Future proofing agricultural production through effective management of acidic soils

Dr Jason Condon and Helen Burns
NSW DPI, Wagga Wagga

Key findings

- Surface-applied lime that is only incorporated by the sowing operation has limited effect on increasing pH and decreasing exchangeable aluminium percent below the surface 0–5 cm layer.
- Incorporation of lime aids lime solubility, increasing pH to the depth of mixing.
- Analysed results within 12 months of lime application can be misleading, particularly in dry seasons; they do not capture the full effect of lime rate, incorporation method and reacidification processes.

Introduction

Producer and advisor surveys indicate that current approaches to managing soil acidity are based on research and guidelines from the 1990s that were developed under very different and less productive farming systems. Most fertiliser, lime and crop selection decisions are guided by analyses of soil samples collected at traditional depths of 0–10 cm. Depending on the crop or pasture sequence, the common trigger to apply lime is when soil pH_{Ca} is around 4.5–4.8. It is applied at minimal rates to remove toxic aluminium (target pH_{Ca} 5–5.2).

These traditional approaches and a failure to monitor the effectiveness of acid soil management programs are responsible for widespread, undetected subsurface acidification in marginally acidic soils; even in those soils with a long history of soil testing and lime application (Burns and Norton 2018). Recent studies challenge the short-term focus of current acid soil management programs:

- Li et al. (2019) recommended revising pH targets and re-liming intervals in order to address subsurface acidification, proposing maintenance of soil pH_{Ca} above 5.5 in the 0–10 cm surface layer to gradually increase subsurface pH.
- Condon et al. (2020) highlighted inadequacies of current acid soil management programs and reinforced the need for a shift from mitigating soil acidity to prevention, particularly in zero tillage farming systems.
- Conyers et al. (2020) concluded that ongoing reaction of limestone and reacidification processes influenced soil pH and that 'the slow but measurable improvement in subsurface acidity, and the sustained residual value to grain yield' required a long-term approach to amelioration efforts to manage and prevent subsurface acidification.

This paper reports preliminary soil test results from three large-scale, replicated field experiments established in October 2019 or February 2020. The sites near Lyndhurst, Culcairn and Canowindra were designed to monitor long-term changes in soil chemical properties and:

1. investigate the optimal rate of lime and application methods to prevent subsurface acidification via incorporation or enhanced movement of the lime effect
2. identify the longevity of the effect of lime application and the acidification rate of current farming practices.

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https://www.dpi.nsw.gov.au/agriculture/broadacre-crops/guides/publications/southern-nsw-research-results

Site details

Location	• Site 1: Approximately 5 km south of Lyndhurst, NSW. • Site 2: Morven; approximately 15 km east of Culcairn, NSW. • Site 3: Toogong; approximately 25 km north of Canowindra, NSW.
Soil type	• Site 1: Lyndhurst; Red Chromosol; soil pH_{Ca} range of 3.9–4.1 in subsurface layers (5–15 cm). • Site 2: Morven; Yellow Chromosol; soil pH_{Ca} range of 4.0–4.3 in subsurface layers (5–15 cm). • Site 3: Toogong; Red Kandosol; soil pH_{Ca} 4.8 in subsurface layers (5–15 cm).

The soil pH was severely acidic (pH_{Ca} <4.5) to a depth of 30 cm at Lyndhurst and to 20 cm at Morven. Neither site had a history of lime application, but had been prioritised for lime application. In comparison, the Toogong site had lime applications in 1997 (2 t/ha) and 2005 (2.5 t/ha). Paddock soil tests returned pH_{Ca} of 5.0 from 0–10 cm soil samples and was therefore not considered a high priority for liming based on current acid soil management principles. However, sampling in 5 cm increments indicated stratified soil pH and subsurface acidification: the 0–5 cm pH_{Ca} was 5.1, decreasing to 4.8 in the 5–15 cm subsurface layers, increasing to 5.2 at 15–20 cm and 6.0 in below 20 cm. It is an ideal site to test the effectiveness of early intervention in arresting subsurface acidification over the long term.

