Re-engineering soil pH profiles to boost water use efficiency by wheat

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Abstract

Conventional surface application of agricultural lime takes many years to increase pH deeper in the soil profile. This is a barrier for the adoption of liming as crop growers want a quick-fix to the subsurface soil acidity. We conducted a small-scale field trial where agricultural lime was incorporated at various depths to re-engineer soil pH profiles for quick improvement of grain yield and water use efficiency (WUE). Results show wheat grain yield was more than doubled due to combined removal of compaction and lime incorporation compared to the untreated control. Removal of compaction only also increased grain yield by 72% over the control. WUE was as high as 24 kg/mm due to deep amelioration of soil compared to 11 kg/mm in the control. Deep incorporation of lime increased soil pH by more than a unit and decreased Al concentration to below the critical toxic level within two months of lime incorporation. Wheat plants produced root systems 60-65 cm deep with amelioration of compaction and acidity compared to 20-25 cm deep for the control. Deeper roots allowed plants to extract water and nutrients from deeper soil horizons and avoid moisture stress, in the absence of sufficient rainfall, during the grain filling in 2018 season.

Key words

Subsoil acidity, aluminium toxicity, lime, re-engineering soils

Introduction

Soil acidity (low soil pH) is widespread in WA. More than 70% of topsoil samples and almost 50% of subsurface (10-20 and 20-30 cm) layer samples collected from the WA wheatbelt were below the minimum recommended pH targets of 5.5 and 4.8 (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. Liming is recommended for managing acidic soils, however, conventional surface application of lime takes many years to increase subsurface soil pH and decrease toxic forms of Al (Whitten 2002). Due to such delayed responses, previously growers did not realise the economic benefit from liming, so they ignored liming which resulted in more acidic soils at deeper depths (Gazey et al. 2013). Now that growers realised the penalty from subsurface acidification, they are looking for more rapid methods to correct subsurface soil acidity.

A large proportion of acidic sandplain is also compacted (van Gool 2011). Literature suggests that physical tillage operations to treat compaction and non-wetting soils can opportunistically be used for the incorporation of lime (Davies 2014). However, such soil amelioration practices are found to only partially remediate soil acidity, hence yield responses can be variable as observed from various long-term field trials (Davies 2018). Scanlan et al. (2014) suggested that if a tillage operation is used to mix lime to the depths where the soil pH constraint occurs then an immediate payback on lime and cultivation might be possible. In paddocks where multiple soil constrains such as compaction and subsoil acidity are present, most crop roots are confined within 20-30 cm of the surface (Davies 2018). With such shallow root systems a large proportion of growing season rainfall quickly drains away beyond the root zone resulting low WUE for major crops. The aim of this filed trial was to test whether '*Re-engineering*' (deep tillage and lime incorporation) soils profile with multiple constraints can significantly improve rooting depth of a grain crop towards optimising WUE and grain yield.

Method

This is on-going field trial established in a continuously cropped paddock near Kalannie, Western Australia (35°42'S, 117°29'E). The soil is classified as a Yellow-orthic acidic Tenosol in the Australian Soil Classification (Isbell 2002). Soils in this region were naturally acidic before being cleared for use in agriculture. These soils are also locally known as Wodjil soils. Both surface and subsurface soils were strongly acidic (surface pH_{Ca} 4.35, subsurface pH_{Ca} 3.95) and, particularly the subsurface soil, extremely aluminium toxic (~30 mg/kg). This soil has a loamy-sand texture throughout the profile. The paddock was highly compacted (penetrometer resistance 3-4 MPa). The soil had low levels of organic carbon (surface 0.85%, subsurface 0.32%). N, P and K contents were in average level in the topsoil.

The trial was established in April 2018 and consisted of plots of 3 x 2 m size within a randomised block design, replicated three times. There were five soil amelioration treatments (Fig. 1) comprising an untreated control (T0) and four treatments involving either removal of compaction only (T1) or removal of both compaction and acidity (T2, T3 and T4). There were a total of 12 control plots, paired with one of the plots in the other four treatments.

