reported by McLeod and Jackson (1965) but is contrary with those reported by Rees and Sidrak (1961), Foy and Brown (1963), Bartlett and Riego (1972), and Helyar and Anderson (1974).

Calcium concentrations in barley tops are presented in Table 14. The Ca concentrations in the plants grown on the Sequoia soil decreased upon treating with wheat straw, corn stalks, or alfalfa applied by either method. However, the effects were not different among the three plant materials and the two methods of application. Generally, the differences in the Ca measured in the plant tops among the rates of each plant material were also not significant. Obviously, there appears

TABLE 14. Effects of Materials, Rates, and Methods of Application on the Concentration of Ca in Barley Tops (%).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	0.92 ab*	1.07 a	0.36 fgh	0.51 defgh
	3	0.80 abcd	0.64 bcdefgh	0.77 abcde	0.30 h
	6	0.46 defgh	0.51 defgh	0.80 abcd	0.33 gh
Corn stalks	0	0.88 abc	0.96 ab	0.45 defgh	0.46 defgh
	3	0.73 abcdef	0.49 defgh	0.64 bcdefgh	0.33 gh
	6	0.72 abcdef	0.66 bcdefgh	0.44 defgh	0.43 defgh
Alfalfa	0	0.96 ab	0.90 abc	0.38 fgh	0.29 h
	3	0.44 defgh	0.41 efgh	0.44 defgh	0.50 defgh
	6	0.51 defgh	0.70 bcdefg	0.54 cdefgh	0.47 defgh

*Means with the same letter are not significantly different at P.05 level.

to be no pattern to the changes in the Ca measured in the plants grown on the Tellico soil. This is possibly due to the lower exchangeable Ca in the soil.

Effects of Materials, Rates, and Methods of Application on the Concentration of Mg in Barley Tops

The concentration of Mg in barley tops did not correlate well with exchangeable Al ($r = 0.207$) and exchangeable Mn ($r = -0.121$) as shown in Table 9, page 36. Table 15 shows that Mg concentrations in the plant grown on the Sequoia soil tended to decrease upon treating with wheat straw, corn stalks, or alfalfa by either method of application. Interestingly, the reverse was noted in the plants grown on the Tellico soil. Generally, for both soils and both methods of application, there were no real differences in the Mg concentrations in the plant tops among the rates and materials. The high content of Mg in the plants grown on the Sequoia soil receiving no wheat straw or treated with 6% rate of corn stalks under surface application was most likely due to random variation.

The higher accumulation of Mg in the plants under severe Al toxicity in this study is in agreement with that reported by Andrew et al. (1973) but is contrary to the findings reported by Helyar and Anderson (1974).

Effects of Materials, Rates, and Methods of Application on the Concentration of K in Barley Tops

The K concentrations in barley tops are presented in Table 16. For both soils and both methods of application, treating with wheat straw, corn stalks, or alfalfa steadily increased the K measured in the plant tops. Plants of the alfalfa treatment showed higher K accumulation

TABLE 15. Effects of Materials, Rates, and Methods of Application on the Concentration of Mg in Barley Tops (%).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	0.25 cdefghij*	0.36 ab	0.14 k	0.18 fghijk
	3	0.18 fghijk	0.19 efghijk	0.24 cdefghijk	0.14 k
	6	0.16 ijk	0.21 defghijk	0.29 bcdef	0.17 hijk
Corn stalks	0	0.30 bcde	0.27 bcdefgh	0.16 ijk	0.18 fghijk
	3	0.24 cdefghijk	0.24 cdefghijk	0.31 abcd	0.17 hijk
	6	0.28 bcdefg	0.39 a	0.34 abc	0.29 bcdef
Alfalfa	0	0.28 bcdefg	0.27 bcdefgh	0.16 ijk	0.15 jk
	3	0.19 efghijk	0.16 ijk	0.21 defghijk	0.21 defghijk
	6	0.19 efghijk	0.18 fghijk	0.22 defghijk	0.23 defghijk

*Means with the same letter are not significantly different at P.05 level.

