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Research Article

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Barley Root and Shoot Responses to Soil Re-engineering and Fertiliser Strategies in an Acidic Duplex Soil in Western Austraia

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Abstract

Purpose Soil acidity, compaction, and low nutrition constrain crop productivity in texture-contrast soils of southern Australia. This study evaluated the effects of soil re-engineering (RE) and fertiliser strategy on root development and early growth of barley (*Hordeum vulgare* L.) grown in a strongly acidic Kurosol. ***Methods*** Four RE treatments: no amendments, clay incorporation, lime incorporation, and lime and clay incorporation were combined with three fertiliser strategies: low-rate banded (F1), moderate-rate banded (F2), and high-rate incorporated at 0–80 cm (F3). Barley was grown for 22 weeks in reconstructed soil columns under semi-controlled conditions. ***Results*** Lime incorporation substantially increased pH_{Ca} from 4.3 to 5.4 and decreased aluminium concentrations to near zero. These changes promoted deeper and denser root systems, resulting in 258% greater volumetric root length density and 195% higher shoot biomass than unlimed treatments. Fertiliser strategy influenced crop performance, with F3 producing the greatest shoot biomass, tiller number, root growth and nutrient uptake. Across RE treatments, the F3 strategy generally produced greater shoot growth and nutrient uptake than the lower-rate banded strategies; however, because F3 differed in both nutrient rate and placement, these responses cannot be attributed independently to either factor. Root growth was positively correlated with soil pH_{Ca} ($r = 0.53$) and negatively correlated with aluminium concentration ($r = -0.69$). ***Conclusions*** These findings demonstrate that lime incorporation into acidic soil profiles is critical for improving root-zone conditions and barley root development in Kurosols, while highlighting the need to optimise fertiliser rate and placement for re-engineered soil profiles.

Keywords

Soil re-engineering, subsoil acidity, lime and clay deep incorporation, barley root development, texture-contrast soils

1. Introduction

The development of a deeper and denser root system enhances a crop's ability to access water and nutrients from the subsoil (Lynch 1995), thereby improving water and nutrient use efficiency and overall productivity (Kell 2011; Azam et al. 2025). In Australia's arid and semi-arid agricultural zones, where rainfall is the primary source of water, the ability of roots to exploit deeper soil layers is a key determinant of crop yield (Sadras and Angus 2006; Barrett-Lennard et al. 2024; Azam et al. 2026b). However, widespread subsoil constraints (van Gool 2016), particularly acidity (Gazey et al. 2019), compaction (Bengough et al. 2011), and low water holding capacity (Azam et al. 2026c), limit root growth and functions (Lynch 2022), ultimately restricting water and nutrient uptake.

Soils in the south-west of Western Australia (WA) are typically ancient, highly weathered, and nutrient-depleted (Eldridge et al. 2018), and approximately half of the subsoils are acidic having soil pH_{Ca} values below the minimum acceptable threshold of 5.5 in the 0–10 cm soil layer and 4.8 for soil layers below 10 cm (Gazey et al. 2019). Many of these soils fall under the Kurosol order, characterised by a strong textural contrast between the A and B horizons (Isbell 2021). In these soils, acidity and compaction frequently occur together (van Gool 2016), resulting in high mechanical impedance (Bengough et al. 2011; Azam and Davies 2023) and elevated concentrations of soluble aluminium (Al) that damage root tips (Delhaize and Ryan 1995) and consequently restrict root elongation (Azam et al. 2025). Under soil water stress, Al toxicity can further increase root oxidative stress and inhibit root elongation of barley due to their combined effects (Tamás et al. 2006; Wickramarachchi and Azam 2026). This interaction can limit water and nutrient uptake during terminal drought, which commonly occurs during the critical grain-filling period (Yang et al. 2013). These factors contribute to shallow rooting, poor water and nutrient extraction, and yield gaps commonly reported in grain-based, rain-fed cropping systems across WA (Gregory 1997; Lawes et al. 2021).

Deep tillage and the incorporation of amendments such as lime, clay and organic and inorganic nutrients have been employed in previous studies to alleviate these subsoil constraints and promote deeper rooting (Azam et al. 2023; Azam et al. 2026c; McBeath et al. 2010; Celestina et al. 2018; Uddin et al. 2025; McEwen and Johnston 1979). Recently developed "soil re-engineering" approaches in WA have extended this concept, incorporating ameliorants to a depth of 80 cm in combination with soil loosening (Azam and Reynolds 2026; Azam and Davies 2023), which is well beyond the typical maximum soil amelioration intervention depth of 40–50 cm recorded previously. These interventions have demonstrated marked improvements in root growth and yield potential (Azam et al. 2025; Wickramarachchi and Azam 2026). Among these amendments, clay incorporation has emerged as particularly promising for enhancing water holding capacity and nutrient retention, especially in coarse-textured or duplex soils with inherently low moisture storage in the sandy layers (Betti et al. 2015; Schapel et al. 2018; Azam and Reynolds 2026). Adding clay to sandy or sandy-loam horizons increases soil aggregation, reduces hydraulic conductivity, and plant-available water (Betti et al. 2016; Hall et al. 2010).

The effectiveness of clay addition, however, depends strongly on clay mineralogy. Expanding 2:1 clay minerals such as smectite generally have greater specific surface area, permanent charge and cation exchange capacity than low-activity 1:1 minerals such as kaolinite, providing greater capacity for water and nutrient retention (Ma and Eggleton 1999; Środoń and McCarty 2008). Consequently, the agronomic effects of clay addition cannot be

inferred from clay concentration alone, and both the amount and mineralogical composition of the added clay need to be considered. This is particularly relevant to highly weathered Western Australian soils, where kaolinite commonly dominates the clay fraction. When combined with lime, clay can also buffer pH_{Ca} variation and stabilise improvements in soil structure and chemical toxicities (Betti et al. 2016; Wickramarachchi and Azam 2026).

Under conventional crop management, inorganic fertilisers supplying nitrogen (N), phosphorus (P) and potassium (K) are typically applied near the soil surface. This practice can result in leaching losses of highly mobile nutrients such as N and K early in the season, when roots are actively developing and rainfall is frequent, as well as N losses through volatilisation (Anderson et al. 1998). Moreover, preferential root proliferation in nutrient-rich surface layers can accelerate surface soil drying, thereby limiting nutrient uptake later in the season and ultimately constraining crop growth and yield (Drew and Saker 1978). In addition, evidence suggests that localised nutrient application can stimulate root proliferation around nutrient dense patches, potentially supressing deeper root growth and exploration (Robinson 1994). As soil re-engineering ameliorates multiple key chemical and physical constraints and has been shown to promote deeper and denser root systems in the soil columns (Wickramarachchi et al. 2025; Wickramarachchi and Azam 2026) as well as in the field (Azam et al. 2025; Azam et al. 2026d). It is therefore important to examine the effects of inorganic nutrient application rates and placement strategies on root and crop growth and yield in re-engineered soil profiles (Angus and Grace 2017; Azam et al. 2026c; Htwe et al. 2023; McLachlan et al. 2024; Uddin et al. 2025; Robinson 1994). Deep incorporation of both organic and inorganic fertilisers, with equivalent nutrient inputs, has been implemented in soil re-engineering field trials (Azam et al. 2026c; Azam et al. 2024). However, this one-off deep placement of nutrients is not a practical long-term strategy, as nutrient supplies require seasonal replenishment to sustain crop productivity. Consequently, a knowledge gap remains in the development of effective nutrient management strategies for re-engineered soil profiles where physical and chemical constraints have been alleviated.

In a related deep soil-column study using the same Kurosol, Wickramarachchi and Azam (2026) showed that deep lime incorporation increased subsoil pH and reduced extractable aluminium to near-undetectable levels throughout the profile. This chemical amelioration promoted deeper and more uniform rooting, increasing total root surface area by 1.5-fold and volumetric root length density by 1.9-fold compared with soil loosening alone. Greater root development was also associated with increased subsoil water extraction under terminal moisture stress. Importantly, grain yield and shoot biomass responded linearly to increasing N supply only in limed soils, whereas responses plateaued at moderate N rates in unlimed soils, demonstrating that subsoil acidity constrained N fertiliser efficiency. Liming also increased subsoil organic carbon and altered residual nutrient distributions. These findings established the importance of alleviating subsoil acidity for improving root-zone function and nutrient-use efficiency, while highlighting the need to better understand fertiliser management strategy in re-engineered soil profiles.

Despite demonstrated improvements in soil conditions following profile re-engineering, uncertainty remains regarding how amendment of the root zone influences barley root development, nutrient acquisition and responses to subsequent fertiliser management strategy. This study therefore aimed to determine how incorporation of lime and predominantly kaolinitic clay within reconstructed loosened soil profiles, together with contrasting N, P and K fertiliser strategies, influenced barley root development, nutrient acquisition and

aboveground growth. We hypothesised that: (i) incorporation of kaolinitic clay, alone or with lime, would modify soil water and nutrient availability and consequently influence barley root and shoot growth; and (ii) barley root distribution, nutrient acquisition and aboveground growth would differ among contrasting fertiliser management strategies. Because fertiliser rate and placement were not manipulated independently, the fertiliser treatments were evaluated as integrated management strategies rather than as independent tests of rate or placement.

2. Materials and Methods

An experiment was conducted during the winter of 2022 in a screenhouse facility at the Department of Primary Industries and Regional Development (DPIRD) in Northam, Western Australia (31.65° S, 116.70° E). The soil used in the experiment was collected from a continuously cropped field near Meenar, WA (31.64° S, 116.89° E) adjacent to, but not part of a parallel re-engineering field experiment. The soil was identified as a Brown Kurosol (Isbell 2021), comprising coarse sandy topsoil (0–10 cm), loamy sand midsoil (10–40 cm), and sandy clay subsoil (40–80 cm) (Table 1).

Table 1 Properties of the soil used in the experiment.

Parameters	**Values in three depths**		
	Topsoil (0–10 cm)	Midsoil (10–40 cm)	Subsoil (40–80 cm)
Soil textural class	Coarse sand	Loamy sand	Sandy clay
Clay content (%)*	4.9	10.2	36.7
Soil organic carbon (SOC, %)	1.29	0.43	0.23
pH_{Ca}	4.5	4.2	4.0
Extractable aluminium (Al, mg kg^{-1})	1.7	14.2	13.7
Inorganic N (mg kg^{-1})	17.0	4.5	4.5
Colwell P (mg kg^{-1})	17.7	11.9	4.0
Colwell K (mg kg^{-1})	25.3	21.9	16.3
Sulfur (mg kg^{-1})	28.1	19.6	65.8
Cation exchange capacity (CEC, cmol kg^{-1})	1.35	0.51	0.80

**More than 95% of the clay fraction was kaolinite.*

The surface soil (0–3 cm) was weakly water repellent (mean ethanol droplet value of approximately 1.5), while the entire profile was strongly acidic, with pH_{Ca} values ranging from 4.0 to 4.5 (measured in 0.01 M $CaCl_2$), whereas extractable Al occurred at potentially toxic concentrations (Gazey et al. 2019) in the acidic soil layers (Table 1), confirming Al toxicity as an important chemical constraint. Soil organic carbon (OC) declined from 1.29% in the topsoil (0–10 cm) to 0.23% in the subsoil. Inorganic N concentrations ranged from 17.0 mg kg^{-1} in the topsoil to 4.5 mg kg^{-1} in the subsoil. Colwell P ranged from 4.0 to 17.7 mg kg^{-1} and Colwell K from 16.3 to 25.3 mg kg^{-1}, both below critical values for cereal production (Bell et al. 2013; Brennan and Bell 2013). Initial soil analyses indicated that sulfur and other measured nutrients were sufficient for barley growth (Robinson 1994). However, the complex mineral fertiliser used in all fertiliser treatments supplied extra sulfur, magnesium, boron and zinc in addition to N, P and K, reducing the likelihood that deficiencies of these nutrients constrained crop growth. The soil had a very low cation exchange capacity (CEC) with maximum of 1.36 cmol kg^{-1} in the topsoil.

