Performance through collaboration

Integrated solutions for underperforming constrained soils: Accessing soil moisture

Final report for research project 4.2.004

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PROJECT PARTICIPANTS

Crown in right of the State of New South Wales acting through the Department of Primary Industries and Regional Development (DPIRD); State of Victoria through the Department of Energy, Environment and Climate Action (DEECA); Murdoch University; Burdekin Productivity Services Ltd; Charles Sturt University; Agripower Australia Limited (Third Party).

DISCLAIMER

PEER REVIEW STATEMENT

The Soil CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2018), and provided constructive feedback which was considered and addressed by the author(s).

KEYWORDS

Subsoil constraints; plant available water capacity; crop water use; subsoil amelioration; novel amendments.

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CONTENTS

EXECUTIVE SUMMARY

The overall purpose of the project was to achieve reliable and profitable crop productivity in soils with multiple constraints and to close the gap between farm production and the rainfall-limited crop yield potential in major soil types in Victoria (Vic), New South Wales (NSW), Queensland (Qld) and Western Australia (WA). Four on-farm field experiments were established to assess the long-term effectiveness of new practices and products to ameliorate multiple soil constraints in representative soil types. The key constraints were dispersive, alkaline poorly structured subsoils in Vic and NSW, dense sodic subsoils in Qld, and low water holding capacity and water repellent sands in WA. Amendments being tested in this project include custom-made organic matter (OM)-based pellets (e.g. lucerne straw, oaten hay), nutrient-enriched urban green-waste compost, agrisilica, various reactive clays, and sugarcane mill mud/ash. Amendments were placed directly into the subsoil using customised deep rippers, chisel ploughs and other heavy-duty tillage implements. Data from the project will be made available to Soil CRC Projects 4.3.005 and 4.3.006 to enable data on crop production and water use efficiency (WUE) to be better modelled and described, with potential benefits to yield (yield, reliability of yield, water stress resilience) being weighed against cost of implementation. The project also has direct engagement with Soil CRC Program 1 to maximise adoption of the project outcomes. The main goal is for maximum adoption of results/techniques to benefit local grower groups, and Australian farmers more broadly.

OBJECTIVES

Aim 1: To establish on-farm field experiments to assess the long-term effectiveness of new practices and products to ameliorate multiple soil constraints in key soil types that support the grains and sugarcane industries.

Aim 2: To quantify the effectiveness of different amelioration strategies to increase soil water storage and crop water use efficiency.

Aim 3: To assemble datasets for use by next users in calibration and validation of hybrid biophysical modelling to develop frameworks and tools for diagnosing and ameliorating multiple soil constraints.

RESULTS

1: To establish on-farm field experiments to assess the long-term effectiveness of new practices and products to ameliorate multiple soil constraints in key soil types that support the grains and sugarcane industries.

Four new field trial sites were successfully established on working farms near: Clare, Qld, on a heavy sodic clay soil of the Burdekin River Irrigation Area; Lockhart, NSW, on an alkaline, dispersive, sodic heavy clay soil in the Riverina cropping area; Wonwondah, Vic, on a poorly drained, highly dispersive sodic Vertosol in the Wimmera broadacre cropping region; and Kweda, WA, on a duplex sandy soil with low pH and multiple subsoil constraints, including aluminium (Al) toxicity, low fertility and water logging, in the WA grain belt. Due to the length of sugarcane crop growth cycles, the Qld trial was established later than the other sites and has only recently completed its first year. Monitoring of this site under project 4.2.004 was extended until 30 September 2025.

2: To quantify the effectiveness of different amelioration strategies to increase soil water storage and crop water use efficiency.

Results from the four trial sites to date have been mixed, with two sites largely unresponsive (Qld and WA) and the other two (NSW and Vic) showing some significant crop responses to some amelioration strategies. Effects from subsoil amelioration are at times not seen in the first year following amendment application, so the lack of treatment effects found at the Qld site may simply be because the amendments have not had sufficient time to have an impact on the soil constraints that are present. The WA site has had average to above average rainfall, and this may have caused the crop to be less affected by the soil constraints at that site in terms of crop water-limited yield potential. The results from the NSW and Vic sites both indicate that the presence of nutrient-rich OM in the ameliorants had the greatest impact on crop performance compared to mineral-only treatments and the controls. Increases in crop yield in the second year of these two sites from OM-based treatments were up to 19% above the untreated control at the NSW site, and an average of 42% greater than the untreated control at the Vic site. The 2023 NSW site wheat crop and Vic site canola crop on the OM-based treatment plots were both able to access substantially more soil water than the other treatments. At this stage it cannot be concluded whether the comparative effectiveness of these ameliorants in improving crop productivity is due to improved nutrition, better soil physicochemical conditions, or a combination of both mechanisms.

3: To assemble datasets for use by next users in calibration and validation of hybrid biophysical modelling to develop frameworks and tools for diagnosing and ameliorating multiple soil constraints.

Data from the four trial sites has been supplied to the Agricultural Systems and Catchment modelling team in the University of Southern Queensland's Centre for Sustainable Agricultural Systems. The modelling team are using the Agricultural Production Systems sIMulator (APSIM) model to assess the impact of subsoil constraints on WUE and crop production (Soil CRC Projects 4.3.005; 4.3.006). By calibrating and testing the model using field trial data from this project and other Soil CRC field experiments, the team hope to evaluate promising amelioration techniques in computer modelling simulations, explore the long-term impacts of subsoil constraints and predict crop responses under varying conditions, including future climate change scenarios. This is an ongoing process, and progress to date was reported on in project milestone M12.1 - Report on the development of biophysical models that include crop-soil-water interactions to predict productivity, uploaded to the Soil CRC's Soil Central portal in July 2024.

NEXT STEPS	TIMING
The WA, NSW and Qld sites will continue to be monitored under Soil CRC project 4.2.006: Capitalising on established field trials for ameliorating (sub)soil constraints.	2024–27

INTRODUCTION

The overall purpose of the project was to achieve reliable and profitable crop productivity responses on soils with multiple constraints, and to close the gap between current on-farm production and the rainfall-limited yield potential in key soil types in Vic, NSW, Qld and WA. Using knowledge recently developed across a range of projects (funded by the Soil CRC, Grains Research and Development Corporation (GRDC) and AgriFutures), field-based studies were undertaken to quantify the effects of promising amelioration strategies on soil water storage and supply, rooting depth, and function and crop productivity. This project combined approaches of crop physiology and soil amelioration innovation to improve the cost effectiveness of addressing subsoil constraints. Whereas previous research considered constraints individually, the approach in this project was to focus on soils with multiple constraints. The combination of constraints considered varied between the clay-textured soils in Vic, NSW and Qld compared to sands in WA. Standardised data generated from this research will be made available to key next users, including modellers, practice change specialists and grower groups. The project hypotheses were developed by the project partners as a result of previous research and known farmer demand for cost-effective subsoil amelioration technologies.

1.1 PROJECT AIMS

The specific aims of the project were:

1. To establish four on-farm field experiments to assess the long-term effectiveness of new practices and products to ameliorate multiple soil constraints in key soil types that support the grains and sugarcane industries. The key constraints were poorly structured dispersive alkaline subsoils in Vic and NSW, dense sodic subsoils in Queensland and low water holding capacity and water repellent sands in WA.
2. To quantify the effectiveness of different amelioration strategies to increase soil water storage and crop water use efficiency.
3. To assemble datasets for use by next users in calibration and validation of a hybrid biophysical modelling to address Milestones 4.3.2 and 4.3.4 on the development frameworks and tools for diagnosing and ameliorating multiple soil constraints.

The longer-term objective of this research was to reduce the yield gap between current water-limited potential and realised yields associated with multiple soil constraints in Australia, thus delivering economic and sustainability benefits to farmers. The means to achieve this was by utilisation of the most effective amelioration strategies tailored to specific soil types and region. The project aims to quantify the multi-year soil and crop responses to these management practices to enable sustained increases in agricultural productivity on key soils in four cropping regions (Vic, NSW, Qld, and WA).

BACKGROUND

Many Australian agricultural soils contain multiple physicochemical constraints that limit effective root growth, thereby limiting water and nutrient use by crops. As a result, yields are significantly less than water-limited potential, resulting in major opportunity costs for growers.

Owing to their effects on root depth, the ability of crops to absorb water and on soil hydraulic properties, subsoil constraints are likely to have large effects on the crop water budget. Quantifying the effect of subsoil constraints on the utilisation of soil water in cropping systems is important for productivity and WUE because yield is linked to transpiration. Despite insufficient rainfall being the key limitation to agricultural production in Australia, many crops regularly yield less than their water-limited potential because of poor use of rainfall and stored soil water. Approximately 75% of Australian soils have one or more constraints, such as high pH, high concentrations of boron (B), deficiencies in macro- and micronutrients, soil acidity, salinity and sodicity as well as dense soils that limit root growth and function and crop utilisation of subsoil water (Dang and Moody, 2016). The ability of roots to grow through soil unhindered by physical or chemical constraints is key to making full use of available water resources. Modest improvements in extraction of moisture from the subsoil by overcoming the constraints can result in significant yield improvements.

2.1 PREVIOUS RESEARCH & LITERATURE

There is a long history of research into the type, extent and management of subsoil constraints in Australia (e.g. reviews by Dang et al., 2006; Adcock et al., 2007; MacEwan et al., 2010; Page et al., 2018; Sale et al., 2021). The GRDC has funded numerous projects investigating the issues, including projects DAV00056 Understanding subsoil constraints in the high rainfall zones (HRZ) (2004–06), ULA00008 Validating subsoil manuring in the High Rainfall Zone (2010–13), DAN00206 Innovative approaches to managing subsoil acidity in the southern grain region (2015–21), CSP00203 - Increasing production on sandy soils in low and medium rainfall areas of the South (2016–23), and DAV00149 Understanding the amelioration processes of the subsoil application of amendments in the Southern Region (2016–24).

In their review on management of the major chemical soil constraints affecting yields in the grain growing region of Qld and NSW, Page et al. (2018) concluded that although much research has been conducted into the management of soil sodicity, acidity and salinity throughout Australia's Qld and NSW grains region, significant gaps exist in our understanding of the best way to profitably manage these constraints. Work is needed to improve our understanding of how to manage these issues when they occur in the subsoil, particularly for Vertosols, and how best to use or combine ameliorants to treat multiple constraints concurrently. In instances where the treatment of constraints is likely to be uneconomical or take a long time, further identification of those crop species or cultivars that are most productive on constrained sites is required. This is particularly the case where multiple constraints are present, and plants require tolerance to a variety of conditions. Increasing our knowledge in these areas represents a significant opportunity to improve the ability of growers throughout the region to profitably manage soil constraints.

In the GRDC Sandy Soils project CSP00203, five field experiments were established across four sandy soil sites in strongly water-limited environments in Mallee sands in the southern cropping region, with a range of tillage interventions and nutrition supplements. Crops responded much more to deep tillage (−15 to 100%, mean 50%) than to crop nutrition interventions (0 to 62%, mean 7%). Increases in crop water use (evapotranspiration) were modest or not evident and generally insufficient to explain the magnitude of yield responses. Increased crop transpiration, ear density (n/m^2) and grain number per ear contributed most to yield increases. Increased crop water use did not appear to be the main driver of grain yield responses to deep tillage in this environment, rather pre-anthesis effects on crop development, radiation interception and transpiration appear to have resulted from direct effects of soil strength on crop tillering caused by hormonal responses (Unkovich et al., 2023).

In the DAV00149 project, yield responses ranged from none (or even negative) to greater than 70% for a range of crops, including wheat, barley, canola and faba bean, encompassing more than 40 site-year trials. However, the majority of yield gains were between 15% and 25% and tended to occur only at particular sites. The higher magnitude yield responses tended to be in the high rainfall zone (HRZ) sites, reflecting higher yielding crops. High relative responses were also recorded in the medium rainfall zone (MRZ) sites, but absolute yields were lower and poor responses were much more common. There was a strong trend for most sites to either respond to soil amelioration or not; for example, Rand and Nile (HRZ) had consistent positive responses, whereas Condowie and Kiata (MRZ) had no positive responses over all or most years of the trial. Responsiveness was attributed principally to a combination of soil water availability and soil properties (texture and location/severity of physicochemical constraints within the soil profile). The response of two MRZ sites (Grogan, NSW, and PBC, Vic) exemplified this relationship between water and soil properties, showing no response in seasons with low growing season rainfall (GSR) but highly responsive in others, for example in 2021, where growing season rainfall was high (Armstrong et al., 2023). Unlike in the Sandy Soils project, deep ripping alone had little impact on crop performance in these trials, and sometimes led to negative responses due to reduced plant establishment. One of the main conclusions from this project was that soil water supply underpins whether soil amelioration will increase crop yields, and there appears to be limited scope for successful soil amelioration on heavier soils in lower rainfall environments (< 400 mm annual rainfall).

The DAV00149 project also concluded that in lower rainfall environments, especially if topsoils have high clay content where the higher plant available water capacity restricts the movement of small rainfall events to the lower soil layers where the amendments are placed (20–40 cm), the organic amendments do not decompose and thus do not mitigate soil constraints or enable increased crop growth. Simulation modelling in APSIM suggested that often there is little opportunity for rainfall in these environments to fully recharge subsoil water reserves in continuously cropping systems in the absence of long fallows. Because subsoil constraints typically become more severe with increasing soil depth, if there is no subsoil water then subsoil constraints will not affect crop growth. This interaction between texture of the topsoil helps to explain the more positive yield responses that grain growers have recorded to subsoil disturbance on sandy soils, even in low rainfall Mallee environments as described in the Sandy Soils project.

2.2 GAPS IN CURRENT KNOWLEDGE

Despite advances made in our understanding of subsoil constraints, adoption of subsoil amelioration technology has remained very low due to a combination of variable yield responses and a number of logistical constraints, such as the limited availability of suitable OM sources and access to appropriate machinery. The recently completed DAV00149 project identified multiple broad research areas where knowledge and understanding on the amelioration of subsoil constraints using organic and other amendments is lacking. These included understanding how different amendments impact on the amelioration, understanding how the soil environment affects amelioration and crop response, understanding how water availability affects the amelioration process, understanding how the crop responds to the amelioration process, and understanding how crop roots impact on the amelioration process.

Areas where more research is needed include determining the optimum form of organic matter biomass (animal and plant based) and the extent of nutrient enrichment needed to achieve amelioration and increase crop response. In research trials, pelletised organic material is often used because it allows for accurate placement and rate of application. However, pelletising

OM is costly (McInerney and McInerney, 2021); therefore, research is needed to investigate other forms of organic matter that are readily available, for example, chopped straw and methods of incorporation into the subsoil that are more economic for farmers to employ. More information is needed on determining the most appropriate rates and depth of application for a given soil type and soil constraint. The factors that affect the longevity of amelioration where it is effective are still relatively unknown, but this is a key requirement to calculate the economic benefit of conducting subsoil amelioration on a commercial basis. There needs to be a better understanding of the factors that affect crop responses in an ameliorated subsoil, including how responses may differ between crop type, how rainfall and subsoil moisture levels affect crop response to amelioration, and the impact of amelioration on the capture and storage of subsequent rainfall and crop water use.

This multi-state, field-based project harnesses recent advances in soil amelioration techniques to address the amelioration of multiple subsoil constraints to improve our understanding of the interactions of these novel strategies with plant use of soil water in contrasting soil types and farming systems.

METHODOLOGY

3.1 CLARE, QUEENSLAND TRIAL SITE

3.1.1 Site selection

Site selection was based on finding a typical soil with challenging subsoil conditions and a grower who was willing to host a small trial plot.

This site was hosted on a grower's property in the Clare region of the lower Burdekin (Figure 1). This grower previously raised concerns about subsoil conditions, and soil pits showed a soil that was compacted, waterlogged and relatively structureless. Soil testing showed that it was sodic and magnesic below 20 cm.

The soil was classified as a heavy cracking clay (Vertosol) and described as a grey-to-brown clay to black earth, with a moderate-to-strong gilgai and moderately to strongly cracking. The soil was typical of many areas in the Burdekin-Haughton Water Supply Scheme area (also known as the Burdekin River Irrigation Area, BRIA).

The block was approximately 1400 m long and was fully irrigated with channel water from the SunWater supply channel.

The block was electromagnetically mapped in November 2022 to determine the paddock variability and establish a location within the block with the least variation. This was found to be at the top end of the block. The trial was designed to fit into this area with treatments running across the block and replications down the block.

3.1.2 Trial design

The trial consisted of eight treatments replicated four times (Figure 2). The treatments were determined by the project team with the application rates being typical for each product. The treatments were:

1. Control – no amendment applied, but the plots were ripped and a furrow created as per all the other treatments.
2. Gypsum at 5 t/ha. This is a typical gypsum application rate for this area of the Burdekin.
3. Mill mud/ash mix from Invicta Mill at 50 t/ha. Mill mud/ash is a by-product of the cane milling process that contains nitrogen (N), phosphorus (P), potassium (K), sulphur (S) and calcium (Ca). The approximate nutrient application from the mill mud/ash mix was 70 kg/ha N, 115 kg/ha P, 85 kg/ha K, 15 kg/ha S, 245 kg/ha Ca and 75 kg/ha magnesium (Mg) (Wilmar Sugar, 2022). Mill mud/ash straight from the mill has a moisture content of approximately 70%. To make it easier to work with it was stockpiled and allowed to dry out before being applied.
4. Compost at 20 t/ha. This was council green waste and contained large amounts of woody waste. To help break down and compost some of this woody material a nutrient blend was applied upon advice from DPIRD staff.
5. Mill mud/ash at 50 t/ha + gypsum at 5 t/ha.
6. Compost at 20 t/ha + gypsum at 5 t/ha.
7. Reactive silicate at 2 t/ha + gypsum at 5 t/ha.
8. Food organics and garden organics (FOGO) at 20 t/ha. This was an opportunistic treatment following discussions with Townsville City Council. The FOGO was a fine product, similar to potting mix.

Once the location was selected, the old cane crop was ploughed out (multiple offset discing and ripping), and the block laser levelled. Plot locations were determined and marked out for soil sampling.

Baseline soil samples were collected, with three samples per plot at increments 0–10, 10–20, 20–50 and 50–80 cm. Following soil sampling, the grower went through and bedformed the block using a three-row bedformer.

The amendments were applied on 15 December 2022. Prior to application, each row was furrowed out using a custom implement, consisting of a tine with boards attached, to create a 'V' furrow approximately 250 mm deep. Each plot was 50 m long by three rows wide (1.65 m row spacing). There was a 1 m buffer between replicates.

Figure 1. Google Earth image of the Queensland trial location, sprayed out laneways are just visible in the trial area (image date 19/6/24).

After furrowing out and before application the plots were marked out, leaving a 1 m break between replicates. This break ensured there was room for any overrun of the applicator not to interfere with the actual plots. The amendments were applied to this V furrow using a three-row gypsum applicator. This applicator consisted of a hopper with conveyer belts across the back to ensure even distribution. A calibration was completed for each treatment product immediately prior to application. This involved running the applicator for 5 m over a tarp, collecting the dispensed material and weighing it, and then calculating the per hectare application rate. It was not possible to match the planned and actual application rates exactly (Table 1).

Table 1. Planned versus applied rates

Treatment	**Planned Rate t/ha**	**Actual Rate t/ha**
Control	0	0
Gypsum	5.0	5.21
Mud/ash mix	50.0	52.21
Compost	20.0	16.0
Mud/ash + gypsum	50.0 + 5.0	52.21 + 5.21
Compost + gypsum	20.0 + 5.0	16.0 + 5.21
Reactive silicate + gypsum	2.0 + 5.0	1.7 + 5.21
FOGO	20.0	19.64

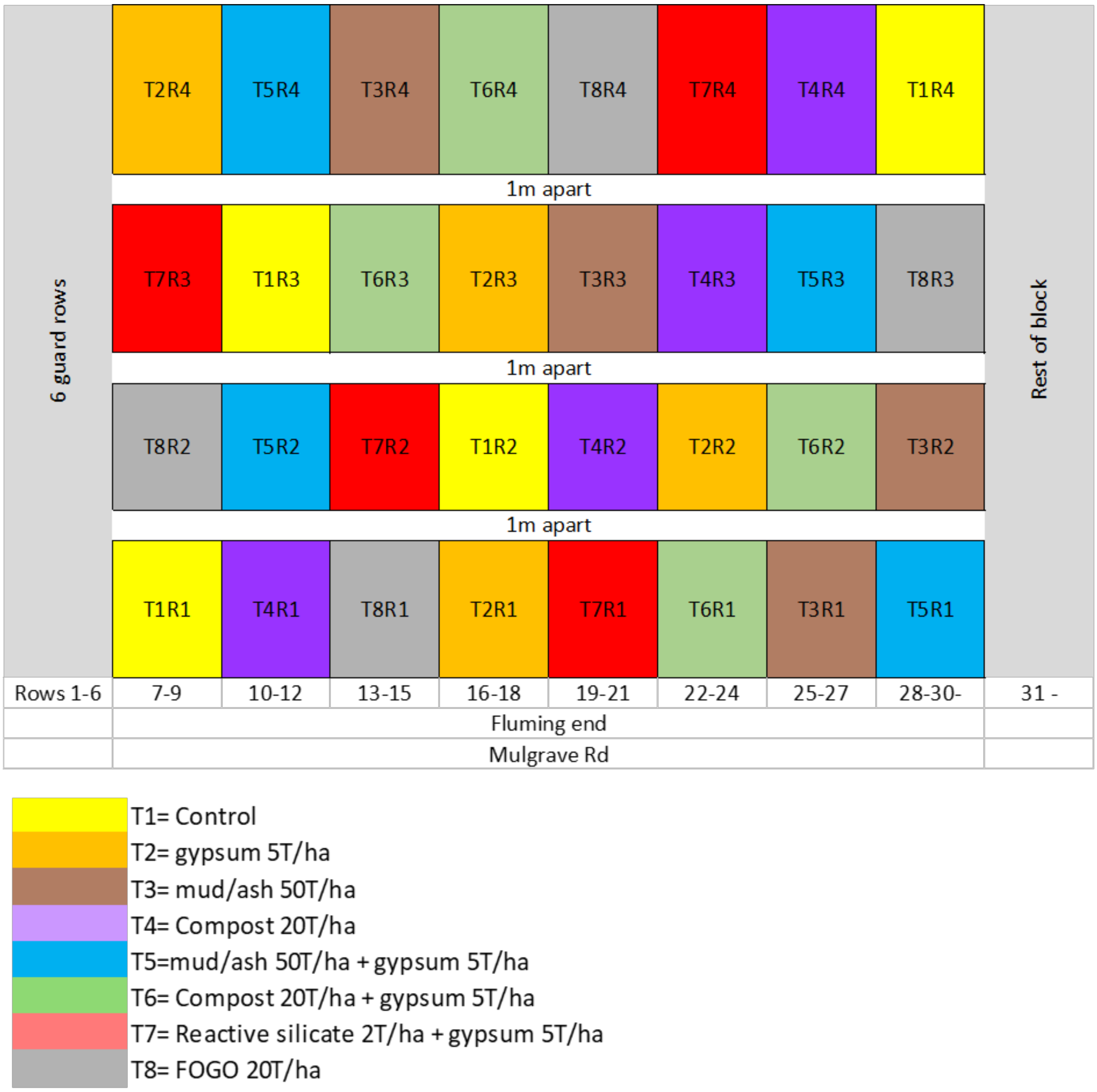


Figure 2. Trial layout and treatments.

Each amendment was applied individually; that is, if the amendment was mill mud/ash + gypsum, the mill mud/ash was applied first (along with all the other mill mud/ash treatments), then the gypsum was applied as a second pass. It was not possible or practical to mix amendments prior to application.

Post-application, each row was bedformed, with the same bedformer that was used pre-application, to cover the amendments and finish with beds approximately 250 mm high. The treated area was around 500 mm below top of bed, and around 250 mm from natural ground level. Herbicides were used to keep the block weed free during the fallow period before cane planting.

Cane was planted in March 2023 using a disc-opener cane planter, which minimises soil disturbance and disturbance of the amendment band.

After cane emergence, the 1 m breaks between replicates were marked and sprayed out with glyphosate. These areas were kept weed free to ensure weed competition did not affect cane yield. Because every plot had a laneway at either end, any extra growth on the ends of plots (due to extra sunlight and water) were consistent across the trial.

In early August 2024, soil core samples were taken of each plot (0–20 cm and 20–40 cm) and sent to the lab for analysis to see if there had been any change to the soil conditions since the amendments were applied. The results are currently pending.

3.1.3 Site visits

A field walk was conducted at the site in October 2023 with various growers and industry representatives. Around 15 locals attended this event, which was an opportunity to discuss general soil health and constraints, along with the promotion of the Soil CRC. A soil health bus trip to the site took place on 31 May 2024, which included 17 growers, six industry advisers and four BPS staff.

3.2 LOCKHART, NSW TRIAL SITE

3.2.1 Site description

The trial site was located approximately 11 km southwest of Lockhart, in the Riverina region of southern NSW (lat. 35°17’31.01” S, long. 146°38’12.01” E) in a long-term low-yielding paddock that had been under continuous cropping (typically a vetch–lupin–canola–wheat–barley rotation) since 2008. Soil pits revealed a hard pan at a depth of 30 cm, and grower records indicated a history of waterlogging. The soil was a Brown Sodosol (Isbell, 2016) with a texture-contrast profile increasing in clay content at depth, and with unfavourable chemical and physical properties, including high alkalinity, sodicity, dispersion and slaking (Table 2). To secure an appropriate trial site, intensive soil sampling was conducted to ensure soils had suitable chemical and physical constraints. Dual EM and EM38 surveys were then conducted to measure variability across the paddock and finalise the location and orientation of experimental plots, to try to minimise heterogeneity within and between blocks.

Table 2. Trial site soil profile initial characteristics.

Depth (cm)	EC (µS/cm)	pH_w	CEC cmol(+)kg	ESP (%)	Mineral N (kg/ha)	NO_3^- (mg/kg)	NH_4^+ (mg/kg)	Colwell P (µg/g)	VWC (Sowing) (cm^3/cm^3)
0–10	80	6.8	17.4	3.4	9.3	3.31	2.63	57.8	0.29
10–20	81	8.2	26.1	6.7	3.5	0.52	1.58	11.0	0.36
20–30	138	8.8	30.1	10.2	2.2	0.30	1.10	5.5	0.33
30–40	213	9.0	31.4	13.0	2.0	0.25	1.04	4.4	0.36
40–60	353	9.4	33.1	18.6	1.7	0.25	0.77	3.8	0.40
60–80	482	9.5	32.6	24.1	1.8	0.30	0.77	3.8	0.41
80–100	604	9.4	32.9	27.5	2.6	0.70	0.80	4.0	0.42

NO_3^- = nitrate
NH_4^+ = ammonium
VWC = volumetric water content

3.2.2 Experimental design, treatments, and application

The trial was established in March 2022 as a randomised complete block with 12 treatments (Table 3) and four replicates (n = 48). Experimental plots were arranged in two ranges of 24, separated north–south by a 52 m cropped buffer. Each range comprised two blocks of 12 treatments, separated east–west by a 17.5 m cropped buffer area. Individual plots within each block were 2.5 m wide (east–west) and 20 m long (north–south), for a total plot area of 50 m^2, separated on their long sides by equivalent sized interspersed buffers of uncultivated ground (Figure 3).

In the first season, ameliorants were incorporated at a depth of 20–40 cm, except for the silicon (Si) treatment, which was incorporated at a depth of 5–25 cm, one month prior to sowing on 24–25 March. Amendment applications were carried out using a custom-built 3D ripping machine developed by Department of Primary Industries and Regional Development (Wagga Wagga, NSW, Australia), through GRDC project DAN00206. The machine consisted of a 'Jack' GM77-04 five-tyne ripper (Grizzly Engineering Pty Ltd, Swan Hill, VIC, Australia), with a width of 2.5 m and tyne spacings at 50 cm intervals.

Two discharge hoppers and a 300L liquid cartage tank were mounted on the ripper to enable the delivery of organic and inorganic amendments, either individually or in combination. Each plot was ripped in the first instance with the initial pass undertaken to ensure the appropriate depth could be achieved. A second pass was then conducted to deliver the amendments. There were five rip lines per plot, oriented in the north–south direction. A multi-tube crumble roller with five tonnes of downward pressure provided a level finish.

The site was then speed tilled to prepare the seedbed for sowing. Plots were sown using a ten-row sowing combine that was positioned to straddle the centre rip line accurately. The tyne spacings of the sowing combine were at 25 cm intervals, ensuring that each sowing row was situated adjacent to and equidistant (~12.5 cm) from a rip line. The sowing combine was a custom-built air seeder designed by Department of Primary Industries and Regional Development (Cowra Agricultural Research and Advisory Station, Cowra, NSW, Australia), retrofitted with an Ausbox metring system (Ausbox, Coonabarabran, NSW, Australia).

The organic amendments were manufactured according to our instructions by Carbon Powered Mineral Technology and Products Pty Ltd (CPMTP; Appleby, NSW, Australia) in pellet form for ease of application. Products CP1 and CP2 comprised a base material of lucerne straw with various mineral supplements. Product CCM contained an oaten hay base, supplemented with basalt and diatomite, pelletised and pyrolysed to biochar.

A biochar-based micronised powdered and liquidised gypsum + polymer (Aquasil), ‘Gypsum Dispersion’ was manufactured according to our instructions by CHT Australia Pty Ltd (Dandenong South, Australia). A cationic polyacrylamide (PAM) water-soluble co-polymer was attained from SNF Australia Pty Ltd (Lara, Vic, Australia). The granular silicate fertiliser, ‘Agrisilica®’ (26% soluble Si) was provided by Agripower Australia Ltd (Sydney, Australia). The liquid fertiliser treatment ‘NPKS’ comprised Agri-Max fertiliser (Agrichem®, NPKS 17-5-12-2 + Trace Elements), and was applied at a rate to give 125 kg N and 184 kg P/ha.

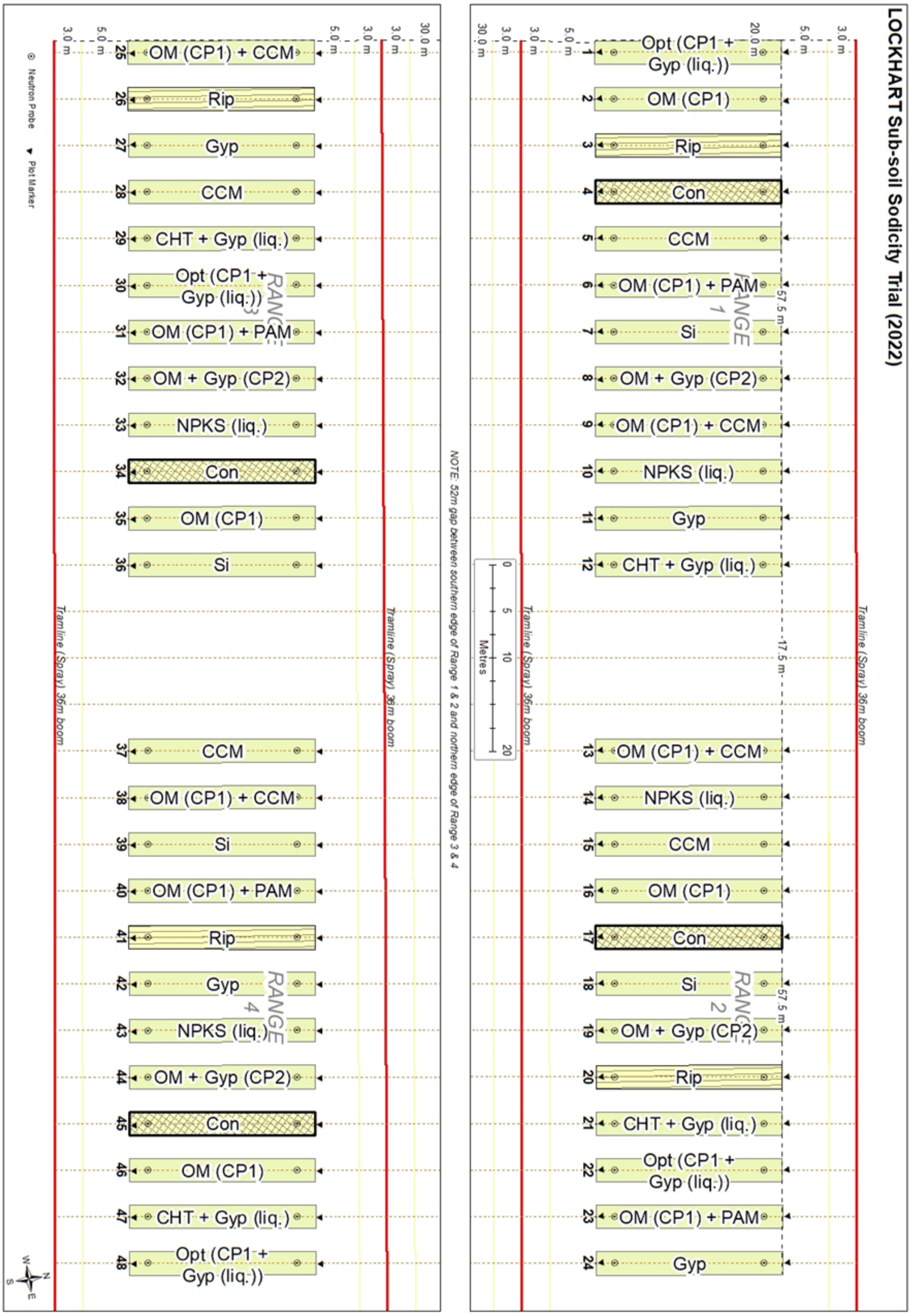


Figure 3. Trial plots and treatment layout, Lockhart NSW site.

Table 3. Trial treatments (trt) descriptions, application rates, and general composition and theoretical mode of action.

Trt	Description/rate	Composition/proposed modes of action
1	Control	• Untreated/undisturbed soil
2	Deep gypsum: 5 t/ha	• $CaSO_4.2H_2O$ applied at depth; increases flocculation of clay particles; reacts with Na_2CO_3 to produce $CaCO_3$ to reduce pH
3	Deep OM (CP1): 15 t/ha	• OM (Lucerne hay); increase OM to reduce slaking and increase microbial activity • Minerals to release Ca and bind with CO_2 to reduce pH; stabilise carbon (C) in the rhizosphere • NPKS; balance nutrition to meet microbial demand
4	Deep OM + gypsum (CP2): 15 t/ha / 5 t/ha	• OM (Lucerne hay); increase OM to reduce slaking and increase microbial activity • Minerals to release Ca and bind with CO_2 to reduce pH; stabilise C in the rhizosphere • NPKS; balance nutrition to meet microbial demand • Gypsum; to reduce pH, release Ca
5	Deep carbon-coated mineral (CCM): 5 t/ha + 77 kg N/ha as urea	• Biochar (oaten hay); mineral component; increase OM to reduce slaking, increase microbial activity and sequester atmospheric C in soil • Minerals to release Ca and bind with CO_2 to reduce pH; stabilise C in the rhizosphere • P to balance nutrients
6	CP1 + CCM: 15 t/ha / 5 t/ha	• Combination of trt 3 and 5 (excl. urea)
7	Deep liquid NPKS: 750 L/ha (125 kg N/ha, 184 kg P/ha)	• Deep mineral nutrient only
8	Deep gypsum dispersion (GD): 0.5 t/ha	• Biochar based, micronised powder in liquid form • Gypsum + polymer; designed to improve surface tension of gypsum to facilitate mobility
9	Shallow silicon: 2 t/ha	• Plant available form of Si • Influences soil availability and uptake of nutrients by plants, and crop tolerance to abiotic and biotic stress, e.g. water/diseases
10	CP1 + PAM: 15 t/ha / 5 t/ha	• Combined with trt 3 • Cationic PAM co-polymer; water-soluble polymer that binds strongly with organic matter and clay particles; reduce slaking through soil aggregation

11	Deep ripping	• Deep rip only control
12	CP1 + GD: 15 t/ha / 0.5 t/ha	• Combination of trt 3 and 8

3.2.3 Crop growing conditions and inputs

In 2022, plots were sown with Faba bean (Pulse Breeding Australia [PBA] Amberley, Glen Osmond, SA, Australia)) on the 25 April at a seeding rate of 150 kg/ha (target plant density 25 plants/m^2). Prior to sowing, seeds were pre-treated at twice the recommended rate with rhizobium legume inoculant F (WSM1455; New Edge Microbials, Albury, NSW, Australia). Diammonium phosphate (DAP; NPK 18:20:0) was applied at 100 kg/ha (18 kg/ha N, 20 kg/ha P) as a starter fertiliser at sowing. The crop was sown after spraying with Roundup Ultramax® (Monsanto, St. Louis, Missouri; discontinued) at 1.5 L/ha (570 g/L glyphosate as potassium salt), Landmark® Sulphate of Ammonia herbicide adjuvant (Nutrien Ag Solutions, Wagga Wagga, NSW, Australia) at 1 kg/ha (980 g/kg ammonium sulphate), and Cavalier® (ADAMA, St. Leonards, NSW, Australia; discontinued) at 75 mL/ha (240 g/L oxyfluorfen) on the 5 April. On the 4 May additional pre-emergent herbicides; Mentor WG (ADAMA) at 200 g/ha (750 g/kg metribuzin) and Genfarm Simazine 900 WG (Nutrien) at 1 kg/ha (900 g/kg simazine) were applied. On the 26 May Telstar 250EC insecticide (FMC Australasia Pty Ltd, North Ryde, NSW, Australia) at 50 mL/ha and Barrack 720 fungicide (Nufarm Australia, Laverton North, Vic, Australia) at 1.5 L/ha (720 g/L chlorothalonil) and were applied to control mites and as a preventative spray for chocolate spot, respectively. This action was repeated on the 11 July. Thereafter, on August 3, Veritas Opti (ADAMA) at 500 mL/ha (azoxystrobin 222 g/L + tebuconazole 370 g/L), was applied to control chocolate spot. The majority of the crop (38 of 48 plots) was harvested on the 2 December, with the remainder completed on the 6 December, due to machinery breakdown.

In 2023, plots were sown with wheat (cv. Scepter (Australian Grain Technologies (AGT), Roseworthy, SA, Australia)) on the 10 May at a seeding rate of 80 kg/ha (target plant density of 150 plants/m^2). DAP was applied at 95 kg/ha (17.1 kg/ha N, 19 kg/ha P) as a starter fertiliser at the time of sowing. The crop was sown after applying an initial site knockdown spray comprising Roundup Ultramax® (Monsanto) at 1.5 L/ha, Genfarm Oxyfluofen 240EC (Nutrien) at 75 mL/ha, and Landmark® Sulphate of Ammonia (Nutrien) at 1 kg/ha on the 22 April, and a second knockdown comprising Hammer (FMC) at 40 mL/ha (400 g/L carfentrazone-ethyl) and Gramoxone (Syngenta®, Macquarie Park, NSW, Australia) at 1.5 L/ha (360 g/L paraquat as paraquat dichloride) on the 24 April. Immediately prior to sowing, Treflan® (Gowan Company, Yuma, Arizona) at 1.5 L/ha (480 g/L Trifluralin) and Sakura® (Bayer CropScience Pty Ltd, East Hawthorn, Vic, Australia) at 118 g/ha (850 g/kg Pyroxasulfone) were applied. Urea at 100 kg/ha (46 kg/ha N) was applied at GS 35–37 just prior to flag leaf emergence on the 15 August, 97 days after sowing (DAS). Soprano® 500 (ADAMA) fungicide at 90 mL/ha (500 g/L Epoxiconazole), as a preventative for stripe rust was applied by the grower on the 26 August. The crop was harvested on the 23 November.

In 2024, canola (cv. HyTTec® Trophy (Nuseed Australia, Laverton North, Vic, Australia)) was sown on the 11 April at a seeding rate of 3.5 kg/ha (target plant density 40 plants/m^2). DAP was applied at 100 kg/ha (18kg/ha N, 20 kg/ha P) as a starter fertiliser at the time of sowing. Prior to this, on 14 December 2023, the grower applied a knockdown spray comprising Roundup Ultramax® (Monsanto) at 1.5 L/ha, Landmark® Sulphate of Ammonia (Nutrien) at 1 kg/ha, Amicide Advance 700 (Nufarm) at 750 mL/ha (700 g/L 2,4-D as dimethylamine and monoethylamine salts), and Genfarm Triclopyr 600EC (Nutrien) at 60 mL/ha (600 g/L triclopyr). Immediately prior to sowing, Treflan® at 1.5 L/ha was applied.

On the 28 May (47 DAS) the grower applied urea at 80 kg/ha (36.8 kg/ha N) and the trial site was sprayed with Genfarm Clethodim (Nutrien) at 330 mL/ha (360 g/L clethodim), Genfarm Atrazine (Nutrien) at 1.1 kg/ha (900 g/kg atrazine), Genfarm Simazine (Nutrien) at 1.1 kg/ha (900 g/kg simazine), Lontrel (Corteva Agriscience Australia Pty Ltd, Chatswood, NSW, Australia) at 60 mL/ha (600 g/L clopyralid), Landmark® Sulphate of Ammonia at 1 kg/ha (Nutrien), and Loveland Agriproducts MSO oil (Nutrien) spray adjuvant at 1 L/ha. On the 22 August (133 DAS) the grower applied Aviator Xpro (Bayer) fungicide at 650 mL/ha (150 g/L prothioconazole + 75 g/L bixafen), as a preventative for blackleg and sclerotinia.

3.2.4 **Crop and soil measurements**

3.2.4.1 Soil chemical properties

The soil chemical profile was characterised (Table 2), with intact soil cores collected from nine locations across the site prior to commencement of the trial, sampled on 8 February 2022. Cores were then dissected at intervals of 0–10, 10–20, 20–30, 30–40, 40–60, 60–80 and 80–100 cm, dried at 40 °C, and the soil pH_w (1:5 soil/water), exchangeable cations, exchangeable sodium (Na) percentage (ESP), electrical conductivity (EC; 1:5 soil/water), Colwell phosphorus, and mineral nitrogen comprising both nitrate (NO_3^-) and ammonium (NH_4^+) (1 M potassium chloride (KCl)) measured at each depth interval. Soil dispersion (aggregate stability) was also assessed at the nominal depth intervals of 0–10, 10–20, 20–30, and 30–40 cm. Soil chemical properties: pH, EC, ESP and mineral nitrogen were measured again in the third season prior to sowing, sampled on 7 March 2024.

3.2.4.2 Crop performance

Crop performance, including plant establishment (plants/m^2), anthesis biomass (t/ha), harvest biomass (t/ha), grain yield (t/ha), and seed quality and size, were measured seasonally. To ensure reliable comparisons between treatments, plant numbers at establishment were determined by counting plants in 1 m transects in four rows to give a combined area of 1.0 m^2. Counts were split between opposing ends of each plot, excluding the outside rows.

Fresh weight and dry matter were determined at anthesis by hand harvesting plants within two 0.5 m^2 quadrats taken from opposing ends and sides of each plot, then bulked. The harvested plants were weighed, then a subsample was taken and dried at 70 °C for 72 hours to achieve constant weight, and dry weights recorded. For grain yield and biomass at maturity, two 1.0 m^2 quadrats were hand harvested, taken from opposing ends and sides of each plot, then bulked. Plants were then dried to constant weight by air-drying in a glasshouse, followed by dehydration at 70 °C for 72 hours. Anthesis wet and dry biomass (t/ha), harvest biomass (t/ha) and grain yield (t/ha) were recorded on a per hectare equivalent basis. Seed quality indices, including percentage of protein (dry matter basis) for cereals were determined by Near Infrared Spectroscopy (NIR) using an Infratec™ 1241 Grain Analyser (FOSS Analytics, Mulgrave, Vic, Australia). Seed size was evaluated by measuring the seed weight in grams of a random sample of one thousand seeds (TSW), or a suitable equivalent according to grain size.

Normalised Difference Vegetation Index (NDVI) crop reflectance measurements were conducted using a GreenSeeker 900-1-038-EM sensor (Trimble, Westminster, Colorado, USA), with data stored in an attached Trimble Nomad mobile computer. Measurements were taken on 20 September 2022 with the faba beans at GS 65-70 (BCCH), on 29 September 2023 with the wheat at GS 65 (Zadoks), and on 24 July 2024 with the canola at GS 55 (BCCH) and on 12 August 2024 at GS 61-62 (BCCH).

3.2.4.3 Water use

The volumetric water content (θv, cm^3/cm^3) in the soil profile at nominal depths of 15, 30, 50, 70, 90, 110, 130 and 170 cm was determined at sowing, anthesis and harvest using a CPN 503TDR HydroProbe neutron soil moisture gauge (CPN International, Concord, California, USA). After the application of ameliorants, two neutron probe access tubes per plot were installed near the centre rip line, approximately 1.5 m inside the northern and southern ends of each plot respectively. To determine the volumetric water content, neutron probe readings were converted by multiplying them with gravimetric soil water content and bulk density measurements of the individual soil layers that were removed for the installation of the access tubes. The net changes in soil water content (mm) between sowing and anthesis, anthesis and harvest and sowing and harvest were determined on a seasonal basis for both the topsoil (0–15 cm) and subsoil (30–170 cm).

Total crop water use (TWU; mm) and water use efficiencies (WUE; kg/ha/mm) for biomass production (WUE_{bm}) and grain yield (WUE_{grain}) were then determined for each experimental treatment. TWU was determined by the method of Robertson and Kirkegaard (2005) with a summer fallow rainfall threshold of 80 mm (i.e. January–March total rainfall 80 mm, multiplied by a storage efficiency factor of 0.5) + in-crop rainfall (April–October) + net change in soil water content between sowing and harvest. WUE_{bm} and WUE_{grain} were then determined by dividing the quantity of biomass or grain in kilograms by the TWU.

3.2.5 **Site visits**

A field walk was conducted at the site on 23 May 2022, attended by about 20 people made up of members of the Soil CRC as well as local farmers and consultants. A second field walk was conducted at the site on 26 October 2023, attended by about ten local farmers and consultants. The trial was selected as one of the field site tours for the 2024 Soil CRC Participants Conference, hosted by Charles Sturt University and Department of Primary Industries and Regional Development (DPIRD), with the site visit taking place on 29 August 2024, with about 30 attendees.

3.3 WONWONDAH, VICTORIA TRIAL SITE

3.3.1 **Site description**

The field trial, comprising of nine deep placed soil amelioration treatments and an untreated control treatment, was established at Wonwondah (lat. 36°52’45.8”S, long. 142°11’45.0”E, 17 km due south of Horsham) in Victoria’s MRZ southern Wimmera district in April 2022.

