

# Slow movement of alkali from surface-applied lime warrants the introduction of strategic tillage for rapid amelioration of subsurface acidity in south-western Australia

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**Abstract.** Conventional surface-application of agricultural lime takes many years to increase pH deeper in the soil profile, which is a barrier to increased adoption of liming. We conducted a series of experiments to measure the rate of vertical movement of alkali and identify the factors that determine this movement into the subsurface, to evaluate the feasibility of ameliorating acidic subsurface soil using residual (undissolved) lime ( $\text{CaCO}_3$ ) at Wongan Hills (30.85°S, 116.74°E) and Merredin (31.48°S, 118.21°E) and to test whether deep tillage and lime incorporation can significantly speed up the amelioration of subsurface soil acidity at Kalannie (30.42°S, 117.29°E). Multiple applications of lime to the surface of the soil at higher rates (total 6–8.5 Mg ha<sup>-1</sup>) significantly increased subsurface soil pH but only in the 0.10–0.20 m depth by 0.049 pH units per year over 10–24 years. A large proportion of the surface-applied lime was stratified in the top few centimetres of the soil and incorporation of this undissolved lime with a rotary hoe to a depth of 0.25 m significantly increased soil pH (by 0.63 units) within a year in the Wongan Hills field experiment. Deep incorporation of 6 Mg ha<sup>-1</sup> lime to a depth of 0.45 m through excavation and spading with a small rotary hoe also increased soil pH by more than a unit and decreased Al concentration to below the toxic level within two months in the Kalannie experiment, allowing wheat (*Triticum aestivum* L.) plants to produce root systems up to 0.59 m deep compared with 0.26 m for the control. Our soil column leaching experiment indicated that surface incorporation of lime in higher rainfall regions can be useful to treat subsurface soil acidity but that the rate of improvement in subsurface pH was slow. Therefore, deeper incorporation of lime using cost-effective strategic deep tillage is likely to be necessary.

**Additional keywords:** aluminium toxicity, deep incorporation, liming, residual  $\text{CaCO}_3$ , Western Australia, wheat.

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## Introduction

Subsurface soil (below 0.1 m) acidity is widespread in Australia (National Land and Water Resources Audit 2001) and many parts of the world (Rengel 2003). In particular, the subsurface soil of the grainbelt of south-western Western Australia (WA) is constrained by severe acidity (soil pH  $\leq$  4.8; pH measured in 0.01 M  $\text{CaCl}_2$ , pH hereafter) (Gazey *et al.* 2013) and to a deeper depth (Whitten 2002) than any other crop-growing regions of Australia (Li *et al.* 2019), costing AU\$0.5–1.6 billion annually (Herbert 2009; Petersen 2016). In WA, agricultural lime ( $\text{CaCO}_3$ ) is typically spread on the soil surface to manage acidic soils; this is done without incorporation mainly due to the wide adoption of minimum tillage farming (Edmeades and Ridley 2003). It takes many years to significantly increase subsurface soil pH via surface-applied lime (Sumner *et al.* 1986; Conyers and Scott 1989). Crop yield increases from liming (compared with unlimed soil) occur in subsequent years, hence the economic benefit is cumulative. However, the upfront cost of applying lime still remains a barrier for many growers

(Fisher 2019), warranting further research on more cost-effective methods of ameliorating subsurface soil acidity.

More recent literature suggests that, under both field and controlled environment conditions, the significant increase in soil pH is restricted to the few centimetres below the liming depth (Li *et al.* 2019; Nunes *et al.* 2019). Some reports indicate that the rate of the vertical movement of alkalinity from lime is affected by soil characteristics (for example, initial soil pH, soil organic carbon (OC) and soil texture), climate, time, application rate and lime quality parameters (Conyers and Scott 1989; Whitten 2002; Caires *et al.* 2005). However, it is not clear whether some of these factors are more important than others in enhancing deeper movement of alkalinity (Caires *et al.* 2005). Given the slow movement of pH change below the depth of lime addition, the most effective tillage operation to incorporate lime for rapid amelioration of subsoil acidity will need to be determined. Additionally, as the requirement for lime has become more widely accepted, many farmers have repeatedly applied agricultural lime to the soil surface. Most of this lime is stratified in the top few

centimetres of soil (Azam *et al.* 2019). It is essential that we understand the amount of undissolved lime in the surface soil in order to test the efficiency of surface liming and identify a potential depth of incorporation for rapid amelioration of subsurface soil.

A large proportion of acidic sandplain soils in the grainbelt of WA are compacted and have developed water-repellency (van Gool 2011). In paddocks where multiple soil constraints such as compaction, water repellence and subsurface soil acidity are present, most crop roots are confined within 0.20–0.30 m of the surface (Reynolds *et al.* 2018). With such shallow root systems, a large proportion of growing-season rainfall quickly drains away beyond the root zone, resulting in inefficient use of stored soil moisture deeper in the profile. Physical tillage operations to treat compaction and water-repellent soils can opportunistically be used for the incorporation of lime (Davies *et al.* 2019). Scanlan *et al.* (2014) suggested that if a tillage operation was used to mix lime to the depths where the soil pH constraint occurs, then theoretically an immediate payback on lime and tillage might be possible. However, re-introduction of deep tillage to a no-till cropping system might have a negative effect on the soil OC, especially in the topsoil (Blanco-Canqui and Lal 2008). Because OC plays an important role in maintaining soil health, it is necessary to evaluate how deep tillage, for incorporation of lime, affects OC.

We conducted a series of laboratory experiments and field experiments to (i) identify the factors that determine the movement of alkalinity into the subsurface, (ii) estimate the amount of undissolved CaCO<sub>3</sub> (residual lime) in the topsoil following different liming strategies, (iii) evaluate the feasibility of ameliorating acidic subsurface soil using residual lime and the extent of amelioration that is possible under field conditions and (iv) test whether deep tillage and lime incorporation could significantly speed up the amelioration of subsurface soil acidity and improve the rooting depth of a grain crop in soil without any previous liming history.

## Methodology

### *pH and lime stratification in long-term field experiments*

The Department of Primary Industries and Regional Development has conducted several long-term soil acidity

management experiments in WA, in which a wide range of lime rates (cumulative total 0–8.5 Mg ha<sup>-1</sup>) was applied. Two current long-term lime field experiment sites were selected for this study (Table 1). These experiments were selected to represent low to medium rainfall regions in the grainbelt of WA and an arid BSh type climate (Peel *et al.* 2007). The experiments also varied due to the rate and frequency of lime application. Both sites were situated on level to gentle slope (0–3°). Soil at the experimental sites had predominantly developed on lateritic parent material (McArthur 2004) and were both classified as Yellow-orthic acidic Tenosols in the Australian Soil Classification (Isbell 2002) and as Profundic Lixosols in World Reference Base (IUSS Working Group WRB 2015).

