

## Amelioration of coarse-textured acidic soils used for macadamia production. II\* Effects of surface applied lime on subsoil properties

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### Abstract

The chemical properties of the soil at depths of 0–5, 5–10, 10–20, 20–30 and 30–50 cm at two field sites with established macadamia trees were monitored for 5 years following the surface application of various rates of lime (0–1200 g/m<sup>2</sup>). The effects of annual applications of N and N plus lime were also studied at one site. Both sites received >1700 mm annual rainfall and had strongly acidic, sandy soils.

A residual effect of increased pH in the surface soil (0–5 cm depth) was evident after 5 years for lime rates  $\geq 200$  g/m<sup>2</sup>. Differences in the nature of the residual effect at each site are discussed in relation to soil acidification, lime dissolution and leaching.

High lime rates (>300 g/m<sup>2</sup>) applied to the soil surface increased pH and reduced extractable Al in the 10–20 cm depth interval after 12 months. Three years after application, the soil pH at depths of 20–30 and 30–50 cm had been significantly ( $P < 0.05$ ) increased by surface applications of 600 and 1200 g lime/m<sup>2</sup>, respectively.

The results of this study show that surface application of lime at economic rates (300 to 600 g/m<sup>2</sup>) can reduce subsoil acidity in coarse-textured soils in high rainfall areas.

*Keywords:* lime, residual value, subsoil, exchangeable acidity, exchangeable calcium.

### Introduction

Strongly acidic subsoils are likely to limit root growth as a result of Al toxicity and/or Ca deficiency (Sumner *et al.* 1986, Bruce *et al.* 1988) with consequential detrimental effects on the uptake of water and nutrients from the subsoil. Subsoil acidity occurs both naturally, and as result of management practices in the tropical and subtropical soils used for horticultural production in eastern Australia. Apart from the recognition of subsoil acidity problems in these soils (Bruce *et al.* 1988, Bruce *et al.* 1989), there has been little work investigating either the prevention or reversal of subsoil acidity. In some of the agricultural systems of southern Australia receiving low annual rainfall (300–600 mm), economic rates of addition of lime have been shown to do little to correct subsoil acidity (Conyers and Scott 1989, McLay *et al.* 1994). For the agricultural systems in tropical Australia, there is a lack of information regarding the decline in soil pH, the residual value of lime and the movement of lime effects from the surface soil. This paper reports the effects of surface-applied lime on the subsoil properties of coarse textured acidic

\* \* Part I, *Aust. J. Agric. Res.*, 1996, **47**, 97–107.

soils at two sites in south-east Queensland receiving annual rainfall in excess of 1700 mm.

## Materials and methods

Field trials were conducted at each of two macadamia plantations at Pomona (6-year-old trees) and Cootharaba (recently established trees) on Kurosols (Isbell 1993). Properties of the soil, treatments, characteristics of the amendments and cultural practices at each site have been described previously (Stephenson *et al.* 1996). Briefly, various rates of lime and single rates of gypsum, elemental S, N and N plus lime were applied to the soil surface through a sieve to ensure even distribution. Lime rates of 0, 50, 100, 200, 300, 600 and 1200 g/m<sup>2</sup> (0–12 t/ha) were applied at the Pomona site, whereas, at the Cootharaba site, lime was applied at rates of 0, 200, 400 and 800 g/m<sup>2</sup> (0–8 t/ha). The various amendments were not incorporated into the soil. The lime used had a neutralizing value of 98.3, a fineness rating (% <0.25 mm) of 96.8% and a Ca content of 39.1%. Treatments were applied to 5 m × 5 m plots centred on the tree and, due to weed control practices, the area receiving amendments was bare soil. At Cootharaba, mulch, obtained from interrow slashing, had been placed around the newly planted trees. This was removed prior to amendment application and then replaced.

Soil samples were collected each year for 5 years after the application of treatments. At each sampling, five cores (8 cm diameter) to a depth of 50 cm (0–5, 5–10, 10–20, 20–30 and 30–50 cm) were taken from each plot and the respective depth intervals bulked. The soil from each depth interval was air dried, sieved <2 mm, and analysed for pH (1:5 soil:solution) in both water (pH<sub>w</sub>) and 0.01 M CaCl<sub>2</sub> (pH<sub>Ca</sub>). Extractable acidity (Al+H) and Al were determined by auto-titration following extraction of samples with 1 M KCl (1:10 soil:solution). Extractable (1 M NH<sub>4</sub>Cl) Ca, Mg, K and Na were determined on each sample as described (method 15A1) by Rayment and Higginson (1992). Selected samples were also equilibrated (1 h) with 0.01 M CaCl<sub>2</sub> (1:5 soil solution) and the amount of extractable Al determined by inductively coupled plasma atomic emission spectroscopy.