Soil sampling	Soil samples were collected 10 to 14 months after lime application for comprehensive chemical analysis. Soil cores were divided into 2.5 cm increments within depths of 0–20 cm and in 5 cm increments from 20–30 cm, to detect change in soil pH and movement of alkali down the soil profile. The effectiveness of each lime treatment is gauged by the increase in soil pH and decrease in exchangeable aluminium percent (Al_{ex}%) compared with the control (nil lime).
Previous crop	• Site 1: Lyndhurst; unimproved naturalised pasture. • Site 2: Morven; degraded phalaris-based pasture. • Site 3: Toogong; grazing wheat (drought affected).
Rainfall (2020)	• Site 1: Lyndhurst; 1030 mm. • Site 2: Morven; 590 mm. • Site 3: Toogong; 730 mm.

Treatments

Large-scale (2 ha), replicated field sites were established in late 2019 and early 2020 to monitor change in soil chemical properties from 0 to 30 cm, under high input, mixed farming systems. A range of lime and incorporation treatments (Table 2) were applied in December 2019 (Morven) and February 2020 (Lyndhurst and Toogong). Lime sourced from NSW crushers, with a neutralising value of 98 and fine particle size (90% passing through a 150 µm sieve) was applied using a direct drop lime spreader. Plot size was either 50 m or 75 m by 9 m wide, with four replicates of seven treatments.

Treatments were designed to answer the following questions raised by local growers and advisors:

- What is the optimal rate of lime and application methods to prevent subsurface acidification?
- Does incorporation increase the rate and depth of pH increase in the soil subsurface?

The lime rate and incorporation treatments applied at each site are described in Table 1 and summarised in Table 2.

Table 1 Incorporation treatments and descriptions.

Treatment ID	Incorporation treatment	Description
1	Control	Nil lime, not incorporated (NI)
2	NI	Maintain pH_{Ca} of the 0–10 cm layer above 5.5, with pH_{Ca} of 5.5 as the trigger to relime.
3	Incorporated (Inc)	
4	NI	Traditional approach – target pH_{Ca} 5.2 in 0–10 cm layer, with trigger to relime when pH_{Ca} decreases to <5.0.
5	Inc	
6	NI	Low initial rate of lime followed by more frequent applications, compared with Treatment 2 and 3; pH_{Ca} of 5.5 in 0–5 cm layer as the trigger to relime. *When lime incorporation is not an option, can subsurface pH be increased by maintaining 0–5 cm pH_{Ca} >5.5?*
7	Inc	Once-in-a-generation treatment. *When incorporation is an option will a high lime rate and one-off incorporation ameliorate and prevent subsurface acidity, while minimising application and incorporation costs, and limiting erosion risk to a single event?* *Does this treatment:* • *ameliorate and prevent subsurface acidification in the long-term; and/or* • *induce nutrient deficiencies?*

Crop and pasture schedule

All sites were sown to crop in 2020 using narrow-point tine seeders.

- Site 1: Lyndhurst; dual-purpose wheat; phalaris/legume pasture in 2021.
- Site 2: Morven; dual-purpose canola; dual-purpose wheat in 2021.
- Site 3: Toogong; dual-purpose canola; perennial pasture 2021.

Table 2 Lime rates and incorporation treatments applied to large-scale field sites at Lyndhurst, Morven, and Toogong.

Treatment ID	Incorporation treatment	Description	Site 1: Lyndhurst Incorporation: Horsch® Tiger	Site 2: Morven Incorporation: disc harrows	Site 3: Toogong Incorporation: disc harrows
			Rate of lime applied (t/ha)		
1	Control	Nil lime, not incorporated (NI)	0	0	0
2	NI	Target 0–10 cm pH_{Ca} >5.5. Trigger for re-liming when pH_{Ca} decreases to 5.5.	5.9	4.0	2.8
3	Incorporated (Inc)				
4	NI	Target 0–10 cm pH_{Ca} > 5.2. Trigger for re-liming when pH_{Ca} decreases ~ 5.0.	4.7	3.0	1.0
5	Inc				
6	NI	Maintain target in 0–5 cm at pH_{Ca} >5.5. Trigger for re-liming: 0–5 cm pH_{Ca} decreases to 5.5.	2.9	2.0	1.4
7	Inc	Once-in-a-generation*	7.0*	6.0*	3.8
Time lag between lime application and soil sampling (months)			11	14	10

* Despite the very high rates of lime applied in Treatment 7 at Lyndhurst and Morven there were no visual symptoms of induced nutrient deficiency; apparent plant vigour in these plots was at least equal to the most vigorous plots.