Soil samples were collected in bulk (four cores per depth interval per plot and bulked) in autumn 2018 from triplicated unlimed plots and limed plots that had received the highest rate of lime from the two lime experiments (Table 1). These samples were collected from 0–0.10, 0.10–0.20 and 0.20–0.30 m depths, using a stainless steel pipe with 4-cm inner diameter, to measure pH in 0.01 M CaCl<sub>2</sub> (Method 4B1, Rayment and Lyons 2011). Another set of samples was also collected from a soil pit face from 0–0.02, 0.02–0.04, 0.04–0.06, 0.06–0.08 and 0.08–0.10 m depths of the control and lime-treated plots. These samples were used to measure pH (Method 4B1, Rayment and Lyons 2011) and the amount of residual carbonate using the pressure calcimeter principle (Horváth *et al.* 2005). All soil samples were dried at 40°C in a forced-draught oven and passed through a 2-mm sieve before chemical analysis.

### *Movement of alkali in the soil column leaching experiment*

Bulk soil samples were collected from 0–0.10 m (topsoil) and 0.15–0.30 m (subsurface soil) depths from both untreated (Soil A) and lime-treated (Soil B) plots in the Merredin experiment (Table 1). These soils were air-dried and sieved using 4-mm mesh. The two topsoils were treated with three rates (0, 3.0 and 6.0 Mg ha<sup>-1</sup>) of lime (94.9 g 100 g<sup>-1</sup> equivalent weight of laboratory-grade CaCO<sub>3</sub> with following particle size distribution: 0–0.125 mm = 21.6 g 100 g<sup>-1</sup>, 0.125–0.250 mm = 69.1 g 100 g<sup>-1</sup>, 0.25–0.50 mm = 8.5 g 100 g<sup>-1</sup> and 0.50–1.0 mm = 0.8 g 100 g<sup>-1</sup>). A rigid polyvinyl chloride (PVC) tube (0.50 m height, 0.10 m

**Table 1. Liming history and characteristics of the two selected experimental sites in the eastern grainbelt of Western Australia**

Parameters	Wongan Hills	Merredin
Map reference	30.85°S, 116.74°E	31.48°S, 118.21°E
Annual rainfall (mm) (2008–2018)	381 ± 113	319 ± 79
Soil type	Tenosol, loamy sand (particle size distribution for 0.10–0.30 m depth 84.7 g 100 g <sup>-1</sup> sand, 1.8 g 100 g <sup>-1</sup> silt and 13.5 g 100 g <sup>-1</sup> clay)	Tenosol, sandy loam (particle size distribution for 0.10–0.30 m depth 76.7 g 100 g <sup>-1</sup> sand, 3.4 g 100 g <sup>-1</sup> silt and 19.9 g 100 g <sup>-1</sup> clay)
Parent material	Lateritic	Lateritic
Age of the experiment (years)	24	10
Lime application (samples were also collected from the unlimed plots in every experimental site)	Surface application in following years and rates: 1994 = 4 Mg ha <sup>-1</sup> , 1998 = 1.5 Mg ha <sup>-1</sup> , 2014 = 3 Mg ha <sup>-1</sup> ; Total = 8.5 Mg ha <sup>-1</sup>	Surface application in following years and rates: 2008 = 3 Mg ha <sup>-1</sup> , 2014 = 3 Mg ha <sup>-1</sup> ; Total = 6 Mg ha <sup>-1</sup>
Cropping history	Continuous cropping: wheat ( <i>Triticum aestivum</i> L.), barley ( <i>Hordeum vulgare</i> L.) and canola ( <i>Brassica napus</i> L.)	Continuous cropping: wheat ( <i>Triticum aestivum</i> L.), barley ( <i>Hordeum vulgare</i> L.) and canola ( <i>Brassica napus</i> L.)

diameter) was used to prepare the soil column. Untreated subsurface soil was filled at 0.10–0.50 m depth. Lime-treated or unlimed control topsoil was filled at 0–0.10 m depth. Five rhizon soil pore water samplers (MOM; porous tube, mean pore size of 0.15  $\mu\text{m}$ ; Rhizosphere Research Products, Wageningen, Netherlands) were installed through a 2.5-mm diameter hole in the PVC at 0.075, 0.125, 0.225, 0.325 and 0.425 m depth from the soil surface. Eighteen soil columns were prepared for each soil source. Half of the columns received the equivalent of 0.40 m annual rainfall via irrigation using distilled water, while the other half received 0.80 m. Each irrigation amount was delivered using 26 equal amounts of fortnightly applications and the soil solution (20 mL per sample) was collected bimonthly using a rhizon sampler to measure pH.

#### *Strategic tillage to incorporate residual lime*

The incorporation of residual lime in the field was conducted at the Wongan Hills experiment (Table 1). Five lime (90 g 100 g<sup>-1</sup> equivalent weight of laboratory-grade CaCO<sub>3</sub> with following particle size distribution: 0–0.125 mm = 2.9 g 100 g<sup>-1</sup>, 0.125–0.250 mm = 61.1 g 100 g<sup>-1</sup>, 0.25–0.50 mm = 35.2 g 100 g<sup>-1</sup> and 0.50–1.0 mm = 0.8 g 100 g<sup>-1</sup>) rates (0, 0.5, 1, 2 and 4 Mg ha<sup>-1</sup>) were surface applied in 1994, in a randomised design with four replications (paired plots of 1.8 m  $\times$  30 m). This soil profile was originally acidic to a depth of 0.3 m when the experiment was established in 1994 (initial pH of 0–0.10 m = 5.11 and of 0.10–0.30 m = 4.20). One plot from each pair was re-limed as surface application in 1998 at 1.5 Mg ha<sup>-1</sup> using the same lime source mentioned above, hence changing the design to a split-plot design (single plots of 1.8 m  $\times$  30 m). In 2014, an additional 3 Mg ha<sup>-1</sup> of lime (again using the same lime source mentioned above) was surface applied to half of the area of each plot (plots of 1.8 m  $\times$  15 m). In April 2018, the plots were divided into three incorporation treatments of 0, 0.15 or 0.25 m depths (plots of 1.8 m  $\times$  5 m). A rotary hoe was used to apply the incorporation treatments. Measurements were not taken from every plot in 2019. The treatments that were evaluated were a 3  $\times$  2 factorial of 0, 2 or 4 Mg ha<sup>-1</sup> lime in 1994, each combined with either no additional lime or an additional 1.5 Mg ha<sup>-1</sup> of lime in 1998 and an additional 3 Mg ha<sup>-1</sup> of lime in 2014 (i.e. total lime rates during 1994–2018 of 0, 2, 4, 4.5, 6.5 and 8.5 Mg ha<sup>-1</sup>), across 0 and 0.25 m tillage depths. Soil samples (four cores per depth interval per plot and bulked) were collected from 0–0.10, 0.10–0.20 and 0.20–0.30 m depths, using a stainless steel pipe with 40-mm inner diameter, to measure pH in 0.01 M CaCl<sub>2</sub> (Method 4B1, Rayment and Lyons 2011) and OC using the Walkley–Black method (Nelson and Sommers 1982).