The soil at Wonwondah is classified as a sodic Vertosol with moderate levels of salinity deeper in the profile that may limit root growth, especially during dry seasonal conditions. It has a dense sandy clay-textured subsoil that is poorly drained and is highly dispersive (> 1000 NTU) at depths greater than 20 cm (Table 4). In a previous study using soil collected from this site, ESP in the subsoil was 18% at 20–60 cm depth and 23% at 60–100 cm depth. Gypsum was spread evenly across the paddock at 2.5 t/ha by the farmer prior to the beginning of the experiment and at this time it was very low in soil mineral nitrogen.

Table 4. Pre-treatment soil pH, electrical conductivity (EC), turbidity, and mineral nitrogen at ammonium (NH4+-N) and nitrate (NO3--N) at Wonwondah, April 2022.

Soil Depth (cm)	pH_{H2O}	EC (µS/cm)	Turbidity (NTU 1:25)	NH_4^+-N (mg/kg)	NO_3^-N (mg/kg)
0–10	6.08	85.9	244	2.7	4.5
10–20	7.00	103.7	628	2.6	1.8
20–40	8.36	198.7	1332	1.3	0.8
40–80	9.33	622.2	1664	0.9	0.6
80–120	9.29	1008.4	2388	0.9	0.7

3.3.2 Treatment application

In early April 2022, a custom-built subsoiler was used to implement nine different amelioration treatments, along with an untreated control, at the experimental site. The subsoiler consisted of three ripping tines, spaced 60 cm apart, that delivered amendments fed from hoppers down behind the ripper tines. After first using the subsoiler to rip to ~20 cm deep, each treatment was applied to a depth of 25–30 cm below the soil surface on the second pass with the subsoiler. Dry, hard soil conditions prevented treatments from being applied any deeper than this. Each treatment was replicated four times in 20 m long by 4 m wide (two working widths of the subsoiler) plots in randomised blocks (n = 40 plots, Figure 4). Spaces were left within blocks where required to allow the farmer's sprayer to pass over without affecting the plots. After ripping, the plots were lightly cultivated with a tine renovator and rolled with a tyre roller to prepare an even seedbed for sowing. After sowing, two 1.5 m deep alloy access tubes were installed in each plot for measuring soil moisture content with a neutron probe.

The ten treatments applied at the site were:

1. Control, non-ripped
2. Deep ripping only
3. Deep gypsum (5 t/ha)
4. Deep lucerne pellets (15 t/ha)
5. Deep lucerne (15 t/ha) + gypsum (5 t/ha)
6. Deep lucerne (15 t/ha) + PAM polymer (polyacrylamide, 0.5 t/ha)
7. Deep inorganic nutrients
8. Deep wheat straw pellets (15 t/ha) + inorganic nutrients
9. Deep recycled urban organic mulch (15 t/ha)
10. Deep recycled urban organic mulch (15 t/ha) + inorganic nutrients.

The deep inorganic nutrient treatment consisted of a selection of inorganic fertilisers (urea, monoammonium phosphate (MAP), KCl, potassium sulphate (K_2SO_4)) blended to apply the equivalent amount of N, P, K, and S applied in the deep lucerne treatment (Table 5). This allowed for examining any potential advantages in ameliorating soil with nutrient-rich organic matter compared to just applying inorganic nutrients. Likewise, the deep wheat straw pellets with inorganic nutrients and the deep recycled organic mulch (subsequently designated as UGW) with inorganic nutrients treatments allowed for examining the effects of applying nutrient-poor organic amendments fortified with inorganic nutrients in order to apply the equivalent amount of N, P, K, and S as applied in the nutrient-rich organic matter treatments (those with deep lucerne pellets). The polymer PAM has been shown to bind clay particles and improve soil aggregation (Wallace and Wallace, 1986) and was applied with lucerne pellets to examine any potential synergistic effect of incorporating PAM with deep applications of organic matter. The lucerne and wheat straw treatments were applied as pellets (ca. 8 mm diameter by 30 mm long) to enable use in the subsoiler. The UGW consisted of material that had been collected and composted for up to two years by the Horsham Rural City Council. This first had to be screened to remove any large pieces of wood and as much fibrous material as possible to prevent the subsoiler from blocking.

Table 5. Quantities of nutrients applied (nutrients from organic product + inorganic nutrients, kg/ha) in the amelioration treatments applied at Wonwondah in April 2022.

Nutrient (kg/ha)	Deep lucerne*	Deep nutrients	Deep wheat straw + nutrients[a]	Deep UGW	Deep UGW + nutrients[b]
N	471	471	88 + 383	140	140 + 313
P	33	33	7 + 26	23	23 + 13
K	311	311	95 + 216	105	105 + 170
S	45	45	12 + 33	20	20 + 21

* Includes all treatments containing 15 t/ha lucerne pellets. [a] Nutrient from organic component + nutrient from inorganic nutrient component. [b] Slightly different concentrations of nutrients than expected in the UGW mulch resulted in slight nutrient imbalances in the deep recycled UGW + nutrients treatment compared to the other nutrient-rich treatments.

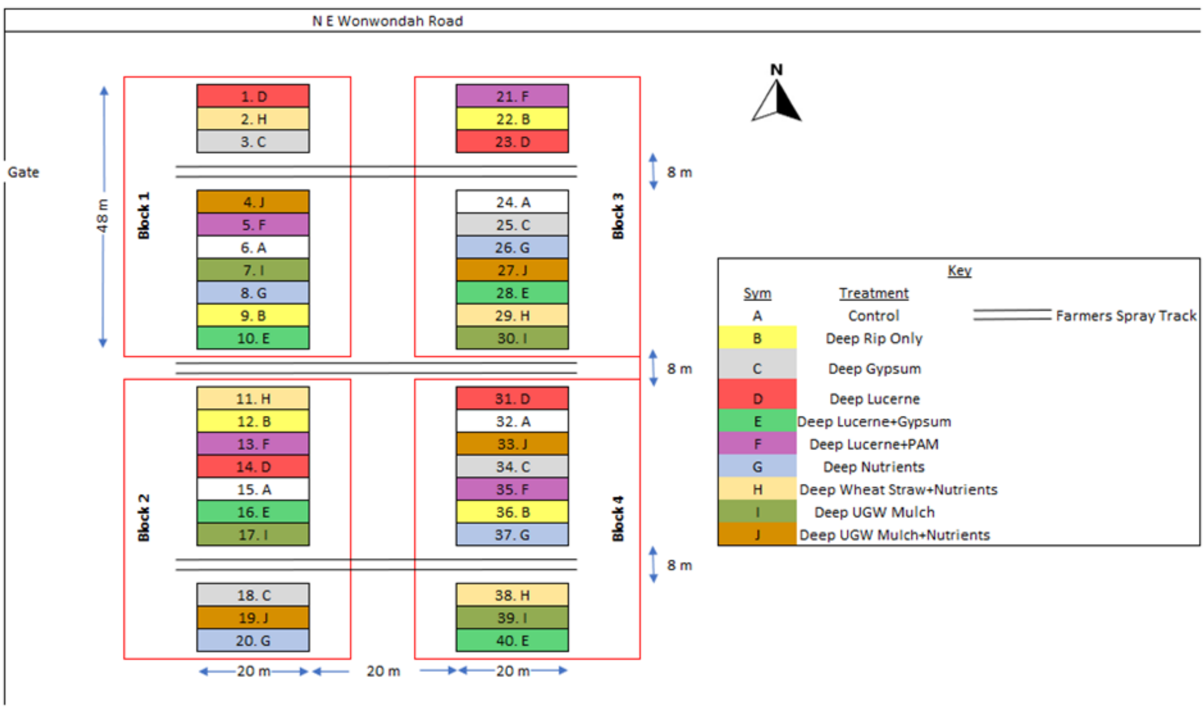


Figure 4. Field plan for the Wonwondah field trial site.

3.4 KWEDA, WA SITE

3.4.1 Site description and trial layout

A detailed study aiming at testing the effect of soil amendments on soil fertility and crop health on duplex sandy soils with low pH and multiple subsoil constraints (Al toxicity, low fertility and possibly compaction, water logging), was conducted at Jeff Edwards's farm (farm area: 500 m × 250 m) at South Kweda Road, Pingelly, WA, 6306 (lat. WA 32°25'16.1"S, long. 117°24'16.8"E). To investigate the potential amelioration on a soil with multiple constraints, a series of amendments were incorporated with a Bednar Terralander plough on the large plots experiment and small plots experiment (Tables 6, 7, Figure 5) in 2022. The total experimental area was divided into four blocks (Figure 5). Each block was divided into seven large plots (250 m × 18 m). Six out of seven plots in each block were utilised to execute the large trial plot with five treatments (including control) while a control was assigned to two plots in each block (Figure 5 and Table 7). One out of seven large plots in each block were divided into sub-plots (18 m × 2 m), which were utilised for the small plots trial with 12 treatments (Figure 5 and Table 7). Each treatment in each experiment was replicated four times in a randomised way using four blocks (Figure 5 and Table 7). Unripped soil with no soil amendments was used as control in the large plots trial, while soil inverted with the Bednar Terralander was used as control in the small plots trial.

Table 6. Description of the novel amendments utilised in small plots experiments (applied in 2022).

Novel soil amendments	Description	Novel soil amendments	Description
Hydrotalcite	A magnesium aluminide hydrocarbonate positively charged clay	Rescaype	Increase water retention and soil carbon
Agrisilica	Natural fertiliser with a silica base: high CEC and water-holding capacity	Carbon Ag	Pelletised clay/gypsum: increase soil nutrient uptake and biological activities
Iron Man Gypsum	Enhanced gypsum high P binding capacity	C-wise compost	Humiclay compost + bentonite (~5%)
Zeolite	Aluminosilicate mineral: high absorbency and CEC		

3.4.2 Inputs used in 2022

Lime was applied to the entire site at the rate of 1.2 t/ha as a one-off treatment 3–4 months before the start of the trial in 2022.

Sowing: Barley (cv. Scope) was sown at 70 kg/ha on 11 May 2022 using a seeder with a 16 m bar with knives and press wheels (25 cm between rows).

Fertiliser application before sowing: On 1 May 2022, muriate of potash was applied at 50 kg/ha (K at 24.75 kg/ha).

Fertilisers application at sowing (11 May 2022): Nutrien's Bulk N solution (42% N) was applied at the time of sowing at 60 L/ha. Muriate of potash was applied at 25.5 kg/ha (K at 12.62 kg/ha). Crop Builder 16 was applied at 59.5 kg/ha (N at 7.97 kg/ha, P at 9.52 kg/ha, and S at 4.11 kg/ha).

On 1 July 2022, Cereal Plus (containing 57 g/L N, 123 g/L P, 35 g/L K, 28 g/L S, 21 g/L Mg, 18 g/L zinc (Zn), 27 g/L manganese (Mn), 3.1 g/L copper (Cu), 2.8 g/L iron (Fe), 3.0 g/L B, 0.1 g/L cobalt (Co), 0.2 g/L molybdenum (Mo)) was applied at 2 L/ha.

On 24 June 2022, Nutrien's Bulk N solution (42% N) was applied at 50L/ha. Another dose of Nutrien's Bulk N solution (42% N) was applied at 60L/ha on 12 August 2022, followed by a 30 L/ha application of Bulk N solution on 20 August 2022.

Herbicides and fungicides used: first knockdown was applied on 20 April 2022 (three weeks before seeding). Second knockdown was applied on 8 May 2022 (three days before sowing). Third knockdown was applied on 10 May 2022 (a day before sowing). Invertix herbicide, along with other herbicides, was applied on 1 July 2022 (seven weeks after sowing) to control wild radish and other weeds (Table 7). Maxentis EC fungicide was applied on 20 August 2022 (14 weeks after sowing) to control fungal diseases.

Table 7. Soil treatments utilised in the small plots and large plots experiment at Kweda, WA.

Treatment No.	Treatment	Shade	Trial
1	Control, unripped		Large plots
2	Bednar only		Large plots
3	Bednar + gypsum (1.1 t/ha)		Large plots
4	Bednar + C-wise humiclay compost (5 t/ha)		Large plots
5	Bednar + gypsum (1.1 t/ha) + C-wise humiclay compost (5 t/ha)		Large plots
6	Small Plots + Bednar		Entire Small plots area
7	Hydrotalcite (7 t/ha)		Small plots
8	Agrisilica Chip (0.15 t/ha)		Small plots
9	Iron Man gypsum (15 t/ha)		Small plots
10	Zeolite (30 t/ha)		Small plots
11	Small Plot Control, Bednar only		Small plots
12	Ryscape (0.1 t/ha)		Small plots
13	Carbon Ag (lime/gypsum) (2 t/ha)		Small plots
14	Compost high rate (10 t/ha)		Small plots
15	Compost low rate (2 t/ha)		Small plots
16	Compost med rate (5 t/ha)		Small plots
17	Zeolite (10 t/ha)		Small plots
18	Iron Man gypsum (5 t/ha)		Small plots
2	Small plot buffers (Bednar only)		Small plots

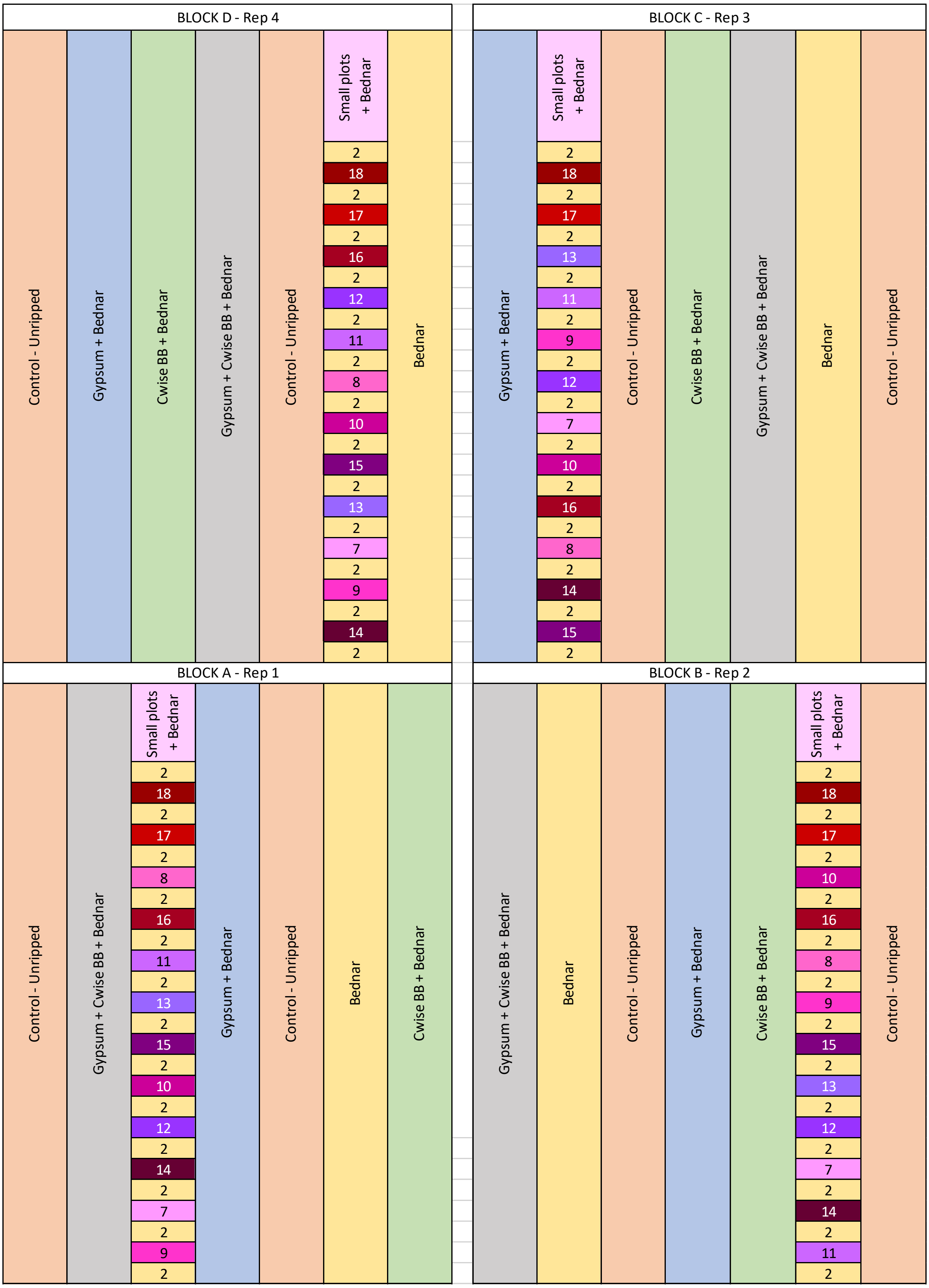


Figure 5. Experimental layout and treatment structure of trials conducted at Kweda, WA, during 2023. Each small plot was treated with the Bednar along with the other treatment.

3.4.3 Inputs used in 2023

Narrow leaf lupin (cv. Jurien) was planted on 15 May 2023 using an air seeder. Sowing rate was 90 kg/ha. At sowing, Nutrien's CroPbuilder16 was applied at 35 kg/ha (N at 4.69 kg/ha, P at 5.60 kg/ha, S at 2.42 kg/ha). Later in the season, muriate of potash was applied at 15 kg/ha (K at 7.43 kg/ha) on 15 May 2023. To maintain the soil moisture at sowing, SACOA's SE14™ (active ingredients: polyethylene glycol/ethoxylated alcohol) was applied at 2 L/ha. At 14 weeks after sowing, FertiMax Manganese Sulphate (active ingredients: manganese sulphate monohydrate) was applied at 1 kg/ha using a boom spray.

3.4.4 Inputs used in 2024

Sowing: Canola (cv. Bonito) was sown through direct drilling at 3.5 kg/ha on 19 April 2024.

Fertilisers at sowing (19 April 2024): Granular sulphate of ammonia was applied at 100 kg/ha (N at 21 kg/ha, S at 24 kg/ha). SACOA's SE14™ was applied at 2 L/ha. CroPbuilder16 Trace was applied at 59.5 kg/ha (N at 8.09 kg/ha, P at 9.46 kg/ha, S at 4.05 kg/ha, Cu at 0.06 kg/ha, and Zn at 0.12 kg/ha). Muriate of potash was applied at 25.5 kg/ha (K at 12.62 kg/ha).

The site was infested with high ryegrass and radish weeds before knockdowns were applied. Details of herbicides/pesticides and other chemicals applied are below.

Pre-emergence and knockdown (18 April 2024): A 1.0% solution of the Herbicide Adjuvant, Genfarm's Ammonium Sulphate 417 (active ingredients: 417 g/L ammonium sulphate), was applied at 0.8 L/ha. Genfarm's Atrazine 900 WG Herbicide (active ingredients: 900 g/kg atrazine) was applied at 1.1 kg/ha. Rustler selective herbicide (active ingredients: 500 g/L propyzamide) was applied at 1 L/ha. Genfarm's Alpha Cypermethrin 250SC Insecticide (active ingredients: 250 g/L Alpha Cypermethrin) was applied at 50 mL/ha. Genfarm's Genfarm Panzer 450 Herbicide (active ingredients: 450 g/L glyphosate present as the isopropylamine salt) was applied at 1.8 L/ha. A 0.2% solution of the Wetter 1000 (active ingredients: 800 g/L nonylphenol ethoxylate, 200 g/L diethylene glycol monobutyl ether) was applied at 160 mL/ha solution. These chemicals were applied using a self-propelled boom spray.

Bug Spray (17 May 2024) through a boom spray: Genfarm's miticide/insecticide, Bifenthrin 250 Ec (active ingredients: 250 g/L bifenthrin), was applied at 80 mL/ha. Chlorpyrifos 500 Insecticide (active ingredients: 500 g/L chlorpyrifos) was applied at 400 mL/ha.

Herbicides/insecticides applied on 4 June 2024: A selective herbicide, Genfarm Clethodim 360 (active ingredients: 360 g/L clethodim), was applied at 330 mL/ha. The herbicide Genfarm Atrazine 900 WG (active ingredients: 900g/kg atrazine) was applied at 1.1 kg/ha. Herbicide Genfarm QPE 200 (active ingredients: 200 g/L quizalofop-P-Ethyl) was applied at 200 mL/ha. Insecticide Omethoate 290 (active ingredients: 290 g/L omethoate) was applied at 150 mL/ha. A 1.0% solution of Hasten Spray Adjuvant (active ingredients: 704 g/L ethyl and methyl esters of vegetable oil with 196 g/L non-ionic surfactants) was also applied at 0.8 L/ha to improve the spreading, wetting and retention of chemicals. These chemicals were applied using a self-propelled boom spray.

Top dressing N on 30 May 2024 (six weeks after seeding): Nutrien Urea (46% N) was applied at 80 kg/ha (N applied at 36.8 kg/ha) using a rotary spreader.

Herbicide applied on 13 June 2024: Lontrel® 750 SG (active ingredients: 750 g/kg clopyralid present as potassium salt) was applied at 120 g/ha. A 0.5% solution of Uptake Spraying Oil (active ingredients: 582 g/L paraffinic oil and 240 g/L alkoxylated alcohol non-ionic surfactants) was applied at 0.4 L/ha.

Liquid N application on 2 August 2024 (six weeks after sowing): Bulk N (42% N w/v) was applied at 70 L/ha.

3.4.5 Soil sampling

Soil samples were collected a couple of months before sowing each year by a ute-mounted drill system, collecting a bulk sample of 15–20 cores from each plot. Samples were sent to the CSBP lab at Bibra Lake, WA, for chemical/nutrient analysis. Diviner tubes were disconnected before sowing and reconnected after sowing. Soil moisture data loggers at Kweda were completely removed before sowing and remounted after sowing. Previous moisture data was retrieved from loggers, new batteries were installed, and loggers were tested to make sure they were working perfectly. Loggers were fenced in the non-crop period (December 2023 to March 2024) to avoid damage by the sheep. Crop establishment data (number of plants and weeds/m^2) and NDVI through the hand device were collected by the Corrigin Farm Improvement Group on 1 July 2024 at Kweda.

Soil samples were collected before the start of experiment each year. In 2022, samples were collected from 0–10 and 10–30 cm profiles of only the four replicates of the control as a baseline sampling. In 2023, samples were collected only from the three treatments of the large plots experiment, that is, from the control, Bednar-treated plots and the plots treated with gypsum and Bednar. In April 2024, samples were collected from all the treatments and all replicates of both the large plots and small plots experiments.

During a visit to the site in March 2024, left over of sheep was noticed in the field indicating sheep-grazing activity.

3.4.6 Satellite-based NDVI (2024)

In 2024, the satellite-based NDVI was recorded by a contractor (Data Farming Pty Ltd) on 18 July (13 weeks after sowing), 5 August (15 weeks after sowing) and 30 August (19 weeks after sowing). Weather was cloudy during the captures taken on 18 July 2024. Captures were taken at 50 cm resolution, and 1300–1400 counts were used to calculate the NDVI values for each plot. The experimental plots were wide enough to create a 1.5 m inner buffer around each plot to minimise error from slight inaccuracy in the plots' locations.

Diviner tube data was not recorded during the 2024 season because of issues with the diviner device; the battery needed to be replaced by a technician and the diviner rod broke, and a replacement was ordered.

RESULTS

4.1 CLARE, QUEENSLAND SITE

The sugarcane crop was harvested in August 2024, weighed and tested for Commercial Cane Sugar (CCS) content. From the harvested cane, data for tonnes per hectare, tonnes of sugar per hectare, and CCS were compiled and analysed. Sugar Research Australia (SRA) supplied a weigh truck and small mill to collect the relevant data, and provided help from their staff in field operations.

The harvesting procedure was for the SRA weigh truck to act as a haul out, following the harvester as it cut each weigh row, recording the weight and taring off the scales each time a new plot was reached. This gave the total tonnes of cane in each weigh row for each treatment.

To get sticks for CCS sampling, eight sticks were hand cut out of each weigh row before the harvester reached each plot (Figure 6). The sticks were zip-tied together and labelled with their associated plots. The hand-cut cane was then put through SRA's small mill, which provided the CCS results.

Figure 6. Hand cutting burned cane at the Clare trial site.

4.1.1 **Clare 2024 results**

The harvest data was analysed for tonnes of cane per hectare (TCH), tonnes of sugar per hectare (TSH) and CCS.

4.1.1.1 Tonnes of cane per hectare

There were no statistically significant differences between treatments in total cane biomass (t/ha) (Figure 7).

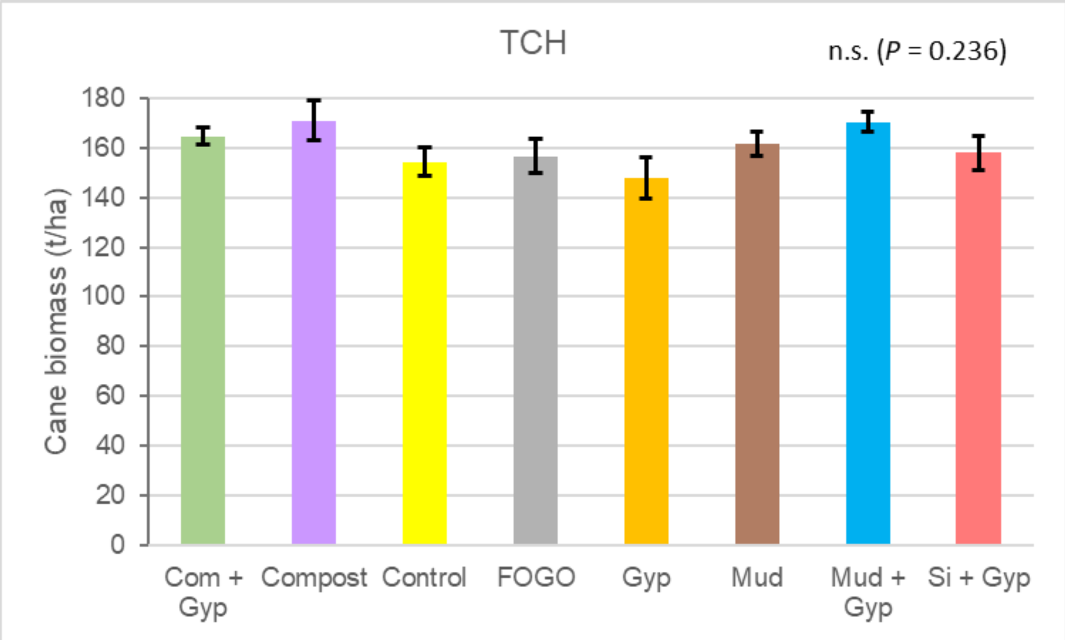


Figure 7. Average tonnes of cane per hectare (TCH) for each treatment (n = 4). Error bars indicate standard error of the mean.

On average, compost produced the highest TCH, though only marginally above the mud and gypsum treatment. The cane biomass measured in the compost treatment (plot 2) of replicate block 1 was an outlier (> 1.5 × IQR) when comparing blocks across all treatments, with a yield of 191.77 t/ha compared to an average of 155.6 t/ha from the other block 1 plots, and 163.85 t/ha from the other compost treatment replicates. It is possible that the area of the paddock where plot 2 was located may have had more favourable growing conditions unrelated to the compost treatment, which led to better performance. Assessing mud and gypsum plot by plot, the tonnes were consistently on the higher end of the range compared to the other treatments for all replications. This suggests that mud and gypsum applications may have potential to improve crop growth conditions in heavy clay. Further statistical analysis of results from the coming seasons should provide firmer evidence on these points.

One unexpected finding was that gypsum appeared to produce the lowest tonnage, being lower than the control. Though once again assessing plot by plot, one gypsum replication (plot 14) produced relatively low tonnes (127.55 t/ha) while the other replications were average compared to the control and other treatments. Plot 14 may have had constraints not related to the gypsum application which led to lower than average tonnes in that plot, although statistically it was not an outlier within the treatment replicates.

Assessing the tonnes of cane harvested across the paddock, there appeared to be a slight general trend, but not consistently in all regions of the paddock. There was also no consistency of one replication being always higher or lower than others (Figure 8).

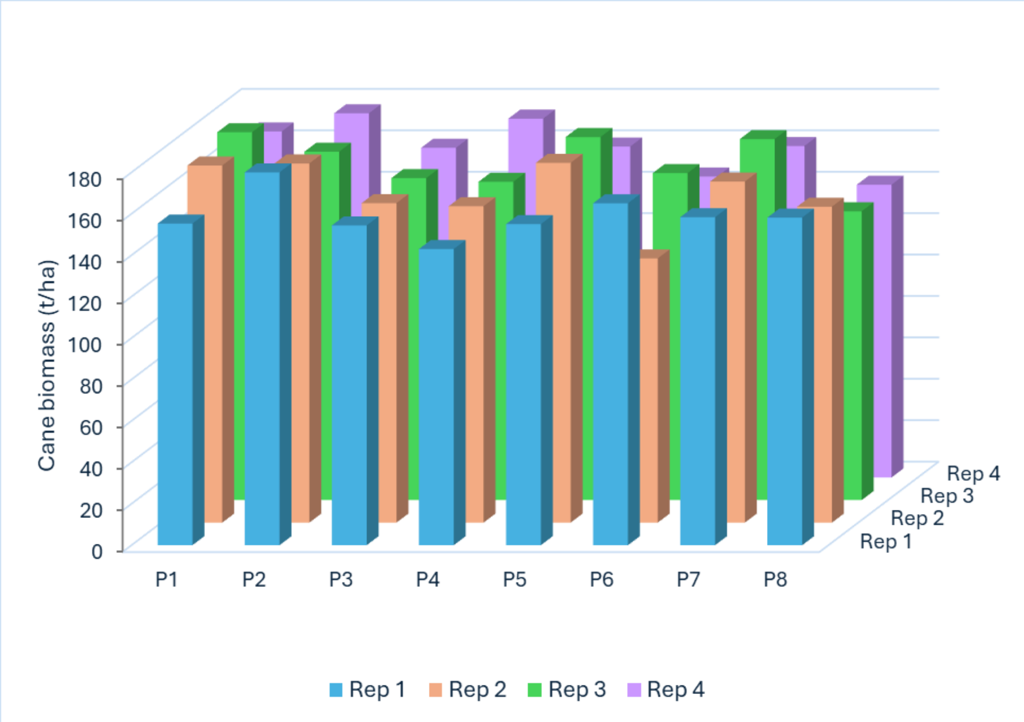


Figure 8. Average tonnes of cane per hectare (TCH) across each replicate block and plot row.

4.1.1.2 Tonnes of Sugar per Hectare

TSH measurements tended to follow a similar pattern to TCH, with compost and mud and gypsum having the highest average, and gypsum the lowest. However, there was still no significant difference between any of the treatments (Figure 9).

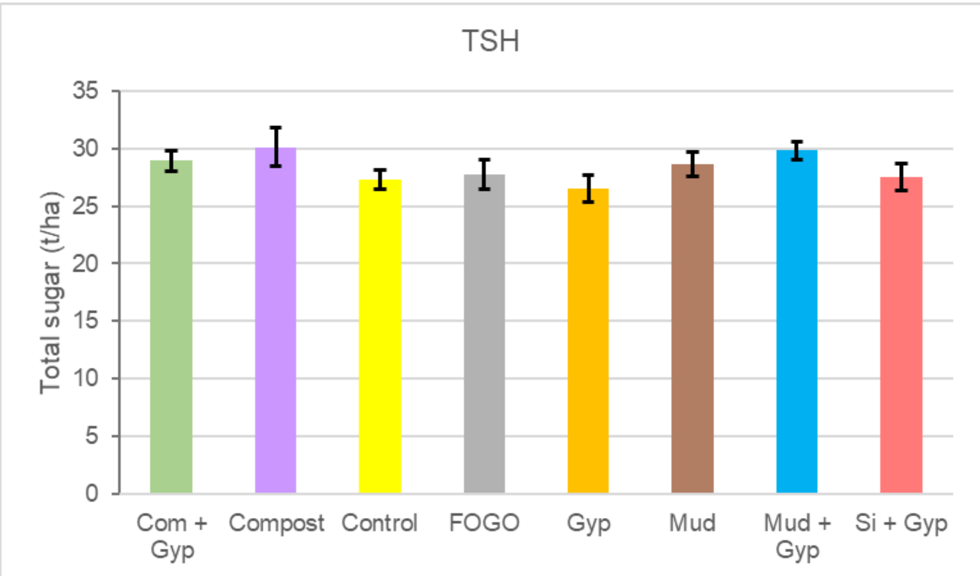


Figure 9. Average tonnes of sugar per hectare (TSH) for each subsoil amendment treatment. Error bars indicate standard error of the mean.

4.1.1.3 Tonnes of Commercial Cane Sugar per Hectare

On average, CCS was very similar for all treatments with no statistically significant differences (Figure 10). The highest CCS yield was found in the gypsum treatment, at 17.96%. Interestingly, silicon and gypsum had a much lower standard error of the mean (0.05) compared to the other treatments (0.15–0.27, mean 0.21), so produced the most consistent replication for CCS yield.

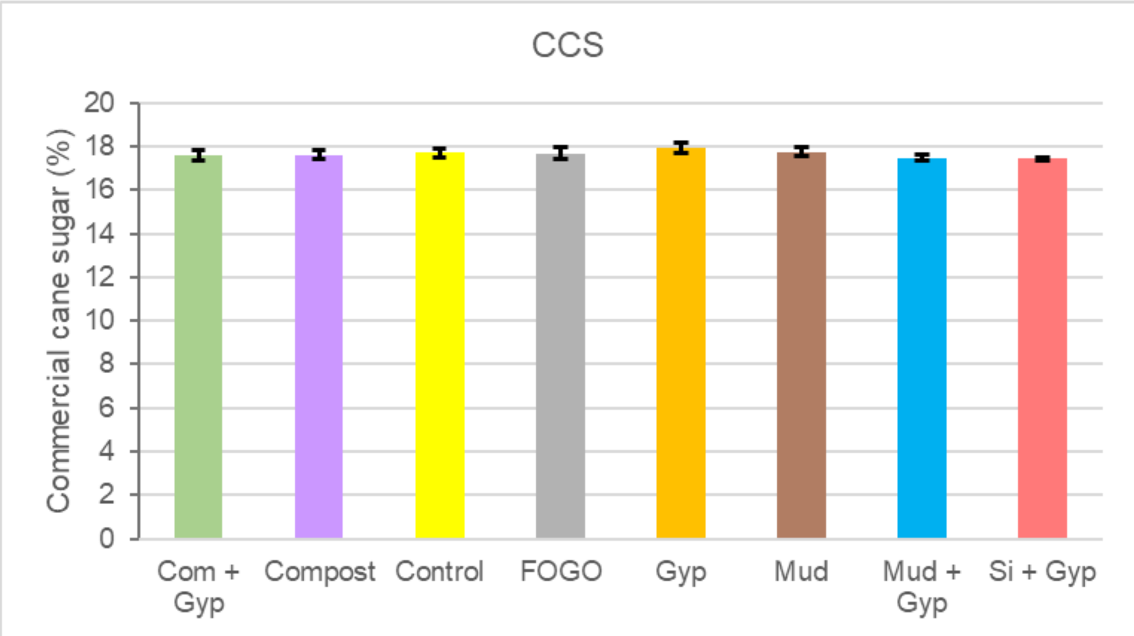


Figure 10. Average CCS of subsoil amendment treatments. Error bars indicate standard error of the mean.

4.1.1.4 Plant tissue analysis

Third leaf samples were taken in November when the cane was six months old. The nitrogen content of each treatment is shown in Figure 11. All treatments had very similar results and the range bars overlap, so there does not appear to be any significant difference between the treatments. All treatments were under the critical value for nitrogen content, specifically for the growth stage and time of year, but also under the critical values for other growth stages. This is particularly unexpected since the tonnes and CCS produced were still high, so the crop appeared not to suffer from lack of nitrogen.

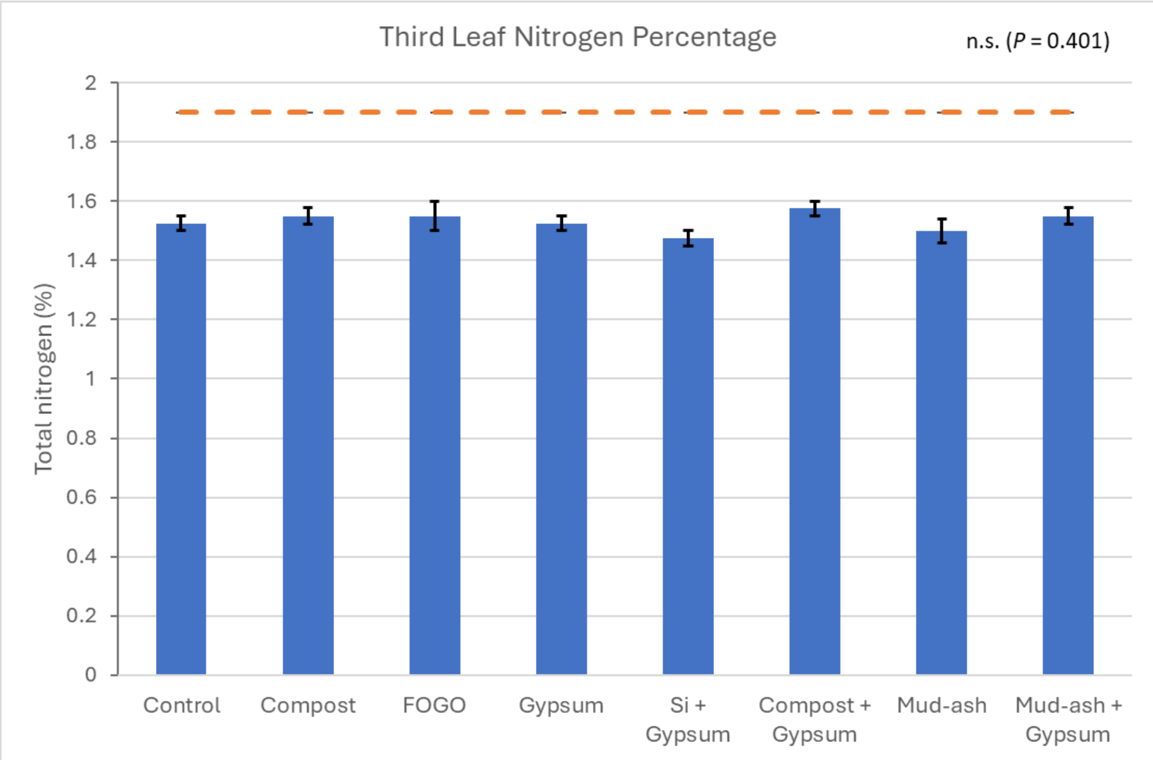


Figure 11. Average nitrogen percentage found in third leaf samples of six-month-old plant cane across different subsoil amendment treatments. Error bars indicate standard error of the mean. Orange dotted line at 1.9% indicates the critical value for six-month-old plant cane in November to mid-January, as cited in the Australian Sugarcane Nutrition Manual (SRA, 2022).

4.2 LOCKHART, NSW TRIAL SITE

4.2.1 **Climatic conditions**

Rainfall over the length of the trial was very variable from year to year (Table 8, Figure 12). The first year of the trial was characterised by extreme rainfall in the first quarter, with approximately 290 mm recorded in the SILO database compared to the long-term average of 104 mm. Overall rainfall for the middle of the year was around average, but October and November also had much greater than average rain, with a sum of 219 mm compared to the long-term average of 84 mm. The first four months of 2023 were also wetter than average, although not to the extreme of 2022, with a total of 244 mm falling from January to April compared to the long-term average of 140 mm. Rainfall from May to October was substantially below the average, however, though November and December were again much above average, leading to the disparity between deciles for the total year’s rainfall (7) compared to that of the growing season (3). In contrast, to date 2024 has been a significantly drier year with all months from February to August being well below average. The total rainfall for the year to date (Jan–Aug) was 202 mm, compared to the long-term average of 319 mm.

Temperatures fell below 2 °C on 67 days over the course of the trial up until August 2024, but no significant chilling or frost damage was evident in any of the crops (data not shown).

Table 8. Monthly rainfall and GSR (April–October, mm) recorded at the trial site between 2022–24 compared with the long-term annual average for the BOM rain gauge located at Lockhart Bowling Club (11 km northeast of the trial site) (1899–2018).

Month	**Rainfall (mm)**			
	Lockhart trial site			**Lockhart Bowling Club**
	2022	**2023**	**2024**	
January	185.2†	78.2	40.0	35.3
February	29.2†	38.6	5.6	33.9
March	75.4†	56.8	28.6	34.8
April	54.2	70.4	25.6	36.3
May	54.0	14.4	26.4	41.2
June	26.2	42.2	19.4	46.4
July	24.8	22.6	33.0	44.5
August	48.4	38.2	23.8	46.5
September	70.2	1.4		43.6
October	132.4	27.6		48.0
November	86.6	62.4		36.0
December	17.8	64.4		35.6
GSR	410.2 (decile 8)	216.8 (decile 3)	-	306.6
Total	804.4 (decile 9)	517.2 (decile 7)	-	485.7

† SILO database values (https://www.longpaddock.qld.gov.au/silo).

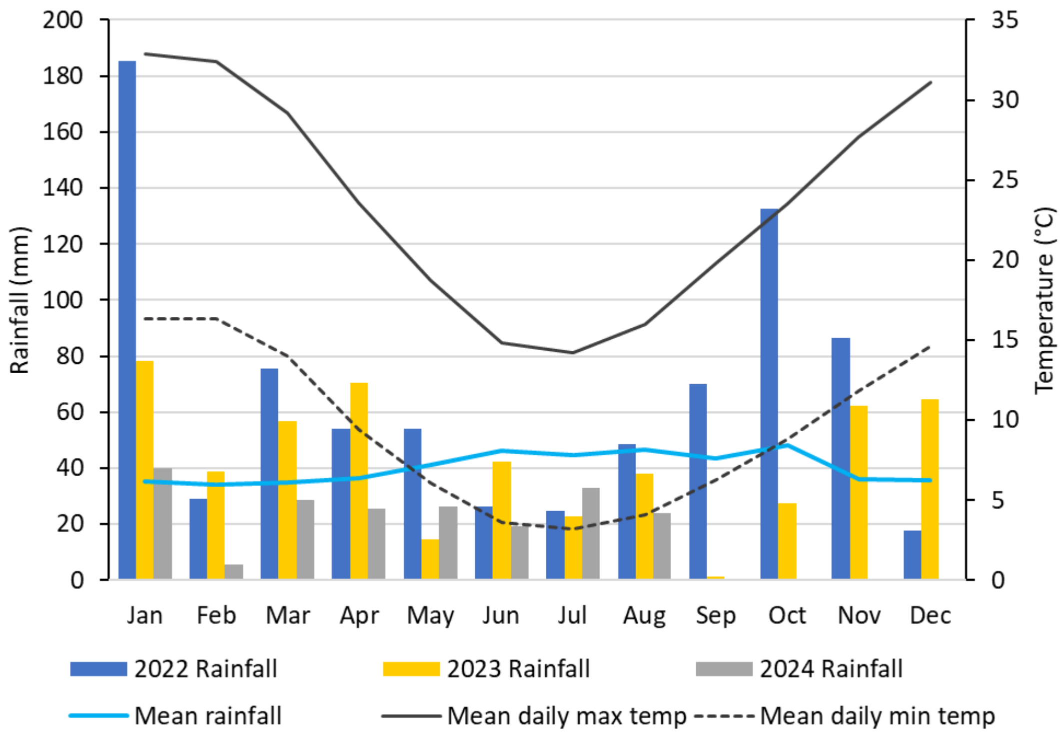


Figure 12. Monthly rainfall at the Lockhart trial site in 2022, 2023 and 2024 to date, compared to the long-term average for the town of Lockhart, NSW, and long-term maximum and minimum mean daily temperatures recorded at Urana, NSW.

4.2.2 **Soil chemistry**

Statistical analysis of the total profile soil chemical metrics by depth class (0–10, 10–20, 20–40, 40–60 and 60–100 cm) was conducted using a repeated-measures analysis of variance (ANOVA), with depth analogous to time interval. This allows autocorrelation in adjacent depths where chemical elements were too mobile to be considered. For soil tests where there was a high level of stratification down the soil profile. For example, pH, EC, Colwell P, the differences between depth classes for the whole soil profile were statistically highly significant ($P < 0.001$). However, in most cases the effects of soil amendments two years after application were not significantly different. The one exception to this was for pH in water, where there was only the deep OM + gypsum (CP2) treatment with a pH (back-transformed from $\log_e$) of 8.35 that was significantly different to the control treatment, pH 8.73 ($P = 0.023$). This significant difference was not seen in the pH($CaCl_2$) analysis. When the soil chemical metrics for the amendment layers only were analysed, there were no significant differences between treatments.

Soil profile mineral N was calculated from extractable nitrate and ammonium-N contents for each depth class and converted to kg N/ha values based on bulk densities of the soil core samples. The data were non-normally distributed, so were transformed as described in the Methods section. Log_e transformed data are shown in Table 9, and back-transformed data are presented in Figures 13, 14 and 15.

Table 9. Soil profile mineral nitrogen (kg N/ha; in transformed data, n = 4) by depth class down to 1.0 m, at pre-sowing 2024.

Treatment	**Depth (cm)**					**Soil profile**
	0–10	10–20	20–40	40–60	60–100	**total**
Control	3.237	2.136	2.347	2.063	1.964	4.107
Deep CCM	2.381	2.167	2.495	2.027	2.205	4.046
Deep gypsum	2.908	2.074	2.3	1.71	1.825	3.881
Deep liq. gypsum (CHT)	3.179	2.043	2.419	1.995	2.314	4.130
Deep liq. NPKS	3.728	2.455	2.591	1.834	2.277	4.418
Deep OM (CP1)	3.608	2.724	3.166	2.349	2.776	4.672
Deep OM (CP1) + CCM	3.818	2.901	3.1	2.322	2.892	4.775
Deep OM (CP1) + liq. gypsum (CHT)	3.349	2.861	2.929	2.542	2.838	4.632
Deep OM (CP1) + PAM	3.08	2.705	3.109	3.049	3.369	4.700
Deep OM + gypsum (CP2)	3.717	2.735	3.327	2.786	3.126	4.866
Deep ripping	3.049	2.369	2.457	1.865	2.253	4.129
Shallow silicon	3.222	2.17	2.352	1.756	2.072	4.098

Statistical analysis of the total profile mineral N contents by depth class was conducted using a repeated-measures ANOVA, with depth analogous to time interval. The total profile mineral N contents of the deep OM (CP1), deep OM (CP1) + CCM, deep OM (CP1) + liquid gypsum, deep OM (CP1) + PAM, and deep OM + gypsum (CP2) treatments were all significantly greater than that of the control treatment ($P < 0.001$) (Figure 13). However, there were no significant differences between the control, deep ripping, shallow silicon, deep CCM, deep gypsum, or deep liquid gypsum treatments (Figure 13). Despite there being a difference between the control and deep liquid mineral nutrients treatments of 25 kg N/ha, the latter was not statistically significantly different from these other treatments. Analysing depth class layers separately, treatment differences were statistically significant at all depths for total mineral N (kg/ha).

