Field Crops Research 108 (2008) 45–53

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Field crop responses to lime in the mid-north region of South Australia

A. Farhoodi [a,b], D.R. Coventry [b,*]

[a] Connolly Environmental, 142 Dynan Road, West Melbourne Victoria 3003, Australia
[b] School of Agriculture, Food and Wine Science, Adelaide University, Roseworthy Campus, Roseworthy, SA 5371, Australia

ARTICLE INFO

Article history:
Received 15 October 2007
Received in revised form 7 February 2008
Accepted 12 February 2008

Keywords:
Acidity amelioration
Lime application
Acidification

ABSTRACT

In the cropping regions of South Australia there is little information on whether acidity and acidification associated with high-input agriculture is affecting crop production and profitability. In much of the mid-north of South Australia, where thermic Calcic Palexeralf soils predominate, the levels of Al are low compared with other acid-soil types reported in comparable studies in Australia. In this study lime requirement curves have been used to predict the lime rate that achieves 80–90% maximum yield for different crop species on 3 sites on the red-brown earth soil type in the mid-north of South Australia. The results given demonstrate that the approach used for predicting lime responsiveness, with lime requirement calculated using the model of [Hochman, Z., Godyn, D.L., Scott, B.J., 1989. The integration of data on lime use by modelling. In: Robson, A.D. (Ed.). Soil Acidity and Plant Growth. Academic Press, Sydney, Australia, pp. 265–301], has provided good estimates of final pH changes. Yield response curves show that the largest yield gains mostly occurred in the second season of the experiment when lime at about 2.0 t/ha increased pH_{Ca} to 5.5–6.0. With the lime treatments calculated, yield of wheat, barley and faba beans were increased by about 70%, and durum by 30% compared with the control. It would appear that liming to achieve a pH_{Ca} of 5.2 has removed Al toxicity, and further liming to achieve pH_{Ca} 5.5–6.0 may have improved other soil properties to realise further yield gains. With cropping in this region commonly using practices that include high fertiliser nitrogen input and retention of crop residues, acidification is likely to be an on-going issue with these red-brown earth soils. Thus it is appropriate that soil testing and, where required, liming at the rate of 1.5 t/ha is used by farmers to both improve cropping profitability and also offset acid input associated with the farming practice.

1. Introduction

Soil acidity is a major factor that affects crop growth in many countries, with soils becoming more acidic from the use of no-till systems, crop rotations incorporating legumes or high inputs of N fertiliser (Xu et al., 2002; Bolan and Hedley, 2003; Godsey et al., 2007a). There is clear evidence that soils in the higher rainfall areas (>500 mm) of south-eastern Australia are affected by acidity (Coventry, 1992), and in western Australia, acidification is affecting the medium rainfall (400–500 mm) cropping areas (Dolling et al., 1994). In South Australia it is estimated that 30% of soils in pasture and crop production areas have $pH_{Ca} < 4.5$, however to date there is little information on whether this acidity is affecting plant production.

To enhance plant productivity on acid soils (pH_w 4.0–6.0), lime application is usually recommended but positive responses may not be immediately obtained (Warman et al., 1996; Edmeades and Ridley, 2003). In studies in north-eastern Victoria and southern NSW, with soil $pH_{Ca} < 4.7$, crop yield increases of the order of 20–100% have been obtained after liming the soil (Cregan et al., 1989; Coventry, 1992). In western Australia, various lime responses have been reported (Dolling et al., 1991), including occasional negative effects (Carr et al., 1991). In some studies on acidic soils in the eastern states of Australia, there are instances of no clear benefit from liming, particularly with pasture species (Coventry, 1992). In South Australia, there have been few attempts to discriminate any responses on the basis of soil type and lime requirement, or to relate methods for determining the amount of lime applied to plant responses (Merry et al., 1990).

Various methods have been tested to estimate requirements for lime and crop responses including target pH (Shoemaker et al., 1961; Adams and Evans, 1962; Curtin et al., 1984; Edmeades et al., 1985), toxic Al removal (Kamprath, 1970; Reeve and Sumner, 1970; Webber et al., 1976; Farina et al., 1980) and soil buffer capacity methods (Edmeades et al., 1985; Noble et al., 1997). In Australia some experience suggests it is better to use a combina-

* Corresponding author. Tel.: +61 8 83037954; fax: +61 8 83037730.
E-mail address: david.coventry@adelaide.edu.au (D.R. Coventry).

0378-4290/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.fcr.2008.02.013

Table 1
Description and chemical characteristics of the 3 soils in this study

Site and location [a]	Texture of A horizon	Handbook of Australian soils [b]	Factual key [c]	World soil map [d]	Exchangeable cations (cmol/kg)						ECEC [e]	B_s [f]	SL_s [g]	Organic C%	pH	
					Ca	Mg	Na	K	Al	Mn					0–10 cm	10-20 cm
Marrabel	Clay loam	Sodic red-brown earth	Dr2.23	Calcic luvisol	4.85	1.46	0.31	0.87	0.11	0.07	7.67	0.92	3.35	1.88	4.62	5.57
South Kapunda	Light sandy clay loam	Sodic red-brown earth	Dr2.13	Calcic luvisol	4.12	0.91	0.31	0.39	0.04	0.04	5.81	1.1	2.56	1.38	4.69	5.09
North Kapunda	Fine sandy loam	Non-calcic brown soil (sodic)	Db1.12	Chromic luvisol	2.49	0.66	0.23	1.35	0.14	0.09	4.96	1.09	2.59	1.30	4.32	4.73

[a] Farmer co-operators (Geoff Rowett, Marrabel; Mick Ryan, South Kapunda; David Shannon, North Kapunda).
[b] Stace et al. (1968).
[c] Northcote (1979).
[d] Northcote et al. (1975).
[e] ECEC (effective cation exchange capacity).
[f] Field buffering capacity (B_s).
[g] Slope of the regression of pH and total exchangeable bases (SL_s) were calculated from the model of Hochman et al. (1989).

tion of soil information (field buffering capacity, exchangeable bases, Al and pH) to estimate lime requirement (Hochman et al., 1989), and to discriminate the response to lime on the basis of soil type, crop species and relative grain yield response (Slattery and Coventry, 1993; Liu et al., 2004). In the present study the lime prediction approach as described by Hochman et al. (1989) is used to estimate lime rates to neutralise acidity as found in the lower and mid-north cropping regions of South Australia and, in field experiments, to establish if this acidity is affecting production for a range of field crops.

2. Materials and methods

2.1. Site selection, soil description and characterisation

Three field sites were established in 1999 on acidic soils in the lower and mid-north regions of South Australia (Table 1). These sites were at Marrabel (longitude 138°53′; latitude 34°08′), at the northern side of Kapunda (longitude 138°55′; latitude 34°18′), and at the southern side of Kapunda (longitude 139°00′; latitude 34°23′). These locations were selected to represent medium–high rainfall cropping regions of South Australia and the most common soil type, red-brown earths (Merry et al., 1990), thermic Calcic Palexeralf (Fitzpatrick and Naidu, 1995). Twenty core samples were taken at each site using a parallel grid pattern (August, 1998), for site characterisation, with sub-samples dried at 40 °C for 24 h and ground (2 mm sieve).