Daily rainfall was recorded at each site and, during the trial period (1988 to 1993), annual average rainfall at Pomona and Cootharaba was 1750 mm and 1709 mm, respectively.

For a given depth interval, treatment effects were assessed using analysis of variance for a completely randomized design.

## Results

### *Residual effects of amendments in the soil surface*

Fig. 1 shows the effect of time after application on soil pH<sub>w</sub> (0–5 cm depth) for various rates of lime at each site. Sixty-eight months after amendment application at Pomona, the pH<sub>w</sub> in the 100 g lime/m<sup>2</sup> treatment had decreased to the original value, whereas the soil pH<sub>w</sub> at high lime rates (≥600 g/m<sup>2</sup>) remained relatively constant for 36 months after lime application before decreasing. In contrast, the decrease in exchangeable Ca with time for high lime rates was approximately linear over 68 months (Fig. 2).

The effect of acidifying treatments on soil pH<sub>w</sub> over time is shown in Fig. 3. The rapid initial decrease in pH<sub>w</sub> as a result of the single initial application of elemental S at Pomona was followed by a partial 'recovery' of pH<sub>w</sub>. Yearly application of N fertilizer (240 g NH<sub>4</sub>SO<sub>4</sub>/m<sup>2</sup>) at Cootharaba resulted in a large pH<sub>w</sub> decrease in the first year with relatively smaller decreases in subsequent years.

### *Effect of amendments on subsoil properties*

Table 1 shows the effect of treatment on soil pH<sub>w</sub> at various depths at each site 12 months after treatment application. In the unamended soil at Pomona,

there was little change in  $pH_W$  with depth, whereas at the Cootharaba site, there was a marked decrease in  $pH_W$  with depth. At each site, acidifying treatments resulted in lower  $pH_W$  values throughout the profile. Lime rates  $\geq 300 \text{ g/m}^2$  significantly increased soil  $pH_W$  in the 10–20 cm depth interval at the Pomona site.