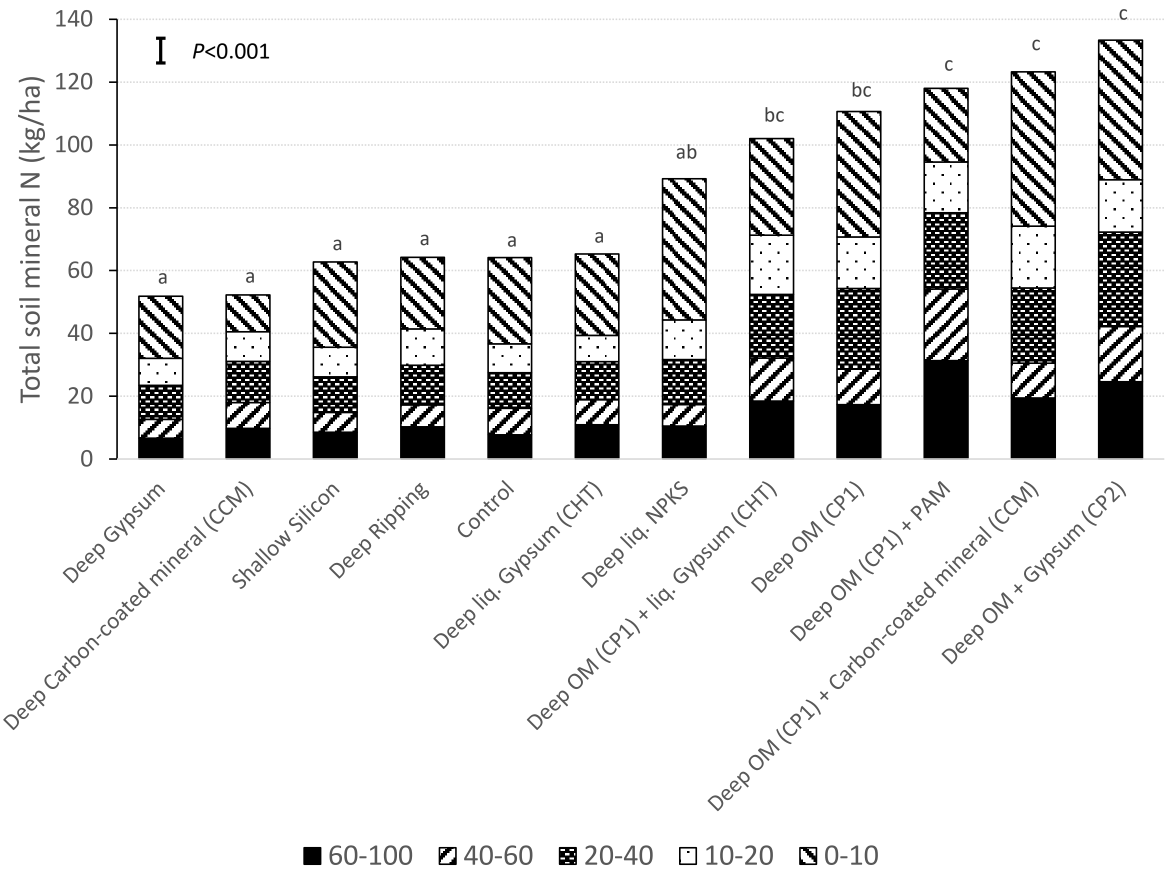


Figure 13. Mean total soil mineral nitrogen at pre-sowing in 2024 (kg N/ha; back-transformed values) by depth class (cm). Letters indicate statistically significant differences ($P \leq 0.05$) between treatments based on analysis of treatments at all depths, i.e., soil profile depth class means.

The profile distribution of soil mineral ammonium-N (kg N/ha) is shown in Figure 14, while the profile distribution of soil mineral nitrate-N (kg N/ha) is shown in Figure 15. Although there were some relatively large differences in ammonium-N content between some treatments and the control, particularly at the 20–40 cm depth, these were not statistically significant. A repeated measures ANOVA for ammonium-N for the soil profile showed that only differences between depths were statistically significant (Figure 14). Nitrate-N through the soil profile was statistically different, with a significant interaction between treatment and depth ($P = 0.009$). Differences between treatments at each individual depth were also statistically significant ($P = 0.013$, 0.015, < 0.001, < 0.001 and < 0.001 for the 0–10, 10–20, 20–40, 40–60 and 60–100cm depths respectively). In the 0–10 cm depth class, only the deep CCM treatment was significantly different from the other treatments. There was an outlier in one control plot at this depth (Plot 34 at 44.4 kg N/ha, compared to a mean of the other three reps of 16.1 kg N/ha), which did skew the analysis. Removing this data point results in a much greater separation of treatment effects, with the deep OM (CP1), deep OM + gypsum (CP2), deep liquid NPKS and deep OM (CP1) + CCM nitrate-N contents being significantly greater than the control (P <

0.001). However, the reason for the control plot outlier could not be determined; therefore it was not excluded from the data shown in Figures 13 and 15.

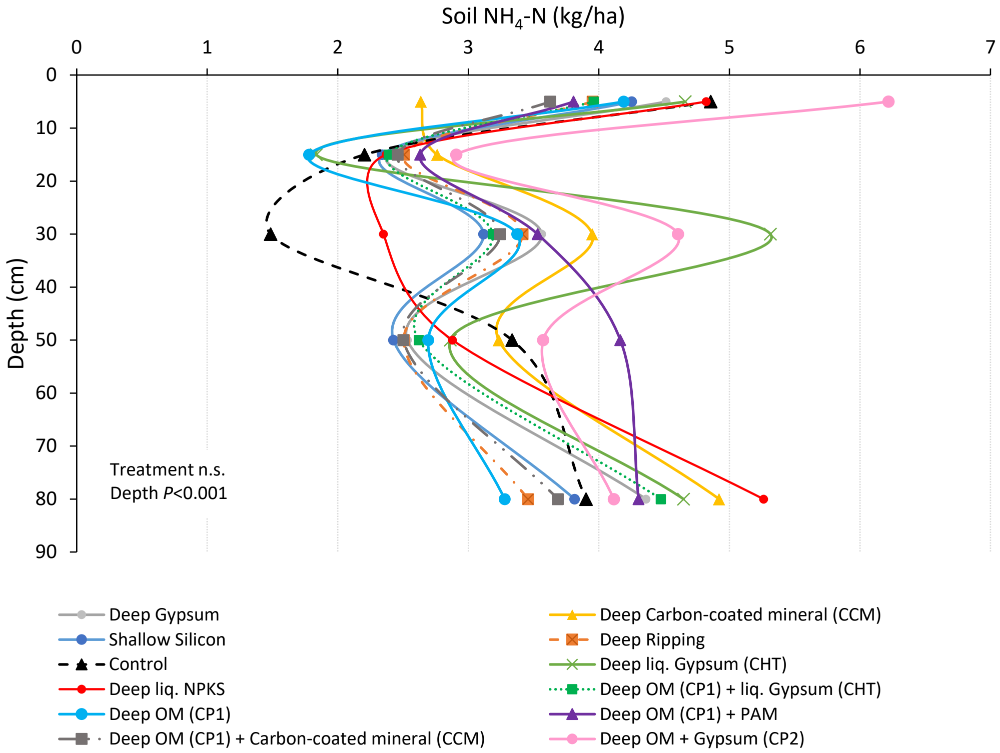


Figure 14. Mean soil ammonium nitrogen profile distribution (kg N/ha; back-transformed values).

Nitrate-N contents in the depth classes below 0–10 cm were generally more consistent between reps in those treatments based on mineral applications and the control and deep ripping treatment. At the 10–20 cm depth, the deep OM + gypsum (CP2), deep OM (CP1), deep OM (CP1) + liquid gypsum and deep OM (CP1) + CCM nitrate-N contents were significantly greater than the control (*P* = 0.015). At the 20–40, 40–60 and 60–100 cm depths the nitrate-N contents of all these treatments and additionally the deep OM (CP1) + PAM treatment were significantly greater than the control (*P* < 0.001) (Figure 15).

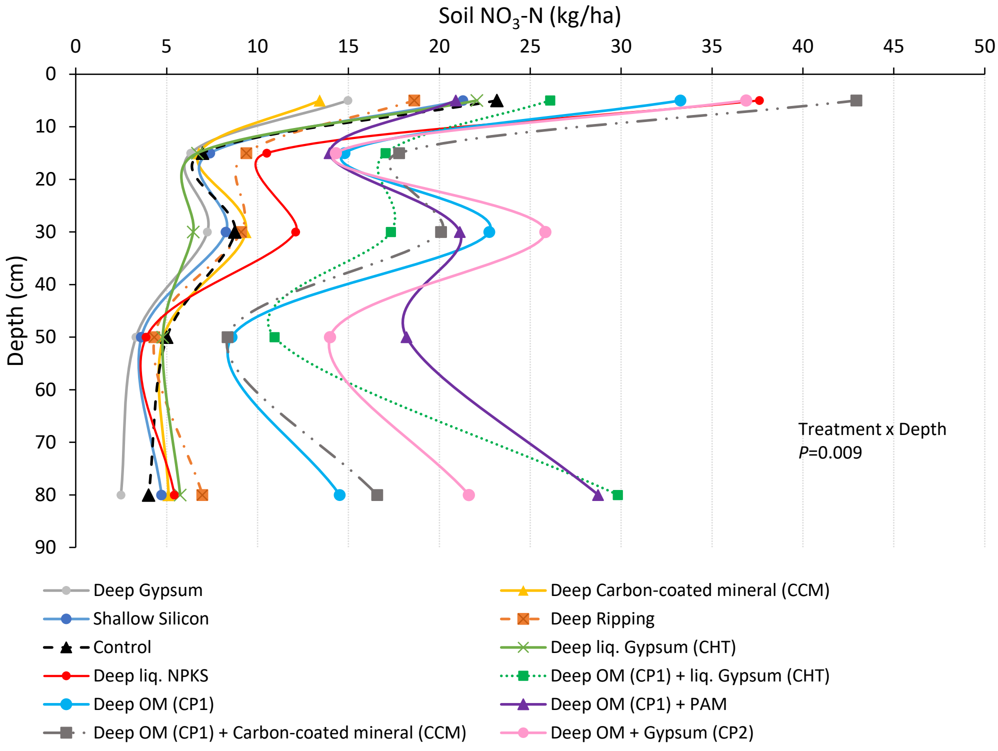


Figure 15. Mean soil nitrate nitrogen profile distribution (kg N/ha; back-transformed values). Differences between treatments at each individual depth were statistically significant ($P < 0.05$).

4.2.3 Crop responses

Crop establishment counts in 2022, 2023 and 2024 were not significantly different between treatments, indicating that the physical disturbance from the amelioration processes and subsequent tillage did not influence the ability of the seed to germinate and develop in the early growth stages with any treatment bias (Table 10).

Anthesis biomass cuts showed no significant treatment differences in 2022 or 2024 (Table 10). However, in the wheat crop in 2023 multiple treatment effects were observed. In terms of dry matter content, the control treatment had the highest amount of DM at 13.43 t/ha, but this was not statistically different from the deep gypsum, deep CCM, deep OM (CP1) + liquid gypsum, deep OM (CP1), deep OM (CP1) + PAM, or deep OM + gypsum (CP2) treatments. The DM content of the deep ripping, deep OM (CP1) + CCM, deep liquid NPKS, deep liquid gypsum and shallow silicon treatments were all significantly less than that of the control ($P = 0.006$) (Table 10). However, when looking at the fresh weight data, the treatment differences were largely reversed. The control treatment had the lowest percentage of moisture content of all treatments, at 66.11%, with the deep ripping, shallow silicon and deep liquid gypsum treatments being statistically grouped with the control ($P < 0.001$). The moisture content of the remaining treatments were all significantly greater than that of this group with the OM-containing treatments having the most moisture content (Table 10).

The differences in crop moisture content at anthesis were largely mirrored in the NDVI data collected at the same time as the biomass cuts. The deep liquid gypsum treatment had the lowest NDVI reading (0.6852) and was statistically grouped with the control, deep ripping and shallow silicon treatments. The deep gypsum, deep CCM, deep OM (CP1), deep liquid NPKS, deep OM (CP1) + liquid gypsum, and deep OM (CP1) + CCM treatments were statistically grouped, with NDVI readings ranging from 0.7587 to 0.8126, while the two highest treatment NDVI readings were found in the deep OM + gypsum (CP2) and deep OM (CP1) + PAM treatments (0.8202 and 0.8353 respectively) ($P < 0.001$) (Table 10).

Harvest data for the two complete growing seasons of the trial to date are shown in Tables 10 and 11. Differences in grain yield in the 2022 faba bean crop were statistically significant, with the deep OM (CP1) + PAM treatment yield (7.23 t/ha) being significantly greater than that of the control (6.19 t/ha), while the yield from the deep OM (CP1) treatment (5.32 t/ha) was actually significantly lower than that of the control treatment ($P = 0.006$) (Table 11). There was large variation between replicates for several treatments, including the control (4.99–7.37 t/ha), the deep liquid NPKS (4.88–7.34 t/ha) and the deep OM + gypsum (CP2) (5.3–7.6 t/ha) treatments.

Treatment differences in the 2022 faba bean crop harvest index values were statistically significantly ($P = 0.014$) (Table 11). However, no treatment was significantly different from the control. Again, there were some treatments with large variation between replicates, including the control (0.21–0.38).

Significant treatment differences were seen in seed weight in the faba beans at harvest ($P = 0.026$) (Table 11, noting that the data is based on three reps only). The seed weights in the deep OM (CP1) + liquid gypsum, deep OM (CP1), deep OM (CP1) + CCM, deep OM + gypsum (CP2), and deep ripping treatments were all significantly lower than that of the control treatment (Table 11). The difference in the protein contents of the faba beans were not statistically significant between treatments.

Differences in grain yields in the 2023 wheat crop were statistically significantly between multiple treatments ($P < 0.001$) (Table 11, Figure 16). The highest yielding treatment was deep OM (CP1) + CCM at 9.5 t grain/ha (10.4% moisture content). This treatment also had the highest grain moisture content, although treatment differences in moisture content were not statistically significant (data not shown). Four other treatments had yields that were statistically grouped with this treatment, namely deep OM (CP1), deep OM (CP1) + PAM, deep OM (CP1) + liquid gypsum, and deep OM + gypsum (CP2) (Figure 16). Yields from the deep liquid NPKS and deep CCM treatments were also statistically greater than that of the control, but less than that of the other aforementioned treatments. These results largely mirror the NDVI data from reflectance measurements at anthesis.

The differences in wheat crop harvest index values were not statistically significant between treatments (Kruskal-Wallis H (11) = 10.58, $P = 0.48$), nor were the thousand seed weights ($P = 0.52$). Differences in grain screenings (< 2 mm) were statistically significant between treatments, with the deep OM (CP1), deep OM (CP1) + liquid gypsum, deep OM (CP1) + PAM and deep OM + gypsum (CP2) treatments all having a greater proportion of screenings (1.05–1.24%) compared to the Control (0.69%) ($P = 0.007$) (Table 11).

Wheat protein contents were also significantly different between treatments (Kruskal-Wallis H (11) = 37.19, $P < 0.001$). The deep liquid gypsum, deep ripping, shallow silicon, deep gypsum, deep CCM and deep liquid NPKS treatment proteins were not statistically different from the control (8.45%). However, the protein content in the deep OM (CP1), deep OM (CP1) + CCM, deep OM (CP1) + liquid gypsum, deep OM + gypsum (CP2) and deep OM (CP1) + PAM treatments were statistically greater than the other treatments (Table 11).

Table 10. Crop establishment and peak biomass (anthesis) quadrat cut data and crop reflectance data (NDVI) for faba bean (2022), wheat (2023) and canola crops (2024), and harvest biomass dry matter (quadrat cuts) for 2022 and 2023. n.s. = not significant ($P > 0.05$), * indicates statistical significance in differences from the nil control.

Treatment	**Crop establishment (plants/m^2)**			**Anthesis biomass (FW) (t/ha)**			**Anthesis biomass (DW) (t/ha)**		
	2022	2023	2024	2022	2023	2024	2022	2023	2024
Control	25.5	121.0	23.5	84.19	39.92	51.1	13.30	13.43	5.91
Deep CCM	23.25	117.5	24.7	83.53	37.87	53.58	12.35	12.04	6.23
Deep gypsum	21.75	112.0	19.5	81.22	38.10	54.05	12.40	11.92	6.23
Deep liq. gypsum (CHT)	25.75	117.0	21.5	95.33	35.29	54.33	15.17	11.42 *	6.44
Deep liq. NPKS	25.0	117.0	20.8	85.74	35.68	55.22	12.82	11.27 *	6.76
Deep OM (CP1)	25.5	111.5	23.5	88.39	40.98	58.03	13.58	12.80	6.78
Deep OM (CP1) + CCM	25.75	115.5	21.7	97.98	38.30	59.95	14.66	11.09 *	6.90
Deep OM (CP1) + liq. gypsum (CHT)	26.25	121.5	22.3	83.29	42.13	60.34	12.55	12.42	6.94
Deep OM (CP1) + PAM	23.75	131.5	22.0	99.70	49.34 *	60.35	15.27	13.24	7.12
Deep OM + gypsum (CP2)	27.75	121.0	22.8	92.18	45.24	65.73	14.09	13.40	7.42
Deep ripping	26.0	133.5	24.0	95.95	32.27 *	66.33	15.05	10.63 *	8.23
Shallow silicon	23.75	118.0	23.7	81.59	35.07	75.18	12.14	11.48 *	8.59
LSD (P = 0.05)	n.s.	n.s.	n.s.	n.s.	5.65	n.s.	n.s.	1.56	n.s.
P-value	> 0.05	> 0.05	> 0.05	> 0.05	< 0.001	> 0.05	> 0.05	0.006	> 0.05

Table 10. *contd*.

Treatment	Anthesis crop moisture content (%)			Anthesis NDVI			Harvest biomass (t/ha)	
	2022	2023	2024	2022	2023	2024	2022	2023
Control	84.21	66.11	89.03	0.881	0.691	0.904	12.41	16.58
Deep CCM	85.18	68.03 *	87.46	0.886	0.771 *	0.899	13.74	17.14
Deep gypsum	84.76	68.55 *	88.74	0.875	0.759 *	0.877	13.60	16.53
Deep liq. gypsum (CHT)	84.22	67.55	87.74	0.878	0.685	0.906	12.53	15.92
Deep liq. NPKS	85.03	68.41 *	88.60	0.887	0.782 *	0.911	12.85	16.88
Deep OM (CP1)	84.61	68.71 *	88.46	0.877	0.775 *	0.884	13.97	17.21
Deep OM (CP1) + CCM	85.02	69.93 *	87.67	0.878	0.813 *	0.908	13.92	16.82
Deep OM (CP1) + liq. gypsum (CHT)	84.99	70.52 *	88.44	0.879	0.791 *	0.898	13.19	18.10
Deep OM (CP1) + PAM	84.71	73.19 *	88.59	0.879	0.835 *	0.915	14.47	17.62
Deep OM + gypsum (CP2)	84.68	70.34 *	88.07	0.878	0.820 *	0.918	14.26	19.44 *
Deep ripping	84.39	66.97	87.89	0.889	0.741	0.896	16.76	16.28
Shallow silicon	85.14	67.16	88.55	0.888	0.716	0.905	14.65	15.43
LSD (*P* = 0.05)	n.s.	1.77	n.s.	n.s.	0.056	n.s.	n.s.	1.92
P-value	> 0.05	< 0.001	> 0.05	> 0.05	< 0.001	> 0.05	> 0.05	0.02

Table 11. Crop grain header yield, harvest index (HI) (quadrat cuts), thousand seed weight (TSW), screenings (%) and protein (%) for faba bean (2022) and wheat (2023) crops. n.a. = not applicable, n.s. = not significant (*P* > 0.05).

Treatment	Grain yield (t/ha)		HI		TSW		Screenings (%)		Protein (%)	
	2022	2023	2022	2023	2022‡	2023	2022	2023	2022	2023#
Control	6.19	8.02	0.28	0.45	295.2	57.00	n.a.	0.69	22.85	8.45
Deep CCM	6.06	8.66 *	0.25	0.46	284.9	56.43	n.a.	0.65	23.23	8.90
Deep gypsum	6.13	8.53	0.29	0.46	285.2	56.04	n.a.	0.81	23.40	8.85
Deep liq. gypsum (CHT)	6.24	8.01	0.33	0.46	289.7	56.55	n.a.	0.87	23.60	8.40
Deep liq. NPKS	6.46	8.75 *	0.24	0.47	286.1	56.93	n.a.	0.83	23.45	9.80
Deep OM (CP1)	5.32 *	8.96 *	0.26	0.46	274.9 *	56.16	n.a.	1.05 *	23.60	10.43 *
Deep OM (CP1) + CCM	5.47	9.49 *	0.23	0.46	275.6 *	55.70	n.a.	0.82	24.55	10.73 *
Deep OM (CP1) + liq. gypsum (CHT)	6.29	9.19 *	0.31	0.44	267.4 *	55.48	n.a.	1.14 *	23.93	10.78 *
Deep OM (CP1) + PAM	7.23 *	9.16 *	0.32	0.46	287.3	55.90	n.a.	1.21 *	23.43	11.08 *
Deep OM + gypsum (CP2)	6.26	9.27 *	0.29	0.45	281.9 *	54.52	n.a.	1.24 *	24.58	10.83 *
Deep ripping	6.56	8.19	0.33	0.46	281.6 *	56.31	n.a.	0.75	24.25	8.70
Shallow silicon	6.52	8.36	0.34	0.46	283.9	56.19	n.a.	0.73	23.23	8.70
LSD (*P* = 0.05)	0.81	0.64	0.065	n.s.	12.5	n.s.		0.37	n.s.	n.a.
P-value	0.006	< 0.001	0.014	> 0.05	0.026	> 0.05		0.007	> 0.05	< 0.001

‡ Faba beans weights shown are for counts of 450 seeds, three reps only.

Kruskal-Wallis (H = 37.19 (11), *P* < 0.001).

* indicates statistical significance in differences from the nil Control.

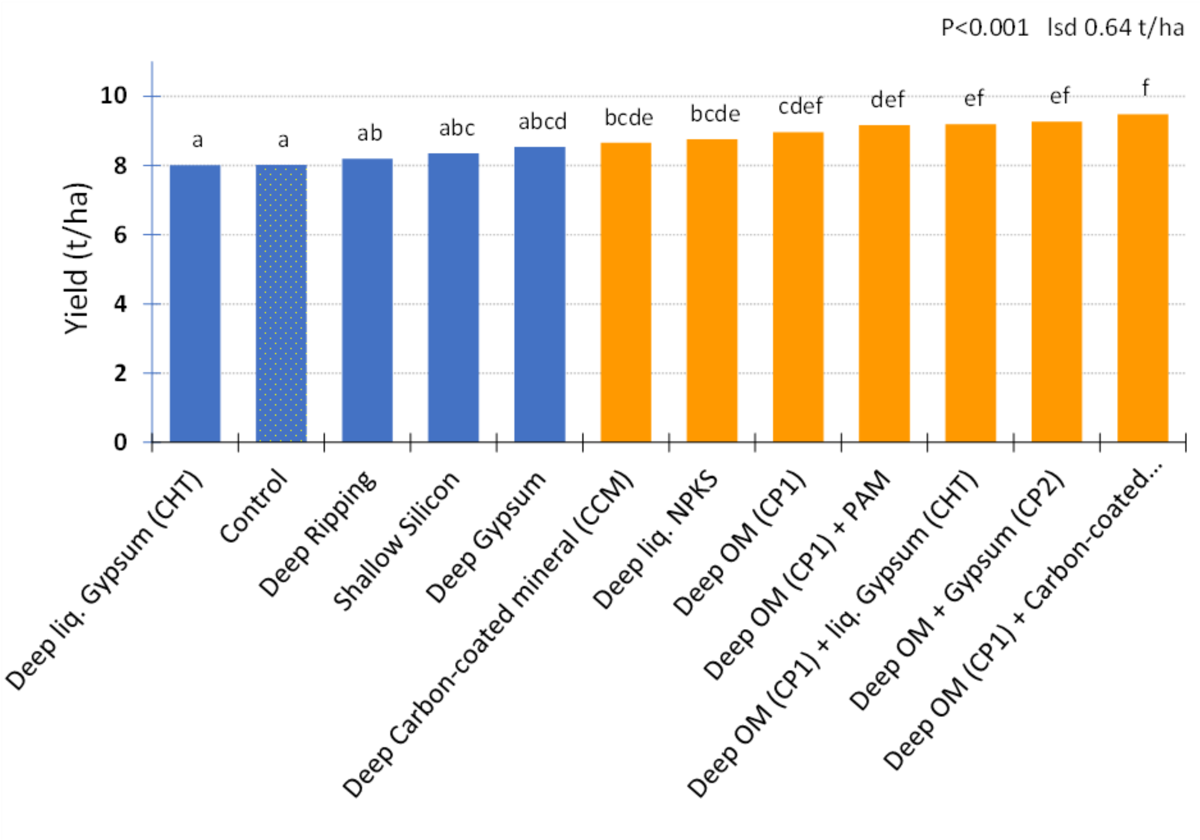


Figure 16. Mean grain yield for the 2023 wheat crop. Different letters indicate significant differences between treatments (LSD $P < 0.05$).

4.2.4 **Water Use efficiency**

Total water use (TWU; mm) and water use efficiencies (WUE; kg/ha/mm) for biomass production (WUE_{bm}) and grain yield (WUE_{grain}) for 2022 and 2023 are shown in Table 12. Seasonal TWU was not significantly different between treatments in either year. Biomass WUE in the 2022 faba beans was also not significantly different, although grain yield WUE was (*P* = 0.007) (Table 12). Only the deep OM (CP1) + PAM treatment was significantly different from the control (15.7 compared to 13.1 kg/ha/mm).

In contrast to the previous year, both WUE_{bm} and WUE_{grain} were significantly different between treatments in the 2023 wheat crop (*P* = 0.024 and 0.002, respectively) (Table 12). For WUE_{bm} only the deep OM (CP1) + liquid gypsum and deep OM + dypsum (CP2) treatments were statistically significantly greater than the control (41.3 and 43.3 compared to 36.5 kg/ha/mm respectively). However, for WUE_{grain}, the deep gypsum, deep CCM, deep OM (CP1), deep OM (CP1) + PAM, deep OM (CP1) + CCM, deep OM + gypsum (CP2), and deep OM (CP1) + liquid gypsum treatments were all statistically significantly greater than the control (19.2–20.9 compared to 17.6 kg/ha/mm) (Table 12).

Table 12. Seasonal total water use (TWU, mm), biomass water use efficiency (WUE_{bm}, kg/ha/mm) and grain yield water use efficiency (WUE_{grain}, kg/ha/mm) for the two full years of the Lockhart trial (2022–23).

Treatment	TWU	WUE_{bm}	WUE_{grain}	TWU	WUE_{bm}	WUE_{grain}
	Faba beans (2022)			Wheat (2023)		
Control	474.4	26.2	13.1	456.4	36.5	17.6
Deep CCM	471.6	29.3	12.9	449.6	38.0	19.3 *
Deep gypsum	448.6	30.2	13.7	445.2	37.3	19.2 *
Deep liq. gypsum (CHT)	459.4	27.3	13.6	421.6	37.9	19.0
Deep liq. NPKS	461.7	27.8	14.0	478.5	35.5	18.4
Deep OM (CP1)	456.4	30.6	11.7	458.5	37.5	19.5 *
Deep OM (CP1) + CCM	450.9	31.0	12.2	464.7	36.2	20.4 *
Deep OM (CP1) + liq. gypsum (CHT)	448.7	29.3	14.0	439.8	41.3 *	20.9 *
Deep OM (CP1) + PAM	461.7	31.2	15.7 *	456.8	38.6	20.1 *
Deep OM + gypsum (CP2)	455.3	31.4	13.7	449.9	43.3 *	20.6 *
Deep ripping	451.0	37.3	14.5	451.8	36.1	18.2
Shallow silicon	476.8	30.7	13.7	447.4	34.6	18.7
LSD (*P* = 0.05)	n.s.	n.s.	1.7	n.s.	4.45	1.5
P-value	> 0.05	> 0.05	0.007	> 0.05	0.024	0.002

* indicates statistical significance in differences from the nil control.

4.3 WONWONDAH, VICTORIA TRIAL SITE

4.3.1 Site weather

An electronic rain gauge and a temperature logger were installed at the site when the treatments were applied in April 2022.

In 2022, after a relatively dry start to the year, much greater than average (decile 10) rainfall fell in the August to November period (Figure 17), resulting in severe waterlogging at the site which hampered crop growth in the first year of the trial. Total rainfall at the site for 2022 was 670 mm, and from April to October GSR was 488 mm. This was much greater than the SILO (1970–2020) long-term average annual rainfall of 493 mm and GSR of 358 mm for the area.

The 2023 season was characterised by average rainfall during the summer fallow, with April and June rainfall well above average prior to a very dry finish, with only 112 mm of rain falling in the four months prior to harvest (July–October, Figure 17). Summer storms after the site was harvested resulted in above average rainfall in November and December. Total rainfall for 2023 was 506 mm, on par with the 1970–2020 long-term average of 493 mm. April to October GSR was 312 mm, slightly lower than the long-term average of 358 mm. However, most of this GSR was concentrated in the April–June period. Compared to the first year of the trial in 2022, rainfall in 2023 was much lower with more favourable conditions for crop production.

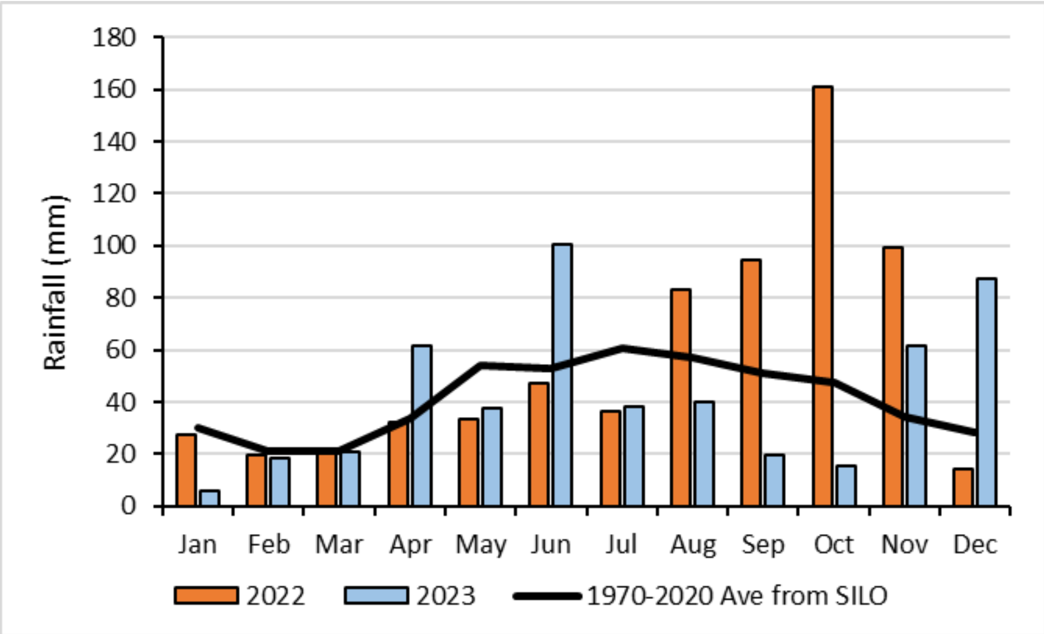


Figure 17. Monthly rainfall at the Wonwondah site in 2022 and 2023, compared to the 1970–2020 long-term average extracted from SILO (https://www.longpaddock.qld.gov.au/silo). January to March rainfall data for 2022 was also extracted from SILO prior to the installation of an electronic rain gauge on site.

4.3.2 **Crop results**

4.3.2.1 Amelioration treatment effects on faba bean crop production in 2022

The trial site was sown to faba beans, cv. 'Samira', on the 18 May 2022 at 128 kg seed/ha with 45 kg/ha of DAP fertiliser and 3.5 kg/ha 'TagTeam' inoculant. During the growing season, treatment effects on crop development and production were measured by assessing crop establishment; the production of shoot biomass at early flowering (GS201), the beginning of podding (GS204) and at maturity/harvest (GS410); and on grain yield and quality and yield components. After harvest, measurements of crop maximum rooting depth and root density immediately below the depth of amelioration were performed. All statistical analysis of amelioration treatment effects on crop development and production were performed by one-way ANOVA in Genstat 22.

The assessment of crop establishment was conducted five weeks after sowing on the 24 June 2022 and showed no differences (P = 0.383) in crop establishment between the control treatment and any of the subsoil amelioration treatments (Figure 18). Despite a relatively low plant density (20.7 ± 0.6 plants/m^2), the consistent establishment across the untreated control and deep ripped amelioration treatments was a positive result. In previous studies, reduced seed germination has often occurred after deep ripping due to reduced soil-seed contact, especially in seasons with dry sowing conditions and deeper than intended sowing depths on cultivated plots.

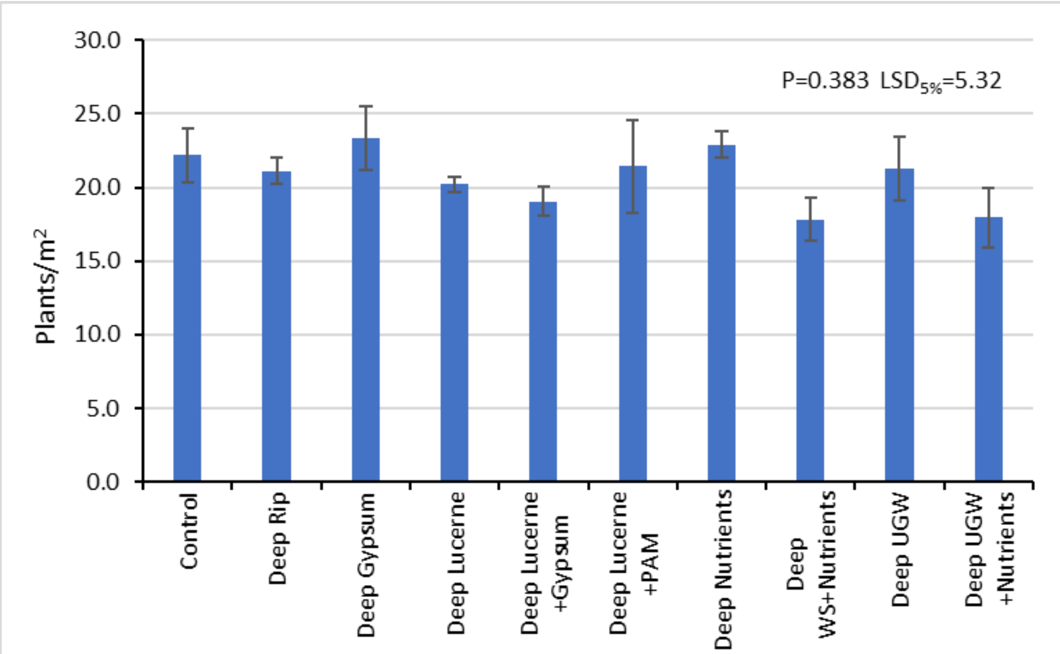


Figure 18. Faba bean crop establishment at the Wonwondah trial site, 24 June 2022.

The first measurements of treatment effects on crop growth occurred at the beginning of flowering (GS201) on the 25 August 2022. While deep ripping alone and the application of the deep UGW mulch treatment did not increase faba bean biomass at this early stage of crop development, deep ripping with the application of the seven other different amendments significantly (P = 0.06) increased faba bean biomass by up to 66% over that of the control treatment (Figure 19).

The development of very wet spring conditions resulted in extensive waterlogging, and the inability of spray equipment to traffic the paddock resulted in ryegrass infestation. By the time shoot biomass measurements were performed at podding on the 20 October there was visual evidence that the crop was beginning to suffer. Despite shoot biomass still being greater than the control treatment across most amelioration treatments (Figure 19), with the exception of the two UGW mulch treatments, waterlogging damage and large variability across the site resulted in these effects not being statistically significant (P = 0.135). Measurements of NDVI performed by handheld Crop Circle and unmanned aerial vehicle (UAV) were also unable to show any consistent amelioration treatment responses on crop growth (data not shown), reflecting the impact of water logging at this time.

Treatment effects on shoot biomass were statistically significantly (P = 0.056) at harvest on the 20 December, with biomass across all amelioration treatments, except for the deep lucerne with PAM treatment, being greater than that of the control (Figure 19). However, due to the extent of the waterlogging at the site, there was large variability within treatments.

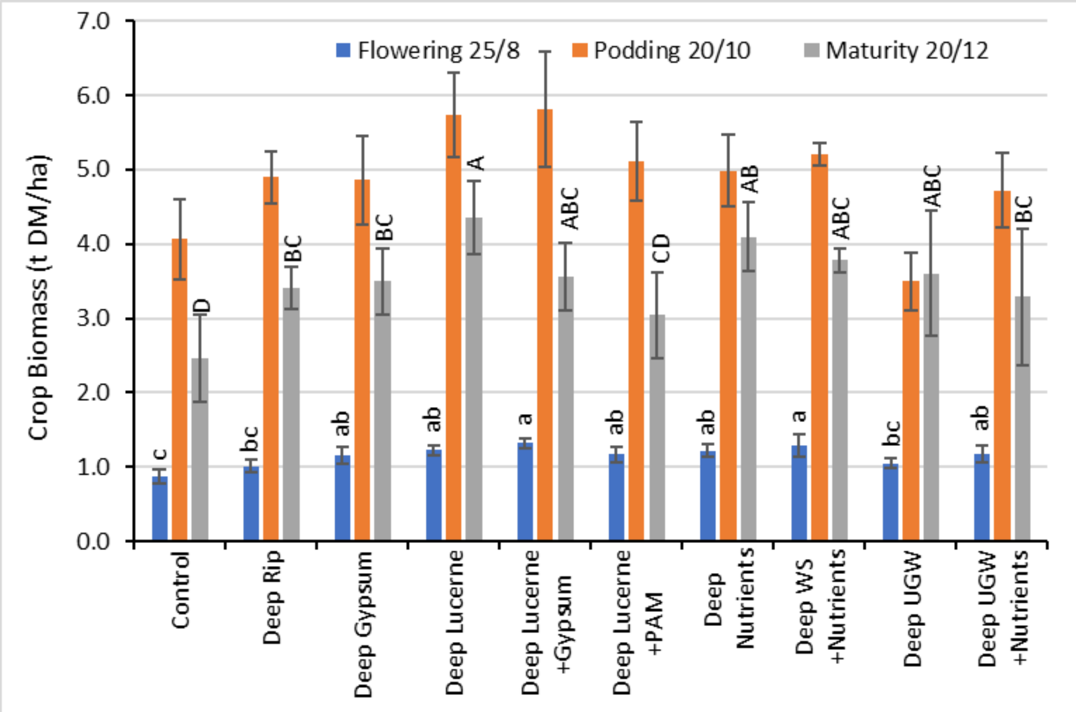


Figure 19. Amelioration treatment effects on faba bean biomass production during the 2022 growing season at Wonwondah.

This variability affected grain yield, which was assessed from both the hand cuts and a full plot length harvest strip cut with a Haldrup plot harvester. Overall, grain yield was very low across all treatments at the site (Figure 20), which was attributed to the effects of waterlogging and crop disease pressures. While grain yield in some of the amelioration treatments stood out above the others (e.g. deep lucerne, deep lucerne + gypsum, deep nutrients and deep UGW + nutrients), the high degree of variability across the site meant these effects were not significant ($P = 0.208$).

The HI was low across all treatments ($P = 0.158$), averaging 9.1 ± 2.5%. The amelioration treatments had no effect on faba bean grain weight (218.3 ± 18.2 g/500 beans, $P = 0.464$), the number of grains produced per pod (3.1 ± 0.4 grains/pod, $P = 0.188$), nor grain protein (15.1 ± 0.7%, $P = 0.507$). Overall, the impact of seasonal conditions and waterlogging (in both our experimental plots and the surrounding farmers paddock) impeded any potential soil amelioration treatment effects on grain production.

After harvest, measurements of maximum rooting depth and root density in the zone of amendment application (30 cm deep) were conducted in selected treatments on the 23 January 2023 (Figure 21). Maximum rooting depth was measured by incrementally breaking and visually assessing three soil cores in each plot to determine the maximum depth crop roots grew down to. Measurements of root density were performed by breaking each core at a depth of 35 cm and counting the number of visible roots on both faces of the broken core (data not shown).

Faba bean roots were relatively shallow (< 60 cm) at the site, which was again attributed to the waterlogging during the season, and maximum root depth was not affected by amelioration treatment (*P* = 0.614). Root densities at 35 cm depth in the zone of amendment application were not affected by any of the amelioration treatments (*P* = 0.695), averaging 4.76 ± 1.67 roots/cm^2.

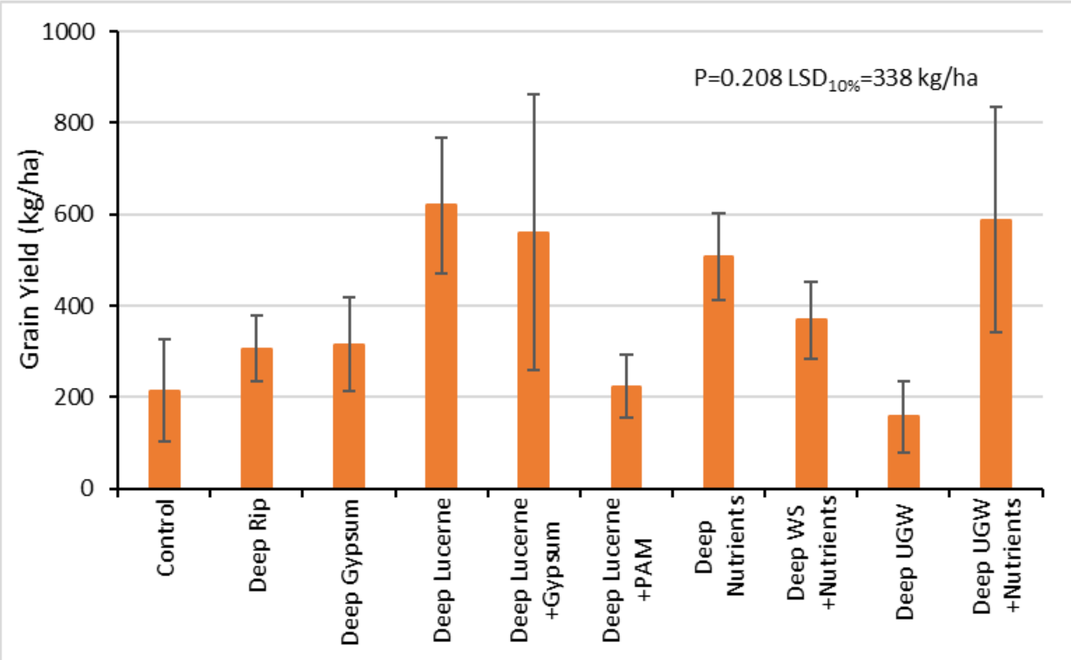


Figure 20. Amelioration treatment effects on faba bean yield at Wonwondah, 20 December 2022.

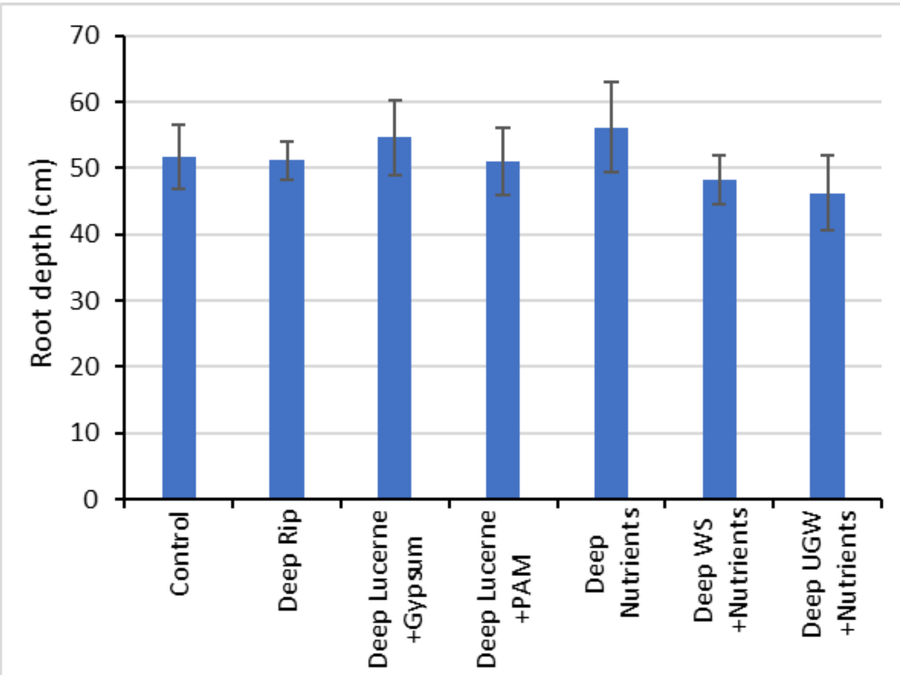


Figure 21. Amelioration treatment effects on faba bean rooting depth at Wonwondah, 23 January 2023.

4.3.2.2 Amelioration treatment effects on canola crop growth in 2023

After some delays due to wet weather, the trial site along with the rest of the paddock was sown with Pioneer 44Y94CL canola at 2.5 kg/ha with 75 kg/ha DAP fertiliser on the 25 April 2023. Urea was spread on the crop in applications of 75 kg/ha and 100 kg/ha during the growing season. Crop emergence was measured on the 18 May 2023 and showed consistent crop emergence across the site with no differences in establishment between any of the amelioration treatments and the control treatment (P = 0.526, Figure 22). Overall, average plant density across the ten treatments at the time of counting was 30.6 plants/m^2.