Soil pH_{Ca} was measured in 1:5, soil to 0.01 M $CaCl_2$, mixed by end-over-end shaking (1 h at 30 rpm). Soil extractable Al (extracted by 0.01 mol/L $CaCl_2$ using 1:5 soil:solution) and exchangeable Al (extracted by 1 mol/L KCl using 1:10 soil:solution) were determined by a modification of the method of Wilson and Sergeant (1963); Mn was determined (in each of the extracts used for Al) with analysis done by ICP-OES. The ECEC (cmol (+) kg^{-1}) as given in Table 1 was determined by summing the concentrations of Ca, Mg, Na, K, and Mn (1 M KCl) and Al (1 M KCl) (Slattery et al., 1995). Calcium, Mg, Na and K were extracted in 0.1 M NH_4Cl (Rayment and Higginson, 1992) and then measured individually by atomic adsorption (Gillman and Sumpter, 1986). Boron was measured similarly to the method (12C1) in Rayment and Higginson (1992) and organic carbon was measured similarly to the method of Walkley and Black (Rayment and Higginson, 1992). Grain protein was measured by the method of O2/O3 Dumas Combustion total nitrogen determination (Rayment and Higginson, 1992).

2.2. Lime requirement estimates

The soil data shown in Table 1 was used to provide a lime requirement estimate as described in the lime requirement model given by Hochman et al. (1989). This approach uses the combined soil information of ECEC, pH and Al to calculate field buffering capacity and to predict lime rates required to raise soil pH to a pre-determined level.

2.3. Experimental treatments and management

Five soil amendment treatments were randomised within 4 replicates in a split-plot design (60 plots/site) (February, 1999). The plots were 1.8 m × 15 m long and the five amendments were: control (nil lime), sulfur (0.3 t S/ha—all sites), L1 (1 t lime/ha—Marrabel and North Kapunda; 0.75 t lime/ha—South Kapunda), L2 (2 t lime/ha—Marrabel and North Kapunda; 1.67 t lime/ha—South Kapunda) and L3 (4 t lime/ha—Marrabel and North Kapunda; 3 t lime/ha—South Kapunda). The L2 lime rate was the value calculated to neutralise acidity (target pH 5.25) based on the

Table 2
Monthly rainfall for the 3 sites used in the study

	January	February	March	April	May	June	July	August	September	October	November	December	April–October	Total
Marrabel														
1999	22.4	11.2	56.8	10.0	72.0	33.8	35.2	39.0	52.2	63.0	65.9	26.0	305	487
2000	0	93.4	18.8	48.6	54.2	59.0	66.2	48.4	55.8	66.0	25.6	7.8	398	544
South Kapunda														
1999	9.2	10.6	62.2	5.6	78.2	36.6	45.8	43.2	61.2	48.4	56.4	22.6	319	480
2000	0.6	118.2	18.6	46.8	66.0	69.2	72.2	51.0	52.2	54.0	33.9	6.6	411	589
North Kapunda														
1999	9.0	11.0	62.0	5.0	79.0	35.0	44.0	41.0	61.0	49.0	57.0	25.0	314	478
2000	0.6	111.0	19.5	44.8	63.2	67.9	71.1	52.6	53.4	55.0	31.8	7.0	408	578

Hochman model. The S (acidity input) rate was calculated assuming that 1 mole $CaCO_3$ equals 3.125 mole S. Lime was spread with a 1.5-m drop spreader and powdered S was spread by hand on the surface soil. After the materials were spread, the soil was cultivated with treatments incorporated to a depth of 10 cm by one pass with a scarifier. The lime was ground agricultural limestone containing 40% Ca (98% $CaCO_3$) and 0.3% Mg (mainly as $MgCO_3$), with an effective neutralising value of 96%, with 100% of the product less than 250 μm in particle size. The lime was supplied by Omya Southern (Linfield, New South Wales).

Crop species were sub-plots within the main soil treatments. The crop species and cultivars used were wheat (*Triticum aestivum*) cultivar Janz; barley (*Hordeum vulgare*) cultivar Franklin; canola (*Brassica napus*) cultivar Dunkeld; durum (*Triticum turgidum*) cultivar Yallaroi and faba beans (*Vicia faba*) cultivar Fiesta, with 3 crop varieties sown in each season. The rotation of crops through the 2 seasons was based on past crop sequence and farmer preference.

In 1999, the sites were sown on 27 and 28 of May, and in 2000, the sowing occurred on 3 and 4 of June. Depths of sowing were 3–4 cm for wheat, durum and barley, 2 cm for canola and 4–5 cm for faba beans. Seeding rates were 72 kg wheat/ha, 83 kg barley/ha, 104 kg durum/ha, 3.5 kg canola/ha, and 180 kg faba beans/ha. The crops were sown with an 8-row cone-seeder with narrow points and press wheels. An overall 80 kg/ha of 18:20:0, N:P:K, with 2.5% Zn, was applied to canola, faba bean, durum and wheat in 1999 and 2000, with an extra 25 kg/ha N at tillering in the 1999 season. Fertiliser for barley at sowing was in the form of triple superphosphate (25 kg P/ha). Before sowing in both years, each site was sprayed for emerged weeds with glyphosate (2 L/ha). Post-emergent weeds were controlled during the growing season according to district recommendations. Where possible, Glean® (18 g/ha) or Achieve® (380 g/ha) was used for ryegrass control. In July 1999, omethoate (50 mL/ha) was sprayed to prevent lucerne-flea and red-legged earth mites on sites coming out from pasture. In the 2000 season, Mancozeb (2.5 kg/ha) was used to prevent chocolate spot on the faba bean plots. Rainfall was measured at each site and is shown in Table 2.

2.4. Treatment measurements

Whole plots were machine-harvested at maturity using a KEW harvester on 29 December 1999 and 4 December 2000 for grain yield and protein. Destructive sampling was performed only in the 2000 season so as to measure dry matter (DM). Data for DM yield (2 m × 0.5 m rows of plants intact, 3 random locations/plot) are shown only for the wheat crop at the North Kapunda site (2000), where grain yield data were not reliable due to extreme frost damage.

Soil samples were collected (0–10 cm depth) from each plot during September of 1999 and 2000, with 15 cores/plot randomly taken: sample preparation and chemical analyses were undertaken as previously described.

