

Full Length Research Paper

## Effects of calcium carbonate, prunings of *Gliricidia Sepium* and maize variety on an ultisol

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The potential of the agroforestry species *Gliricidia sepium*, as a liming material needs to be investigated in the search for alternatives to slash and burn agriculture. Lime ( $\text{CaCO}_3$ ) and organic residue in the form of *Gliricidia sepium* prunings, were incubated with an acid, P deficient ultisol from Sierra Leone at different rates to target pH values 5.0, 5.5, and 6.3 for 70 day. Although in several cases the target pH values were not met, the rates of application of the amendments, based on soil pH buffer capacity and neutralising value of the amendment, decreased the Al saturation from 89% to less than 10%. While  $\text{CaCO}_3$  often decreased P, Mg and K availability in the soils, *Gliricidia* prunings increased these essential nutrients. The Al-sensitive and Al-tolerant maize genotypes subsequently grown for 28 day in the amended soils following incubation decreased the soil pH, but also decreased the Al saturation by markedly increasing the effective cation exchange capacity of the soil.

**Key words:** Aluminium toxicity, soil acidity, maize growth, liming, aluminium tolerance, P availability, *Gliricidia sepium*, agroforestry.

### INTRODUCTION

The soils of Sierra Leone are mostly Oxisols and Ultisols that are characterised by high exchangeable Al concentrations and low pH (Odell et al., 1974). In these tropical soils, the most serious crop production problems associated with soil acidity are Al and Mn toxicity and deficiencies in plant available P, Ca, Mg, N, Zn, Mo and Fe (Sanchez, 1976; Kamprath, 1984, Foy, 1984; Wild, 1988). In most cases, P is the major limiting nutrient due to its fixation by Al and Fe oxides (Mokwunye and Vlek, 1986; Kochain et al., 2004).

Phytotoxic  $\text{Al}^{3+}$  dominates in the soil solution and on the cation exchange complex at soil pH values below 5, but if the soil is limed to  $\text{pH} > 5.5$ , exchangeable and soluble Al become positively charged monomeric  $\text{AlOH}^{2+}$  and  $\text{Al}(\text{OH})_2^+$  species which can polymerize to form positively

polynuclear complexes; these become sorbed to clay and organic matter surfaces in relatively non-exchangeable forms that are less toxic to plants (Kinraide and Parker, 1990; Rengel, 1996, Kochain, 2004). If the pH reaches neutrality, solid  $\text{Al}(\text{OH})_3$  (gibbsite) can form, and under alkaline conditions  $\text{Al}(\text{OH})_4^-$  forms (Evans, 1988; Kinraide, 1991; Kochain, 1995). Several authors (Sanchez, 1976; Haynes and Mokolobate, 2001; Vitorello et al., 2005; Kamprath, 1984) have reported that below pH 5.5 the phytotoxic effect of Al and Mn in acid soils become evident, and according to Haynes and Mokolobate (2001), above pH 5.5 concentrations of soluble and exchangeable Aluminium (Al) are lowered to negligible levels at which Al toxicity no longer limits plant growth. Soil pH and aluminium saturation (exchangeable

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**Table 1.** Particle size distribution and chemical properties of the Taiama soil before incubation with CaCO<sub>3</sub> or *Gliricidia*.

Soil properties	Value
<b>Particle size distribution &lt;2 mm (%)</b>	
Total sand (2.0–0.05 mm)	42.12
Total silt (0.05–0.002 mm)	27.48
Total clay (<0.002 mm)	30.34
Organic carbon (%)	1.47
Organic matter (%)	2.53
Bulk density (g/ cm <sup>3</sup> )	1.34
<b>Exchangeable cation chemistry [cmol(+)/ kg]</b>	
Ca <sup>2+</sup>	0.12
Mg <sup>2+</sup>	0.02
K <sup>+</sup>	0.05
Na <sup>+</sup>	0.03
Al <sup>3+</sup>	3.89
Effective cation exchange capacity (ECEC)	4.15
Exchangeable acidity ( H + Al)	4.12
<sup>β</sup> Al <sup>3+</sup> saturation (%)	93.73
Total P (mg/ kg)	146.97
pH (H <sub>2</sub> O)	3.87
pH (1 M KCl)	3.42
pH buffer capacity (mmol OH/ kg/pH)	28.65
Water holding capacity (g 100/ g)	43.76
Olsen P (mg P/ kg)	0.78

$$^{\beta}\text{Al}^{3+} \text{ saturation}(\%) = (\text{Al}^{3+} / \text{ECEC})100.$$

Al/ECEC) are generally used as indices of soil acidity in making decisions on liming and improvement of crop production on acid soils (Fageria and Baligar, 2003).

Traditionally, lime in the form of calcium carbonate or dolomite is applied to acid soils to increase the pH, Ca concentration, CEC and base saturation, and to eliminate Al and Mn toxicity and P fixation (Fageria and Baligar, 2003; Caires et al., 2006; Ano and Ubochi, 2007). However, these conventional liming materials are scarce, very expensive and beyond the reach of the majority of the traditional farmers in Africa (Sumner, 2003; Ano and Ubochi, 2007). A good management practice that has been shown to ameliorate Al toxicity and its related problems in acid soil is the application of high quality organic residues (Hue et al., 1986; Hue and Amein, 1989; Bell and Bessho, 1993; Wong et al., 2000; Haynes and Mokolobate, 2001; Ano and Ubochi, 2007). The supply of inorganic base cations to the soil upon decomposition of high quality organic matter has been proposed as the probable long-term soil liming mechanism (Sumner, 2003).