#### *Deep tillage to incorporate lime for rapid pH improvement*

This ongoing field experiment was established in April 2018 in a continuously cropped paddock near Kalannie, WA (30.42°S, 117.29°E), and the site has an arid BSh type climate (Peel *et al.* 2007). The soil is classified as a Yellow-orthic acidic Tenosol in the Australian Soil Classification (Isbell 2002) and a

Profundic Lixosol in World Reference Base (IUSS Working Group WRB 2015). Both surface and subsurface soils were strongly acidic (pH of 0–0.10 m = 4.35 and of 0.10–0.30 m = 3.95). This soil had a loamy-sand texture throughout the sampling depths. The paddock was highly compacted (penetrometer resistance 3.0–4.0 MPa through 0.1–0.6 m depth at field capacity). The soil had low levels of OC: 0.85 g 100 g<sup>-1</sup> for 0–0.1 m and 0.32 g 100 g<sup>-1</sup> for 0.1–0.3 m.

The experiment consisted of plots of 3 m  $\times$  2 m size within a randomised block design, replicated three times. There were five soil amelioration treatments comprising an untreated control (T0) and four treatments involving tillage for the removal of only compaction to a depth of 0–0.45 m (T1) or removal of both compaction (0–0.45 m depth) and acidity at three different depths (T2–T4).

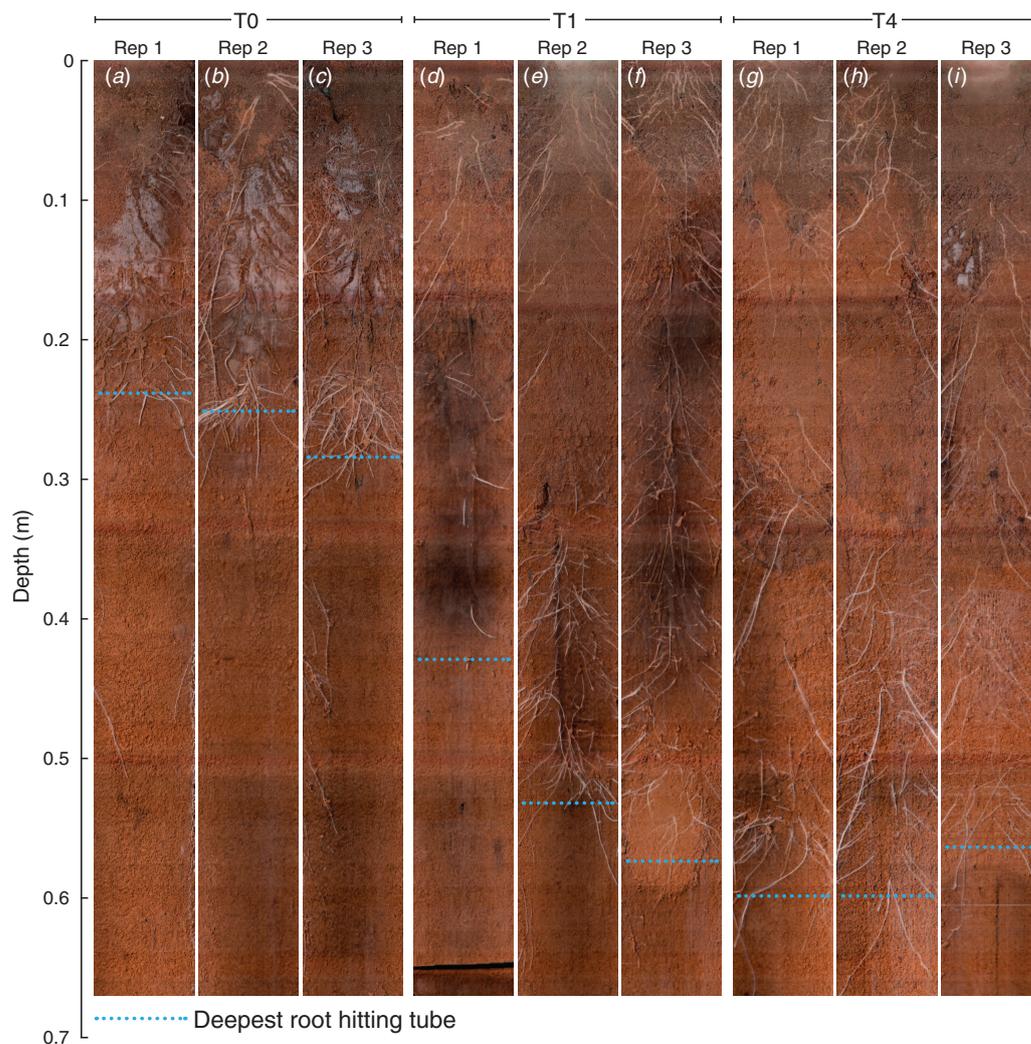
For the four amelioration treatments (i.e. T1–T4), two soil layers (0–0.10 and 0.10–0.30 m depths) were removed separately and then replaced. A third layer (0.30–0.45 m depth) was then spaded *in situ* using a small rotary hoe to a depth of ~0.45 m. For T4, 1.5 Mg ha<sup>-1</sup> lime (94.9 g 100 g<sup>-1</sup> equivalent weight of laboratory-grade CaCO<sub>3</sub>) was spread on top of the third layer before rotary hoeing. The second layer (0.10–0.30 m depth) was then back-filled and 3 Mg ha<sup>-1</sup> lime was applied for T3 and T4 before all the plots were rotary hoed. The top layer was then returned and 1.5 Mg ha<sup>-1</sup> lime was applied to the T2–T4 plots before all the plots were rotary hoed.

