Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Improved root-zone functionality sustains canola root proliferation and resource acquisition on a constrained duplex soil

Gaus Azam
gaus.azam@dpird.wa.gov.au
Department of Primary Industries and Regional Development https://orcid.org/0000-0002-3356-5425
Kanch Wickramarachchi
Department of Primary Industries and Regional Development https://orcid.org/0009-0007-5960-0907
Md Hasinur Rahman
Department of Primary Industries and Regional Development
Jackie Bucat
Department of Primary Industries and Regional Development https://orcid.org/0009-0001-4614-6748
Ed G Barrett-Lennard
Department of Primary Industries and Regional Development https://orcid.org/0000-0001-9945-1044
Geoffrey C Anderson
Department of Primary Industries and Regional Development https://orcid.org/0000-0002-0163-1600
Felix Fritschi
University of Missouri https://orcid.org/0000-0003-0825-6855

Research Article

Keywords: Duplex soil, nutrient acquisition, root plasticity, root-zone functionality, soil re-engineering, sustained root development

Posted Date: July 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10331414/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: The authors declare no competing interests.

Abstract

Background and aims

Root development is critical for crop adaptation to water-limited environments, yet canola responses to the simultaneous alleviation of multiple soil constraints remain poorly understood. This study investigated whether soil re-engineering could improve root-zone functionality, resource acquisition and crop productivity in a constrained duplex soil.

Methods

Using minirhizotron imaging and physiocochemical assays, we investigated whether soil re-engineering to 80 cm depth could transform root-zone functionality and enhance resource acquisition canola performance. Treatments comprised a control (T1), deep loosening with lime incorporation (T2), and deep loosening with lime, clay and compost incorporation (T3).

Results

Soil re-engineering increased soil pH_{Ca} from 4.37 to 5.40, while reducing exchangeable aluminium from 17.5 to 1.30 mg kg^{-1} and soil strength from 2.62 to 0.87 MPa across the 0–80 cm profile. Total root length increased by 106%, and rooting depth doubled from 40 to 80 cm. Consequently, stored soil water extraction increased by 35–45 mm, N, P, K and S uptake by 114%, 228%, 142% and 129%, biomass production by 56%, and grain yield by 48%. Although T2 developed the largest root system, T3 achieved the highest grain yield, demonstrating that crop performance depended on root-zone functionality rather than root size alone.

Conclusions

Simultaneous alleviation of multiple soil constraints transformed the rooting environment, promoting deeper rooting, greater water and nutrient acquisition, and substantially improved canola productivity. These findings demonstrate that improving root-zone functionality, rather than simply increasing root size, is fundamental to enhancing crop performance in constrained soils.

Introduction

Root system architecture plays a fundamental role in crop adaptation to water- and nutrient-limited environments because it determines the capacity of plants to explore soil profiles and acquire essential resources (Gregory, 2006; Lynch, 1995). In rainfed Mediterranean-type cropping systems, as found in southern Australia, deeper root systems extending throughout the soil profile is particularly important for improving water-use efficiency and sustaining productivity under variable climatic conditions, especially during terminal drought (Azam et al., 2025; Hammond et al., 2009; Wasson et al., 2012).

Root development is regulated by complex interactions among genetic, environmental, and edaphic factors (Conyers et al., 2023; Costa and Coutinho, 2022; Liu et al., 2011; Peng et al., 2025; Uddin et al., 2025; Wu et al., 2017). While substantial progress has been made in understanding the genetic regulation of root system architecture, particularly under favourable growth conditions (de Dorlodot et al., 2007; French et al., 2019; Hamblin and Hamblin, 1985; Kochian et al., 2005), our understanding of how root systems respond to multiple interacting soil constraints, including soil acidity, compaction, and deficiencies of essential macronutrients (N, P, K and S), remains limited.

The effectiveness of a root system depends not only on its architecture but also on the functionality of the surrounding root-zone environment. Root-zone functionality encompasses the physical, chemical, and biological conditions as well as nutrient densities that determine the ability of roots to proliferate, maintain activity, and acquire resources throughout the soil profile (Koevoets et al., 2016). Consequently, crop productivity is often governed not only by root size, but also by the capacity of the soil environment to support efficient root functioning (Lynch, 1995). Understanding how modifications to the root-zone environment, i.e. the functionality, influence root development and resource acquisition is therefore critical for improving crop adaptation to increasingly variable climatic conditions.

Canola (*Brassica napus* L.) is one of the world's most important oilseed crops, contributing approximately US$50 billion annually to global agricultural production (Shahidi, 1990; Yildiz, 2025). Despite considerable advances in breeding and crop management, canola remains particularly sensitive to subsoil constraints because its productivity depends on the ability of its taproot system to penetrate deeply and maintain access to water and nutrients during reproductive growth (Azam et al., 2026a; Farooq et al., 2024; Nuttall and Armstrong, 2010; Peng et al., 2025). Restrictions to root elongation and proliferation can therefore have disproportionately large impacts on canola productivity compared with many cereal crops.

Subsoil acidity, compaction and low nutrient availability are among the most widespread constraints limiting crop production globally and throughout southern Australia (Gazey et al., 2019; Hamza and Anderson, 2005; Rengel, 2003; Schneider et al., 2017). These constraints frequently co-occur in texture-contrast soils, where dense subsoil horizons, elevated soil strength, low nutrient availability, and aluminium (Al) toxicity interact to restrict root penetration and function (Dracup et al., 1992; Isbell, 2021; van Gool, 2016). Soil acidity inhibits root elongation through Al toxicity and nutrient imbalances (Delhaize and Ryan, 1995), whereas soil compaction limits root growth by increasing mechanical impedance (hereafter soil strength) (Azam et al., 2014; Bengough et al., 2011; Materechera et al., 1991). Nutrient deficiencies restrict overall

crop growth, which subsequently limits root biomass development due to reduced carbon allocation from the shoots (Hermans et al., 2006; Marschner, 2011).

Recent advances in soil profile modification have demonstrated that multiple interacting constraints can be alleviated simultaneously through soil re-engineering, which combines deep loosening with incorporation of amendments such as lime, clay, organic matter, and nutrients throughout the rooting zone (Azam and Gazey, 2019; Azam et al., 2024a; Azam and Reynolds, 2026; Davies et al., 2024; Uddin et al., 2025). Previous studies have shown that soil re-engineering can generate substantial and persistent improvements in various soil properties, resulting in enhanced crop growth and yield (Azam and Reynolds, 2026; Wickramarachchi et al., 2025b). More recently, field and controlled-environment studies have demonstrated that alleviation of soil acidity and soil strength can promote root development and resource acquisition in wheat, barley and triticale (Azam et al., 2026a; Azam et al., 2025; McBeath et al., 2026; Wickramarachchi and Azam, 2026; Wickramarachchi et al., 2025b). However, the extent to which canola root systems respond to integrated alleviation of multiple subsoil constraints under field conditions remains poorly understood.

Despite increasing recognition of the importance of root systems in determining crop adaptation to water-limited environments (Chen et al., 2015; Koevoets et al., 2016; Lynch, 2022; Lynch et al., 2024; White et al., 2013), there remains limited field-based evidence describing how canola root systems respond temporally and spatially to the integrated alleviation of multiple subsoil constraints. Most previous studies investigating canola responses to soil amelioration have relied on destructive root sampling at a single growth stage, providing limited information on the temporal dynamics of root development (Gregory and Eastham, 1996; Severini et al., 2020; Wasson et al., 2012). Moreover, it remains unclear whether improvements in root system alone are sufficient to enhance resource acquisition or whether the functionality of the root-zone environment plays an equally important role in determining crop productivity. Therefore, this study employed repeated *in situ* minirhizotron imaging to quantify the temporal and spatial dynamics of canola root development throughout the soil profile in a Brown Kurosol under rainfed conditions in Western Australia following soil re-engineering.

We tested two overarching hypotheses: (i) that soil re-engineering would transform a constrained root zone into a more functional rooting environment by alleviating soil physical and chemical constraints throughout the soil profile; and (ii) that the improved root-zone functionality, facilitated by the incorporation of organic matter, would sustain root proliferation, improve root continuity across the duplex boundary, and enhance exploration of deeper soil resources. Consequently, we expected these benefits to improve access to subsoil water and nutrients, ultimately boosting crop productivity under water-limited conditions.

To test these hypotheses, this study addressed four specific questions: (i) how does soil re-engineering alter the physical and chemical properties of an acidic Kurosol throughout the soil profile? (ii) how do canola root systems respond temporally and spatially to the progressive alleviation of subsoil constraints? (iii) to what extent does improvement in root system influence water extraction, macronutrient (N, P, K and S) acquisition and crop productivity? and (iv) is crop productivity more strongly associated with root system size or with improvements in root-zone functionality?

Materials and methods

Experimental site and treatments

The study was conducted during the 2023 growing season at the long-term soil re-engineering experiment, established in 2021, located at Meenar, Western Australia (31.52°S, 118.12°E). Prior to this study, the experimental site was cropped with a canola in 2021 and barley in 2022 and reported in Azam et al. (2026c). While this manuscript presents comprehensive data on soil properties, root development, water extraction, nutrient uptake, grain yield, and grain quality from the 2023 canola season. Consequently, some overlap in the description of the experimental site, treatments, and management is unavoidable. However, the present study provides substantially expanded datasets and new mechanistic insights by integrating temporal root development with changes in root-zone functionality, resource acquisition, and canola productivity. Therefore, this results also demonstrates the legacy benefits of soil re-engineering after three consecutive cropping seasons, highlighting the persistence of treatment effects on soil function and crop performance.

The soil was classified as a Brown Kurosol according to the Australian Soil Classification and consisted of a sandy surface horizon overlying a clay-enriched subsoil or duplex boundary occurring at 35–45 cm (Isbell, 2021). The site experiences a Mediterranean-type climate characterised by cool, wet winters and hot, dry summers. Rainfall during the growing season was recorded using an on-site automatic weather station. The 2023 growing season was characterised by a below-average rainfall environment, receiving only 240 mm annual rainfall compared with the long-term average of 429 mm. The 2023 season had an estimated water-limited yield potential of 1,420 kg ha^{-1} based on the model developed by Oliver et al. (2009), providing an opportunity to evaluate the capacity of soil re-engineering treatments to improve root development, resource acquisition, and crop productivity under severe water limitation.

The experiment consisted of a randomised complete block design with three replicates. Eight soil re-engineering treatments were imposed to alleviate physical, chemical and biological constraints (Azam et al., 2026c). For the present study, three treatments representing contrasting levels of soil modification were selected for detailed root investigation. The T1 treatment was an untreated control, while the T2 treatment consisted of deep loosening with incorporation of agricultural lime (6.8 t ha^{-1}, 90% equivalent weight of laboratory-grade $CaCO_3$) throughout the 0–80 cm soil profile. The T3 treatment consisted of deep loosening with incorporation of agricultural lime (6.8 t ha^{-1}) throughout the 0–80 cm profile, clay (329 t ha^{-1}, collected from the subsoil that contained 36 ± 2% clay particles) into the 0–40 cm layer, and compost (125 t ha^{-1}, sourced from a commercial supplier that contained 18% organic carbon and 1.13%, 0.45%, 0.77% and 0.77% N, P, K and S, respectively) into the 20–80 cm layer. Each treatment plot measured 4 m × 5 m and was separated by a 1 m × 4 m buffer zone.