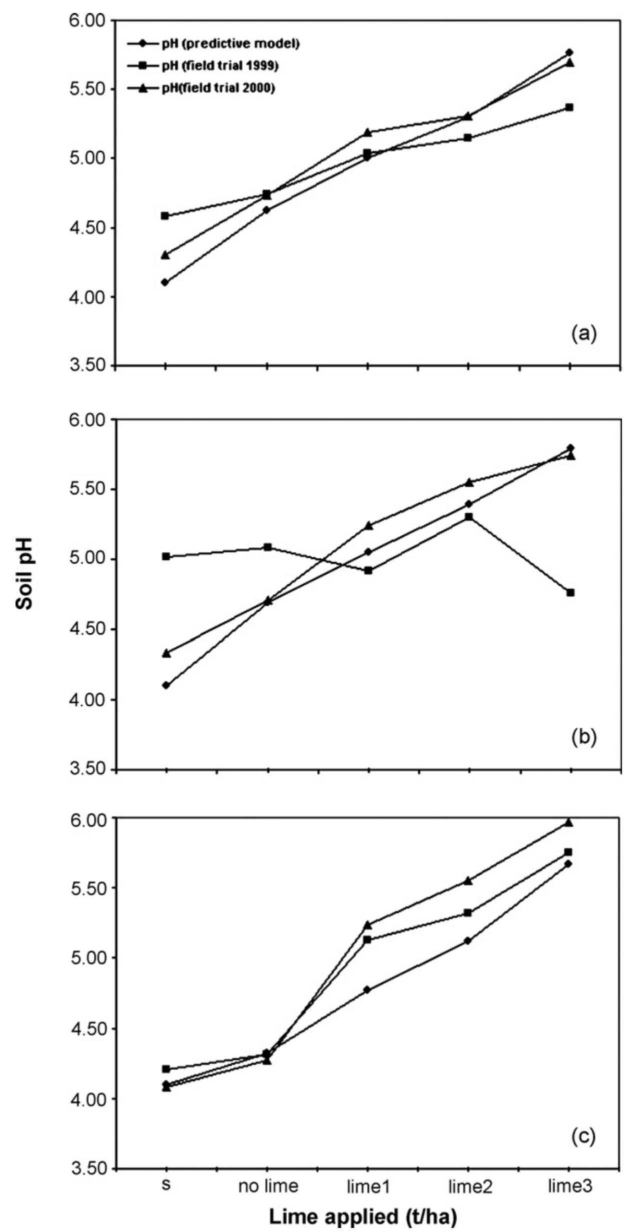

Fig. 1. Relationship between the lime applied and the change in soil pH_{Ca} at 3 sites in 1999 and 2000. (a) Marrabel, (b) South Kapunda, and (c) North Kapunda. Lime rates were determined from the Hochman et al. (1989) predictive model.

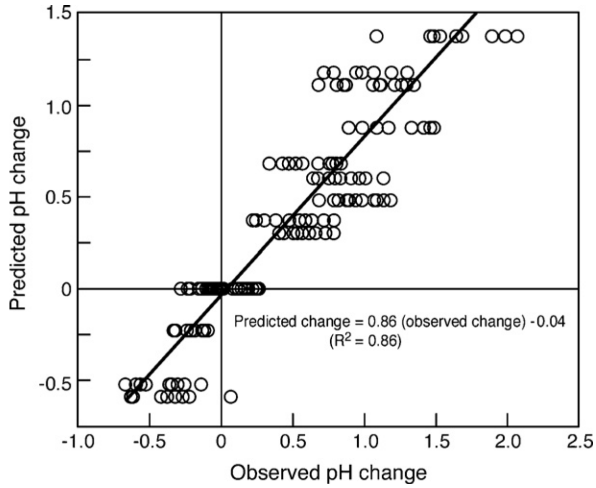

Fig. 2. Field-observed versus predicted values from the Hochman model for all soil treatments in the 2000 season at 3 sites. The solid diagonal line shows best-fit line.

2.5. Statistical analysis

Both linear and non-linear regression analysis was applied to the means of the yield data, plotted with the mean soil pH collected over 2 growing seasons, for wheat, durum, barley and one growing season for canola and faba bean. Backward elimination was used to calculate the relationship between relative yield, and means of pH and extractable Al and Mn for each species at each site to predict yield. Analysis of variance (ANOVA) was applied to the relative yields of the crops over 2 growing seasons to determine significant differences between these sites. ANOVA was also used to determine the least significant differences among treatments for soil extraction analysis and between yields for the treatments at three sites. All data were analysed using Genstat 5 statistical analysis software, release 5, 2001 (Lawes Agricultural Trust, Rothamstead, UK), using SUPER ANOVA statistical analysis software version 1.1 (Abacus Concepts Incorporation, 1991).

3. Results

3.1. Lime requirement calculations

The relationships between the lime applied and the actual change in soil pH_{Ca} at the 3 sites in 1999 and 2000 seasons, and the pH values that are predicted from the Hochman model, are shown in Fig. 1. There was a difference in pH measured in 1999 and 2000, indicating a delay in S and lime dissolution in these soil types, after a time period of almost 12 months the target pH was achieved. By 2000 this model provided a very good estimate ($R^2 = 0.86$) of the final pH for soil treatments at each of the 3 sites (Fig. 2).

3.2. Soil chemical characteristic relationships

The Al_{Ca} and Mn_{Ca} measures decreased with lime application, and increased with S application ($P < 0.05$). These data are shown plotted against site-combined measures of pH_c (Fig. 3), with the "break of curve" value of pH_{Ca} 4.75. The regression equations at each site show a negative relationship for pH with extractable aluminium (Al_{Ca}) and extractable manganese (Mn_{Ca}) (Table 3). Liming also increased ($P < 0.05$) exchangeable Ca, and the S treatment decreased exchangeable Ca ($P < 0.01$) at all sites. The regression equations developed for pH and individual cations had significant ($P < 0.01$) positive correlations with Ca, but Mg, Na and K were not changed ($P = 0.05$) with soil amendment (Table 3). These data suggest that the exchange sites vacated by H^+, Al and Mn were almost all taken up by Ca after liming.

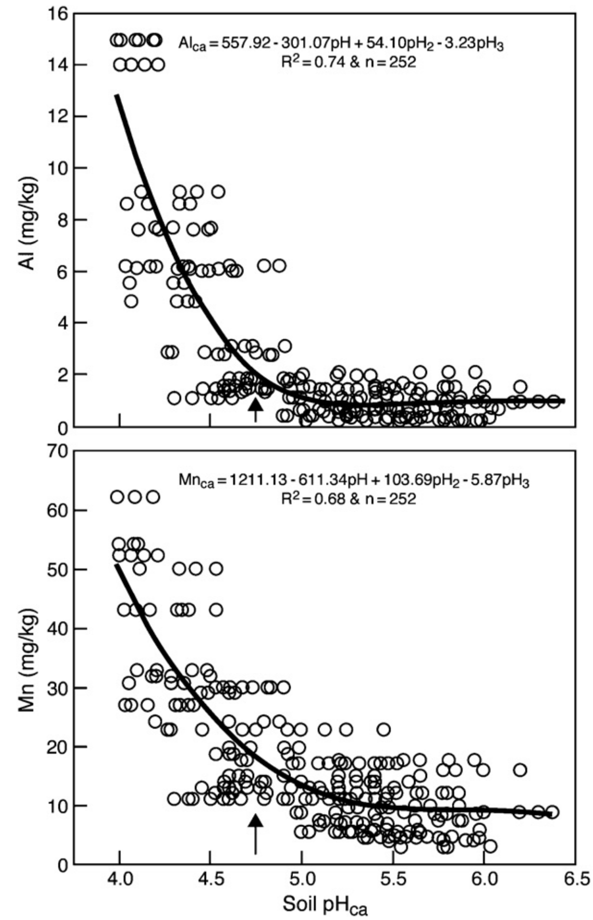

Fig. 3. Relationship between pH_{Ca} and 0.01 M $CaCl_2$ extractable Al and Mn for all 3 sites. Arrow indicates 'break of curve'.