Lime application dates and incorporation method

Site 1: Lyndhurst; 5 February 2020; incorporation to estimated depth of 20 cm with Horsch® Tiger.

Site 2: Morven; 24–25 October 2019; incorporation to an estimated depth of 10 cm with initial pass with disc harrows in October 2019 (very dry, cloddy) and again in January 2020.

Site 3: Toogong; 6 February 2020; incorporation to about 10 cm with disc harrows.

Seasonal conditions

Exceptionally dry conditions throughout 2019 until late January 2020 (Decile 1) were followed by average to above average rainfall at all sites. This produced ideal conditions for incorporation at Site 1 (Lyndhurst) and Site 3 (Toogong) in February with a single pass. Two passes were required at Site 2 (Morven). Rainfall at Morven was near average from when lime was applied to sampling in December 2020; annual rainfall was approximately 30% above average at Lyndhurst and Toogong.

Results and discussion

Soil test results

Only soil pH and Al_{ex}% results are discussed here. Collecting crop production data is beyond the scope of this project.

Despite significant rainfall at all sites in 2020, a considerable proportion of the applied lime would not have reacted (Conyers et al. 2020). Therefore, the soil test results presented should be used as an early indication of the relative effectiveness of the lime and incorporation treatments. We expect that pH will continue to increase until most of the lime has dissolved. Eventually, ongoing acidification will outstrip the neutralising processes being driven by alkali released from the unreacted lime. When this occurs, the soil will reacidify and pH will decrease.

Site 1: Lyndhurst

Although the Horsch® Tiger disturbed the soil to an estimated depth of 20 cm, lime was only mixed to about 15 cm, as indicated by the depth to which soil pH was increased under all incorporated lime treatments compared with the nil lime treatment (Figure 1 and Table 3).

