Combined application of lime and gypsum boosts grain yield in acidic soil

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Key messages

- Liming, with or without incorporation, significantly increased wheat grain yield from the first year of the trial. This is due to the increase in soil pH and hence a decrease in aluminium (Al) toxicity. Higher soil pH, due to liming, improved uptake of major macronutrients but decreased Zn and Mn.
- Gypsum also improved grain yield; but not by improving soil pH or reducing total Al concentration. Gypsum greatly increased the ionic strength of soil throughout the profile which might have reduced the relative activity of Al. Gypsum provided an extra amount of S and Ca as well as improved uptake of B, Mn, and Zn by wheat.
- The application of lime and gypsum together had a greater synergistic effect to improve grain yield than the application of either individually. This can be explained because lime increased soil pH and hence decreased total amount of Al in soil solution. Gypsum likely altered toxic Al into non-toxic forms and leached deeper in the soil. Combined application of lime and gypsum also had a synergistic effect, improving the uptake of most macronutrients.

Aims

Subsurface soil acidity (low pH) is a widespread phenomenon in the Mediterranean climatic region of south Western Australia (Gazey et al., 2014). At low soil pH the toxic forms of aluminium (Al) increase and significantly limit root growth and crop yield (Kopittke et al., 2015). Incorporation of agricultural lime to an acidic soil can increase soil pH which reduces the level of the toxic forms of Al. However, lime is usually applied at the surface soil and it can take several years to increase subsurface soil pH (Li et al., 2019).

Previous work suggests that physical incorporation of lime in the subsurface soil increases the rate of change of subsurface soil pH (Scanlan et al., 2017). However, physical incorporation using tillage equipment makes the liming process expensive for many growers. Another suggested method for quick amelioration of acidic subsoil is the application of gypsum on the soil surface. Surface applied gypsum rapidly moves into the subsoil and may reduce toxic forms of Al, as well as supplying additional calcium (Ca) and sulphur (S) where it is deficient (Sumner et al.,1986). The addition of extra Ca may play a role in reducing Al activity by increasing electrical conductivity (EC) and ionic strength (I_s) of the soils (McLay et al., 1994b; Rengel, 1992). McLay et al. (1994a) reported an initial, large increase in wheat grain yield, due to gypsum application, in the eastern wheatbelt of Western Australia (WA). However, there was a negative effect of gypsum on grain yield after the second year of the trial. Treatment with gypsum alone produced inconsistent results in improving crop yield in acidic soil (Smith et al., 1994). Therefore, there is confusion amongst growers in adopting gypsum application as part of management strategies for acidic soils. There is also a large gap in understanding the underlying mechanism of how gypsum improves soil pH, reduces aluminium toxicity or brings other beneficial chemical changes in soils (Zoca and Penn, 2017).

We conducted a field experiment to evaluate the interactive effect of lime and gypsum application on subsoil acidity, Al toxicity and grain yield in the low rainfall region of WA. We also tested whether ameliorants are more effective when they are incorporated using traditional tillage equipment compared to surface application.

Method

Trial description

This is an on-going field trial established in a continuously cropped paddock of Bob and Amanda Nixon in Kalannie, Western Australia (35°42’S, 117°29’E). Soil in the paddock is classified as a yellow-orthic acidic tenosol in the Australian Soil Classification. Soil in this region, known as Wodjil soil, was naturally acidic before being cleared for use in agriculture. Both surface and subsurface soils were strongly acidic and, particularly the subsoil, extremely aluminium toxic. The soil had low levels of organic carbon. N, P and K contents were in average level in the topsoil, however, subsoil had very limited level of Colwell P which also had very very low phosphorus buffering index (Table 1).

The trial was established in March 2017. At the beginning, the whole site was ripped to 500 mm depth, to remove soil compaction as a covariate. The trial plots were set at 15° angle to the ripping line. The trial consisted of small plots of 1.8 x 20 m. The trial had a complete factorial design replicated three times. There were three factors: tillage, lime rate and gypsum rate. Four lime rates were used: 0(L0), 2(L1), 4(L2) and 6(L3) t/ha lime (neutralising value of 91.9%, 99.2% particles < 0.5 mm). Four gypsum rates were also used: 0(G0), 1(G1), 2(G2), 3(G3) t/ha (gypsum purity 96%). Lime and gypsum were applied on the surface of the soil before tillage treatments were applied as blocks. The two tillage treatments were (i) no cultivation and (ii) deep incorporation of lime and gypsum using DPIRD's one-way plough (200 mm depth).