3.3. Yield data

Irrespective of crop type, there were no grain yield responses ($P = 0.05$) to the addition of lime in the 1999 season (Table 4). Only the S treatment produced a significant change ($P < 0.05$) with reduced yield for all species at the Marrabel site. In the 2000 growing season, the lime treatments produced higher yields ($P > 0.001$) compared to the control, the S treatment at all sites decreased yield ($P > 0.001$) (Fig. 4). The L2 treatment produced significantly higher yield response compared to L1 and L3 treatments for all species at South Kapunda. At Marrabel, the trend was similar and L2 had higher yield compared to L1 and L3, but only for faba beans and barley. At North Kapunda, increasing lime rates significantly ($P > 0.001$) improved yield for the 2 species harvested. It was not possible to get grain yield for wheat due to severe frost damage at this site, but the DM yields suggest the likelihood of a grain yield response to lime (Fig. 3). Grain protein data for wheat are shown in Table 5.

Regression analyses and responses between grain yield and pH are given for all sites (Table 6 and Fig. 4). The relationships for extractable Al and extractable Mn with yield (data not shown) show a significant decline in yield with increasing Al or Mn. These declines in yield are evident after the value for Al and Mn exceeds 1 and 10 mg/kg, respectively.

Table 3
(a) Relationships between pH_{Ca} and extractable Al and extractable Mn and (b), Coefficients (R^2) and slopes (b = cmol (+) kg^{-1}/pH unit) for relationships between exchangeable cations and soil pH, for all sites, for 3 sites in year 2000

Regression equation	A (±S.E.)	B (±S.E.)	C (±S.E.)	R^2
a				
Marrabel site				
$pH = A \times Al + B \times Al^2 + C$	−41.22 ± 6.85	3.73 ± 0.88	114.17 ± 16.99	0.73
$pH = A \times Mn + B \times Mn^2 + C$	−156.73 ± 30.34	13.39 ± 3.03	467.37 ± 75.22	0.81
South Kapunda site				
$pH = A \times Al + B \times Al^2 + C$	−23.20 ± 3.29	2.05 ± 0.33	65.89 ± 8.24	0.82
$pH = A \times Mn + B \times Mn^2 + C$	−103.74 ± 13.73	8.85 ± 1.36	307.81 ± 34.35	0.91
North Kapunda site				
$pH = A \times Al + B \times Al^2 + C$	−48.46 ± 5.32	6.35 ± 0.63	140.39 ± 15.74	0.89
$pH = A \times Mn + B \times Mn^2 + C$	−122.56 ± 29.49	10.31 ± 2.92	375.80 ± 73.13	0.76

	Ca		Mg		K		Na		Al		Mn	
	R^2	b	R^2	b	R^2	b	R^2	b	R^2	b	R^2	b
b												
Marrabel	0.82	1.79	ns[a]	0.05	ns	−0.06	ns	−0.01	0.65	−0.12	0.84	−0.06
South Kapunda	0.92	1.34	ns	0.07	ns	0.02	ns	0.02	0.63	−0.05	0.86	−0.03
North Kapunda	0.91	1.12	ns	0.04	ns	−0.01	ns	0.02	0.78	−0.14	0.77	−0.04

[a] Not significant ($P = 0.05$).

Table 4
Grain yield data (t/ha) for season 1999 for the 3 sites

Marrabel		Wheat (barley[a])	Barley (wheat)	Durum (beans)
	S	1.36	2.00	2.29
	C	1.75	2.13	2.51
	L1	1.85	2.15	2.69
	L2	1.90	2.11	2.55
	L3	1.98	2.03	2.67
	l.s.d. (P = 0–05)	0.11	0.09	0.12
South Kapunda		Wheat (barley)	Durum (wheat)	Canola (durum)
	S	2.56	2.75	1.95
	C	2.72	2.39	2.00
	L1	2.68	2.78	2.12
	L2	2.76	2.83	2.12
	L3	2.51	2.59	2.07
	l.s.d. (P = 0–05)	0.20	0.20	0.13
North Kapunda		Wheat (barley)	Barley (beans)	Canola (wheat)
	S	2.46	2.40	1.88
	C	2.29	2.46	1.94
	L1	2.33	2.48	1.87
	L2	2.44	2.35	1.92
	L3	2.38	2.17	1.99
	l.s.d. (P = 0–05)	0.21	0.05	0.31

[a] Rotation crop for 2000 season.

3.4. *Prediction of yield and field lime requirement*

In order to determine which of the soil acidity factors (pH, Al, Mn) could most accurately predict yield, the yield of the various crops was modelled using backward elimination analysis (Table 7). The backward elimination used first pH alone, and was continued with pH + Al, pH + Mn and pH + Al + Mn until the highest regression coefficient was found for each relationship. The 'maximum' grain yield was determined from the response curves shown in Fig. 5, and the equations in Table 7 are derived from the field-determined lime rate to reach 80–90% relative to the maximum yield. In this analysis, pH alone accounted for 44–77% of the variation in the Marrabel and South Kapunda site for wheat, and 63–90% for barley, durum and faba bean at 3 sites. The addition of Al and Mn into the model in 3 sites improved the relationship. At the Marrabel site the inclusion of Al and Mn together improved the relationship from 44 to 77% for wheat, and from 63 to 74% for barley for Al alone and from 44 to 77% for faba bean for Al and Mn together. For the South Kapunda site, these improvements were 77–85% for wheat, 79–97% for barley for Al and Mn inclusion and nothing for durum. With the North Kapunda data, the fitness of the model increased from 90 to 98% for barley and 87 to 97% for faba bean by inclusion of Al or Mn individually or together.

4. Discussion

4.1. *Efficacy of the lime requirement model*

In this study field experimental data was used to test and validate a chosen model's ability to predict change in soil pH with rates of lime. The lime requirement calculated using the model of Hochman et al. (1989) provided good estimates of the final pH

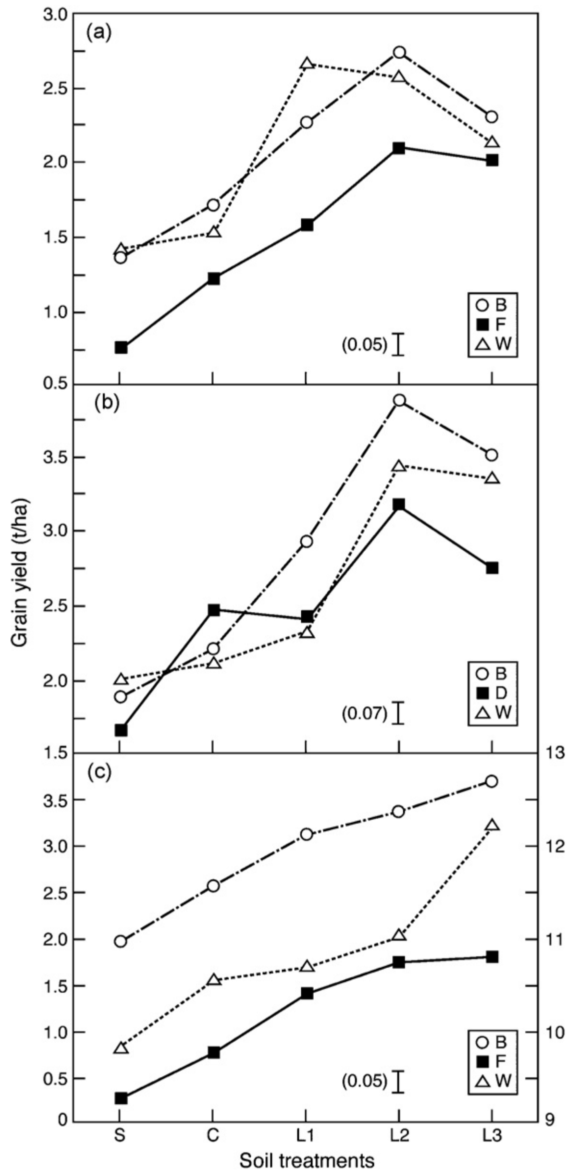

Fig. 4. Relationship between crop × lime treatment for grain yield at (a) Marrabel, (b) South Kapunda and (c) North Kapunda sites in 2000. B, barley, F, faba beans, and W, wheat. The data shown in section c for wheat is DM (t/ha) production; l.s.d. ($P < 0.5$) shown with error bars.