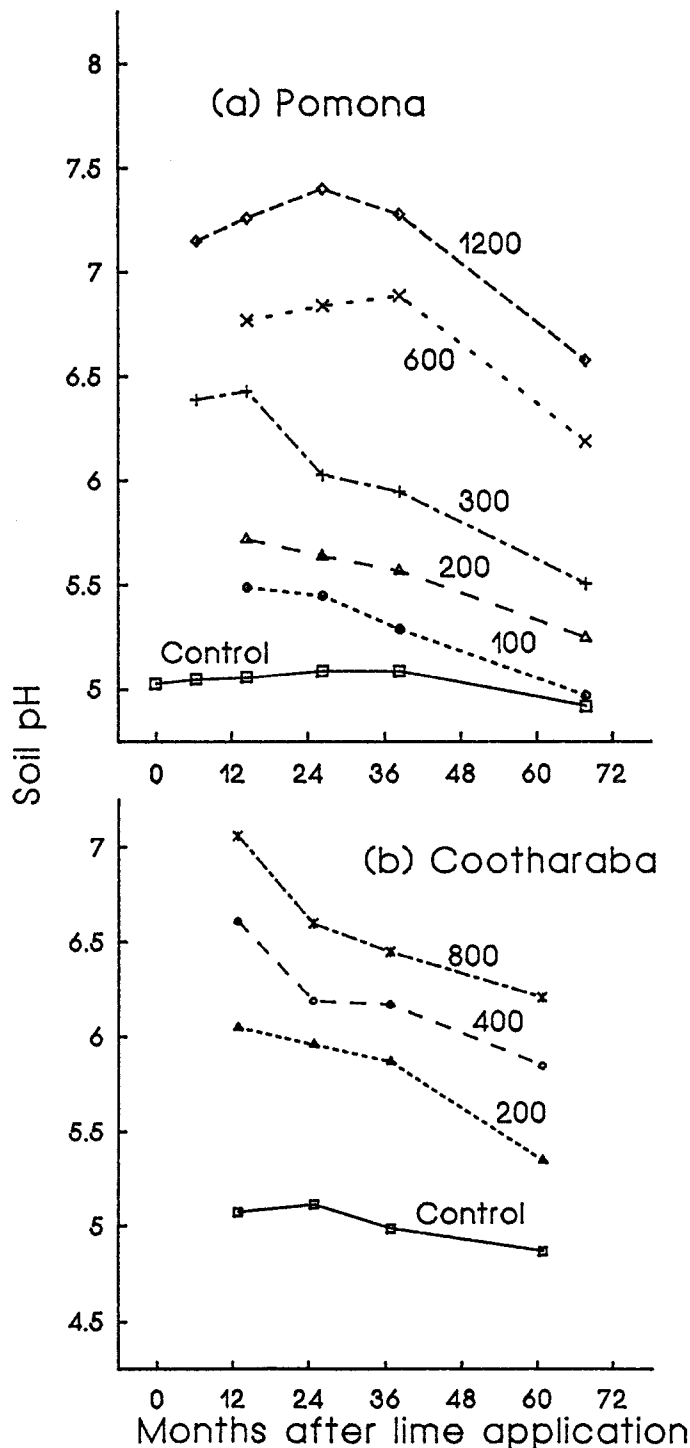
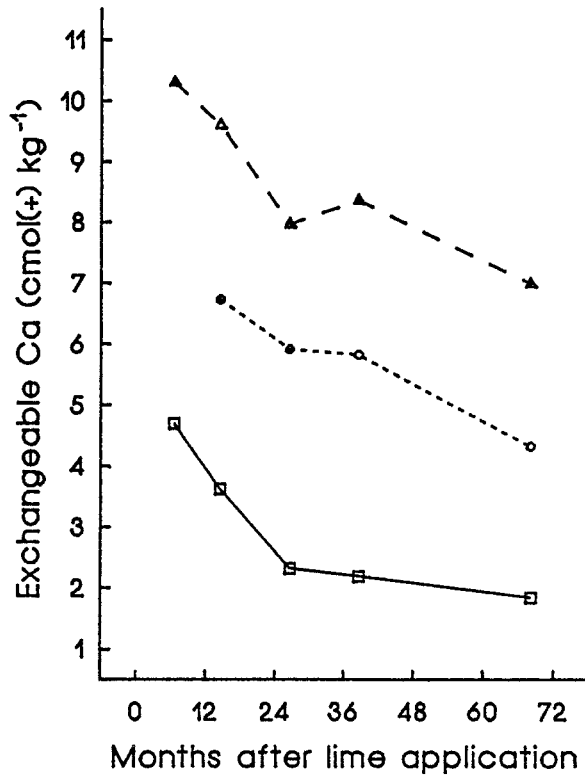
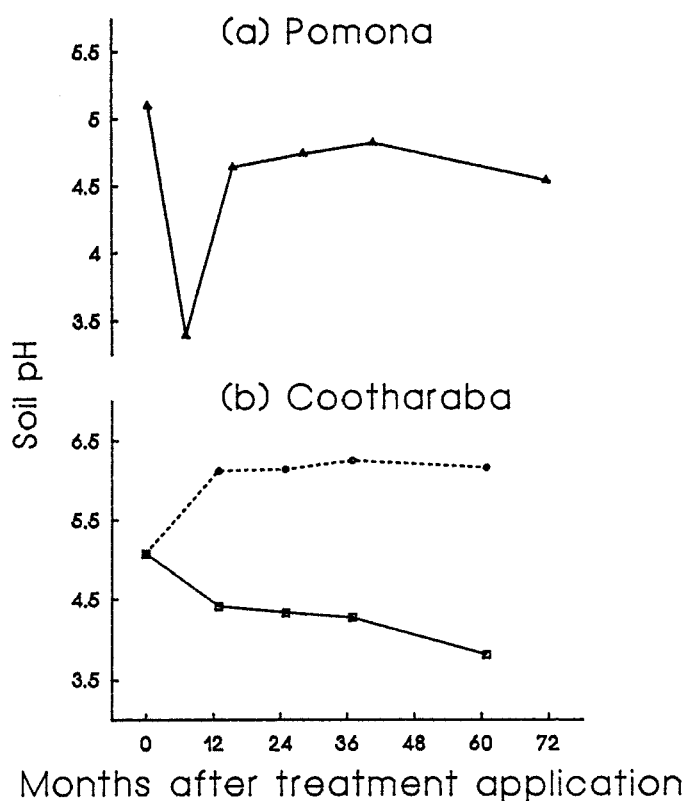


Fig. 1. The effect of time on soil  $pH_W$  (0–5 cm depth) for various rates of lime ( $\text{g/m}^2$ ) at (a) Pomona and (b) Cootharaba.

The effect of treatment application on soil properties at various depths at the Pomona site after 36 months is shown in Table 2. Although significant increases in subsoil  $pH_W$  were confined to high lime rates, the effects extended to deeper depths (Table 2), compared to those observed 12 months after application (Table 1).