The trial was sown to Mace wheat in both 2017 and 2018. In both seasons the seeding rate was 60 kg/ha and the crops were sown on 23 May in 2017 and 4 June in 2018. In both season 30 kg/ha of N (using urea and MAP) was applied. The annual fertiliser program also included 8 k/ha of P applied using MAP. N and P fertiliser rates were given as non-limiting rates (in an extremely acidic soils) to potentially produce a 2 t/ha wheat grains. We also applied 45 kg/ha K and 18.5 kg/ha S in the first year (2017) to replace the potential uptake of these nutrients from the soil bank for the duration of the trial (4-5 years). The pre-sowing herbicide program consisted of Triflur 2 L/ha, Sprayseed 250 2 L/ha, Sakura 118 g/ha. Velocity (670 ml/ha) and MSO (1%) were applied on 11 July 2018.

Table 1. Properties of surface- and subsurface soil used in the experiments

Parameters	Surface soil	Subsurface soil
Sampling depth (cm)	0-10	20-40
Texture	Sandy loam	Sandy loam
Bulk density (g/cm^3)	1.34	1.52
pH_{Ca}	4.35	3.95
Al_{Ca} ($mg\ kg^{-1}$)	2.47	22.2
Total N ($mg\ kg^{-1}$)	19	9
Colwell P ($mg\ kg^{-1}$)	31.3	4.33
PBI	24.2	63.1
Colwell K ($mg\ kg^{-1}$)	53.3	32.3
OC (%)	0.85	0.32
S ($mg\ kg^{-1}$)	7.4	28.6
CEC (meq 100 g^{-1})	1.51	1.09

Data collection

Soil profile moisture contents were repeatedly measured during two growing seasons using PVC access tubes with the help of Diviner 2000. Moisture measurements were taken only from the following selected treatments in both cultivation and no-cultivation blocks: (i) control (no lime or gypsum), (ii) 4 t/ha lime, (iii) 2 t/ha gypsum and (iv) 4 t/ha lime plus 2 t/ha gypsum. NDVI data were collected at the tillering stage in both growing seasons. In spring 2017, only topsoil (0-10 cm) samples were collected for chemical analysis. Plant samples (Z65) were collected for measuring nutrient uptakes in 2018, but not in 2017 due to large variations in flowing time between tillage treatments. In spring 2018, soil profile samples were collected at 0-5, 5-10, 10-15, 15-20, 20-30 and 30-40 cm depths from each plot. A separate set of topsoil (0-10 cm) samples were also collected for chemical analysis. Wheat crops were harvested using both hand-cuts as well as plot harvester for measuring number of tillers, biomass and grain yield. Post-harvest grain quality parameters (e.g. thousand grain weight, hector litre weight, % flour production, % protein) were determined for 2017 harvest.

Data analyses

A linear model was fitted to each of the measurements using the ANOVA procedure in GenStat (Version 18.1, VSN International, Oxford, UK) to compare the factorial treatments of lime by gypsum by tillage with polynomial contrasts. For non-normal data, a log-transformation (log_{10}) was performed to stabilise the variance, data are presented as back-transformed means. Fisher's protected least significant difference (LSD) was applied at the 0.10 significance level.

Results

Rainfall in 2017 and 2018

The two growing seasons were contrasting in terms of rainfall for sowing and finishing the crop (Fig. 1a). Season 2017 had a dry start but finished with average rainfall for the district. In contrast, 2018 started with greater than average rainfall but received well below average rainfall in the month of September. In 2017, the growing months (May-September) received only 124 mm rainfall compared to 187 mm for the same months in 2018. There were only two days with negative air temperature in both years and these were not low enough to cause crop damage (Fig. 2b).