changes (Figs. 1 and 2) at the 3 sites, after a time period of almost 12 months, the target pH was achieved ($R^2 = 0.86$). The equation obtained in this study (predicted pH change = 0.86 × (observed pH change) − 0.04) is very similar to the equation obtained by Hochman et al. (1995) (predicted pH change = 0.85 × (observed pH change) − 0.02), also the buffering capacity (B_s) and the slope of the regression of pH and total exchangeable bases (SL_s) for all 3 sites agrees well with the Hochman predicted data (Table 1).

The closeness between observed and predicted pH values would indicate that the values associated with pH buffering are likely to be important in lime reaction in these soils. Parameters affecting the pH buffering that have been used to predict the effects of lime rates are ECEC, Al and pH of unlimed soil. There is evidence that these reactions are the main pH buffering reactions between pH 4.5 and 6.5 (Helyar et al., 1993; Magdoff and Bartlett, 1985). At this pH_{Ca} range (4.5–6.5) the soil pH is mainly buffered by association/dissociation reactions of H^+ ions (Helyar and Porter, 1989). Thus in the current study, the factors affecting the lime requirement model utilised (ECEC, Al and pH) of unlimed soil have worked well, especially as the pH_{Ca} was in the range between 4.0 and 6.0 (Hochman et al., 1989).

According to Hochman et al. (1995), addition of an equal amount of lime to different sites with the same ECEC, Al and Mn, though with different initial pH values, gives a smaller pH change in the soil wherever there were higher initial pH values. This prediction is consistent with the equation of Bailey et al. (1989) but not with the observation of Magdoff and Bartlett (1985) that soils are least buffered in the pH range 5.0–5.6. This outcome was also obtained in the current study where the North Kapunda site with a lower initial pH value, compared with Marrabel and South Kapunda sites with higher pH values, almost reached the same final pH level with the same lime rates. The buffering capacity of the Marrabel and South Kapunda sites were higher than the North Kapunda soil (Table 1). For example at the Marrabel and South Kapunda sites, the pH values increased by 0.9 of a pH_{Ca} unit after addition of 4 t/ha (L3) of lime, whereas increases of 1.7 of pH_{Ca} unit was obtained for the North Kapunda site for the same lime rate. The lower soil ECEC at the South Kapunda and North Kapunda sites will account for the difference in the observed buffering capacity when compared with the Marrabel site.

The use of single or double buffer methods (with either NaOH or $Ca(OH)_2$) have been recommended for estimating lime requirement of soils (Woodruff, 1948; Shoemaker et al., 1961; Adams and Evans, 1962; Mehlich, 1976; Yuan, 1976; Godsey et al., 2007b). Such methods were previously used in the study by Richards (1992) in South Australia, but produced discrepancies in predicting a final pH, particularly for pH_{Ca} 5.0 and 5.5. The reaction of different buffer solutions on soils from the 3 sites in this study has also been used to calculate lime requirement (data not shown). Here the pHBC measured with either NaOH or $Ca(OH)_2$ underestimated the lime to achieve best pH and yield responses. A major difficulty in obtaining a 'right' lime requirement with analytical methods is the lack of calibration against observed crop responses in the field. Whilst the lime requirement calculated by buffer methods may ameliorate toxicity due to the effect of Al and Mn, they may not be

Table 5
Grain protein and N content for the wheat crop on 2 sites in the 1999 and 2000 growing seasons

		Grain protein (%)	N content (kg N/ha)	Grain protein (%)	N content (kg N/ha)
		1999		2000	
Marrabel[a]	Control	11.40	119	8.27	133
	2 t/ha lime added	12.50	237	8.75	224
	l.s.d. (P = 0–05)	ns	47	ns	44
South Kapunda[b]	Control	12.5	340	9.35	199
	1.67 t/ha lime added	11.80	307	9.00	313
	l.s.d. (P = 0–05)	ns	ns	ns	54

[a] 1999 wheat crop followed canola, 2000 wheat crop followed barley.
[b] 1999 wheat crop followed pasture, 2000 wheat crop followed durum.

Table 6
Regression equations for the relationship between grain yield (Y) of each crop species and pH_{Ca}; the data are presented in Fig. 5

Site[a]	Regression equation	A (±S.E.)	B (±S.E.)	C (±S.E.)	R^2
Wheat					
M	Y = A × pH + B × pH^2 + C	7.54 ± 3.12	−0.68 ± 0.31	−18.49 ± 7.81	0.89
SK	Y = A × pH + B	0.97 ± 0.13	−2.32 ± 0.64		0.88
Barley					
M	Y = A × pH + B × pH^2 + C	5.98 ± 2.15	0.53 ± 0.22	−14.43 ± 5.29	0.85
SK	Y = A × pH + B	1.29 ± 0.16	−3.75 ± 0.82		0.89
NK	Y = A × pH + B × pH^2 + C	2.35 ± 0.85	−0.16 ± 0.08	−4.66 ± 2.12	0.92
Durum					
SK	Y = A × pH + B × pH^2 + C	5.22 ± 2.24	−0.45 ± 0.22	−12.37 ± 5.61	0.85
Faba					
M	Y = A × pH + B	0.92 ± 0.10	−3.14 ± 0.52		0.91
NK	Y = A × pH + B × pH^2 + C	4.27 ± 1.01	−0.35 ± 0.10	−11.27 ± 2.49	0.92
Canola					
NK	Y = A × pH + B	0.02 ± 0.02	1.84 ± 0.12		ns
SK	Y = A × pH + B	−0.05 ± 0.05	2.28 ± 0.24		ns

[a] M, Marrabel; SK, South Kapunda; NK, North Kapunda.