Crop management

A hybrid canola (*Brassica napus* L.; cultivar Hyola Regiment XC, Pacific Seeds, Queensland, Australia) was sown on 17 May 2023 across all treatments at a seeding rate of 3 kg ha^{-1} with 30 cm row spacing. Crop establishment, fertiliser application, weed control, and pest and disease management were undertaken by the collaborating grower following commercial best-management practices. The experiment was maintained within the existing controlled traffic under a no-till system to minimise machinery-induced recompaction of the re-engineered soil profiles and to avoid any further tillage operation.

Prior to seeding, the topsoil (0–10 cm) contained 17.7 mg kg^{-1} mineral N (ammonium-N plus nitrate-N), 22 mg kg^{-1} Colwell P, 27 mg kg^{-1} Colwell K, and 6.1 mg kg^{-1} KCl40 S. These levels of macronutrients were not sufficient to achieve 100% water-limited yield potential for this site (Anderson et al., 2013; Bell et al., 2013; Brennan and Bell, 2013; Seymour and Brennan, 2017). Consequently, the crop received a basal fertiliser application equivalent to 100 kg N ha^{-1}, 20 kg P ha^{-1}, and 20 kg K ha^{-1}, together with 25 kg S ha^{-1} applied according to local agronomic recommendations for canola.

Root imaging and analysis

Root development was monitored non-destructively using minirhizotron technology. Transparent acrylic tubes (130 cm length, 70 mm internal diameter) were installed at approximately 45° to the soil surface within the crop row. One tube was installed in each experimental plot, resulting in three replicates per treatment (n = 3).

Root images were collected using a CI-600 *in-situ* root imager (CID Bio-Science, Camas, WA, USA), which acquires high-resolution digital images of roots growing along the soil–tube interface. Images were collected at 7, 14, 21, 28, 36, 46, 57, 67, and 83 days after seeding (DAS). At each sampling date, images were obtained from six observation windows spanning approximately 0–80 cm vertical soil depth. Each window represented approximately 13.3 cm of vertical soil depth, enabling repeated assessment of temporal and spatial changes in root development throughout the growing season.

Images were analysed using RootSnap! software (Version 1.4.0.108, CID Bio-Science, USA). Prior to analysis, image brightness and contrast were standardised across all images. Visible roots were manually traced using the software's semi-automated tracing algorithm, which automatically aligns tracing points with root centre lines. Total root length (TRL; m $tube^{-1}$) was calculated for each image and summed across the depths. Planar root length density (pRLD) was calculated as the ratio of root length to the scanned image area following established minirhizotron procedures (Wacker et al., 2024). The rate of root proliferation (δpRLD; cm cm^{-2} d^{-1}) was calculated as:

$$\delta pRLD = (pRLD_2 - pRLD_1) / \delta t \quad (i)$$

where δt is the number of days between successive sampling dates.

Root continuity was defined as the persistence of root proliferation across successive soil depth intervals and sampling dates, indicating continued access to deeper portions of the soil profile.

Soil sampling and analyses

Soil samples were collected in July 2023 (approximately 75 DAS) when treatment differences in crop growth and root development were clearly evident. Samples were collected from 10-cm increments to 80 cm depth using a stainless-steel pipe with 4 cm inner diameter. At each sampling event, four soil cores per plot and depth were collected, bulked and processed for various analysis.

All soil analytical procedures are described in Rayment and Lyons (2011). Soil pH was measured in 0.01 M $CaCl_2$ (1:5 soil-to-solution ratio) (Method 4B2). Soil organic carbon was determined using dry combustion (Method 6A1). Mineral N was measured following extraction with 2 M

KCl (Method 7C2). Colwell P was determined using sodium bicarbonate extraction (Method 9B1), while Colwell K was measured using the same bicarbonate extraction procedure followed by determination of K concentration in the extract (Method 18A1). Soil S was measured using 0.25 M KCl (Method 10D1) while extractable Al was used using method described by Bromfield (Bromfield, 1987). Soil data were analysed as the weighted average for 0–30 cm (e.g. pH_{30}) (Anderson et al., 2026), 30–80 cm (e.g. pH_{30-80}) and 0–80 cm depth (e.g. pH_{80}).

Soil strength measurements

Soil strength was assessed in July 2023 using a digital cone penetrometer (CP40II; Rimik Pty Ltd, Toowoomba, QLD, Australia). Measurements were conducted on the same day as soil sampling to facilitate interpretation of penetration resistance in relation to soil water content and soil chemical properties. Assessments were undertaken during the peak vegetative growth stage of canola, approximately two days after a rainfall event. Penetrometer resistance was recorded at 2.5 cm depth increments to 80 cm and expressed as MPa.

Because soil profile re-engineering substantially altered soil bulk density, root development, and water extraction, volumetric soil water content differed among treatments at the time of measurement (see Results). Although soil penetration resistance is strongly influenced by soil water content, the untreated control retained substantially more profile water than the re-engineered treatments because restricted root development limited water extraction. Consequently, the greater penetration resistance measured in the untreated control cannot be attributed to drier soil conditions but instead reflects the persistence of mechanical impedance within the unmodified soil profile.

Soil water extraction

Volumetric soil water content was monitored throughout the growing season using EnviroPro® capacitance probes (Model EP100G-12, EnviroPro Sensors Pty Ltd, Stepney, SA, Australia) installed within each plot. The probes measure soil dielectric properties and convert them to volumetric water content using soil-specific calibration equations. Soil water content was recorded at 1 h intervals at 10 cm depth increments from the soil surface to 80 cm depth throughout the growing season.

Plant measurements

Above-ground biomass was sampled at anthesis, corresponding to approximately 50% flowering, when canola nutrient demand and biomass accumulation were near their seasonal maximum (Meier, 2018). Three biomass samples were collected from each plot by harvesting two adjacent crop rows over a 0.5 m length. Samples were oven-dried at 60°C until constant mass, weighed to determine shoot biomass, and subsequently ground for chemical analysis as describe in Rayment and Lyons (2011). Plant tissue N concentration was determined by dry combustion (Method 6B2). Phosphorus, K and S concentrations were measured following nitric acid–hydrogen peroxide digestion and subsequent analysis by inductively coupled plasma optical emission spectrometry (ICP-OES) (McQuaker et al., 1979). Total nutrient uptake (N, P, and K) was calculated as the product of shoot dry matter and nutrient concentration and expressed on an area basis (kg ha^{-1}). We used the critical tissue concentration for N of 3.2%, for P of 0.30% (Reuter and Robinson, 1997), for K of 2.0 and for S of 0.25% (Brennan and Bolland, 2007).

Above-ground biomass and grain yield were determined at physiological maturity by hand-harvesting plants from a 2 m × 4 m quadrat within each plot. Biomass samples were oven-dried at 60°C to constant mass and weighed to determine total dry matter production. Following threshing, grain yield was determined and expressed on a dry weight basis (kg ha^{-1}). A representative grain subsample from each plot was retained for grain quality analyses. Harvest index (HI) was calculated as the ratio of grain yield to total above-ground biomass × 100. Grain protein concentration (%) was determined using near-infrared reflectance spectroscopy (NIR, Infratec 1241 Grain Analyzer, FOSS, Hillerød, Denmark). Grain size was assessed as thousand-seed weight (TSW) by counting and weighing a representative grain subsample from each plot.

Statistical analysis

The experimental design consisted of a randomised complete block design with three biological replicates (n = 3) per treatment. Treatment effects on soil properties, root system traits, water extraction, nutrient uptake, biomass production, and grain yield were assessed using analysis of variance (ANOVA) in GenStat Version 22 (VSN International, Hemel Hempstead, UK).

Treatment was treated as a fixed effect and block as a random effect. For variables measured repeatedly through time, including root development and soil water content, sampling date was included as a repeated factor and treatment × date interactions were examined. Assumptions of normality and homogeneity of variance were evaluated using residual diagnostic plots. Where treatment effects were significant ($P \leq 0.05$), means were separated using Tukey's honestly significant difference (HSD) test. Pearson correlation and regression analyses were used to investigate relationships among root development, soil properties, resource acquisition, and crop productivity.

Results

Soil re-engineering alleviated physical and chemical constraints

Soil re-engineering substantially modified the physical and chemical properties of the Kurosol profile (Table 1). Deep incorporation of lime increased soil pH throughout the profile and markedly decreased extractable Al, thereby alleviating subsoil acidity. Within the 0–30 cm profile, pH_{Ca} increased from 4.33 in the untreated control (T1) to 4.81 in both T2 and T3 ($P < 0.05$), while extractable Al declined from 13.8 to 1.5 and 2.8 mg kg^{-1}, respectively ($P < 0.05$). Greater changes occurred across the 30–80 cm and 0–80 cm profile compared to the 0–30 cm depth. For example, at 30–80 cm depth, pH_{Ca} increased from 4.39 in T1 to 5.35 in T2 and 5.75 in T3. Over the same depth, extractable Al decreased from 22.42 mg kg^{-1} in T1 to 2.34 mg kg^{-1} in T2 and only 0.30 mg kg^{-1} in T3, representing more 90% reduction in Al concentration.

Soil strength declined markedly following soil re-engineering. Penetrometer resistance at 0–30 cm decreased from 2.04 MPa in T1 to 0.80 MPa in T2 and 0.73 MPa in T3 ($P < 0.001$). Similar responses occurred at 30–80 cm and 0–80 cm depths. Overall, at 0–80 cm depth soil strength declined from 2.62 MPa in T1 to 1.14 MPa in T2 and 0.87 MPa in T3, equivalent to reductions of 56 and 67%, respectively.

Organic carbon concentrations tended to increase following amendment incorporation, particularly in T3, where organic carbon at 0–80 cm was 44% greater than the control (0.52 vs 0.36%; $P < 0.05$). Soil CEC capacity also doubled from 1.53 cmol kg^{-1} in T1 to 3.16 cmol kg^{-1} in T3 at 0–80 cm ($P < 0.05$).

Deep incorporation of clay and compost also increased nutrient availability at depth. Colwell P at 0–80 cm increased from 7.30 T1 to 11.89 mg kg^{-1} in T3 (63%; $P < 0.05$), while Colwell K increased from 20.49 in T1 to 26.12 mg kg^{-1} in T3 (27%; $P < 0.05$), S level increased from 10.95 mg kg^{-1} in T1 to 19.97 mg kg^{-1} in T3 (100%; $P < 0.05$), however, inorganic N decreased from 10.65 mg kg^{-1} in T1 to 5.41 mg kg^{-1} in T2 (51%, $P < 0.05$). Collectively, these changes indicate that soil re-engineering simultaneously alleviated major physical, chemical and nutrients related soil constraints to root growth and resource acquisition.

Table 1

Effect of soil re-engineering treatments on selected soil chemical and physical properties of a Brown Kurosol measured during the 2023 canola growing season at Meenar, Western Australia. Values represent treatment means (n = 3). Within a row, means followed by different letters are significantly different according to Tukey's honestly significant difference (HSD) test at $P < 0.05$. T1, untreated control; T2, deep loosening with lime incorporation; and T3, deep loosening with lime, clay, and compost incorporation.