2.1 Experimental design

This experiment was designed as a factorial combination of four soil re-engineering treatments and three fertiliser treatments, with three replications (Table 2, n = 36). The reconstructed soil columns were used to systematically assess the effects of deep soil loosening alone and in combination with the deep incorporation of lime, clay, or both lime and clay as re-engineering treatments. Three fertiliser treatments were: F1, a low rate of N, P and K placed below the seed; F2, double the F1 fertiliser rate and applied below the seed; and F3, a deep incorporation treatment. For F3, the F1 fertiliser rate was multiplied by eight to represent eight of 10-cm increments at the F1 rate, and this total amount was evenly distributed throughout the soil profile from 0 to 80 cm (Table 2). The fertiliser treatments therefore represented three contrasting management strategies that differed in nutrient rate and, for F3, also in vertical placement. Accordingly, comparisons involving F3 were interpreted as responses to the overall fertiliser strategy rather than as independent effects of fertiliser placement or rate.

Table 2 Description of the re-engineering and fertiliser treatments used in the experimental design.

Factors	Code	Levels
Soil re-engineering [1]	L	No amendments
	LC	Clay incorporated at 0–40 cm
	LL	Lime incorporated at 0–80 cm
	LLC	Clay incorporated at 0–40 cm and lime incorporated at 0–80 cm
Fertiliser strategy	F1	Low NPK banded below seeds (27 kg N ha^{-1}, 13 kg P ha^{-1} and 21 kg K ha^{-1})
	F2	Moderate NPK banded below seed (54 kg N ha^{-1}, 26 kg P ha^{-1} and 43 kg K ha^{-1})
	F3	High NPK, uniformly incorporated at 0-80 cm soil depth prior to column filling (216 kg N ha^{-1}, 104 kg P ha^{-1} and 168 kg K ha^{-1})

[1]All soil re-engineering treatments represented loosened soil profiles; the treatment codes have been retained for consistency with the associated field experiment and previous publications. For lime treatment, 1g of lime kg^{-1} of soil was added to the soil/soil mixture of each layer (Azam and Gazey 2023); bulk clay was added to clay treatment to get a final 7% (topsoil, 0–10 cm) or 13% (mid soil, 10–40 cm) of clay in the soil mixture.

2.2 Soil collection and preparation of columns

Three distinct soil layers were collected from the field by excavating and handled separately to account for the vertical physio-chemical stratification observed in the soil profile at the experimental site: topsoil (0–10 cm), midsoil (10–40 cm), and subsoil (40–80 cm). Each layer was air-dried, sieved (<2 mm), and homogenised before being used to reconstruct soil columns that resembled the re-engineered soil profiles developed in a parallel field experiment (Azam et al. 2024).

Soil columns were constructed using polyvinyl chloride (PVC) tubes (15.1 cm internal diameter, 85 cm height) fitted with perforated base caps to allow drainage. A wick extending through the base facilitated drainage and prevented waterlogging at the bottom of the column (Zhu et al. 2003). The inner surfaces of the tubes were lightly coated with a lithium-based lubricant (Kincrome NLGI2 Lithium Complex, Kincrome Australia Pty Ltd., Scoresby, Victoria, Australia) to minimise edge-rooting effects. The soils were packed into three layers (0–10, 10–40, and 40–80 cm) following the method described by Wickramarachchi et al. (2025).

Soil collected from each of the three field layers was individually homogenised using a rotary cement mixer before packing into the columns. For all incorporation treatments, each soil layer was thoroughly mixed with the required amounts of lime, clay and fertiliser before being packed into the PVC tubes. Fertiliser was incorporated at this homogenising stage only in columns receiving the F3 treatment. For the clay treatments, sandy clay subsoil collected from the 40–80 cm layer of an adjacent area of the same paddock was used as the amendment. The clay content of this material was measured before treatment preparation, and >95% of its clay fraction was kaolinite. The amount of clay-rich subsoil added to each layer was calculated by mass balance using the measured clay contents of the amendment and receiving soil to achieve final clay contents (w/w) of 7% in the topsoil (0–10 cm), to eliminate water repellence (Hall et al. 2010), and 13% in the midsoil (10–40 cm), to optimise plant-available water (Betti et al. 2016). No clay-rich subsoil was added to the naturally clay-rich subsoil layer (40–80 cm).

The respective layers were compacted to target bulk densities of 1.4 g cm^{-3} for the topsoil and 1.5 g cm^{-3} for the underlying layers, corresponding to an optimum soil strength (Azam et al. 2025). These densities closely matched those achieved under field soil-loosening treatments in the re-engineering trial (Azam and Reynolds 2026). However, the dry-column filling approach used in the column setup did not permit accurate replication of the higher bulk densities (1.80 g cm^{-3}) observed in field control plots that had not been physically loosened. Therefore, all treatments in this experiment represent loosened soil profiles from the field re-engineering trial. Due to the technical constraints described above, no treatment representing the unloosened paddock control was included; consequently, this experiment was not designed to quantify the independent effect of soil loosening as reported in Wickramarachchi and Azam (2026).

2.3 Crop seeding and management

Before sowing, all soil columns were gradually wetted to near saturation and then allowed to drain under gravity for 48 h to reach field capacity (FC). To minimise evaporative water loss during this equilibration period, the topsoil surface of each column was covered with a thin polyethylene film. A barley (*Hordeum vulgare* L. cv. Maximus) crop was selected for the experiment. Sowing was conducted manually on 22 August 2022 by placing ten seeds per column at a uniform depth of 3 cm. Seeds were arranged in a circular pattern approximately 3.8 cm from the column centre, midway between the centre and the tube wall. Thinning was performed 13 days after sowing (DAS), retaining four healthy and uniform seedlings per column, corresponding to an equivalent plant density of approximately 224 plants m^{-2}. The crop was grown for 72 days, from 22 August to 1 November 2022, corresponding to the Western Australian winter growing season.

The experiment followed a randomised complete block design with three replicates and was conducted in a semi-controlled screenhouse environment to minimise environmental variability. The screenhouse was covered with a woven fabric that allowed approximately 70% of incoming sunlight and about 95% of rainfall to pass through, while permitting air movement and maintaining a suitable microenvironment for plant growth.

After crop emergence, irrigation was applied twice per week throughout the growing period using an overhead sprinkler system to maintain soil water content at approximately 75% of the FC of the clay-amended columns. Prior to each irrigation event, columns were weighed to estimate the volume of water required to restore 75%

FC. This approach ensured that all columns were maintained at or above 75% FC. Consequently, columns without clay addition received slightly higher moisture levels relative to their FC.

The FC of the clay-amended columns was determined by saturating the pre-weighed soil columns and allowing them to drain freely to FC. The FC was calculated as the difference between the weight of the columns at FC and the weight of the soil columns before saturation. This FC was also confirmed by using the pressure plate method (models 1500F1 and 1600; Soil Moisture Equipment Co., Santa Barbara, CA, USA). Irrigation was applied using a calibrated overhead sprinkler system, and three rain gauges positioned among the columns were used to monitor irrigation distribution. The same gauges were also used to quantify natural rainfall reached the columns and irrigation between consecutive events, allowing calculation of the total water input received by the crop during the entire growth period. Overall, all columns received approximately the same total volume of water, either through irrigation or rainfall passing through the screenhouse roof made of mesh.

Fertiliser treatments were prepared using granular complex mineral fertiliser (Elixir Supreme™, Elixir Zorka – Mineral Fertilizers Production, Serbia; containing 12% ammoniacal N, 11% P_2O_5, 18% K_2O in sulfate form, 2% magnesium oxide, 15% sulfur, 0.01% boron and 0.02% zinc) and urea, with the latter supplying N in the amide form. The fertiliser mixtures were formulated so that N supplied as ammoniacal N from the complex fertiliser and as amide N from urea was applied at a 1:1 ratio. Prior to sowing fertilisers were banded 3 cm below the seeding depth in a single band for the F1 and F2 treatments. In contrast, fertilisers in the F3 treatment were incorporated into each of the three soil layers separately during homogenisation, prior to the construction of the soil columns.

2.4 Soil and plant measurements

At 72 DAS, when approximately 75% of plants had reached head emergence (Zadoks growth stage Z57) (Zadoks et al. 1974), productive tillers were counted for each column before harvest and expressed as the number of productive tillers per plant. Plants were then harvested by clipping the shoots 1 cm above the soil surface. The harvested aboveground material from each column was oven-dried at 60°C until constant weight and weighed to determine shoot dry biomass, expressed as g column^{-1}. The dried shoot material was subsequently ground and subsampled for determination of N, P and K concentrations and calculation of plant nutrient uptake. Following harvest, PVC columns were positioned horizontally and cut longitudinally to expose the soil profile (Supplimentary Fig. S1b). The soil column was divided into discrete depth intervals of 0–10, 10–20, 20–30, 30–40, 40–60, and 60–80 cm. Sampling was conducted at 10 cm increments for the upper four layers and at 20 cm increments for the deeper two layers considering the typically lower root density below 40 cm (Wacker et al. 2024).

Roots were retrieved by wet sieving through a 0.7 mm mesh, gently washed to minimise damage, and stored in water at 3–4°C until imaging. Root systems were scanned underwater using a flatbed scanner (Epson Perfection V800; Epson, Japan) at 400 dpi, and image analysis was performed using WinRHIZO Pro 2007a (Regent Instruments, Québec, Canada) to quantify root traits such as total root length and root diameter using the global threshold method. Before scanning, roots were gently dispersed in water to minimise overlap. Where root abundance was too high to permit adequate separation within a single scanning tray, the sample was divided

among multiple scans, and the root lengths obtained from individual scans were summed to calculate total root length for that depth interval. To account for differing sampling depths across the soil profile, root length measurements were converted to volumetric root length density (vRLD; cm root length cm^{-3} soil) for each depth interval and for the entire soil profile (Wacker et al. 2024).

At the time of root extraction, soil samples were collected from each depth interval for chemical analyses. A subsample was immediately used to determine gravimetric soil moisture at harvest by oven drying at 105 °C. The remaining soil was air-dried at 40 °C and sieved (<2 mm) before laboratory analysis. Soil pH_{Ca} and extractable aluminium concentration (EAC) were measured in 0.01 M $CaCl_2$ following (Bromfield 1987). Soil organic carbon, ammonium, nitrate, Colwell P ($P_{Colwell}$), and Colwell K ($K_{Colwell}$) were analysed according to the methods described by Rayment and Lyons (2011) (Methods 6A1, 7C2b[GA2.1], 9B2, and 18A1, respectively).

2.5 Statistical Analyses

All statistical analyses were performed using GenStat (Version 22, VSN International, Oxford, UK). The experimental data were analysed with a two-factor or three-factor analysis of variance (ANOVA) to determine the effects of soil re-engineering (RE) treatment, fertiliser strategy, sampling depth and their interactions on the measured soil properties and plant growth responses. Where the overall ANOVA F-test indicated a significant treatment effect ($P \leq 0.05$), treatment means were compared using Fisher's protected least significant difference (LSD) test at $P \leq 0.05$. Pairwise comparisons were not performed where the corresponding overall F-test was non-significant.

Associations between soil attributes and root traits were examined using Pearson correlation and simple linear regression. For each relationship, the correlation coefficient (r), coefficient of determination (r^2), and associated probability (P) were reported to describe the strength and significance of the relationship. Statistical significance was accepted at $P \leq 0.05$.

