Recurring lime applications to fix acidity in the whole soil profile

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Key messages

- Unlimed soil was acidified in the subsurface by almost a pH unit over 23 years. Once-off lime application in 1994 was not sufficient to move any alkalinity from lime to the subsurface soil.
- Soil that was limed three times over the 23-year period had higher soil pH throughout the top 30 cm. These soils had a soil pH higher than 5.5 in the top 10 cm, thus allowed movement of alkalinity to the subsurface soil.
- A large proportion of applied lime was stratified in the top few centimetres of the soil especially where lime was recently applied at higher rates (e.g., South Burracoppin site) and it is possible to improve soil pH of the whole profile through incorporation.
- The long-term benefit of surface liming to boost the grain yield was clear, however, deep re-incorporation of undissolved *in situ* lime (without any new application) was able to increase grain yield further within a cropping season.

Aims

Soil acidity (low soil pH) is a widespread problem in Western Australia (WA) (Gazey et al., 2013). At low soil pH the increase in the concentration of toxic forms of aluminium (Al) significantly limits root growth and crop yield (Kopittke et al., 2015). Agricultural lime is usually applied to the surface of the soil to manage acidic soils. Li et al. (2019) found that surface application of superfine (≤250 µm) agricultural limestone with 98% neutralising value at high rates and multiple supplementary maintenance applications took almost two decades to increase subsurface soil pH and decrease exchangeable Al. However, the improvement in subsurface acidity was not up to the target pH_{Ca} of 4.8. Hence the changes in the subsurface soil pH did not equate to the large amount of lime used by Li et al (2019). What fraction of applied lime remained undissolved and how it stratified in the soil profile are yet to be quantified. There are not very many studies on the repeated applications of lime to manage acidity in whole soil profile for the long-term (e.g. 20 years after lime application)—this is particularly the case for WA lime which is coarser (0-1000 µm) than that available in the eastern states (0-250 µm).

The aim of this study was to estimate the long-term effect of recurring lime applications on subsurface soil acidity, to estimate the amount of undissolved lime at increments of 2 cm soil depth and to measure the potential use of undissolved lime to improve subsurface soil pH through incorporation at different equivalent depths. The study consisted of both laboratory and field based experimentation using several long-term soil acidity management trials conducted by the Department of Primary Industries and Regional Development.

Method

Department of Primary Industries and Regional Development has conducted several long-term soil acidity management trials where a wide range of lime rates (0-8.5 t/ha) were applied. Using four long-term lime trials, we estimated the long-term effect of recurring lime applications on improvement of subsurface soil acidity. In a laboratory experiment, we estimated the amount of undissolved lime at increments of 2 cm soil depth and measured the potential use of undissolved lime to improve subsurface soil pH through incorporation at different equivalent depths. We also measured grain yield responses in one of the field trials where residual lime was incorporated using a rotary spader at three different depths.

Laboratory experiment

Soils were collected in autumn 2018 from the unlimed plots and limed plots that had received the highest rate of lime from the following four lime trials: (i) Wongan Hills (established 1994), (ii) Merredin (established 2008), (iii) South Burracoppin (established 2008) and (iv) Northam (established 2012). Sites (i) and (iv) are located in the medium rainfall zone and in both sites acidic soils were found only within 0-40 cm soil depth. Whereas sites (ii) and (iii) are in low rainfall region and both soil profiles were acidic throughout the depths. All sites had a loamy sand textural class. More detail description of soil types, cropping history and long-term annual rainfall of the cropping districts are represented in Table 1.

Bulk soil samples were collected from 0–2, 2–4, 4–6, 6–8, 8–10, 10–15, 15–20 and 20–30 cm depths. These samples were used to measure pH and total Al in 0.01 M $CaCl_2$ extract. Soil samples from lime treated plots were used to measure the amount of undissolved CO_3 using the pressure calcimeter principle (Horváth et al. 2005). Surface limed soil (0-4 cm) from each trial with the highest amount of CO_3 was then incorporated with the acidic subsurface soil (20-30 cm) at seven topsoil:subsoil ratios, i.e., 1:0, 1:1, 1:3, 1:4, 1:5.67, 1:9, and 1:19 to represent seven different incorporation depths, i.e., 4, 8, 16, 20, 27, 40 and 80 cm. Soils were wetted in petri dishes at field capacity (16 cm^3 per cm^3 moisture content) and incubated at 25°C for six weeks before reanalysing pH and Al.