The experiment was sown on 10 May 2018 to wheat (*Triticum aestivum* L.) cv Mace at 60 kg ha<sup>-1</sup> with 0.22-m row spacing and 0.03-m sowing depth. All plots were fertilised with 37 kg ha<sup>-1</sup> of mono-ammonium phosphate (21.9 g phosphorus 100 g<sup>-1</sup>, 10 g nitrogen 100 g<sup>-1</sup>), 100 kg ha<sup>-1</sup> of sulfate of potash (41.5 potassium 100 g<sup>-1</sup> and 17 g sulfur 100 g<sup>-1</sup>) and 57 kg ha<sup>-1</sup> of urea (46 g nitrogen 100 g<sup>-1</sup>) at sowing. Mono-ammonium phosphate was drilled at 0.07 m depth using an offset disc and sulfate of potash and urea were broadcasted using a hand spreader.

Wheat root architecture (for T0, T1 and T4 as shown in Fig. 1) was imaged repeatedly *in situ* using a 360° scanner (CI-600, CID Bio-Science, Camas, WA, USA) inserted in clear glass tubes (Rhizo tubes, ICT International, Armidale, NSW). Soil profile samples were collected at 0–0.10, 0.10–0.20, 0.20–0.30, 0.30–0.40 and 0.40–0.50 m depths from each plot in July 2018. These samples were used to measure pH (Method 4B1, Rayment and Lyons 2011) and CaCl<sub>2</sub>-extractable total aluminium (Al) (Bromfield 1987). Soil resistance (SR) was measured in July 2018 when soil moisture was at field capacity using a hand-held electronic cone penetrometer (CP40II, Rimik Pty Ltd, Toowoomba, Qld).

#### *Statistical analyses*

For the long-term field experiments at Wongan Hills and Merredin, a one-way ANOVA was performed in GENSTAT (Version 18.1, VSN International, Oxford, UK) at each depth with lime rates as the factor and soil pH, annual changes in soil pH or the amount of residual carbonate as the variate. In order to cater for the random effects of repeated liming programs in the above two experiments, a linear mixed model, using the



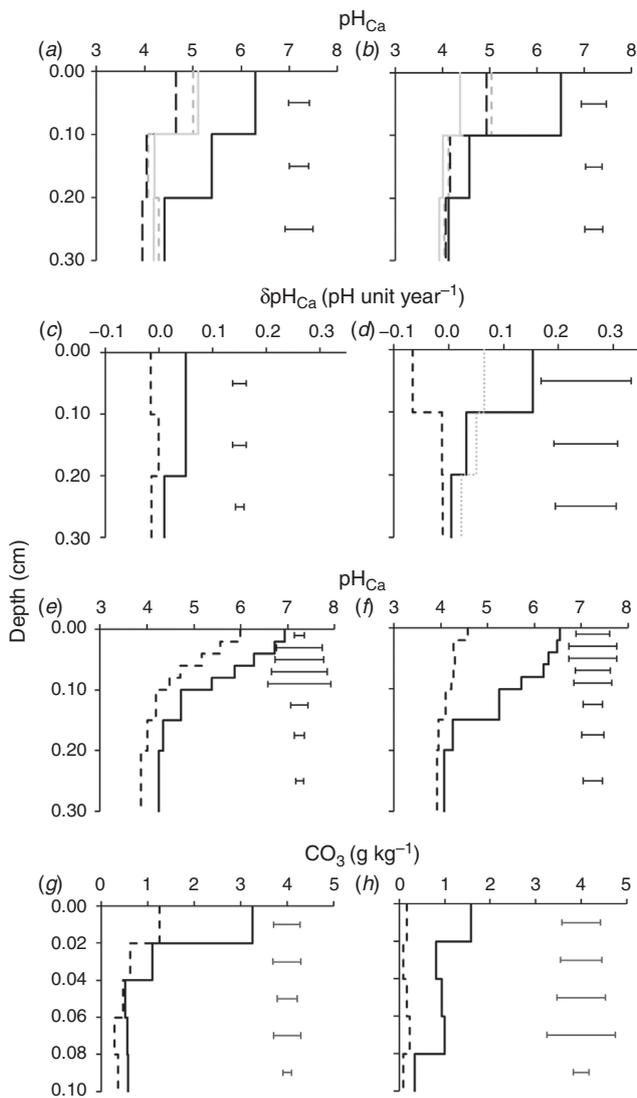
**Fig. 1.** Wheat (*Triticum aestivum* L.) rooting depth in deep loamy sand at Kalannie WA, 56 days after sowing under control (T0; *a–c*), removal of compaction only (T1; *d–f*) and compaction plus deep incorporation of lime (T4; *g–i*).

GENSTAT restricted maximum likelihood (REML) algorithm directive, was applied. For the soil column leaching experiment, a two-way ANOVA was performed at each depth with irrigation rates and lime rates as the factors and soil solution pH as the variate. For the strategic tillage experiment at Wongan Hills, a three-way ANOVA was performed at each depth with tillage depths, lime rates in 1994 and subsequent lime application in 1998 and 2014 as the factors and soil pH or OC as the variate. For the deep tillage experiment at Kalannie, a one-way ANOVA was performed at each depth with lime incorporation treatment as the factor and SR, soil pH or Al as the variate. In order to cater for the random effects of the farmers' machinery-based activities (strategic tillage in Wongan Hills and deep tillage in Kalannie), a linear mixed model, using the GENSTAT REML algorithm directive, was applied. In all ANOVA tests, Fisher's least significant difference (l.s.d.) was applied at  $P < 0.05$  to compare treatment effects.

## Results

### *pH and lime stratification in long-term field experiments*

The soil pH of the 0.10-m increment samples significantly increased in the 0–0.10 m depth in the limed plots compared with the initial pH in 1994 for the Wongan Hills experiment and in 2008 for the Merredin experiment (Fig. 2*a* and *b*). The three applications of lime totalling  $8.5 \text{ Mg ha}^{-1}$  lifted the pH from an initial 5.11 to 6.30 in Wongan Hills (Fig. 2*a*). Similarly, at Merredin, two applications of lime totalling  $6 \text{ Mg ha}^{-1}$  increased pH in the 0–0.10 m depth to 6.61 from an initial pH of 4.93 (Fig. 2*b*). There was a 1.18 pH unit increase (from 4.21 in 1994 to 5.39 in 2018) in the 0.10–0.20 m depth at Wongan Hills and a 0.40 pH unit increase (from 4.17 in 2008 to 4.57 in 2018) at Merredin. The pH in the 0.20–0.30 m depth did not significantly increase at either site from initial pH values over the duration of 24 or 10 years respectively. The pH in the 0–0.10 m depth of the unlimed control plots decreased by almost 0.50 pH units in



**Fig. 2.** Soil pH in  $\text{CaCl}_2$  (a and b) at 0.10-m depth increments, annual net changes in soil pH in  $\text{CaCl}_2$  (c and d) at 0.10-m depth increments, stratified changes in soil pH in  $\text{CaCl}_2$  (e and f) at 0.02-m increments and residual  $\text{CO}_3$  (g and h) at 0.02-m increments at Wongan Hills (a, c, e and g) and Merredin (b, d, f and h) experimental sites. Grey dotted and solid lines represent initial soil pH for the untreated and lime-treated plots in 1994 at Wongan Hills and in 2008 at Merredin. Black dotted and solid lines represent soil pH for the untreated and lime-treated plots in 2018 at both sites. Horizontal error bars within depth interval represent l.s.d. ( $P < 0.05$ ) for the measured parameters.

both experiments with respect to initial pH at each site. The pH in the 0.10–0.20 and 0.20–0.30 m depths in the untreated control plots did not significantly decrease from their initial values. However, soil pH in 2018 from the 0.10–0.20 and 0.20–0.30 m depths in the control plots was significantly lower than the limed plots.