For the four amelioration treatments (T1-T4), two soil horizons (0-10 and 10-30 cm depths) were removed separately and then replaced. A third horizon (30-45 cm depth) was then spaded *in situ* using a small rotary hoe to a depth of approximately 45 cm. For T4, 1.5 t/ha lime was spread on top of the third horizon before spading. The second horizon (10-30 cm depth) was then back-filled and 3 t/ha lime was applied for T3 and T4 before all the plots were rotary hoed. Top soil was then returned and 1.5 t/ha lime was applied to the plots of T2, T3 and T4 before all the plots were rotary hoed. The lime used had a 94.9% neutralising value.

The trial was sown to c.v. Mace wheat at 60 kg/ha with 22cm row spacing. All plots were fertilised with 37 kg/ha of mono-ammonium phosphate (21.9% phosphorus, 10% nitrogen), 100 kg/ha of sulphate of potash (41.5% potassium and 17% sulphur) and 57 kg/ha of urea (46% nitrogen) at sowing.

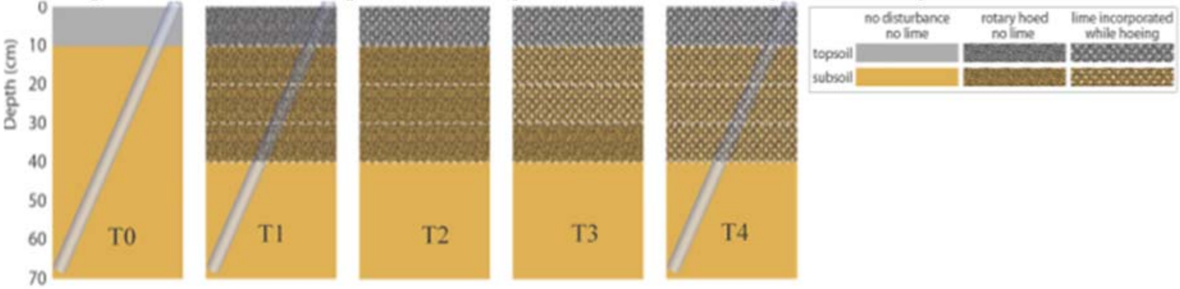

Figure 1: A schematic diagram of the four amelioration treatments and the control.

Soil profile moisture content was measured in July (wettest soil profile) and October (after the grain filling) from all plots using a Diviner 2000 (Sentek Technology, Adelaide, SA). Changes in soil moisture for different depths were calculated by subtracting October measurements from corresponding measurements in the July. Wheat root architecture (for T0, T1 and T4 as shown in Fig. 1) was also imaged repeatedly *in situ* using a clear glass tubes (Rhizo tubes, ICT International, Armidale, NSW) and a 360° scanner (CI-600, CID Bio-Science, Camas, Washington, USA). Soil profile samples were collected at 0-10, 10-20, 20-30, 30-40 and 40-50 cm depths from each plot to measure soil pH and Al concentration using 1:5 soil:0.01M $CaCl_2$ extract. Plant samples were collected at the tillering for measuring nutrient uptake. The wheat crop was harvested by hand-cuts for measuring biomass and grain yields. 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 treatment effects with polynomial contrasts. Fisher's protected least significant difference (LSD) was applied at the 0.05 significance level.

Results

Soil excavation significantly decreased soil resistance (i.e., compaction) from 3-4 MPa in T0 to 0.5-1.5 MPa in T1-T4 and there was no significant difference between four excavated treatments (Fig. 2a). Lime incorporation increased soil pH to the minimum recommended pH_{Ca} of 5.5 in the surface and 4.8 in the most lime incorporated horizons (Fig. 2b). Liming also decreased total Al from a very toxic range to below the critical level for wheat. Incorporation of soil only (T1) also decreased Al concentration, especially at 10-20 cm depth (Fig. 2c).