Table 7
Regression equations derived from backward elimination of field determined lime requirement to reach 80–90% of relative grain yield

Regression equation	R^2	P^A
	Wheat—Marrabel	
Yield = −1.39 + 0.68 pH	0.44	***
Yield = 1.92 + 0.09 pH − 0.16 Al	0.56	ns
Yield = 4.63 − 0.34 pH − 0.04 Mn	0.65	ns
Yield = 8.57 − 0.88 pH + 0.57 Al − 0.16 Mn	0.77	***
	Barley—Marrabel	
Yield = −1.62 + 0.74 pH	0.63	***
Yield = 0.16 + 0.42 pH − 0.1 Al	0.74	**
Yield = 1.14 + 0.27 pH − 0.02 Mn	0.72	ns
Yield = −0.28 + 0.5 pH − 0.13 Al + 0.01 Mn	0.74	ns
	Faba bean—Marrabel	
Yield = −1.39 + 0.68 pH	0.44	***
Yield = 1.92 + 0.09 pH − 0.16 Al	0.56	ns
Yield = 4.63 − 0.34 pH − 0.04 Mn	0.65	ns
Yield = 8.57 − 0.88 pH + 0.57 Al − 0.16 Mn	0.77	***
	Wheat—South Kapunda	
Yield = −2.32 + 0.77 pH	0.77	***
Yield = −4.11 + 1.29 pH + 0.1 Al	0.79	ns
Yield = −3.96 + 1.25 pH + 0.02 Mn	0.78	ns
Yield = 0.86 + 0.53 pH + 1.04 Al − 0.22 Mn	0.85	**
	Barley—South Kapunda	
Yield = −3.75 + 1.29 pH	0.79	***
Yield = −0.74 + 0.78 pH − 0.32 Al	0.82	*
Yield = 0.71 + 0.55 pH − 0.06 Mn	0.85	*
Yield = 0.79 + 0.6 pH + 2.73 Al − 0.42 Mn	0.97	***
	Durum—South Kapunda	
Yield = −1.15 + 0.71 pH	0.66	***
Yield = 2.27 + 0.12 pH − 0.23 Al	0.81	ns
Yield = 3.20 − 0.02 pH − 0.05 Mn	0.76	ns
Yield = −0.16 + 0.52 pH − 0.49 Al + 0.07 Mn	0.83	ns
	Barley—North Kapunda	
Yield = −0.57 + 0.69 pH	0.91	***
Yield = 1.74 + 0.31 pH − 0.07 Al	0.97	***
Yield = 1.56 + 0.36 pH − 0.02 Mn	0.98	***
Yield = 1.49 + 0.38 pH − 0.01 Al − 0.02 Mn	0.98	*
	Faba—North Kapunda	
Yield = −2.74 + 0.79 pH	0.87	***
Yield = −0.31 + 0.37 pH − 0.06 Al	0.96	***
Yield = −0.12 + 0.38 pH − 0.02 Mn	0.97	***
Yield = −0.10 + 0.37 pH − 0.01 Al − 0.02 Mn	0.97	*

[A] Significant at ***p = 0.001, **p = 0.01, *p = 0.05, ns not significant.

sufficient to achieve 90% of potential yield (as shown in this study). This would suggest that the only true standard against which rapid methods for the estimation of lime requirement can be calibrated is lime requirement based on the results of field experimentation on the crops and soils of interest. When such calibrations are carried out, meaningful estimates of LR can be obtained from laboratory methods (Sumner, 1997).

Many Australian studies have reached a similar conclusion that, on determining lime requirement to reduce exchangeable Al to a pre-determined level, they did not then maximise plant growth (Aitken et al., 1990; Aitken, 1992; Slattery and Coventry, 1993). The importance of calibration for lime requirement based on a local or regional soil basis has been highlighted by Godsey et al. (2007b). This need for calibration is particularly important in the mid-north cropping region of South Australia, as in this region the levels of Al are low compared with most other acidic soil types in Australia. The best option for the South Australian situation would be increasing pH, and subsequently Ca and ECEC of the soil to reach a target yield, rather than what would be indicated by liming to just remove Al toxicity. Thus predicting pHBC from soil properties (such as OM, exchangeable Al, initial soil pH and ECEC) to predict lime requirement to reach a target pH is likely to be more suitable to these soil types.

4.2. Yield responses

Yield increases with lime application were not evident in 1999, but in 2000 the lime treatments resulted in substantially increased yield of the field crops compared with the control at all sites. Wheat, barley and faba beans were similar in their response (70–75%), and durum was increased by about 30%. The response at the lower rates (1 t/ha) did not provide the same yield advantage compared to L2 and L3 (the only exception was the wheat crop at the Marrabel site for 2000 season), whilst sometimes there was a small ($P < 0.05$) yield reduction with L3.

Data provided in this study (Table 6) indicate that pH alone mostly explains the differences observed in grain yield. The regression of Al and Mn against yield shows that the yield decreases as the soil pH decreases (here almost entirely influenced by the S treatment), and yield increases as the Al and Mn decreases (data not shown). The S treatment was found to have an Al_{Ca} around 5 mg/kg for all sites, and at the Marrabel and South Kapunda sites the Al level on the unlimed treatment (control) was 2 and 3 mg/kg, respectively (Fig. 3). With these latter values, only

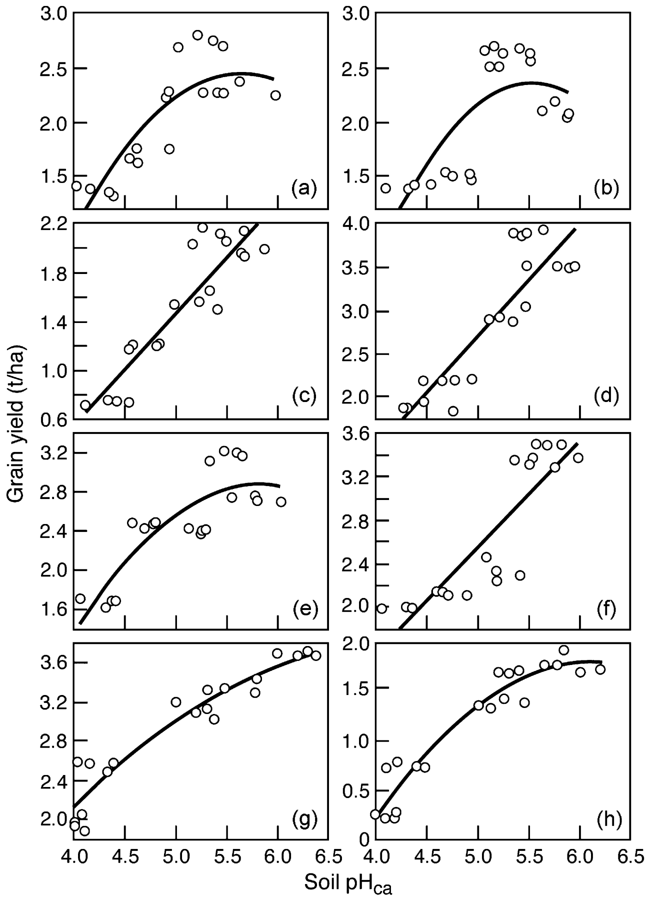

Fig. 5. Relationship between grain yield (t/ha) and pH_{Ca} for (a) barley—Marrabel, (b) wheat—Marrabel, (c) faba beans—Marrabel, (d) barley—South Kapunda, (e) durum—South Kapunda, (f) wheat—South Kapunda, (g) barley—North Kapunda, and (h) faba beans—North Kapunda, 2000 season.