**Fig. 2.** The effect of time after application of lime at rates of 300 g/m<sup>2</sup> (□), 600 g/m<sup>2</sup> (○) and 1200 g/m<sup>2</sup> (△) on exchangeable Ca in the surface soil (0–5 cm depth) at Pomona.



**Fig. 3.** Soil pH<sub>w</sub> (0–5 cm depth) at various times after application of acidifying treatments of (a) elemental S (▲) at Pomona and (b) N (■) and N plus lime (●) at Cootharaba.

Fig. 4 shows the changes in subsoil pH<sub>w</sub> over time following the application of 600 g lime/m<sup>2</sup>. As expected, the changes in pH<sub>w</sub> in the subsoil tended to lag behind those in the surface soil (Fig. 1). Lime application rates of 300 and 1200 g/m<sup>2</sup> also resulted in similar relationships (not shown) to those in Fig. 4.

**Table 1. Effect of treatment on soil pH<sub>w</sub> at various depths at each site 12 months after treatment application**

Site	Depth (cm)	Lime rate (g/m <sup>2</sup> )							Sulfur
		0	50	100	200	300	600	1200	
Pomona	0-5	5.0	5.1	5.5*	5.7*	6.4*	6.8*	7.3*	4.6
	5-10	5.0	5.0	5.2	5.3*	5.7*	5.8*	6.1*	4.5*
	10-20	5.0	4.9	5.0	5.1	5.2*	5.3*	5.4*	4.4*
	20-30	5.0	4.9	5.0	5.1	5.2	5.2	5.2	4.4*
	30-50	5.1	4.9	5.1	5.2	5.2	5.2	5.2	4.5*
Cootharaba	0-5	5.1	6.1*	6.6*	7.1*	4.4*	6.1*		
	5-10	4.8	5.6*	5.6*	5.7*	4.3*	4.9		
	10-20	4.7	5.0	5.0	5.2*	4.4	4.6		
	20-30	4.6	4.8	4.9	5.0	4.5	4.5		

\* Significantly different ( $P < 0.05$ ) from the control pH<sub>w</sub> value for a given depth interval.

The changes in exchangeable Ca and acidity (Al+H) with time at two depths for selected lime rates at Pomona are shown in Fig. 5. The rates of increase in exchangeable Ca per unit time were greater than the rates of decrease in exchangeable acidity as indicated by the slopes of the regression lines fitted to the data (Fig. 5).

## Discussion

### *Residual effects in the surface soil*

As expected, the longevity of the effect of lime in the surface soil depended upon the rate of application (Fig. 1). However, the residual effect of high lime rates ( $\geq 600$  g/m<sup>2</sup>) differed between sites. At Pomona, high lime rates maintained pH<sub>w</sub> values for 36 months (Fig. 1a), whereas at Cootharaba, pH<sub>w</sub> values for all lime treatments decreased throughout the trial period (Fig. 1b). The relationships between soil pH<sub>w</sub> (0-5 cm depth) and rate of applied lime at each site were similar (not shown, see Table 1), indicating that the soils had similar pH buffer capacities, as would be expected from their organic carbon and clay contents (Stephenson *et al.* 1996). Given the almost identical soil characteristics at each site (Stephenson *et al.* 1996), it is suggested that the greater residual value at Pomona may have been due to (a) a lower acidification rate and/or (b) slower lime dissolution and movement through the soil. Soil pH<sub>w</sub> values in the control plots (Fig. 1) suggest little or no acidification at the Pomona site whereas a trend for decreased pH<sub>w</sub> was evident at Cootharaba (Fig. 1b). The limited root system (and N demand) of the juvenile trees at Cootharaba would be conducive to nitrate leaching with consequential acidification. The older trees at Pomona also had a well-established canopy which may have reduced rainfall input, and hence lime movement in the undertree area, whereas, at Cootharaba there was negligible canopy cover. In addition, the presence of a mulch cover at Cootharaba may have maintained a higher moisture status in the surface soil and enhanced the dissolution of lime.