Field trial at Wongan Hills

Incorporation of residual lime in the field was conducted in the Wongan Hills trial. Five lime (neutralising value of 90.0%, 99.0% particles <0.6mm) rates (0, 0.5, 1, 2 and 4 t/ha) were applied in 1994 , in a randomised design with four replications (paired plots of 1.8 m by 30 m). This soil profile was originally acidic to a depth of 0-30 cm when the trial was established in 1994 (initial pH_{Ca} of 0-10cm = 5.0 and 10-30cm = 4.2; Al_{Ca} of 0-10cm = <1.0 mg/kg and 10-30cm = 7 mg/kg). One of each pair of plots was re-limed in 1998 at 1.5 t/ha<<cite NV and fineness, in parathenses>>,, changing the design to a split plot design with four replications (single plots of 1.8 m by 30 m). In 2014 an additional 3 t/ha of lime <<cite NV and fineness, in parathenses>>, was applied to half of the area of each plot, changing the design to a split-split plot design with 4 replications (plots of 1.8 m by 15 m). In 2018 the plots were split into three incorporation treatments of 0, 15 or 25 cm depths, changing the design to split-split-split plot design with four replications (plots of 1.8 m by 5 m). A rotary hoe was used to apply the incorporation treatments at 15 and 25 cm. Measurements were not taken from every plot in 2018. The treatments that were measured were 0, 2 or 4 t/ha lime in 1994, an additional 0 or 1.5 t/ha of lime in 1998, and an additional 0 or 3 t/ha of lime in 2014 (i.e. total lime rates from 1994 to 2018 of 0, 1.5, 2, 3.5, 4, 4.5, 5.5, 6.5, 8.5 t/ha), across each of the three tillage depths carried out in 2018.

Table 1: Characteristics of the four selected trial sites in the eastern wheatbelt of Western Australia and the historic lime treatments selected for tillage treatments in 2018. Nil limed plots in every trial site were also included in the experiment.

Parameters	**Wongan Hills**	**Merredin**	**Burracoppin South**	**Northam**
Annual rainfall (mm)	381 ± 113	319 ± 79	344 ± 57	395 ± 96
Soil type	Tenosol, loamy sand, deep (>60 cm)	Tenosol, loamy sand, deep (>60 cm)	Tenosol, loamy sand, deep (>60 cm)	Tenosol, loamy sand, deep (>60 cm)
Surface lime application (years and rates) of historic treatments.	1994 = 4 t/ha 1998 = 1.5 t/ha 2014 = 3 t/ha *Total = 8.5 t/ha*	2008 = 3 t/ha 2014 = 3 t/ha *Total = 6 t/ha*	2008 = 2 t/ha 2016 = 5 t/ha *Total = 7 t/ha*	2012 = 5 t/ha *Total = 5 t/ha*
Cropping history	Continuous cropping (cereal, lupin (early years of trial) and canola)	Continuous cropping (cereal and canola)	Continuous cropping (cereal and canola)	Continuous cropping (cereal and canola)

Soil samples were collected in autumn 2018 (before tillage treatments were applied and the wheat crop was sown) from 0-10, 10-20, 20-30 and 30-40 cm depths. Changes in soil pH and Al were measured using 1:5 calcium chloride extract (0.01 M). The trial was sown to Mace wheat on 28 May 2018 using 60 kg/ha seed rate. Plant emergence was counted and grain yields were measured using small plot harvester.

An ANOVA was used to analyse the data, with 1994 lime as the main plot effect, three combinations of lime 1998 and 2014 (0 and 0 t/ha, 0 and 1.5 t/ha, 1.5 and 3 t/ha lime) as the sub-plot effect (to make a balanced design of the lime treatments of interest in 2018) and tillage as the sub-sub-plot effect. Each level was compared using Fisher's least significant difference (LSD) test at the 5% level of significance. In order to cater for the random effects of repeated liming programs and also the farmers' machinery-based activities, a linear mixed model, using the GenStat restricted maximum likelihood (REML) algorithm directive, was applied. Yield data have been presented as both predicted and actual grain yields.