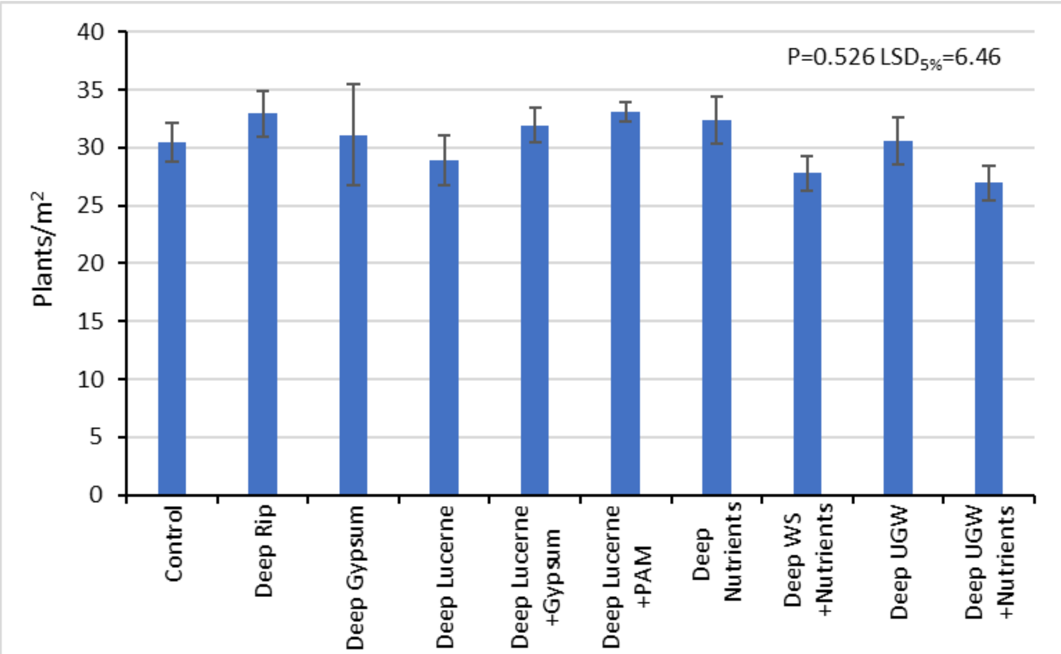


Figure 22. Canola crop establishment and plant density at Wonwondah, 18 May 2023.

The first measurements of amelioration treatment effects on canola crop production were undertaken at the beginning of stem elongation on the 27 July 2023 (Figure 23). One-way ANOVA showed highly significant (P < 0.001) treatment effects on canola biomass, with all amelioration treatments, including the UGW mulch and UGW mulch + nutrients treatments, increasing canola biomass over that of the control (1.8 t DM/ha) and deep ripping-only treatment. Overall, the deep nutrient treatment produced the largest shoot biomass (3.0 t DM/ha), while all other amelioration treatments were all similar and non-significantly different from each other (2.3–2.6 t DM/ha).

Peak canola shoot biomass at peak flowering was measured on 5 September 2023 (Figure 23). Again, there were highly significant amelioration treatment effects (P = 0.002) on canola biomass compared to the control treatment.

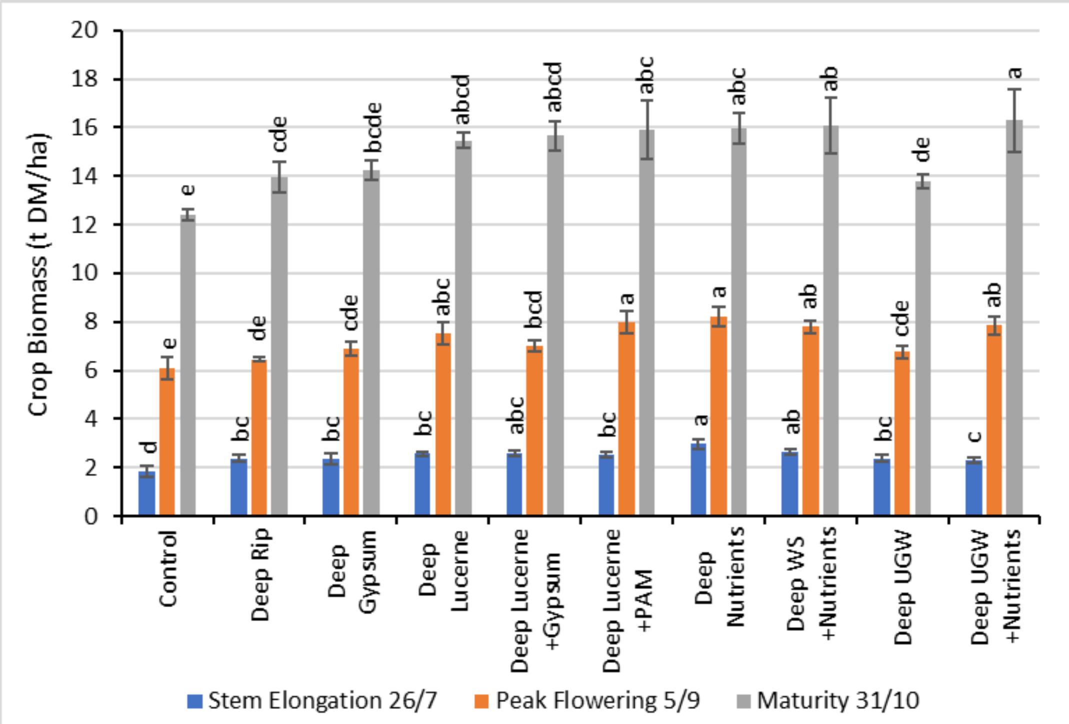


Figure 23. Amelioration treatment effects on canola biomass production during the 2023 growing season at Wonwondah.

At this time the deep ripping only, deep gypsum and deep UGW mulch treatments were no longer producing a significant biomass advantage over the control treatment (6.1 t DM/ha). Meanwhile, all of the 'nutrient-rich' amelioration treatments (deep lucerne, deep lucerne + gypsum, deep lucerne + PAM, deep nutrients, deep wheat straw (WS) + nutrients, and deep UGW mulch + nutrients), which were all nutrient stoichiometrically balanced, produced significantly greater biomass than the control treatment and produced mostly consistently even biomass (7.0–8.2 t DM/ha).

Assessments of canola maturity biomass, grain yield and yield components were conducted at the time the farmer windrowed the remainder of the paddock on the 31 October 2023. At this time, the deep ripping alone, deep gypsum and deep UGW mulch amelioration treatments produced small, but non-significant, increases in canola biomass (13.8–14.2 t DM/ha) over that of the control treatment (12.4 t DM/ha). As with at peak flowering, it was only the 'nutrient-rich' amelioration treatments, including the UGW mulch + nutrients treatment, that produced significantly greater canola biomass at maturity (P = 0.006, average 15.9 t DM/ha) over the control treatment, an average increase of 28%.

Canola yield (Figure 24) was also consistent in these stoichiometrically balanced 'nutrient-rich' treatments (average 4.54 t/ha), with a 42% mean increase in seed yield (P = 0.009) over the control treatment (3.20 t/ha). The deep ripping alone treatment had a slight but non-significant effect on canola yield (3.7 t/ha), while yield in the deep gypsum and deep UGW mulch treatments (both 4.0 t/ha) was significantly greater than the control but not as great as the various 'nutrient-rich' amelioration treatments. In addition to quadrat cuts, a 1.7 m wide strip was direct headed from the plots on the 21 November and showed the same trend.

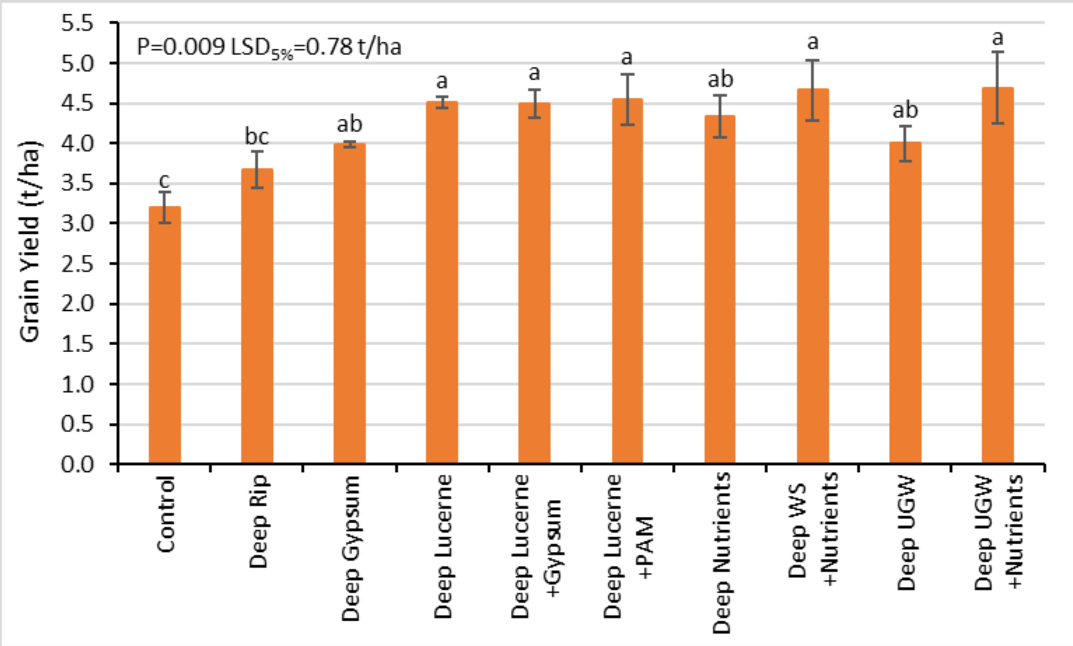


Figure 24. Amelioration treatment effects on canola yield at Wonwondah, 31 October 2023.

Along with the effects on canola yield, there was also a significant amelioration treatment effect on HI, with all of the subsoil amelioration treatments, aside from the deep ripping only and the deep nutrients treatments, increasing canola HI over the control treatment (*P* = 0.090). Collectively, these treatments increased HI to 28.8%, compared to 25.7% in the control. There were no treatment effects (*P* = 0.110) on the thousand seed weight (3.63 g). Oil and protein content analysis was performed on machine-harvested seed. While the 'nutrient-rich' amelioration treatments reduced canola oil content (*P* < 0.001, Figure 25), the higher seed yield in these treatments still resulted in increased oil content on a per-hectare basis (2.07 t/ha compared to 1.60 t/ha in the control treatment, data not shown). Canola protein content was increased (*P* = 0.002, Figure 26) by the 'nutrient-rich' amelioration treatments (excluding the deep UGW mulch + nutrients treatment) to a mean of 29.7% protein, compared to 21.7% in the control treatment.

Assessment of canola crop N uptake and use was made by converting grain protein to N using a conversion factor of 6.25 and by measuring N in ground straw material by ICP-OES analysis. Unlike grain yield and protein content, which was mostly equal across the 'nutrient-rich' amelioration treatments, total N uptake (grain + straw) differed between these treatments (*P* < 0.001, Figure 27). Total N uptake was greatest in the deep wheat straw + nutrients treatment, which was greater than the deep lucerne and deep UGW + nutrients treatments, despite yielding equally. This result was mostly driven by changes in canola straw N uptake (*P* < 0.001).

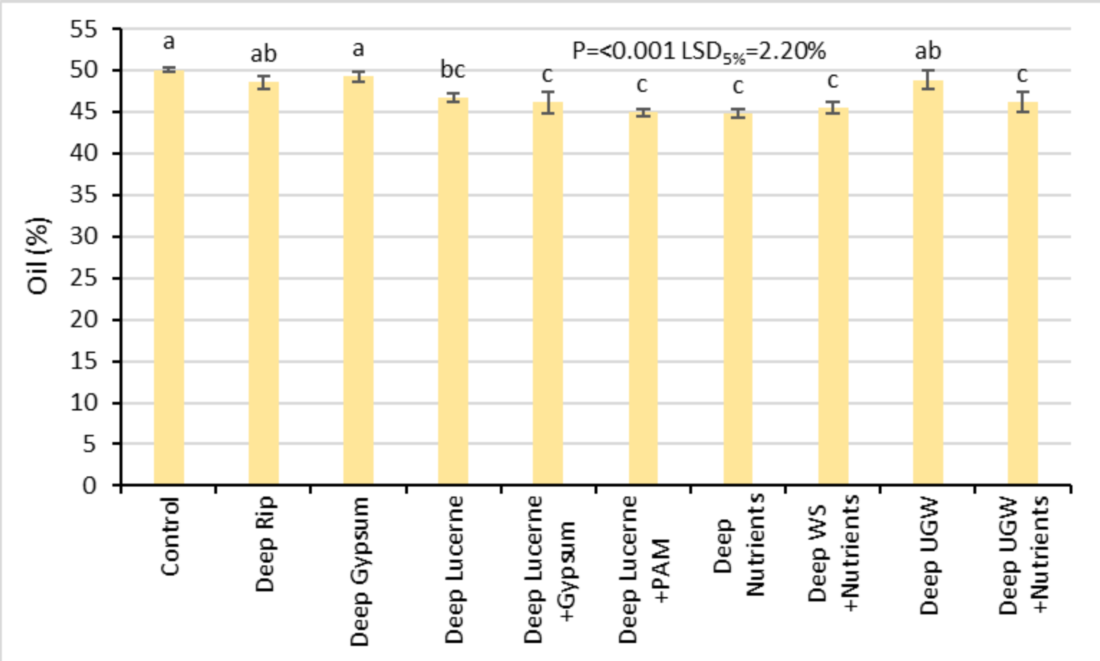


Figure 25. Amelioration treatment effects on canola oil content at Wonwondah in 2023.

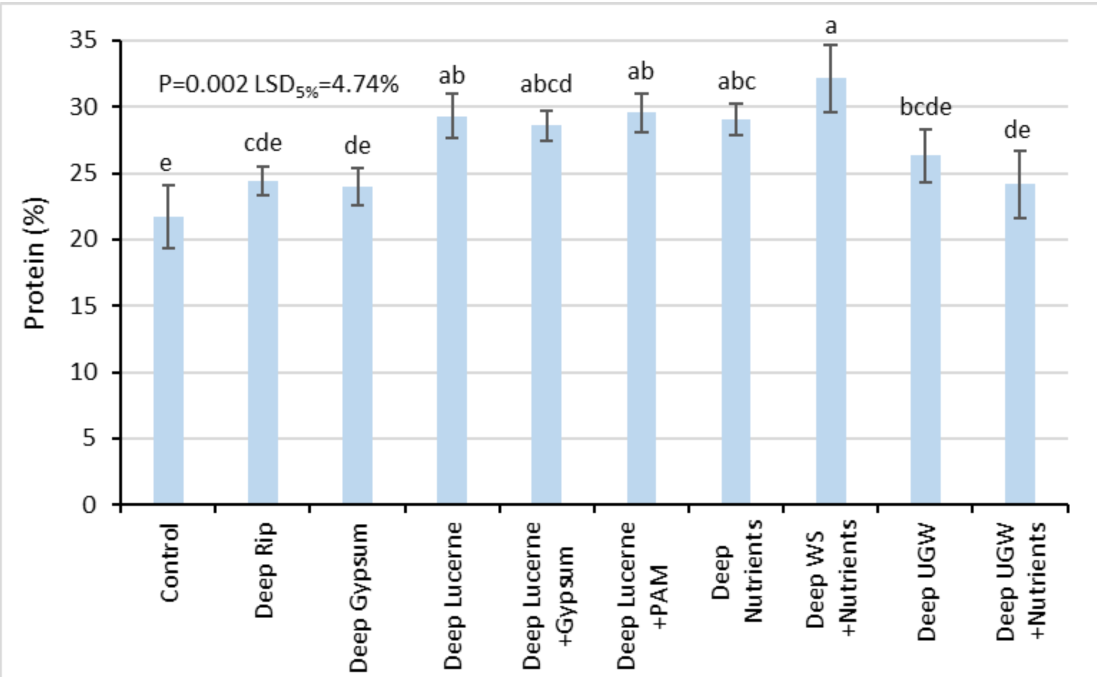


Figure 26. Amelioration treatment effects on canola protein content at Wonwondah in 2023.

Canola grain N use efficiency (NUE), as a function of total grain produced per unit of total N taken up (grain + straw), was lower in the ‘nutrient-rich’ amelioration treatments compared to the other treatments (P < 0.001, Figure 28) despite the increase in yield. This was again attributed to the increase in straw N uptake in these treatments, as well as increases in the grain protein (Figure 27).

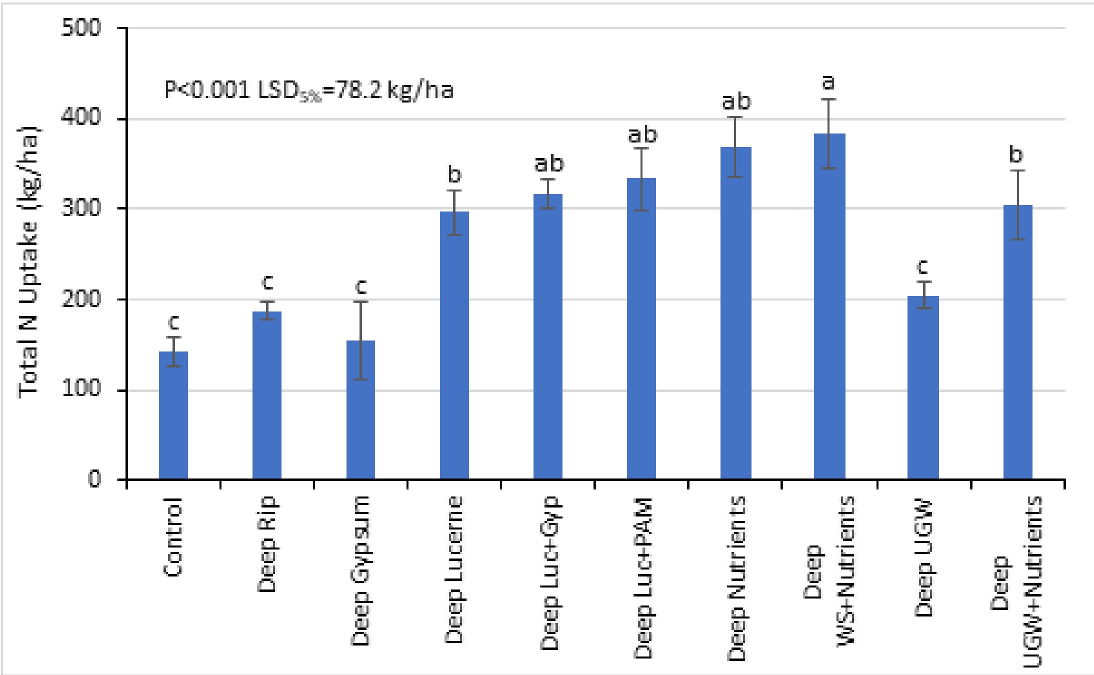


Figure 27. Amelioration treatment effects on canola crop total nitrogen uptake (grain + straw) at harvest, 31 October 2023.

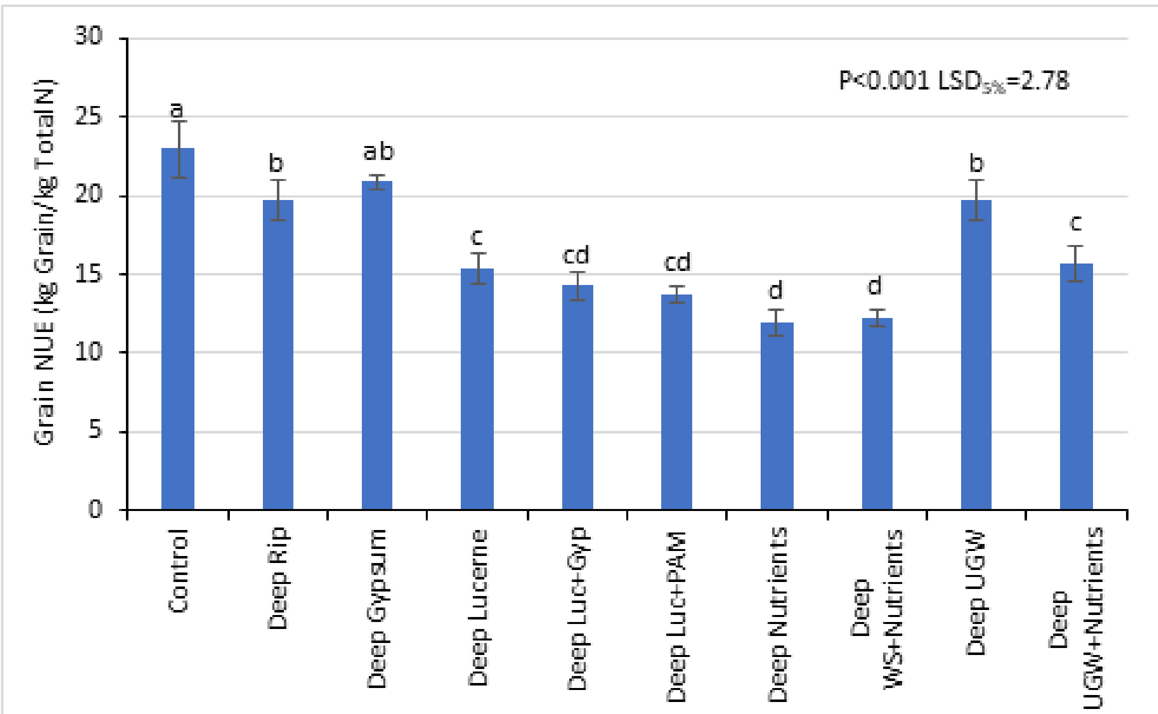


Figure 28. Amelioration treatment effects on canola crop grain nitrogen use efficiency (NUE) as a function of total N uptake at harvest, 31 October 2023.

After the canola harvest was completed, maximum rooting depth and root count at 30 cm depth (just below the depth of ameliorant application) was measured on the 21 December 2023. Remaining non-decomposed organic amendments were still visible in the soil cores. One-way ANOVA of amelioration treatment effects on maximum rooting depth and root counts, averaged from the three cores taken in each plot, showed no differences on maximum root depth ($P = 0.599$, Figure 29) or root count at 30 cm depth ($P = 0.306$, Figure 30), with overall rooting depths of the canola much greater than those recorded for the faba bean crop in the previous year.

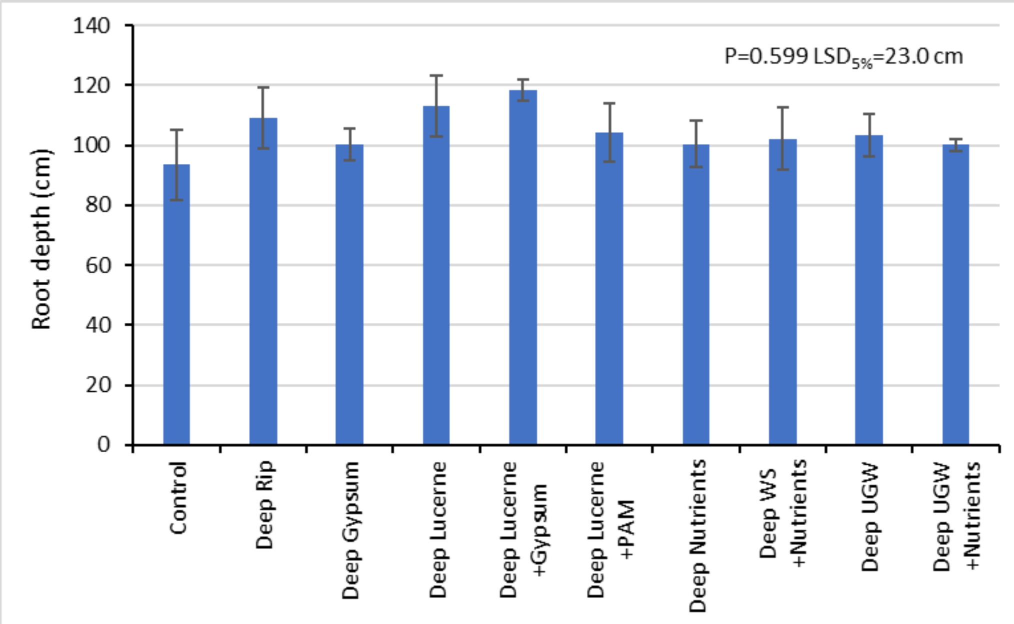


Figure 29. Amelioration treatment effects on maximum canola rooting depth at maturity at Wonwondah in 2023.

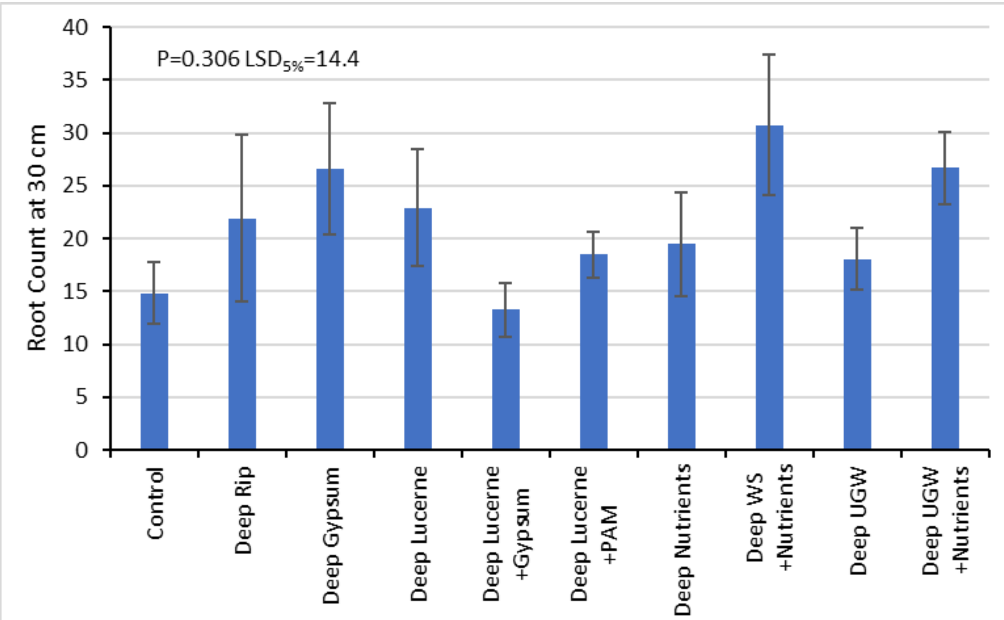


Figure 30. Amelioration treatment effect on canola root density at 30 cm depth at maturity at Wonwondah in 2023.

4.3.3 **Soil water results**

4.3.3.1 Amelioration treatment effects on soil water storage capacity

Soil water storage capacity, and soil amelioration treatment effects on this, was assessed using soil collected from the control, deep rip and deep lucerne + gypsum treatments at the beginning of 2024, two years post amelioration. Pressure plates were used to determine crop lower storage limit (LSL, permanent wilting point) at −1500 kPa and upper storage limit (USL, field capacity) at −33 kPa (Figure 31).

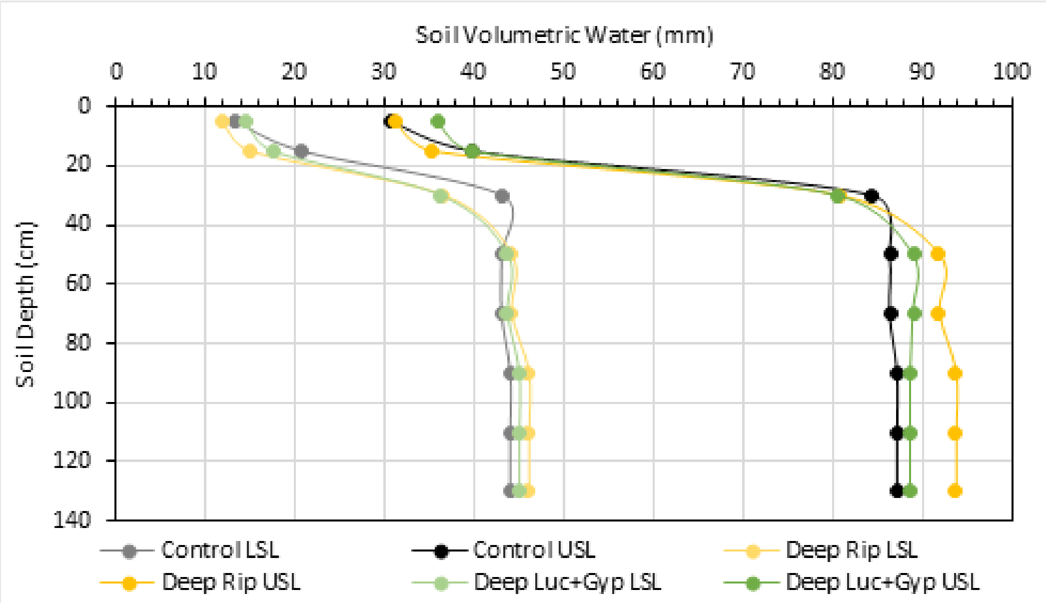


Figure 31. Selected amelioration treatment effects on crop upper and lower storage limits two years after amelioration at Wonwondah, 10 April 2024.

Despite some small reductions in crop LSL in the top 40 cm of the soil profile, deep ripping and the application of the deep lucerne + gypsum amelioration treatment had no effect of crop LSL when assessed across the whole soil profile (0–140 cm) compared to the untreated control (P = 0.105). Crop USL was also not affected by the amelioration treatments at any depth (P = 0.454). Therefore, plant available water (PAW) content, as the volume of water between crop LSL and USL, was unaffected by amelioration treatments (P = 0.385), totalling 309 mm for the whole soil profile (0–140cm).

4.3.3.2 Soil amelioration treatment effects on soil moisture use in 2022

Immediately after sowing, two neutron probe access tubes were installed in each plot and neutron probe readings were immediately undertaken. Repeated readings were taken to coincide with in-season measurements of crop biomass and flowering and podding, and at harvest. Calibration functions to convert neutron probe count data into volumetric soil moisture content were developed from wet sumps using standard procedures on both undisturbed (one) and ripped soil (two) in the central area of the trial.

Measurements of soil gravimetric water content at the time of neutron probe access tube installation showed that in the process of deep ripping and application of amendments, drying of the cultivated soil in the top 40 cm of the soil profile occurred compared to in the untreated control ($P < 0.001$, data not shown). This drying was also visible in volumetric water content measured with the neutron probe; however, due to variation within the probe counts the difference between the control and ameliorated plots was non-significant ($P = 0.587$, Figure 32).

Repeated measures ANOVA to assess volumetric water content by depth also showed no differences between the control and any of the amelioration treatments at flowering ($P = 0.404$), podding ($P = 0.112$) and finally at harvest ($P = 0.328$). After a very dry beginning to the 2022 growing season, the onset of wet conditions and waterlogging of the soil, particularly at podding and harvest, was evident in the increase in soil water content over time. Some drying of the topsoil had occurred by harvest on the 20 December, but the subsoil remained much wetter than it had been at the beginning of the cropping season.

While there was no overall effect of amelioration treatment on soil volumetric water content down the soil profile (Figure 32), and no amelioration treatment effects on total profile (0–140 cm) water content (Table 13) at Wonwondah throughout 2022, there were significant differences in subsoil (40–100 cm) water content between amelioration treatments at both podding ($P = 0.005$) and harvest ($P = 0.011$). This indicates greater water infiltration into the subsoil of these treatments and is reflected in the calculations for the amount of water 'used' by the crop (only accounting for rainfall minus change in profile moisture content, and not including losses from ponding, evaporation and run-off) by the time of podding ($P = 0.011$) and harvest ($P = 0.036$). In this, there was greater infiltration into the deep gypsum and the 'nutrient-rich' amelioration treatments, aside from the deep lucerne + PAM treatment, below the depth of treatment application (30 cm).

Despite deep ripping, infiltration into the subsoil of the deep ripping only and deep UGW was less than for the 'nutrient-rich' and gypsum fortified amelioration treatments. It is possible the PAM component of the deep lucerne + PAM treatment was the cause of less infiltration. Due to this effect on infiltration and 'crop water use' at podding, coupled with increased biomass production, resulted in higher WUE for peak biomass production ($P = 0.001$), with all of the 'nutrient-rich' amelioration treatments, aside from the deep lucerne + PAM treatment, producing more biomass per millimetre of profile water used compared to the untreated control.

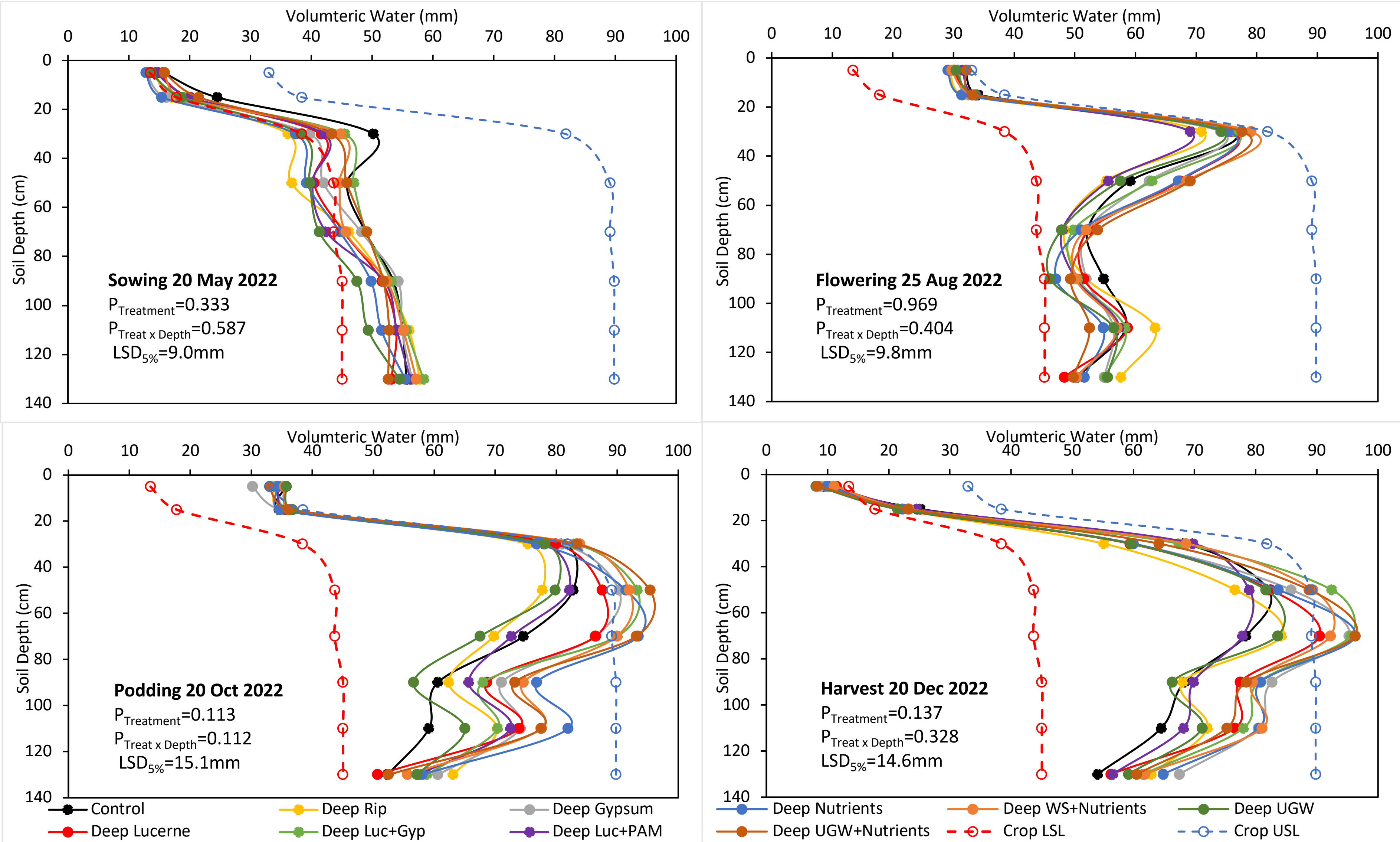


Figure 32. Amelioration treatment effects on soil profile volumetric water content at sowing, flowering, podding and harvest at Wonwondah in 2022.

Table 13. Soil profile water content, soil water use and WUE at Wonwondah in 2022.

Treatment	Soil profile (0–140 cm) water content (mm)				Water used sowing to podding (mm)[a]	Podding biomass WUE (kg DM/mm)	Water used sowing to harvest (mm)[b]	Harvest Grain WUE (kg grain/mm)*
	Sowing	Flowering	Podding	Harvest				
Control	349	417	481	450	247 a	17.1 d	454 a	*
Deep rip	316	408	487	451	226 ab	23.4 bcd	422 ab	
Deep gypsum	325	415	528	502	187 bcd	26.5 bc	371 bc	
Deep lucerne	321	418	519	476	177 cd	35.6 ab	397 abc	
Deep luc + gyp	341	417	534	510	204 abc	29.1 b	375 bc	
Deep luc + PAM	321	396	498	456	210 abc	24.8 bcd	412 abc	
Deep nutrients	306	407	547	498	150 d	36.7 a	355 c	
Deep WS +nutrients	334	420	545	507	182 bcd	30.9 ab	368 bc	
Deep UGW	303	401	477	451	216 abc	19.2 cd	399 abc	
Deep UGW + nutrients	333	417	544	495	184 cd	28.3 bc	381 bc	
Grand mean	325	412	516	480	198	27.2	393	
$P_{treatment}$	0.333	0.969	0.113	0.137	0.011	0.001	0.036	
$LSD_{5\%}$	40	42	61	58	50	8.6	58	

[a] Sowing to podding rainfall was 380 mm at the site. [b] Sowing to harvest rainfall was 557 mm at the site. * Not determined in 2022 due to waterlogging effects on grain production.

The Amelioration treatment differences on soil water 'used' since sowing persisted through to harvest (P = 0.036). However, by this time the faba bean crop at the trial site had greatly suffered from being waterlogged over spring and had failed to produce any meaningful yield. Therefore, harvest grain water use WUE was not determined.

4.3.3.3 Soil amelioration treatment effects on soil moisture use in 2023

Soil moisture measurements were performed at sowing, the two in-season biomass cuts at the beginning of stem elongation and peak flowering, and at harvesting of the plots in 2023 (Figure 33).

A legacy effect of increased subsoil water content in the 'nutrient-rich' and deep gypsum amelioration treatments left from harvest time the previous year persisted through to sowing in 2023 (P = 0.050, Figure 33, Table 14). With more early season rain in 2023, by the time of the first in-season crop biomass measurement at the beginning of stem elongation subsoil water content had increased, especially in the deep lucerne + PAM treatment, which was at that time no different to other wetter amelioration treatments. Only the control, deep rip and deep UGW remained drier in subsoil at 40–100 cm depth (P < 0.001) and these treatments were drier overall across the whole 0–140 cm soil profile (P = 0.004). This treatment difference was consistent through to peak biomass sampling at flowering (P = 0.014) and crop water use across all treatments was consistent (P = 0.809).

With the onset of dry spring conditions and the dry finish at the site, the canola was able to substantially draw down soil water content. Throughout the profile, and especially in the subsoil, canola was able to extract more water from the 'nutrient-rich' amelioration treatments compared to the non-nutrient-rich treatments and the untreated control (P < 0.001). This was especially the case in the deep gypsum treatment, which earlier had allowed for greater infiltration into the subsoil, but then failed to utilise stored subsoil water, presumably from a lack of N nutrition, resulting in leftover water at harvest (P = 0.007).

As with the canola yield, canola grain WUE (as a function of total millimetres of water used between sowing and harvest, rather than just millimetres of rainfall received) was consistent across the 'nutrient-rich' amelioration treatments, apart from the deep nutrients treatment which used more total soil water overall. Despite reduce water use, the deep gypsum and deep UGW treatments produced as much canola grain per millimetre of water used as the 'nutrient-rich' amelioration treatments. Canola WUE appeared to reach a ceiling of 14.0–14.4 kg grain/mm at the site, significantly more than the control (P = 0.031).

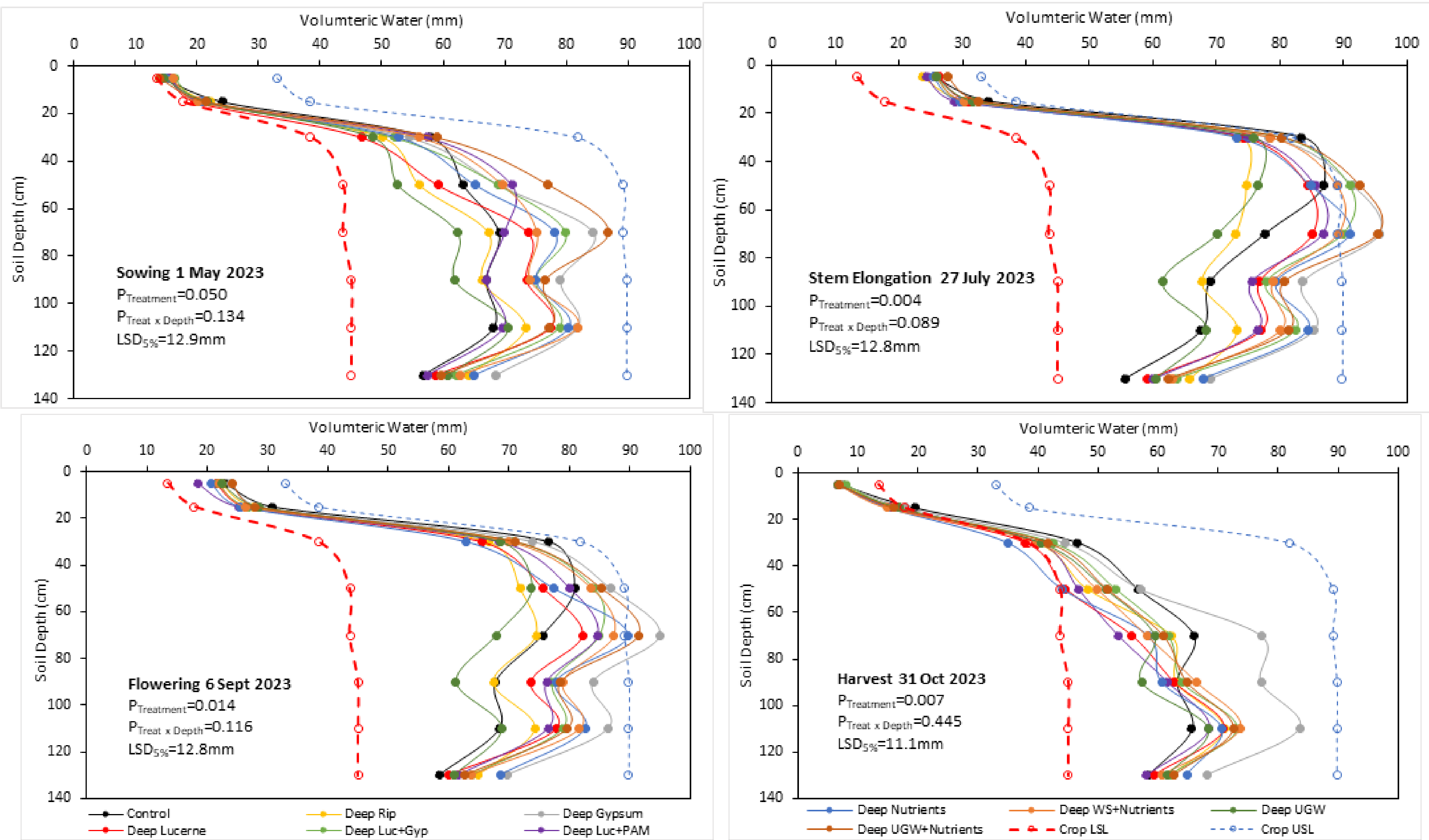


Figure 33. Soil volumetric water content at sowing, stem elongation, flowering and harvest at Wonwondah in 2023.

Table 14. Soil profile water content, soil water use and WUE at Wonwondah in 2023.

Treatment	**Soil profile (0–140 cm) water content (mm)**				**Water used sowing to flowering[a]**	**Flowering biomass WUE (kg DM/mm)**	**Water used sowing to harvest[b]**	**Harvest Grain WUE (kg grain/mm)**
	Sowing	Elongation	Flowering	Harvest				
Control	421 bcd	500 bc	481 bcd	383 b	155	40.9 c	288 d	11.1 b
Deep rip	415 cd	482 c	470 cd	370 b	161	40.5 c	294 bcd	12.7 ab
Deep gypsum	474 a	560 a	548 a	433 a	142	47.0 abc	291 cd	14.0 a
Deep lucerne	425 abcd	514 abc	483 bcd	353 b	158	48.0 ab	322 abc	14.1 a
Deep luc + gyp	454 abc	541 ab	508 abc	381 b	162	44.0 bc	323 abc	14.1 a
Deep luc + PAM	429 abcd	512 abc	491 bcd	351 b	154	50.1 ab	328 ab	14.2 a
Deep nutrients	452 abc	536 ab	505 abc	355 b	163	51.2 a	347 a	12.6 ab
Deep WS + nutrients	456 abc	535 ab	513 abc	370 b	158	49.9 ab	336 a	14.0 a
Deep UGW	392 d	470 c	452 d	362 b	156	43.7 bc	280 d	14.4 a
Deep UGW + nutrients	471 ab	553 a	521 ab	377 b	167	47.8 ab	344 a	13.7 a
Grand mean	439	520	497	374	158	46.3	315	13.5

$P_{treatment}$	0.050	0.004	0.014	0.007	0.809	0.062	< 0.001	0.031
$LSD_{5\%}$	52	48	49	40	24	6.5*	34	1.9

[a] Sowing to flowering (peak biomass) rainfall was 216 mm at the site. [b] Sowing to harvest rainfall was 250 mm at the site. * Stated value and letters representing significant treatment differences are at the LSD10% level.

4.3.4 Amelioration treatment effects on soil pre-sowing mineral nitrogen results

4.3.4.1 Amelioration treatment effects on pre-sowing mineral nitrogen in 2023

Profile (0–120 cm) soil mineral ammonium-N (Figure 34) and nitrate-N (Figure 37) was measured on 30 March prior to sowing of the 2023 crop to assess available soil N in each plot one year after the initial treatment implementation.