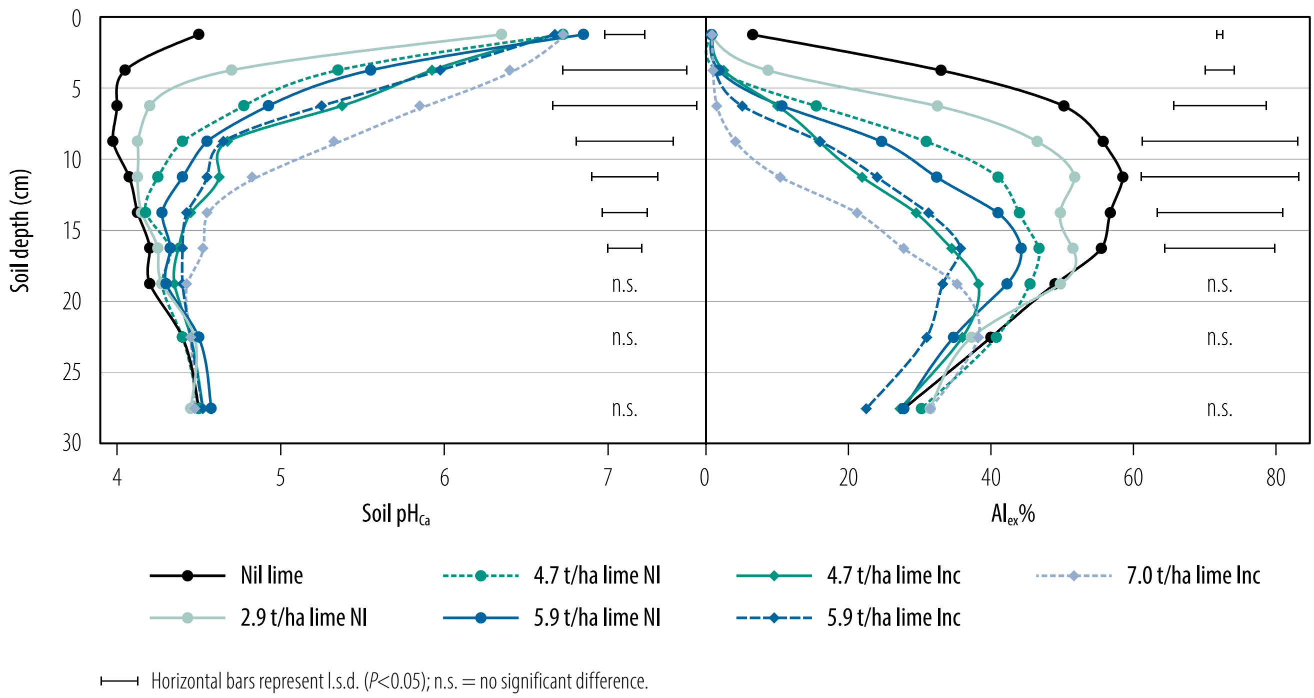


Figure 1 The soil profiles for pH_{Ca} and exchangeable aluminium percent (Al_{ex}%) at Site 1 (Lyndhurst, NSW) showing the effects of lime rates of Nil, 5.9, 4.7, 2.9 or 7 t/ha, with incorporation (Inc) or without incorporation (NI), 11 months after application.

There was a significant increase in soil pH_{Ca} ($P<0.05$) of 0.3, 0.3 and 0.4 pH units down to the 12.5–15.0 cm layer for all incorporated lime rates of 4.7, 5.9 and 7 t/ha, respectively, which targeted 0–10 cm pH_{Ca} >5.2, > 5.5 and ~ 6.2. However, where lime was not incorporated the depth to which pH increased was influenced by lime rate, i.e. pH increase was just significant down to the 7.5–10.0 cm layer for the highest lime rate targeting pH_{Ca} >5.5 (5.9 t/ha NI). For a target pH_{Ca} >5.2 (4.7 t/ha NI) the increase in pH was confined to the surface 0–5 cm. Treatment 6 (2.9 t/ha NI: target pH_{Ca} >5.5 in 0–5 cm), which closely approximates traditional lime rates of 2.5 t/ha, only increased pH significantly in the surface 0–2.5 cm layer.

Figure 1 shows the influence of lime application on the Al_{ex}% profile below the depth of significant change in soil pH. The decrease in Al_{ex}% was significant for all incorporated treatments to a depth of 15.0–17.5 cm. However, only the 'once-in-a-generation' treatment (7 t/ha of lime) increased pH significantly to that depth. This observation indicates that some of the added alkali from lime reacted with Al_{ex} and that alkali is no longer in solution to increase pH. That is, the reaction of Al_{ex} to forms not available to plants buffers the pH change due to lime.

For the unincorporated lime treatments, the higher the lime rate, the deeper the effect on Al_{ex}%, with a significant decrease down to 10.0–12.5 cm for 5.9 t/ha (NI: target pH_{Ca} >5.5), to 7.5–10.0 cm for 4.7 t/ha (NI: target pH_{Ca} >5.2) and to 5.0–7.5 cm for 2.9 t/ha of lime. As was the case for change in soil pH, the magnitude of the lime effect on Al_{ex}% declined with depth for all treatments.

Table 3 Increase in soil pH_{Ca} and decrease in exchangeable aluminium percent (Al_{ex}%) relative to nil lime applied (control treatment), demonstrating response to lime rate and incorporation treatment at Site 1 (Lyndhurst NSW), expressed as deviations from the control.