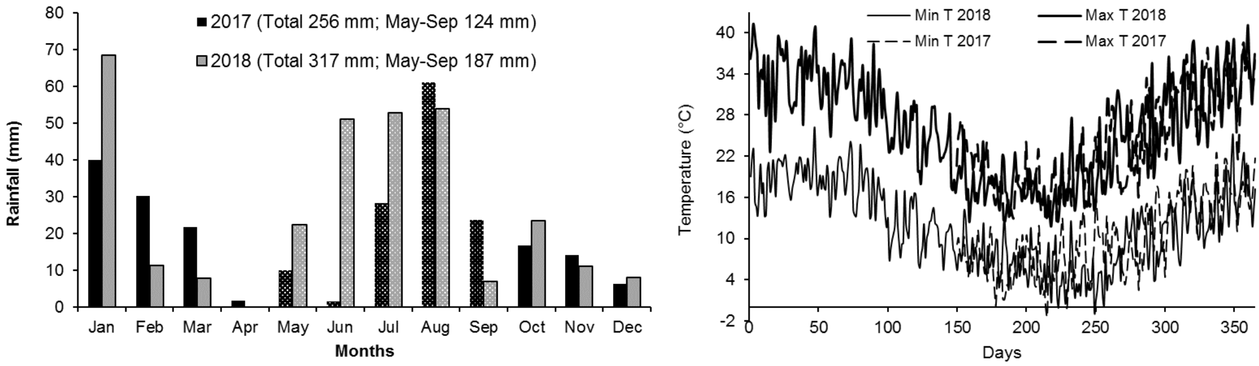

Figure 1: (a) Monthly total rainfall, and (b) daily minimum and maximum temperatures at the trial site during 2017 and 2018.

Grain yield

There was a large difference between the overall trial wheat yield for 2017 (0.95 t/ha) and 2018 (1.85 t/ha) primarily due the differences in rainfall during crop growing months. An extra 64 mm rainfall in 2018 produced an extra 0.9 t/ha wheat crop compared to 2017 season.

protein compared to 10.9% in non-incorporated plots.