Soil ammonium-N (NH_4-N) was significantly greater (P = 0.003) in the deep nutrients (deep nutrients) treatment at depths of 10–40 cm compared to all other treatments, all of which were no different to the control (Figure 34). There were greater treatment differences in pre-sowing soil nitrate-N (NO_3-N) concentrations (Figure 35). NO_3-N concentrations were again greatest in the deep nutrient (deep nutrients) treatment throughout the soil profile (P = 0.003). The effects of inorganic fertiliser applied in the previous year on NO_3-N concentrations are also evident with in both the deep wheat straw + nutrients (deep WS + nutrients) and deep UGW mulch + nutrients (deep UGW + nutrients) treatments. In comparison to the deep UGW mulch + nutrients treatment, NO_3-N concentrations in the deep UGW mulch only (deep UGW) treatment were no different to the control, likely indicating that little to no decomposition and mineralisation of stored N from the organic material occurred. However, decomposition and mineralisation of NO_3-N from the deep applied nutrient-rich lucerne pellets was evident by elevated NO_3-N concentrations in each of the deep lucerne (deep luc), deep lucerne + gypsum (deep luc + gyp) and deep lucerne + PAM (deep luc + PAM) treatments, with N derived from the PAM likely further increasing NO_3-N concentrations in the deep lucerne + PAM treatment. Elevated NO_3-N concentrations below the depth of amendment application (30–35 cm) indicates that some leaching of NO_3-N down the soil profile occurred, likely the result of wet seasonal conditions in 2022.

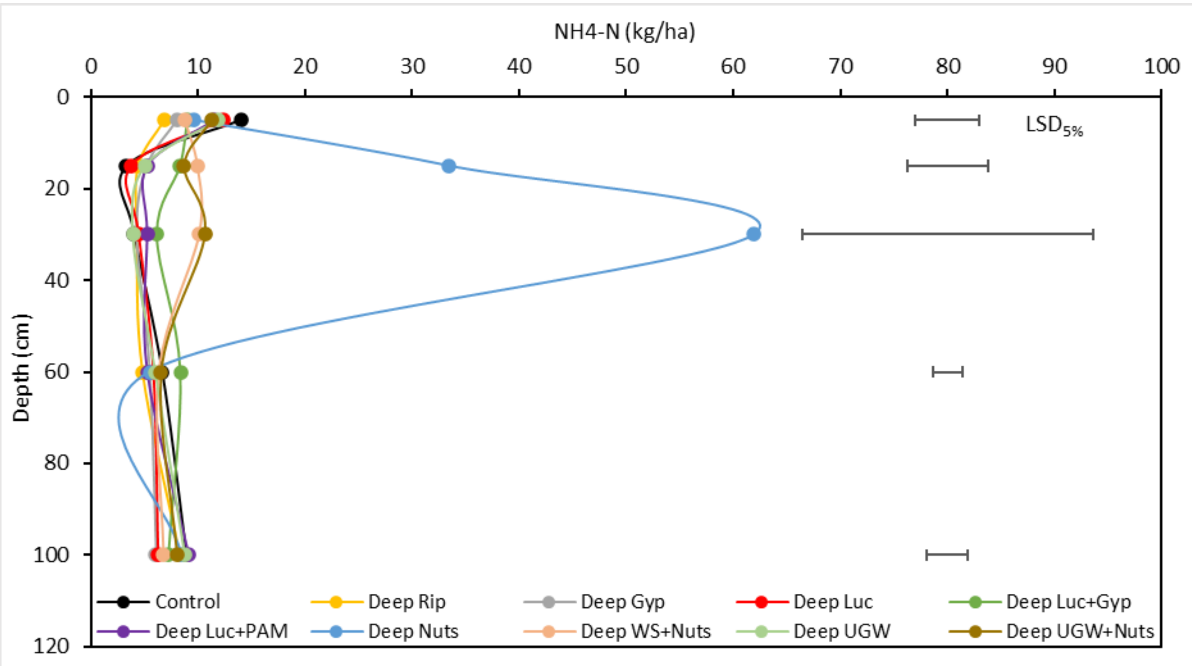


Figure 34. Pre-sowing soil ammonium-N (NH_4-N) in each treatment at the Wonwondah trial site, 30 March 2023.

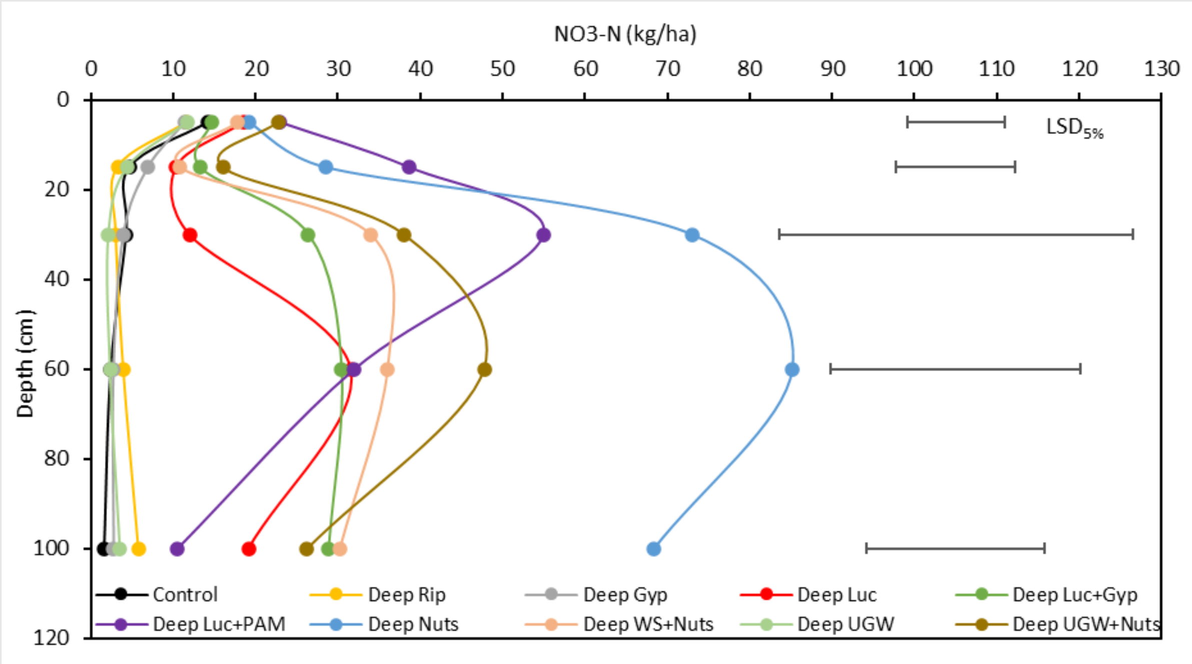


Figure 35. Pre-sowing soil nitrate-N (NO_3-N) in each treatment at the Wonwondah trial site, 30 March 2023.

4.3.5 Amelioration treatment effects on pre-sowing mineral nitrogen in 2024

Pre-sowing mineral N was again measured in April 2024 prior to the site being sown to assess changes in soil mineral N content after the growth of the 2023 canola crop. A total of 94 kg N/ha was applied to the canola at the site by the grower in 2023. Evidence of some of this applied N remaining as NO_3-N was evident in the accumulation of NO_3-N in the top 10 cm of the soil profile (Figure 37) compared to 2023 (Figure 35). However, concentrations of NO_3-N deeper in the soil profile in the nutrient-rich amelioration treatments decreased since pre-sowing in 2023, indicating use of subsoil N by the canola crop.

By the beginning of 2024, the spike in soil NH_4-N that occurred in the deep nutrients treatment in 2023 had completely reduced and there were no longer any NH_4-N concentration differences between any of the amelioration treatments and the untreated control ($P = 0.632$, Figure 36).

While subsoil NO_3-N concentrations were greater in all of the nutrient-rich amelioration treatments compared to the non-nutrient-rich treatments in 2023, after two years of the trial it was only in the deep nutrients and deep lucerne + PAM treatments where NO_3-N concentrations remained significantly greater ($P = 0.045$), especially at 40–80 cm depth, compared with non-nutrient-rich treatments (Figure 37). The greatest reductions or use of subsoil NO_3-N were in the deep nutrients, deep wheat straw + nutrients (deep WS + nutrients) and the deep lucerne + gypsum (deep luc + gyp) treatments. Interestingly, NO_3-N use by the canola crop was higher in the deep lucerne + gypsum treatment compared to the just deep lucerne treatment (Table 15).

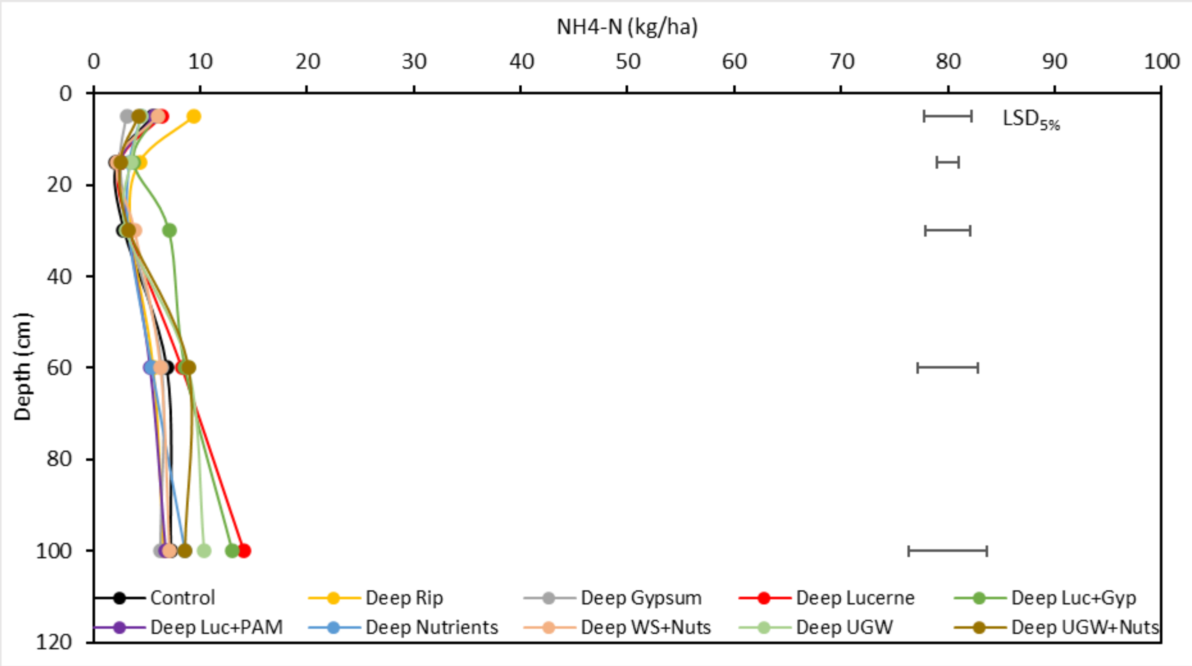


Figure 36. Pre-sowing soil ammonium-N (NH_4-N) in each treatment at the Wonwondah trial site, 10 April 2024.

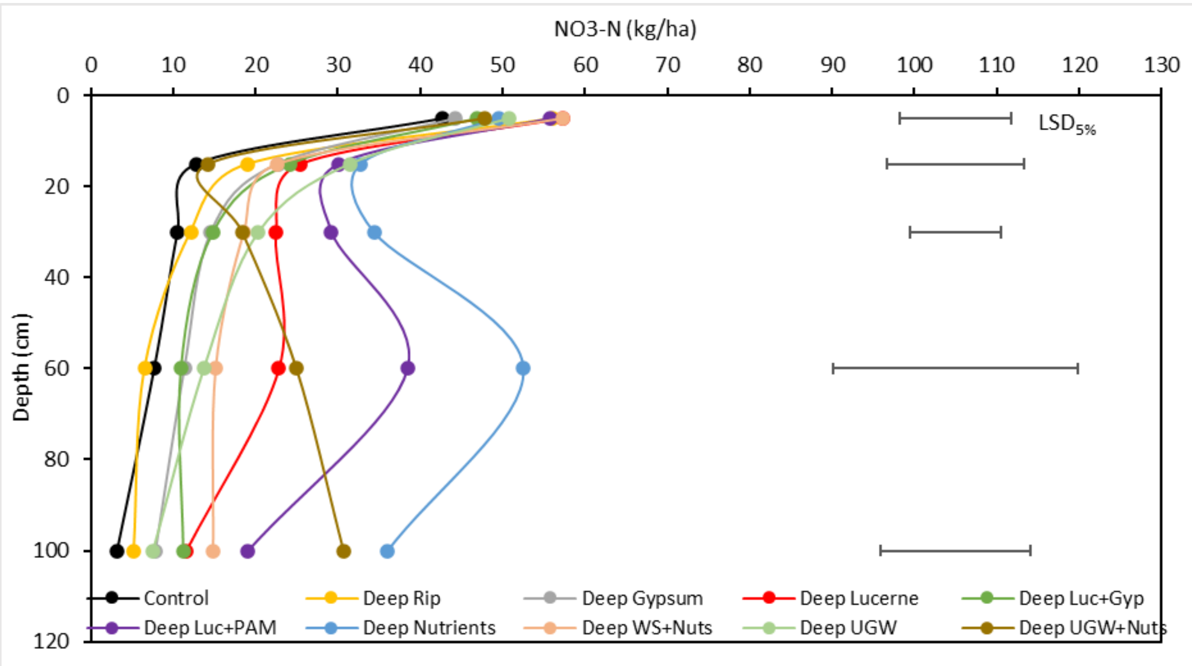


Figure 37. Pre-sowing soil nitrate-N (NO_3-N) in each treatment at the Wonwondah trial site, 10 April 2024.

Increases in soil NO_3-N in the deep UGW treatment in 2024 indicate that the UGW was beginning to break down and release N into the soil. Interestingly, NO_3-N concentrations in the deep rip and deep gypsum treatments increased more so than did those in the control going in to 2024, despite these treatments yielding more (Figure 24) in 2023.

Table 15. Soil profile (0–120 cm) ammonium-N (NH_4-N) and nitrate-N (NO_3-N) concentrations (kg/ha) at Wonwondah prior to treatment application in 2022, and prior to site sowing in 2023 and 2024.

Treatment	2022		2023		2024	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Control	8.4	8.4	37.0	26.3	24.7	76.8
Deep rip			28.8	27.8	29.6	99.1
Deep gypsum			29.1	27.7	21.8	100.9
Deep lucerne			32.7	91.8	34.7	139.6
Deep luc + gyp			36.7	116.3	38.3	108.1
Deep luc + PAM			35.5	135.7	23.6	172.6
Deep nutrients			110.7	267.0	25.2	205.3
Deep WS + nutrients			42.1	129.0	25.4	128.6
Deep UGW			35.9	24.2	30.3	123.9
Deep UGW + nutrients			45.3	150.9	27.6	136.3
$P_{Treatment}$			0.005	< 0.001	0.632	0.045
$LSD_{5\%}$			36.8	90.6	17.0	72.0

4.3.6 **Amelioration treatment effects on soil physical properties results**

4.3.6.1 Amelioration treatment effects on soil cone penetration resistance in 2022

Wet spring conditions in 2022 resulted in a full profile of soil moisture (Figure 32), which allowed for assessments of soil penetration resistance to be made using a cone penetrometer. A Rimik CP40II cone penetrometer with a 130 mm^2 cone was used for eight measurements per plot to a depth of 600 mm. Two readings were taken both on and off the centre rip line at each of the plots in seven of the ten amelioration treatments (Figure 38). Statistical analysis was performed by a repeated measures ANOVA.

Firstly, when assessing only the mean treatment effects (the mean of both on and off rip line insertions) on penetration resistance compared to the control treatment, the deep ripping-only treatment reduced ($P < 0.001$) penetration resistance to a depth of 275 mm, roughly equivalent to the depth of ripping and treatment application. However, mean penetration resistance in the amelioration treatments where amendments were applied was slightly, but significantly ($P < 0.05$), reduced compared to the untreated control to a depth of 600 mm (maximum sampling depth). This effect was possibly due to the subsoil being wetter in these deep ripped amelioration treatments compared to the untreated control due to improve rainfall infiltration.

By splitting the cone penetration resistance data into either on or off the rip line, it can be seen that to the 275–300 mm depth of ripping, penetration resistance was reduced much more on the rip line compared to in between the rip lines ($P < 0.001$). Overall, penetration resistance was lower both on and off the rip line for ameliorated plots compared to the untreated control to this depth.

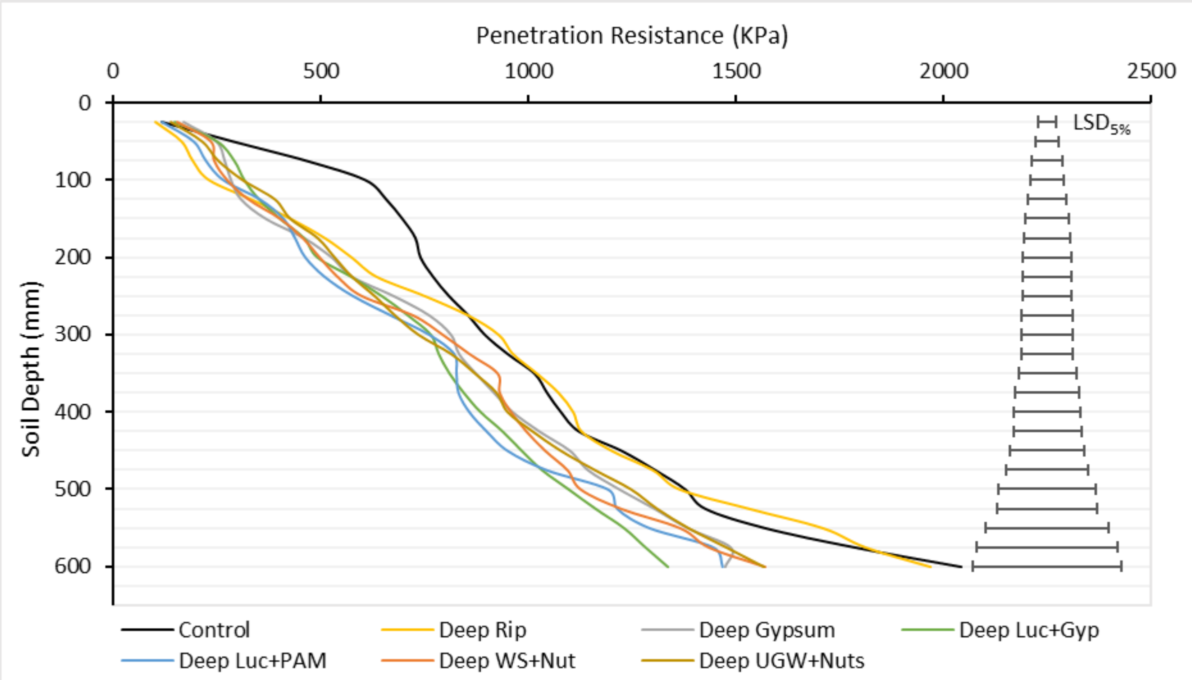


Figure 38. Amelioration treatment effects on soil cone penetration resistance at Wonwondah, 29 September 2022.

To graph these differences between on and off rip line penetration resistance, results for the seven treatments assessed have been split across two graphs (Figures 39a and b) for ease of viewing.

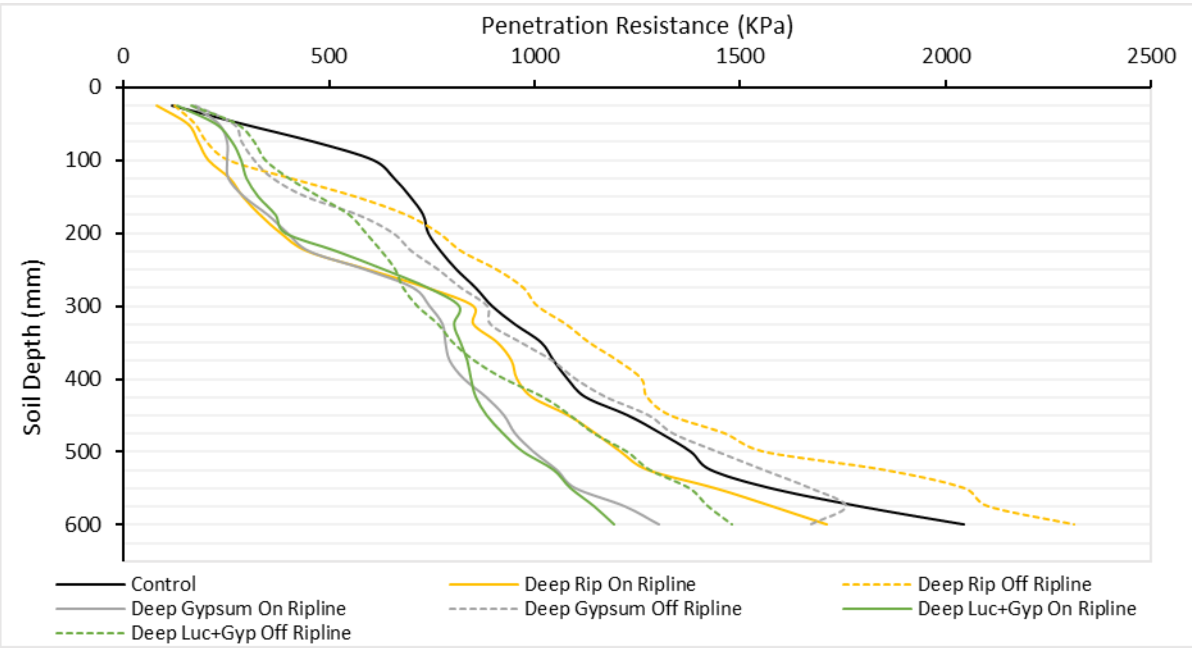


Figure 39a. Comparing soil cone penetration resistance for on ripline versus to off ripline sampling position in selected amelioration treatments at Wonwondah, 29 September 2022.

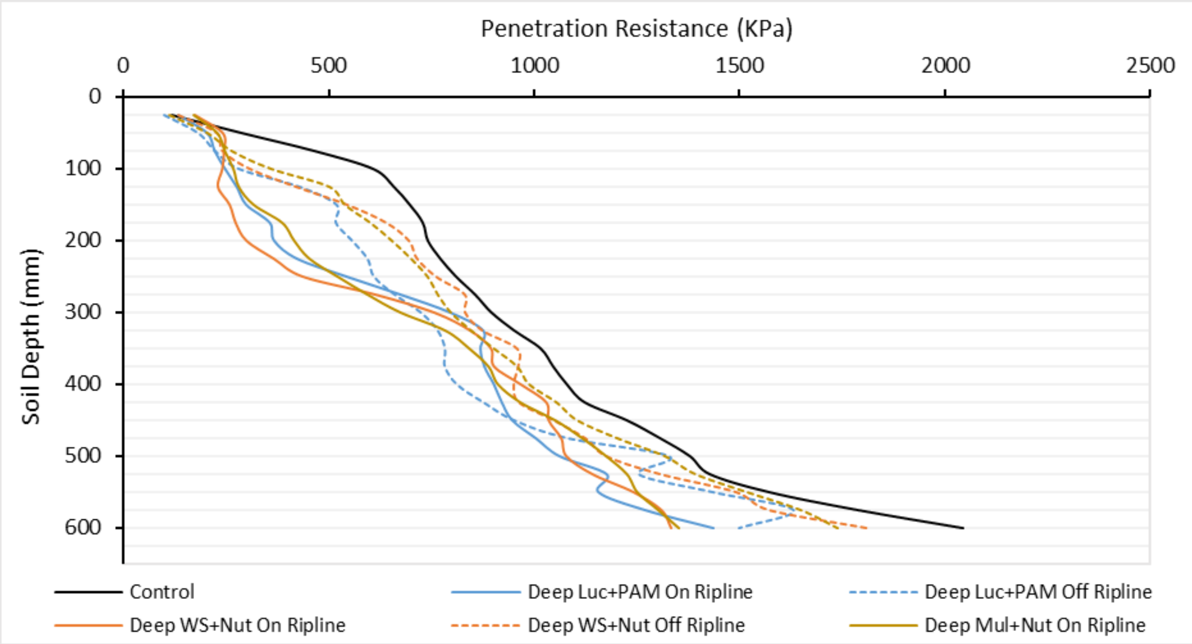


Figure 39b. Comparing soil cone penetration resistance for on rip line compared to off rip line sampling position in selected amelioration treatments at Wonwondah, 29 September 2022.

4.4 KWEDA, WA TRIAL SITE

4.4.1 **Rainfall (2022–2024)**

Rainfall data were retrieved from the online resources of the nearby weather stations. The nearest weather stations are in Bulyee and Kweda, WA, which are 11 and 12 km away from the site respectively. The Bulyee station (Station number 10527) is monitored by the Bureau of Meteorology, Government of Australia. The Kweda station (KW001) is monitored by the Department of Primary Industries and Regional Development of Western Australia.

The long-term rainfall data (1990–2023) from various weather stations in and around the Kweda region show that it receives an average annual rainfall of 327 mm. However, the last nine years of rainfall data (2015–2023) reported by the Kweda weather station show that the average annual rainfall received was 393 mm.

Rainfall data of the Kweda weather station show that total rainfall received during 2022 and 2023 was 429 and 418 mm respectively (Figure 40A, B). May was recorded as the wettest month in 2022 with 103 mm rainfall followed by August with 87 mm (Figure 40A). However, in 2023, the wettest month recorded was June, receiving 139 mm of rainfall, followed by April, receiving 84 mm (Figure 40B). So far in 2024, July and August have been recorded with the highest monthly rainfall (Figure 40C). The total rainfall received in 2024 by the end of August reported by the Kweda weather station was 345 mm.

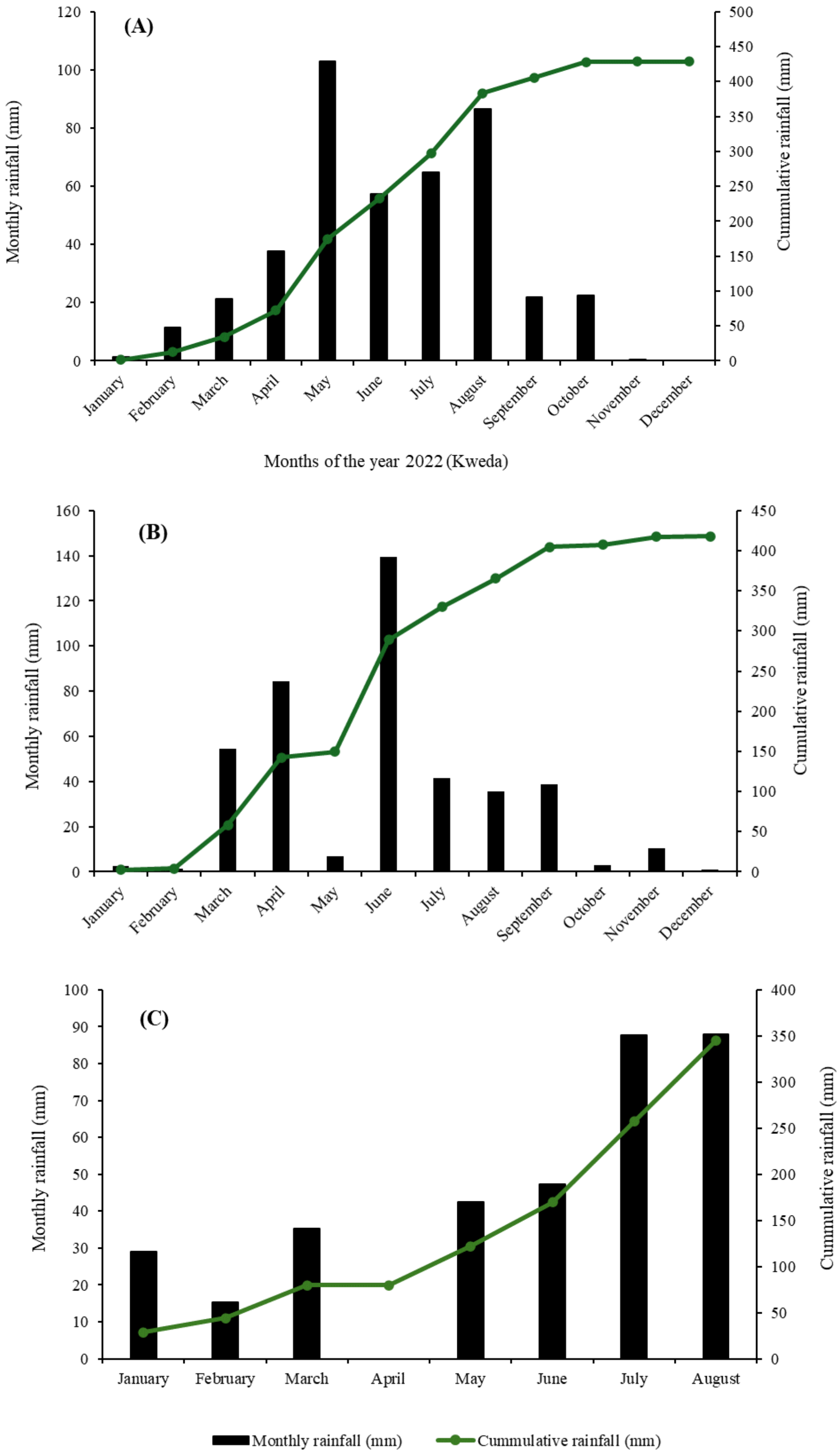
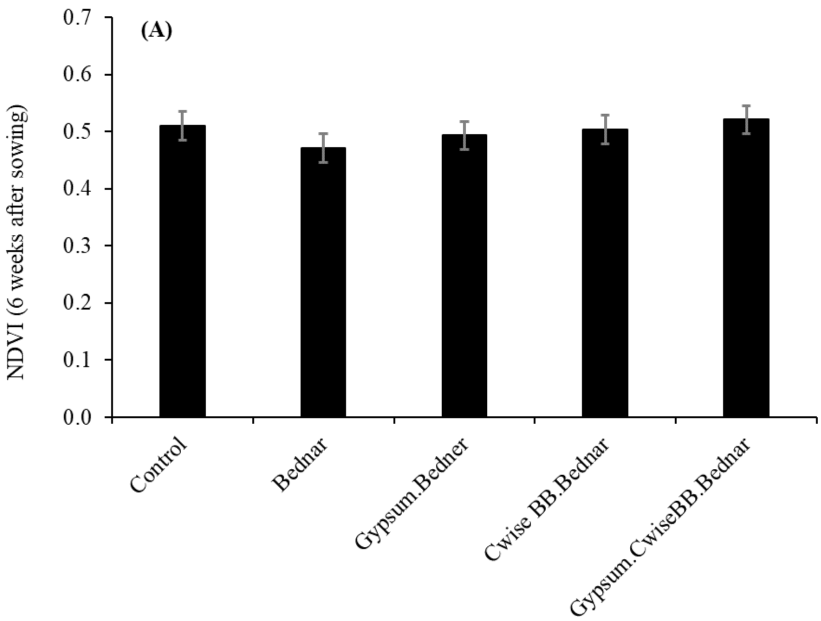


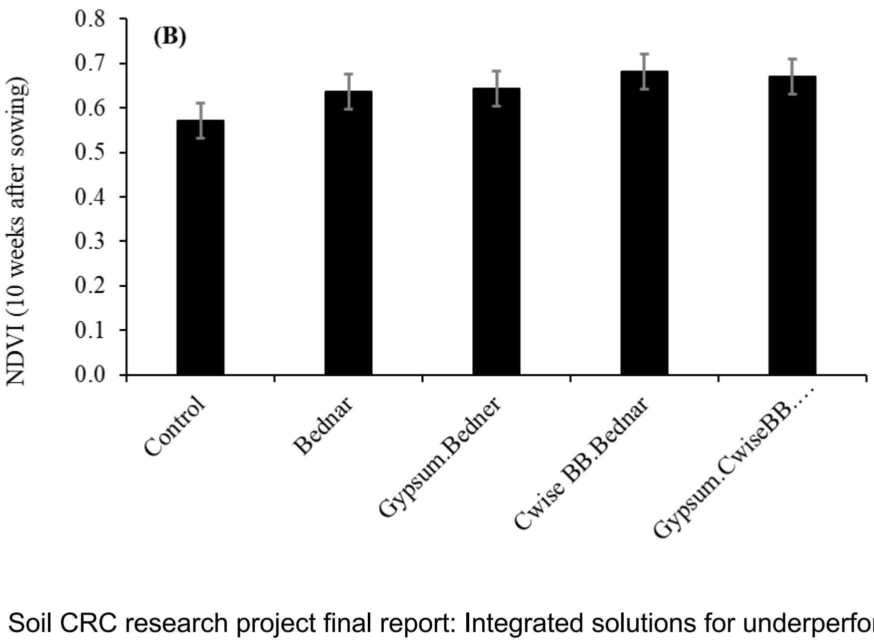
Figure 40. (A) The 2022 total monthly and cumulative rainfall data recorded by the weather station at Kweda (KW001); (B) the 2023 total monthly and cumulative rainfall data recorded by the weather station at Kweda (KW001); (C) the 2024 total monthly and cumulative rainfall data recorded by the weather station at Kweda (KW001) up to August. Data was retrieved from the official website of the WA DPIRD of the Government of Western Australia at: https://weather.agric.wa.gov.au/.

4.4.2 **Crop data (2022)**

In the large plots experiment, no measured parameters were statistically different across the applied treatments except grain yield (Figure 41 A–C). The large plots experiment showed an improvement between the unripped (control) and the Bednar-ameliorated treatments, with a significant increase in yield for the gypsum and the gypsum + C-wise treatments versus the control. The C-wise (humiclay) alone showed a larger yield and a reduced variability between blocks; however, it was not significantly different from the control. Overall, gypsum was the most beneficial amendment. Plant establishment ranged from 118–125 plants/m^2 and were not statistically affected by the applied treatments.

No significant differences were seen for plant health (NDVI at six and ten weeks after seeding) (Figure 41 A, B). A possible explanation for this might occur from the variability of the blocks, which were found to be significantly different and included in the model for the statistical analysis.





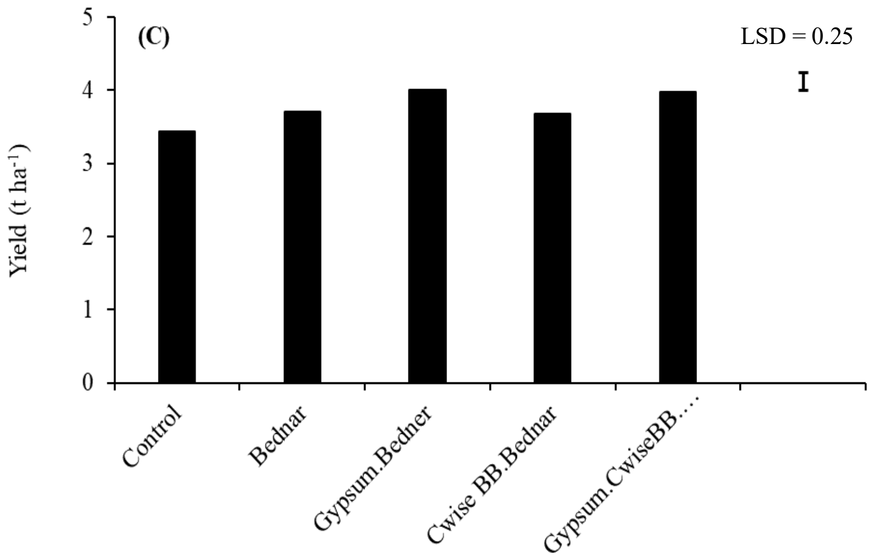


Figure 41. 2022 large plot experiment (A) NDVI at six weeks after seeding; (B) NDVI at 11 weeks after seeding; (C) Barley yield (t/ha). Where the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar. Where the treatments effect was significant ($P \leq 0.05$), LSD (α = 95%) was used as a separate error bar.

The small plots experiment investigated a series of novel amendments and variable rates, all incorporated by the Bednar plough. The Bednar treatment was therefore considered as the control for this trial. In the small plots experiment, none of the measured crop parameters were significantly affected by any treatment relative to the control (Bednar), as shown in Figures 42 and 43. As mentioned above, as a potential limitation on the results, a significant difference between the blocks was identified, which increased the variability and potentially reduced the statistical power of the analysis. Another likely cause for the lack of differences between treatments could be explained by the rainfall data, which showed to be above average for the cropping season 2022. Hence, optimal soil moisture reduced the potential benefit of the incorporated amendments.

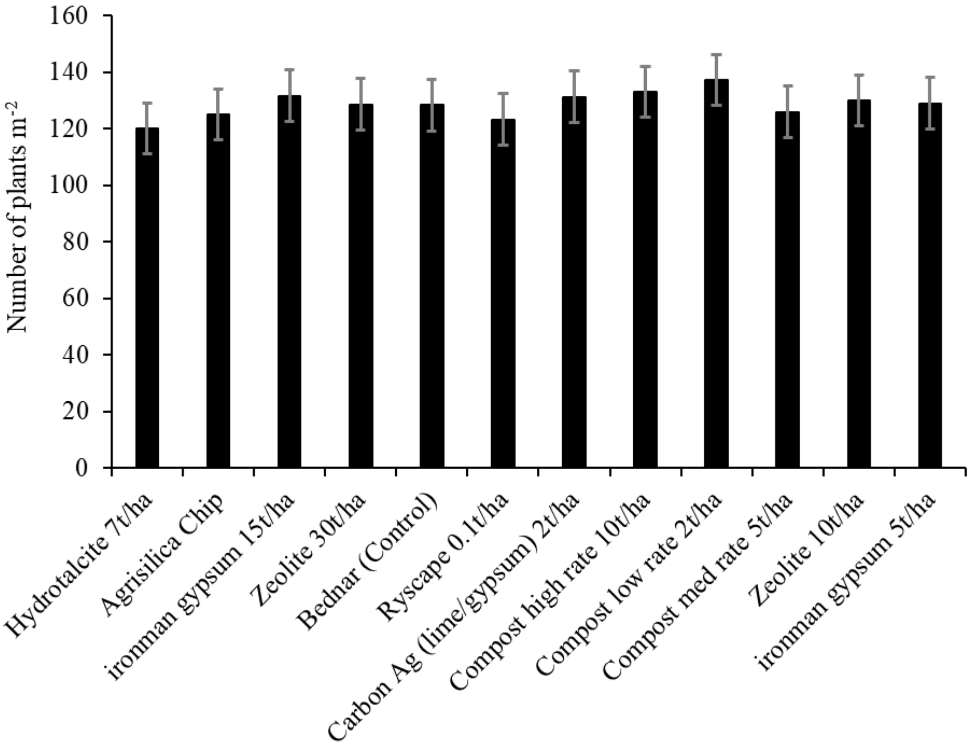


Figure 42. Plant establishment in 2022 small trial plot (plants/m^2).

4.4.3 Crop data 2023

Target density of lupins has been reported as 40–45 plants/m^2 in WA. All treatments in the large plots experiment produced within or above the targeted range in 2023, ranging from 44–62 plants/m^2. The Bednar and Gypsum.CwiseBB.Bednar treatments had significantly lower counts than the control (52 and 44.3 vs. 61.5, respectively ($P < 0.05$, LSD = 7.2)). NDVI measurements at 11 weeks after seeding were statistically similar between all treatments (Figure 44A). The non-significant difference could be partially attributed to the significant variations between the blocks which was included as a source of variation in the model. Yield and protein content were not significantly affected by the treatments. Yield ranged from 2.3 to 2.5 t/ha (Figure 44B) while protein content ranged narrowly between 34.9 and 35.7% (Figure 44C).

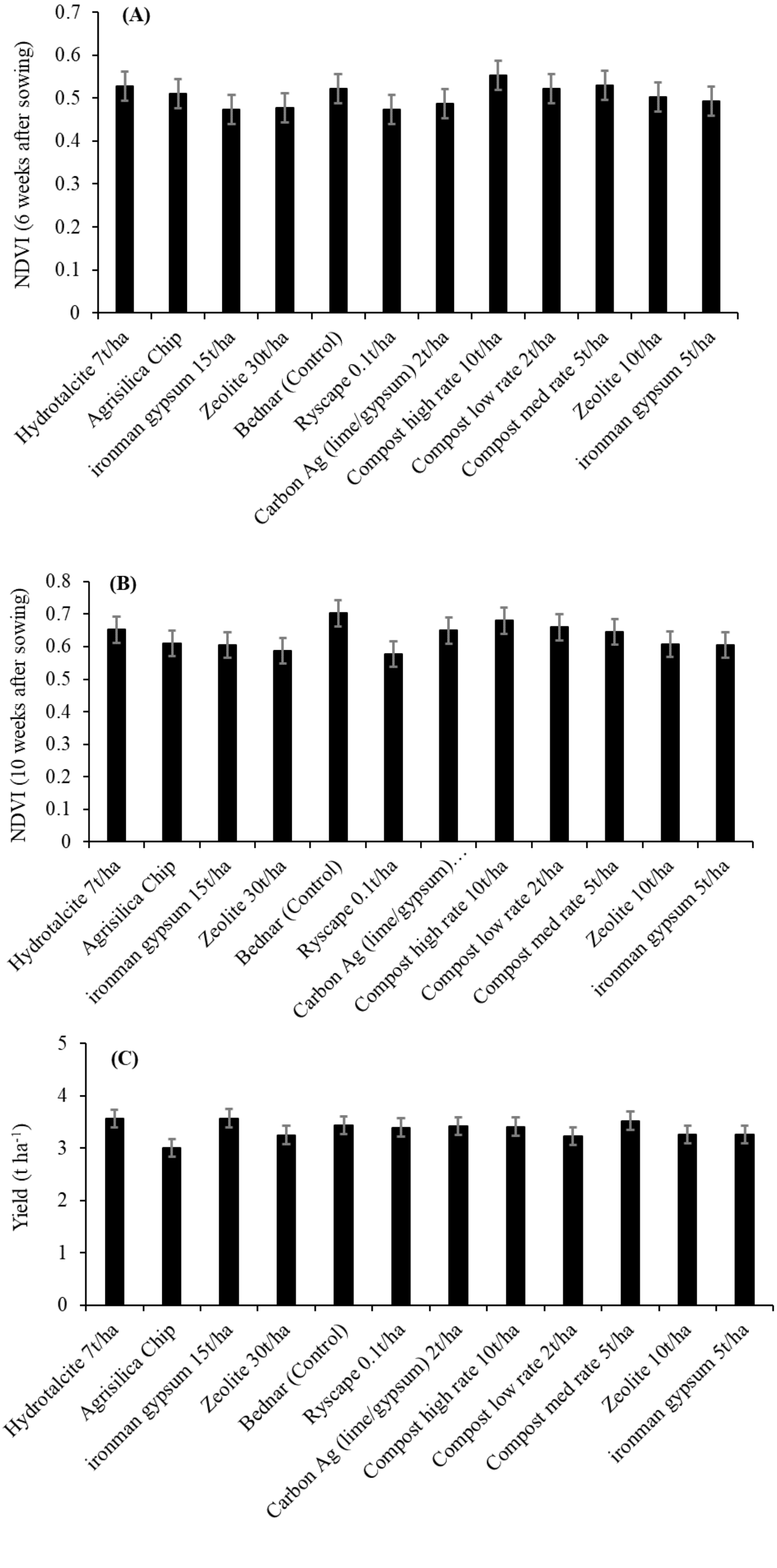


Figure 43. 2022 small plots experiment (A) NDVI at six weeks after seeding; (B) NDVI at 11 weeks after seeding; (C) Barley yield (t/ha). Where the treatments effect was non-significant (P > 0.05), standard error of the mean was used as error bars on each data bar.

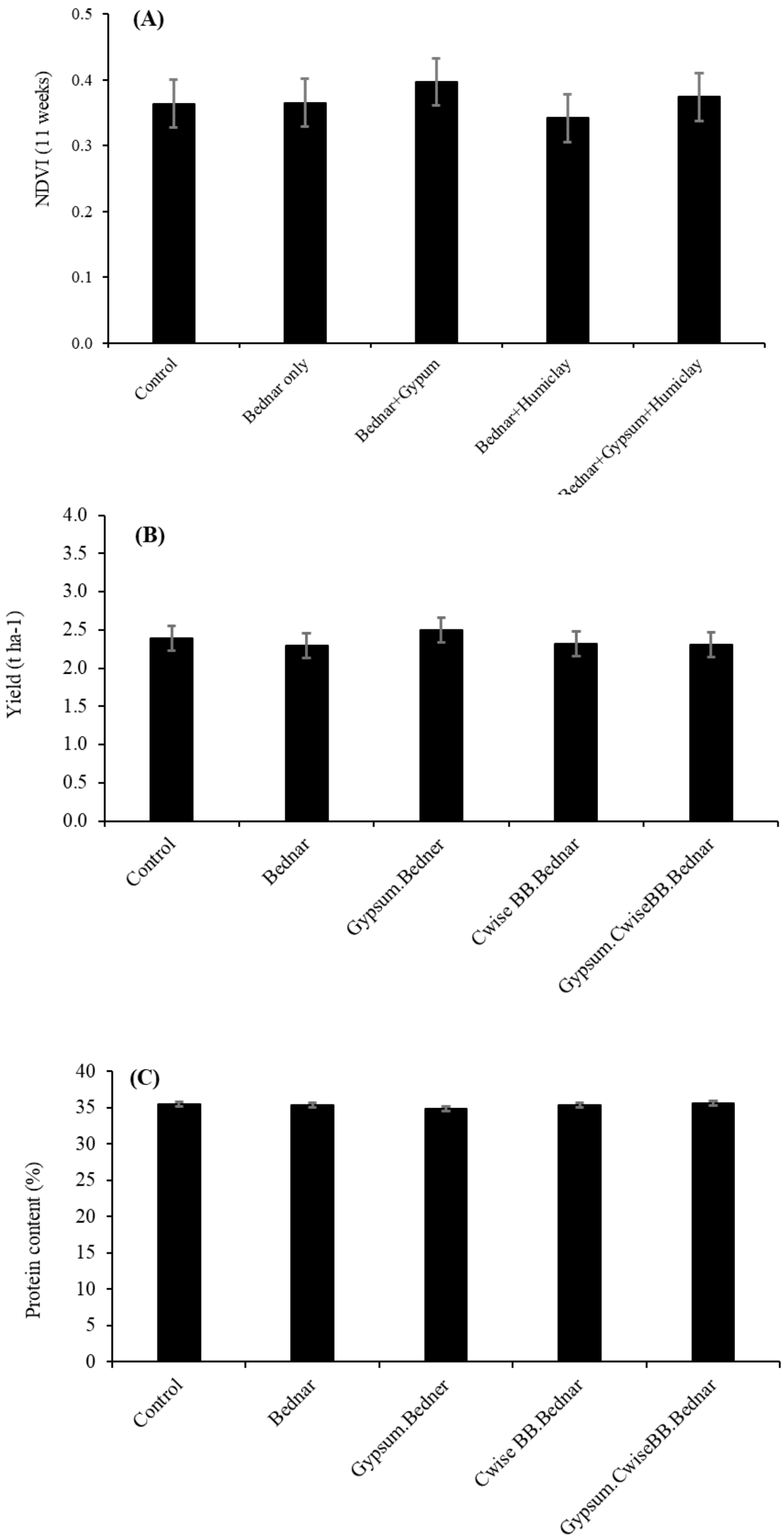


Figure 44. 2023 large plot experiment (A) NDVI at 11 weeks after seeding; (B) lupin yield (t/ha); (C) lupin protein content (%) at harvest. Where the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar.