3. Results

3.1 Shoot growth and biomass and tiller production

There was no significant interaction between re-engineering (RE) treatment and fertiliser strategy in barley shoot biomass and tiller count (Table 3, $P > 0.05$). However, there were significant main effects of RE treatment ($P < 0.001$) and fertiliser strategy ($P = 0.003$) (Table 3, Fig. 1a and 1d). The LL and LLC treatments had significantly higher shoot biomass and tiller count than the L and LC treatments (Table 3, Fig. 1a and 1b). There was no difference between LL and LLC treatments and there was also no difference between L and LC treatments. The highest shoot biomass (11.8 g $column^{-1}$) and tiller number (2.9 tillers $plant^{-1}$) was observed in LL treatment, and the lowest shoot biomass (3.5 g $column^{-1}$) and tiller number (1.4 tillers $plant^{-1}$) was found in L treatment. These improvements equate to 241% and 112% increases in shoot biomass and tiller count in LL treatment compared to L treatment. These improvements were also visually evident in Figure 2.

Across fertiliser strategies, shoot biomass (Fig. 1d) and tiller count (Fig. 1e) increased stepwise in the order F1 < F2 < F3. The highest shoot biomass (9.6 g $column^{-1}$) and tiller number (2.6 tillers $plant^{-1}$) were observed under the F3 strategy, whereas the lowest shoot biomass (5.4 g $column^{-1}$) and tiller number (1.7 tillers $plant^{-1}$)

occurred under the F1 strategy. These improvements correspond to 78% and 53% increases in shoot biomass and tiller number, respectively, in the F3 strategy compared with F1. In contrast, increases in shoot biomass and tiller number under the F3 strategy compared with F2 were only 20% and 13%, respectively. These improvements were also visually evident in as shown in Figure 2.

Table 3 Summary of the analysis of variance to evaluate the effect of re-engineering treatment (RE), fertiliser strategy (F), and soil depth (D) and their interactions on plant growth and nutrient uptake. SB = shoot biomass (per column), PT = productive tiller (per plant), TRL = total root length (per column), vRLD = volumetric root length density (cm root per cm^3 soil) of barley (*Hordeum vulgare* L. var. Maximus). N = nitrogen, P = phosphorus and K = potassium.

Variate	SB	PT	TRL	vRLD	N uptake	P uptake	K uptake
RE	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F	0.003	0.007	0.018	<0.001	0.030	<0.001	0.004
D	-	-	-	<0.001	-	-	-
RE x F	0.379	0.597	0.958	0.584	0.887	0.156	0.609
F x D	-	-	-	0.445	-	-	-
RE x D	-	-	-	<0.001	-	-	-
RE x F x D	-	-	-	0.911	-	-	-

3.2 Root length, root density and distribution across the depth

Total root length (TRL) per soil column was significantly influenced by both soil re-engineering (RE) treatment and fertiliser strategy (Table 3; Fig. 1c and 1f). The LL and LLC treatments produced significantly greater TRL than L and LC, with no significant difference between LL and LLC or between L and LC (Fig. 1c). TRL was highest in LL (122 m $column^{-1}$) and lowest in L (31 m $column^{-1}$), representing a 293% increase with lime incorporation. Fertiliser strategy also significantly affected TRL, with F3 producing greater TRL than F1 and F2, while F1 and F2 did not differ significantly (Fig. 1f). TRL under F3 was 28.5% greater than under F1.

Volumetric root length density (vRLD) responded strongly to RE treatment and varied with soil depth (Fig. 3a). The significant RE treatment × depth interaction ($P < 0.001$; LSD = 0.19; Table 3) showed that the effect of RE treatment varied across the soil profile. Overall, the lime-incorporated treatments (LL and LLC) maintained greater vRLD throughout the profile than L and LC, consistent with the visual root distribution shown in Figure 4. In L and LC, vRLD declined sharply with depth, whereas LL and LLC supported deeper and more uniform root distribution (Figs. 3a, 3b and 4). LL treatment had significantly greater vRLD than LLC at 20–30 cm depth, but the two treatments did not differ at other depths. Similarly, no significant differences in vRLD were detected between L and LC at any depth (Fig. 3a).

Fertiliser strategy had a significant main effect on vRLD, whereas its interactions with RE treatment and sampling depth were not significant (Table 3). The vRLD was the highest under F3 (0.73 cm cm^{-3}) and the lowest under F2 (0.58 cm cm^{-3}), representing a 25.9% increase under F3 relative to F2 (data not shown).

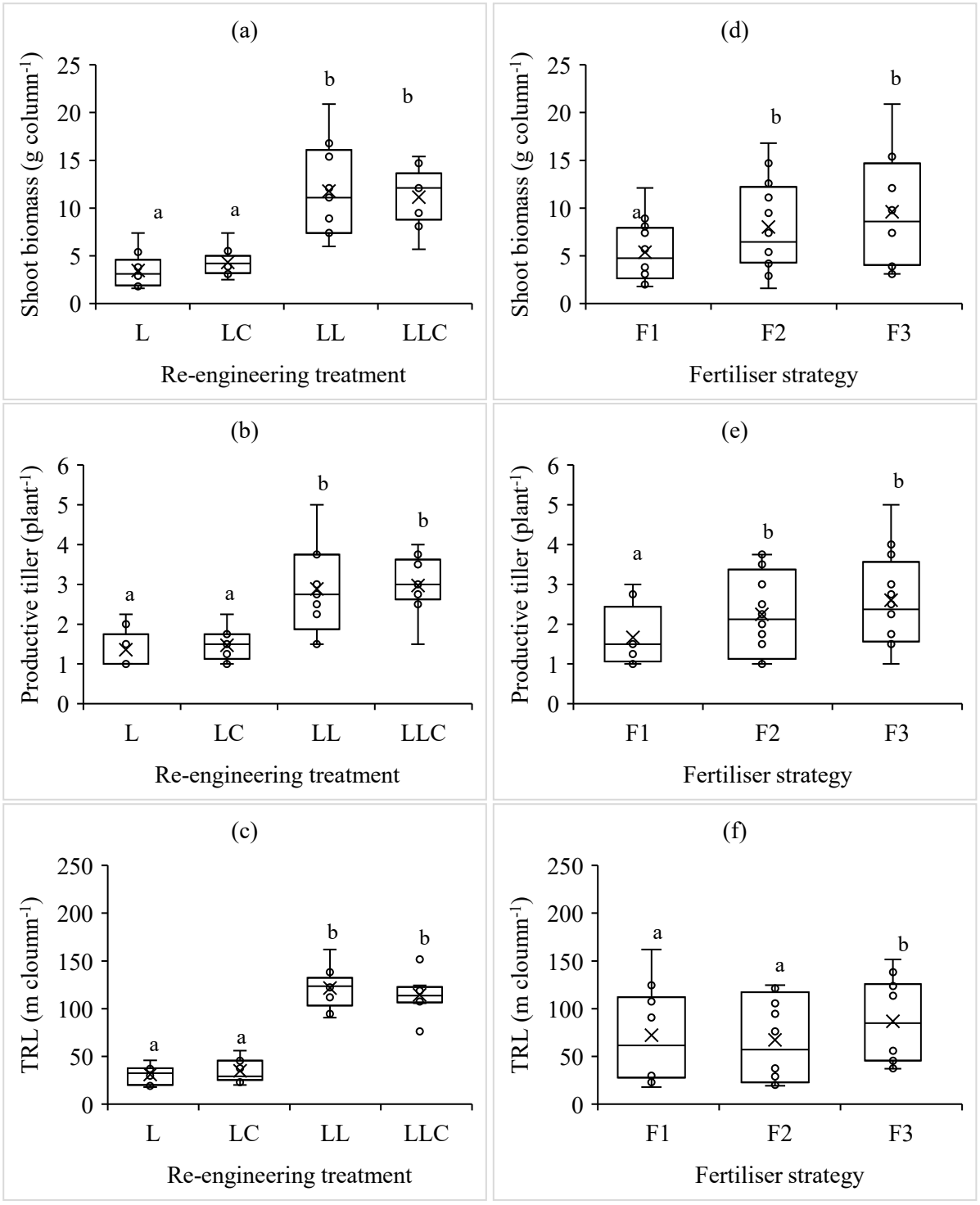


Fig. 1 Effects of soil re-engineering (RE) treatments and fertiliser strategies on (a and d) shoot biomass, (b and e) productive tiller count and (c and f) total root length (TRL) of barley (*Hordeum vulgare* L. var. Maximus) crop in Kurosol from Meenar, Western Australia. Soil RE treatments were: L = no amendments, LC = clay incorporated at 0–40 cm, LL = lime incorporated at 0–80 cm and LLC = clay incorporated at 0–40 cm and lime incorporated at 0–80 cm. Fertiliser strategies (F) were: F1 = low NPK banded below seeds (27 kg N ha^{-1}, 13 kg P ha^{-1} and 21 kg K ha^{-1}), F2 = moderate NPK banded below seed (54 kg N ha^{-1}, 26 kg P ha^{-1} and 43 kg K ha^{-1}) and F3 = High NPK, uniformly incorporated at 0-80 cm soil depth prior to column filling (216 kg N ha^{-1}, 104 kg P ha^{-1} and 168 kg K ha^{-1}). Different letters within the same panel are statistically different at $P \leq 0.05$ based on Fisher's protected LSD test. LSD for shoot biomass: RE = 2.58 and F = 2.24; for productive tiller: RE = 0.65 and F = 0.56; for TRL: RE = 15.4 and F = 13.2.