Properties†	T1	T2	T3	lsd (5%)
pH_{30}	4.33[a]	4.81[b]	4.81[b]	0.38
pH_{30-80}	4.39[a]	5.35[b]	5.75[b]	0.85
pH_{80}	4.37[a]	5.14[b]	5.40[b]	0.66
Al_{30}	13.75[a]	1.51[b]	2.83[b]	5.45
AL_{30-80}	22.42[a]	2.34[b]	0.30[b]	11.38
Al_{80}	17.49[a]	2.03[b]	1.33[b]	6.23
SS_{30}	2.04[b]	0.80[a]	0.73[a]	0.09
SS_{30-80}	3.34[c]	1.58[b]	1.10[a]	0.28
SS_{80}	2.62[c]	1.14[b]	0.87[a]	0.11
OC_{30}	0.53	0.86	0.88	0.34
OC_{30-80}	0.25[a]	0.20[a]	0.32[b]	0.05
OC_{80}	0.36[a]	0.46[ab]	0.52[b]	0.12
CEC_{30}	1.32[a]	2.65[b]	2.54[b]	1.12
CEC_{30-80}	1.65[a]	2.25[ab]	3.54[b]	1.32
CEC_{80}	1.53[a]	2.40[ab]	3.16[b]	1.15
N_{30}	21.99[b]	10.85[a]	12.27[ab]	8.41
N_{30-80}	3.85	2.15	7.07	6.65
N_{80}	10.65	5.41	9.02	4.51
P_{30}	14.82	14.37	17.05	5.73
P_{30-80}	2.79[a]	2.61[a]	8.80[b]	1.55
P_{80}	7.30[a]	7.02[a]	11.89[b]	2.37
K_{30}	19.23[a]	20.34[a]	45.90[b]	16.37
K_{30-80}	21.25[b]	9.50[a]	14.25[a]	6.55
K_{80}	20.49[ab]	13.56[a]	26.12[b]	8.95
S_{30}	3.23	2.89	9.05	10.47
S_{30-80}	15.59[a]	21.57[ab]	26.53[b]	9.78
S_{80}	10.95	14.59	19.97	9.18

Note: † pH_{30}, pH_{30-80} and pH_{80}, soil pH ($CaCl_2$); Al_{30} Al_{30-80} and Al_{80}, aluminium concentration ($CaCl_2$, mg kg^{-1}); SS_{30}, SS_{30-80} and SS_{80}, soil strength (MPa); OC_{30}, OC_{30-80} and OC_{80}, organic carbon (%); CEC_{30}, CEC_{30-80} and CEC_{80}, cation exchange capacity (cmol kg^{-1}); N_{30}, N_{30-80} and N_{80}, mineral nitrogen (NO_3^--N + NH_4^+-N; mg kg^{-1}); P_{30} P_{30-80} and P_{80}, Colwell phosphorus (mg kg^{-1}); and K_{30}, K_{30-80} and K_{80}, Colwell potassium (mg kg^{-1}) and S_{30}, S_{30-80} and S_{80}, sulfur (mg kg^{-1}) for the 0–30 cm, 30–80 and 0–80 cm soil profiles, respectively. lsd (5%) = least significant difference at $P < 0.05$.

Soil re-engineering promoted root development throughout the growing season

Root development differed significantly among treatments and diverged progressively as the season advanced (Fig. 1). During crop establishment (7–21 DAS), total root length (TRL) increased similarly across treatments. Thereafter, treatment differences became increasingly pronounced, with the greatest difference occurring between 28 and 57 DAS ($P < 0.05$). By 83 DAS, TRL reached approximately 79 m tube^{-1} in T1, compared with 163 m tube^{-1} in T2 and 92 m tube^{-1} in T3 (Fig. 1a). Relative to the control, TRL increased by 106% in T2 and 16% in T3.

The rate of root proliferation (δpRLD) peaked between 28 and 46 DAS in all treatments but was substantially greater in T2 than in either T1 or T3 (Fig. 1b). Root growth in T1 and T3 slowed markedly after 57 DAS, whereas T2 continued to accumulate root length throughout the monitoring period. Amelioration of subsoil acidity and soil strength promoted sustained root development, while further addition of clay and organic matter moderated the magnitude of root proliferation relative to the lime-only treatment.

Root distribution with depth responded strongly to subsoil amelioration

Canola root distribution across the depths differed among treatments as roots developed deeper into the soil profile (Fig. 2). At 7 DAS, TRL did not differ significantly among treatments, sampling depths, or their interaction ($P > 0.05$; Fig. 2a), indicating similar early root establishment across treatments. By 28 DAS, TRL differed significantly among treatments and sampling depths ($P < 0.05$), although the treatment × depth interaction was not significant ($P > 0.05$; Fig. 2b). From 57 DAS onwards, TRL differed significantly among treatments, depths, and their interaction ($P < 0.05$; Fig. 2c and 2d), demonstrating that treatment effects became increasingly depth-dependent as the season progressed.

In the untreated control, root abundance declined sharply below the duplex boundary, with little or no roots in deeper soil layers. In contrast, soil re-engineering substantially increased root proliferation throughout the profile. In the three deepest measurement depths, TRL increased from near zero in T1 to approximately 23–32 m per 13.3 cm depth in T2. A similar depth response was observed in T3, although TRL was generally lower than in T2, especially at 39–65 cm depth. These results indicate that soil re-engineering enabled canola roots to penetrate and exploit subsoil layers that were largely inaccessible in the untreated profile.

Enhanced root development increased soil water extraction

Treatment effects on profile soil water were significant from 14 DAS onwards. Several rainfall events immediately after seeding replenished soil water across all treatments (Fig. 3a), resulting in similar cumulative profile water contents during early crop establishment (Fig. 3b). As the season progressed, however, treatment differences became increasingly pronounced. During early vegetative growth, profile water declined at similar rates across treatments, whereas marked divergence occurred during stem elongation and flowering, coinciding with rapid root proliferation (Fig. 1).

At most measurement dates, T1 retained significantly greater volumetric soil water content than T2 and T3, particularly between 20 and 70 cm depth (Fig. 4). At harvest, approximately 115 mm of water remained within the 0–80 cm soil profile of T1, compared with only 80 and 70 mm in T2 and T3, respectively. Consequently, soil re-engineering increased profile water extraction by approximately 35 mm in T2 and 45 mm in T3 relative to the untreated control. The large amount of residual soil water in T1 indicates that a substantial proportion of stored subsoil water remained inaccessible because restricted root development limited water uptake below the duplex boundary. In contrast, sustained root proliferation throughout the re-engineered soil profile, particularly below the duplex boundary, enabled greater extraction of stored subsoil water during crop growth.

Improved root-zone conditions enhanced nutrient acquisition and crop productivity

Improved soil conditions and root development translated into substantial increases in nutrient concentration and uptake, biomass production, grain yield, and grain quality (Table 2). Nitrogen uptake increased from 68 kg ha^{-1} in T1 to 102 kg ha^{-1} in T2 and 145 kg ha^{-1} in T3, representing increases of 50 and 114%, respectively ($P < 0.05$). Phosphorus uptake increased from 5.6 kg ha^{-1} in T1 to 10.9 kg ha^{-1} in T2 and 18.3 kg ha^{-1} in T3, equivalent to increases of 96 and 228%, respectively ($P < 0.001$). Potassium uptake increased from 36 kg ha^{-1} in T1 to 59 kg ha^{-1} in T2 and 87 kg ha^{-1} in T3, representing increases of 64 and 142%, respectively. Sulfur uptake increased from 9.2 kg ha^{-1} in T1 to 16.7 kg ha^{-1} in T2 and 21.1 kg ha^{-1} in T3, representing increases of 84 and 129%, respectively.

Biomass production increased from 4,989 kgha^{-1} in T1 to 6,653 kg ha^{-1} in T2 and 7,793 kg ha^{-1} in T3, corresponding to increases of 33 and 56%, respectively (Table 2, $P < 0.001$). Grain yield increased from 1,983 kg ha^{-1} in T1 to 2,518 t ha^{-1} in T2 and 2,926 kg ha^{-1} in T3, representing improvements of 27 and 48%, respectively.

Grain protein concentration increased from 19.4% in T1 to 22.5% in T2 and 25.2% in T3 (Table 2, $P < 0.05$), whereas thousand-seed weight was not significantly affected by treatment ($P > 0.05$). Collectively, these responses demonstrate that soil re-engineering substantially enhanced resource acquisition and crop productivity.

Table 2
Effect of soil re-engineering treatments on nutrient concentration and uptake, biomass production, grain yield, and grain quality of canola grown on a Brown Kurosol during the 2023 growing season at Meenar, Western Australia. Values represent treatment means (n = 3). Within a row, means followed by different letters are significantly different according to Tukey's honestly significant difference (HSD) test at P < 0.05.

Properties	T1	T2	T3	lsd (5%)
N concentration (%)	2.70^{a}	3.07^{a}	3.71^{b}	0.77
N uptake (kg ha^{-1})	67.9^{a}	101.6^{b}	145.0^{c}	26.9
P concentration (%)	0.22^{a}	0.33^{a}	0.47^{b}	0.12
P uptake (kg ha^{-1})	5.59^{a}	10.94^{b}	18.34^{c}	3.70
K concentration (%)	1.43^{a}	1.78^{ab}	2.24^{b}	0.81
K uptake (kg ha^{-1})	36.00^{a}	59.15^{ab}	87.00^{b}	28.90
S concentration (%)	0.37^{a}	0.50^{ab}	0.54^{b}	0.15
S uptake (kg ha^{-1})	9.20^{a}	16.72^{b}	21.08^{b}	5.00
Biomass yield (kg ha^{-1})	4,989^{a}	6,653^{b}	7,793^{c}	585
Grain yield (kg ha^{-1})	1,983^{a}	2,518^{b}	2,926^{c}	442
Protein (%)	19.43^{a}	22.47^{ab}	25.17^{b}	3.63
Thousand seed weight (g)	3.63	3.57	3.46	0.22
Note: lsd (5%) = least significant difference at P < 0.05.				

Relationships among root development, resource acquisition and crop performance

Total root length was negatively related to residual soil water at harvest (Fig. 5a), demonstrating that greater root proliferation increased the capacity of canola to utilise stored soil water. Consequently, T2 and T3 retained substantially less water within the 0–80 cm profile at harvest than the untreated control. Residual soil water was strongly negatively associated with grain yield (Fig. 5b), indicating that treatments capable of extracting a greater proportion of stored soil water achieved superior crop performance. Together, these relationships highlight the importance of sustained root development for water acquisition under water-limited conditions.

Correlation analyses revealed strong associations among soil properties, soil nutrient availability, nutrient uptake, crop growth and grain production (Table 3, Table and Table 5). Total root length was positively correlated with soil pH, but negatively correlated with Al concentration, OC_{30-80} and soil strength (Table 3), indicating that root development was favoured by a less acidic and less mechanically restrictive rooting environment. The association between TRL and Al (r = -0.53 to -0.60) was stronger than that with soil pH (r = 0.30–0.48), suggesting that alleviation of aluminium toxicity was a key driver of root proliferation. Total root length was generally negatively correlated with the residual availability of the four macronutrients (Table 4). This negative relationship most likely reflects greater nutrient depletion from the soil by larger and more active root systems, rather than reduced soil fertility, and is consistent with the higher total nutrient uptake observed in T2 and T3 (Table 2).

Uptake of the four macronutrients (N, P, K, and S) was strongly and positively correlated, indicating that treatments promoting acquisition of one nutrient generally enhanced acquisition of the others (Table 5). Biomass production was also strongly associated with the uptake of all four nutrients (r = 0.85–0.94), with the strongest relationship observed for sulfur uptake, suggesting that balanced nutrient acquisition was a major driver of crop growth. Grain yield was highly correlated with biomass production (r = 0.95) and positively associated with the uptake of all four macronutrients (r = 0.70–0.92), highlighting the importance of nutrient acquisition for grain production.