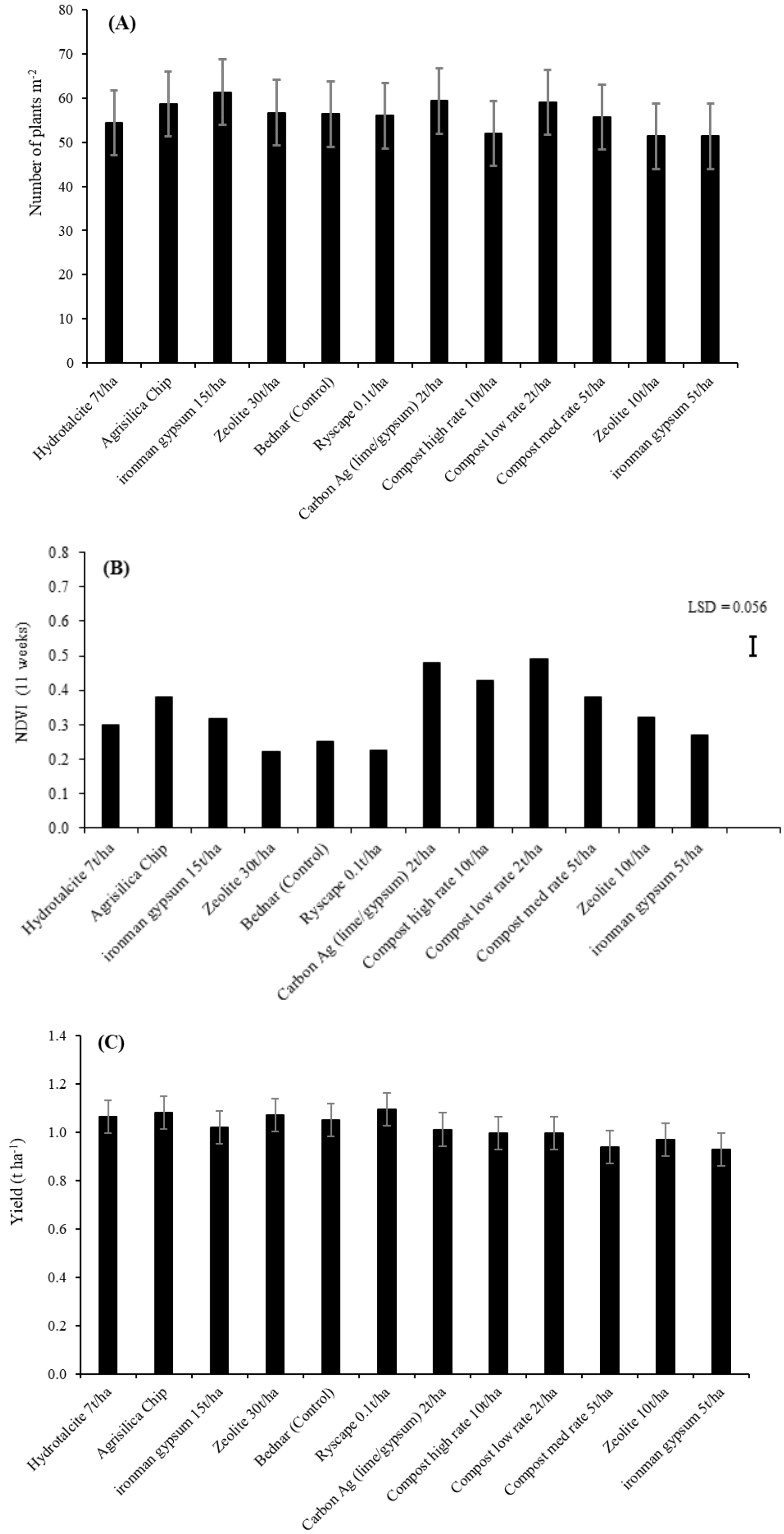
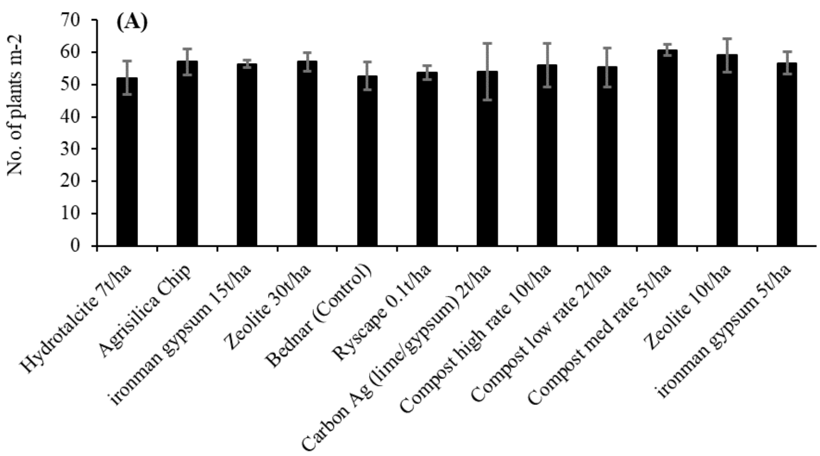


Figure 45. Treatment effects on various growth and developmental parameters of lupin crop in the small plots experiment in 2023. (A) Number of plants/m^2: (B) Hand-based NDVI recorded at 11 weeks after seeding; (C) Yield (t/ha). Where the treatments effect was non-significant ($P > 0.05$), standard error of the mean was used as error bars on each data bar.

Plant density recorded at nine weeks after seeding in the small plots experiment in 2023 was above the target range (40–45 plants/m^2) with no statistical differences between the treatments (Figure 45A). Lupins in different treatments were found with significantly different NDVI at 11 weeks after seeding (Figure 45B). Low rate of compost (2 t/ha) was found to have the greatest NDVI of 0.49 (> 2 times of Zeolite at 30 t/ha, two times of control, 1.8 times of Iron Man Gypsum at 5 t/ha, 1.6 times of hydrotalcite, 1.6 times of Iron Man Gypsum at 15 t/ha, 1.3 times of Agrisilica chip) (Figure 45B). However, NDVI recorded in all the three compost treatments was statistically similar.

4.4.1 **Crop data 2024**

So far in 2024, none of the recorded crop parameters (plant establishment counts, NDVI) have shown any significant differences between the treatments in either of the experiments. Plant establishment counts in the large plot experiment ranged from 51–60 plants/m^2. NDVI measurements ranged from 0.57–0.61, 0.46–0.48, and 0.62–0.64 at six, eight and 11 weeks after sowing respectively. In the small plot experiment, plant establishment counts ranged from 52–60.7 plants/m^2, while NDVI measurements ranged from 0.41–0.52 (Figure 46A, B).



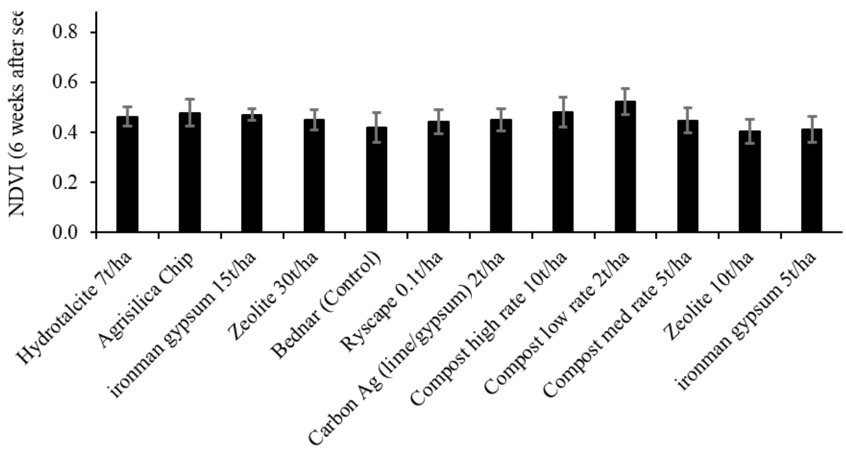


Figure 46. Treatment effects on canola crop in the small plots experiment in 2024. (A) Number of plants/m^2: (B) Hand-based NDVI recorded at six weeks after seeding. Where the treatments effect was non-significant (P > 0.05), standard error of the mean was used as error bars on each data bar.

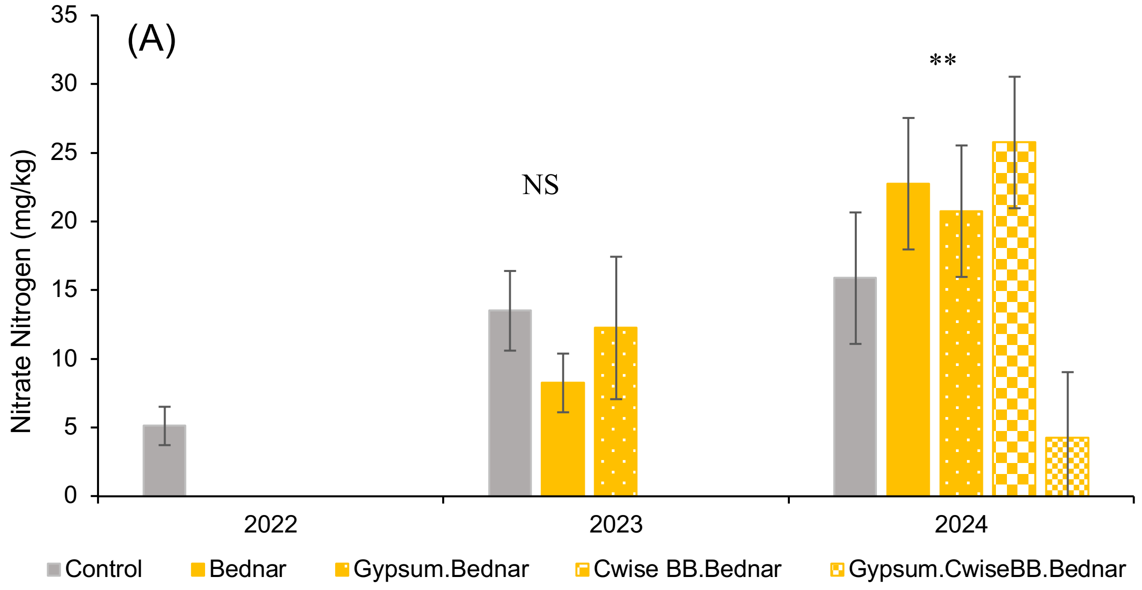
4.4.2 **Soil Data (2022–2024)**

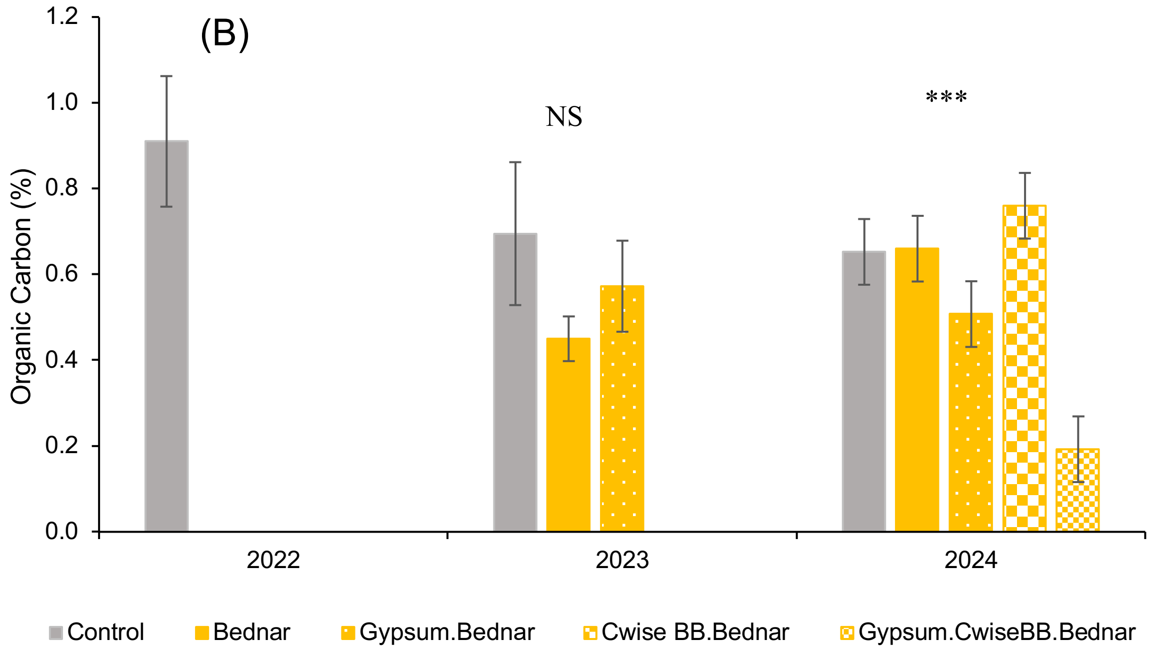
Statistical analysis of the soil data was carried out. There was no treatment comparison in 2022, hence only the mean value of the four replications of the control was calculated with standard error of the mean. For 2023 and 2024 data, a one-way ANOVA was performed using block (rep) and treatment as a source of variation in the analysis. Data was found to be significantly affected by the treatments in both 2023 and 2024 ($P \leq 0.05$), a standard error of the population mean for the experiment/year was inserted as an error bar on the data bars to compare the means in the figures. Where data was not significantly affected in any of the years ($P > 0.05$), the data is represented in the tables rather than figures. Tables 16 and 17 show such data of the large plots trial, while Tables 18 and 19 show such data of the small plots trial. Tables 16 and 18 show non-significant data of the 0–10 cm profile from the large and small plot experiments respectively, while Tables 17 and 19 show non-significant data of the 10–30 cm profile from the large and small plot experiments respectively.

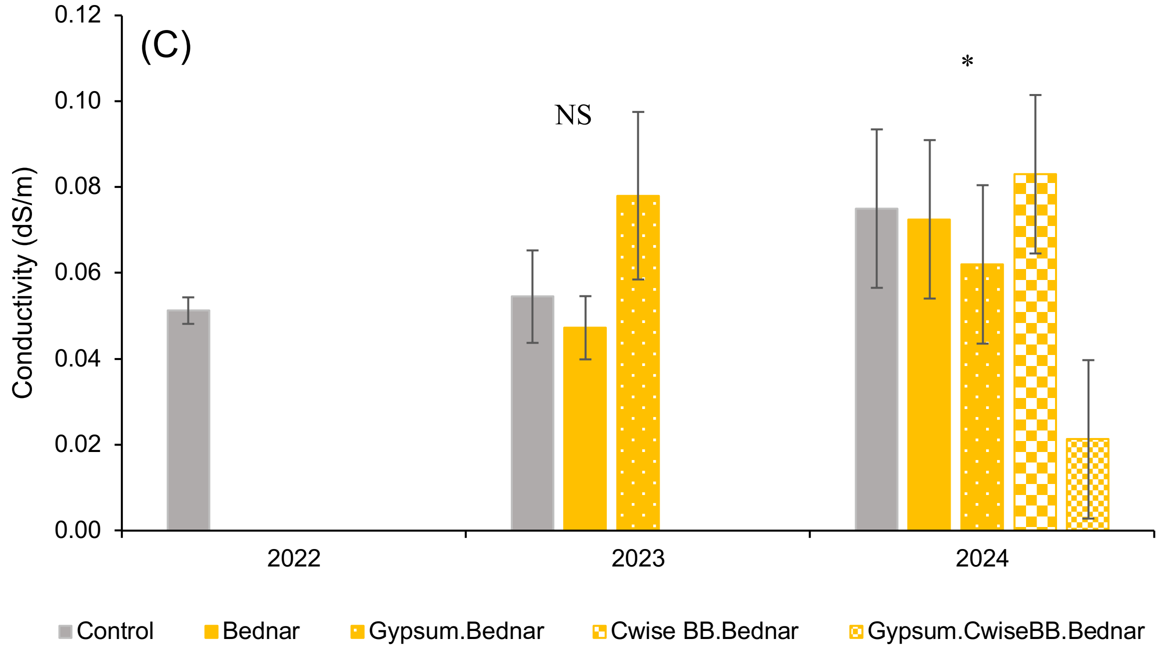
Soil data of the large plots experiment show that soil physicochemical properties were different between the applied treatments mainly in the top 10 cm while they remained similar between the treatments in the 10–30 cm profile (Figure 47 and Tables 16 and 17). Between the years, 2024 was found with more differences between the treatments in the large plots experiment relative to 2023 (Figure 47A-I). In the large plots experiment in 2024, a reduction in the majority of soil characteristics of the soil treated with Gypsum.CwiseBB.Bednar, such as nitrate-nitrogen, organic carbon, conductivity, DTPA Mn, DTPA Zn, exchangeable Ca, and Mg, was found relative to the control (Figure 47A-I). However, the soil treated with C-wise BB + Bednar had significantly greater nitrate-nitrogen and DTPA copper relative to the control (Figure 47A and E).

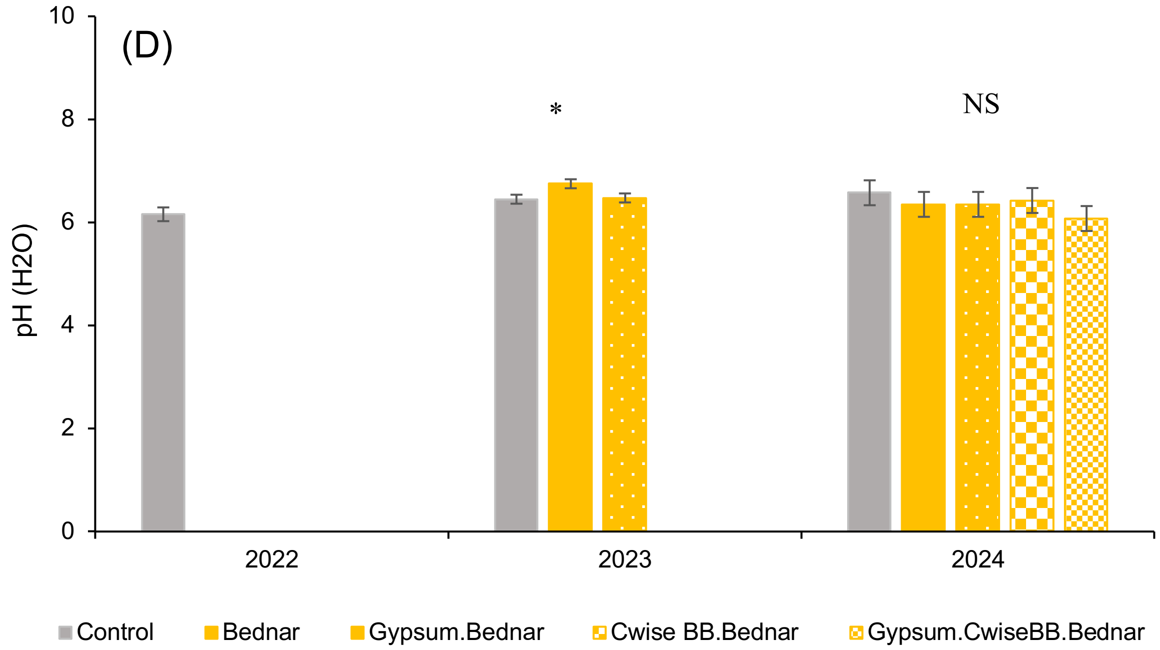
Contrasting to the large plots trial, changes in the physicochemical attributes of soil were detected in both the topsoil (0–10 cm) and sub-soil (10–30 cm) in the small plots (Figures 48 and 49). Compost-treated soil was found with a significantly greater value of Colwell phosphorus and potassium (mg/kg), DPTA copper, DTPA zinc, exchangeable calcium, exchangeable magnesium, exchangeable potassium, exchangeable sodium and boron hot $CaCl_2$ in the top 10 cm soil in the small plots trial (Figure 48). This is consistent with the greater NDVI recorded by in the compost treatments (Figure 43B). However, compost treatment did not stand out in the 10–30 cm soil profile (Figure 49).

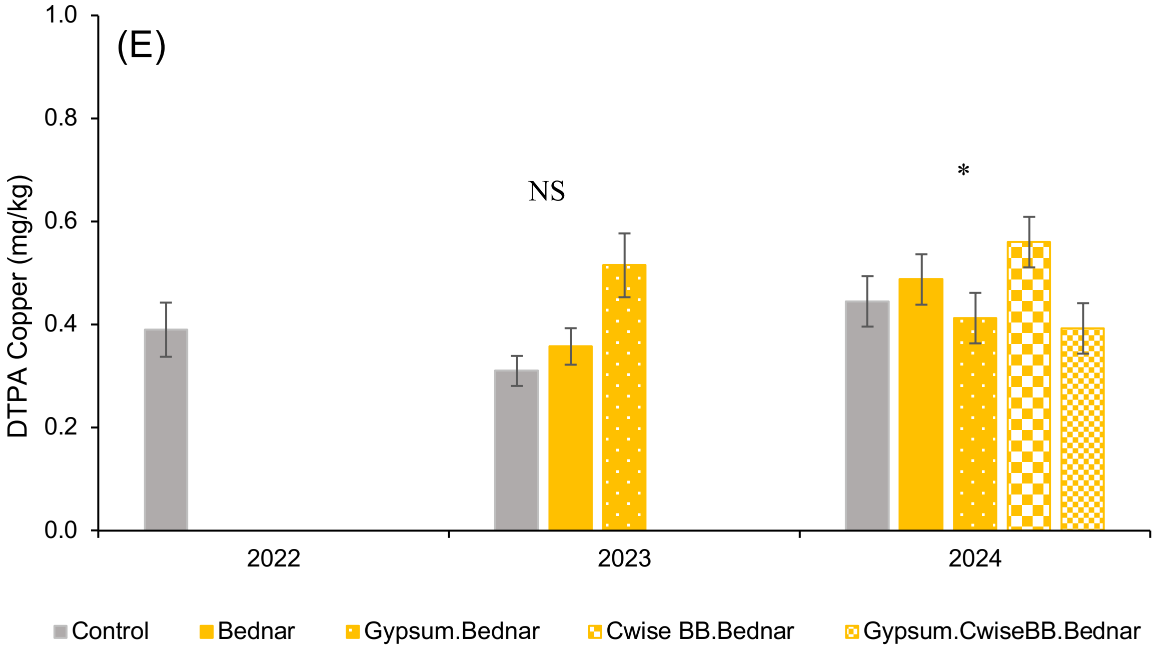
Soil moisture data have been collected and are currently being organised and analysed.

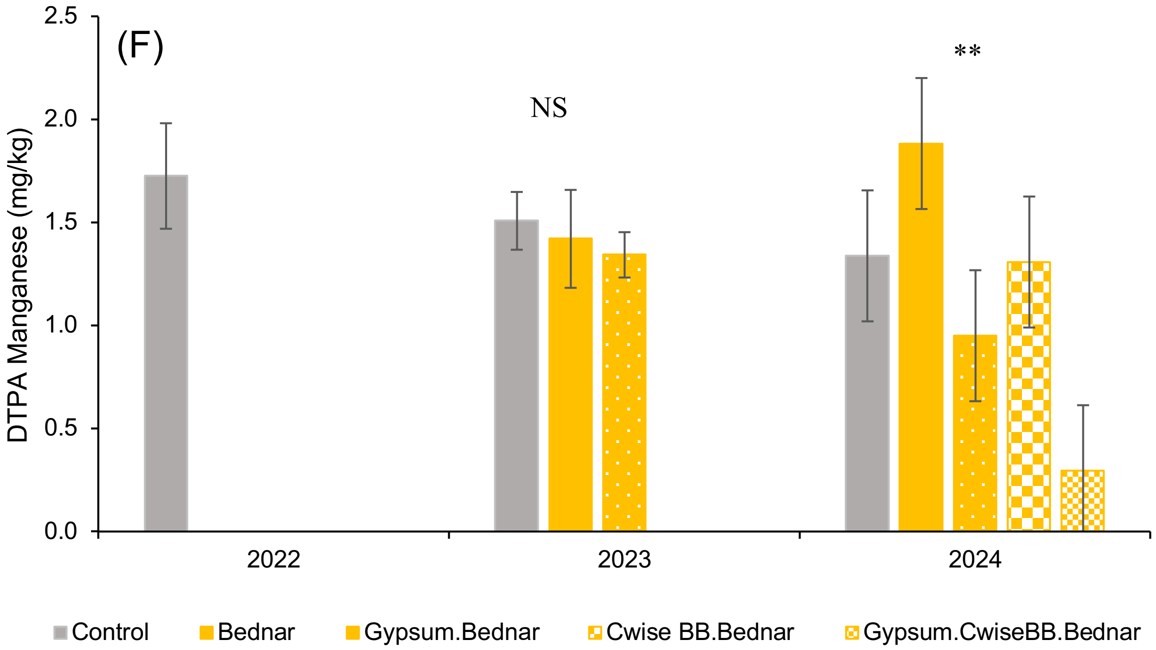

(A)
Nitrate Nitrogen (mg/kg)
0
5
10
15
20
25
30
35
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar

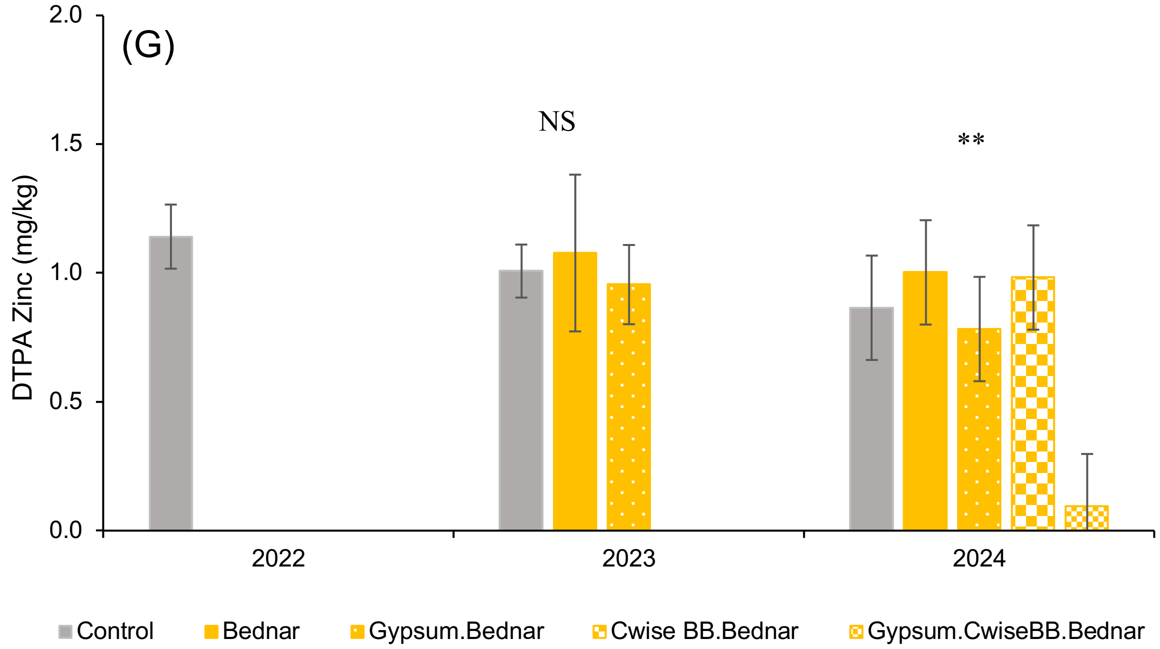

(B)
Organic Carbon (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
NS
***
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar

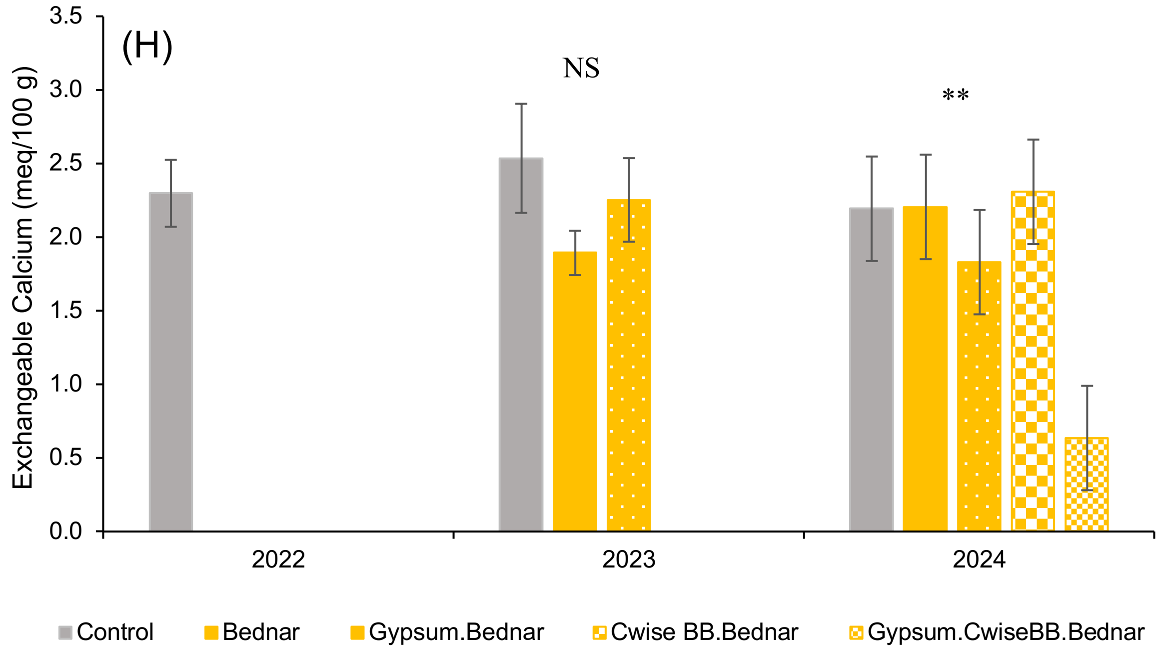

(C)
Conductivity (dS/m)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
NS
*
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(D)
pH (H2O)
10
8
6
4
2
0
*
NS
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(E)
DTPA Copper (mg/kg)
1.0
0.8
0.6
0.4
0.2
0.0
NS
*
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(F)
DTPA Manganese (mg/kg)
2.5
2.0
1.5
1.0
0.5
0.0
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(G)
DTPA Zinc (mg/kg)
2.0
1.5
1.0
0.5
0.0
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar


(H)
Exchangeable Calcium (meq/100 g)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
NS
**
2022
2023
2024
Control
Bednar
Gypsum.Bednar
Cwise BB.Bednar
Gypsum.CwiseBB.Bednar

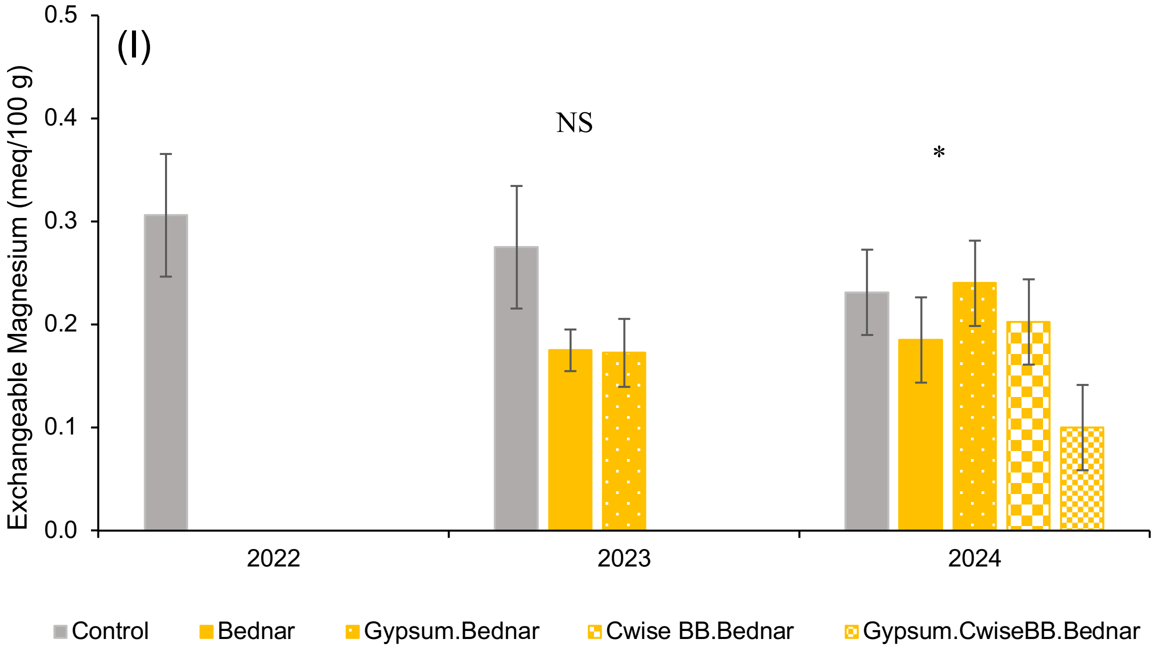


Figure 47. Soil physico-chemical properties and nutrients in 0–10 cm profile in the large plots experiment during different years (2022–24). **(A)** Nitrate nitrogen (mg/kg). **(B)** Organic carbon (%). **(C)** Conductivity (dS/m). **(D)** pH (H_2O). **(E)** DTPA copper (mg/kg). **(F)** DTPA manganese (mg/kg). **(G)** DTPA zinc (mg/kg). **(H)** Exchangeable calcium (meq/100 g). **(I)** Exchangeable magnesium (meq/100 g). NS = $P > 0.1$, † = $P < 0.1$, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$.

Table 16. Soil properties (0–10 cm) measured in different soil treatments in the large plots experiment at Kweda in 2023 and 2024. Samples were taken each year before seeding. Data is the mean of four reps ± standard error of the mean (n = 4) (- indicates no data).

Soil properties	Year	Control	Bednar	Gypsum.Bednar	CWise BB.Bednar	Gypsum.Cwise BB.Bednar
Ammonium nitrogen (mg/kg)	2022	2.51 ± 0.28	-	-	-	-
	2023	0.95 ± 0.03	1.95 ± 0.61	0.98 ± 0.03	-	-
	2024	4.61 ± 1.2	6.73 ± 5.1	4.7 ± 3.44	5.48 ± 3.24	0.93 ± 0.03
Phosphorus Colwell (mg/kg)	2022	14.75 ± 0.81	-	-	-	-
	2023	14.5 ± 0.96	14.5 ± 0.87	13.5 ± 1.55	-	-
	2024	14.88 ± 2.66	13.25 ± 2.32	12.75 ± 1.44	14.75 ± 2.06	16.5 ± 2.47
Potassium Colwell (mg/kg)	2022	16.75 ± 3.82	-	-	-	-
	2023	10.48 ± 5.63	19.74 ± 7.79	10.98 ± 5.8	-	-
	2024	30.63 ± 3.35	29.75 ± 3.73	29.5 ± 4.35	27 ± 5.02	21.75 ± 5.92
Sulphur (mg/kg)	2022	5.98 ± 0.46	-	-	-	-
	2023	3.7 ± 1.81	6.83 ± 4.35	14.88 ± 4.05	-	-
	2024	16.38 ± 8	18 ± 8.33	12.33 ± 3.97	19.73 ± 8.75	3.48 ± 1.04
pH level ($CaCl_2$)	2022	5.69 ± 0.11	-	-	-	-
	2023	5.85 ± 0.06	6.13 ± 0.13	5.9 ± 0.09	-	-
	2024	5.85 ± 0.2	5.7 ± 0.15	5.68 ± 0.1	5.85 ± 0.21	5.13 ± 0.23
DTPA iron (mg/kg)	2022	17.8 ± 6.52	-	-	-	-
	2023	10.65 ± 1.59	9.38 ± 0.5	9.13 ± 1.22	-	-
	2024	26.03 ± 11.2	27.18 ± 13.02	17.58 ± 4.91	17.23 ± 3.72	20.4 ± 5.89
Exc. aluminium (meq/100 g)	2022	0.16 ± 0.02	-	-	-	-
	2023	0.05 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	-	-
	2024	0.06 ± 0.02	0.06 ± 0	0.04 ± 0.01	0.05 ± 0.01	0.1 ± 0.03
Exc. potassium (meq/100 g)	2022	0.04 ± 0.01	-	-	-	-
	2023	0.05 ± 0.01	0.06 ± 0.02	0.05 ± 0.01	-	-
	2024	0.07 ± 0.01	0.06 ± 0.01	0.08 ± 0.01	0.05 ± 0	0.05 ± 0.01

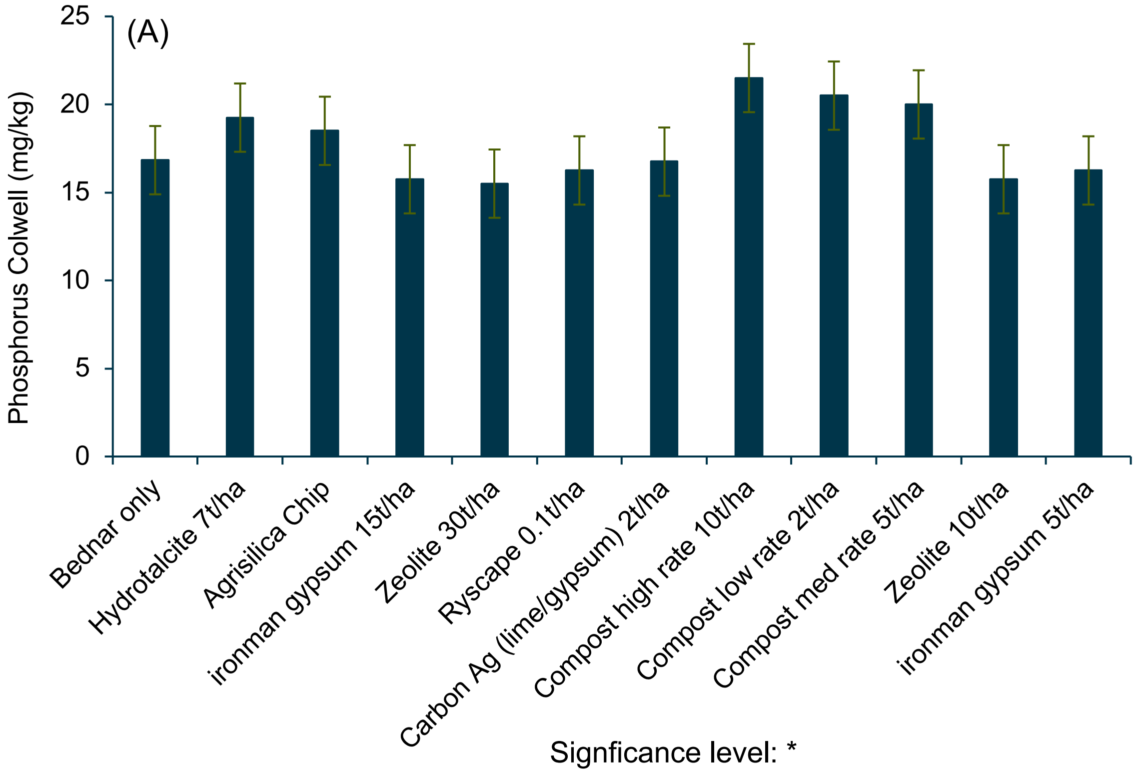
Soil properties	Year	Control	Bednar	Gypsum.Bednar	CWise BB.Bednar	Gypsum.Cwise BB.Bednar
Exc. sodium (meq/100 g)	2022	0.06 ± 0.01	-	-	-	-
	2023	0.05 ± 0.01	0.02 ± 0	0.05 ± 0.01	-	-
	2024	0.06 ± 0.03	0.05 ± 0.02	0.05 ± 0.02	0.06 ± 0.02	0.02 ± 0
Aluminium $CaCl_2$	2022	1 ± 0	-	-	-	-
	2023	-	-	-	-	-
	2024	0.61 ± 0.2	0.57 ± 0.16	0.44 ± 0.04	0.33 ± 0.07	0.86 ± 0.08
Boron hot $CaCl_2$ (mg/kg)	2022	0.26 ± 0.03	-	-	-	-
	2023	0.23 ± 0.03	0.19 ± 0.03	0.18 ± 0.02	-	-
	2024	0.22 ± 0.03	0.21 ± 0.02	0.18 ± 0.02	0.22 ± 0.02	0.21 ± 0.03
PBI	2022	7.15 ± 1.2	-	-	-	-
	2023	3.93 ± 1.39	5.75 ± 1.43	7.8 ± 2.64	-	-
	2024	8.23 ± 0.35	11.7 ± 0.31	7.45 ± 0.91	8.45 ± 1.53	22.4 ± 8.93

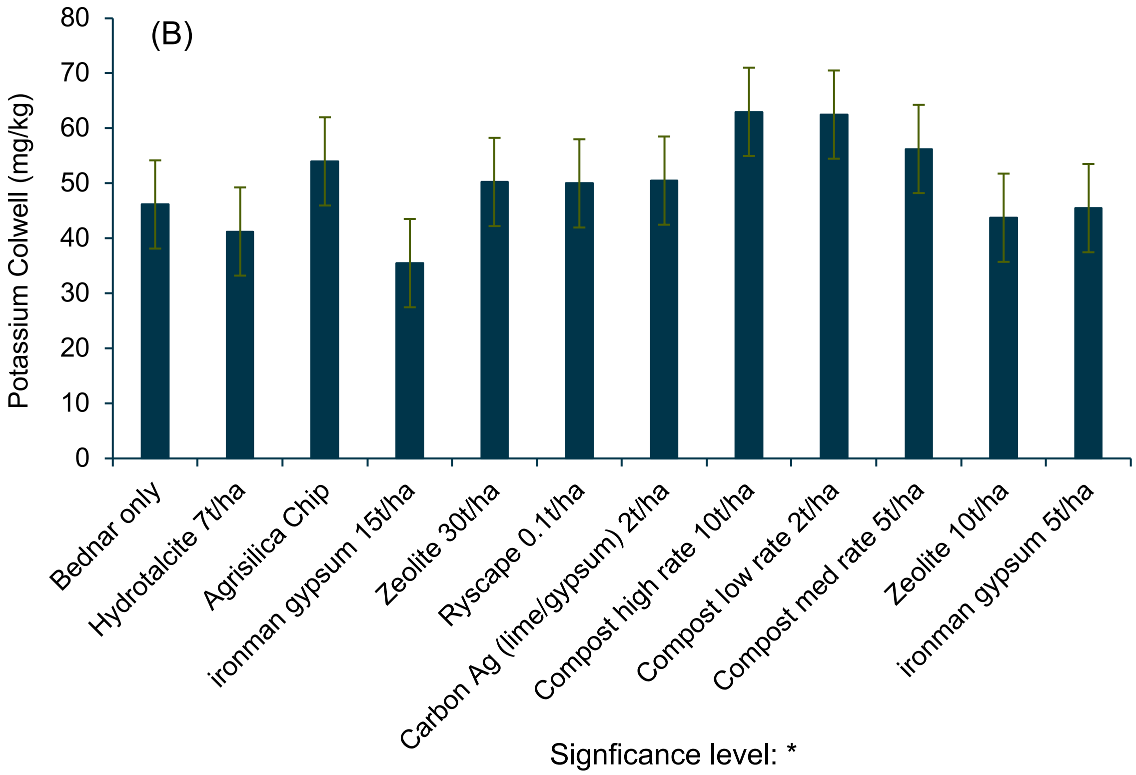
Table 17. Soil properties (0–30 cm) measured in different soil treatments of the large plots experiment at Kweda in 2023 and 2024. Samples were taken each year before seeding. Data is the mean of four reps ± standard error of the mean (n = 4) (- indicates no data).