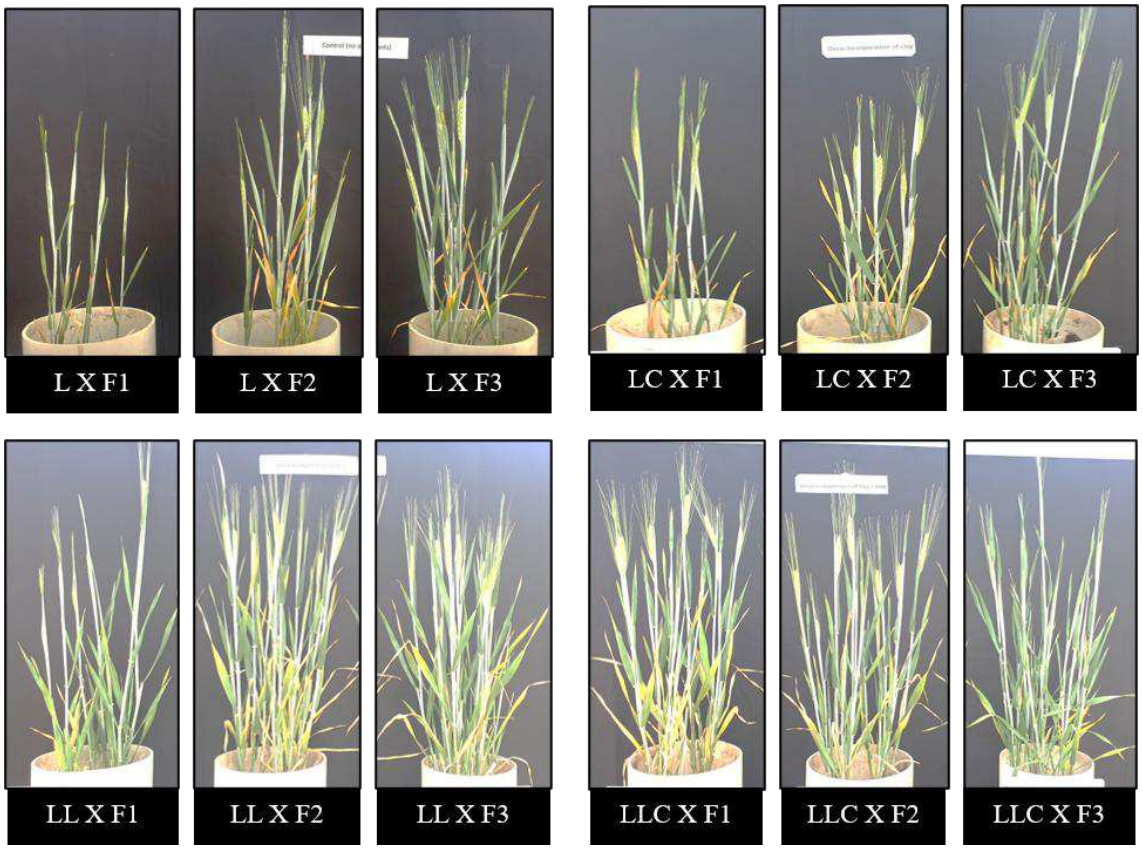


Fig. 2 Effects of soil re-engineering (RE) treatments and fertiliser strategies on barley (*Hordeum vulgare* L. var. Maximus) growth at 71 days after sowing (DAS) in Kurosol from Meenar, Western Australia. Soil RE treatments were: L = no amendments, LC = clay incorporated at 0–40 cm, LL = lime incorporated at 0–80 cm and LLC = clay incorporated at 0–40 cm and lime incorporated at 0–80 cm. Fertiliser strategies were: F1 = low NPK banded below seeds (27 kg N ha^{-1}, 13 kg P ha^{-1} and 21 kg K ha^{-1}), F2 = moderate NPK banded below seed (54 kg N ha^{-1}, 26 kg P ha^{-1} and 43 kg K ha^{-1}) and F3 = High NPK, uniformly incorporated at 0-80 cm soil depth prior to column filling (216 kg N ha^{-1}, 104 kg P ha^{-1} and 168 kg K ha^{-1}).

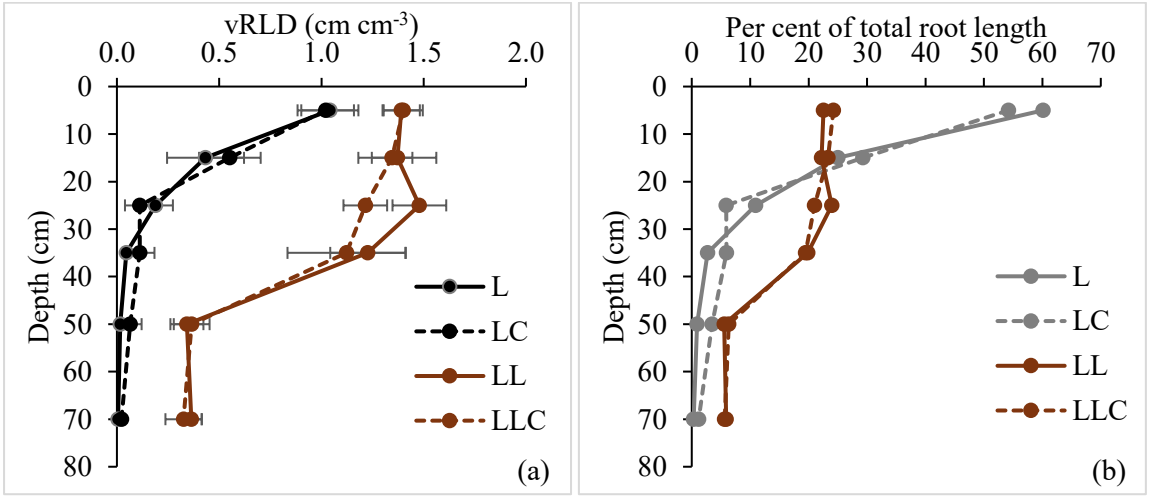


Fig. 3 Effects of soil reengineering (RE) on (a) volumetric root length density (vRLD) per sampling depth (D) and (b) distribution of the rot length density of barley (*Hordeum vulgare* L. var. Maximus) in a Kurosol from Meenar, Western Australia. Soil RE treatments were: L = no amendments, LC = clay incorporated at 0–40 cm, LL = lime incorporated at 0–80 cm and LLC = clay incorporated at 0–40 cm and lime incorporated at 0–80 cm. Horizontal bars in panel (a) represent standard error of the mean values. LSD for vRLD for the interaction of RE x D = 0.19. Panel (b) shows the relative distribution of root length within the soil profile and is presented descriptively; therefore, no separate significance test is shown for these proportional values.

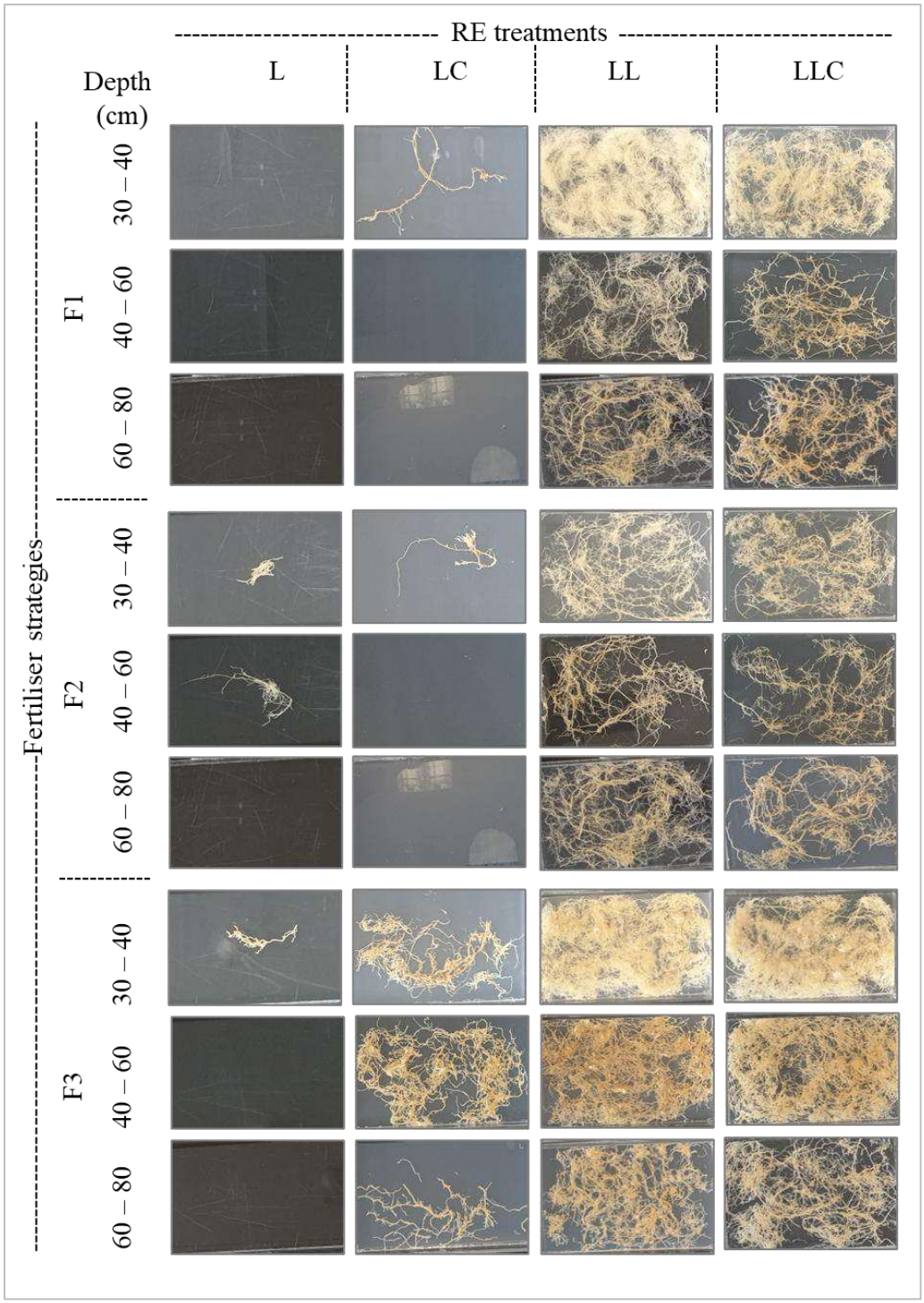


Fig. 4 Visual evidence of the effects of soil re-engineering (RE) treatments and fertiliser strategies on total planar root length density of roots harvested from the columns in different depth segments in the midsoil and subsoil (30-40, 40-60 and 60-80 cm). Root images are shown from 30 cm soil depth onwards only. Soil RE treatments were: L = no amendments, LC = clay incorporated at 0–40 cm, LL = lime incorporated at 0–80 cm and LLC = clay incorporated at 0–40 cm and lime incorporated at 0–80 cm. The fertiliser strategies were: F1 = low NPK banded below seeds (27 kg N ha^{-1}, 13 kg P ha^{-1} and 21 kg K ha^{-1}), F2 = moderate NPK banded below seed (54 kg N ha^{-1}, 26 kg P ha^{-1} and 43 kg K ha^{-1}) and F3 = High NPK, uniformly incorporated at 0-80 cm soil depth prior to column filling (216 kg N ha^{-1}, 104 kg P ha^{-1} and 168 kg K ha^{-1}).

3.3 Nitrogen, phosphorus and potassium uptake and their relationships with root length

The main effects of soil RE treatment and fertiliser strategy significantly influenced N, P and K uptake, whereas their interaction was not significant (Table 3; Fig. 5). Soil RE treatments affected the uptake of all three nutrients similarly, with LL and LLC having significantly greater N, P and K uptake than L and LC (Fig. 5a–5c). There were no significant differences between LL and LLC or between L and LC for the uptake of any of the three nutrients.