Due to the above improvement in soil chemical and physical properties, there was significant improvement in root growth. Root growth was restricted to within 20-25 cm depth for the unameliorated control. For treatments T1-T4 wheat roots grew down to 60-65 cm depth, where lime was incorporated at depths (T3 and T4), there were more fine roots and roots hairs in the deeper horizons. The wheat crop growing on ameliorated soil profiles was found to extract more water from subsurface soil, especially below from 30cm depth, than from the untreated control. There were no significant differences in soil moisture status between four amelioration treatments. Large variation in soil moisture status was observed within the treatment (Fig. 2d).

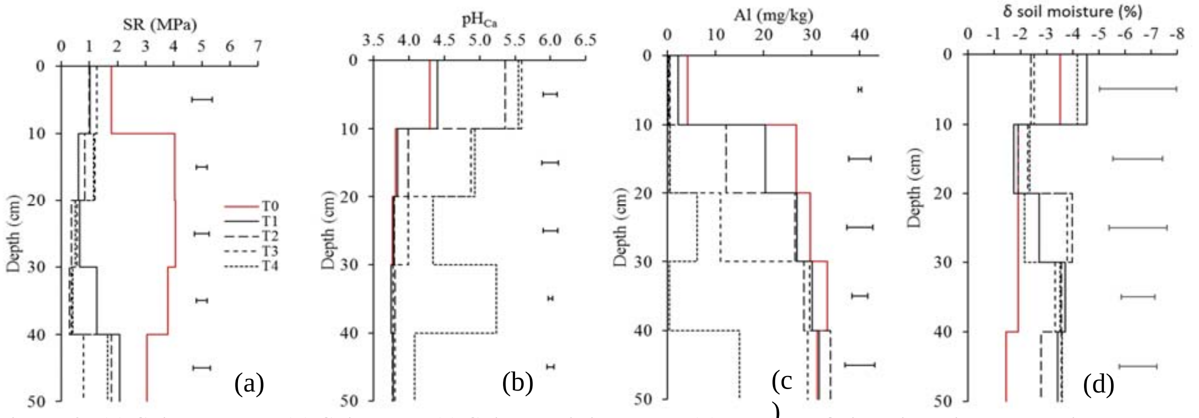

Figure 2: (a) Soil strength, (b) Soil pH$_{Ca}$, (c) Soil aluminium, and (d) changes, δ, in soil moisture. Horizontal bars represent least significant difference at the 0.05 significance level.

Liming significantly increased N, P, K, Ca, Mg, Mo and Cu concentration in wheat tissue at tillering stage (Fig. 3a-h). Lime and incorporation had some negative effect on Mn (Fig. 3h) and Zn (data not presented) concentration in wheat tissue, but their concentrations were still higher than the critical levels.