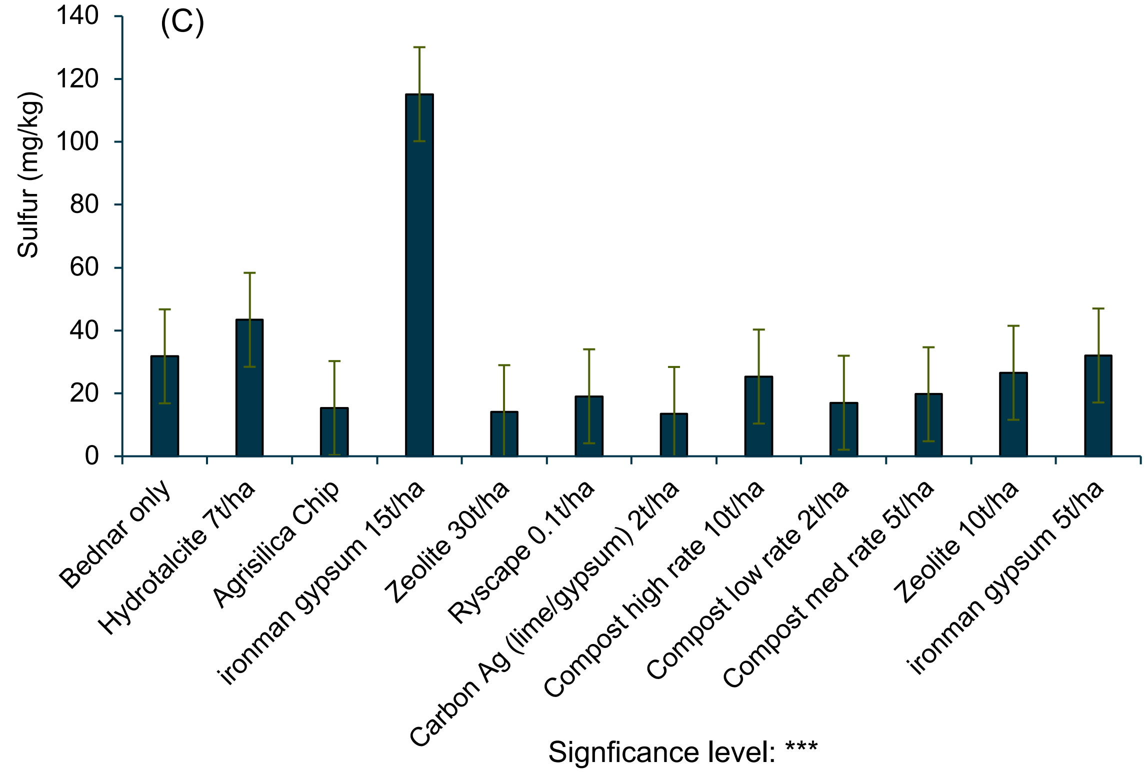
Soil properties	Year	Control	Bednar	Gypsum. Bednar	Cwise BB.Bednar	Gypsum.CwiseBB.Bednar
Ammonium nitrogen (mg/kg)	2022	1.14 ± 0.1	-	-	-	-
	2023	0.9 ± 0	0.93 ± 0.03	0.9 ± 0	-	-
	2024	0.9 ± 0	0.93 ± 0.03	0.9 ± 0	0.93 ± 0.03	0.9 ± 0
Nitrate nitrogen (mg/kg)	2022	2.5 ± 0.14	-	-	-	-
	2023	1 ± 0	5.75 ± 3.77	2 ± 0.41	-	-
	2024	5.1 ± 0.63	8.5 ± 2.1	7.25 ± 1.44	6.5 ± 0.65	5.75 ± 0.85
Phosphorus Colwell (mg/kg)	2022	21.1 ± 8.49	-	-	-	-
	2023	18 ± 3.16	12.75 ± 2.29	15 ± 1.78	-	-
	2024	17.5 ± 2.21	17.25 ± 0.85	15.75 ± 3.09	17 ± 2.55	16.25 ± 1.75
Potassium Colwell (mg/kg)	2022	13 ± 3	-	-	-	-
	2023	0.95 ± 0	4.96 ± 4.01	0.95 ± 0	-	-
	2024	18.7 ± 3.68	14.75 ± 0.25	20.75 ± 5.22	18.25 ± 1.11	14.5 ± 0.5
Sulphur (mg/kg)	2022	3.33 ± 0.88	-	-	-	-
	2023	0.58 ± 0.06	3.73 ± 2.86	2.2 ± 0.67	-	-
	2024	2.95 ± 0.91	2.93 ± 0.78	7.58 ± 2.98	4.1 ± 1.4	4.73 ± 0.78

Soil properties	Year	Control	Bednar	Gypsum. Bednar	Cwise BB.Bednar	Gypsum.CwiseBB.Bednar
Organic carbon (%)	2022	0.43 ± 0.18	-	-	-	-
	2023	0.14 ± 0.02	0.21 ± 0.03	0.19 ± 0.03	-	-
	2024	0.18 ± 0.01	0.31 ± 0.06	0.31 ± 0.04	0.25 ± 0.03	0.18 ± 0.02
Conductivity (dS/m)	2022	0.02 ± 0	-	-	-	-
	2023	0.01 ± 0	0.03 ± 0.02	0.02 ± 0	-	-
	2024	0.02 ± 0	0.03 ± 0	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0
pH Level ($CaCl_2$)	2022	4.92 ± 0.18	-	-	-	-
	2023	5.1 ± 0.09	5.28 ± 0.05	5.33 ± 0.16	-	-
	2024	5 ± 0.12	5 ± 0.04	4.78 ± 0.13	5.05 ± 0.09	5 ± 0.04
pH level (H_2O)	2022	5.73 ± 0.12	-	-	-	-
	2023	6.03 ± 0.07	6.15 ± 0.06	6.08 ± 0.22	-	-
	2024	5.9 ± 0.11	5.93 ± 0.05	5.55 ± 0.18	5.88 ± 0.13	5.8 ± 0.04
DTPA copper (mg/kg)	2022	0.11 ± 0.01	-	-	-	-
	2023	0.21 ± 0.02	0.34 ± 0.05	0.32 ± 0.02	-	-
	2024	0.32 ± 0.05	0.36 ± 0.05	0.46 ± 0.07	0.33 ± 0	0.29 ± 0.03
DTPA iron (mg/kg)	2022	16.27 ± 3.27	-	-	-	-
	2023	19.88 ± 6.47	11.43 ± 2.07	15.33 ± 3.7	-	-
	2024	24.08 ± 6.32	13.83 ± 3.07	30.05 ± 18.4	14.95 ± 3.47	15.48 ± 1.39
DTPA manganese (mg/kg)	2022	0.23 ± 0.06	-	-	-	-
	2023	0.51 ± 0.01	0.64 ± 0.06	0.57 ± 0.03	-	-
	2024	0.29 ± 0.07	0.33 ± 0.05	0.45 ± 0.17	0.26 ± 0.03	0.28 ± 0.03
DTPA zinc (mg/kg)	2022	0.21 ± 0.06	-	-	-	-
	2023	5.47 ± 2	3.58 ± 2.04	2.78 ± 1.4	-	-
	2024	0.18 ± 0.07	0.29 ± 0.08	0.17 ± 0.03	0.21 ± 0.04	0.13 ± 0.01
Exc. aluminium (meq/100 g)	2022	0.29 ± 0.07	-	-	-	-
	2023	0.1 ± 0.02	0.07 ± 0.01	0.07 ± 0.01	-	-
	2024	0.11 ± 0.02	0.08 ± 0.01	0.17 ± 0.06	0.08 ± 0.01	0.09 ± 0.01
Exc. calcium (meq/100 g)	2022	0.47 ± 0.16	-	-	-	-
	2023	0.43 ± 0.05	0.76 ± 0.15	0.7 ± 0.09	-	-
	2024	0.5 ± 0.12	0.78 ± 0.2	0.68 ± 0.09	0.64 ± 0.08	0.57 ± 0.05
Exc. magnesium (meq/100 g)	2022	0.11 ± 0.04	-	-	-	-
	2023	0.08 ± 0.02	0.1 ± 0.03	0.07 ± 0.01	-	-
	2024	0.09 ± 0.01	0.1 ± 0.01	0.08 ± 0.01	0.1 ± 0.02	0.08 ± 0.01
Exc. potassium (meq/100 g)	2022	0.03 ± 0.02	-	-	-	-
	2023	0.04 ± 0	0.05 ± 0.01	0.04 ± 0	-	-
	2024	0.04 ± 0.01	0.04 ± 0	0.04 ± 0.01	0.04 ± 0	0.03 ± 0
Exc. sodium	2022	0.04 ± 0.01	-	-	-	-
	2023	0.01 ± 0	0.03 ± 0.02	0.02 ± 0.01	-	-

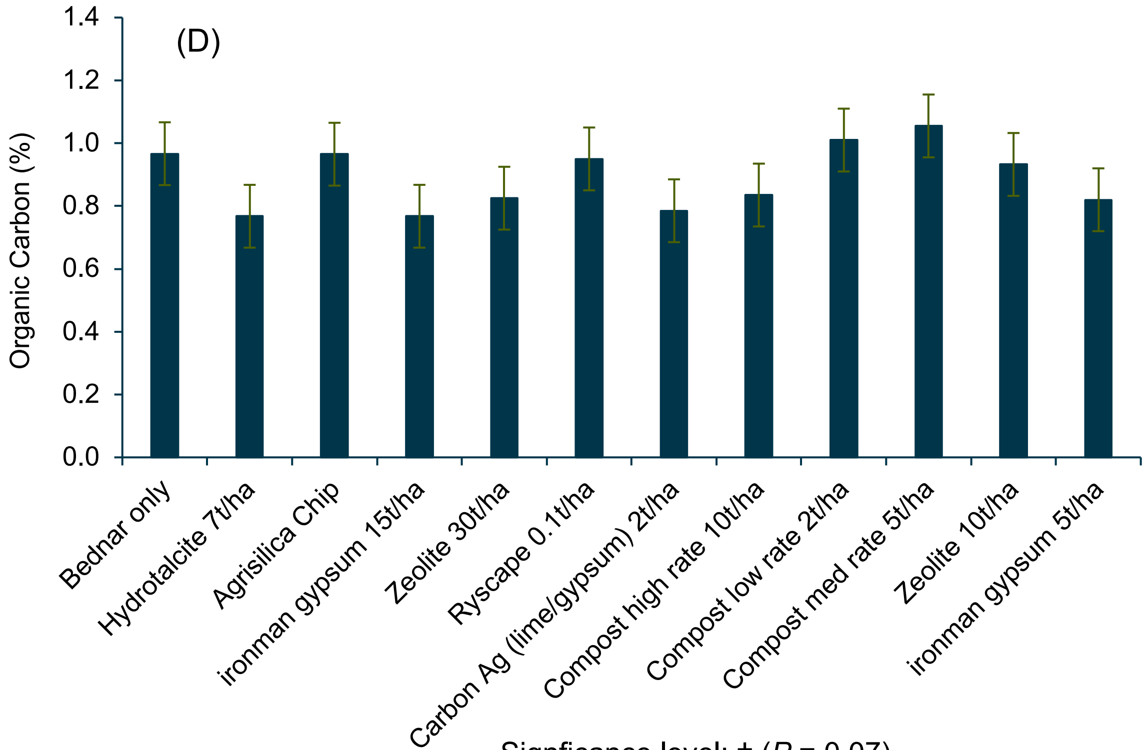
Soil properties	Year	Control	Bednar	Gypsum. Bednar	Cwise BB.Bednar	Gypsum.CwiseBB.Bednar
(meq/100 g)	2024	0.03 ± 0.01	0.02 ± 0	0.03 ± 0.02	0.02 ± 0.01	0.03 ± 0.01
Aluminium $CaCl_2$	2022	2.93 ± 0.63	-	-	-	-
	2023	-	-	-	-	-
	2024	1.24 ± 0.41	1.14 ± 0.18	2.17 ± 0.84	1.5 ± 0.18	1.43 ± 0.17
Boron hot $CaCl_2$ (mg/kg)	2022	0.17 ± 0.06	-	-	-	-
	2023	0.12 ± 0.01	0.14 ± 0.01	0.17 ± 0.05	-	-
	2024	0.22 ± 0.02	0.18 ± 0.01	0.24 ± 0.02	0.18 ± 0.01	0.19 ± 0.02
PBI	2022	16.05 ± 6.23	-	-	-	-
	2023	7 ± 2.27	9.03 ± 3.5	7.47 ± 2.04	-	-
	2024	17.49 ± 6.62	8.9 ± 0.9	8.9 ± 2.63	10.25 ± 0.92	12.03 ± 1.03


(A)
Phosphorus Colwell (mg/kg)
0
5
10
15
20
25
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: *

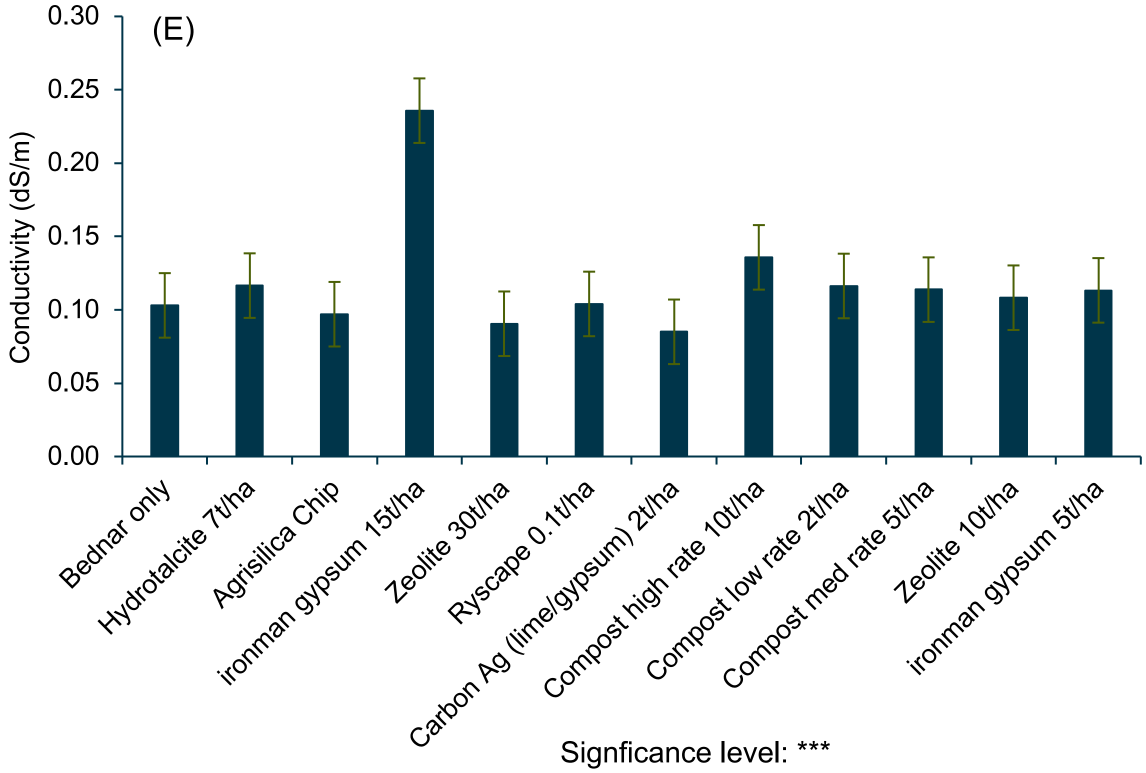

(B)
Potassium Colwell (mg/kg)
0
10
20
30
40
50
60
70
80
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: *



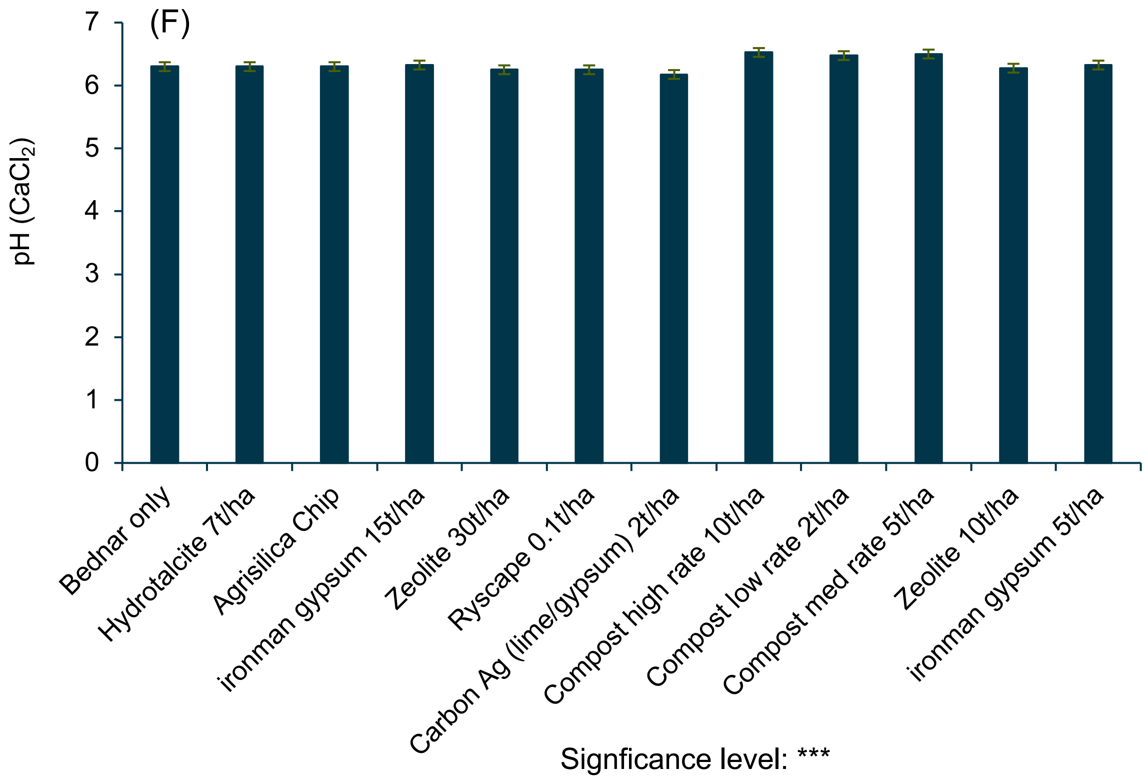
Signficance level: ***



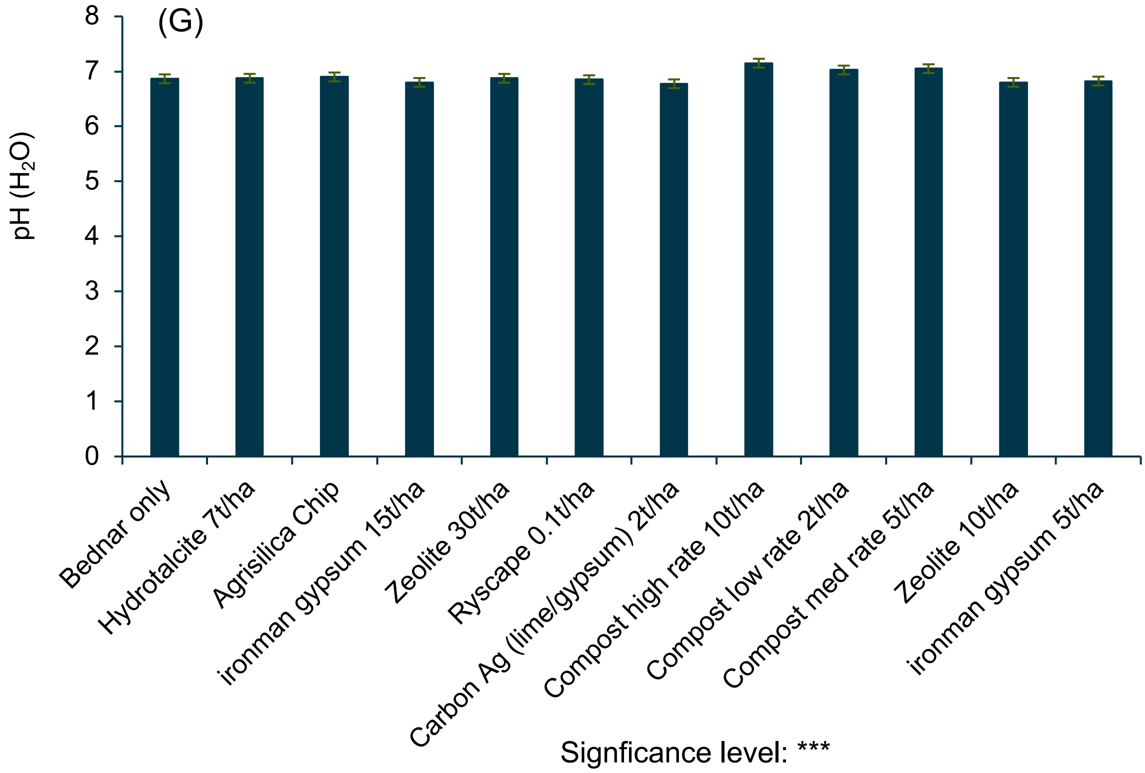
Signficance level: † (*P* = 0.07)

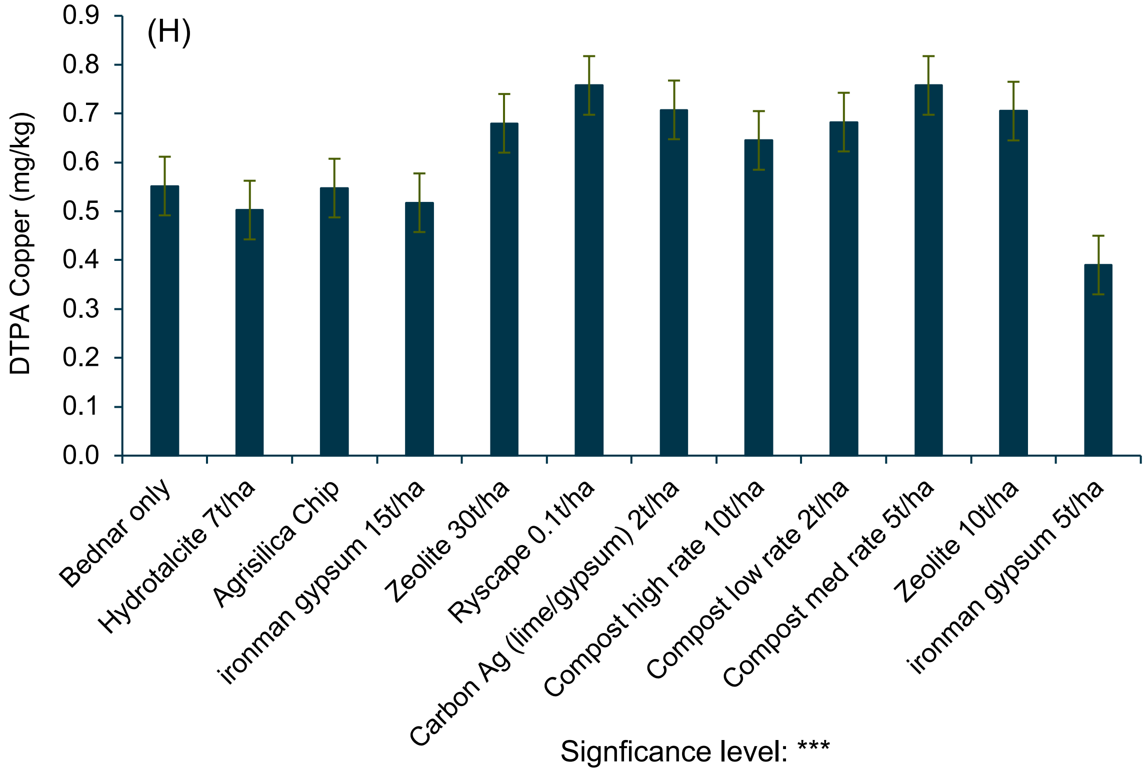


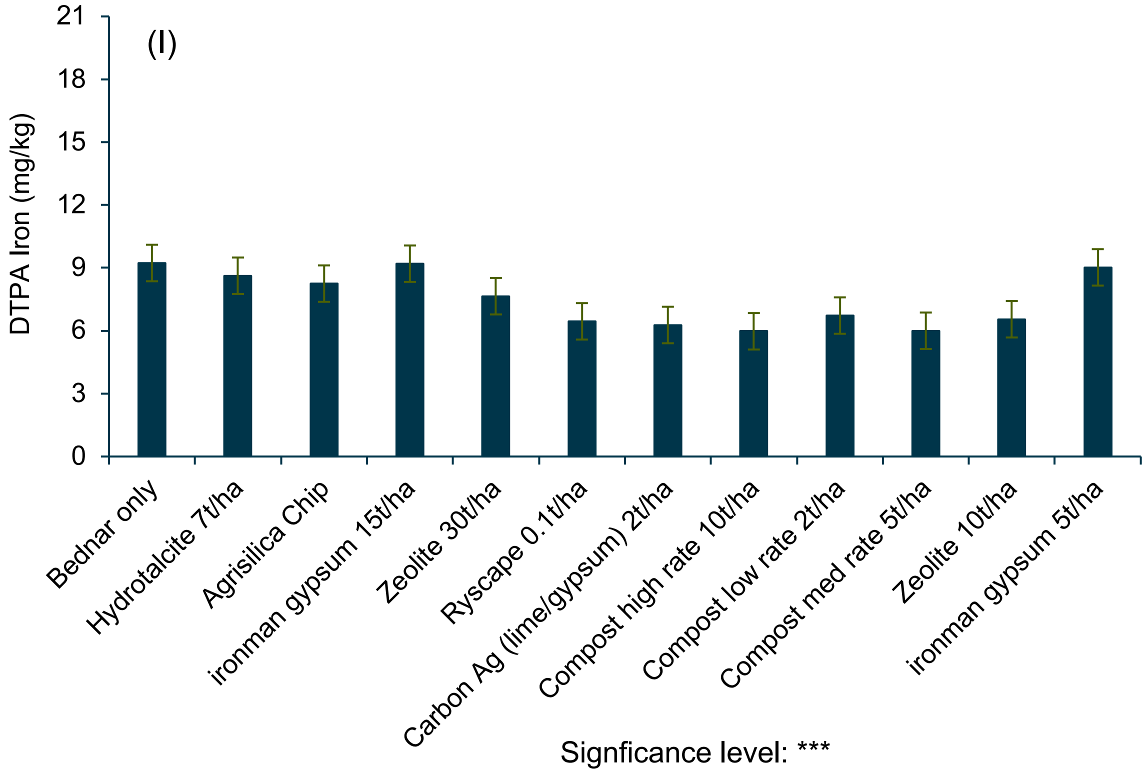
Signficance level: ***

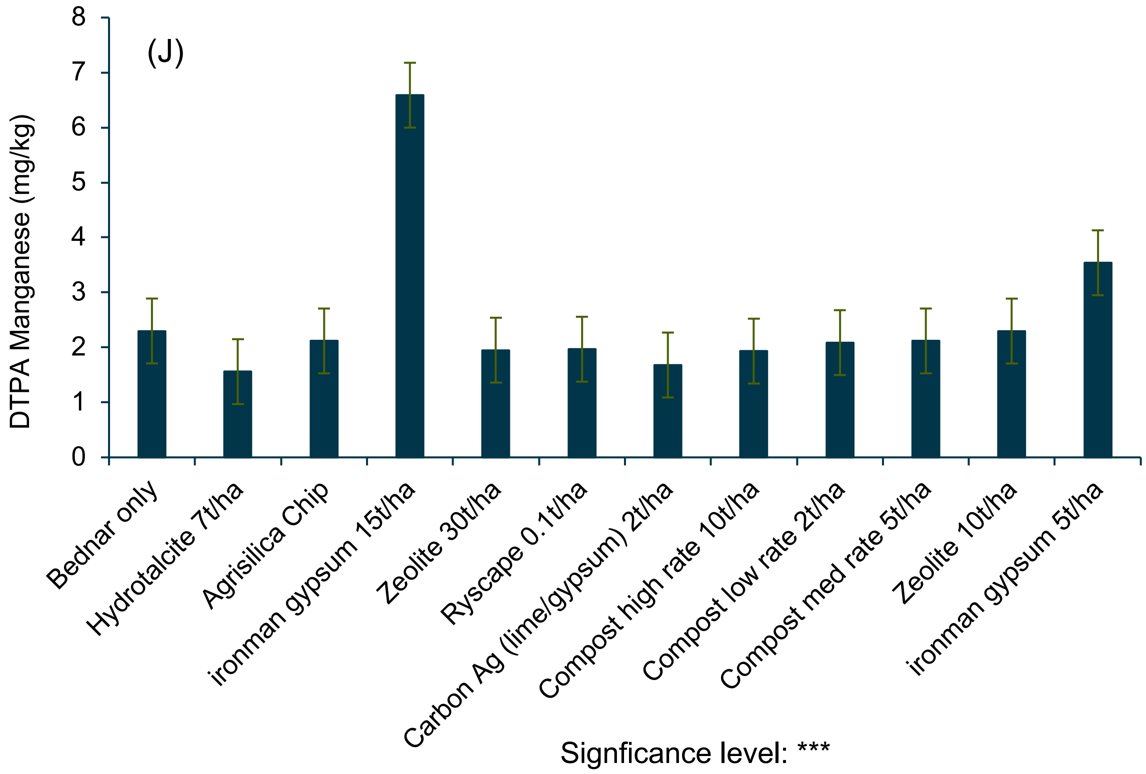


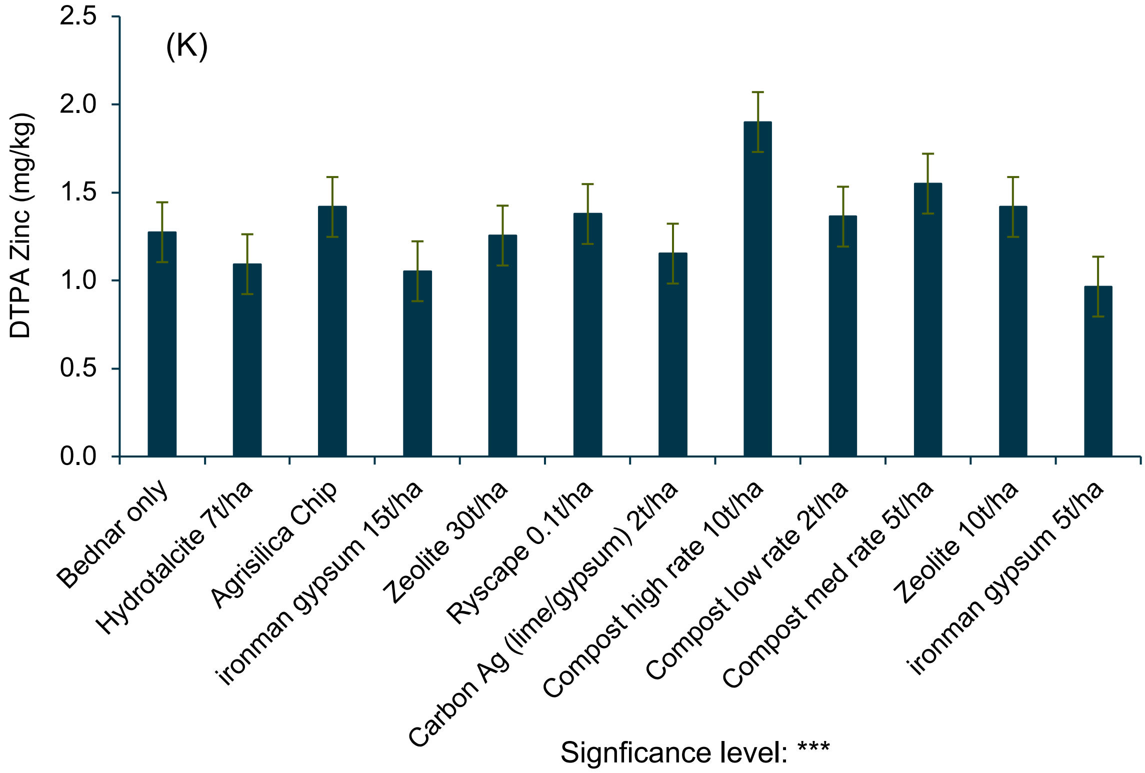
Signficance level: ***

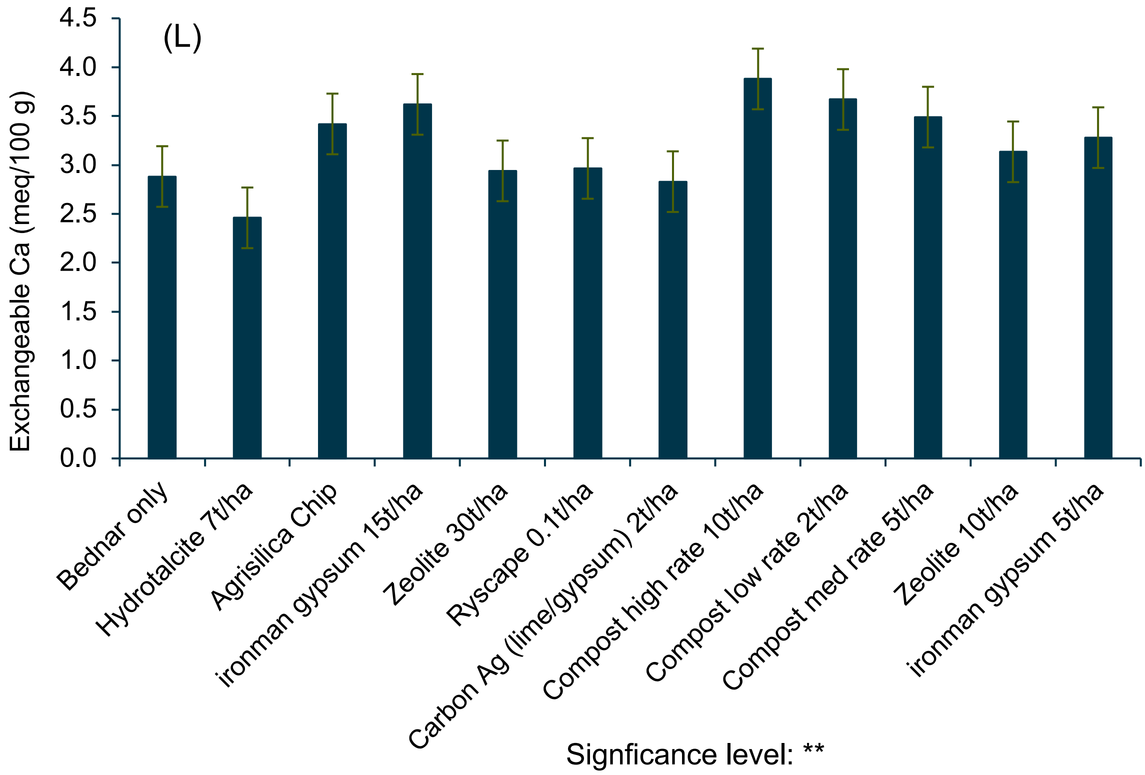

(G)
pH (H_2O)
0
1
2
3
4
5
6
7
8
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: ***

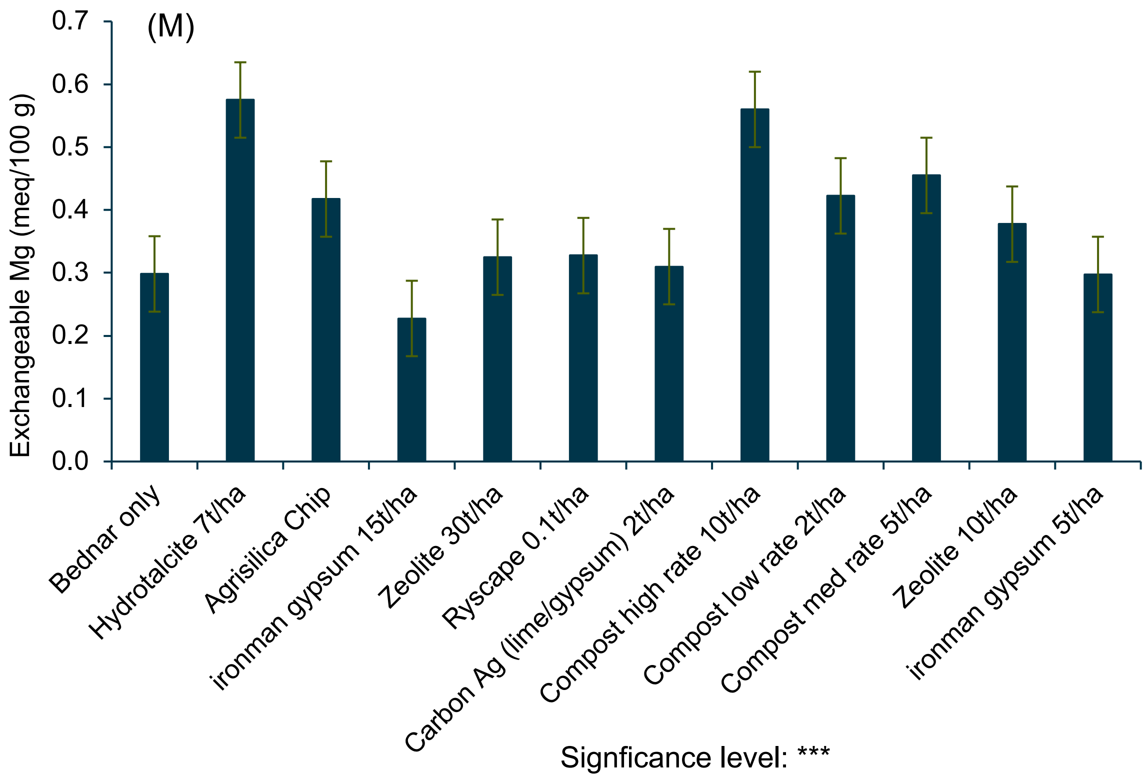

(H)
DTPA Copper (mg/kg)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: ***


(I)
DTPA Iron (mg/kg)
21
18
15
12
9
6
3
0
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: ***


(J)
DTPA Manganese (mg/kg)
8
7
6
5
4
3
2
1
0
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: ***


2.5
2.0
1.5
1.0
0.5
0.0
(K)
DTPA Zinc (mg/kg)
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: ***


4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
(L)
Exchangeable Ca (meq/100 g)
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: **



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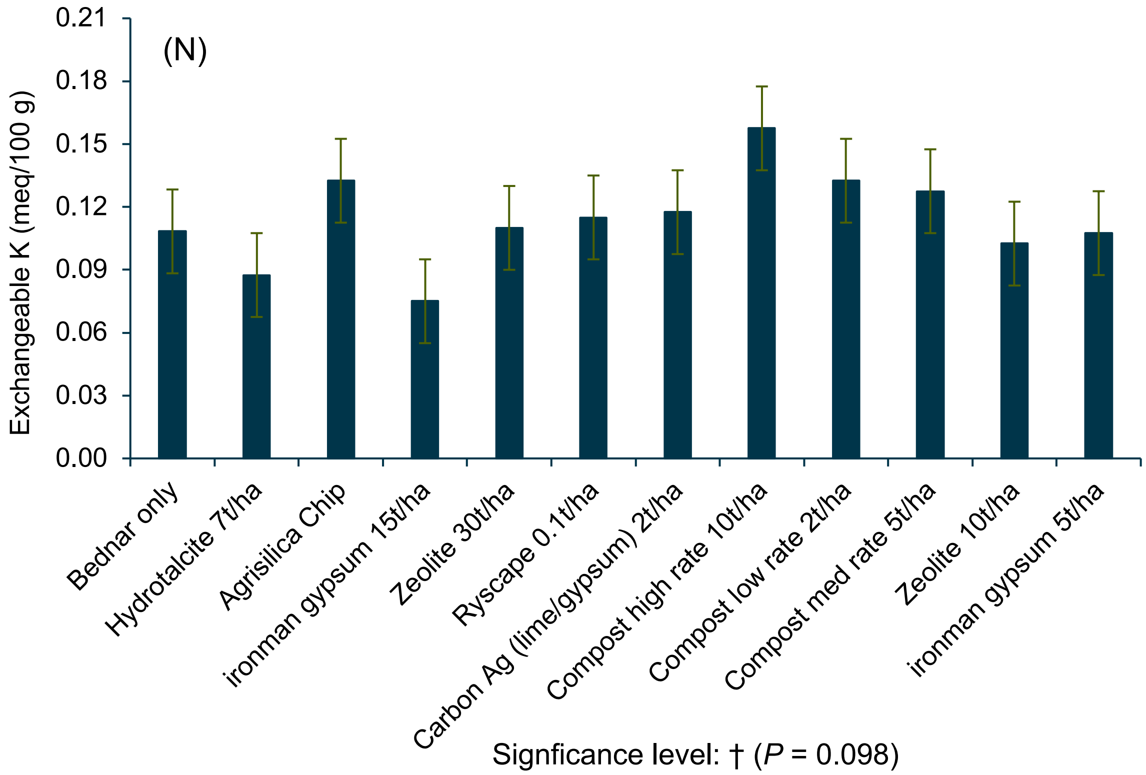
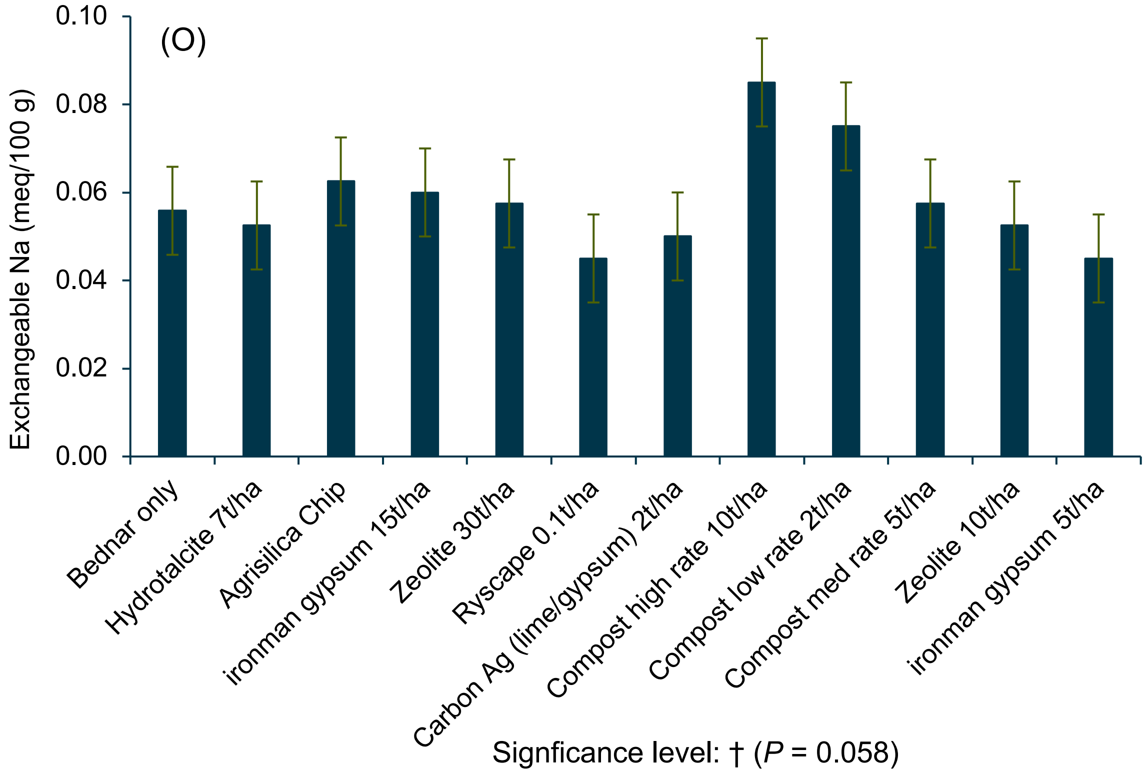
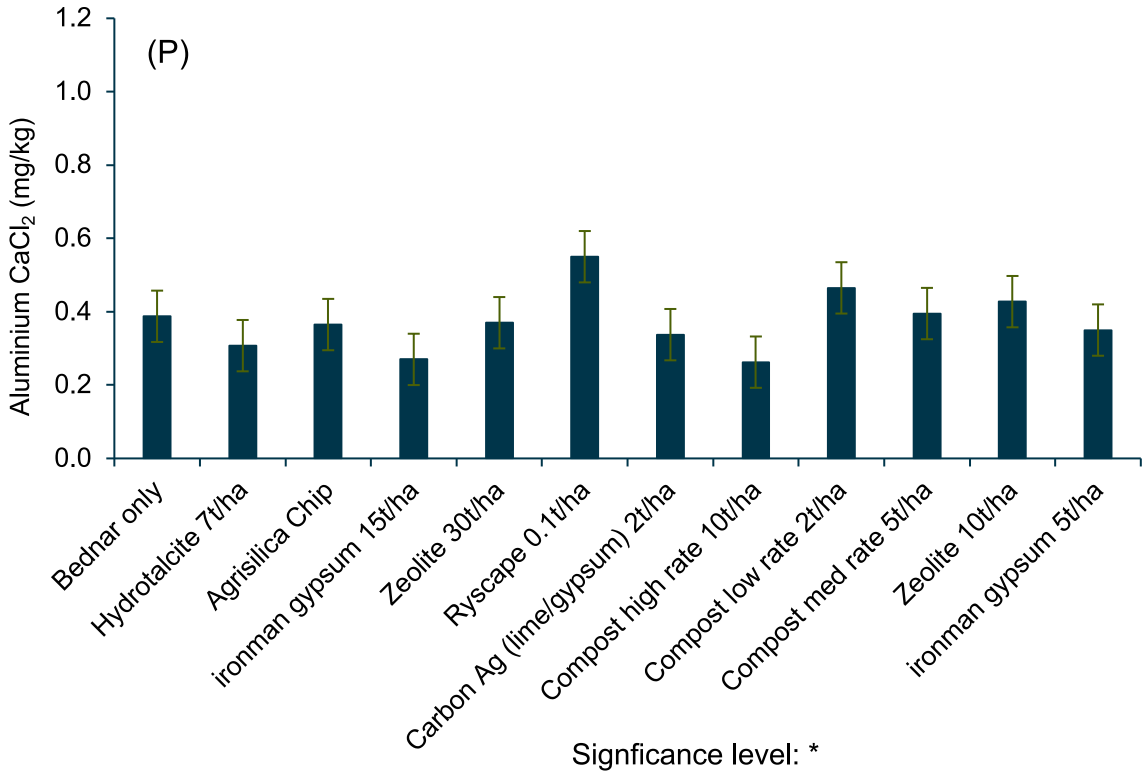


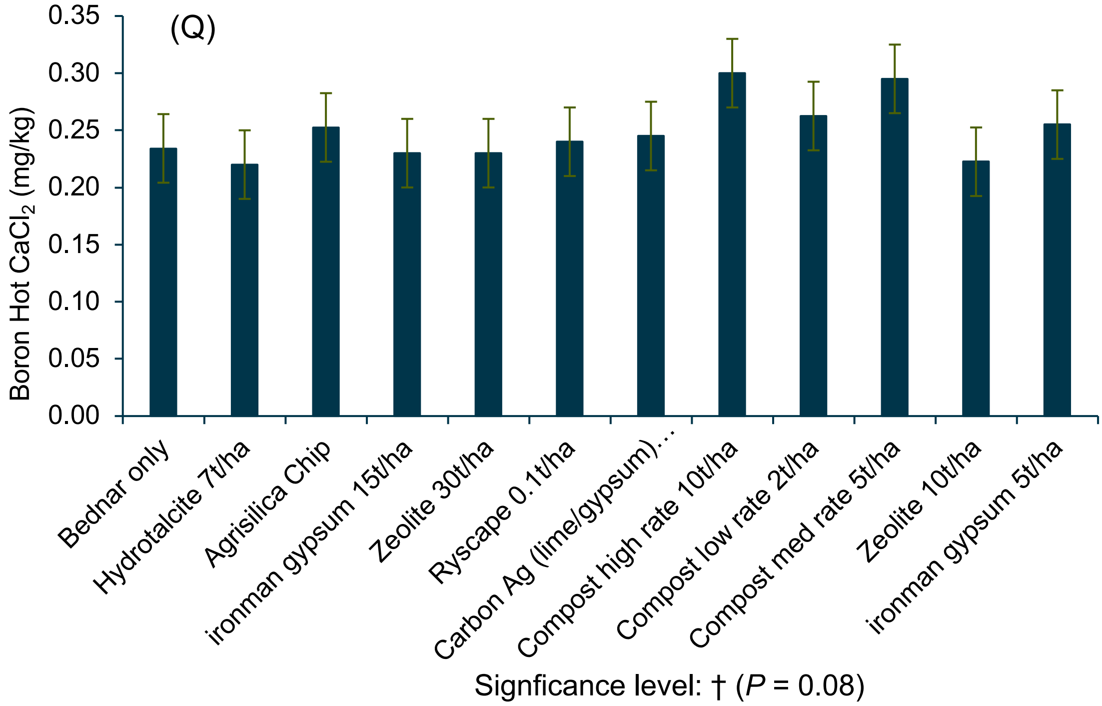
Signficance level: † (*P* = 0.098)



Signficance level: † (*P* = 0.058)