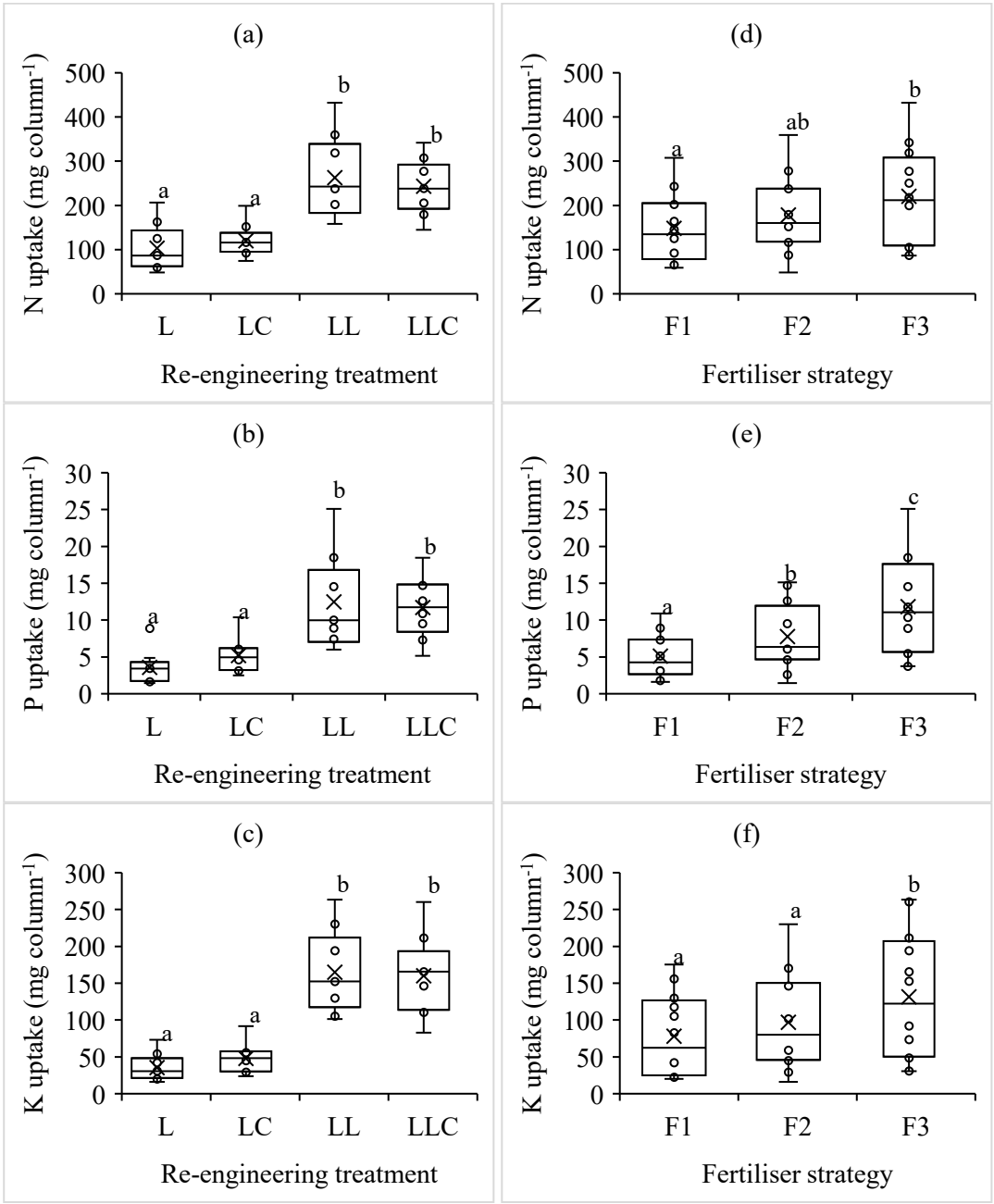


Fig. 5 Effects of soil re-engineering (RE) treatments and fertiliser strategies on (a and d) nitrogen (N), (b and e) phosphorus (P), and (c and f) potassium (K) uptakes by barley (*Hordeum vulgare* L. var. Maximus) in a Kurosol from Meenar, Western Australia. Soil RE treatments were: L = no amendments, LC = clay incorporated at 0–40 cm, LL = lime incorporated at 0–80 cm and LLC = clay incorporated at 0–40 cm and lime incorporated at 0–80 cm. Fertiliser strategies were: F1 = low NPK banded below seeds (27 kg N ha^{-1}, 13 kg P ha^{-1} and 21 kg K ha^{-1}), F2 = moderate NPK banded below seed (54 kg N ha^{-1}, 26 kg P ha^{-1} and 43 kg K ha^{-1}) and F3 = High NPK, uniformly incorporated at 0-80 cm soil depth prior to column filling (216 kg N ha^{-1}, 104 kg P ha^{-1} and 168 kg K ha^{-1}). Different letters within the same panel are statistically different at $P \leq 0.05$ based on Fisher's protected LSD test.

The response to fertiliser strategy differed among the nutrients. Nitrogen uptake was significantly greater under F3 than F1, while F2 did not differ significantly from either F1 or F3 (Fig. 5d). Phosphorus uptake increased significantly in the order F3 > F2 > F1 (Fig. 5e). Potassium uptake was significantly greater under F3 than under F1 and F2, with no significant difference between F1 and F2 (Fig. 5f).

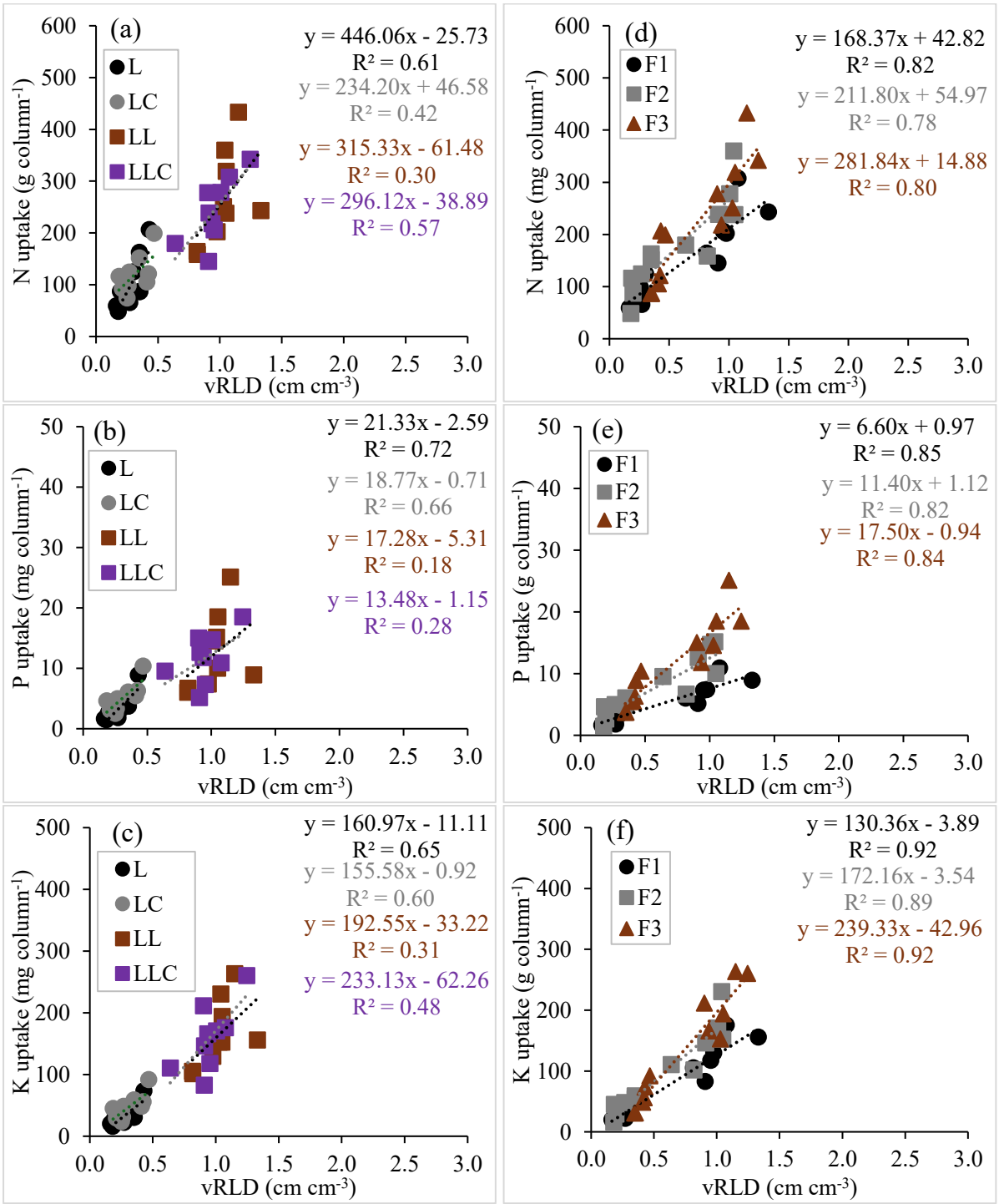


Fig. 6 Relationship between volumetric root length density (vRLD) and (a and d) nitrogen (N), (b and e) phosphorus (P), and (c and f) potassium (K) uptakes by barley (*Hordeum vulgare* L. var. Maximus) in a re-engineered Kurosol from Meenar, Western Australia. Soil RE treatments were: L = no amendments, LC = clay incorporated at 0–40 cm, LL = lime incorporated at 0–80 cm and LLC = clay incorporated at 0–40 cm and lime incorporated at 0–80 cm. The fertiliser strategies were: F1 = low NPK banded below seed (27 kg N ha^{-1}, 13 kg P ha^{-1} and 21 kg K ha^{-1}), F2 = moderate NPK banded below seed (54 kg N ha^{-1}, 26 kg P ha^{-1} and 43 kg K ha^{-1}) and F3 = High NPK, uniformly incorporated at 0-80 cm soil depth prior to column filling (216 kg N ha^{-1}, 104 kg P ha^{-1} and 168 kg K ha^{-1}).

Uptake of N, P and K was significantly and positively related to total volumetric root length density (vRLD) of barley (Fig. 6). The increase in P uptake per unit increase in vRLD was smaller than those observed for N and K (Fig. 6a–6c). The relationships between nutrient uptake and vRLD also varied among fertiliser strategies and were generally stronger under F1 and F3 than under F2 (Fig. 6d–6f).

3.4 Soil nutrient status and chemical properties at harvest

The interaction between soil RE treatment and fertiliser strategy significantly affected mean Colwell K at harvest ($P \leq 0.05$; Table 4). The F3 strategy resulted in higher residual K at harvest under the L and LC treatments compared with the LL and LLC treatments. Soil RE treatments also had significant effects on inorganic N, Colwell K, soil pH_{Ca}, and extractable Al concentration. The L and LC treatments had higher inorganic N, Colwell K, and EAC than the LL and LLC treatments ($P \leq 0.05$; Table 4). Conversely, soil pH_{Ca} was higher in the LL and LLC treatments than in the L and LC treatments. Nither Colwell P nor soil OC was affected by soil RE treatment and fertiliser strategy ($P > 0.05$; Table 4).

Table 4 Soil properties at the harvest. SOC = soil organic carbon and EAC = extractable aluminium concentration Soil RE treatments were: L = no amendments, LC = clay incorporated at 0–40 cm, LL = lime incorporated at 0–80 cm and LLC = clay incorporated at 0–40 cm and lime incorporated at 0–80 cm**.** The fertiliser strategies (F) were: F1 = low NPK banded below seeds (27 kg N ha^{-1}, 13 kg P ha^{-1} and 21 kg K ha^{-1}), F2 = moderate NPK banded below seed (54 kg N ha^{-1}, 26 kg P ha^{-1} and 43 kg K ha^{-1}) and F3 = High NPK, uniformly incorporated at 0-80 cm soil depth prior to column filling (216 kg N ha^{-1}, 104 kg P ha^{-1} and 168 kg K ha^{-1}).

Treatments	Residual inorganic N (mg $column^{-1}$)	Residual Colwell P (mg $column^{-1}$)	Residual Colwell K (mg $column^{-1}$)	SOC (%)	pH_{Ca}	EAC (mg kg^{-1})
L						
F1	442	198	345	0.51	4.22	12.1
F2	405	203	335	0.51	4.29	11.5
F3	853	254	528	0.51	4.27	9.9
LC						
F1	344	190	329	0.52	4.29	8.9
F2	344	194	369	0.59	4.34	8.7
F3	849	256	529	0.58	4.38	7.5
LL						
F1	231	183	337	0.53	5.60	0.3
F2	187	195	317	0.52	5.59	0.3
F3	584	249	383	0.65	5.39	0.5
LLC						
F1	207	186	315	0.53	5.42	0.3
F2	247	177	319	0.58	5.36	0.5
F3	669	277	406	0.52	5.26	0.5
LSD (5%)						
RE	*27*	*NS*	*23*	*NS*	*0.11*	*1.31*
F	*23*	*15*	*20*	*NS*	*NS*	*NS*
RE x F	*NS*	*NS*	*41*	*NS*	*NS*	*NS*

3.5 Correlations among soil properties and volumetric root length density at harvest

Several soil properties were correlated with vRLD (Table 5). The vRLD was positively correlated with pH_{Ca} (r = 0.53), residual Colwell P (r = 0.47) and OC (r = 0.40), and negatively correlated with Al concentration (r = −0.69) and clay concentration (r = −0.51). Residual inorganic N showed only a weak positive correlation (r = 0.17). Colwell K was weakly negatively correlated with vRLD (r = −0.21). Strong negative correlations existed between pH_{Ca} and Al (r = −0.78), and between clay concentration and residual Colwell P (r = −0.77).