Total root length was positively correlated with the uptake of N, P, K, and S (r = 0.19–0.42), above-ground biomass (r = 0.43), and grain yield (r = 0.46). However, these relationships were consistently weaker than those among nutrient uptake, biomass production, and grain yield. This finding suggests that crop productivity was influenced not only by root system size but also by the efficiency with which the root system

acquired soil water and nutrients, supporting the concept that root-zone functionality, rather than root length alone, governed crop performance.

Residual soil water at harvest explained a large proportion of the variation in grain yield (R^2 = 0.77), indicating that access to stored soil water was a major determinant of crop performance (Fig. 5b).

Interestingly, T2 developed the largest root system, consistent with its greater capacity to exploit deep soil water. However, T3 achieved the highest nutrient uptake, biomass production, and grain yield despite producing approximately 43% less TRL than T2. Specifically, T3 increased phosphorus uptake by 43%, potassium uptake by 47%, biomass production by 17%, and grain yield by 16% relative to T2. These findings suggest that while extensive root systems were important for accessing stored soil water, improvements in root-zone functionality through clay and compost incorporation enhanced nutrient availability and resource acquisition efficiency, enabling a smaller root system to support greater crop productivity.

Table 3
Pearson correlation coefficients (r) between total root length (TRL; m tube^{-1}) and selected soil physical and chemical properties measured in the 0–80 cm soil profile of a Brown Kurosol during the 2023 canola growing season at Meenar, Western Australia. Correlations were calculated using treatment means across all observations. Positive values indicate positive associations, whereas negative values indicate inverse relationships.

† pH_{30}	TRL	pH_{30}	$pH_{30–80}$	pH_{80}	Al_{30}	$Al_{30–80}$	Al_{80}	SS_{30}	$SS_{30–80}$	SS_{80}	OC_{30}	$OC_{30–80}$	OC_{80}	CEC_{30}	$CEC_{30–80}$
	0.48														
$pH_{30–80}$	0.26	0.88													
pH_{80}	0.30	0.92	1.00												
Al_{30}	-0.60	-0.80	-0.73	-0.75											
$Al_{30–80}$	-0.49	-0.76	-0.79	-0.79	0.92										
Al_{80}	-0.53	-0.81	-0.80	-0.82	0.97	0.98									
SS_{30}	-0.57	-0.85	-0.78	-0.81	0.91	0.90	0.93								
$SS_{30–80}$	-0.39	-0.84	-0.76	-0.79	0.89	0.85	0.90	0.97							
SS_{80}	-0.49	-0.84	-0.79	-0.82	0.90	0.90	0.92	1.00	0.98						
OC_{30}	0.40	0.85	0.94	0.94	-0.66	-0.68	-0.71	-0.70	-0.65	-0.69					
$OC_{30–80}$	-0.66	0.02	0.37	0.31	-0.06	-0.17	-0.15	-0.06	-0.19	-0.14	0.15				
OC_{80}	0.11	0.75	0.96	0.94	-0.60	-0.66	-0.68	-0.64	-0.64	-0.66	0.93	0.50			
CEC_{30}	0.52	0.96	0.89	0.92	-0.79	-0.82	-0.83	-0.81	-0.77	-0.80	0.86	-0.01	0.75		
$CEC_{30–80}$	-0.05	0.73	0.89	0.87	-0.53	-0.60	-0.62	-0.64	-0.69	-0.69	0.73	0.64	0.87	0.69	
CEC_{80}	0.14	0.86	0.95	0.95	-0.66	-0.72	-0.74	-0.75	-0.77	-0.78	0.83	0.46	0.89	0.85	0.97

Note: † pH_{30}, $pH_{30–80}$ and pH_{80}, soil pH ($CaCl_2$); Al_{30} $Al_{30–80}$ and Al_{80}, aluminium concentration ($CaCl_2$, mg kg^{-1}); SS_{30}, $SS_{30–80}$ and SS_{80}, soil strength (MPa); OC_{30}, $OC_{30–80}$ and OC_{80}, organic carbon (%); CEC_{30}, $CEC_{30–80}$ and CEC_{80}, cation exchange capacity (cmol kg^{-1} for the 0–30 cm, 30–80 and 0–80 cm soil profiles, respectively.

Table 4
Pearson correlation coefficients (r) between total root length (TRL; m tube⁻¹) and status of selected macronutrients measured in the 0–30 and 0–80 cm soil profile of a Brown Kurosol during the 2023 canola growing season at Meenar, Western Australia. Correlations were calculated using treatment means across all observations. Positive values indicate positive associations, whereas negative values indicate inverse relationships.

†N_{30}	TRL	N_{30}	$N_{30–80}$	N_{80}	P_{30}	$P_{30–80}$	P_{80}	K_{30}	$K_{30–80}$	K_{80}	S_{30}	$S_{30–80}$
	-0.57											
$N_{30–80}$	-0.37	0.23										
N_{80}	-0.61	0.81	0.75									
P_{30}	-0.25	0.29	0.51	0.50								
$P_{30–80}$	-0.38	-0.21	0.71	0.29	0.49							
P_{80}	-0.38	-0.04	0.73	0.42	0.77	0.93						
K_{30}	-0.28	-0.23	0.79	0.32	0.55	0.96	0.93					
$K_{30–80}$	-0.80	0.64	0.29	0.60	0.05	-0.04	-0.01	-0.01				
K_{80}	-0.68	0.16	0.82	0.60	0.49	0.78	0.78	0.83	0.55			
S_{30}	-0.24	-0.12	0.22	0.05	0.77	0.56	0.72	0.58	-0.05	0.46		
$S_{30–80}$	0.25	-0.65	-0.03	-0.45	0.28	0.43	0.43	0.50	-0.41	0.20	0.66	
S_{80}	0.12	-0.54	0.04	-0.34	0.45	0.50	0.55	0.56	-0.33	0.29	0.81	0.97

Note: † N_{30}, $N_{30–80}$ and N_{80}, mineral nitrogen (NO_3^--N + NH_4^+-N; mg kg⁻¹); P_{30} $P_{30–80}$ and P_{80}, Colwell phosphorus (mg kg⁻¹); and K_{30}, $K_{30–80}$ and K_{80}, Colwell potassium (mg kg⁻¹) and S_{30}, $S_{30–80}$ and S_{80}, sulfur (mg kg⁻¹) for the 0–30 cm, 30–80 *and 0–80 cm soil profiles, respectively.*

Table 5
Pearson correlation coefficients (r) among total root length (TRL), nutrient uptake, biomass production, grain yield, grain protein concentration, thousand-seed weight (TSW), and harvest index (HI) of canola grown under contrasting soil re-engineering treatments at Meenar, Western Australia, during the 2023 growing season. Correlations were calculated using treatment means across all observations. Positive values indicate positive associations, whereas negative values indicate inverse relationships.

N uptake	TRL	N uptake	P uptake	K uptake	S uptake	Biomass yield	Grain yield	Protein
	0.30							
P uptake	0.42	0.98						
K uptake	0.19	0.68	0.76					
S uptake	0.39	0.92	0.93	0.76				
Biomass yield	0.43	0.85	0.90	0.90	0.94			
Grain yield	0.46	0.70	0.81	0.92	0.84	0.95		
Protein	0.28	0.92	0.92	0.77	0.89	0.83	0.72	
TSW	0.00	-0.82	-0.74	-0.50	-0.75	-0.63	-0.40	-0.80

Rooting efficiency and harvest index

Rooting efficiency, expressed as root length required to produce a unit of biomass or grain yield, differed among treatments (Fig. 6). Among the three treatments, T3 had the highest rooting efficiency, while T2 had the lowest. The greatest improvement occurred in T3, where enhanced nutrient availability and improved root-zone conditions enabled greater biomass and grain production despite a smaller root system than T2.

Harvest index varied only modestly among treatments, suggesting that treatment effects on grain yield were primarily driven by increased biomass production rather than major shifts in biomass partitioning. Despite exhibiting the greatest rooting efficiency, T3 had the lowest harvest index, indicating that enhanced resource acquisition and biomass accumulation were not fully converted into grain yield. This response may reflect a degree of reproductive limitation during grain filling, although the underlying mechanisms require further investigation.

Discussion

This study investigated whether improving the functionality of a constrained root zone could enhance root development, resource acquisition, and crop productivity in canola grown on a severely acidic duplex soil. Soil re-engineering improved soil pH, cation exchange capacity (CEC), and nutrient availability while reducing aluminium concentration and soil strength throughout the 0–80 cm profile. These changes promoted sustained root proliferation into deeper soil layers, enhanced extraction of stored subsoil water, and increased N, P, K, and S uptake, resulting in biomass and grain yield increases of up to 56% and 48%, respectively. Deep root proliferation was particularly important for accessing stored subsoil water, whereas incorporation of clay and compost increased nutrient retention and availability within the rooting zone, enabling a smaller root system to acquire resources more efficiently. Consequently, although T2 developed the largest root system, T3 achieved greater nutrient uptake and crop productivity despite producing fewer roots. These findings demonstrate that crop performance depends not only on root system size but also on the capacity of the surrounding root-zone environment to supply water and nutrients efficiently.

Improved root-zone functionality promoted sustained root development

Root system is highly responsive to the physical and chemical conditions of the soil environments (Koevoets et al., 2016; Lynch, 1995; Lynch, 2022). In the present study, soil re-engineering improved root-zone functionality through simultaneous alleviation of multiple constraints, including soil acidity, Al toxicity, and soil strength. Soil pH increased and Al toxicity reduced substantially throughout the profile, while soil strength declined by more than 50%, creating a more favourable environment for root elongation and proliferation.

The strong root response observed in T2 and T3 is consistent with extensive evidence demonstrating that acidic and compacted subsoils restrict root growth and limit exploration of deeper soil layers (Bengough et al., 2011; Conyers et al., 2023; Delhaize and Ryan, 1995). In acidic soils, Al toxicity can rapidly inhibit root elongation, reducing access to subsoil water and nutrients (Azam et al., 2026a; Delhaize and Ryan, 1995), whereas high soil strength increases the mechanical resistance encountered by growing roots and restricts root penetration (Azam et al., 2014; Bengough et al., 2011; Hamza and Anderson, 2005). The substantial reduction in soil strength and increase in soil pH and reduced Al concentration following soil re-engineering therefore removed two major limitations to root growth.

The temporal dynamics of root development provide additional evidence for the importance of root-zone functionality. Root growth trajectories were similar among treatments during crop establishment but diverged markedly after approximately 36 DAS, when crop demand for water and nutrients increased. In T1 and T3, the increases in pRLD slowed considerably after 57 DAS, whereas T2 maintained root growth throughout reproductive development (Fig. 1b). Similar responses have been reported in wheat and barley following amelioration of acidic and compacted soils, where improvements in root-zone conditions enabled greater and deeper root system (Azam et al., 2025; Wickramarachchi and Azam, 2026). The increased root abundance at deeper depths, further demonstrates that soil re-engineering expanded the functional rooting volume available to canola and allowed roots to exploit soil layers that were largely inaccessible in the untreated profile.

Sustained root development enhanced water and nutrient acquisition

The improvements in root development translated directly into greater acquisition of water and nutrients. Root systems function primarily as organs for resource capture, and their contribution to crop productivity depends largely on their ability to access limiting resources rather than simply their size (Gregory, 2006; Lynch, 1995; Lynch, 2019). In this study, treatments with larger (T2) and deeper root (both T2 and T3) systems extracted more water from the soil profile, retained less residual soil water at harvest, and achieved substantially greater nutrient uptake than the untreated control (Table 2).