TABLE 16. Effects of Materials, Rates, and Methods of Application on the Concentration of K in Barley Tops (%).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	1.90 m*	1.64 mn	3.89 ghij	3.91 ghij
	3	2.00 lm	3.17 k	4.03 fghij	4.13 fgh
	6	2.36 l	3.58 j	4.40 ef	4.07 fghi
Corn stalks	0	1.64 mn	1.41 n	3.71 hij	3.87 ghij
	3	2.89 k	3.67 hij	4.32 efg	4.74 de
	6	3.11 k	3.65 ij	4.32 efg	4.70 de
Alfalfa	0	1.72 mn	1.88 m	3.60 ij	3.78 hij
	3	6.71 b	6.94 b	6.84 b	6.72 b
	6	7.44 a	6.29 c	6.73 b	4.88 d

*Means with the same letter are not significantly different at P.05 level.

in their tops than those of corn stalks or wheat straw treatments, though the differences between 3 and 6% rates were not consistently significant. Generally, the effects of adding wheat straw were not different than those of adding corn stalks. In most instances, treating with 3 or 6% rates of these materials increased the K measured in the plant tops as compared to the untreated, though the differences between the two rates were not significant.

The results indicate that K in the plants was highest in the alfalfa treatment, followed by the corn stalks and wheat straw treatments respectively. The results also suggest that applying the materials by the surface application method increased the accumulation of K in the plants compared to the mixed application method. However, the K measured in the plants grown on the Sequoia or Tellico soil treated with 6% rate of alfalfa by surface application were lower than the mixed application. It suggests that the higher concentration of alfalfa in the soils was unfavorable to plant growth.

The concentration of K in barley tops did correlate well with exchangeable Al ($r = -0.788$), plant height ($r = 0.766$) and plant weight ($r = 0.812$), and Al in the plant tops ($r = -0.543$). However, it did not correlate as well with exchangeable Mn ($r = 0.402$) and Mn in plant tops ($r = 0.292$). The correlation coefficients were presented earlier in Table 4, page 27, and Table 9, page 36. The same effect of Al toxicity on the uptake of K by plants has been reported by Foy and Brown (1963) and Helyar and Anderson (1974).

Effects of Materials, Rates, and Methods of Application on the Concentration of P in Barley Tops

Table 17 indicates the P concentrations in the plants grown on both soils tended to increase upon treating with wheat straw, corn stalks, or alfalfa by either method of application. However, the differences among the plant materials, rates, and methods of application were generally not significant.

As shown in Table 4, page 27, and Table 9, page 36, the concentration of P in barley tops did correlate significantly with plant height ($r = 0.343$) and plant weight ($r = 0.463$) but did not correlate well with exchangeable Al ($r = -0.182$) and Mn ($r = 0.121$). This effect of Al toxicity on the uptake of P by plants is consistent with those reported by Bartlett and Riego (1972) and Helyar and Anderson (1974).

TABLE 17. Effects of Materials, Rates, and Methods of Application on the Concentration of P in Barley Tops (%).

Treatment	Treatment rate (%)	Sequoia		Tellico	
		Mixed	Surface	Mixed	Surface
Wheat straw	0	0.15 cdefgh*	0.11 fgh	0.10 h	0.10 h
	3	0.16 cdefgh	0.13 efgh	0.21 abcd	0.11 h
	6	0.12 efgh	0.15 cdefgh	0.20 bcde	0.11 gh
Corn stalks	0	0.10 h	0.11 fgh	0.12 efgh	0.10 h
	3	0.20 bcdef	0.15 cdefgh	0.19 bcdefg	0.13 efgh
	6	0.14 defgh	0.10 h	0.18 bcdefg	0.13 efgh
Alfalfa	0	0.11 gh	0.17 cdefgh	0.14 defgh	0.11 gh
	3	0.28 a	0.25 ab	0.17 bcdefgh	0.25 ab
	6	0.19 bcdefg	0.17 cdefgh	0.22 abc	0.16 cdefgh

*Means with the same letter are not significantly different at P.05 level.