Depth (cm)[1]	Treatment 2 5.9 t/ha NI		Treatment 3 5.9 t/ha Inc		Treatment 4 4.7 t/ha NI		Treatment 5 4.7 t/ha Inc		Treatment 6 2.9 t/ha NI		Treatment 7 7 t/ha Inc		l.s.d. Δ pH_{Ca}	l.s.d. Δ Al_{ex}%
	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%		
0–2.5	2.4*	5.8*	2.2*	5.6*	2.2*	5.8*	2.2*	5.7*	1.9*	5.8*	2.2*	5.7*	0.24	0.74
2.5–5.0	1.5*	31.2*	1.9*	31.7*	1.3*	31.4*	1.9*	30.5*	0.7	24.3*	2.4*	32.0*	0.76	4.02
5.0–7.5	0.9*	39.6*	1.3*	45.2*	0.8*	34.8*	1.4*	40.2*	0.2	17.8*	1.9*	48.7*	0.88	12.95
7.5–10.0	0.6*	31.1*	0.7*	39.7*	0.4	24.8*	0.7*	39.8*	0.2	9.3	1.4*	51.6*	0.59	21.80
10.0–12.5	0.3	26.1*	0.5*	34.5*	0.2	17.5	0.6*	36.6*	0.1	6.8	0.8*	48.1*	0.40	22.06
12.5–15.0	0.2	15.8	0.3*	25.5*	0.1	12.8	0.3*	27.3*	0.0	7.0	0.4*	35.5*	0.27	17.58
15.0–17.5	0.1	11.3	0.2	19.8*	0.1	8.9	0.2	21.0*	0.1	4.0	0.3*	27.8*	0.21	15.36

[1] Results below the 15–17.5 cm layers are not shown as there was no significant treatment effect on pH or Al_{ex}% below this depth.
* Significantly different ($P<0.05$).

Site 2: Morven

Disc harrows used for incorporation at the Morven site were much less effective in mixing lime to depth than the aggressive mixing of the Horsch® Tiger used at the Lyndhurst site. However, while soil was estimated to have been disturbed to about 10 cm deep, soil tests for Al_{ex}% indicated a significant lime effect in layers from 0 cm to 12.5 cm for all lime treatments (Figure 2 and Table 4).

There was a significant change in pH down the profile to a depth of 10–12.5 cm for all incorporated lime treatments and at the highest rate of unincorporated lime applications (4 t/ha NI: target pH_{Ca} >5.5). Where lime was not incorporated, change in pH relative to the nil lime treatment, indicates that the lime effect is concentrated in the surface 0–2.5 cm (Table 4) with a small change in pH at 2.5–5 cm. There was no significant change in pH below 5 cm at the lower unincorporated lime rates (3 t/ha NI: target pH_{Ca} >5.2; and 2 t/ha NI: target 0–5 cm pH_{Ca} >5.5). In contrast, incorporation appears to have effectively mixed the applied lime to a depth of at least 7.5 cm, with pH increasing by 0.7, 0.7 and 1.2 pH units in the 5–7.5 cm layer for the 3, 4, and 6 t/ha of incorporated lime, respectively, which targeted 0–10 cm pH_{Ca} >5.2, >5.5 and ~ 6.2.

The change in Al_{ex}% mirrored pH change. Lime incorporation produced a greater and more uniform decrease in Al_{ex}% down the profile, particularly in the 2.5–7.5 cm layers. For example, at the same lime rate of 3 t/ha (target pH_{Ca} >5.5) Al_{ex}% decreased significantly by 25.9, 28.7 and 15.8% within the 2.5–5.2, 5.0–7.5 and 7.5–10 cm layers in the incorporated treatment, compared with 21.9, 15.8 and 13.3 for the corresponding depths in the 3 t/ha unincorporated treatment.

Changes in pH and Al_{ex}% for the incorporation treatments was of greater magnitude and more consistent down the profile compared with unincorporated treatments, at the same rates.