The cultivation of Al-resistant plant genotypes in combination with good agronomic management has also been reported as an economical means of improving crop

production in acid soils and a sustainable alternative to traditional liming with CaCO<sub>3</sub> (Delhaize et al., 2004; Delhaize et al., 2004). However, the relative impact of Al toxicity on plant performance in acid soils differs among plant genotypes (Vitorello et al., 2005). Aluminium-sensitive genotypes tend to accumulate higher concentrations of Al in their root tissues, with Al-tolerant genotypes exhibiting a lower threshold pH than those less tolerant to high Al concentrations. Some Al-tolerant varieties increase the pH of the growth medium, whereas sensitive ones have been shown to decrease it. Such changes are believed to be a result of differential cation-anion uptake, secretion of organic acids, carbon dioxide and bicarbonate (Sanchez, 1976), plants roots and their associated microorganisms, soil pH and buffering capacity, spatial variation along the root axes and nutritional constraints (e.g. Fe and P deficiency, which can both enhance H<sup>+</sup> release by plant roots) and metal toxicities (e.g. Al toxicity) to which plants respond (Fageria and Stone, 2006; Hinsinger et al., 2003; Liu et al., 2004).

Shifting cultivation (slash and burn agriculture) is still widely practised in West and Central Africa but it is unsustainable in the face of increasing population densities and contributes to deforestation and emission of CO<sub>2</sub>. Alternatives such hedgerow intercropping, biomass transfer, improved fallows have been evaluated (Karim et al., 1993; Amara and Mansaray, 1989). *Gliricidia sepium* has proven to be adaptable to the acid soils, and its prunings have been shown to increase soil organic matter content and uptake of nitrogen by maize. However, its potential as a liming material, compared to CaCO<sub>3</sub>, has not been investigated on these soils.

The objective of the study was to evaluate (1) the effects of CaCO<sub>3</sub> and *Gliricidia* prunings on the chemical properties of an acid Ultisol and (2) effects of Al-tolerant and –sensitive maize growth on the chemical properties of the amended soil. It is hypothesized that the shifts in soil pH following maize growth coincide with measurable changes in soil available Al, base cations and P; and the extent of these changes depend on whether the soil has been previously amended with lime or *Gliricidia* prunings.

## MATERIALS AND METHODS

### Soil classification, sampling and properties

The soil used (Taiama series) is an Ultisol (clay loam, Plinthic Paleudult) collected from Njala, one of the major maize growing areas in Southern Sierra Leone, West Africa (latitude 8°30'N and longitude 11°30'W) (Odell et al., 1974). The particle size distribution and chemical analysis of this soil (0–20 cm depth) are shown in Table 1. The characteristics of this soil are generally representative of the upland acid soils of Sierra Leone.

The sand, silt and clay contents of the soil were determined by pipette analysis following dispersion by sodium hexametaphosphate. Soil pH was determined both in water and 1 MKCl soil suspension using a 1:2.5 soil: solution

**Table 2.** Chemical composition of *Gliricidia sepium*.

Al	Ca	Mg	K	Fe	Mn	Na	P	C:N	C	N	Lignin	Polyphenol
g /kg											(%)	
0.19	9.54	3.95	33.22	0.25	0.08	0.04	2.34	13.6	43.6	3.20	12.5	0.87

Values in shaded area are adapted from Wong et al. (2000).

ratio (w/v) at 20°C. The soil buffer capacity was measured using the method described by Robinson et al. (1992). The effective cation exchange capacity (ECEC) was determined using the unbuffered salt (NH<sub>4</sub>Cl) extraction method (Sumner and Miller, 1996), and calculated by summing the cations (Na + K + Ca + Mg + Al). The soil exchangeable acidity was measured using the method of Van Ranst et al. (1999). Total carbon was analysed on the Total Carbon Analyser (LECO SC 444) at 1400°C, and the soil organic matter (SOM) was estimated from soil organic carbon (SOC) using a correction factor of 1.72 (Rengasamy and Churchman, 1999). Oven-dry soil moisture content (MC) was determined using the method of Rowell (1994).

Olsen P was determined by extraction of the soil in 0.5 M NaHCO<sub>3</sub>, followed by P analysis using the colorimetric method described by Murphy and Riley (1962).

### Chemical characteristics of plant residue

Young leaves of the agro-forestry shrub *G. sepium* (Gliricidia) collected from Sierra Leone were used for this study. Using 100 ml Kjeldhal digestion tubes, air-dried and finely ground samples of Gliricidia were digested with 10 ml concentrated nitric acid in a digestion block and cautiously heated to 60°C for 3 h and then gradually heated to 110°C for another 6 h. The filtered digests were analysed on the ICP-AES for total Al, Ca, Mg, P, Mn, K, Fe and Na (Table 2).