The annual net increase was significant for soil pH in the 0–0.10 and 0.10–0.20 m depths of the limed plots (compared with the original pH measured in 1994) for Wongan Hills, but not for the 0.20–0.30 m depth (Fig. 2c). The rate of increase in

pH in the top 0.20 m of soil was also quite uniform at around 0.050 pH unit per year (over 24 years), but only 0.009 pH unit per year in the 0.20–0.30 m depth. The net annual pH change at Merredin was also significant, but only for the 0–0.10 m depth (Fig. 2d). At Merredin the rate of increase in pH in the top 0.10 m soil was 0.154 pH unit per year, compared with only 0.032 and 0.005 pH unit per year in the 0.10–0.20 and 0.20–0.30 m depths respectively. The annual net decrease in soil pH (net acidification rate) in the control plots was not significant for any of the depth intervals at Wongan Hills. However, it was significant only for the 0–0.10 m depth at Merredin. The net acidification rate in the 0–0.10 m depth of the control plots was 0.066 and 0.015 pH unit per year Merredin and Wongan Hills respectively. At both sites the acidification rates in the deeper depths were similar, but much smaller (annual decrease of 0.010 pH unit) compared with the top 0.10 m of soil.

The significant effect of lime to increase soil pH in the traditional 0.10-m depth increment (Fig. 2a and b) represents an underestimation of the change in 0–0.04 m and an overestimation of the change in 0.06–0.10 m compared with the results from soil samples collected from the soil pit face at smaller increments (Fig. 2e and f). Soil pH in both limed and control plots was stratified and more prominent in limed plots. For all limed soils, the highest soil pH was recorded in the 0–0.04 m depths. The magnitude of the differences in subsurface soil pH between limed and unlimed soils, however, varied between experimental sites. The Wongan Hills experiment – being the oldest, with a total of 8.5 Mg  $\text{ha}^{-1}$  lime applied (over three applications), having less clay content and receiving medium rainfall – had a consistently larger improvement in subsurface soil pH compared with Merredin (Fig. 2e and f).

Residual carbonate was detected for both unlimed and limed soils (Fig. 2g and h). The residual carbonate in the 0–0.02 m depth in the limed plots was significantly higher than the unlimed plots at Wongan Hills and Merredin ( $P < 0.05$ ). The residual carbonate in the 0.02–0.04 m depth in the limed plots was also significantly higher than the unlimed plots in both sites, but only at  $P < 0.10$ . The residual carbonate in the 0.04–0.10 m depth was not significantly different for the lime rates; however, lime-treated soils tended to have higher residual carbonate. There was 1.96 Mg  $\text{ha}^{-1}$  more residual carbonate in the 0–0.10 m depth of the lime-treated than the control plots at Wongan Hills and correspondingly 2.56 Mg  $\text{ha}^{-1}$  more at Merredin.

#### *Movement of alkali in the soil column leaching experiment*

For Soil A (unlimed field soil) there was a significant increase ( $P < 0.05$ ; l.s.d. 0.22) in the pH of the soil solution of the 0–0.10 m layer for the 3 and 6 Mg  $\text{ha}^{-1}$  lime treatments in both irrigation treatments (Fig. 3a and b). Soil solution pH increased to 6.10 and 7.34 for the 3 and 6 Mg  $\text{ha}^{-1}$  lime treatments respectively, from an initial pH 5.11. There was also a significant increase in the soil solution pH of the 0–0.10 m layer for ‘Soil B’ (previously limed field soil), but only for the 6 Mg  $\text{ha}^{-1}$  lime rate under 0.4-m irrigation treatment (Fig. 3c and d). The irrigation treatment affected soil

solution pH collected from the 0–0.10 m layers of both soils. The 0.8-m irrigation treatment had significantly higher pH than the 0.4-m irrigation treatment for all lime treatments, except the 6 Mg ha<sup>-1</sup> lime rate in Soil B (Fig. 3c and d). In general, soil solution pH in the 0–0.10 m layer of the untreated controls decreased from the initial pH over one year of leaching. This was more evident for Soil A under 0.4-m irrigation treatment (Fig. 3a).

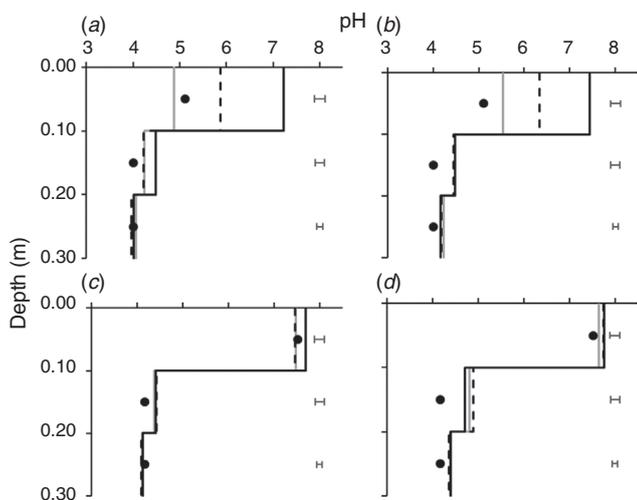
There was some movement of alkali into the 0.10–0.20 m layer in the lime-treated columns (Fig. 3). The 0.8-m irrigation treatment (Fig. 3b and d) had significantly higher pH in this layer than the 0.4-m irrigation treatment (Fig. 3a and c). The higher irrigation treatment was more effective in increasing soil solution pH of Soil B (0.40 pH unit) than that of Soil A (0.15 pH unit). Under the 0.4-m irrigation treatment

only the highest lime rate was effective in increasing soil solution pH of the 0.10–0.20 m layer compared with the initial soil solution pH (Fig. 3a). The higher irrigation treatment (Fig. 3b and d) significantly increased pH in the 0.20–0.30 m layer compared with the initial soil solution pH. This was consistent for both soils, but greater change occurred for Soil B than A. In contrast, there was no change in pH in the 0.20–0.30 m layer for the lower irrigation treatment (Fig. 3a and c). Lime rates and liming history of the soil did not affect soil solution pH of the 0.20–0.30 m layer. There was no evidence of increasing soil solution pH below 0.30 m for any treatment (data not presented).