Table 5 Correlations between various soil properties and volumetric root length density (vRLD). SOC = soil organic carbon and EAC = extractable aluminium concentration.

	Clay (%)	Residual inorganic N (mg kg^{-1})	Residual Colwell P (mg kg^{-1})	Residual Colwell K (mg kg^{-1})	SOC (%)	pH_{Ca}	EAC (mg kg^{-1})
Clay (%)							
Inorganic N (mg kg^{-1})	-0.53						
Colwell P (mg kg^{-1})	-0.77	0.34					
Colwell K (mg kg^{-1})	-0.02	0.46	0.01				
SOC (%)	-0.57	0.19	0.59	-0.02			
pH_{Ca}	0.22	-0.36	-0.13	-0.29	-0.07		
EAC (mg kg^{-1})	-0.03	0.20	-0.15	0.35	-0.13	-0.78	
vRLD (cm cm^{-3})	-0.51	0.17	0.47	-0.21	0.40	0.53	-0.69

3.6 Effects of clay incorporation

Clay incorporation produced relatively small effects on plant growth compared with lime incorporation. Shoot biomass, productive tiller number and total root length did not differ significantly between L and LC or between LL and LLC (Fig. 1 and Fig. 2). Similarly, clay addition did not consistently increase vRLD across soil depths (Fig. 3). At harvest, clay-amended treatments generally contained less residual inorganic N and, depending on fertiliser strategy, lower residual Colwell K than their corresponding non-clay treatments (Table 4).

4. Discussion

The principal finding of this study was that amelioration of soil acidity through lime incorporation had a substantially greater influence on barley root and shoot growth than clay incorporation. Lime increased soil pH, reduced extractable Al and enabled greater root growth throughout the reconstructed profile. Clay addition provided comparatively limited additional benefits under the conditions tested. Fertiliser strategy also influenced plant growth and nutrient uptake; however, because F3 differed from F1 and F2 in both nutrient rate and vertical placement, its effects represent an integrated fertiliser-management response rather than an independent placement effect.

The strong response to lime incorporation was closely associated with substantial improvement in the chemical environment of the root zone. Soil RE treatments involving lime incorporation (LL and LLC) increased pH_{Ca} by more than one unit and reduced extractable Al to below 0.5 mg kg^{-1}, which is well below recognised toxicity

levels *(Anderson and Bell 2019)*. These improvements closely match long-standing observations that liming acidic soils alleviates aluminium toxicity, enhances calcium availability and improves conditions for root elongation (Rengel 2003; Moody and Aitken 1997; Kochian et al. 2015; Delhaize and Ryan 1995). The strong negative correlation between Al concentration and vRLD (r = –0.69) further supports the interpretation that Al toxicity was a major inhibitor of barley deep rooting in the untreated soil.

Consistent with these chemical improvements, lime incorporation substantially increased rooting depth and root density throughout the soil profile. This response agrees with previous studies in Australian duplex soils, where lime incorporation improved root penetration into subsoil horizons, increased water extraction and enhanced overall crop performance (Conyers 2003; Azam et al. 2025). The deeper distribution of roots observed in LL and LLC suggests that acidity was rapidly ameliorated throughout the profile because of deep lime incorporation, an outcome less likely to be achieved through surface liming alone (Tang et al. 2013; Moody and Aitken 1997; Azam and Gazey 2021; Wickramarachchi and Azam 2026). Thus, alleviating subsoil acidity and Al toxicity was central to creating a deeper and more favourable root-zone environment.

Liming may also have influenced nutrient availability by increasing microbial activity and modifying P reactions under acidic conditions (Haynes and Naidu 1998). Although soil Colwell P at harvest did not differ statistically among treatments (Table 4), the positive correlation between residual soil Colwell P and vRLD (r = 0.47, Table 5) indicates an association between P availability and root density. Previous work has shown that adequate Ca supply can enhance P acquisition in cereals by promoting finer root branching and greater exploration of upper and mid-profile soil layers (Marschner 2011; White et al. 2013). Collectively, these responses indicate that the benefits of lime incorporation extended beyond pH correction and were associated with a more favourable chemical environment for root development and nutrient acquisition.

In contrast to the strong response to lime, incorporation of the predominantly kaolinitic clay produced comparatively limited effects on root development and residual nutrient status. Contrary to our literature-based expectation of improved nutrient retention following clay incorporation (Hall et al. 2010; Schapel et al. 2018; Azam et al. 2026c; Anderson et al. 1998; Wickramarachchi et al. 2025), the clay amendment did not consistently increase residual nutrient concentrations at harvest. Residual inorganic N and, in some treatments, Colwell K were lower in clay-amended treatment than in corresponding non-clay treatments, despite no consistent increase in plant N or K uptake. Thus, these lower residual concentrations cannot be attributed to greater crop nutrient acquisition and provide no clear evidence of enhanced nutrient retention following clay incorporation. This limited effect may partly reflect the mineralogy of the amendment, as >95% of its clay fraction was kaolinite, which has relatively low surface area and charge compared with higher-activity clay minerals (Ma and Eggleton 1999; Środoń and McCarty 2008). Differences in soil water retention, drainage and associated nutrient redistribution or leaching may also have contributed to the observed patterns; however, drainage and nutrient losses were not measured, and these mechanisms cannot be distinguished in the present study.

Nevertheless, clay incorporation may have provided physical benefits that were not fully captured by residual nutrient concentrations at harvest. Although clay content was negatively correlated with vRLD (r = –0.51), the clay-amended treatments did not show evidence of severe restriction of root development under the conditions tested. Clay addition to sandy soils can improve water-holding capacity and other physical properties, although

these benefits depend on clay mineralogy, application rate and the properties of the receiving soil (Schapel et al. 2018; Azam et al. 2026c; Hall et al. 2010). Mechanical impedance was not measured in the present experiment, so the contribution of changes in soil strength to the observed root responses cannot be determined. Clay additions may also modify microbial activity and organic matter dynamics because clay–organic matter associations can stabilise soil OC and influence nutrient cycling and soil biological functioning (Hayes and Roulia 2025; Baldock 2007). Overall, however, the additional benefit of clay incorporation was relatively small compared with the pronounced response to lime.

Alongside the effects of soil amelioration, fertiliser strategy independently influenced barley growth, root development and nutrient acquisition. F3 generally produced greater shoot biomass, tiller number, total root length and nutrient uptake than F1 and F2. However, F3 differed from the other strategies in both nutrient rate and vertical distribution: it supplied substantially greater amounts of N, P and K while distributing these nutrients throughout the 0–80 cm profile. Consequently, the greater response to F3 cannot be attributed independently to either increased nutrient supply or deeper nutrient placement but instead represents their combined effect. Previous studies have demonstrated that nutrient distribution within the soil profile can influence root growth because roots respond to spatial nutrient availability (Hodge 2004; Drew and Saker 1975; Htwe et al. 2023). Deeper nutrient availability may also encourage root exploration of ameliorated subsoil and improve access to water and nutrients as surface soil dries. However, because fertiliser rate and placement were confounded in the present experiment, these mechanisms cannot be separated and require further testing using equivalent nutrient rates applied at contrasting depths.

The root distribution observed under F2 also raises a possible additional effect of concentrated near-seed fertiliser application. The apparently lower subsoil root density under F2 may reflect localised effects of the fertiliser band on early root development (Pan et al. 2016). Although urea supplies N in amide form, its hydrolysis can generate locally high ammonium and ammonia concentrations and temporarily increase pH around fertiliser granules, potentially inhibiting root growth. Such effects may be particularly relevant in coarse-textured soils with low buffering capacity (Angus et al. 2014). However, the RE × fertiliser × depth interaction was not significant, and ammonium/ammonia concentrations around the fertiliser bands were not measured. Therefore, ammonia toxicity cannot be established as the cause of the observed root distribution and should be considered only as a possible mechanism requiring further investigation.

The potential value of deeper nutrient availability may become more important under water-limited field conditions than under the relatively well-watered conditions of this experiment. Deep nutrient placement can enhance root exploration and access to water and nutrients from deeper soil layers, particularly when surface soil dries (Vido et al. 2023; Azam et al. 2025). However, soil water availability was maintained at relatively high levels in the present screenhouse experiment, and crop growth rates consequently exceeded those typically observed under field conditions, with shoot biomass increasing by up to 241%. Therefore, while F3 produced strong crop responses, the present experiment does not demonstrate that these responses resulted specifically from deep nutrient placement. Rather, they reflect the combined effects of greater nutrient supply and distribution throughout the soil profile.

The relationships among soil properties, root development and nutrient availability further demonstrate that the crop responses were driven by multiple components of the reconstructed root-zone environment. The positive associations of vRLD with pH_{Ca} and OC, together with its strong negative relationship with extractable Al, indicate that improvement of the soil chemical environment was closely associated with deeper root growth. Relationships between vRLD and residual nutrients were more complex because concentrations measured at harvest reflect the combined effects of initial nutrient availability, fertiliser supply, plant uptake and redistribution within the soil profile. Consequently, correlations between residual Colwell K or P and root density should not be interpreted as direct evidence of nutrient retention or depletion caused by root growth. This highlights the importance of interpreting end-of-season soil nutrient concentrations together with plant uptake and root distribution.

Importantly, although both soil RE and fertiliser strategy significantly increased barley growth, their interaction was not significant. Their effects should therefore be interpreted as largely independent rather than synergistic: lime incorporation improved the root-zone environment primarily by ameliorating soil acidity and Al toxicity, while increased nutrient supply independently supported greater plant growth and nutrient acquisition. Studies in similar soil systems increasingly emphasise that addressing a single soil constraint may produce suboptimal outcomes when other physical, chemical or nutritional limitations remain (Hall et al. 2020; Vido et al. 2023; Azam et al. 2026a; Wickramarachchi et al. 2025). The present study extends this understanding by demonstrating that deep amelioration of acidity can substantially improve root-system development throughout a reconstructed duplex profile, while appropriate nutrient management is independently required to support the resulting crop growth.

While these findings demonstrate important effects of soil amelioration and fertiliser management on barley root development and growth, several limitations should be considered when interpreting their broader agronomic significance. Firstly, this study was conducted using reconstructed soil columns under controlled screenhouse conditions, which cannot fully reproduce the spatial heterogeneity, climatic variability and soil–plant interactions occurring under field conditions. Although the columns were reconstructed using soils collected from distinct field layers and packed to bulk densities representative of corresponding field soil RE treatments, an unloosened control could not be accurately reproduced using this approach. Consequently, the experiment was not designed to quantify the independent effect of soil loosening, and the results should be interpreted as responses to amendment and fertiliser strategies within reconstructed loosened soil profiles.

Secondly, the experiment evaluated barley responses over a single growing cycle. While this enabled detailed assessment of root distribution, nutrient acquisition and aboveground growth, longer-term effects of soil RE on soil structure, nutrient dynamics, root development and crop productivity could not be determined. The persistence of benefits from lime and clay incorporation, particularly as soils undergo settling and recompaction and amendments interact with the soil over time, therefore requires validation through multi-season field experiments.