Results

Laboratory experiment

The pH samples from the field showed that lime treated plots in all four long-term trials had significantly higher pH_{Ca} than their respective untreated plots in both top- and subsurface soil (Fig. 1). For all limed soils, the highest soil pH_{Ca} was recorded in top 4 cm of soil suggesting most of the applied lime has been stratified in this top few centimetre of surface soil. However, 4-10 cm soil pH_{Ca} was also around 5.5 or higher which probably allowed some movement of alkalinity into the subsurface soil. Topsoil from the control plots in Wongan Hills had relatively higher soil pH because the contracted grower had applied 1 t/ha of dolomite in 2016 over the whole site (Fig. 1a). A similar result was found for the control topsoil from South Burracoppin due to shallow incorporation of 2 t/ha lime before DPIRD conducted this trial (Fig. 1c).

The magnitude of the differences in subsurface soil pH between limed and unlimed soils, however, varied between trial sites. Wongan Hills trial, being the oldest with a total of 8.5 t/ha lime applied (over three applications), had consistently larger improvement in subsurface soil pH_{Ca} (Fig. 1a). A similar result was found in Northam trial where a once off 5 t/ha lime treatment was applied (Fig. 1d). In the Merredin trial (Fig. 1b) trial, subsurface soil pH_{Ca} below 20 cm depth was just slightly higher that the control plots. However, in the South Burracoppin trial (Fig. 1c), subsurface soil pH_{Ca} below 20 cm depth was not significantly different from the control plots despite having at least 5.5 topsoil pH_{Ca}.

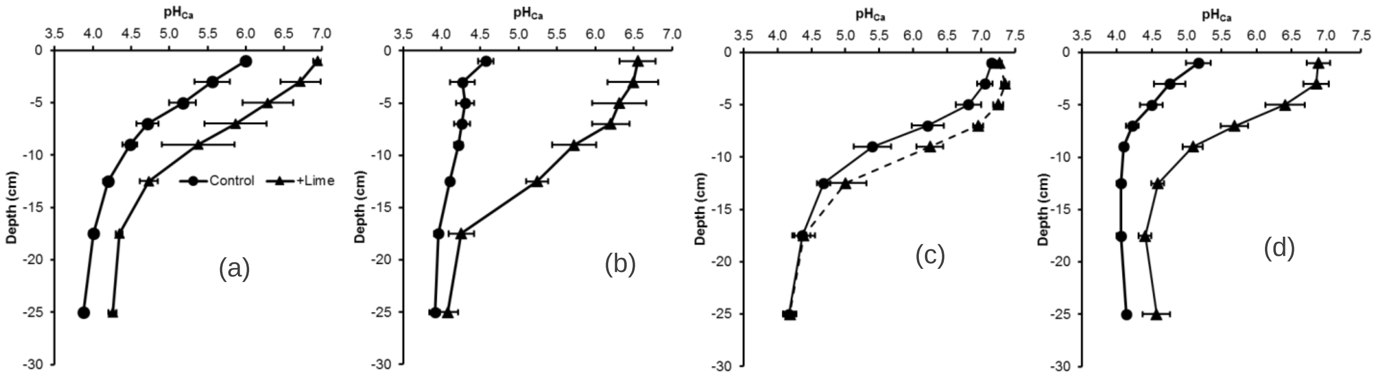

Figure 1: Soil pH profiles measured in 2 cm (in top 10 cm soil) and 5 cm (below 10 cm) incremental depths during autumn 2018 for (a) Wongan Hills, (b) Merredin, (c) Northam and (d) South Burracoppin trials. Line graphs with circles represent soils from control plots while with triangles represent limed plots. Horizontal bars represent ± standard error of the mean soil pH_{Ca}.

The measurements of undissolved $CaCO_3$ indicated that a large proportion of the surface-applied lime remained undissolved in the top 4 cm of the soil profile (data not presented). Data from the incubation experiment showed increased pH_{Ca} to at least the target of 4.8 for 20-80 cm equivalent depth (Fig. 2a) with incorporation of this top 4 cm soil. Again the improvement in soil pH_{Ca} depended on the total amount of lime applied and the time elapsed after the last application of lime. Northam and South Burracoppin were re-limed recently with high rates and had the highest amount of undissolved lime in the surface soil. Incorporation of this soil with acidic subsurface soil also improved acidity of the whole soil profile (equivalent incorporation depth of up to 80 cm). Such incorporation also rectified Al toxicity in whole soil profile except for Merredin (Figure 2b).