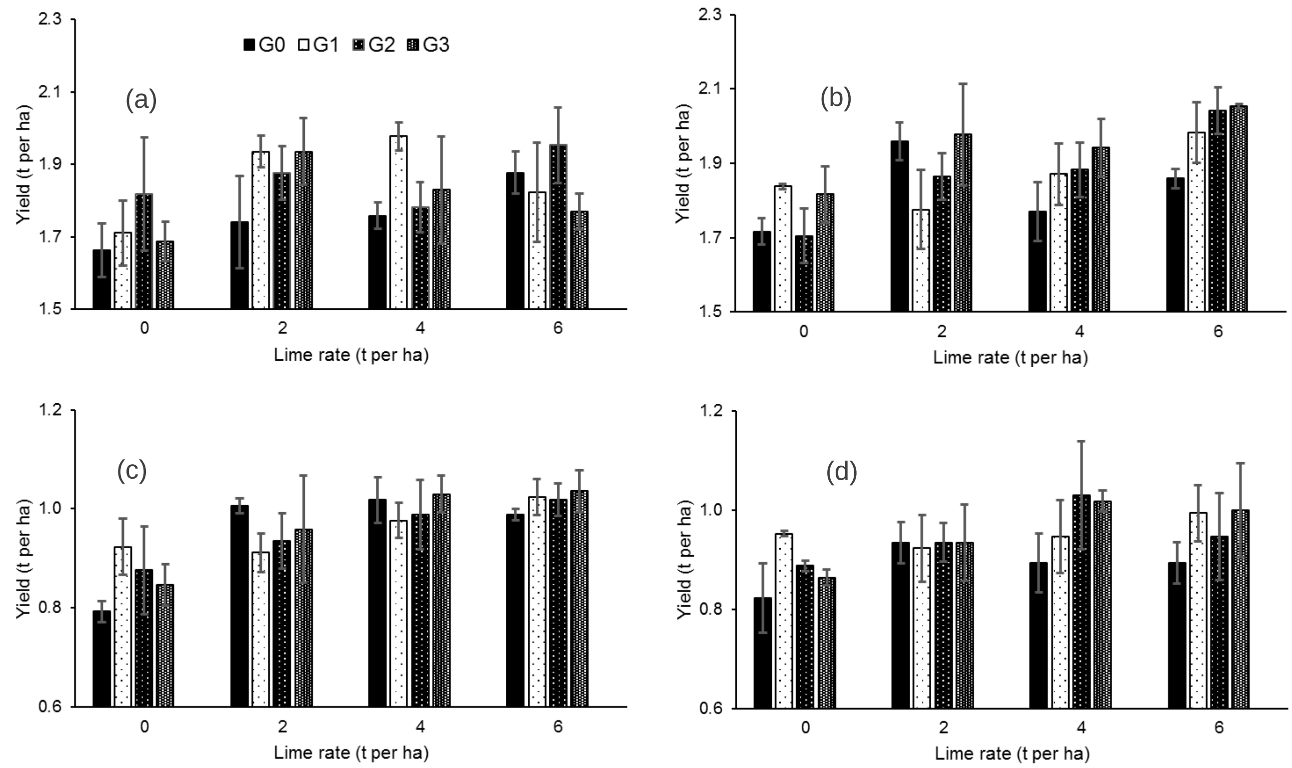

Figure 2: Improvement in wheat grain yield in 2017 (c and d) and 2018 (a and b) due to interactive application of lime and gypsum under no incorporation (a and c) and incorporation (b and d) treatments. Vertical bars represent ± standard error of the mean wheat yield. Scales on Y-axes are different due to varying responses from crop in two different seasons. Trend lines show the mean grain yield across the lime rates.

The interaction of tillage x lime rate x gypsum rate was not significant in either growing season (Fig. 2). The interaction of lime rate x gypsum rate was significant in 2017 ($P=0.040$) with a polynomial contrast, but it was not significant in season 2018. The main effect of tillage was significant in 2017 ($P=0.078$), but not significant in season 2018. The main effect of lime was significant in both 2017 ($P \leq 0.001$) and 2018 ($P \leq 0.001$). The grain yield increase in response to lime rate was significant in 2017 but not in 2018. The main effect of gypsum was also significant in both 2017 ($P=0.087$) and 2018 ($P=0.054$). However, yield responses to gypsum rate were not significant in either season as 1 t/ha gypsum was optimal for the wheat grain yield.

Overall there was a 13% increase in wheat grain yield from lime treated plots over the control (ripping only) in 2017 (Fig. 2c and 2d). Gypsum did not increase crop yield as much (average 5% increase in yield). In general, combined application of lime and gypsum increased yield more than either ameliorant alone. For example, application of 6 t/ha of lime with 3 t/ha of gypsum without incorporation produced 30% more grain (1.04 t/ha) than the control (0.79 t/ha). Whereas 6 t/ha lime alone increased yield to 0.99 t/ha and 3 t/ha gypsum increased yield to 0.85 t/ha.

Similarly to 2017, there was an average 12% increase in wheat grain yield from lime treated plots over the control (ripping only) in 2018 (Fig. 2a and 2b). Overall application of gypsum had an 11% yield benefit over the control. As with 2017, the combined application of lime and gypsum increased yield by more than the application of lime or gypsum individually. Incorporation of 6 t/ha lime plus 3 t/ha gypsum produced 23% more grain (2.05 t/ha) than the control (1.66 t/ha). Whereas 6 t/ha lime alone increased yield to 1.86 t/ha and 3 t/ha gypsum increased yield to 1.82 t/ha.

The wheat grain yield was positively correlated with the number of tillers or heads per unit area, plant biomass yield and the size of the wheat head. However, no such relationship was found between the grain yield and plant emergence count nor the NDVI reading (collected at tillering stage).

Lime and gypsum treatments did not affect any grain quality parameters in 2017. However, there was a significant increase in wheat protein content due to incorporation in 2017. Wheat grain from the incorporated plots had 12.4%

Amelioration of acidity and Al toxicity

The interaction of lime rates x tillage treatments as well as the individual effects of these two factors significantly increased soil pH_{Ca} in the top 20 cm (Fig. 3a and 3b). There was no interaction with gypsum and the main effect of gypsum did not change soil pH_{Ca}.

Without incorporation, all lime treated plots had higher soil pH_{Ca} in 0-5 and 5-10 cm depths compared to the unlimed control plots. Top soil target pH_{Ca} (>5.50) was achieved but only in 0-5 cm depth. No significant increase in soil pH_{Ca} was recorded in soil below 0-10 depth. On the other hand, with incorporation all lime rates had significantly higher pH_{Ca} to the depth of cultivation (in top 20 cm). There were some positive changes in soil pH_{Ca} in 20-30 cm depth but the difference was not significant. Under both tillage treatments, higher lime rates tended to have higher pH_{Ca}.