*Strategic tillage to incorporate residual lime*

Soil pH of the without-tillage treatment did not significantly differ for 0 and 2 Mg ha<sup>-1</sup> single lime application in 1994 at all depths, but the 4 Mg ha<sup>-1</sup> lime treatment significantly increased pH at the 0.20–0.30 m compared with 0 Mg ha<sup>-1</sup> lime rate (Table 2). Plots that received additional applications of lime in 1998 (1.5 Mg ha<sup>-1</sup>) and 2014 (3.0 Mg ha<sup>-1</sup>) had significantly higher soil pH at the 0–0.10 m depths compared with the plots that received a single application of 0, 2 or 4 Mg ha<sup>-1</sup> lime in 1994. Plots that received 2 or 4 Mg ha<sup>-1</sup> lime in 1994 and an additional application of lime in 1998 (1.5 Mg ha<sup>-1</sup>) and 2014 (3.0 Mg ha<sup>-1</sup>) also had significantly higher soil pH at the 0.10–0.20 m depths compared with the control. Only the plots that received 4 Mg ha<sup>-1</sup> lime in 1994 and an additional application of 1.5 Mg ha<sup>-1</sup> lime in 1998 and 3.0 Mg ha<sup>-1</sup> in 2014 had significantly higher soil pH at the 0.20–0.30 m depths compared with the control.

With deep tillage, soil pH in the 0–0.10 m depth of the unlimed plots significantly decreased (–0.32 pH units, *P* < 0.10) compared with the unlimed plots in the no tillage treatment, but no significant changes were recorded for any other lime treatments at 0–0.10 m depth. Deep tillage significantly increased soil pH in the 0.10–0.20 m depth for 4 Mg ha<sup>-1</sup> single application and other rates that had an additional application of 1.5 Mg ha<sup>-1</sup> lime in 1998 and 3.0 Mg ha<sup>-1</sup> in 2014 compared with unlimed plots. Deep tillage also significantly increased soil pH in the 0.20–0.30 m depth for the two highest cumulative lime rates compared with unlimed plots.



**Fig. 3.** Soil solution pH from different sampling depths of column experiments of the Merredin site for ‘Soil A’ (a and b) from unlimed field plots and ‘Soil B’ (c and d) from previously limed field plots following leaching with 400 mm (a and c) and 800 mm (b and d) of irrigation. Lime was incorporated in the 0–0.10 m depth of both soils at three rates where grey-solid, black-dashed and black-solid lines represent 0, 3 and 6 Mg ha<sup>-1</sup> lime rates respectively. Circular marker points represent initial soil solution pH for each soil at the onset of the experiment. Horizontal error bars within depth interval represent 1 s.d. (*P* < 0.05) for the soil solution pH.

**Table 2.** Soil pH in 0.01 M CaCl<sub>2</sub> under different liming strategies and tillage treatments in autumn 2019 in a loamy sand at Wongan Hills

l.s.d. (*P* < 0.05) for deep tillage × lime rates at 0–0.10 m depth = 0.36, at 0.10–0.20 m depth = 0.60 and at 0.20–0.30 m depth = 0.45

Depth (m)	Applications of lime (Mg ha <sup>-1</sup> ) – 1994, 1998, 2014					
	0, 0, 0	2, 0, 0	4, 0, 0	0, 1.5, 3.5	2, 1.5, 3	4, 1.5, 3
	Without deep tillage					
0–0.10	5.60	5.80	5.83	6.48	6.58	6.45
0.10–0.20	4.58	4.60	4.63	4.95	5.35	5.40
0.20–0.30	4.13	4.28	4.65	4.45	4.58	4.95
	With deep tillage					
0–0.10	5.28	5.90	5.90	6.33	6.50	6.55
0.10–0.20	4.73	5.23	5.48	5.63	5.73	6.00
0.20–0.30	4.25	4.43	4.48	4.45	4.85	5.20

**Table 3. Soil organic carbon ( $\text{g } 100 \text{ g}^{-1}$ ) under different liming strategies and tillage treatments in loamy sand at Wongan Hills**

l.s.d. ( $P < 0.05$ ) for deep tillage  $\times$  lime rates at 0–0.10 m depth = 0.150, at 0.10–0.20 m depth = 0.126 and at 0.20–0.30 m depth = 0.072

Depth (m)	Applications of lime ( $\text{Mg ha}^{-1}$ ) – 1994, 1998, 2014					
	0, 0, 0	2, 0, 0	4, 0, 0	0, 1.5, 3	2, 1.5, 3	4, 1.5, 3
	Without deep tillage					
0–0.10	0.810	0.885	0.775	0.880	0.845	0.850
0.10–0.20	0.465	0.475	0.493	0.463	0.415	0.515
0.20–0.30	0.246	0.288	0.335	0.260	0.250	0.265
	With deep tillage					
0–0.10	0.623	0.765	0.790	0.715	0.760	0.780
0.10–0.20	0.418	0.613	0.595	0.478	0.465	0.543
0.20–0.30	0.240	0.333	0.310	0.233	0.270	0.303