The relationship between root development and water extraction was positive. Treatments T2 and T3 extracted an additional 35–45 mm of water from the 0–80 cm profile compared with T1. This additional water likely contributed significantly to grain production because reproductive growth in Mediterranean environments frequently coincides with declining rainfall and increasing evaporative demand (Barrett-Lennard et al., 2024; Kirkegaard et al., 2007; Nuttall and Armstrong, 2010; Wickramarachchi et al., 2025a). Previous studies have demonstrated that deeper rooting systems improve drought avoidance by increasing access to stored subsoil water during grain filling (Wasson et al., 2012; White et al., 2015). Consistent with these findings, residual soil water at harvest was strongly associated with grain yield, indicating that water acquisition was a major determinant of crop performance.

Enhanced root development also improved nutrient acquisition. Nitrogen, P, K and S uptake increased substantially following soil re-engineering, reflecting both improved soil fertility and greater root exploration of the profile (Table 2). Strong positive relationships among nutrient uptake, biomass production, and grain yield suggest that increased access to soil resources contributed directly to productivity gains. Similar relationships have been reported in canola and cereal crops where improved root development enhanced nutrient capture and increased crop growth (Azam et al., 2025; Hammond et al., 2009; Lynch, 2019; Wickramarachchi et al., 2025b). Collectively, these results support the concept that sustained root development increases crop productivity by improving access to both water and nutrients during critical growth stages.

The influence of soil re-engineering on nutrient acquisition was further demonstrated by comparing shoot nutrient concentrations with established critical values for canola (Brennan and Bolland, 2007; Reuter and Robinson, 1997). Plants grown in T8 showed no nutritional limitations, with shoot concentrations of N (3.7%), P (0.47%), K (2.2%), and S (0.47%) all exceeding their respective critical concentrations of 3.2%, 0.30%, 2.0%, and 0.25%. In contrast, plants grown in T5 exceeded the critical concentrations for P (0.33%) and S (0.50%), whereas N and K remained below the critical thresholds. The untreated control (T1) was deficient in N, P, and K, with only S concentration exceeding the critical level.

Root-zone functionality was more important than root size alone

The most significant finding of this study was that the treatment producing the largest root system did not achieve the highest crop productivity. Although T2 produced approximately 77% greater total root length than T3 (Fig. 1), T3 achieved greater nutrient uptake, biomass production, and grain yield. This finding challenges the common assumption that larger root systems necessarily result in superior crop performance and demonstrates that root-zone functionality can be as important as root size in determining crop productivity. Under comparable root-zone conditions, larger root systems would be expected to enhance resource acquisition because they explore a greater volume of soil. However, in the present study, soil re-engineering in T3 increased nutrient availability, CEC, organic carbon and water availability, enabling a smaller root system to acquire resources more efficiently than the substantially larger root system in T2. These results indicate that crop performance depends on the interaction between root system and the functionality of the surrounding root-zone environment, rather than on root size alone.

The superior performance of T3 likely reflects improvements in the quality of the rooting environment rather than the quantity of roots produced. The addition of clay and compost increased soil organic carbon and nutrient availability throughout the profile and likely improved nutrient retention, microbial activity, and soil hydraulic properties (Lal, 2020; Oldfield et al., 2019; Six et al., 2004). Consequently, individual roots in T3 may have acquired more water and nutrients per unit root length than those in T2. This interpretation is supported by the rooting-efficiency analysis, which showed that T3 produced more biomass and grain per unit root length despite developing a smaller root system (Fig. 6).

These findings align with emerging concepts in root biology suggesting that resource acquisition efficiency is often more important than root size alone (Lynch, 2019; Lynch, 2022; Schneider and Lynch, 2020). Root systems require substantial carbon investment to construct and maintain, and larger root systems do not necessarily maximise crop productivity if the additional roots provide limited gains in resource acquisition (Van Noordwijk et al., 1998). The present study agrees with other studies demonstrating that a moderately sized root system operating within a highly functional root zone can outperform a much larger root system growing in a less favourable environment (Fig. 1 and Fig. 2). This observation may help explain why relationships between root size and crop productivity are often inconsistent across environments and highlights the importance of considering both root traits and soil conditions when evaluating crop adaptation strategies.

Implications for crop adaptation and soil management

The findings have important implications for crop production in Mediterranean-type environments where water availability frequently limits productivity. Climate projections indicate increasing rainfall variability and greater incidence of seasonal drought across many rainfed cropping regions (Government-of-Western-Australia, 2021; Lee et al., 2023). Under these conditions, improving access to stored soil water and nutrients will become increasingly important for maintaining crop yields (Azam et al., 2026b; Azam et al., 2024b; Barrett-Lennard et al., 2024).

The present study demonstrates that integrated management of multiple soil constraints can substantially increase the functional rooting volume available to crops and improve access to resources that would otherwise remain unavailable (Azam and Gazey, 2019; Azam et al., 2026a; Azam et al., 2026c; Uddin et al., 2025). Traditional management approaches often target individual constraints such as acidity or compaction in isolation (Davies et al., 2024; Isbister et al., 2024; Li et al., 2019). In contrast, soil re-engineering simultaneously improved the physical (e.g. soil strength), chemical (e.g. pH and Al), and biological (e.g. organic carbon) properties of the root zone, generating benefits that persisted throughout the growing season.

More broadly, the results suggest that future efforts to improve crop productivity should focus not only on breeding larger or deeper root systems but also on enhancing the functionality of the root environment in which those roots operate. The concept of root-zone functionality provides a useful framework for integrating soil management and crop physiology and may help identify new opportunities to improve resource-use efficiency under increasingly variable climatic conditions (Azam et al., 2026b; Hayman et al., 2012). Future research should investigate how soil physical properties, nutrient dynamics, microbial processes, and root traits interact to regulate resource acquisition efficiency in field-grown crops.

Conclusions

Soil re-engineering improved the functionality of a constrained root zone in an acidic duplex soil by alleviating subsoil acidity along with Al toxicity and soil strength while increasing nutrient availability throughout the profile. These improvements promoted sustained root development, greater root proliferation throughout the depth of amelioration, and enhanced access to water and nutrients stored in deeper soil layers, resulting in up to 56% greater biomass production and 48% greater grain yield than the untreated control. Importantly, the treatment producing the largest root system did not achieve the highest crop productivity, demonstrating that root-zone functionality may be as important as root size in determining crop performance. The superior performance of T3 despite a smaller root system compared to T2 suggests that water and nutrient acquisition efficiency is a more meaningful indicator of productivity than root length alone. Collectively, these findings highlight the importance of improving the effectiveness of the root environment to enhance crop productivity, resource-use efficiency, and climate resilience in Mediterranean-type cropping systems.

Declarations

Generative AI Statement

During the preparation of this manuscript, the authors used OpenAI's ChatGPT to improve language quality, readability, and manuscript presentation. No AI tool was used to generate, analyse, or interpret experimental data and formulate scientific conclusions. All scientific content, interpretations, and conclusions were developed, verified, and approved by the authors, who take full responsibility for the final manuscript.

Role of the funding source

The funding sources were not involved in the design of this study, the collection, analysis or interpretation of data or the writing of this paper.

Conflict of Interest

The authors have no conflict of interest to declare.

Author’s contribution

G. A. - Fund sourcing, trial design, execution, data analysis and manuscript preparation; K.W. - data collection, root image processing, data analysis and manuscript preparation; M.H.R. - data collection, root image acquisition, data analysis and manuscript preparation; J.B. - data analysis and manuscript preparation; E.B.L. - data analysis and manuscript preparation; G.C.A. - data analysis and manuscript preparation; F.F. - data analysis and manuscript preparation.

Acknowledgments

The authors gratefully acknowledge the Department of Primary Industries and Regional Development (DPIRD) and the Grains Research and Development Corporation (GRDC) for supporting this research under project DAW1902_003RTX. We sincerely thank the Fulwood family for generously hosting our field experiments and Tim Boyes (AgVivo) for helping with the site selection. The assistance of Chad Reynolds, Jennie Clausen, Joanne Walker, James Fisher, Alistair Hall, Shelley Hall, Tashfiqur Rahman Talukder and Steve Rossi (DPIRD, WA) during the establishment and maintenance of the experiments is greatly appreciated. We also thank Yinglong Chen and Sue Bestow for their constructive internal review of this manuscript and Dr Andrew van Burgel for valuable advice on trial design and statistical analysis.

Data availability

The datasets used and/or analysed during the current study will be made available by the corresponding author upon reasonable request.

References

1. Anderson G, Hall D, Parker W, Barrett-Lennard E, Zhou S, Riethmuller G, Azam G, Reynolds C, Edwards T, Correndo A (2026) What soil properties predict crop response to management practices used on alkaline-sodic-saline soils of the eastern wheatbelt? GRDC Research Updates, Perth
2. Anderson GC, Peverill KI, Brennan RF (2013) Soil sulfur—crop response calibration relationships and criteria for field crops grown in Australia. Crop Pasture Sci 64:523–530

3. Azam G, Gazey C (2019) Re-engineering soil pH profiles to boost water use efficiency by wheat Agronomy Australia Conference, Wagga Wagga, p. 4
4. Azam G, Grant CD, Murray RS, Nuberg IK, Misra RK (2014) Comparison of the penetration of primary and lateral roots of pea and different tree seedlings growing in hard soils. Soil Res 52:87–96
5. 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
6. Azam G, Rahman MS, Scanlan C, Rahman MH, Gazey R, Gazey C (2024a) Soil Profile Re-engineering Doubled the Yield and Water Use Efficiency of Crops over Six Years on Acidic and Compacted Sand in a Water-limited Environment. Scientific Reports
7. 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
8. Azam G, Gamage W, Fritsch HK, Gain O, A (2026b) Beyond forecasts: reframing climate services for broadacre rainfed agriculture in Western Australia. Australasian J Environ Manage 33:1–10
9. 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 Research (under review).
10. Azam G, Wickramarachchi K, Rahman H, Rahman MS, Reynolds C, McDonald G, Parker W, Hall D, Scanlan C, Davies S, Gazey C (2024b) The resilience of re-engineered sandy soils in wet and dry seasons in Western Australia, Australian Agronomy Conference, Albany
11. 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 512:1405–1420
12. 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 and Pasture Science 75, -.
13. Bell MJ, Moody PW, Anderson GC, Strong W (2013) Soil phosphorus—crop response calibration relationships and criteria for oilseeds, grain legumes and summer cereal crops grown in Australia. Crop Pasture Sci 64:499–513
14. 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 62:59–68
15. Brennan R, Bolland M (2007) Comparing the potassium requirements of canola and wheat. Aust J Agric Res 58:359–366
16. Brennan RF, Bell MJ (2013) Soil potassium—crop response calibration relationships and criteria for field crops grown in Australia. Crop Pasture Sci 64:514–522
17. Bromfield S (1987) Simple tests for the assessment of aluminium and manganese levels in acid soils. Aust J Exp Agric 27:399–404
18. Chen Y, Đalović I, Rengel Z (2015) Phenotyping for Root Traits, pp. 102–128
19. Conyers MK, Moroni JS, Poile GJ, Oates AA, Lowrie R, Swan AD, Angus JF, Peoples MB, Hamblin P, Kirkegaard JA (2023) Response of canola and cereals to amendment of subsurface soil acidity and a hardpan. Crop Pasture Sci 74:1128–1141
20. Costa MCG, Coutinho ÍAC (2022) Root systems of agricultural crops and their response to physical and chemical subsoil constraints, Subsoil constraints for crop production. Springer, pp 225–261
21. Davies S, Parker W, Azam G, Hall D, Edwards T, Mwenda G, Reynolds C, McDonald G, Isbister B, Butler A, Scanlan C, Blake A, Newman P, Sands R, Ryan K, Curtis B, Bunny H, Gazey C (2024) Soil amelioration in Western Australian cropping systems: a review of thebenefits, adoption, and value, Australian Agronomy Conference, Albany, Western Australia
22. de Dorlodot S, Forster B, Pagès L, Price A, Tuberosa R, Draye X (2007) Root system architecture: opportunities and constraints for genetic improvement of crops. Trends Plant Sci 12:474–481
23. Delhaize E, Ryan PR (1995) Aluminum Toxicity and Tolerance in Plants. Plant Physiol 107:315–321
24. Dracup M, Belford R, Gregory P (1992) Constraints to root growth of wheat and lupin crops in duplex soils. Aust J Exp Agric 32:947–961
25. Farooq M, Rafique S, Zahra N, Rehman A, Siddique KH (2024) Root system architecture and salt stress responses in cereal crops. J Agron Crop Sci 210:e12776
26. French B, Miyan S, Azam G (2019) Towards improved aluminium tolerance in canola Agronomy Australia Conference, Wagga Wagga
27. Gazey C, Azam G, Clausen J, Rengel Z (2019) Soil Quality: 4 Soil Acidity, Perth, WA
28. Government-of-Western-Australia (2021) Western Australian climate projections - summary, In: Regulation, D.o.W.a.E. (Ed.), Perth, p. 32
29. Gregory P (2006) Roots, rhizosphere and soil: The route to a better understanding of soil science? Eur J Soil Sci 57:2–12
30. Gregory P, Eastham J (1996) Growth of shoots and roots, and interception of radiation by wheat and lupin crops on a shallow, duplex soil in response to time of sowing. Aust J Agric Res 47:427–447