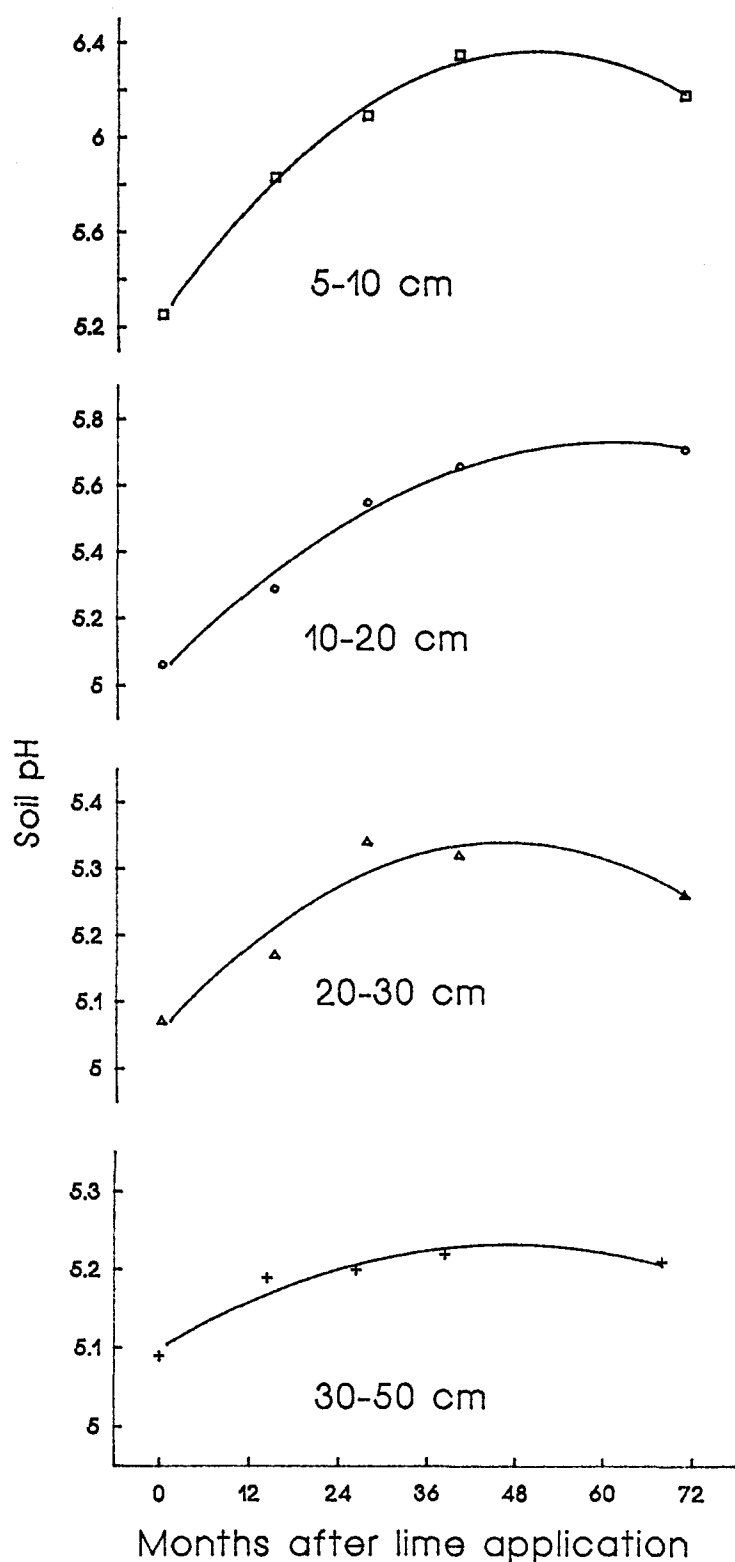
Table 2. Soil pH<sub>w</sub>, exchangeable Ca and Al and extractable Al at various depths 36 months after treatment application at the Pomona site