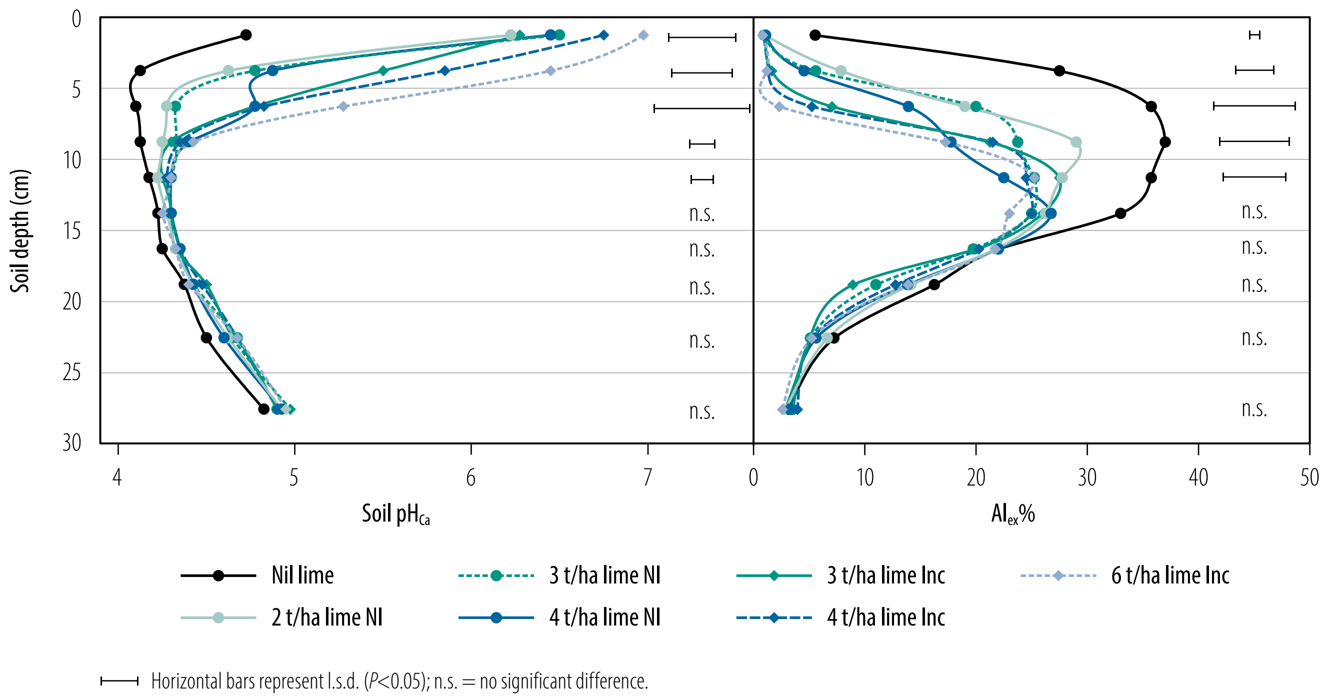


Figure 2 The soil profiles for pH_{Ca} and exchangeable aluminium percent (Al_{ex}%) at Site 2 (Morven NSW) showing the effects of lime rates of Nil, 4.0, 3.0, 2.0 and 6.0 t/ha, with incorporation (Inc) or without incorporation (NI), 10 months after application.

Table 4 Increase in soil pH_{Ca} and decrease in exchangeable aluminium percent (Al_{ex}%) relative to nil lime applied (control treatment), demonstrating the response to lime rate and incorporation at Site 2 (Morven NSW), and expressed as deviations from the control.

Depth (cm)[1]	Treatment 2 4.0 t/ha NI		Treatment 3 4.0 t/ha Inc		Treatment 4 3.0 t/ha NI		Treatment 5 3.0 t/ha Inc		Treatment 6 2.0 t/ha NI		Treatment 7 6.0 t/ha Inc		l.s.d. Δ pH_{Ca}	l.s.d. Δ Al_{ex}%
	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%		
0–2.5	1.7*	4.5*	2.0*	4.6*	1.8*	4.6*	1.6*	4.4*	1.5*	4.5*	2.3*	4.7*	0.38	0.86
2.5–5.0	0.8*	23.0*	1.7*	26.1*	0.7*	21.9*	1.4*	25.9*	0.5*	19.6*	2.3*	26.3*	0.34	3.38
5.0–7.5	0.7*	21.8*	0.7*	30.5*	0.2*	15.8*	0.7*	28.7*	0.2	16.8*	1.2*	33.4*	0.53	7.22
7.5–10.0	0.3*	19.3*	0.2*	15.5*	0.2*	13.3*	0.2*	15.8*	0.1	8.0*	0.3*	19.8*	0.14	6.22
10.0–12.5	0.1*	13.3*	0.1	11.3*	0.1*	10.5*	0.1	8.3*	0.1	8.0*	0.1*	10.5*	0.13	2.77