Finally, the experiment was conducted under relatively well-watered conditions, with soil water maintained at or above approximately 75% of FC. These conditions differ from the episodic and frequently water-limited conditions experienced by rain-fed crops in Western Australia. Under field conditions, drying of the surface soil

may restrict nutrient mobility and root access to nutrients concentrated in upper soil layers, potentially increasing the value of deeper nutrient placement. Therefore, the relative performance of the fertiliser strategies observed in this study should not be directly extrapolated to water-limited field environments. Further field studies across contrasting seasonal conditions are required to determine how soil water availability influences crop responses to fertiliser rate and placement following soil re-engineering.

5. Conclusions

This study demonstrates that profile incorporation of lime was the dominant factor improving the root-zone environment of this strongly acidic Brown Kurosol, increasing soil pH, reducing extractable Al and enabling substantially greater barley root growth and aboveground growth. Incorporation of predominantly kaolinitic clay provided comparatively limited additional benefits under the conditions tested. Fertiliser strategy also influenced plant growth and nutrient acquisition, with the high-rate, profile-incorporated strategy generally producing greater responses than lower-rate banded strategies. However, because nutrient rate and placement differed simultaneously, these responses cannot be attributed independently to either factor. The results therefore highlight the need to optimise fertiliser rate and placement after soil constraints have been ameliorated rather than assuming that greater or deeper fertiliser application is necessarily required. Under rain-fed field conditions, this optimisation must also consider the risk that nutrients concentrated in drying surface soil may become less accessible to roots. Future field studies using equivalent nutrient rates across contrasting placement depths are required to determine the most agronomically and economically efficient fertiliser strategy for re-engineered acidic soils.

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Declarations

Conflict of Interest

All authors declare no conflicts of interest.

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contributed additional time outside normal working hours to undertake image processing and data analysis as part of a Doctor of Philosophy program at the University of Western Australia.

Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Author's contribution

Kanchana Wickramarachchi: Trial design, execution, root image collection and analysis, data analysis and manuscript preparation.

Gaus Azam: Fund sourcing, trial design, data analysis and manuscript preparation.

References

Anderson G, Bell R (2019) Wheat grain-yield response to lime application: relationships with soil pH and aluminium in Western Australia. Crop Pasture Sci 70 (4):295-305. https://doi.org/10.1071/CP19033

Anderson GC, Fillery IRP, Dolling PJ, Asseng S (1998) Nitrogen and water flows under pasture-wheat and lupin-wheat rotations in deep sands in Western Australia. 1. Nitrogen fixation in legumes, net N mineralisation,and utilisation of soil-derived nitrogen. Aust J Agric Res 49 (3):329-344. https://doi.org/10.1071/A97141

Angus J, Grace P (2017) Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. Soil Res 55 (6):435-450. https://doi.org/10.1071/SR16325

Angus J, Gupta V, Pitson G, Good A (2014) Effects of banded ammonia and urea fertiliser on soil properties and the growth and yield of wheat. Crop Pasture Sci 65 (4):337-352. https://doi.org/10.1071/CP13337

Azam G, Davies S (2023) A diagnostic framework for reengineering soil: Potential strategies to manage combinations of soil constraints for sands and texture contrast soils. Department of Primary Industries and Regional Development, Perth. https://doi.org/10.13140/RG.2.2.14724.08325

Azam G, Gazey C (2021) Slow movement of alkali from surface-applied lime warrants the introduction of strategic tillage for rapid amelioration of subsurface acidity in south-western Australia. Soil Res 59 (1):97-106. https://doi.org/10.1071/SR19329

Azam G, Rahman MS, Scanlan C, Rahman MH, Gazey R, Barrett-Lennard EG, Wickramarachchi K, Nixon B, Gazey C (2026a) Deep amelioration of compaction and acidity doubled the water use efficiency of cereal crops on a sandy soil in a long-term experiment in a water-limited environment. Geoderma 466:117700. https://doi.org/10.1016/j.geoderma.2026.117700

Azam G, Rahman MS, Wickramarachchi K (2023) Strategic Tillage for Sustaining the Productivity of Broadacre Cropping in the Arid and Semi-Arid Regions of Southern Australia. In: Dr. Rodrigo De S (ed) Strategic Tillage and Soil Management - New Perspectives. IntechOpen, Rijeka, p Ch. 3. https://doi.org/10.5772/intechopen.112875

Azam G, Reynolds C (2026) Soil re-engineering in Western Australia, Part I: a novel approach for rapid and lasting improvement of soil physical and chemical properties. Soil Res 64 (3). https://doi.org/10.1071/sr25234

Azam G, Walakada Gamage HK, Fritsch O, Gain A (2026b) Beyond forecasts: reframing climate services for broadacre rainfed agriculture in Western Australia. Australasian Journal of Environmental Management 33 (1):1-10. https://doi.org/10.1080/14486563.2026.2640665

Azam G, Wickramarachchi K, Rahman H, Rahman MS, Reynolds C (2026c) Benchmarking crop performance following soil profile reengineering: Four-year field studies in an Arenosol and a Kurosol of Western Australia. Soil Res (under review). https://doi.org/10.21203/rs.3.rs-8297071/v1

Azam G, Wickramarachchi K, Rahman H, Rahman MS, Reynolds C, McDonald G, Parker W, Hall D, Scanlan C, Davies S, Gazey C (2024) The resilience of re-engineered sandy soils in wet and dry seasons in Western Australia. Paper presented at the Australian Agronomy Conference, Albany.

Azam G, Wickramarachchi K, Rahman MH, Bucat J, Barrett-Lennard EG, Anderson GC, Fritschi F (2026d) Improved root-zone functionality sustains canola root proliferation and resource acquisition on a constrained duplex soil. https://doi.org/10.21203/rs.3.rs-10331414/v1

Azam G, Wickramarachchi K, Scanlan C, Chen Y (2025) Deep and continuous root development in ameliorated soil improves water and nutrient uptakes and wheat yield in water-limited conditions. Plant Soil 512 (1):1405-1420. https://doi.org/10.1007/s11104-024-07153-0

Baldock JA (2007) Composition and Cycling of Organic Carbon in Soil. In: Marschner P, Rengel Z (eds) Nutrient Cycling in Terrestrial Ecosystems. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 1-35. https://doi.org/10.1007/978-3-540-68027-7_1

Barrett-Lennard EG, George N, D'Antuono M, Holmes KW, Ward PR (2024) Rain and potential evapotranspiration are the main drivers of yield for wheat and barley in southern Australia: insights from 12 years of National Variety Trials. Crop Pasture Sci 75 (6):-. https://doi.org/10.1071/CP23320

Bell R, Reuter D, Scott B, Sparrow L, Strong W, Chen tlW (2013) Soil phosphorus–crop response calibration relationships and criteria for winter cereal crops grown in Australia. Crop Pasture Sci 64 (5):480-498. https://doi.org/10.1071/cp13016

Bengough AG, McKenzie BM, Hallett PD, Valentine TA (2011) Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. J Exp Bot 62 (1):59-68. https://doi.org/10.1093/jxb/erq350

Betti G, Grant C, Churchman G, Murray R (2015) Increased profile wettability in texture-contrast soils from clay delving: case studies in South Australia. Soil Res 53 (2):125-136. https://doi.org/10.1071/SR14133

Betti G, Grant CD, Murray RS, Churchman GJ (2016) Size of subsoil clods affects soil-water availability in sand–clay mixtures. Soil Res 54 (3):276-290. https://doi.org/10.1071/SR15115

Brennan RF, Bell MJ (2013) Soil potassium—crop response calibration relationships and criteria for field crops grown in Australia. Crop Pasture Sci 64 (5):514-522. https://doi.org/10.1071/CP13006

Bromfield S (1987) Simple tests for the assessment of aluminium and manganese levels in acid soils. Aust J Exp Agric 27 (3):399-404. https://doi.org/10.1071/EA9870399

Celestina C, Midwood J, Sherriff S, Trengove S, Hunt J, Tang C, Sale P, Franks A (2018) Crop yield responses to surface and subsoil applications of poultry litter and inorganic fertiliser in south-eastern Australia. Crop Pasture Sci 69 (3):303-316. https://doi.org/10.1071/CP17439

Conyers M (2003) Amelioration of acidity with time by limestone under contrasting tillage. Soil Tillage Res 72 (1):85-94. https://doi.org/10.1016/s0167-1987(03)00064-3

Delhaize E, Ryan PR (1995) Aluminum Toxicity and Tolerance in Plants. Plant Physiol 107 (2):315-321. https://doi.org/10.1104/pp.107.2.315

Drew M, Saker L (1978) Nutrient supply and the growth of the seminal root system in barley: III. Compensatory increases in growth of lateral roots, and in rates of phosphate uptake, in response to a localized supply of phosphate. J Exp Bot 29 (2):435-451. https://doi.org/10.1093/jxb/29.2.435

Drew MC, Saker LR (1975) Nutrient Supply and the Growth of the Seminal Root System in Barley: II. Localized, compensatory increases in lateral root growth and rates of nitrate uptake when nitrate supply is restricted to only part of the root system. J Exp Bot 26 (1):79-90. https://doi.org/10.1093/jxb/26.1.79

Eldridge DJ, Maestre FT, Koen TB, Delgado-Baquerizo M (2018) Australian dryland soils are acidic and nutrient-depleted, and have unique microbial communities compared with other drylands. J Biogeogr 45 (12):2803-2814. https://doi.org/10.1111/jbi.13456

Gazey C, Azam G, Clausen J, Rengel Z (2019) Soil Quality: 4 Soil Acidity. Perth, WA
Gregory PJ (1997) Alternative crops for duplex soils: growth and water use of some cereal, legume, and oilseed crops, and pastures. Aust J Agric Res 49 (1):21-32. https://doi.org/10.1071/A97053

669 Hall DJM, Davies SL, Bell RW, Edwards TJ (2020) Soil Management Systems to Overcome Multiple
670 Constraints for Dryland Crops on Deep Sands in a Water Limited Environment on the South Coast of
671 Western Australia. Agronomy 10 (12):1881. https://doi.org/10.3390/agronomy10121881

672 Hall DJM, Jones HR, Crabtree WL, Daniels TL (2010) Claying and deep ripping can increase crop yields and
673 profits on water repellent sands with marginal fertility in southern Western Australia. Soil Res 48
674 (2):178-187. https://doi.org/10.1071/SR09078

675 Hayes MHB, Roulia M (2025) Relevance of Organic Matter Compositions, Structures and Associations to Soil
676 Aggregates and to Sustainable Productivity. Agronomy 15 (9):2182.
677 https://doi.org/10.3390/agronomy15092182

678 Haynes RJ, Naidu R (1998) Influence of lime, fertilizer and manure applications on soil organic matter content
679 and soil physical conditions: a review. Nutr Cycl Agroecosyst 51 (2):123-137.
680 https://doi.org/10.1023/A:1009738307837

681 Hodge A (2004) The plastic plant: root responses to heterogeneous supplies of nutrients. New Phytol 162 (1):9-
682 24. https://doi.org/10.1111/j.1469-8137.2004.01015.x

683 Htwe KK, Guppy C, Blair G, Flavel R (2023) Mung bean nutrient uptake and root response to phosphorus and
684 potassium placement strategies. Commun Soil Sci Plant Anal 54 (19):2625-2634.
685 https://doi.org/10.1080/00103624.2023.2240363

686 Isbell RF (2021) The Australian Soil Classification. 3 edn. CSIRO Publishing, Melbourne.

687 Kell DB (2011) Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water
688 sequestration. Ann Bot 108 (3):407-418. https://doi.org/10.1093/aob/mcr175

689 Kochian LV, Piñeros MA, Liu J, Magalhaes JV (2015) Plant Adaptation to Acid Soils: The Molecular Basis for
690 Crop Aluminum Resistance. Annu Rev Plant Biol 66:571-598. https://doi.org/10.1146/annurev-arplant-
691 043014-114822