### Potential alkalinity of the liming materials

The potential alkalinity of the prunings from Gliricidia and CaCO<sub>3</sub> was determined based on the method of Jarvis and Robson (1983). Triplicate samples of 0.5 g of dried and ground Gliricidia prunings were slowly heated to 400°C in a muffle furnace and then held at 500°C for 1 h. The ash was treated with 5 ml of 1 M HCl followed by addition of three drops of phenolphthalein indicator. The excess HCl was titrated against 0.25 M NaOH. Without ashing CaCO<sub>3</sub>, 0.5 g was also treated with 1 M HCl followed by addition of three drops of phenolphthalein indicator and the excess HCl titrated against 0.25 M NaOH.

### Soil-CaCO<sub>3</sub>/Gliricidia prunings incubation

To 2 kg of < 2 mm air-dried soil in polythene bags (25 cm x 36 cm) was added 3.5 and 4.4 t/ha CaCO<sub>3</sub> or 45.56 and 57.79 t/ha Gliricidia to meet target pH 5.5 and 6.3; these additions were based on the soil buffer capacity and the potential alkalinity of the liming material. Triplicate samples of each treatment were thoroughly mixed and ultra pure water added to bring them to 70% soil water holding capacity. Small holes were pierced through each polythene bag to allow aeration, and stored in a dark room at 30°C for an incubation period of 70 days. The boxes were reweighed every 3 days and any water lost by evaporation was replaced to maintain

the moisture content. At the end of the 70-day incubation period, soil samples were air dried for determination of pH, exchangeable Al, Ca, Mg, K, Na, Mn and Olsen P.

### Sampling and analyses of incubated soils

Sub-samples of incubated soil, equivalent to 5 g air-dried soil, were taken from each treatment every 10 days during the incubation period for determination of soil pH. At the end of the incubation period, the soils were air-dried at 30°C for determination of ECEC, Olsen P, exchangeable acidity and exchangeable bases (Ca, Mg, K, and Na).

### Maize planting, harvesting and data collection

Seeds of the Al-tolerant (ATP-SR) and Al-sensitive (ACR. 9928) maize varieties, were sterilized in sodium hypochlorite solution at 1% (v/v) for 20 min and rinsed with deionised water before pre-germination on moistened No. 540 filter paper in a Petri dish at 25°C for four days.

At 70 day, the incubated soil was emptied into a plant pot (18 cm x 15 cm) with saucer and lined at the bottom with a No. 540 Whatman filter paper in a greenhouse with controlled temperature (maximum and minimum temperatures ranged between 22 and 25°C, respectively), and relative humidity of 60% with 12 to 14 h of daylight. Three uniform seedlings were sown 2 cm below the soil surface. Deionised water was added to each pot to bring the soil to 70% field capacity. The treatments consisted of two maize varieties plus a zero maize treatment, two target pH levels, three sources of lime (including the control) and three replicates. Water was added to the pots every two days to account for losses due to evaporation and transpiration. After 4 weeks, the plants were harvested and sub-samples of the wet soil in each pot were taken for measurement of soil pH and the rest of the soil was spread in acid washed trays and air-dried at 30°C. The air-dried soil was crushed in acid washed ceramic pot for determination of exchangeable Al, Ca, Mg, K, Na and Mn, ECEC and Olsen P.

### Statistical analysis

The experimental design was a completely randomised factorial (2 maize varieties x 2 lime sources x 5 lime rates) with three replications. Analysis of Variance was determined using SPSS 15.0 for Windows to determine significant differences between treatments. Treatment means were compared using the Duncan's multiple range tests at 95% confidence level.

## RESULTS

### Effects of CaCO<sub>3</sub> and Gliricidia prunings on soil pH

The Gliricidia prunings had 13% potential alkalinity as

**Table 3.** Potential alkalinity of *G. Sepium* prunnings.

Lime source	pH <sub>(1M KCl)</sub>	mmol OH	CaCO <sub>3</sub> equivalent	mmol OH/kg
Gliricidia	5.75	0.63	0.13	1250
CaCO <sub>3</sub>	-	4.93	1.00	9850

that of CaCO<sub>3</sub> (Table 3). Maximum pH reached was higher for Gliricidia than CaCO<sub>3</sub>. Most of the CaCO<sub>3</sub> amended soils reached their maximum pH at 10 days of incubation and were generally stable throughout the incubation period (Figure 1). The residue on the other hand was slower in reaching its maximum pH, generally between 30 and 50 days of incubation, and then started declining to a similar pH as CaCO<sub>3</sub> at 60 day of incubation for all three target pH, and by the end of the incubation the actual pH was similar to that at just 10 days after incubation (Figure 1).

#### Effect of CaCO<sub>3</sub>, Gliricidia prunnings and maize varieties on soil pH

All CaCO<sub>3</sub> and Gliricidia treatments increased the soil pH relative to the control, but the subsequent growth of both maize varieties lowered the soil pH of all the treatments slightly but significantly ( $P < 0.05$ ). For example, following soil incubation with CaCO<sub>3</sub> towards a target pH of 6.3, the maize varieties decreased the soil pH by 0.26 units (ATP-SR) and 0.37 units (ACR 9928); the corresponding decrease on 70 days incubated soils for the Gliricidia amended soil was 0.30 units (ATP-SR) and 0.22 units (ACR 9928) (Table 4, Figure 2). For the targeted values (Table 4), pH attained after 70 days, before planting was in the order 6.04 (CaCO<sub>3</sub> target of 6.3) > 5.2 (Gliricidia target of 6.3) > 5.02 (CaCO<sub>3</sub> target of 5.5) > 4.80 (Gliricidia target of 5.5) > 3.68 (control) (Table 4). No significant ( $P > 0.05$ ) decreases were observed in the controls (zero amendments). The pH decreases effected by the maize varieties were statistically significant ( $P < 0.05$ ) in most cases. However, in most cases, the negative effects of the maize on pH were not significantly different ( $P < 0.05$ ) between the two maize varieties (Figure 2).