Depth (cm)	Lime rate (g/m <sup>2</sup> ):						Sulfur	
	0	50	100	200	300	600		1200
<i>Soil pH</i>								
0-5	5.1	5.1	5.3	5.6*	6.0* <sup>A</sup>	6.9*	7.7*	4.7
5-10	5.0	4.9	5.2	5.3	5.6*	6.4*	6.9*	4.8
10-20	5.0	4.9	5.1	5.1	5.3	5.7*	6.2*	4.7
20-30	4.9	4.9	5.0	5.1	5.1	5.3*	5.5*	4.5*
30-50	4.9	4.9	5.0	5.2	5.2	5.1	5.4*	4.5*
<i>Exchangeable Ca (cmol/kg)</i>								
0-5	0.55	0.54	0.81	1.6	2.2	5.8*	8.4*	0.35
5-10	0.35	0.37	0.42	0.66	1.2*	2.4*	3.2*	0.15
10-20	0.26	0.23	0.28	0.33	0.58*	1.1*	1.2*	0.09
20-30	0.17	0.15	0.19	0.20	0.37*	0.48*	0.75*	0.07
30-50	0.16	0.14	0.14	0.21	0.50*	0.36*	0.58*	0.07
<i>Exchangeable Al (cmol/kg)</i>								
0-5	0.45 (22) <sup>B</sup>	0.51 (26)	0.33 (15)	0.33 (13)	0.26 (8)	ND <sup>C</sup>	ND	0.62 (30)
5-10	0.56 (32)	0.59 (34)	0.51 (32)	0.51 (28)	0.45 (19)	ND	ND	0.61 (38)
10-20	0.70 (42)	0.77 (49)	0.67 (45)	0.66 (43)	0.67 (36)	0.39 (19)	0.25 (22)	0.75 (50)
20-30	0.82 (52)	0.70 (53)	0.66 (51)	0.70 (52)	0.69 (43)	0.49 (35)	0.46 (26)	0.75 (55)
30-50	0.86 (57)	0.85 (63)	0.66 (58)	0.75 (55)	0.56 (37)	0.49 (39)	0.54 (31)	1.0 (60)
<i>Extractable Al (mg/kg)</i>								
0-5	9.3	11	5.9	5.5	1.3	0.54	0.40	8.9
5-10	13	15	10	11	4.6	0.46	0.74	15
10-20	18	20	17	14	11	2.7	2.5	23
20-30	23	21	19	17	16	7.7	4.8	24
30-50	24	22	16	15	10	10	6.3	32

<sup>A</sup> \* Significantly different ( $P < 0.05$ ) from the no lime pH value for a given depth interval.

<sup>B</sup> Al saturation % shown in parentheses.

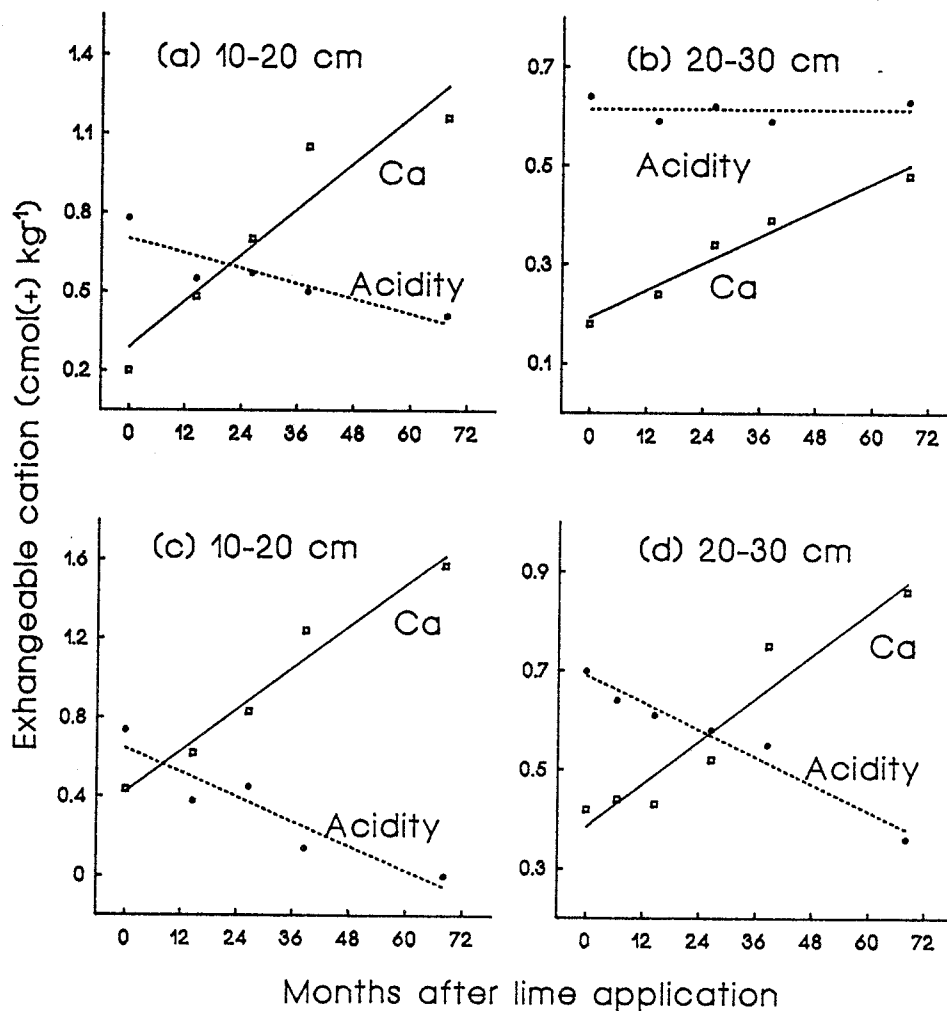
<sup>C</sup> Not detectable.