31. Hamblin A, Hamblin J (1985) Root characteristics of some temperate legume species and varieties on deep, free-draining entisols. Aust J Agric Res 36:63–72
32. Hammond JP, Broadley MR, White PJ, King GJ, Bowen HC, Hayden R, Meacham MC, Mead A, Overs T, Spracklen WP (2009) Shoot yield drives phosphorus use efficiency in Brassica oleracea and correlates with root architecture traits. J Exp Bot 60:1953–1968
33. Hamza MA, Anderson WK (2005) Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Tillage Res 82:121–145
34. Hayman P, Rickards L, Eckard R, Lemerle D (2012) Climate change through the farming systems lens: challenges and opportunities for farming in Australia. Crop Pasture Sci 63:203–214
35. Hermans C, Hammond JP, White PJ, Verbruggen N (2006) How do plants respond to nutrient shortage by biomass allocation? Trends Plant Sci 11:610–617
36. Isbell RF (2021) The Australian Soil Classification, 3 edn. CSIRO Publishing, Melbourne
37. Isbister B, Rahman H, Azam G, Walker J, Kupsch M, Wilkins R (2024) To rip on or off the old rip line: a paddock-scale study on deep ripping and topsoil inclusion in a dry season. GRDC Research Updates, Perth
38. Kirkegaard JA, Lilley JM, Howe GN, Graham JM (2007) Impact of subsoil water use on wheat yield. Aust J Agric Res 58:303–315
39. Kochian LV, Piñeros MA, Hoekenga OA (2005) The Physiology, Genetics and Molecular Biology of Plant Aluminum Resistance and Toxicity. Plant Soil 274:175–195
40. Koevoets IT, Venema JH, Elzenga JT, Testerink C (2016) Roots withstanding their environment: exploiting root system architecture responses to abiotic stress to improve crop tolerance. Front Plant Sci 7:215317
41. Lal R (2020) Soil organic matter content and crop yield. J Soil Water Conserv 75:27A–32A
42. Lee H, Calvin K, Dasgupta D, Krinner G, Mukherji A, Thorne P, Trisos C, Romero J, Aldunce P, Barrett K (2023) Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change
43. Li GD, Conyers MK, Helyar KR, Lisle CJ, Poile GJ, Cullis BR (2019) Long-term surface application of lime ameliorates subsurface soil acidity in the mixed farming zone of south-eastern Australia. Geoderma 338:236–246
44. Liu L, Gan Y, Bueckert R, Van Rees K (2011) Rooting systems of oilseed and pulse crops. II: Vertical distribution patterns across the soil profile. Field Crops Res 122:248–255
45. Lynch JP (1995) Root Architecture and Plant Productivity. Plant Physiol 109:7–13
46. Lynch JP (2019) Root phenotypes for improved nutrient capture: an underexploited opportunity for global agriculture. New Phytol 223:548–564
47. Lynch JP (2022) Harnessing root architecture to address global challenges. Plant J 109:415–431
48. Lynch JP, Galindo-Castañeda T, Schneider HM, Sidhu JS, Rangarajan H, York LM (2024) Root phenotypes for improved nitrogen capture. Plant Soil 502:31–85
49. Marschner H (2011) Marschner's mineral nutrition of higher plants. Academic
50. Materechera SA, Dexter AR, Alston AM (1991) Penetration of very strong soils by seedling roots of different plant species. Plant Soil 135:31–41
51. McBeath T, Davies S, Kirkegaard J (2026) Never say never: The interdependence of no-till and strategic deep tillage in sustainable production systems. Crop Environ, 100130
52. McQuaker NR, Brown DF, Kluckner PD (1979) Digestion of environmental materials for the determination of trace elements by inductively coupled plasma–atomic emission spectrometry. Anal Chem 51(7):1082–1084
53. Meier U (2018) Growth stages of mono-and dicotyledonous plants
54. Nuttall J, Armstrong R (2010) Impact of subsoil physicochemical constraints on crops grown in the Wimmera and Mallee is reduced during dry seasonal conditions. Soil Res 48:125–139
55. Oldfield EE, Bradford MA, Wood SA (2019) Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 5:15–32
56. Oliver YM, Robertson MJ, Stone PJ, Whitbread A (2009) Improving estimates of water-limited yield of wheat by accounting for soil type and within-season rainfall. Crop Pasture Sci 60:1137–1146
57. Peng Y, Chen A, Chen S, Chen Y (2025) Genotypic Variability in Root Morphological Traits in Canola (Brassica napus L.) at the Seedling Stage. Crops 5:18
58. Rayment GE, Lyons DJ (2011) Soil chemical methods: Australasia. CSIRO Publishing, Collingwood, Australia
59. Rengel Z (2003) Handbook of Soil Acidity. Marcel Dekker, New York, USA

60. Reuter D, Robinson JB (1997) Plant analysis: an interpretation manual. CSIRO publishing
61. Schneider F, Don A, Hennings I, Schmittmann O, Seidel SJ (2017) The effect of deep tillage on crop yield – What do we really know? Soil Tillage Res 174:193–204
62. Schneider HM, Lynch JP (2020) Should root plasticity be a crop breeding target? Front Plant Sci 11:546
63. Severini AD, Wasson AP, Evans JR, Richards RA, Watt M (2020) Root phenotypes at maturity in diverse wheat and triticale genotypes grown in three field experiments: Relationships to shoot selection, biomass, grain yield, flowering time, and environment. Field Crops Res 255:107870
64. Seymour M, Brennan RF (2017) Cultivars of canola respond similarly to applied nitrogen in N-deficient soils of south Western Australia. J Plant Nutr 40:2631–2649
65. Shahidi F (1990) Rapeseed and canola: global production and distribution, Canola and rapeseed: production, chemistry, nutrition and processing technology. Springer, pp 3–13
66. Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res 79:7–31
67. Uddin S, Rohan M, Weng ZH, Tahmasbian I, Fang Y, Hayden HL, Armstrong R, Tavakkoli E (2025) Enhancing root proliferation in an alkaline dispersive subsoil: a comparative study of organic and inorganic amendments with different amelioration mechanisms. J Soil Sci Plant Nutr 25:7381–7396
68. van Gool D (2016) Identifying soil constraints that limit wheat yield in South-West Western Australia, In: Department of Agriculture and Food, W.A. (Ed.), Perth
69. Van Noordwijk M, Martikainen P, Bottner P, Cuevas E, Rouland C, Dhillion SS (1998) Global change and root function. Glob Change Biol 4:759–772
70. Wacker TS, van der Bom F, Delory BM, Vetterlein D, Postma JA, Nagel KA, Schnepf A, Dresbøll DB (2024) Back to the roots: standardizing root length density terminology. Plant and Soil
71. Wasson AP, Richards RA, Chatrath R, Misra SC, Prasad SVS, Rebetzke GJ, Kirkegaard JA, Christopher J, Watt M (2012) Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. J Exp Bot 63:3485–3498
72. White CA, Sylvester-Bradley R, Berry PM (2015) Root length densities of UK wheat and oilseed rape crops with implications for water capture and yield. J Exp Bot 66:2293–2303
73. White PJ, George TS, Gregory PJ, Bengough AG, Hallett PD, McKenzie BM 2013. Matching roots to their environment. Ann Botany 112, 207–222
74. Wickramarachchi K, Azam G (2026) Improving Barley (Hordeum vulgare L.) Yield through Deeper Root Architecture Impacted by Nitrogen Management in a Reengineered Kurosol. Soil Research
75. Wickramarachchi K, Betti G, Azam G (2025a) Effect of Clay Amendment and Strategic Deep Tillage on Soil Water Dynamics and Plant Growth Under Controlled Environments. Plants (Basel) 14
76. Wickramarachchi K, Chen Y, Azam G (2025b) Re-engineering a compacted acidic coarse sand enhanced the yield of triticale (x Triticosecale) by excelling root architecture and uptake of resources – a soil columns study. Plant and Soil
77. Wu W, Duncan RW, Ma B-L (2017) Quantification of canola root morphological traits under heat and drought stresses with electrical measurements. Plant Soil 415:229–244
78. Yildiz DG (2025) Global Oilseed Supply and Demand Strengthen in the New Season. International magazine for animal feed & additives industry