692 Lawes R, Chen C, Whish J, Meier E, Ouzman J, Gobbett D, Vadakattu G, Ota N, van Rees H (2021) Applying
693 more nitrogen is not always sufficient to address dryland wheat yield gaps in Australia. Field Crops Res
694 262:108033. https://doi.org/10.1016/j.fcr.2020.108033

695 Lynch JP (1995) Root Architecture and Plant Productivity. Plant Physiol 109 (1):7-13.
696 https://doi.org/10.1104/pp.109.1.7

697 Lynch JP (2022) Harnessing root architecture to address global challenges. Plant J 109 (2):415-431.
698 https://doi.org/10.1111/tpj.15560

699 Ma C, Eggleton RA (1999) Cation exchange capacity of kaolinite. Clays Clay Miner 47 (2):174-180.
700 https://doi.org/10.1346/CCMN.1999.0470207

701 Marschner H (2011) Marschner's mineral nutrition of higher plants. Academic press.

702 McBeath T, Grant C, Murray R, Chittleborough D (2010) Effects of subsoil amendments on soil physical
703 properties, crop response, and soil water quality in a dry year. Soil Res 48 (2):140-149.
704 https://doi.org/10.1071/SR08254

705 McEwen J, Johnston A (1979) The effects of subsoiling and deep incorporation of P and K fertilizers on the
706 yield and nutrient uptake of barley, potatoes, wheat and sugar beet grown in rotation. J Agric Sci 92
707 (3):695-702. https://doi.org/10.1017/S0021859600053946

708 McLachlan JW, Flavel RJ, Guppy CN (2024) Preferential phosphorus placement improves the productivity and
709 competitiveness of tropical pasture legumes. Legume Science 6 (2). https://doi.org/10.1002/leg3.235

710 Moody PW, Aitken RL (1997) Soil acidification under some tropical agricultural systems. 1. Rates of
711 acidification and contributing factors. Aust J Soil Res 35 (1):163-174. https://doi.org/10.1071/s96069

712 Pan WL, Madsen IJ, Bolton RP, Graves L, Sistrunk T (2016) Ammonia/ammonium toxicity root symptoms
713 induced by inorganic and organic fertilizers and placement. Agron J 108 (6):2485-2492.
714 https://doi.org/10.2134/agronj2016.02.0122

715 Rayment GE, Lyons DJ (2011) Soil chemical methods: Australasia. CSIRO Publishing, Collingwood, Australia.

716 Rengel Z (2003) Handbook of Soil Acidity. Marcel Dekker, New York, USA.

717 Robinson D (1994) The responses of plants to non-uniform supplies of nutrients. New Phytol 127 (4):635-674.
718 https://doi.org/10.1111/j.1469-8137.1994.tb02969.x

719 Sadras VO, Angus JF (2006) Benchmarking water-use efficiency of rainfed wheat in dry environments. Aust J
720 Agric Res 57 (8):847-856. https://doi.org/10.1071/AR05359

721 Schapel A, Marschner P, Churchman J (2018) Clay amount and distribution influence organic carbon content in
722 sand with subsoil clay addition. Soil Tillage Res 184:253-260. https://doi.org/10.1016/j.still.2018.08.001

723 Środoń J, McCarty DK (2008) Surface area and layer charge of smectite from CEC and EGME/H2O-retention
724 measurements. Clays Clay Miner 56 (2):155-174. https://doi.org/10.1346/CCMN.2008.0560203

725 Tamás L, Huttová J, Mistrík I, Šimonovic M, Široká B (2006) Aluminium-induced drought and oxidative stress
726 in barley roots. J Plant Physiol 163 (7):781-784. https://doi.org/10.1016/j.jplph.2005.08.012

727 Tang C, Weligama C, Sale P (2013) Subsurface Soil Acidification in Farming Systems: Its Possible Causes and
728 Management Options. In: Xu J, Sparks DL (eds) Molecular Environmental Soil Science. Springer
729 Netherlands, Dordrecht, pp 389-412. https://doi.org/10.1007/978-94-007-4177-5_13

730 Uddin S, Rohan M, Weng ZH, Tahmasbian I, Fang Y, Hayden HL, Armstrong R, Tavakkoli E (2025) Enhancing
731 root proliferation in an alkaline dispersive subsoil: a comparative study of organic and inorganic
732 amendments with different amelioration mechanisms. J Soil Sci Plant Nutr 25 (3):7381-7396.
733 https://doi.org/10.1007/s42729-025-02602-w

734 van Gool D (2016) Identifying soil constraints that limit wheat yield in South-West Western Australia,
735 Department of Primary Industries and Regional Development, Perth.

736 Vido JJ, Jin J, Hayden HL, Celestina C, Sale PW, Armstrong R, Tang C, Wood J, Franks AE (2023) Enriched
737 Saprotrophic Fungal Communities Associated with Organic Substrate Deep-Banded in Dense Clay
738 Subsoils Two Years Prior. Available at SSRN 4465427. https://dx.doi.org/10.2139/ssrn.4465427

739 Wacker TS, van der Bom F, Delory BM, Vetterlein D, Postma JA, Nagel KA, Schnepf A, Dresbøll DB (2025)
740 Back to the roots: standardizing root length density terminology. Plant Soil 511:91–98.
741 https://doi.org/10.1007/s11104-024-07075-x

742 White PJ, George TS, Gregory PJ, Bengough AG, Hallett PD, McKenzie BM (2013) Matching roots to their
743 environment. Ann Bot 112 (2):207-222. https://doi.org/10.1093/aob/mct123

744 Wickramarachchi K, Azam G (2026) Improving barley (Hordeum vulgare L.) yield through deeper root
745 architecture impacted by nitrogen management in a re-engineered Kurosol. Soil Res 64 (3).
746 https://doi.org/10.1071/SR25235

747 Wickramarachchi K, Chen Y, Azam G (2025) Re-engineering a compacted acidic coarse sand enhanced the
748 yield of triticale (x Triticosecale) by excelling root architecture and uptake of resources – a soil columns
749 study. Plant Soil. https://doi.org/10.1007/s11104-025-08190-z

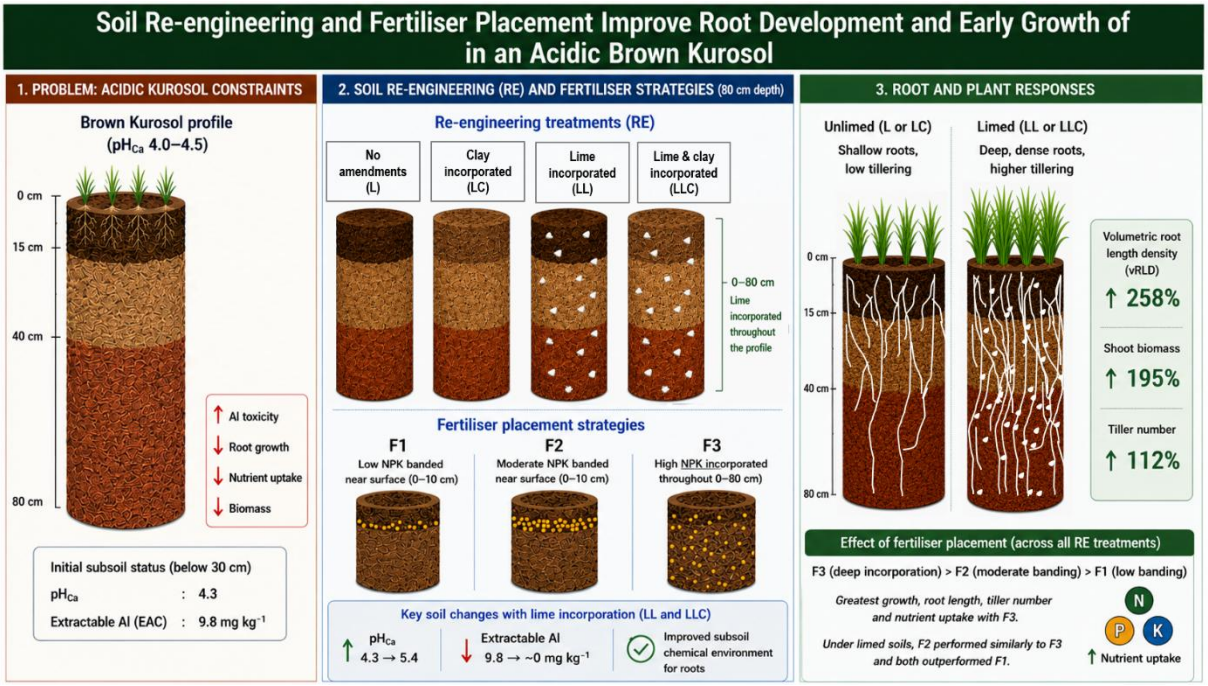
750 Yang ZB, Rao IM, Horst WJ (2013) Interaction of aluminium and drought stress on root growth and crop yield
751 on acid soils. Plant Soil 372 (1):3-25. https://doi.org/10.1007/s11104-012-1580-1

752 Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14
753 (6):415-421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

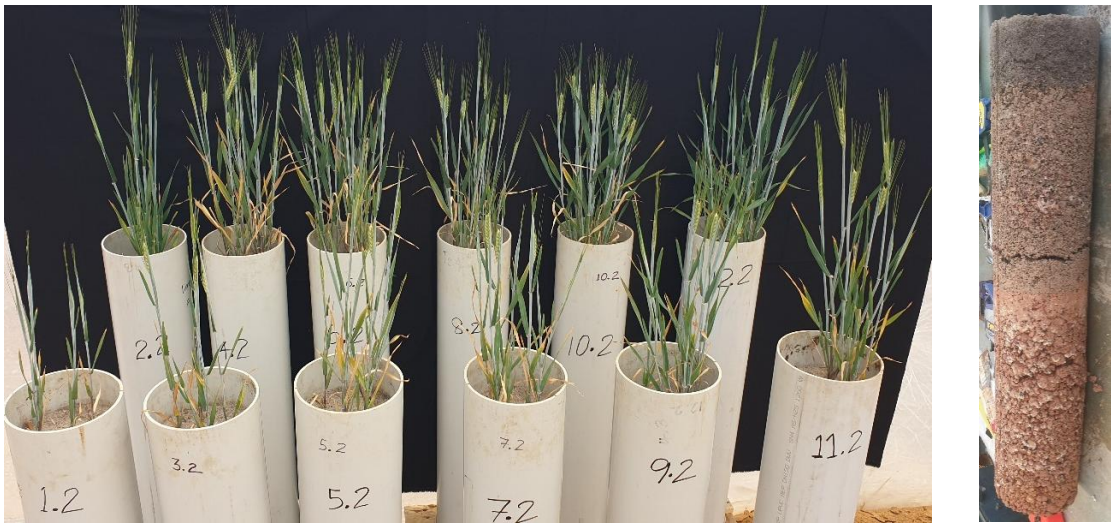
754 Zhu Y, Fox RH, Toth JD (2003) Tillage Effects on Nitrate Leaching Measured by Pan and Wick Lysimeters. Soil
755 Sci Soc Am J 67 (5):1517-1523. https://doi.org/10.2136/sssaj2003.1517

756

Graphical Abstract



Supplementary Materials



Supplementary Fig. S1 (a) Barley plants from a single replicate growing in re-engineered soil columns at 72 days after seeding, highlighting differences among treatment responses; and (b) reconstructed soil column showing the topsoil (0–10 cm), midsoil (10–40 cm), and subsoil (40–80 cm) layers at the end of the semi-controlled environment experiment.