#### Effect of CaCO<sub>3</sub>/ Gliricidia/ maize variety on soil exchangeable cations and cation exchange capacity

Generally, neither maize variety had a significant effect ( $P > 0.05$ ) on the exchangeable major cations (Al, Ca, Mg, K) in the soil (Table 5). There was no significant difference ( $P > 0.05$ ) in Ca<sup>2+</sup>, K<sup>+</sup> and Mg<sup>2+</sup> in the soil between the control- and planted treatments. Exchangeable Mn<sup>2+</sup> in the Gliricidia-amended soils was increased significantly ( $P < 0.05$ ) by both maize varieties

relative to the zero plant treatments. The positive effects of the two maize varieties on ECEC were not significantly different ( $P > 0.05$ ) (Table 5).

#### Effect of CaCO<sub>3</sub>, Gliricidia and maize variety on soil Al saturation

Maize growth in the non-amended soil showed that Al saturation in the ATP-SR and ACR-9928-cropped soil decrease to less than half of that in the absence of the maize (Table 6). Whether cropped with maize or not, Al saturation was higher in the soils amended to target pH 5.5 than to 6.3.

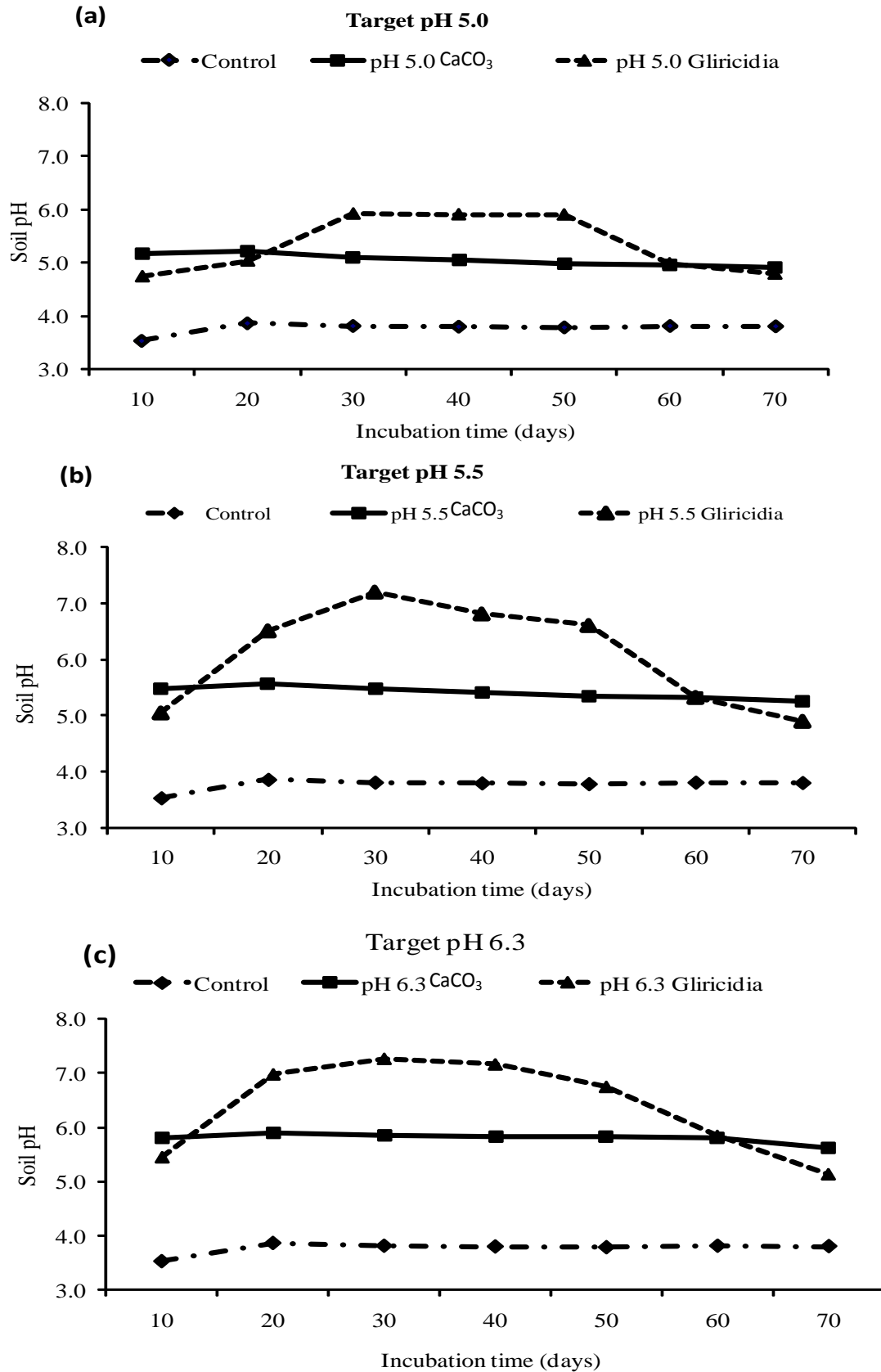
#### Effect of CaCO<sub>3</sub>, Gliricidia and maize variety on soil available P