**Fig. 4.** The relationship between soil  $pH_w$  and time after surface application of  $600 \text{ g lime/m}^2$  for various depths at Pomona. Lines represent regression equations fitted to the data for depth intervals of 5–10 cm ( $Y = 5.25 + 0.0459X - 0.000474X^2$ ,  $R^2 = 0.99$ ), 10–20 cm ( $Y = 5.04 + 0.0236X - 0.000201X^2$ ,  $R^2 = 0.99$ ), 20–30 cm ( $Y = 5.06 + 0.0127X - 0.000143X^2$ ,  $R^2 = 0.92$ ) and 30–50 cm ( $Y = 5.10 + 0.00564X - 0.000060X^2$ ,  $R^2 = 0.94$ ).

The decreases in  $pH_w$  and exchangeable Ca in the surface soil (0–5 cm) over time are attributed to leaching of lime reaction products into the soil, slow pH buffering reactions, and acidification. The latter factor is considered to have had a minimal effect at the Pomona site since the  $pH_w$  of the unamended treatment changed little over the duration of the trial. The changes in  $pH_w$  for the limed treatments (Fig. 1) are in contrast to the results of Scott *et al.* (1992) who found that  $pH_{Ca}$  achieved by liming a duplex soil in southern New South Wales remained virtually constant for 3 years after liming. Rainfall and soil textural differences

presumably account for these differences, as Scott *et al.* (1992) concluded that there was limited lime movement below the depth of incorporation. Decreases in  $\text{pH}_W$  (Fig. 1) and Ca (Fig. 2) tended to be more pronounced at high lime rates (high pH), and are in agreement with results reported by Friesen *et al.* (1982). Greater leaching losses of Ca from the surface soil at high lime rates might be expected, since the amounts of Ca dissolved would exceed the soil's cation exchange capacity.



**Fig. 5.** Changes in exchangeable acidity (Al+H) and Ca over time in selected depths for lime application rates of 600 [(a) and (b)] and 1200 [(c) and (d)]  $\text{g m}^{-2}$  at Pomona. Regressions of exchangeable calcium (Ca) and acidity (Ac) against months after lime application ( $T$ ) were

$$(a) \text{ Ca} = 0.015T + 0.29 \quad (r^2 = 0.90) \text{ and } \text{Ac} = -0.0048T + 0.70 \quad (r^2 = 0.81),$$

$$(b) \text{ Ca} = 0.0045T + 0.19 \quad (r^2 = 0.96),$$

$$(c) \text{ Ca} = 0.018T + 0.42 \quad (r^2 = 0.97) \text{ and } \text{Ac} = -0.010T + 0.65 \quad (r^2 = 0.87),$$

$$(d) \text{ Ca} = 0.0072T + 0.39 \quad (r^2 = 0.91) \text{ and } \text{Ac} = -0.0046T + 0.69 \quad (r^2 = 0.96).$$

Despite the observed decrease in pH with time for limed treatments, the results suggest that high lime rates or repeated applications of lime will give rise to elevated pH values in the surface soil that may persist for some years. However, any lime-induced micronutrient deficiencies as a consequence of the high pH values may prove difficult to correct.



Acidity produced from the application of elemental S decreased soil pH and exchangeable Ca throughout the profile (Table 2). Six months after the application of S at the Pomona site the soil  $\text{pH}_W$  in the 0–5 cm depth was 3.4 (Fig. 3). The subsequent increase in  $\text{pH}_W$  of the surface soil (Fig. 3) with a corresponding decrease in subsoil  $\text{pH}_W$  (Table 1, 12 months after treatment application) suggests that the acidity associated with the oxidation of the S was readily leached. Similarly, the acidity produced from the surface application of N fertilizer at Cootharaba decreased  $\text{pH}_W$  in the 5–10 cm depth (Table 1). The  $\text{pH}_W$  values in the surface soil at Cootharaba for the N plus lime treatment 12 months after commencement of the trial show that the lime rate overcompensated for the acidification arising from N fertilizer (Fig. 3*b*). However, despite the re-application of lime each year for this treatment, the surface soil  $\text{pH}_W$  values remained fairly constant at around 6.2 (Fig. 3*b*).