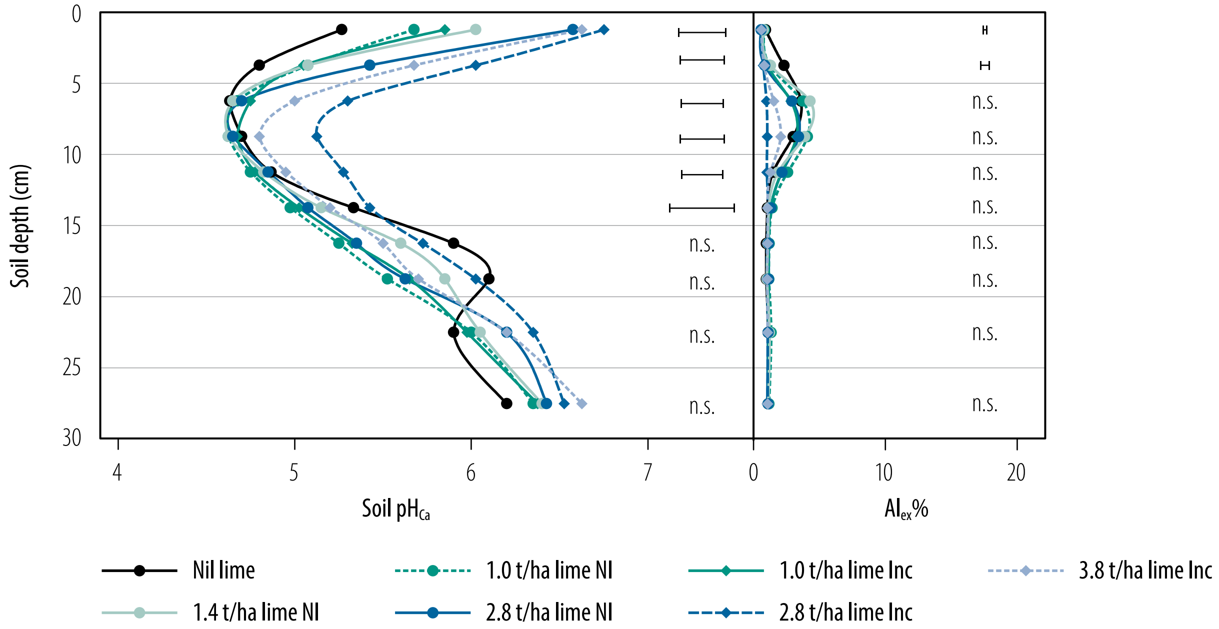
[1] Results below the 10–12.5 cm layers are not shown as there was no significant treatment effect on pH or Al_{ex}% below this depth.
* Significantly different ($P<0.05$).

Site 3: Toogong

The Toogong site is typical of moderately acidic soils that support the highly productive farming systems in the medium to high rainfall zones of central and southern NSW, having no obvious chemical or physical soil constraints affecting productivity. The site was established to monitor the medium- to long-term benefit of early intervention acid soil management programs in preventing subsurface acidification.

There was a small, but significant response to lime rate and incorporation treatments (Figure 3 and Table 5). There was no significant change in pH and Al_{ex}% below 5 cm for unincorporated treatments 2, 4 and 6, or the incorporated treatment 5 (1 t/ha Inc: target pH_{Ca} >5.2). Treatments 3 and 7, which comprised incorporation of lime applied at rates to achieve a target pH_{Ca} >5.5 (2.8 and 3.8 t/ha), produced the greatest change in pH and Al_{ex}% in the layers from 0–7.5 cm. Note that despite being a lower rate of lime, treatment 3 produced significant change in pH and Al_{ex}% further down the profile, to the 10–12.5 cm layer. Analysing soil samples collected in the future will help explain whether this is an anomaly, or whether the high rate of lime applied in treatment 7 elevated pH sufficiently to reduce lime solubility.