Essentially, Olsen P values in all CaCO<sub>3</sub> treatments remained below 1 mg/kg (Table 7). The Olsen P values in the Gliricidia-amended soils were significantly higher ( $P < 0.05$ ) than the control and the CaCO<sub>3</sub>-amended soils, especially in those at the higher target pH of 6.3. In the Gliricidia amended soils increase in Olsen P was observed both in the maize-planted and –unplanted soils. In most other cases, Olsen P did not change significantly ( $P < 0.05$ ) as a function of incubation period. However, in the soils that received CaCO<sub>3</sub>, regardless of maize growth or not, Olsen P was lower than in the corresponding control treatments. There did appear to be a positive effect of maize growth on Olsen P but only in the Gliricidia-treated soil, and with very little difference between the varieties.

## DISCUSSION

### Changes in soil pH

The response of the soil to Gliricidia addition at all three target pH agrees with the reports of previous studies (Hue, 1992; Wong et al., 1998; Haynes and Mokolobate, 2001) who suggest that following the addition of organic residue to acid soils, there is often a transient increase in soil pH over the first one or two months of residue decomposition which is then followed by a decline to above or below the initial pH level. The subsequent declines in pH may be attributed to a faster or more

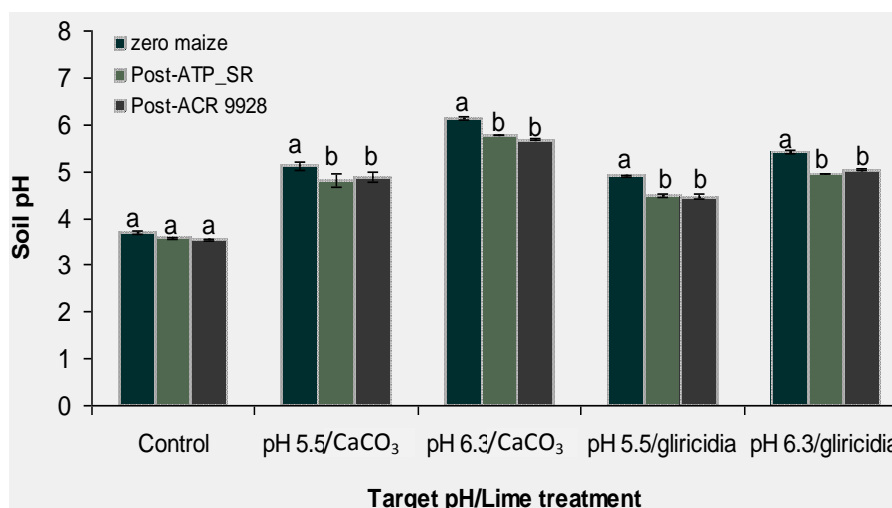


**Figure 1.** pH of soil during incubation with  $\text{CaCO}_3$  and gliricidia to target pH values 5.0 (a), 5.5 (b) and 6.3 (c).

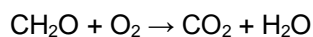
**Table 4.** pH of soil incubated for 70-d: with additions of CaCO<sub>3</sub> or Gliricidia to meet pH targets 5.5 and 6.3: before (pre-) planting and after (post-) a further 4-weeks' growth of the ATP-SR and ACR 9928 maize varieties, or of zero maize.

Target pH/lime treatment	Pre-planting	Post-ATP_SR	Post-ACR 9928	Zero maize
Control	3.68 <sup>e</sup>	3.57 <sup>d</sup>	3.55 <sup>e</sup>	3.71 <sup>e</sup>
pH 5.5/ CaCO <sub>3</sub>	5.02 <sup>c</sup>	4.81 <sup>b</sup>	4.88 <sup>c</sup>	5.12 <sup>c</sup>
pH 6.3/ CaCO <sub>3</sub>	6.04 <sup>a</sup>	5.78 <sup>a</sup>	5.67 <sup>a</sup>	6.15 <sup>a</sup>
pH 5.5/ Gliricidia	4.80 <sup>d</sup>	4.48 <sup>c</sup>	4.46 <sup>d</sup>	4.89 <sup>d</sup>
pH 6.3/ Gliricidia	5.25 <sup>b</sup>	4.95 <sup>b</sup>	5.03 <sup>b</sup>	5.41 <sup>b</sup>

Values with the same letter (s) in a column are not statistically different from each other ( $P < 0.05$ ). All values are means of triplicates.