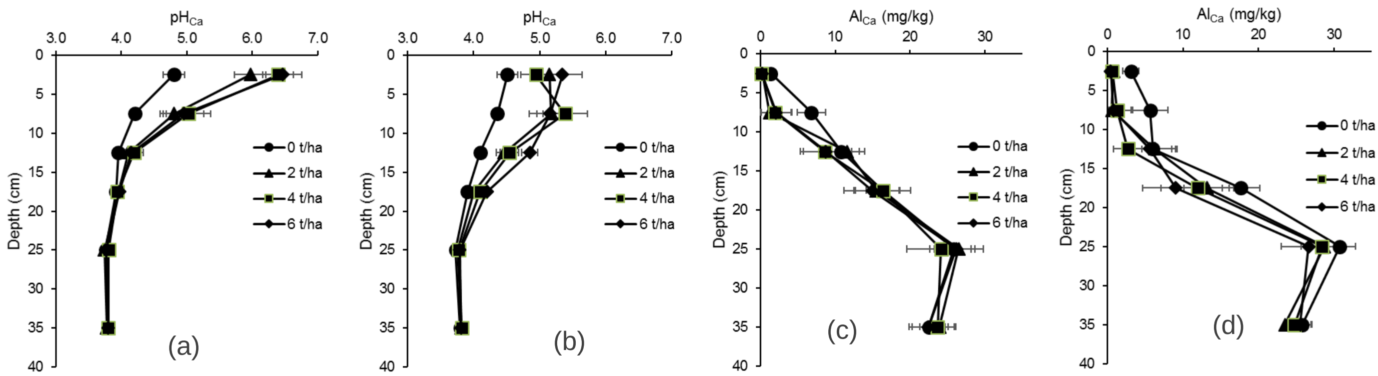

Figure 3: Changes in soil pH (a and b) and aluminium chemistry (c and d) due to application of lime under no incorporation (a and c) and incorporation (b and d) treatments. Horizontal bars represent ± standard error of the mean pH and aluminium concentration.

Again the interaction of lime rates by tillage treatments was significant to decrease soil Al_{Ca}. The individual effect of lime was also significant to decrease concentration of Al_{Ca} (Fig. 3c and 3d). Without incorporation, all lime rates decreased Al_{Ca} concentration but only in 0-10 cm depth (Fig. 3c). Whereas with incorporation lime decreased Al_{Ca} in 0-30 cm depth (Fig. 3d). It was noticed that a very small increase (statistically not significant) in soil pH_{Ca} (Fig. 3b) could decrease the concentration of Al_{Ca} significantly in 20-30 cm depth (Fig. 3d). The interaction of tillage and gypsum had a negative effect on Al_{Ca} below 20 cm depth where there was an increase in Al_{Ca} concentration (probably a less toxic aluminium complex, for example, aluminium sulphate) accumulated from the leachate of the gypsum incorporated layer (data not presented).

Gypsum application significantly increased soil EC throughout the profile (0-40 cm) and hence the ionic strength (I_s) of the soil (data not presented). In general, the I_s of gypsum treated soil was at least doubled compared to the control. The effect of lime rates on EC and I_s was inconsistent and not as great as gypsum. Tillage treatment had no effect to increase soil EC and I_s.

There was no difference between treatments in soil moisture content (data not presented). Lime treated plots tended to have lower soil moisture in the subsoil but it was not significant and not consistent throughout the season.

Nutrient concentration in wheat tissue

The interaction of lime and gypsum application had a significant effect to increase total N concentration in wheat tissue at Z65 growth stage but no such effect was noticed in P and K concentrations. The main effect of liming was significant to increase the concentrations of total N (data not presented), P (Fig. 4a) and K (data not presented). Liming also increased Ca (Fig. 4c) and Mg (data not presented) uptake as we saw higher concentration in wheat tissue collected from limed plots. The main effect of gypsum was not significant for N, P and K but, as expected, gypsum application significantly improved S and Ca concentration in wheat tissue (Fig. 4b and 4c). Tillage did not decrease or increase the concentration of macronutrients in plant tissue.

Gypsum application increased the concentration of B (data not presented), Mn (Fig. 4d) and Zn concentration (data not presented) in wheat tissue collected at Z65 stage. On the other hand, lime decreased the concentration of Mn (Fig. 4d) and Zn in wheat tissue (data not presented). Neither lime nor gypsum application affected the concentration of Cu, Mo and Fe (data not presented). None of the treatments decreased nutrient level below the critical levels.