CHAPTER V

SUMMARY AND CONCLUSIONS

The effects of adding 0, 3, and 6% rates (soil weight basis) of wheat straw, corn stalks, and alfalfa to acid Sequoia and Tellico soils on barley root growth were studied in soil slurries in order to avoid difficulties in measuring the root growth in the soil or pot experiment. The pH values measured in the soil solution were higher than in the soil sediment. This was very important since the pH(solution) more directly influenced the root growth than did the pH(sediment).

The effects on pH and root growth varied with application rates, plant materials, and soils. There was no significant difference in the root lengths among the rates and plant materials in the Sequoia soil. The root lengths in the Tellico soil treated with wheat straw or corn stalks were significantly longer than those of the untreated, though the differences between 3 and 6% were not significant. However, there was no significant difference in the root lengths measured in the Tellico soil treated with different rates of alfalfa. Increasing the amounts of plant materials added to both soils increased the pH(solution) values with the alfalfa treatment giving the highest increases, followed by corn stalks and wheat straw treatments respectively. The effects on the pH(sediment) values closely followed those of the pH(solution). Root weights were not responsive to the various treatments in this study.

In the greenhouse pot experiment, the effects of two different methods of application on the soil chemical changes, barley growth, and

the accumulation of selected ions in barley tops were also studied in addition to the effects of plant materials and rates. The $\text{pH}(\text{KCl})$ values were lower than those of the $\text{pH}(\text{H}_2\text{O})$ as the KCl salt maximized the measurable acidity in each treatment. The pH values of both soils increased with the increasing amounts of each plant material added. This was indicated by the increase in the values from one rate to the next higher rate. All surface application rates produced greater pH increases than did the mixed application method. Alfalfa was the most effective in raising the pH values, followed by corn stalks and wheat straw respectively.

The exchangeable Al levels in the Sequoia and Tellico soils treated with alfalfa decreased significantly as compared to the untreated. Treating those soils with corn stalks or wheat straw did reduce exchangeable Al but without consistent significant effects. Exchangeable Al generally decreased with increasing amounts of added plant materials in both soils but the reverse was true for exchangeable Mn. Probably the reducing effect of the decomposing plant materials in the soils (lower Eh) released more Mn^{2+} than that complexed by organic compounds.

The poor growth of barley plants grown on the Sequoia soil was most likely due to the toxic effects of Al. The only treatment that significantly increased the barley growth compared to the untreated was alfalfa, though the differences between 3 and 6% rates were not significant. Adding wheat straw or corn stalks to the Sequoia soil did decrease the soil exchangeable Al and yet the plant heights and weights of these treatments were lower than those of the untreated, though mostly not significant. The results of exchangeable Mn and plant Mn

ruled out the possible effects of Mn toxicity in these treatments. Therefore, it could be concluded that the decreases were due to the other factors, possibly the immobilization of N and/or P by the decomposing wheat straw or corn stalks. It also could be concluded that the superiority of alfalfa over wheat straw and corn stalks was most likely due to its higher N and/or P contents.

The poor growth of barley plants grown on the Tellico soil was most likely due to the toxic effects of Mn. Similar to the Sequoia soil, only the alfalfa treatment significantly increased the plant heights and weights in the Tellico soil. However, surface application at the 6% rate of alfalfa caused a decrease in barley growth. This was probably due to the toxic effects of Mn. Unlike the Sequoia soil, the effects of the immobilization of N and/or P, if any, was not observable in the Tellico soil, possibly due to the predominant effects of Mn toxicity. It could be concluded that Sequoia and Tellico soils represented soils having Al and Mn toxicities problems respectively.

Exchangeable Al in the soil was more appropriate in determining the threshold level of Al toxicity to barley than was Al measured in the plant tops. Earlier workers have shown that most Al absorbed by the plants was precipitated with P within the root tissues. In contrast, Mn measured in the plant tops served as a better indicator in determining the threshold level of Mn toxicity to barley than did the exchangeable Mn in the soils.