very sensitive cultivars would be likely affected by Al toxicity (Fenton et al., 1996). The amount of lime required to reduce Al_{Ca} to lower than 1 mg/kg for the 3 sites was about 1 t/ha. These lime rates correspond to raising the soil pH_{Ca}, to a value of 5.2 for all sites. At this pH_{Ca} most of the crop species in this study were at about 55–75% of their potential yield (Fig. 5). At pH_{Ca} 5.2, the extractable Mn_{Ca} levels were about 20–30 mg/kg and increasing pH to higher levels further decreased Mn levels to levels of 8–10 mg/kg (at pH_{Ca} 5.5–6.0). At pH_{Ca} 5.5–6.0, most plant species reached 80–90% of their potential yield. Wherever Al was higher than 1 mg/kg it would seem that liming to achieve a pH_{Ca} of 5.2 (L1) has removed Al toxicity (Fig. 3), and further liming to achieve pH_{Ca} 5.5–6.0 (L2-L3) may have improved other soil components to realise the further yield gains. No plant tissue analyses were conducted in this study, which may have given an indication on possible micro-nutrient benefits (e.g. Ca, Mg, Zn). Many of these soil types are characterised by low Zn availability (Reuter, 1992). Zn availability also declines at higher pH values (pH_{Ca} range 5.5–7.0), or by over liming (Kamprath and Foy, 1971; Bolland et al., 2000). Liming soil can increase the availability of nitrogen through stimulating mineralisation of N (Ridley et al., 1990). Nitrogen was applied as fertiliser at sowing and tillering in 1999 and at sowing in 2000, and each site had a good recent history of rotation with legume-based pasture or pulse crops, so it is unlikely that the sites would be N limiting for realising yield. Thus in this study the large increase in N uptake evident in wheat harvested in 2000 may be due to liming enhancing root growth (alleviating Al toxicity) rather than from increased N availability.

The information provided in this paper suggests that to improve lime prediction, an agreement between plant response and lime required to reach maximum yield for each species is needed. So the importance of calculating the amount of lime required to achieve 90% of maximum yield/species would help to decide cost to benefit ratios of tonnes of lime to the percent of achieved yield. With this approach, the level of tolerance of each species to the toxic effects of elements such as Al and Mn is considered in the lime requirement model, similarly to the approach used by Slattery and Coventry (1993). In order to determine which of the soil properties could most accurately predict yield, yield was modelled using backward elimination analysis against soil pH, Al, and Mn. Backward elimination was continued until the greatest regression coefficient was found for each relationship. In this analysis, pH accounted for 44–77% of the variation at the Marrabel and South Kapunda sites for wheat, and 63–90% for barley, durum and faba bean at 3 sites. The addition of Al and Mn into the model in 3 sites improved the relationship but with pH_{Ca} the more sensitive indicator of soil chemical changes than Al_{Ca} or Mn_{Ca}, pH alone may still be the best soil measurement for obtaining accurate lime predictions over a range of soil types. Response curves for wheat and durum show that its largest yield gains occurred at pH_{Ca} 5.2–5.5, which requires a lower amount of lime (about 1 t/ha, Fig. 5) for wheat at Marrabel site and medium amount of lime (about 1.5 t/ha) at the Marrabel site for wheat and durum. With these soil types, wheat and durum reaches 80–90% of maximum yield at about pH 5.5, and it is unlikely to be economic to attempt to obtain 100% yield by applying additional lime (about 3 t/ha). For barley 90% of maximum yield was reached at pH_{Ca} of 5.3–5.5 with the addition of 2 (Marrabel), 1.5 (South Kapunda) and 4 t/ha (North Kapunda). The cost of raising soil pH to a higher level of pH for greater yields probably is a decision that could be related to the cost of lime in the area. The precise rate of lime requirement to achieve target pH may not be an issue in places where lime application is cheap (such as South Australia), but can be important for places where lime is expensive (such as in Victoria and New South Wales). In South Australia the cost of lime spread and incorporated is about $30/t, and using this value and season 2000 grain and input prices, the optimum gross margin for wheat is at the 1.5–2.0 t lime/ha level. Consideration also has to be given to the rate of acidification occurring on these soils with current cropping practices. There is clear evidence of acidification occurring on cropping soils in the medium rainfall cropping regions, and that this rate is being accelerated with commonly used practices of nitrogen fertiliser input and stubble retention (Xu et al., 2002). As shown in this study there are economic benefits from liming to achieve 90% of a target yield, but also on-going benefits from off-setting acid input associated with soil acidification.

Acknowledgments

We thank the farmers (Geoff Rowett, David Shannon and Mick Ryan) who provided land for undertaking these field experiments. We also thank Mr. Bob Macoun from Omya Southern who supplied the lime for these experiments. This project was supported by a Grain Research and Development Corporation postgraduate grant to Ali Farhoodi.

References

Adams, F., Evans, C.E., 1962. A rapid method for measuring lime requirement of red yellow Podzolic soils. Soil Sci. Soc. Am. Proc. 26, 355–357.

Aitken, R.L., 1992. Relationships between extractable Al, selected soil properties, pH buffer capacity and lime requirement in some acidic Queensland soils. Aust. J. Soil Res. 30, 119–130.