**Figure 2.** pH of soil incubated for 70d with additions of CaCO<sub>3</sub> or Gliricidia to meet pH targets 5.5 and 6.3: after a further 4 weeks of zero planting or of growth of the ATP-SR and ACR 9928 maize varieties. Bars with the same letters for a treatment/target pH are not statistically different from each other ( $P < 0.05$ ).

complete process of decomposition. For example, complete oxidation of organic components can release H<sup>+</sup> according to the following sequence of reactions:



Also, the release of NH<sub>4</sub><sup>+</sup> during mineralization reactions is vulnerable to subsequent nitrification to NO<sub>3</sub><sup>-</sup>; this reaction is accompanied by a release of protons:



If soil conditions favour ammonification, such as those in the incubation mixtures, then it is possible for the soil pH to rise initially, but if nitrification proceeds rapidly, the pH will decline (Haynes and Mokolobate, 2001). The temporal variability of pH in the soil amended with

Gliricidia prunings was much greater than that amended with CaCO<sub>3</sub>, and tended to increase as the application rate of residue increased. For example, for the target pH 5.0 incubations, the pH increase in the residue treatment ranged between 1.1 and 2.4 units, whereas in the target pH 6.3 incubations, the pH increase ranged between 1.5 and 3.7 units (Figure 1a and c). Conversely, the pH in the CaCO<sub>3</sub> treatments for target pH 5.0 and 6.3 incubations ranged between 1.3-1.7 units and 1.9-2.4 units, respectively. These pH changes in the soil during plant growth can be the result of two processes; first, roots and rhizosphere microorganisms rely on root exudates to produce CO<sub>2</sub> through respiration, the build-up of CO<sub>2</sub> partial pressure thereby occurring in the rhizosphere can contribute to soil acidification (Jaillard et al., 2003; Hinsinger et al., 2003); secondly, pH changes in the rhizosphere are related to the release of H<sup>+</sup> and OH<sup>-</sup> to counterbalance a net excess of cations or anions, respectively entering the roots (Jaillard et al., 2003).

**Table 5.** Exchangeable cations and ECEC in soil incubated for 70 days with additions of CaCO<sub>3</sub> or Gliricidia to meet pH targets 5.5 and 6.3: after a further 4 weeks of zero planting or of growth of the ATP-SR and ACR 9928 maize varieties.

Target pH/ lime treatment	Al <sup>3+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>	ECEC*	Mn <sup>2+</sup>
	cmol(+)/ kg					mmol(+)/kg	
<b>Zero planting</b>							
Control	3.76 <sup>a</sup>	0.20 <sup>e</sup>	0.05 <sup>c</sup>	0.06 <sup>c</sup>	0.08 <sup>a</sup>	4.22 <sup>c</sup>	0.013 <sup>b</sup>
pH 5.5/CaCO <sub>3</sub>	0.09 <sup>d</sup>	2.50 <sup>b</sup>	0.04 <sup>c</sup>	0.04 <sup>c</sup>	0.07 <sup>ab</sup>	4.04 <sup>d</sup>	0.002 <sup>c</sup>
pH 6.3/CaCO <sub>3</sub>	0.06 <sup>d</sup>	3.04 <sup>a</sup>	0.04 <sup>c</sup>	0.04 <sup>c</sup>	0.07 <sup>ab</sup>	4.64 <sup>c</sup>	0.001 <sup>c</sup>
pH 5.5/Gliric	0.25 <sup>b</sup>	0.98 <sup>d</sup>	1.08 <sup>b</sup>	0.59 <sup>b</sup>	0.06 <sup>b</sup>	4.58 <sup>c</sup>	0.009 <sup>b</sup>
pH 6.3/Gliric	0.13 <sup>c</sup>	1.22 <sup>c</sup>	1.31 <sup>a</sup>	0.70 <sup>a</sup>	0.07 <sup>ab</sup>	4.87 <sup>c</sup>	0.007 <sup>c</sup>
<b>Post- ATP_SR</b>							
Control	3.50 <sup>a</sup>	0.19 <sup>e</sup>	0.04 <sup>c</sup>	0.06 <sup>c</sup>	0.05 <sup>a</sup>	12.02 <sup>a</sup>	0.016 <sup>b</sup>
pH 5.5/CaCO <sub>3</sub>	0.03 <sup>d</sup>	2.26 <sup>b</sup>	0.03 <sup>c</sup>	0.04 <sup>c</sup>	0.06 <sup>a</sup>	10.65 <sup>b</sup>	0.004 <sup>c</sup>
pH 6.3/CaCO <sub>3</sub>	0.01 <sup>d</sup>	2.72 <sup>a</sup>	0.02 <sup>c</sup>	0.04 <sup>c</sup>	0.05 <sup>a</sup>	11.30 <sup>b</sup>	0.001 <sup>c</sup>
pH 5.5/Gliric	0.31 <sup>b</sup>	0.98 <sup>d</sup>	0.77 <sup>b</sup>	0.56 <sup>b</sup>	0.06 <sup>a</sup>	11.14 <sup>b</sup>	0.037 <sup>a</sup>
pH 6.3/Gliric	0.05 <sup>d</sup>	1.22 <sup>c</sup>	1.00 <sup>a</sup>	0.69 <sup>a</sup>	0.05 <sup>a</sup>	11.63 <sup>b</sup>	0.041 <sup>a</sup>
<b>Post- ACR 9928</b>							
Control	3.80 <sup>a</sup>	0.20 <sup>e</sup>	0.04 <sup>c</sup>	0.06 <sup>c</sup>	0.06 <sup>a</sup>	11.84 <sup>a</sup>	0.017 <sup>b</sup>
pH 5.5/CaCO <sub>3</sub>	0.00 <sup>d</sup>	2.32 <sup>b</sup>	0.03 <sup>c</sup>	0.04 <sup>c</sup>	0.05 <sup>a</sup>	10.55 <sup>b</sup>	0.005 <sup>c</sup>
pH 6.3/CaCO <sub>3</sub>	0.00 <sup>d</sup>	2.90 <sup>a</sup>	0.03 <sup>c</sup>	0.04 <sup>c</sup>	0.05 <sup>a</sup>	10.65 <sup>b</sup>	0.002 <sup>c</sup>
pH 5.5/Gliric	0.38 <sup>b</sup>	0.98 <sup>d</sup>	0.85 <sup>b</sup>	0.59 <sup>b</sup>	0.05 <sup>a</sup>	11.04 <sup>b</sup>	0.044 <sup>a</sup>
pH 6.3/Gliric	0.03 <sup>d</sup>	1.20 <sup>c</sup>	1.05 <sup>a</sup>	0.66 <sup>a</sup>	0.05 <sup>a</sup>	12.02 <sup>a</sup>	0.043 <sup>a</sup>