#### *Effect of amendments on subsoil properties*

Given the finding that macadamia is relatively tolerant of acidity (Aitken *et al.* 1990, Stephenson *et al.* 1996), the existence of subsoil acidity may be of less concern in macadamia plantations than in other agricultural systems. However, the results of this study show that surface application of lime can reduce subsoil acidity in coarse textured soils in high rainfall areas. Economic lime rates (300 to 600 g/m<sup>2</sup>) significantly increased  $\text{pH}_W$  in the 10–20 cm depth interval 12 months after application and resulted in increases in both  $\text{pH}_W$  and exchangeable Ca in the 30–50 cm depth after 36 months. However, caution needs to be exercised in extrapolating these results to other sites. At both sites, the surface 25 to 30 cm of soil contained  $\leq 14\%$  clay and organic C values were low (Stephenson *et al.* 1996). In combination with the high rainfall, these factors would be conducive to leaching.

At the Cootharaba site, lime applied at a rate of 400 g/m<sup>2</sup> to the surface significantly increased  $\text{pH}_W$  in the 5–10 cm depth 12 months after application (Table 1). However, a similar lime rate (360 g/m<sup>2</sup>) applied with N did not significantly affect pH in the 5–10 cm depth. Because of the differential solubilities of lime and N fertilizer and different leaching rates of their dissolution products, subsoil acidification may occur despite the regular application of lime.

Lime rates  $\geq 300$  g/m<sup>2</sup> resulted in marked increases in exchangeable Ca throughout the profile (0–50 cm) 36 months after application. Although 300 g lime/m<sup>2</sup> produced a fourfold increase in exchangeable Ca in the 0–5 cm depth 36 months after application, it was not statistically significant ( $P < 0.05$ , Table 2). In contrast, the twofold increase in exchangeable Ca in the 20–30 cm depth for the same lime rate was significant ( $P < 0.05$ ). This is attributed to the greater variability between replicates in the surface soil compared with those in the subsoil.

The coarse-textured nature of the soils in this study, together with the fineness of the lime used, raises the possibility that the increases in subsoil pH and exchangeable Ca may have arisen from the movement of undissolved lime particles into the subsoil prior to reaction, in addition to the leaching of alkaline products of lime dissolution from the surface soil. The chemical analyses used in this study would not discriminate these mechanisms. Conyers and Scott (1989) were able to detect undissolved particles ( $>0.5$  mm) of lime in the depth of incorporation

5 years after application by observing the effervescence of particles in dilute acid. An attempt was made to use the method of Conyers and Scott (1989) to detect the presence of undissolved lime in subsoil samples from the present study. No effervescence was observed, owing either to the absence of lime particles or to the particles being too small for their reaction with acid to be observed under a binocular microscope. Scott *et al.* (1992) found that the extent of surface-incorporated lime effects on subsoil pH and Ca increased with decreasing particle size and rate of application.

Aluminium extracted with  $\text{CaCl}_2$  appeared to be more sensitive to the subsoil effects of surface applied lime than exchangeable Al. After 36 months, the highest rate of lime resulted in a decrease in exchangeable Al in the 20–30 cm depth of 44% compared with that in the unamended soil (Table 2). However, in the corresponding treatment and depth there was almost a 79% decrease in  $\text{Al}_{\text{Ca}}$  (Table 2). This discrepancy arises because exchangeable Al, measures both quantity and intensity aspects of labile Al whereas  $\text{Al}_{\text{Ca}}$  measures intensity and only a portion of the exchangeable Al. It would therefore be expected to be relatively more sensitive to changes in Al concentration in the soil solution.

For a given lime rate and subsoil depth, increases in exchangeable Ca over time were much greater than the decreases in exchangeable acidity (Fig. 5). This could arise through Ca from the lime being leached to a greater extent than alkalinity. The decrease in exchangeable Ca values with time in the surface soil (Fig. 2) compared to  $\text{pH}_w$  values tending to remain at elevated levels (Fig. 1) provides some support for this contention. There have been some suggestions in the literature that Ca is leached more than alkalinity (Friesen *et al.* 1982, Conyers and Scott 1989). However, the results observed (Fig. 5) could also arise through equivalent leaching of Ca and alkalinity with a portion of the alkalinity being neutralized by deprotonation of mineral surfaces rather than neutralization of exchangeable acidity. The additional exchange sites created would then be preferentially occupied by Ca.

### Acknowledgment

This work was financially assisted by a research grant from the Australian Macadamia Society. The technical assistance of Peter McKinley and Bruce Compton is gratefully acknowledged.

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Manuscript received 24 March 1995, accepted 23 August 1995