The treatment responses at Toogong are not as distinct as at the severely acidic Lyndhurst and Morven sites. This is to be expected as lime solubility is influenced by starting pH, solubility being lower at higher pH, as is the case at the Toogong site. We anticipate that differentiation between treatments will develop over the next 2–10 years.



Horizontal bars represent l.s.d. (P<0.05); n.s. = no significant difference.

Figure 3 The soil profiles for pH_{Ca} and exchangeable aluminium percent (Al_{ex}%) at Site 3 (Toogong NSW) showing the effects of lime rates, with incorporation (Inc) or without incorporation (NI).

Table 5 Change in soil pH_{Ca} and exchangeable aluminium percent (Al_{ex}%) relative to nil lime applied (control treatment), demonstrating response to lime rate and incorporation treatment at Site 3 (Toogong NSW), expressed as deviations from the control.

Depth (cm)[1]	Treatment 2 2.8 t/ha NI		Treatment 3 2.8 t/ha Inc		Treatment 4 1.0 t/ha NI		Treatment 5 1.0 t/ha Inc		Treatment 6 1.4 t/ha NI		Treatment 7 3.8 t/ha Inc		l.s.d. Δ pH_{Ca}	l.s.d. Δ Al_{ex}%
	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%	pH_{Ca}	Al_{ex}%		
0–2.5	1.4*	−0.4*	1.5*	−0.4*	0.5*	−0.2*	0.6*	−0.3*	0.8*	−0.3*	1.4*	−0.4*	0.27	0.14
2.5–5.0	0.6*	−1.5*	1.2*	−1.7*	0.3*	−1.1*	0.3*	−1.3*	0.3*	−1.1*	0.9*	−1.6*	0.27	0.60
5.0–7.5	0.1	−0.7	0.7*	−2.6	0.0	0.2	0.1	−0.7	0.0	0.7	0.4*	−2.2	0.24	n.s.
7.5–10.0	−0.1	0.4	0.4*	−2.0	−0.1	1.1	−0.1	0.3	−0.1	0.9	0.1	−0.9	0.25	n.s.
10.0–12.5	−0.1	0.8	0.4*	−0.4	−0.2	1.2	−0.1	0.8	−0.1	0.5	0.1	−0.1	0.23	n.s.

[1] Results below the 10.0–12.5 cm layers are not shown as there was no significant treatment effect on pH or Al_{ex}% below this depth.

* Significantly different (P<0.05).

Summary

Preliminary soil test results indicate that across all sites and treatments, targeting pH_{Ca} >5.5 results in greater depth of alkali movement (i.e. treatments 2, 3 and 7). When lime was incorporated, the magnitude of pH and Al_{ex}% change was accelerated to the depth of incorporation, or deeper. When lime was not incorporated the depth of lime effect increased with the rate of lime application, but even then, the greatest change in pH and Al_{ex}% was concentrated in the 0–5 cm surface layer.

At the Lyndhurst and Morven sites, treatment 6 unincorporated lime applied at rates of 2.9 and 2.0 t/ha, respectively, approximate traditional practices, i.e. unincorporated lime applied at rates of 2–2.5 t/ha and a 0–10 cm pH_{Ca} target of 5.2. These produced limited change in pH or Al_{ex}% below 2.5 cm.

Initial results indicate that:

- a target pH_{Ca} >5.5 in the 0–10 cm layers is needed to influence subsurface acidity
- incorporation will accelerate the lime reaction and increase the depth of the lime effect.

Average to above average rainfall at all sites following lime application aided lime reaction. The response to lime treatments in marginal years/seasons is yet to be investigated. Further monitoring of these sites is required to assess the role for more frequently applied, lower rates of lime in zero tillage systems, the residual value of lime and potential to prevent subsurface acidification through early intervention on marginally acidic sites.

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Contact

Helen Burns
Wagga Wagga Agricultural Institute, Wagga Wagga
helen.burns@dpi.nsw.gov.au
0427 721 816