Values with the same letter (s) in a column are not statistically different from each other ( $P < 0.05$ ). All values are means of triplicates.  
\*ECEC<sub>NH4Cl</sub>

**Table 6.** Al saturation (%) in soil incubated for 70 days: with additions of CaCO<sub>3</sub> or Gliricidia to meet pH targets 5.5 and 6.3: after a further 4 weeks of zero planting or of growth of the ATP-SR and ACR 9928 maize varieties.

Target pH/Lime treatment	Zero maize	Post-ATP-SR	Post-ACR 9928
Control	89.10	29.12	32.09
pH 5.5/CaCO <sub>3</sub>	2.23	0.28	0.00
pH 6.3/CaCO <sub>3</sub>	1.29	0.09	0.00
pH 5.5/gliricidia	5.46	2.78	3.44
pH 6.3/gliricidia	2.67	0.43	0.25

**Table 7.** Olsen P (mg/kg soil) in soil incubated for 70 d: with additions of CaCO<sub>3</sub> or Gliricidia to meet pH targets 5.5 and 6.3: after a further 4 weeks of zero planting or of growth of the ATP-SR and ACR 9928 maize varieties.

Target pH/Lime treatment	Zero maize	Post-ATP_SR	Post-ACR 9928
Control	1.33 ± 0.12 <sup>b</sup>	1.25 ± 0.02 <sup>b</sup>	1.12 ± 0.17 <sup>b</sup>
pH 5.5/CaCO <sub>3</sub>	0.77 ± 0.09 <sup>c</sup>	0.65 ± 0.05 <sup>c</sup>	0.61 ± 0.03 <sup>c</sup>
pH 6.3/CaCO <sub>3</sub>	0.95 ± 0.05 <sup>c</sup>	0.65 ± 0.07 <sup>c</sup>	0.85 ± 0.03 <sup>c</sup>
pH 5.5/gliricidia	3.50 ± 0.11 <sup>a</sup>	4.26 ± 0.21 <sup>a</sup>	4.75 ± 0.13 <sup>a</sup>
pH 6.3/gliricidia	3.55 ± 0.10 <sup>a</sup>	4.38 ± 0.02 <sup>a</sup>	4.60 ± 0.32 <sup>a</sup>

Values with the same letter (s) in a column are not statistically different from each other ( $P < 0.05$ ). All values are means of triplicates.

Some plant species counteract the change in cytoplasm pH by excreting  $H^+$  ions into the soil solution and at the same time taking in basic nutrient cations to balance the charge thus the soil becomes more acid (Bolan and Hedley, 2003).

The results of this study are in agreement with those of Eckert and McLean (1981) who observed pH decreases in pre-incubated soils following harvest of millet that had been grown for four weeks. Conversely, other authors have reported root induced increases in soil pH; for example, Bagayoko et al. (2000) reported root induced increases in soil pH by sorghum (0.3 units) and millet (0.7 units) grown on acid sandy soils of Sudano-Sahelian West Africa. Some studies (Wild, 1988; Hinsinger et al., 2003) have explained that when more cations than anions are taken up,  $H^+$  will be released into the apoplasm to compensate for the excess of positive charges entering the cell, resulting in increased pH in the cytosol. Conversely, when more anions are taken up than cations,  $OH^-$  (or  $HCO_3^-$  resulting from  $OH^-$  carbonation) will be released into the apoplasm (or  $H^+$  will be taken up from the apoplasm) to compensate for the excess of negative charges entering the cell, resulting in decreased pH in the cytosol (Hinsinger et al., 2003). Ions crossing the plasma membrane of root cells, e.g., organic anions (e.g. citric, oxalic and malic acids) exuded by plant roots (protons or bicarbonate ions) need to be balanced by an exchange of charges, that is, by the release of either  $H^+$  or  $OH^-$  to maintain electrical neutrality at the root surface (Wild, 1988; Hinsinger et al., 2003). Root exudation and respiration can therefore contribute some proportion of rhizosphere pH decrease as a result of a build-up of the  $CO_2$  concentration (Hinsinger et al., 2003).

### Exchangeable Al and soil Al saturation

It is clear that in most cases both  $CaCO_3$  and Gliricidia decreased soil exchangeable Al resulting in increases of soil pH. This is primarily attributed to the much larger content and release of Ca in the  $CaCO_3$ -amended soils, which can displace a larger reserve of exchangeable Al from the exchange sites to the soil solution where it is subjected to hydroxylation and polymerisation reactions (Curtin and Smillie, 1983). The data agree with the report by Thomas and Hargrove (1984), that for many tropical soils at  $pH > 5$ , lime reduces the exchangeable Al to nearly zero. In the present study, liming reduced Al saturation from toxic levels of 89% to less than 10%; which is even less than 20% acceptable for economic reasons (Sanchez, 1976; Kamprath, 1984).