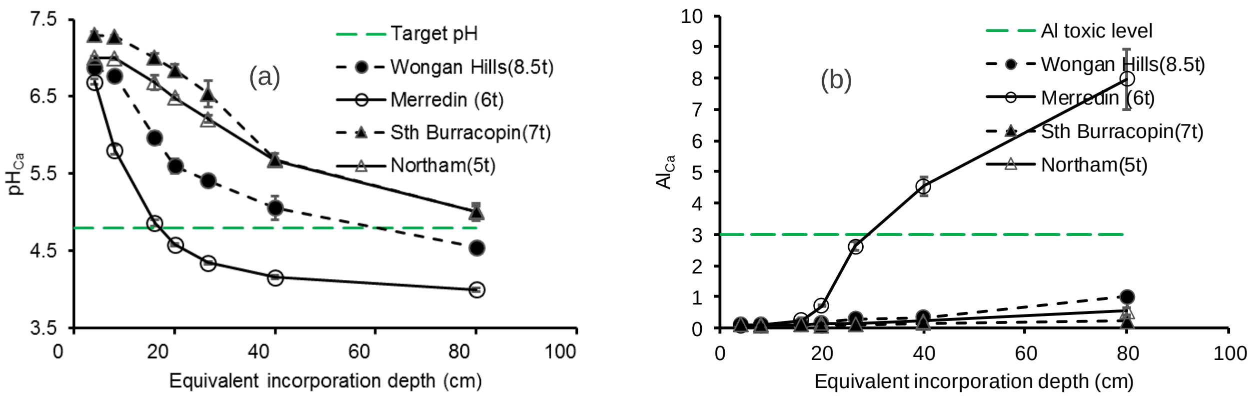

Figure 2: Measured changes in soil (a) pH_{Ca} and (b) total aluminium concentration following incorporation in a petri dish of 4 cm top soil (with residual lime) to the different equivalent depths (4-80 cm) of acidic subsurface soils and incubation for six weeks. Vertical bars represent ± standard error of the mean soil pH_{Ca} and total aluminium.

Wongan Hill Field trial

The 2018 measurements from the Wongan Hills trial showed that soil pH_{Ca} (0–10 cm) was significantly higher than the untreated control following a single lime application in 1994 of either 2 or 4 t/ha (Fig. 3a). The nil lime and 2 t/ha lime application treatments was significantly more acidic deeper in the profile, especially in 30-40 cm depth, by nearly 1 pH unit than the original pH profile measured in 1994 (baseline pH). The 4 t/ha treatment in 1994 had higher pH at 30–40 cm than either the nil or 2 t/ha treatment, but no such difference was observed at 10–20 cm and 20–30 cm soil depths.

Re-liming half the plots with 1.5 t/ha lime in 1998 increased topsoil pH_{Ca} compared to the original levels (Fig. 3b). This re-liming, in addition to the previously applied 2 t/ha, did not increase the soil pH_{Ca} of 20-30 and 30-40 cm soil above the original 1994 level nor the nil lime treatment. However, addition of 1.5 t/ha of lime with previously applied 4 t/ha in 1994 resulted in higher pH_{Ca} throughout the profile (Fig. 3b) compared with the nil limed treatment (Fig. 3a).

A second re-liming of 3 t/ha in 2014 resulted in significantly higher pH_{Ca} in 0-10 and 10-20 cm depths in 2018 for all treatments, including the nil lime, compared with the original pH in 1994 (Figure 3c). Plots receiving the highest cumulative lime rate (8.5 t/ha) had the highest soil pH_{Ca} at all depths.

The measurements of total Al show that liming had a stronger effect in decreasing total Al than on increasing soil pH_{Ca} (Fig. 4). A single lime application in 1994 of 2 or 4 t/ha significantly decreased concentration of total Al at all depths (Fig. 4a). Such difference was not observed in soil pH_{Ca} (Fig. 3a) because pH is measured in a logarithmic scale. Application of additional 1.5 t lime with previously applied 2 or 4 t/ha had significantly lower total Al than the plots that were not limed in 1994 (Fig. 4b). Total Al concentration decreased further with the second re-liming at 3 t/ha in 2014 (Fig. 4c). All experimental plots (including zero limed plots in 1994) that received two additional applications (in 1998 and 2014, Fig. 4c) had significantly lower total Al at all depths compared to the untreated control (Fig. 4a).