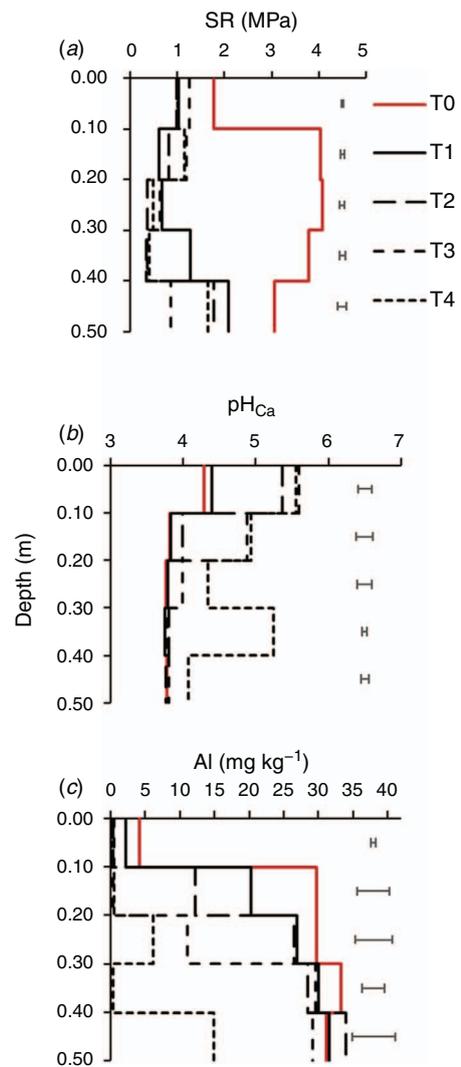
The highest lime rate ( $8.5 \text{ Mg ha}^{-1}$ ), with or without deep tillage, increased pH above the recommended subsurface soil pH of 4.80 (Gazey *et al.* 2014) down to 0.30 m depth. The second and third highest lime rates ( $6.5$  and  $4.5 \text{ Mg ha}^{-1}$ ), without deep tillage, also increased pH to the recommended level in the 0.10–0.20 but not the 0.20–0.30 m depth. Combining deep tillage with the second highest lime ( $6.5 \text{ Mg ha}^{-1}$ ) increased pH to the recommended level in the 0.20–0.30 m depth but not for the third highest lime rate ( $4.5 \text{ Mg ha}^{-1}$ ). Treatments with 2 or 4  $\text{Mg ha}^{-1}$  of lime in 1994 (no additional lime afterwards), without deep tillage, did not increase subsurface soil pH above the recommended level. Deep tillage combined with 2 or 4  $\text{Mg ha}^{-1}$  of lime in 1994 increased pH above the recommended level for the 0.10–0.20 but not the 0.20–0.30 m depth. The pH at 0–0.10 m depth was above the recommended surface soil pH of 5.5 for all plots except for the unlimed tilled plots.

There was no significant increase in OC corresponding to improved soil pH profiles in the lime-treated plots (Table 3). Tillage significantly decreased OC in the 0–0.10 m depth of the unlimed plots. No significant effect of deep tillage on OC was observed in the 0.10–0.20 and 0.20–0.30 m depths.

#### Deep tillage to incorporate lime for rapid pH improvement

Deep tillage significantly decreased SR from 3–4 MPa in the control plots to 0.5–1.5 MPa in the tilled plots by removing soil compaction and there was no significant difference among the four amelioration treatments (Fig. 4a). All lime incorporation treatments increased soil pH to the minimum recommended pH of 5.5 in the 0–0.10 m depths and 4.8 in most lime-incorporated subsurface soil layers within two months (Fig. 4b). Within the same duration, liming also decreased total Al from a toxic range to below the critical level for major grain crops. The tillage-only treatment (T1) also decreased Al concentration, especially at 0.10–0.20 m depth (Fig. 4c).

There was a significant visual improvement in root growth (e.g. maximum rooting depth, thickness of root and production of root hairs) in treatments T1 (Fig. 1d–f) and T4 (Fig. 1g–i)



**Fig. 4.** (a) Soil resistance (SR) at field capacity, (b) soil pH in  $\text{CaCl}_2$  and (c) soil Al concentration in  $\text{CaCl}_2$  in deep loamy sand at Kalannie. Horizontal error bars within depth interval represent l.s.d. ( $P < 0.05$ ) for the measured parameters.

compared with T0 (Fig. 1a–c). However, all the images showed that the appearance of roots on the surface of the rhizotron tubes was not uniform due to variation in the distance between one wheat plant and another. Maximum rooting depth for the unameliorated control (T0) was restricted to  $0.26 \pm 0.01$  m depth compared with  $0.51 \pm 0.04$  m in T1 and  $0.59 \pm 0.01$  m in T4. There was no significant visual difference between the treatments in abundance and thickness of roots at 0–0.10 and 0–0.20 m depths. Treatment T0 had fewer and thicker roots in 0.20–0.30 m depth compared with more and finer roots for T1 and T4. Treatment T4 had had more roots below 0.30 m compared with T1. There were also more fine roots and roots hairs in the deeper layers where lime was incorporated (T4 compared with T1).

## Discussion

### *Restricted vertical movement of alkali in long-term lime experiments*

Our results from two long-term lime experiments using traditional 0.10-m increment soil sampling showed that repeated surface applications of lime (totalling 6.0 or 8.5 Mg ha<sup>-1</sup>) over a duration of 10–24 years maintained pH above 5.50 in the 0–0.10 m depth. We also found subsurface soil pH increased from the initial pH measured at the onset of the experiments (Fig. 2a and b), but it was restricted to the top 0.20 m. The improvement in surface soil pH resulted in movement of alkali, which increased subsurface soil pH and decreased net acidification due to continuous cropping, consistent with results of Conyers *et al.* (2003a). Li *et al.* (2019) reported a significant increase in soil pH to 0.30 m from a long-term experiment with a vigorous lime regime (18 years old, cumulative lime rate 8.6 Mg ha<sup>-1</sup>) in southern New South Wales, Australia. Differences between our study and that of Li *et al.* (2019) that may explain greater movement include finer (250 µm) and higher neutralising value (98 g 100 g<sup>-1</sup> equivalent weight of laboratory-grade CaCO<sub>3</sub>) lime at a site with higher annual rainfall (0.63 m). With more-precise sampling from the soil pit face, the increase in soil pH in our study was restricted to the top 0.15 m depth (Fig. 2e and f), similar to that measured by Nunes *et al.* (2019). Unlimed control plots were acidified at all sampling depths at 0.010 pH units per year. This is mainly due to leaching of nitrate nitrogen (from an organic or ammonium based nitrogen source) into deeper soil horizons, a process that generates more H<sup>+</sup> in the soil profile and acidifies soil (a decrease in pH from the initial pH) as suggested by Helyar (1976). Although the difference in pH in the 0.20–0.30 m depth between the control and limed plots was significant, it was mainly due to net acidification in the control plots (Fig. 2c and d).

The net increase in soil pH was restricted to the 0.10–0.20 m depth and only at the Wongan Hills site. Although the Merredin site had a greater rate of increase in soil pH in the 0–0.10 m depth compared with Wongan Hills, there was higher variability at Merredin and the net annual increase was significant in the 0–0.10 m depth only (Fig. 2c and d). The difference between the two sites could be due to the differences in experiment duration and crop productivity.

Similar to the findings of Scott *et al.* (1999), the Wongan Hills experiment (24 years old and highly productive site) is likely to have re-acidified after liming to a greater extent than the Merredin site (10 years old, low productive site). The Wongan Hills soil also has higher organic matter content and, therefore, would have had higher pH buffering capacity than the Merredin soil (Li *et al.* 2019).