In the Sequoia soil where Al was present at a high level, adding wheat straw, corn stalks, or alfalfa increased the K and P contents but decreased the Ca and Mg contents measured in barley tops. In the Tellico soil where Mn was present at a high level, adding those

materials increased the Mg, K, and P contents but had no effect on the Ca content measured in barley tops.

LITERATURE CITED

LITERATURE CITED

- Adams, F., and Z. F. Lund. 1966. Effect of chemical activity of soil aluminum on cotton root penetration of acid subsoils. *Soil Sci.* 101: 193-198.
- Andrew, C. S., A. D. Johnson, and R. L. Sandland. 1973. Effect of Aluminum on growth and chemical composition of some tropical and temperate pasture legumes. *Aust. J. Agric. Res.* 24: 325-339.
- Armiger, W. H., C. D. Foy, A. L. Fleming, and B. E. Caldwell. 1968. Differential tolerance of soybean varieties to an acid soil high in exchangeable aluminum. *Agron. J.* 60: 67-70.
- Asghar, M., and Y. Kanehiro. 1980. Effects of sugarcane trash and pineapple residue on soil pH, redox potential, extractable Al, Fe and Mn. *Trop. Agric.* 57: 245-258.
- Bartlett, R. J., and D. C. Riego. 1972. Effect of chelation on the toxicity of aluminum. *Plant Soil* 37: 419-423.
- Bloom, P. R., M. B. McBride, and R. M. Weaver. 1979. Aluminum organic matter in acid soils: Buffering and solution aluminum activity. *Soil Sci. Soc. Am. J.* 43: 488-493.
- Bortner, C. E. 1935. Toxicity of manganese to Turkish tobacco in acid Kentucky soils. *Soil Sci.* 39: 15-33.
- Chapman, H. D., and P. F. Pratt. 1961a. Methods of analysis for soils, plants, and waters. P. 23-24. Div. of Agric. Sci. Univ. of Calif., Berkeley.
- . 1961b. Methods of analysis for soils, plants and waters. P. 168-169. Div. of Agric. Sci. Univ. of Calif., Berkeley.
- Christensen, P. D., S. J. Toth, and F. E. Bear. 1950. The status of soil manganese as influenced by moisture, organic matter and pH. *Soil Sci. Soc. Am. Proc.* 15: 279-282.
- Clark, J. S. 1964. Aluminum and iron fixation in relation to exchangeable hydrogen in soils. *Soil Sci.* 98: 302-306.
- Clark, J. C., and W. E. Nichol. 1966. The lime potential, percent base saturation relations of acid surface horizons of mineral and organic soils. *Can. J. Soil Sci.* 46: 281-315.
- Clarkson, D. T. 1965. The effect of aluminum and some other trivalent metal cations on cell division in root apices of *Allium cepa*. *Ann. Botany* 29: 309-315.