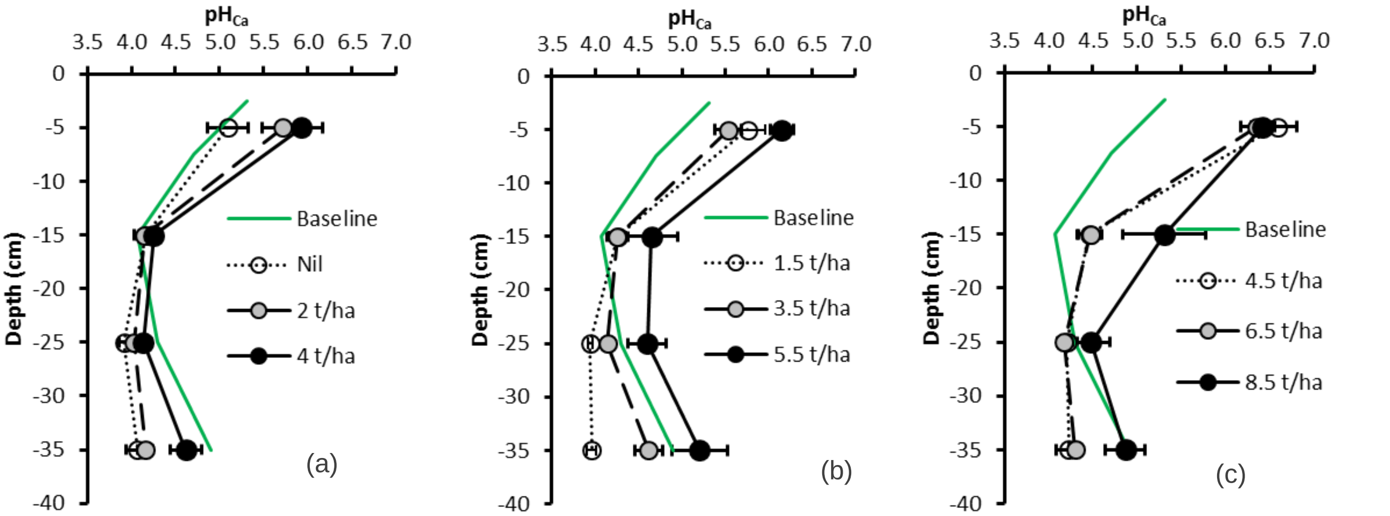

Figure 3: Soil pH profiles measured in autumn 2018 for (a) three original lime treatments applied in 1994, (b) re-limed with an additional 1.5 t in 1998, and (c) re-limed with 3 t in 2014. Green solid lines represent baseline soil pH_{Ca} profile measured in 1994 before the application of lime treatments. Horizontal bars represent ± standard error of the mean soil pH_{Ca}.