Our results show that liming lifted soil pH close to the maximum where lime dissolution slows down (Nelson and Su 2010), hence a large proportion of the lime applied was stratified in the top few centimetres of surface soil (Fig. 2g and h). However, soil pH in the 0.04–0.10 m depths was also around 5.5 or higher, which probably allowed some movement of alkali into the subsurface soil (Li *et al.* 2019). Data from both long-term experiments confirm that the vertical movement of alkali is slow, restricted to 0.15–0.20 m. This led us into further studies to identify whether soil with higher initial pH along with higher rainfall has potential to speed up the movement of alkali.

### *Factors affecting vertical movement of alkali in soil columns*

Our results demonstrated lime incorporation rapidly and significantly increases soil solution pH of acidic topsoil (Soil A) but not for the soil that was previously limed (Soil B). This is because the lime dissolution rate is higher in acidic conditions; the rate decreases with increasing pH and dissolution stops in neutral or alkaline conditions (Nelson and Su 2010). However, we found an increase in the surface 0.10 m soil solution pH for Soil B with the 6 Mg ha<sup>-1</sup> lime rate (Fig. 3c and d), which could be due to an increased cation exchange capacity after liming (Aitken *et al.* 1990). Our results agree with those of Whitten (2002), finding that leaching decreases surface soil solution pH. This is because leaching enhances the nitrification rate (due to changes in soil biological activity) and downward movement of nitrate that generates release of H<sup>+</sup> and acidifies soil (Helyar 1976). A decrease in surface pH can also be due to downward movement of soluble alkali contained in organic matter of the surface soil (Butterly *et al.* 2013).

Both 3 and 6 Mg ha<sup>-1</sup> lime rates increased the soil solution pH in the 0–0.10 m layer to above 5.5, which is the recommended minimum pH for acidic soil in the WA grainbelt (Gazey *et al.* 2014) and has been shown to enhance the movement of alkali from the surface soil to the more acidic subsurface soil (Li *et al.* 2019). However, only the highest rate of lime (6 Mg ha<sup>-1</sup>) was effective at increasing soil solution pH in the 0.10–0.20 m depth of the previously untreated control soil under the 0.4-m irrigation treatment (Fig. 3a). Movement of alkali into the 0.10–0.20 m layer was more effective in previously limed soil, but only in the higher irrigation treatment. The higher irrigation treatment probably generated a greater rate of movement of soluble alkali resulting from increased water content and hydraulic conductivity (van Genuchten and Wierenga 1976). There was no evidence of increasing soil solution pH below 0.20 m depth, contrary to the evidence reported by Whitten (2002) in which a much higher watering regime was applied compared with our experiment. Our experiment suggests

that the potential to treat subsurface soil acidity by surface incorporation of high rates (3–6 Mg ha<sup>-1</sup>) of lime is limited and likely only to be effective in less-acidic topsoil (pH > 5) in higher rainfall regions, but the rate of improvement in pH is slow as measured by Nunes *et al.* (2019), and slower than that measured by Whitten (2002). This prompted us to test whether strategic deep tillage is a better solution for deep incorporation of lime for rapid amelioration of subsurface soil acidity.

#### *Strategic deep tillage for faster improvement in soil pH profile*

Results from two long-term experiments at Wongan Hills and Merredin suggest that soil pH was stratified at the centimetre-scale where the top 0.04 m of soil had pH around 7.0 (Fig. 2e and f) and hence, a large fraction of applied lime remained undissolved (Fig. 2g and h). To overcome lime and pH stratification, a once-off deep tillage could opportunistically be used for the incorporation of lime (Davies *et al.* 2019). From a laboratory experiment, Azam *et al.* (2019) showed that residual lime could manage subsurface soil acidity to a depth of 0.80 m if it can be incorporated and adequately mixed. The application of deep tillage treatments to incorporate residual lime significantly increased subsurface soil pH to the recommended pH of 4.8 to the depth of incorporation in the plots that received a cumulative lime rate of 6.5 or 8.5 Mg ha<sup>-1</sup> at Wongan Hills (Table 2). Deep tillage in the limed plots resulted in an increase of 0.63 pH unit at 0.10–0.20 m depth within a growing season, which is 12 times the annual net increase in pH without tillage (Fig. 2c). With deep tillage, however, soil pH and OC in the 0–0.10 m depths of the unlimed plots significantly decreased ( $P < 0.10$ ), supporting the findings of Conyers *et al.* (2003b) as well as of Blanco-Canqui and Lal (2008), demonstrating the negative effect of tillage in absence of lime. This is mainly due to dilution of topsoil containing higher pH and OC with subsurface soil that had lower pH and OC. Deep tillage to all plots that were previously limed did not decrease OC at any depth.

Our results from the Kalannie experiment demonstrate that deep lime incorporation with tillage increased soil pH by more than a pH unit to the depth of lime incorporation within two months, which decreased Al concentration below the critical level toxic for major crops grown in the WA broadacre farming system. Tillage decreased SR by removing compaction as reported by Davies *et al.* (2019). Removal of compaction together with lime incorporation produced deep root systems (with root hairs), which allowed plants to extract soil water and nutrients from deeper soil horizons (Azam and Gazey 2019). Mace wheat has a medium level of tolerance to Al toxicity (Amjad *et al.* 2014), which is why the roots (mainly seminal roots) grew down to 0.59 m depth. In lime-incorporated soil layers, there were more fine roots and roots hairs due to an increase in soil pH which reduced toxic Al below the critical level (Menzies *et al.* 1994).

#### Conclusions

Surface liming with 5–8.5 Mg ha<sup>-1</sup> rate could allow some movement of alkali into the subsurface soil, but the rate of

movement is very slow. We found only ~0.5 unit change in soil pH and only in the 0.10–0.20 m depths over a period of 10–24 years, noting that the sites have been subjected to ongoing acidification from continuous cropping. Sampling from the pit face in small increments better defined soil pH stratification than the traditional 0.10-m increment. A large proportion of the surface-applied lime remained undissolved and stratified due to high pH in the top 0.04 m of soil. This residual lime, which we showed could raise pH above 4.8 to the equivalent of 0.80 m soil depth under laboratory conditions (incorporated and adequately mixed) was also able to rapidly raise pH above 4.8 to the depth of incorporation by deep tillage under field conditions at Kalannie and Wongan Hills. Therefore, we conclude that under current conditions of low subsurface soil pH (<4.5) in many parts of the agricultural region of south-western WA, incorporation of lime using cost-effective strategic tillage is likely to be necessary. The opportunity to address multiple soil constraints (for example compaction and hydrophobicity) in the same operation will help to make soil amelioration more cost-effective.

#### Conflicts of interest

The authors declare no conflicts of interest.

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