Figures

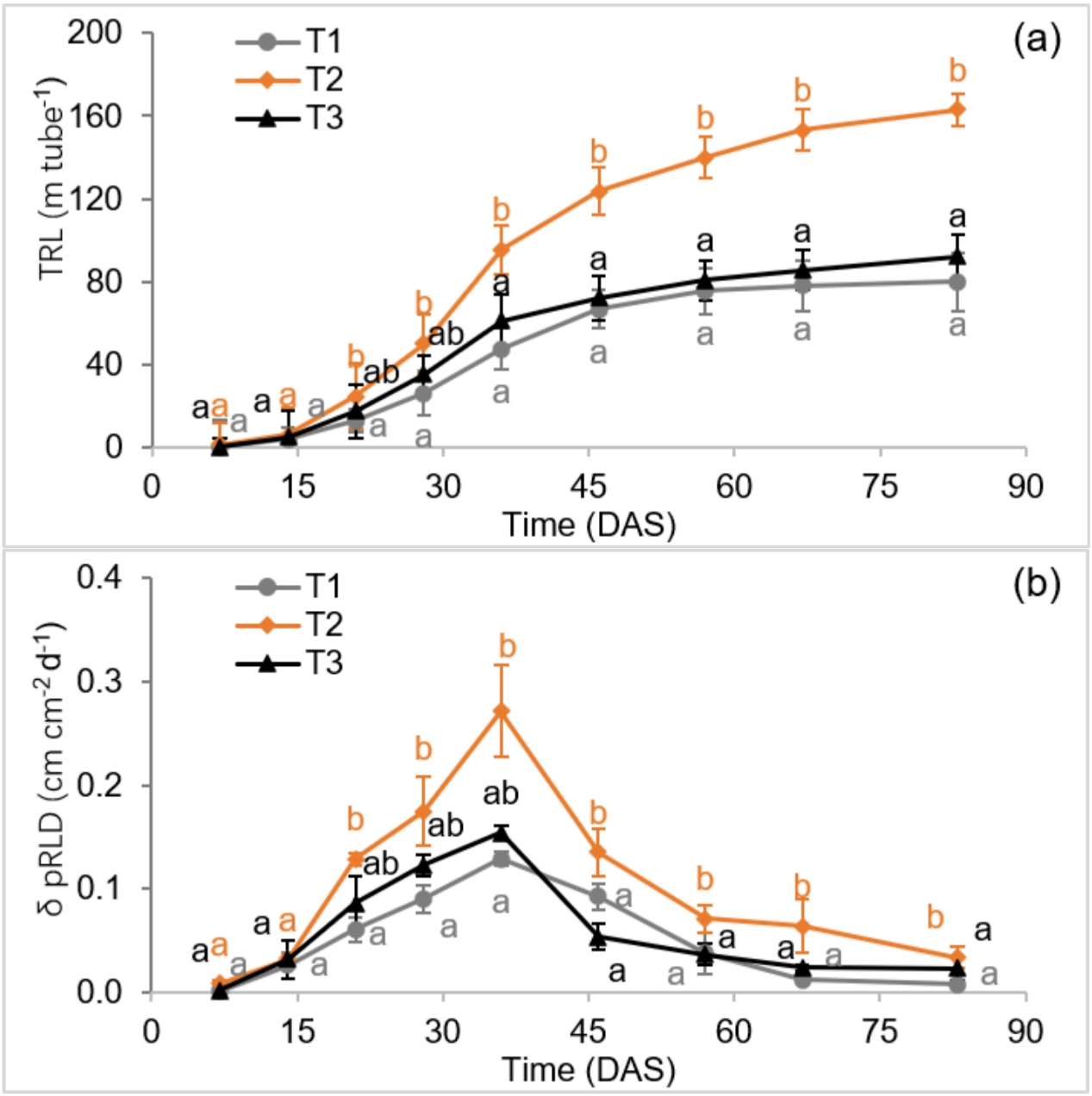


Figure 1

Temporal changes in (a) total root length (TRL; m tube⁻¹) and (b) root proliferation rate (δpRLD; cm cm⁻² d⁻¹) of canola grown under different soil re-engineering treatments during the 2023 growing season at Meenar, Western Australia. Values represent treatment means (n = 3). Error bars indicate standard errors of the mean. Within each panel and measurement time different letters are significantly different according to Tukey's honestly significant difference (HSD) test at $P < 0.05$. T1, untreated control; T2, deep loosening with lime incorporation; and T3, deep loosening with lime, clay, and compost incorporation. pRLD = planar root length density.

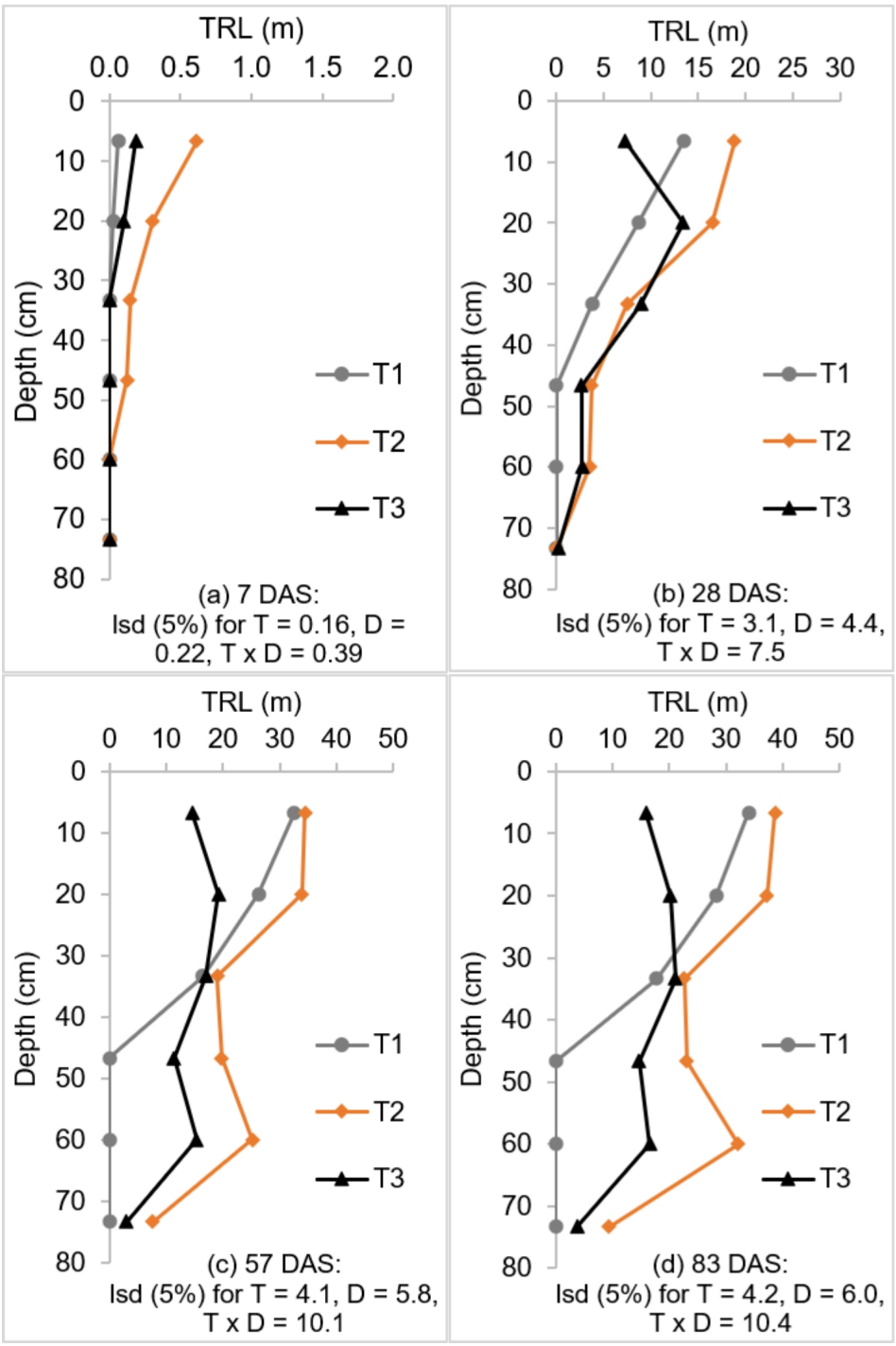


Figure 2

Temporal development and vertical distribution of canola roots measured as total root length (TRL; m) within successive minirhizotron scanning windows at 7, 28, 57 and 83 days after seeding (DAS) in 2023 growing season at Meenar, Western Australia. Individual sampling depth represents progressively deeper sections of the soil profile. Values represent treatment means (n = 3). T1, untreated control; T2, deep loosening with lime incorporation; and T3, deep loosening with lime, clay, and compost incorporation.

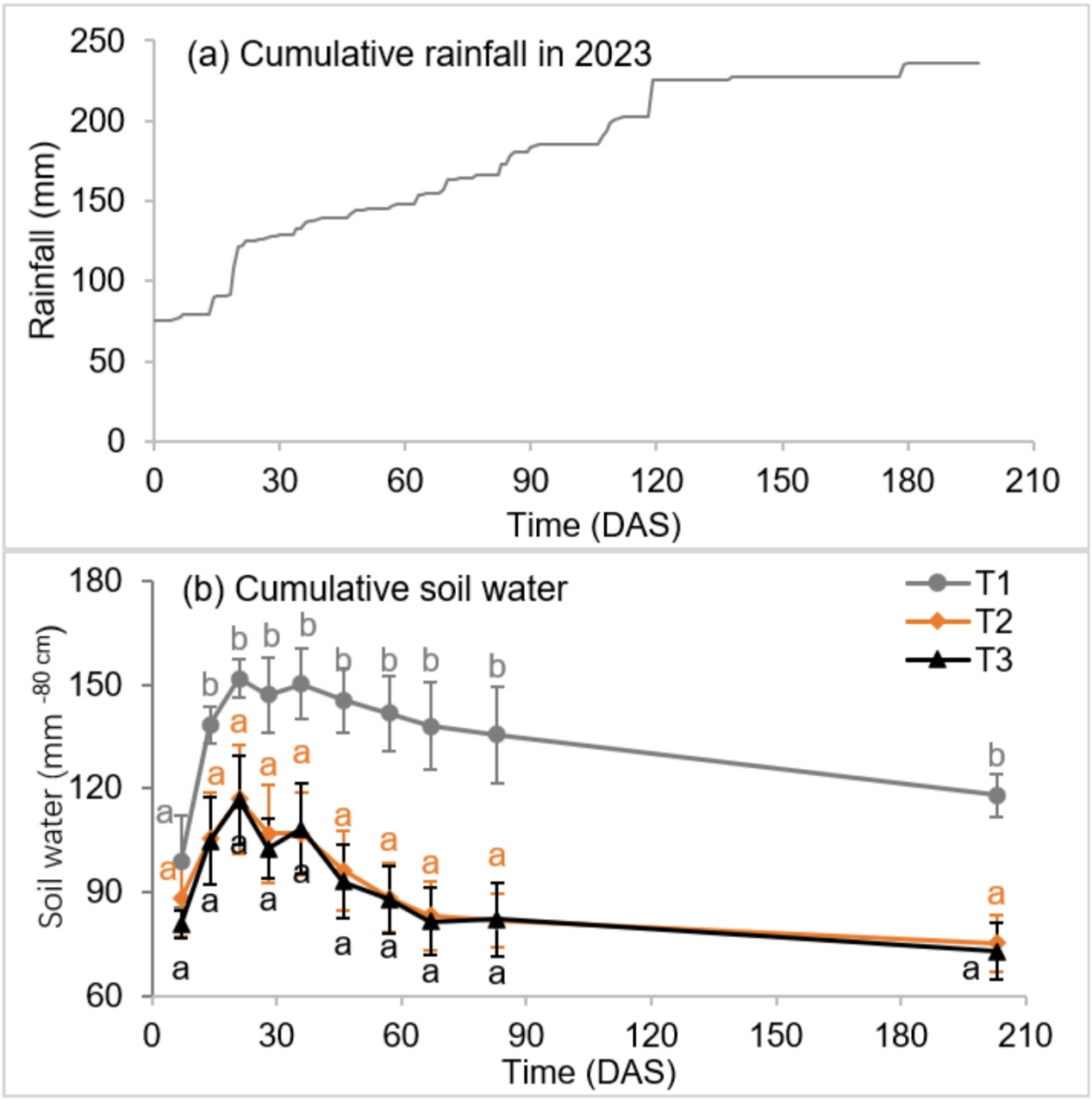


Figure 3

(a) Cumulative rainfall and (b) soil water status during the 2023 growing season at Meenar, Western Australia. Values represent treatment means (n = 3). Error bars indicate standard errors of the mean. Within each measurement time different letters are significantly different according to Tukey's honestly significant difference (HSD) test at $P < 0.05$. T1, untreated control; T2, deep loosening with lime incorporation; and T3, deep loosening with lime, clay, and compost incorporation.