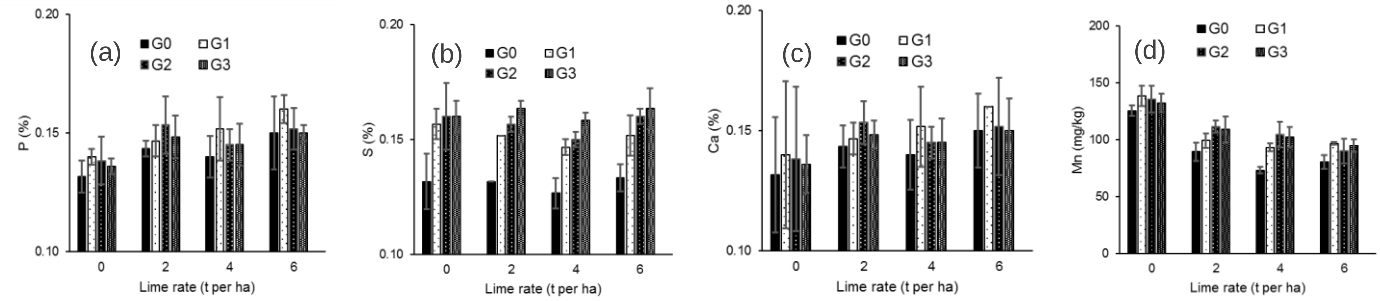

Figure 4: Concentration of (a) P, (b) S, (c) Ca and (d) Mn in wheat tissue at Z65 growth stage due interactive application of lime and gypsum. It should be noted that measurements on some of the nutrients are not presented here. Vertical bars represent ± standard error of the mean nutrient concentration.

Conclusion

It is clear from this field trial that liming can significantly increase grain yield. This effect was consistent across two contrasting seasons in the low rainfall zone of WA. This yield improvement is driven by the increase in soil pH and hence decrease in Al toxicity (e.g. our data and Li et al., 2019). Increased soil pH also leads to improved uptake of major macronutrients (Scanlan et al., 2017). In this experiment, increased soil pH resulted in a decreased uptake of some micronutrients (especially for Zn and Mn). However, none of nutrients was below the critical level and therefore there was no negative effect of these micronutrient levels on grain yield nor quality.

It is also evident from this trial that gypsum can improve wheat grain yield, which is similar to McLay et al. (1994a), but not by improving soil pH nor total aluminium concentration, as found by McLay and his colleagues (1994b). In our experiment, the result was consistent whether gypsum was applied at the surface or incorporated. However, gypsum increased total Al concentration deeper in the soil horizon. A large proportion of this total Al measurement could be in non-toxic forms of Al, as shown by Damon et al. (2018). Gypsum greatly improved the ionic strength of soil and this was observed at every depth as found by McLay et al. (1994b). Obviously, gypsum provided extra S and Ca in the soil solution that led to their increased uptake by the crop. Gypsum also increased plant uptake of some micronutrients such as B, Mn, and Zn.

The application of lime and gypsum together had a synergistic effect on grain yield. This is a similar result to that reported by others (e.g. McLay et al., 1994a). This is likely due to the fact that lime increased soil pH and hence decreased the total amount of toxic Al in soil solution. Gypsum on the other supplied additional Ca and S as well as improving the uptake of micronutrients. In addition, gypsum probably helped by changing toxic Al into non-toxic forms and caused Al to leach deeper. Increases in the 20-40 cm soil samples were observed with gypsum application, however, it did not reduce the total amount of Al in soil solution. The combined application of lime and gypsum also had a synergistic effect in improving uptake of the most macronutrients, especially total N.

In the first year, the lime and gypsum incorporation by tillage (one-way plough) treatment was not as good as surface application of the ameliorants. It is likely that ploughing induced higher loss of soil water through evaporation, as evidenced by a negative effect on crop establishment. Ploughing is also likely to degrade soil structure and change soil chemistry established in a minimum tillage system (Whitten et al, 2000). However, the grain quality, especially the protein content, was higher under tillage treatments as ploughing enhanced the mineralisation of organic matters and the uptake of nitrogen. In the second year, lime and gypsum incorporation treatments, especially with higher rates, outperformed the surface application. This trend is likely to continue in future years.

Key words

Lime, gypsum, grain crop, aluminium toxicity, acid soil

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