Even though maize growth and variety had little effect on exchangeable Al in the incubated soils, there was a marked decrease in Al saturation; this effect was particularly apparent in the control soils. However, the Al decrease, compared with those in the controls, appear to be masked by the overriding effect of the amendments rather than clear evidence of any difference between the

varieties.

### Basic cation chemistry and effective CEC

The source and rate of liming material had a very marked influence on the content of exchangeable cations in the soils. For example, the relatively high contents of Ca in  $CaCO_3$  and of K and Mg in Gliricidia were clearly reflected in the concentrations of these cations in the amended soils, both for planted and unplanted treatments. However, neither maize variety had a significant effect on the exchangeable major cations (Al, Ca, Mg, K). These observations do not appear to support reports in the literature that Ca uptake by Al-tolerant varieties of maize is greater than that by varieties that are Al-susceptible (Marschner et al., 1986). Alternatively, it is possible that measurements of soil exchangeable Ca is not sufficiently sensitive to differentiate among the cropped and uncropped treatments in terms of Ca uptake by maize (which was not determined in this study). According to theory, the maize-induced decreases in soil pH might have been expected to cause an increase in exchangeable  $Al^{3+}$  on the exchange complex with an associated decline in the main exchangeable base cations (Ca, Mg, K); these simple, acid / base cation – pH relationships have been reported previously (Noble et al., 2000).

A soil's effective CEC is an important indicator of the presence of phototoxic Al and soil acidity. When the soil pH is increased by liming, the bound Al and H ions are released and precipitate as amorphous  $Al(OH)_3^0$ , thus freeing negative cation exchange sites thus increasing the availability of  $Ca^{2+}$  and other essential cations on a larger cation exchange complex (ECEC) of the soil (Brady and Weil, 2002). Organic matter is a source of strong pH-dependent charge in soils, and as the pH increases, ECEC increases exponentially (Sumner, 2003). The very marked increases in soil ECEC due to maize growth in this study agrees with the results of Bagayoko et al. (2000) who also obtained large increases in ECEC following the millet crop in the acid sandy soils of Sudano-Sahelian West Africa and attributed the increase to increase in soil pH and soluble Ca and Mg. Increase in pH, however cannot be used to explain the increases in ECEC in this study because maize decreased soil pH. Also, plant roots and soil micro-organisms have been reported (Arsova, 1995; Crooke and Knight, 2006a, b) to possess ECEC and due to  $H^+$  adsorption and release of cations into the soil solution the ECEC of the soil could be increased. Even though maize growth was shown to play a significant role in increase in ECEC, maize variety did not.

### Changes in soil available P

Plant residues increase soil P availability in acid soil by



decreasing the activity of Al and Fe in soil solution by increasing soil pH and forming strong complexes with these metallic cations. The lowered Al and Fe activities decrease the precipitation of P with these cations and decrease the amount made unavailable to plants. As expected, available P was much higher in the Gliricidia- than CaCO<sub>3</sub>-amended soils or control soils, owing to the P content of the decomposing Gliricidia. Reduced P adsorption and increased P availability following application of organic amendments to soils has been attributed by Haynes and Mokolobate (2001) to several mechanisms including the release of inorganic P from decaying residues, blockage of P adsorption sites by organic molecules released from the residue, a rise in soil pH during decomposition and complexation of soluble Al and Fe by organic molecules. The rise in pH during decomposition of the residue increases surface negative charge (ECEC) and, therefore, decreases P adsorption. The decrease in Olsen P in the CaCO<sub>3</sub> and non-amended soils may largely be due to plant uptake and immobilization by the microbial biomass decomposing the residue (McLaughlin and Alston, 1986). Surprisingly, in the Gliricidia amended soils plant growth seemed to have accelerated further mineralization of P which was not completed during the incubation period and therefore the increase in soil available P. Also, the Gliricidia may not have only enhanced P availability through direct additions of P, but also accelerated native P solubilization by release of weak organic acids (Garg and Bahl, 2008). Moreover, residue derived organic acids may become adsorbed onto surfaces of Fe and Al oxides thus blocking adsorption of P and increasing its availability (Mokolobate and Haynes, 2003). Although tolerant plants can take up sufficient P even at low concentrations than sensitive ones as a result of root-induced changes in the rhizosphere (Marschner et al., 1986), maize growth rather than variety seemed to influence the changes in soil available P.

## Conclusions

Cropping the amended soils with either the acid tolerant or susceptible maize variety caused decline in soil pH (ranging between 0.1 and 0.3 units), with no significant variation in the effect of the two maize genotypes on soil pH, exchangeable Al and exchangeable bases cations – Ca and Mg. While growth of both maize genotypes decreased available P in soils amended with CaCO<sub>3</sub>, their growth seemed to enhance further release of P from the soil amended with Gliricidia prunings. Owing to the much larger effects of maize growth on soil ECEC than on exchangeable Al, the net effect of the maize growth in the soil was a marked decrease in Al saturation; this effect was particularly apparent in the control. Further studies on the effects of maize on soil calcium status and calcium uptake by maize are required.

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