- Coleman, N. T., and G. W. Thomas. 1967. The basic chemistry of soil acidity. P. 1-41. In R. W. Pearson and F. Adams (ed.). Soil Acidity and Liming. Am. Soc. of Agron., Madison, Wis.
- Evans, C. E., and E. J. Kamprath. 1970. Lime response as related to percent Al saturation, solution Al, and organic matter content. Soil Sci. Soc. Am. Proc. 34: 893-896.
- Foy, C. D. 1974. Effects of aluminum on plant growth. P. 601-642. In E. W. Carson (ed.) The Plant Root and Its Environment. University Press of Virginia, Charlottesville, Va.
- Foy, C. D., and J. C. Brown. 1963. Toxic factors in acid soils: I. Characterization of aluminum toxicity in cotton. Soil Sci. Soc. Am. Proc. 27: 403-407.
- _____. 1964. Toxic factors in acid soils. II. Differential aluminum tolerance of plant species. Soil Sci. Soc. Am. Proc. 28: 27-32.
- Foy, C. D., G. R. Burns, J. C. Brown, and A. L. Fleming. 1965. Differential aluminum tolerance of wheat varieties associated with plant induced pH changes around their roots. Soil Sci. Soc. Am. Proc. 29: 64-67.
- Foy, C. D., A. L. Fleming, G. R. Burns, and W. H. Armiger. 1967. Characteristics of differential aluminum tolerance among varieties of wheat and barley. Soil Sci. Soc. Am. Proc. 31: 513-521.
- Fujimoto, C. K., and G. D. Sherman. 1948. Behavior of manganese in the soil and the manganese cycle. Soil Sci. 66: 131-145.
- Funchess, M. J. 1919. Acid soils and toxicity of manganese. Soil Sci. 8: 69.
- Hartwell, B. L., and F. R. Pember. 1918. The presence of aluminum as a reason for the difference in the effect of so called acid soil on barley and rye. Soil Sci. 6: 259-281.
- Helyar, K. R., and A. J. Anderson. 1974. Effects of calcium carbonate on the availability of nutrients in an acid soil. Soil Sci. Soc. Am. Proc. 38: 341-346.
- Hoyt, P. B. 1977. Effects of organic matter content on exchangeable Al and pH-dependent acidity of very acid soils. Can. J. Soil Sci. 57: 221-222.
- Hoyt, P. B., and R. C. Turner. 1975. Effects of organic materials added to very acid soils on pH, aluminum, exchangeable NH_4 and crop yields. Soil Sci. 119: 227-237.
- Jackson, M. L. 1963. Aluminum bonding in soils: A unifying principle in soil science. Soil Sci. Soc. Am. Proc. 27: 1-10.

- Jackson, W. A. 1967. Physiological effects of soil acidity. P. 43-124. In R. W. Pearson and F. Adams (ed.) *Soil Acidity and Liming*. Am. Soc. of Agron., Madison, Wis.
- Johnson, R., and W. A. Jackson. 1964. Calcium uptake and transport by wheat seedlings as affected by aluminum. *Soil Sci. Soc. Am. Proc.* 28: 381-386.
- Jones, L. H. 1961. Aluminum uptake and toxicity in plants. *Plant Soil* 13: 297-310.
- Kamprath, E. J. 1970. Exchangeable aluminum as a criterion for liming leached mineral soils. *Soil Sci. Soc. Am. Proc.* 34: 252-254.
- MacLeod, L. B., and L. P. Jackson. 1965. Effect of concentration of the aluminum ion on root development and establishment of legume seedlings. *Can. J. Soil Sci.* 45: 221-234.
- Magistad, O. C. 1925. The aluminum content of the soil solution and its relation to soil reaction and plant growth. *Soil Sci.* 20: 181-225.
- Marion, G. M., D. M. Hendricks, G. R. Dutt, and W. R. Fuller. 1976. Aluminum and silica solubility in soils. *Soil Sci.* 121: 76-82.
- Matsumoto, H., and E. Hirasawa. 1979. Less involvement of phosphorus deficiency in the inhibition of root elongation of pea seedlings by aluminum. *Soil Sci. Plant Nutr.* 25: 93-101.
- McLean, E. O. 1976. Chemistry of soil aluminum. *Comm. Soil Sci. Plant Anal.* 7: 619-636.
- McLean, E. O., and E. J. Owen. 1969. Effects of pH on the contribution of organic matter and clay to soil exchange capacities. *Soil Sci. Soc. Am. Proc.* 33: 855-858.
- McLean, F. T., and B. E. Gilbert. 1927. The relative aluminum tolerance of crop plants. *Soil Sci.* 24: 163-175.
- Morris, H. D. 1948. The soluble manganese content of acid soils and its relation to the growth and manganese content of sweet clover and Lespedeza. *Soil Sci. Soc. Am. Proc.* 13: 362-371.
- Mortensen, J. L. 1963. Complexing of metals by soil organic matter. *Soil Sci. Soc. Am. Proc.* 27: 179-186.
- Morchler, W. W., G. D. Jones, and G. W. Thomas. 1960. Lime and soil acidity effects on alfalfa growth in a red-yellow podzolic soil. *Soil Sci. Soc. Am. Proc.* 24: 507-509.
- Mugwira, L. M., and S. M. Elgawhary. 1979. Aluminum accumulation and tolerance of triticale and wheat in relation to root cation exchange capacity. *Soil Sci. Soc. Am. J.* 43: 736-740.