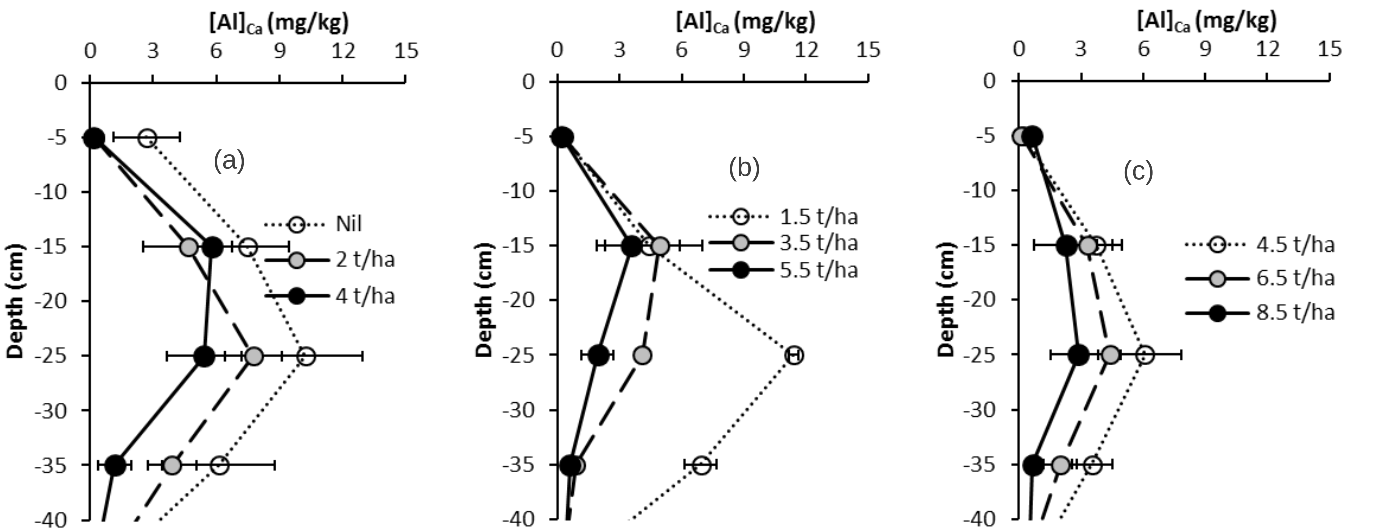

Figure 4: Soil Al profiles measured in autumn 2018 for (a) three original lime treatments applied in 1994, (b) re-limed with an additional 1.5 t/ha in 1998, and (c) re-limed with 3 t/ha in 2014. Horizontal bars represent ± standard error of the mean total Al.

Grain yield

The original lime rates in 1994 x tillage treatments in 2018 significantly increased wheat grain yield (Table 2). Plots that were limed in 1994 at 2 or 4 t/ha and were spaded at 25 cm depth had an extra yield of up to 0.9 t/ha (31% yield advantage) over the plots that had never been limed and not been spaded in 2018. Shallow incorporation (15 cm) had some negative effect on grain yield compared to the no incorporation or deep incorporation (25 cm). The interaction of re-liming in 2014 and tillage treatments in 2018 also had a positive effect on grain yield. No such effect on grain yield was observed for 1998 re-liming.

Table 2: Effect of original lime rates and incorporation depths on the wheat grain yield in 2018. The yield predicted from REML mode is shown first, with the measured mean grain yield data in parentheses.

1994 lime rates (t/ha)	No incorporation	Spading (15 cm)	Spading (25 cm)
0	2.86 (2.82)	2.76 (2.70)	2.96 (3.06)
2	3.49 (3.19)	3.36 (3.16)	3.51 (3.33)
4	3.62 (3.20)	3.48 (3.07)	3.75 (3.29)
LSD(5%) = 0.50			

Conclusion

Soil pH profile data from the Wongan Hills field trial showed that overall lime treated plots had higher soil pH and lower total aluminium concentration than the untreated soils. In untreated soil, pH decreased further from the baseline pH measured at the onset of the trial, in line with results of Li et al. (2019). Two lime rates applied in 1994 were able to increase surface soil pH and protect subsurface soils from further acidification. This once-off lime application was not sufficient to maintain top soil pH high enough to move any alkalinity in the subsurface soil. Plots that received recurrent applications of lime increased soil pH throughout the top 30 cm over the 23-year period. These plots with higher rates consistently had a soil pH higher than 5.5 in 0-10 cm depth that allowed movement of alkalinity from lime to the subsurface. Total Al concentration was negligible in top 10 cm soil with one application of lime in 1994. Subsurface total Al also decreased over time to very low levels (< 5 mg/kg).

It is clear from the laboratory experiment that a large proportion of applied lime was stratified in top few centimetres of the soil reinforcing the results of Whitten (2000). Soil recently limed at higher rates (e.g., South Burracopin site) has the potential to improve soil pH of up to 80 cm depth if they can be incorporated.

The long-term liming benefit to increase the grain yield was evident from the Wongan Hills field trial. However, re-incorporation of undissolved lime in the top soil to 25 cm depth was able to increase grain yield further from no incorporation within a cropping season. Incorporation of lime can rapidly increase soil pH and decrease Al concentration to the depth of incorporation (Azam et al. 2019). This also can improve availability and uptake of nutrients (Scanlan et al., 2017). Liming also decreased weed growth and density that reduced the competition for water and nutrient (Borger et al., 2019). We recommend that soil should be limed routinely to maintain soil pH profile and grain yield. Lime rates should be sufficient to maintain 0-10 cm soil pH ≥5.5 allowing movement of alkalinity to the subsurface soils.

Key words

Residual lime, Spading, Lime incorporation, grain yield, aluminium toxicity, subsoil acidity

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