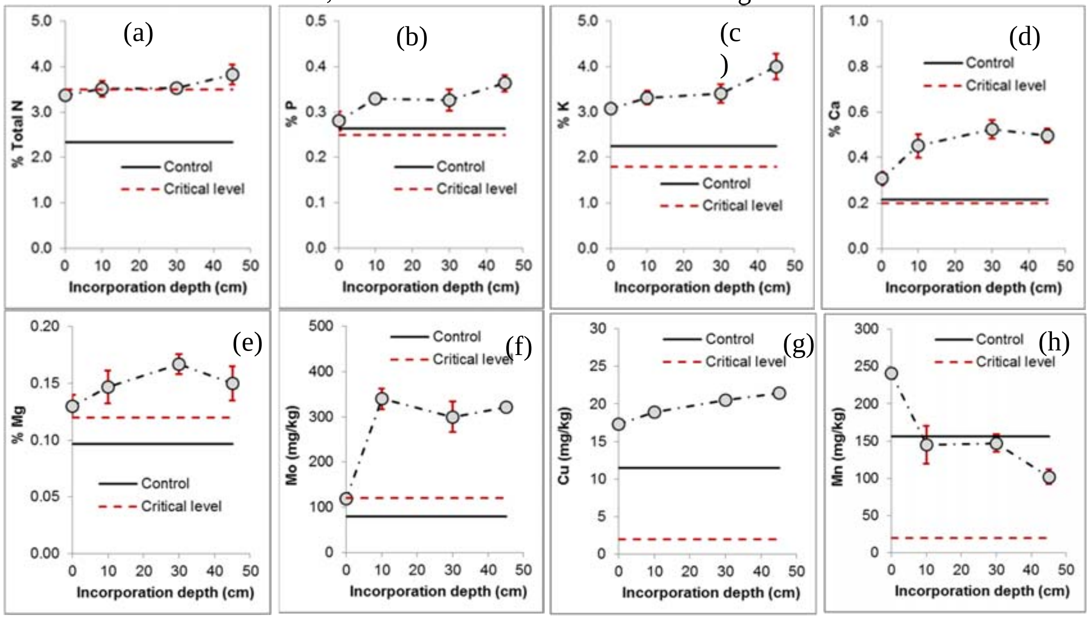

Figure 3: Concentration of nutrients wheat tissue at tillering. Incorporation depths, on X-axis, correspond to T1 (incorporation only), T2 (1.5 t lime incorporated to 10 cm depth), T3 (4.5 t lime incorporated to 30 cm depth) and T4 (6 t lime incorporated to around 45 cm depth). Vertical bars represent ± standard error of the mean.

Plant biomass production in was doubled in T2, T3 and T4 compared to the untreated control (Fig. 4a). Ultimately, wheat grain was more than double in the deep lime incorporated treatment compared to the untreated control (Fig. 4b). Incorporation of 6 t/ha lime to 0-45 cm depth produced significantly greater yield than the incorporation of 1.5 t/ha lime to 0-10 cm soil. Removal of compaction only also increased biomass and grain yield by 72% compared to the untreated control. WUE was also doubled (24 kg/mm in T4) compared to the untreated control (11 kg/mm). These improvements in plant growth, grain yield and WUE strongly correlated with depth of amelioration of in soil acidity and compaction.

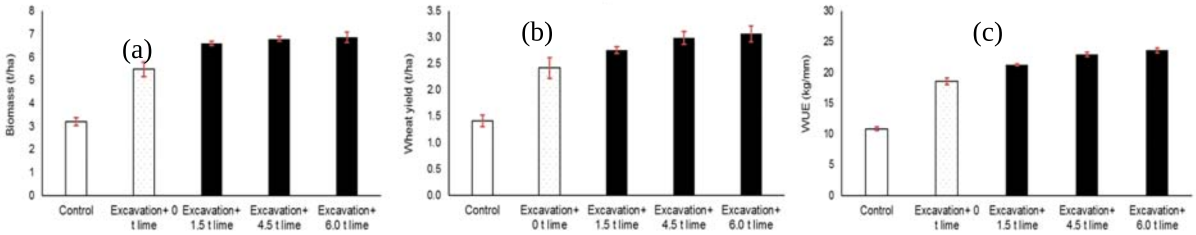

Figure 4: Improvement in wheat (a) biomass, (b) grain yield, and, (c) water use efficiency in 2018 due deep incorporation of lime. Vertical bars represent ± standard error of the mean.

Conclusions

Our results demonstrate that lime incorporation increased soil pH by more than a pH unit at the depths of lime incorporation within two months, which decreased Al concentration below the critical toxic level for wheat. Removal of compaction and lime incorporation together produced deep root systems (with root hairs), which allowed plants to extract soil water and nutrients from deeper soil horizons (Scanlan et al. 2014). Removal of compaction only also yielded >70% higher biomass and grain yield compared to the control. This is due to decreased soil resistance and some decrease in Al concentration (probably due to redistribution of organic material and clay particles at depths). Mace wheat also has medium level of tolerance to Al toxicity which is proven by the fact the roots (mainly seminal roots) grew down to 60-65 cm depth.

In general, producing large biomass in low rainfall regions of WA is considered highly risky of haying off the crops especially in a dry finishing season. Our soil amelioration treatments (T2-T4) produced twice the amount of biomass, compared to the control, but extraction of soil water from the deeper horizons protected the crop from haying off in a dry finish of the season 2018.

This trial demonstrated that deep amelioration of soil compaction and acidity could double the wheat grain yield, which exceeded the modelled yield potentials and WUE for the low rainfall region of WA, reported in van Gool (2001). Data will be collected in 2019 and 2020 to quantify the longevity of the benefits.

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