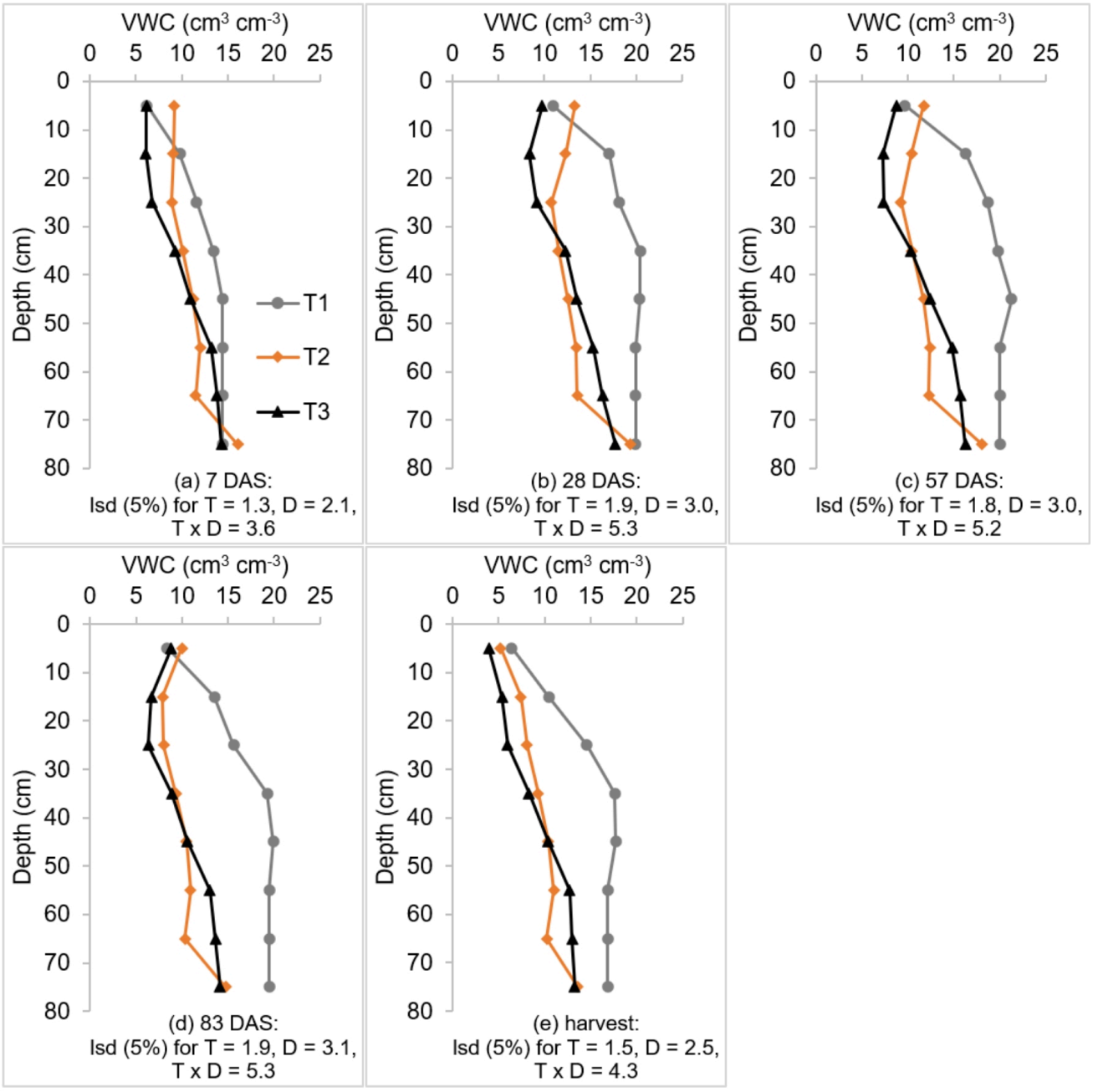


Figure 4

Soil volumetric water content (cm^3 cm^{-3}) across the profile at 7, 28, 57 and 83 days after seeding (DAS) and at the time of harvest in 2023 growing season at Meenar, Western Australia. Values represent treatment means (n = 3). T1, untreated control; T2, deep loosening with lime incorporation; and T3, deep loosening with lime, clay, and compost incorporation.

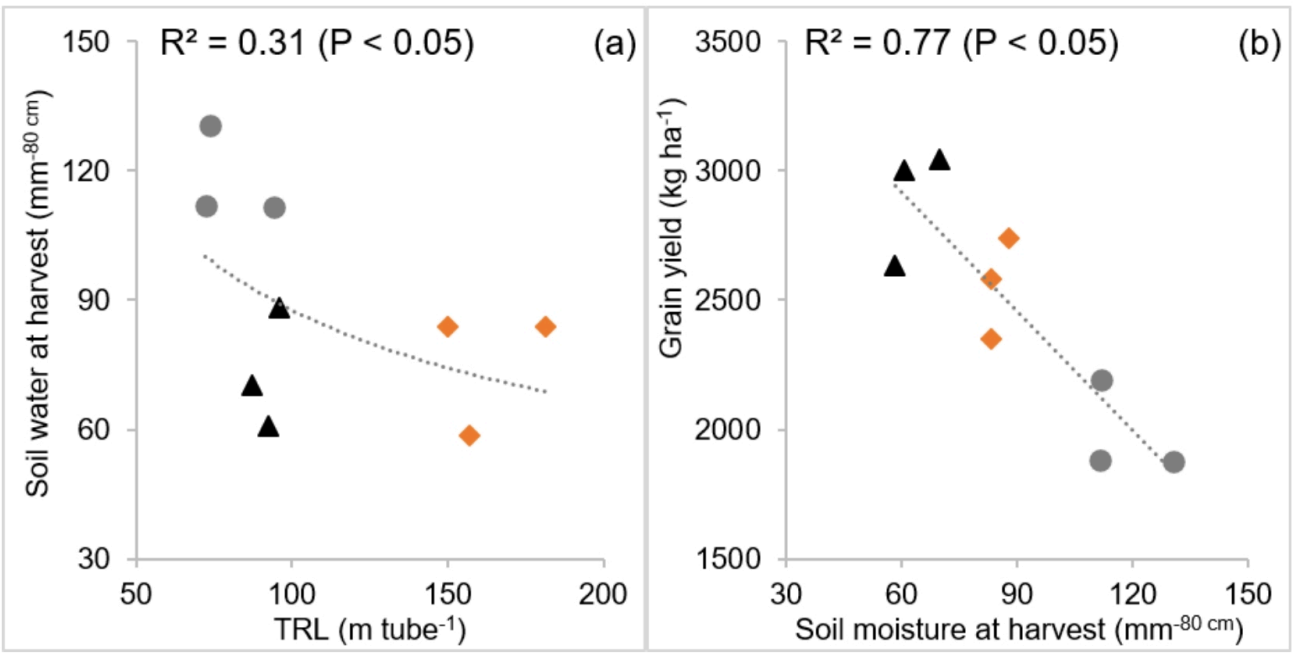


Figure 5

Relationship of soil water with (a) root development and (b) grain yield of canola during the 2023 growing season at Meenar, Western Australia. Grey circles = T1(untreated control); orange diamond = T2 (deep loosening with lime incorporation); and black triangle = T3 (deep loosening with lime, clay, and compost incorporation).

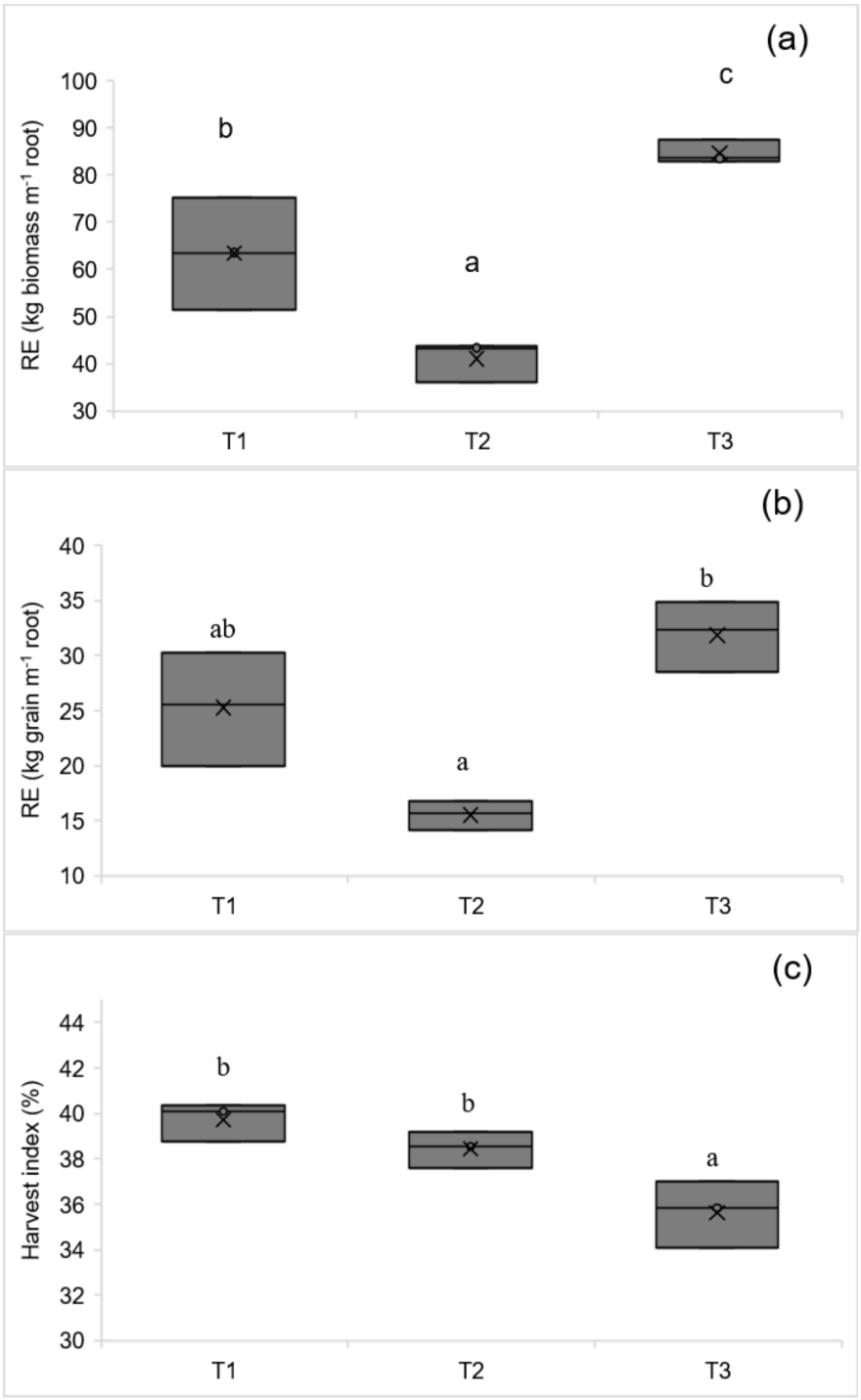


Figure 6

Rooting efficiency (RE) of canola under contrasting soil re-engineering treatments during the 2023 growing season at Meenar, Western Australia. Rooting efficiency was expressed as the amount of root length required to produce (a) 1 kg of above-ground biomass and (b) 1 kg of grain yield. (c) Harvest index calculated as grain yield divided by total above-ground biomass × 100. Higher rooting-efficiency values indicate greater productivity per unit root length. Values represent treatment means (n = 3). Error bars indicate standard errors of the mean. T1, untreated control; T2, deep loosening with lime incorporation; and T3, deep loosening with lime, clay, and compost incorporation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- floatimage1.jpeg