Aitken, R.L., Moody, P.W., McKinley, P.G., 1990. Lime requirement of acidic Queensland soils comparison of laboratory methods for predicting lime requirement. Aust. J. Soil Res. 28, 703–715.
Bailey, J.S., Stevens, R.J., Kilpatrick, D.J., 1989. A rapid method for predicting the lime requirement of acidic temperate soils with widely varying organic matter contents: development of the lime requirement model. J. Soil Sci. 40, 807–820.
Bolan, N.S., Hedley, M.J., 2003. Role of carbon, nitrogen, and sulphur cycles in sil acidification. In: Rengel, Z. (Ed.), Handbook of Soil Acidity. Marcel Dekker, Inc., New York, Basel, pp. 29–56.
Bolland, M.D.A., Siddique, K.H.M., Brennan, R.F., 2000. Grain yield responses of faba bean to applications of fertiliser phosphorus and zinc. Aust. J. Exp. Agric. 40, 849–857.
Carr, S.J., Ritchie, G.S.P., Porter, W.M., 1991. A soil test for aluminium toxicity in acidic subsoils of yellow earths in western Australia. Aust. J. Agric. Res. 42, 875–892.
Coventry, D.R., 1992. Acidification problems of duplex soils used for crop-pasture rotations. Aust. J. Exp. Agric. 32, 901–914.
Cregan, P.D., Hirth, J.R., Conyers, M.K., 1989. Amelioration of soil acidity by liming and other amendments. In: Robson, A.D. (Ed.), Soil Acidity and Plant Growth. Academic Press, Sydney, Australia, pp. 205–264.
Curtin, D., Rostad, H.P.W., Huang, P.M., 1984. Soil acidity in relation to soil properties and lime requirement. Can. J. Soil Sci. 64, 545–554.
Dolling, P.J., Porter, W.M., Robson, A.D., 1991. Effect of soil acidity on barley production in the south-west of western Australia The interaction between lime and nutrient application. Aust. J. Exp. Agric. 31, 803–810.
Dolling, P.J., Porter, W.M., Rowland, I.C., 1994. Acidification rates in the central wheatbelt of western Australia 1. On a deep yellow sand. Aust. J. Exp.Agric. 34, 1165–1172.
Edmeades, D.C., Wheeler, D.M., Waller, J.E., 1985. Comparison of methods for determining lime requirements of New Zealand soils. N.Z. J. Agric. Res. 28, 93–100.
Edmeades, D.C., Ridley, A.M., 2003. Using lime to ameliorate topsoil and subsoil acidity. In: Rengel, Z. (Ed.), Handbook of Soil Acidity. Marcel Dekker, Inc., New York, Basel, pp. 297–336.
Farina, M.P.W., Sumner, M.E., Plank, C.O., Letzsch, W.S., 1980. Exchangeable aluminium and pH as indicators of lime requirement for corn. Soil Sci. Soc. Am. J. 44, 1036–1041.
Fenton, I.G., Helyar, K.R., Abbott, T., Orchard, P., 1996. Soil acidity and liming, Agfact AC, second ed., vol. 19. NSW Agriculture.
Fitzpatrick, R.W., Naidu, R., 1995. Properties, genesis and classification of a 'Sodic' red-brown earth (Calcic natrixeralf) near Kapunda South Australia. In: Naidu , R., Sumner, M.E., Rengasamy, P. (Eds.), Australian Sodic Soils—Distribution, Properties and Management. CSIRO Publications, East Melbourne, Australia.
Gillman, G.P., Sumpter, E.A., 1986. Modification of the compulsive exchange method for measuring exchange characteristics of soils. Aust. J. Soil Res. 24, 61–66.
Godsey, C.B., Pierzynski, G.M., Mengel, D.B., Lamond, R.E., 2007a. Changes in soil pH, organic carbon, and extractable aluminium from crop rotation and tillage. Soil Sci. Soc. Am. J. 71, 1038–1044.
Godsey, C.B., Pierzynski, G.M., Mengel, D.B., Lamond, R.E., 2007b. Evaluation of common lime requirement methods. Soil Sci. Soc. Am. J. 71, 843–850.
Helyar, K.R., Porter, W.M., 1989. Soil acidification, its measurement and the processes involved. In: Robson, A.D. (Ed.), Soil Acidity and Plant Growth. Academic Press, Sydney, Australia, pp. 61–101.
Helyar, K.R., Conyers, M.K., Munns, D.N., 1993. Soil solution aluminium activity related to theoretical Al mineral solubilities in four Australian soils. J. Soil Sci. 44, 317–333.
Hochman, Z., Godyn, D.L., Scott, B.J., 1989. The integration of data on lime use by modelling. In: Robson, A.D. (Ed.), Soil Acidity and Plant Growth. Academic Press, Sydney, Australia, pp. 265–301.
Hochman, Z., Crocker, G.J., Dettman, E.B., 1995. Predicting lime-induced changes in soil pH from exchangeable aluminium, soil pH, total exchangeable cations and organic carbon values measured on unlimed soils. Aust. J. Soil Res. 33, 31–41.
Kamprath, E.J., 1970. Exchangeable aluminium as a criterion for liming leached mineral soils. Soil Sci. Soc. Am. Proc. 34, 252–254.
Kamprath, E.J., Foy, C.D., 1971. Lime-fertiliser-plant interaction in acid soils. In: Olson, R.A. (Ed.), Fertiliser Technology and Use. Soil Science Society of America, Madison, Wisconsin, pp. 105–151.
Liu, D.L., Helyar, K.R., Conyers, M.K., Fisher, R., Poile, G.J., 2004. Response of wheat, triticale and barley to lime application in semi-arid soils. Field Crops Res. 90, 287–301.
Magdoff, F.R., Bartlett, R.J., 1985. Soil pH buffering revisited. Soil Sci. Soc. Am. J. 49, 145–148.
Mehlich, A., 1976. New buffer pH method for the rapid estimation of exchangeable acidity and lime requirement of soils. Commun. Soil Sci. Plant Anal. 7, 637–652.
Merry, R.H., Tiller, K.G., Richards, A.F., 1990. Variability in characteristics of some acidic pasture soils in South Australia and implications for lime application. Aust. J. Soil Res. 28, 27–38.
Noble, A.D., Cannon, M., Muller, D., 1997. Evidence of accelerated soil acidification under stylosanthes-dominated pastures. Aust. J. Soil Res. 35, 1309–1322.
Northcote, K.H., 1979. A Factual Key for the Recognition of Australian Soils, fourth ed. Rellim Technical Publications, Glenside, South Australia.
Northcote, K.H., Hubble, G.D., Isbell, R.F., Thompson, C.H., Bettenay, E., 1975. A Description of Australian Soils. Wilke and Co., Clayton, Victoria.
Rayment, G.E., Higginson, F.R., 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne.
Reuter, D.J., 1992. National Workshop on Subsoil Constraints to Root Growth and High Soil Water and Nutrient Use by Plants, Vol. 1. CSIRO Division of Soils, Adelaide.
Reeve, N.G., Sumner, M.E., 1970. Lime requirements of natal oxisols based on exchangeable aluminium. Soil Sci. Soc. Am. Proc. 34, 595–598.
Richards, A.F., 1992. Improved criteria for predicting and ameliorating soil acidity in the higher rainfall areas of South Australia. Technical Report No. 196. CSIRO and Department of Agriculture South Australia.
Ridley, A.M., Slattery, W.J., Helyar, K.R., Cowling, A., 1990. The importance of the carbon cycle to acidification of a grazed annual pasture. Aust. J. Exp. Agric. 30, 529–537.
Shoemaker, H.E., McLean, E.O., Pratt, P.F., 1961. Buffer methods for determining lime requirement of soils with appreciable amounts of extractable aluminium. Soil Sci. Soc. Am. Proc. 25, 274–277.
Slattery, W.J., Coventry, D.R., 1993. Response of wheat, triticale, barley and canola to lime on four soil types in north-eastern Victoria. Aust. J. Exp. Agric. 33, 609–618.
Slattery, W.J., Morrison, G.R., Coventry, D.R., 1995. Liming effects on soil exchangeable and soil solution cations of four soil types in north-eastern Victoria. Aust. J. Soil Res. 33, 277–295.
Stace, H.C.T., Hubble, G.E., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J., Hallsworth, E.G., 1968. A Handbook of Australian Soils. Rellim Technical Publications, Glenside, South Australia.
Sumner, M.E., 1997. Procedures used for diagnosis and correction of soil acidity: a critical review. In: Moniz, A.C. (Ed.), Plant-Soil Interactions at Low pH (printed in Brazil).
Warman, P.R., Harnish, B., Muizellar, T., 1996. A lime requirement test for maritime Canada, and response time and effect of liming source on soil pH. Commun. Soil Sci. Plant Anal. 27, 1427–1436.
Webber, G.D., Cocks, P.S., Jefferies, B.C., 1976. Farming systems in South Australia. Department of Agriculture and Fisheries, Adelaide, South Australia.
Wilson, A.D., Sergeant, G.A., 1963. The colorimetric determination of aluminium in minerals by pyrocatechol violet. Analyst 88, 109–112.
Woodruff, C.M., 1948. Testing soils for lime requirement by means of a buffered solution and the glass electrode. Soil Sci. 66, 53–63.
Xu, R.K., Coventry, D.R., Farhoodi, A., Schultz, J.E., 2002. Soil acidification as influenced by crop rotations, stubble management and application of nitrogenous fertiliser, Tarlee, South Australia. Aust. J. Soil Res. 40, 483–494.
Yuan, T.L., 1976. Anomaly and modification of pH-acidity relationships in the double buffer method for lime requirement determination. Soil Sci. Soc. Am. J. 40, 800–802.