- Ng Kee Kwong, K. F., and P. M. Huang. 1979. Surface reactivity of aluminum hydroxides precipitated in the presence of low molecular weight organic acids. *Soil Sci. Soc. Am. J.* 43: 1107-1113.
- Othieno, C. O. 1973. The effect of organic mulches on yields and phosphorus utilization by plants in acid soils. *Plant Soil* 38: 17-32.
- Pionke, H. B., and R. B. Corey. 1967. Relations between acidic aluminum and soil pH, clay, and organic matter. *Soil Sci. Soc. Am. Proc.* 31: 749-752.
- Ragland, J. L., and N. T. Coleman. 1959. The effect of soil solution aluminum and calcium on root growth. *Soil Sci. Soc. Am. Proc.* 23: 355-357.
- Rees, W. J., and G. H. Sidrak. 1961. Inter-relationship of aluminum and manganese toxicities toward plants. *Plant Soil* 14: 101-117.
- Reeve, N. G., and M. E. Sumner. 1970. Lime requirement of Natal Oxisols based on exchangeable aluminum. *Soil Sci. Soc. Am. Proc.* 34: 595-598.
- Rios, M. A. and R. W. Pearson. 1964. The effect of some chemical environmental factors on cotton root behavior. *Soil Sci. Soc. Am. Proc.* 28: 232-235.
- Robinson, J. B. D., and P. H. Hosegood. 1965. Effects of organic mulch on fertility of latosolic coffee soil in Kenya. *Expt. Agric.* 1: 67-80.
- Rodriguez, S. A., and R. Schaefer. 1971. Interaction between organic matter and aluminum in a hydromorphic soil developed over volcanic ash (Nadi, Southern Chile). *Turrialba* 21: 149-156.
- Sanchez, C., and E. J. Kamprath. 1959. Effect of liming and organic matter content on the availability of native and applied manganese. *Soil Sci. Soc. Am. Proc.* 23: 302-304.
- Schnitzer, M., and J. G. Desjardins. 1962. Molecular and equivalent weights of the organic matter of a podzol. *Soil Sci. Soc. Am. Proc.* 26: 362-365.
- Schnitzer, M., and S. I. M. Skinner. 1963. Organo-metallic interactions in soils: 1. Reactions between a number of metal ions and the organic matter of a podzol Bh horizon. *Soil Sci.* 96: 86-93.
- _____. 1965. Organo-metallic interactions in soils. 4. Carboxyl and hydroxyl groups in organic matter and metal retention. *Soil Sci.* 99: 278-284.

- Schofield, R. K., and A. W. Taylor. 1953. The hydrolysis of aluminum salt solutions. *J. Chem. Soc.* 18: 4445-4448.
- Swenson, R. M., C. V. Cole, and D. H. Seiling. 1949. Fixation of phosphate by iron and aluminum, and replacement by organic and inorganic ions. *Soil Sci.* 67: 3-22.
- Thomas, G. W. 1975. The relationship between organic matter content and exchangeable aluminum in acid soil. *Soil Sci. Soc. Am. Proc.* 39: 591.
- U. S. Salinity Laboratory Staff. 1969a. Methods for soil characterization. P. 102. In L. A. Richards (ed.) *Diagnosis and Improvement of Saline and Alkali Soils*. Agric. Handb. No. 60, USDA, U. S. Government Printing Office, Washington, D. C.
- _____. 1969b. Methods for soil characterization. P. 105-106. In L. A. Richards (ed.) *Diagnosis and Improvement of Saline and Alkali Soils*. Agric. Handb. No. 60, USDA. U. S. Government Printing Office, Washington, D. C.
- Vlams, J. 1953. Acid soil infertility as related to soil solution and solid phase effects. *Soil Sci.* 75: 383-394.
- Wright, K. E., and B. A. Donahue. 1953. Aluminum toxicity studies with radioactive phosphorus. *Plant physiol.* 28: 674-680.

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