Signficance level: *



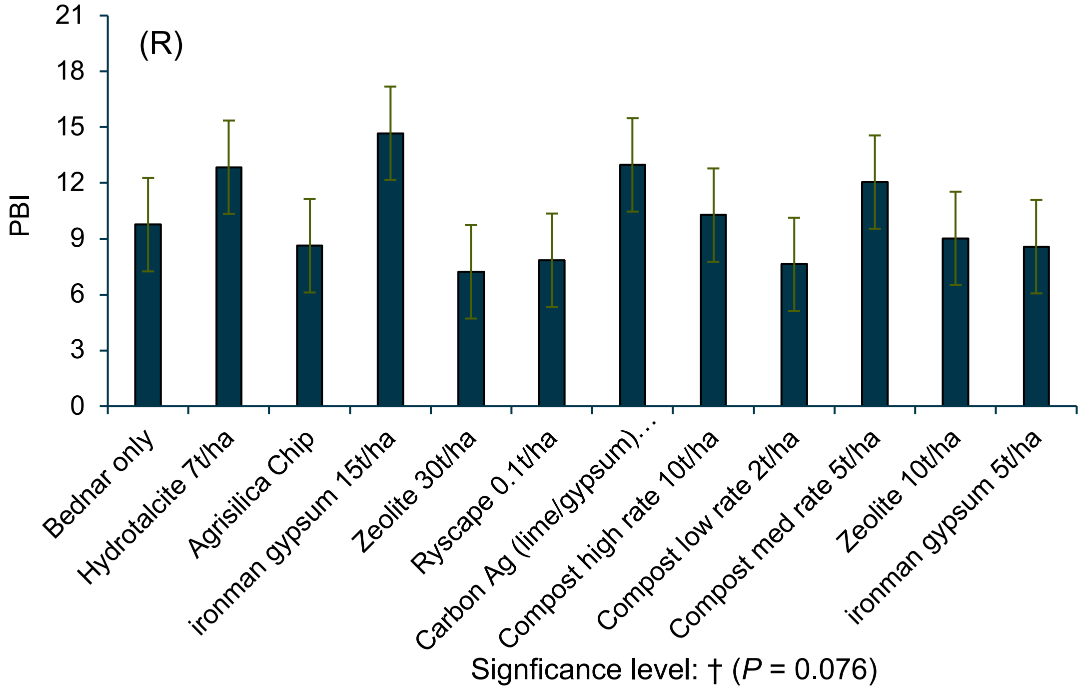
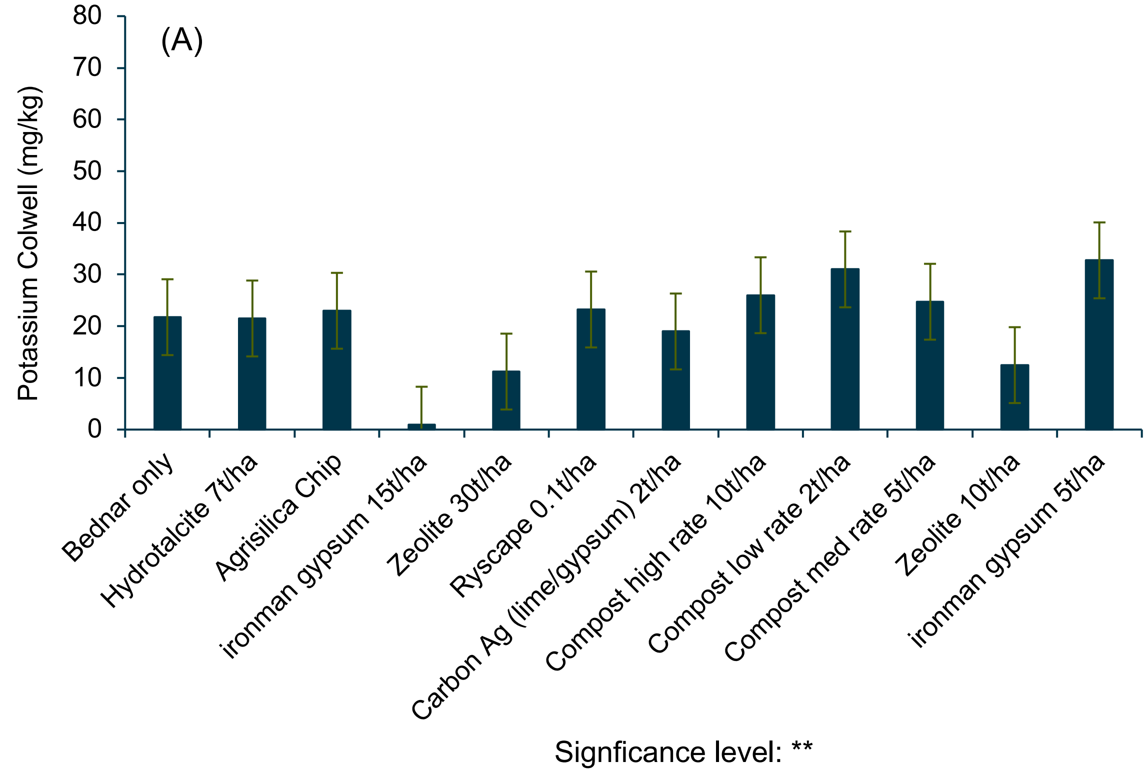
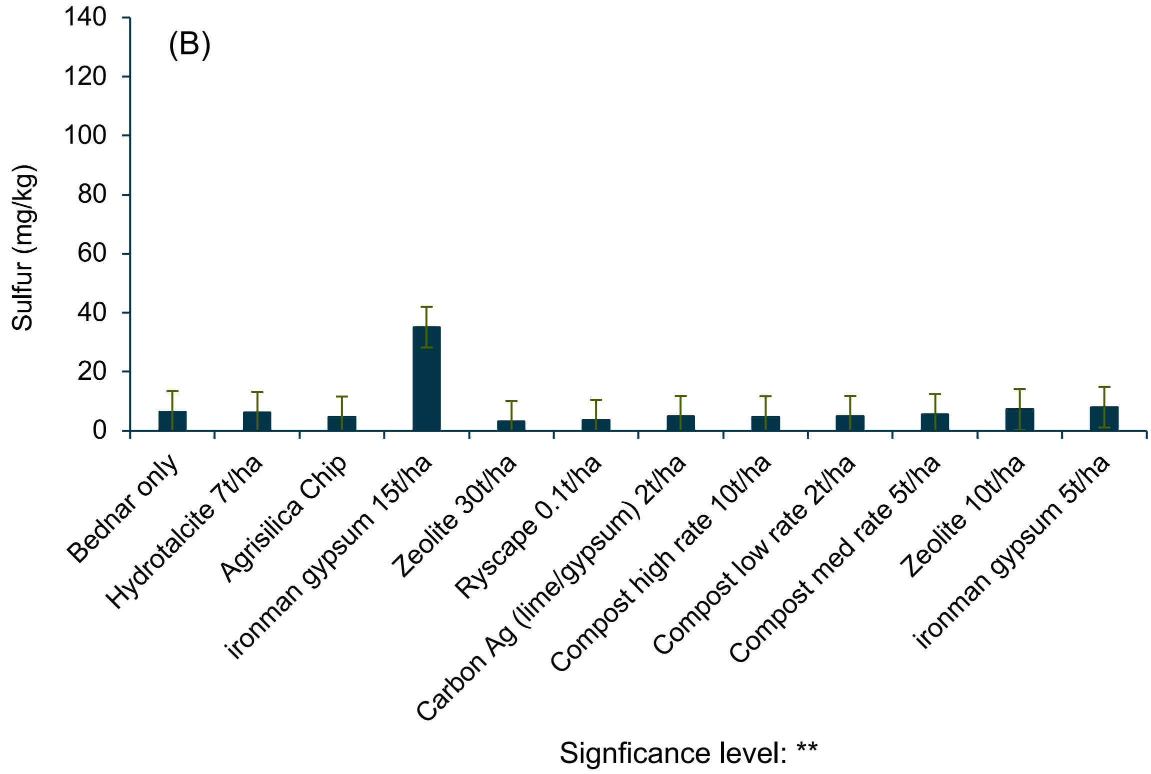
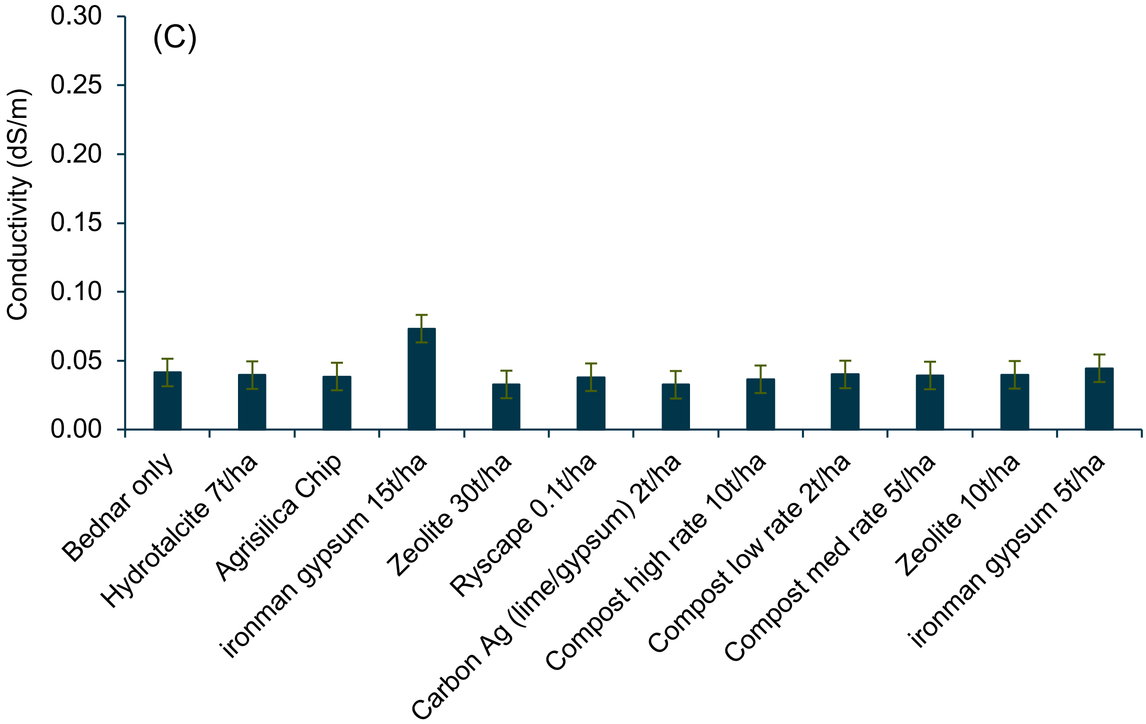


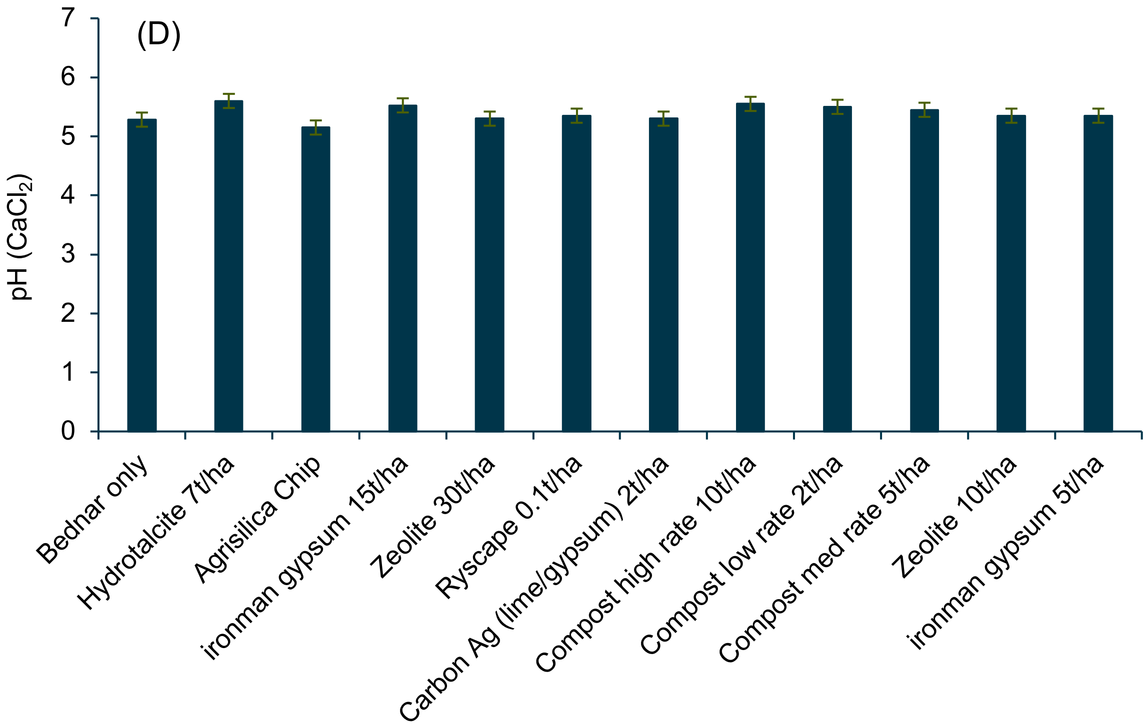
Figure 48. Soil physicochemical properties and nutrients in 0–10 cm profile in the small plots experiment during different years (2022–24). **(A)** Phosphorus Colwell (mg/kg). **(B)** Potassium Colwell (mg/kg). **(C)** Sulphur (mg/kg). **(D)** Organic carbon (%). **(E)** Conductivity (dS/m). **(F)** pH ($CaCl_2$). **(G)** pH (H_2O). **(H)** DTPA copper (mg/kg). **(I)** DTPA iron (mg/kg). **(J)** DTPA manganese (mg/kg). **(K)** DTPA zinc (mg/kg). **(L)** Exchangeable calcium (meq/100 g). **(M)** Exchangeable magnesium (meq/100 g). **(N)** Exchangeable potassium (meq/100 g). **(O)** Exchangeable sodium (meq/100 g). **(P)** Aluminium $CaCl_2$ (mg/kg). **(Q)** Boron $CaCl_2$ (mg/kg). **(R)** PBI. NS = $P > 0.1$, † = $P < 0.1$, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$.


(A)
Potassium Colwell (mg/kg)
80
70
60
50
40
30
20
10
0
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: **

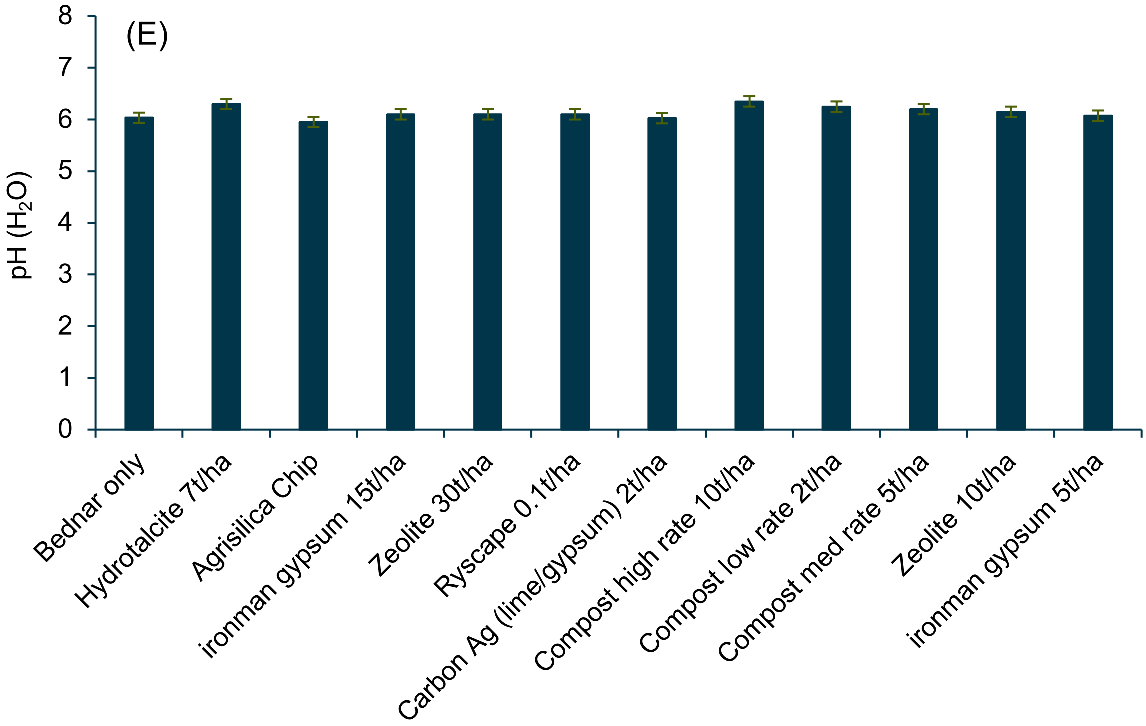

(B)
Sulfur (mg/kg)
140
120
100
80
60
40
20
0
Bednar only
Hydrotalcite 7t/ha
Agrisilica Chip
ironman gypsum 15t/ha
Zeolite 30t/ha
Ryscape 0.1t/ha
Carbon Ag (lime/gypsum) 2t/ha
Compost high rate 10t/ha
Compost low rate 2t/ha
Compost med rate 5t/ha
Zeolite 10t/ha
ironman gypsum 5t/ha
Signficance level: **



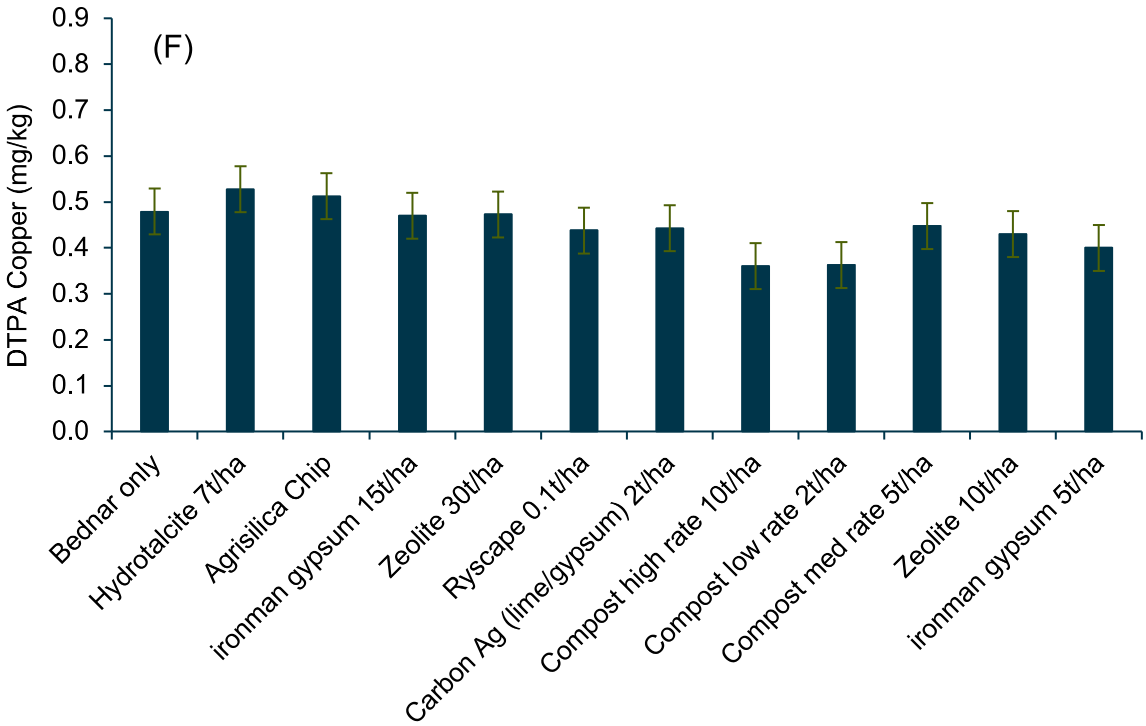
Signficance level: *



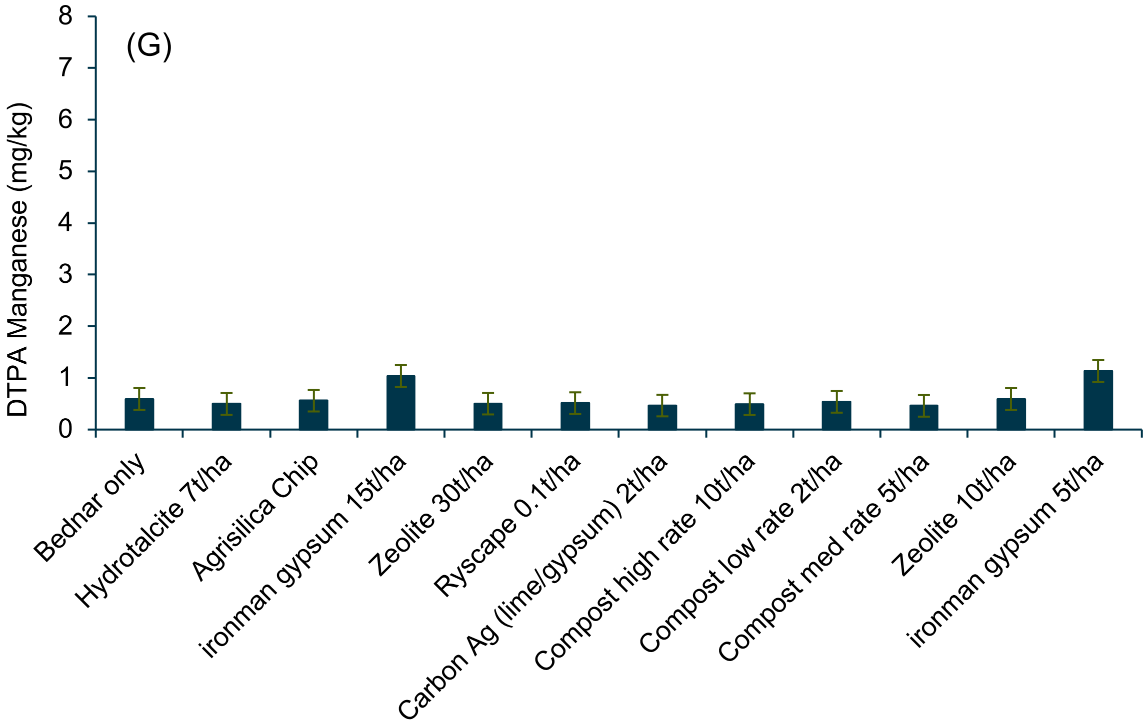
Signficance level: *



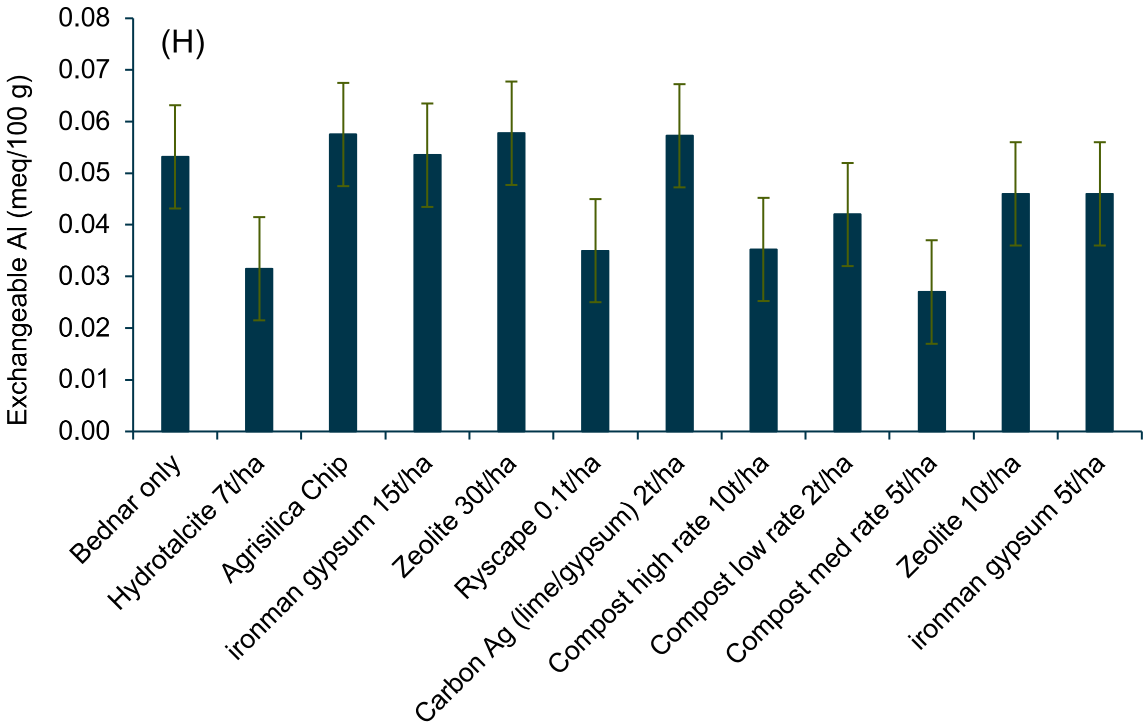
Signficance level: *



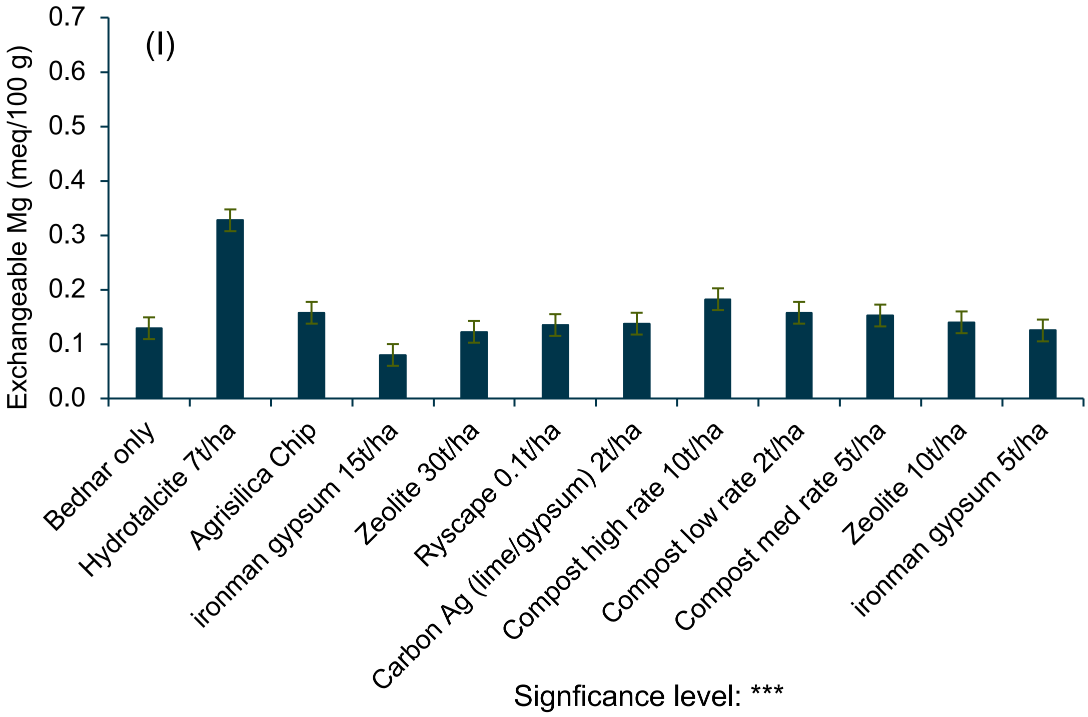
Signficance level: *



Signficance level: *



Signficance level: *



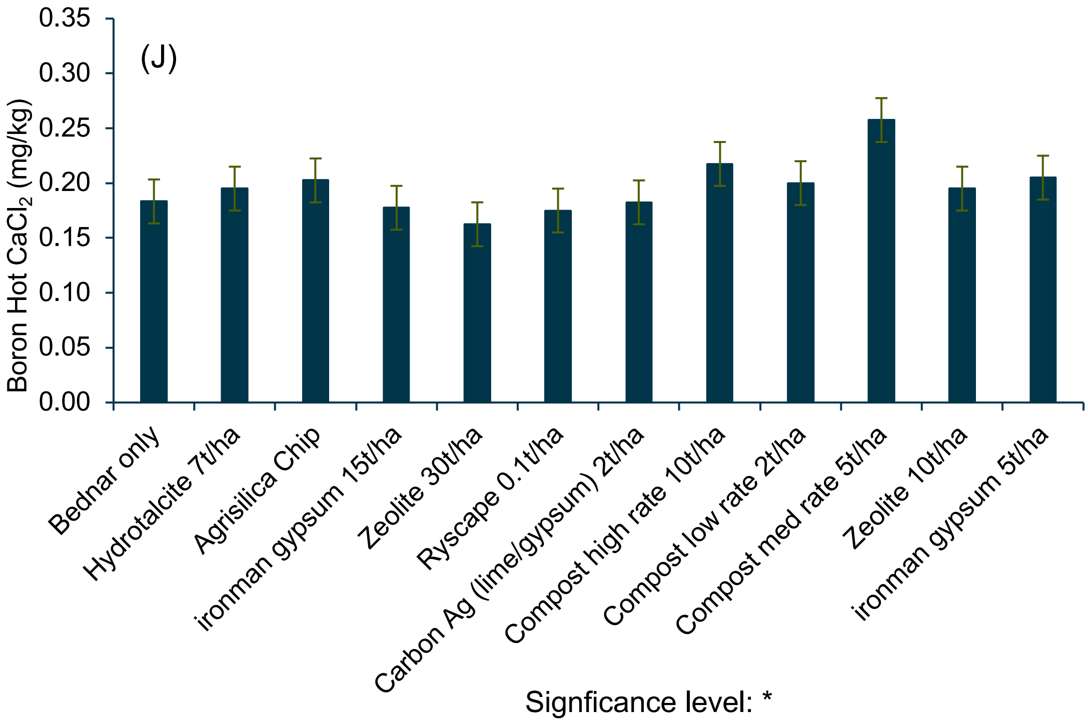


Figure 49. Soil physicochemical properties and nutrients in 10–30 cm profile in the small plots experiment during different years (2022–24). **(A)** Potassium Colwell (mg/kg). **(B)** Sulphur (mg/kg). **(C)** Conductivity (dS/m). **(D)** pH ($CaCl_2$). **(E)** pH (H_2O). **(F)** DTPA copper (mg/kg). **(G)** DTPA manganese (mg/kg). **(H)** Exchangeable aluminium (meq/100 g). **(I)** Exchangeable magnesium (meq/100 g). **(J)** Boron hot $CaCl_2$ (mg/kg). NS = $P > 0.1$, † = $P < 0.1$, * = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$.

Table 18. Soil properties (0–10 cm) measured in different soil treatments in the small plots experiment at Kweda in 2023 and 2024. Samples were taken each year before seeding. Data is the mean of four replications ± standard error of the treatment mean (n = 4).

Treatments	Ammonium nitrogen (mg/kg)	Nitrate nitrogen (mg/kg)	Organic carbon (%)	Exc. aluminium (meq/100 g)	Exc. potassium (meq/100 g)	Exc. sodium (meq/100 g)	Boron hot $CaCl_2$ (mg/kg)	PBI
Bednar only	12.58 ± 2.86	29.67 ± 3.79	0.97 ± 0.1	0.03 ± 0	0.11 ± 0.01	0.06 ± 0.01	0.23 ± 0.03	9.76 ± 1.42
Hydrotalcite 7t/ha	21.75 ± 14.87	26 ± 1.47	0.77 ± 0.08	0.03 ± 0	0.09 ± 0.01	0.05 ± 0	0.22 ± 0.02	12.85 ± 0.83
Agrisilica chip	7.25 ± 0.75	31.75 ± 3.17	0.97 ± 0.19	0.04 ± 0	0.13 ± 0.04	0.06 ± 0.02	0.25 ± 0.04	8.63 ± 3.06
Iron Man Gypsum 15 t/ha	16.5 ± 6.84	26.75 ± 3.71	0.77 ± 0.09	0.03 ± 0.01	0.08 ± 0.01	0.06 ± 0.02	0.23 ± 0.02	14.68 ± 1.59
Zeolite 30 t/ha	7.75 ± 1.7	27 ± 5.46	0.83 ± 0.16	0.04 ± 0.01	0.11 ± 0.02	0.06 ± 0.01	0.23 ± 0.03	7.23 ± 0.86
Ryscape 0.1 t/ha	10.75 ± 3.33	25 ± 5.48	0.95 ± 0.17	0.03 ± 0	0.12 ± 0.02	0.05 ± 0.01	0.24 ± 0.04	7.85 ± 1.04
Carbon Ag (lime/gypsum) 2 t/ha	6 ± 1.08	27.5 ± 6.03	0.79 ± 0.16	0.04 ± 0	0.12 ± 0.04	0.05 ± 0.02	0.25 ± 0.03	12.98 ± 2.24
Compost high rate 10 t/ha	13.25 ± 5.69	37.25 ± 3.75	0.835 ± 0.06	0.03375 ± 0	0.1575 ± 0.02	0.085 ± 0.01	0.3 ± 0.02	10.275 ± 1.17
Compost low rate 2 t/ha	6.75 ± 1.89	36.5 ± 6.59	1.01 ± 0.11	0.0405 ± 0.01	0.1325 ± 0.02	0.075 ± 0.02	0.2625 ± 0.03	7.625 ± 2.64
Compost med rate 5 t/ha	14.75 ± 5.94	28.75 ± 4.96	1.055 ± 0.17	0.0295 ± 0.01	0.1275 ± 0.03	0.0575 ± 0.01	0.295 ± 0.04	12.05 ± 1.66
Zeolite 10 t/ha	14.5 ± 3.71	24.5 ± 5.74	0.93 ± 0.17	0.05 ± 0	0.1 ± 0.02	0.05 ± 0.02	0.22 ± 0.04	9.03 ± 2.55
Iron Man Gypsum 5 t/ha	6.5 ± 1.85	27.25 ± 3.35	0.82 ± 0.12	0.03 ± 0	0.11 ± 0.02	0.05 ± 0.01	0.26 ± 0.05	8.58 ± 2.64

Table 19. Soil properties (10–30 cm) measured in different soil treatments in the small plots experiment at Kweda in 2023 and 2024. Samples were taken each year before seeding. Data is the mean of four replications ± standard error of the treatment mean (n = 4).

	Ammonium nitrogen (mg/kg)	Nitrate nitrogen (mg/kg)	Phosphorus Colwell (mg/kg)	Organic carbon (%)	DTPA iron (mg/kg)	DTPA zinc (mg/kg)	Exc. calcium (meq/100 g)	Exc. potassium (meq/100 g)	Exc. sodium (meq/100 g)	Aluminium $CaCl_2$ (mg/kg)	PBI
Bednar only	1 ± 0.09	9.08 ± 1.66	12 ± 1.24	0.43 ± 0.06	10.03 ± 2.68	0.51 ± 0.09	1.36 ± 0.17	0.05 ± 0	0.03 ± 0	0.75 ± 0.24	9.39 ± 0.93
Hydrotalcite 7 t/ha	0.9 ± 0	11.25 ± 2.02	12 ± 0.41	0.52 ± 0.06	8.28 ± 1.24	0.51 ± 0.03	1.57 ± 0.24	0.04 ± 0	0.04 ± 0.01	0.48 ± 0.04	6.9 ± 1.05
Agrisilica chip	1.45 ± 0.52	15.25 ± 3.94	14.75 ± 1.6	0.56 ± 0.11	11.55 ± 3.42	0.53 ± 0.1	1.5 ± 0.25	0.05 ± 0.01	0.04 ± 0.01	0.68 ± 0.11	8.15 ± 1.8
Iron Man Gypsum 15 t/ha	0.93 ± 0.03	11 ± 1.29	10.5 ± 1.26	0.39 ± 0.02	9.23 ± 3.04	0.34 ± 0.06	1.41 ± 0.07	0.04 ± 0.01	0.04 ± 0.01	0.51 ± 0.05	7.78 ± 0.94
Zeolite 30 t/ha	0.98 ± 0.03	11.25 ± 1.44	12 ± 1.22	0.48 ± 0.06	8.5 ± 2.28	0.44 ± 0.04	1.25 ± 0.14	0.04 ± 0.01	0.03 ± 0	0.49 ± 0.08	8.2 ± 2.04
Ryscape 0.1 t/ha	0.93 ± 0.03	13 ± 2.27	10.75 ± 1.11	0.43 ± 0.08	7.25 ± 1.03	0.47 ± 0.05	1.39 ± 0.16	0.05 ± 0.01	0.03 ± 0.01	0.65 ± 0.1	6.75 ± 1.56
Carbon Ag (lime/gypsum) 2 t/ha	0.9 ± 0	10 ± 1.47	11.25 ± 1.93	0.37 ± 0.05	8.03 ± 2.34	0.41 ± 0.06	1.42 ± 0.11	0.06 ± 0.01	0.03 ± 0.01	0.73 ± 0.22	9.68 ± 1.39
Compost high rate 10 t/ha	0.9 ± 0	11.75 ± 2.56	12.25 ± 0.63	0.47 ± 0.06	8 ± 0.96	0.62 ± 0.16	1.45 ± 0.17	0.06 ± 0	0.03 ± 0.01	0.44 ± 0.05	6.93 ± 0.93
Compost low rate 2 t/ha	0.93 ± 0.03	12.5 ± 1.44	12.25 ± 1.65	0.45 ± 0.04	8.25 ± 1.97	0.46 ± 0.04	1.55 ± 0.1	0.05 ± 0.01	0.03 ± 0.01	0.51 ± 0.06	9.03 ± 1.89

Compost med rate 5 t/ha	0.93 ± 0.03	13 ± 1.58	14.25 ± 1.44	0.47 ± 0.05	8.83 ± 2.61	0.47 ± 0.07	1.33 ± 0.16	0.05 ± 0.01	0.03 ± 0.01	0.51 ± 0.1	8.88 ± 0.83
Zeolite 10 t/ha	2.43 ± 1.53	13 ± 2.74	11.5 ± 0.87	0.58 ± 0.16	7.15 ± 1.9	0.43 ± 0.12	1.29 ± 0.3	0.04 ± 0.01	0.03 ± 0.01	0.7 ± 0.1	7.73 ± 1.01
Iron Man Gypsum 5 t/ha	1.48 ± 0.51	12.25 ± 1.11	13 ± 3.39	0.43 ± 0.04	11.75 ± 5.74	0.38 ± 0.03	1.24 ± 0.11	0.05 ± 0.01	0.03 ± 0.01	0.49 ± 0.13	8.58 ± 1.78

DISCUSSION

Clare, Qld, sugarcane trial

Due to the long length of the growing season for sugarcane, the Queensland site only had one harvest at time of writing, in July 2024. In a high-yielding season, all treatments had similar results for total tonnes of cane harvested, tonnes of sugar/ha, and Commercial Cane Sugar (CCS; %), with no significant treatment differences seen. It is important to note that this block did produce high tonnage and CCS in general. The high performance of the crop, also being plant cane which typically yields higher than ratoons, may have masked effects of the amendments since all treatments performed well, including the control. This could suggest none of the amendments make a difference to cane performance in this soil type. Or it may suggest they do not make a difference in the first year of application and first year of growing the crop. The latter has been found elsewhere in heavy soils with constraints from sodicity and dispersiveness (Armstrong et al., 2015; 2021; McPhee et al., 2023). This trial is still in the early stages, therefore, and little if any conclusions can be drawn at present. It will be interesting to see what the results are over the following consecutive years of ratooning the crop, where yields will be expected to be reduced compared to the first year. Several site tours have been held over the course of the first year of the trial, generating a lot of interest from local growers and industry advisers.

Lockhart, NSW, broadacre crops trial

This trial examines the effects of novel subsoil and subsurface amelioration on crop production and water use on a constrained soil, with the long-term aim to provide multiple-year data to properly assess the longevity of treatment effects and hence ultimately the economic viability of such interventions at a paddock/farm scale.

There was large variability in rainfall at the site in the first two years of this trial. Rainfall in the growing season in 2022 was at decile 8, whereas in 2023 it was decile 3. There were several statistically significant treatment effects observed in the first year in the faba bean crop. However, these were of an inconsistent nature, such as the deep organic matter (CP1) treatment having the lowest grain yield whereas the deep OM (CP1) with the addition of polyacrylamide (PAM) had the highest yield. This difference between CP1 treatments with/without the presence of 5 t/ha of PAM (7.23 compared to 5.32 t/ha) was not seen in any of the other measurements at either anthesis or harvest, and so is probably just an anomalous result. Other significant results were either between treatments other than the control (HI), with relatively poor replication, or showed a negative impact compared to the control (seed weight), but only based on a partial dataset. The crop performance results from the first year could therefore be considered to carry relatively little significance overall in the context of the full term of the trial.

Results from the 2023 wheat crop indicate that the soil at the trial site was responsive to subsoil amelioration for certain types of amendment. Deep ripping alone seldom had any significant effect on soil or crop measurements, and when there was a difference to the nil control it was a negative one. Previous research has found that crop responses to deep ripping on heavy clay soils are typically very variable and negative impacts have been found before (Kirkegaard et al., 2008; GRDC, 2021). Physical disturbance itself, that is, loosening the heavy soil structure, was thus insufficient to overcome the physical constraints, such as compaction, that may have been reducing crop yield potential. While the order of greatest treatment effectiveness was variable, generally the treatments having the greatest impact on crop performance were those with an organic matter component. This could be ascribed to being predominantly driven by improved crop nutrition via the nitrogen, phosphorus and other major plant nutrients contained in these amendments (Celestina et al., 2018). However, the nutrient content of the amendments was designed to be stoichiometrically balanced, in particular with regards to nitrogen, hence the nitrogen inputs of the OM-based amendments were about the same as that of the mineral NPKS treatment. Despite this, the OM-based treatments typically had significantly greater effects than the liquid NPKS treatment.

One point of difference between the OM-based treatments and the liquid NPKS is of course that most of the N in the former was in an organic chemical form, not readily available ammonium- or nitrate-N. Hence, the nitrogen in the OM-based amendments became slowly available as the organic matter was mineralised by soil microorganisms, whereas that of the liquid NPKS was all readily available N, and so was subject to possible losses through leaching and denitrification. This may account for the differences between the total mineral N in the 20–40 cm amendment layer and below in the soil profile, with an average of 10.6 kg N/ha for those depths in the liquid NPKS treatment compared to 20.8 kg N/ha for the various deep OM treatments (Figure 13).

Such a difference in N remaining in the soil profile two years after amendment application could support the suggestion that the treatment effects on crop performance were mainly due to nutrition. While the relationships between soil profile mineral N and both crop yield and grain protein content in the 2023 wheat crop were statistically significant ($P < 0.001$), the relationships were quite weak, accounting for low proportions of the variance. Further research is necessary before the causes of the treatment effects can be ascribed to a particular mechanism with any confidence.

Wheat crop measurements at anthesis in 2023 showed multiple treatment differences to the control, including the deep gypsum treatment, where no additional nitrogen or other nutrients were added at the start of the trial. Differences in biomass were illuminating when looking at the fresh weight (i.e. moisture content) rather than dry matter content. With corroborating data from the NDVI sensor, it was clear that those treatments significantly different to the control (Table 10) were able to access more soil water and were much healthier as a result. These differences largely carried forward to harvest, except for the deep gypsum treatment.

Statistically, there were no significant differences in the topsoil (0–15 cm), subsoil (30–130 cm) or total soil water use from the profile (0–130 cm) in the first season of the trial irrespective of treatment, and there was a net negative change in soil water content between sowing and harvest, whereby the profile was wetter at harvest than at sowing. This was reflected in the annual rainfall distribution, which was characterised by significant fallow period rainfall, especially in January where almost 200 mm was recorded, and monthly rainfall totals were above the long-term average prior to and during sowing, and from anthesis to harvest. In contrast, the net change in topsoil, subsoil and total soil water use during the second season were positive, with the soil profile dryer at harvest than at sowing. While monthly rainfall during the fallow period and in the months prior to sowing exceeded the long-term average, from May through to October monthly rainfall was below average with seasonal conditions characterised by a dry spring. While statistically there were again no significant differences in soil water use, those treatments that exhibited the greatest yield responses extracted greater volumes of water from the profile, specifically from the subsoil.

When soil water use was combined with contributions from growing season rainfall and fallow, again there were similarly no significant statistical differences in TWU (mm) during the first or second season of the trial, with all treatments consuming statistically similar quantities of water. Because biomass production is largely determined by total crop water use (de Wit, 1958), this was likely reflected by seasonal harvest biomass totals, which bar one exception in the second season, were for the most part statistically similar, with all treatments generating similar quantities of above ground biomass.

In contrast, seed production is mainly determined by water use that occurs in the period after anthesis coinciding with the reproductive phase (Passioura, 1976), which in seasons with a dry spring is often accompanied by periods of water stress (Farooq et al., 2014). In the first season, where annual rainfall from August through to November exceeded the long-term average and there was a net negative change in soil water use, crops were able to achieve yield potential without the need to extract water from the profile, and with the exception of deep OM (CP1) + PAM, there were no significant differences in yield responses nor improvements in the proportion of aboveground biomass that was converted to grain (HI) when treatments were compared to controls. This was reflected by similar water use efficiencies both for vegetative (WUE_{bm}) and reproductive (WUE_{grain}) growth, wherein again, the only significant improvement related to the deep OM (CP1) + PAM treatment, which produced on average an additional 2.6 kg of grain per hectare per mm of transpired water.

In the second season, which was characterised by a dry spring where average monthly rainfall was below average from May through to October, and the reproductive period coincided with a period of water stress, crops were instead forced to rely on soil water to achieve yield potential. There was thus a net positive change in the soil water content between sowing and harvest for all treatments. While soil water use totals were not statistically different between treatments, those treatments with greater yield responses did extract additional soil water from the profile, particularly from the subsoil. Subsoil water is particularly important, because it becomes available in the period after anthesis, later in the season during the reproductive period, and water use during this time is known to have a greater conversion efficiency to grain (Passioura, 1976; Kirkegaard et al., 2007). As a result, those treatments that extracted additional subsoil water produced greater yields and showed improvements in WUE_{grain}. For the most part, treatments containing OM formulations CP1 and CP2, and combinations thereof, showed significant improvements when compared with controls, and on average produced an additional 2.4 kg of grain/ha/mm.

Unexpectedly, improvements in WUE were not reflected by an increase in HI, nor by differences in grain weight, although many of the same treatments had a higher grain protein content, and thus a greater nitrogen offtake in seed. Notably, many treatments had grain protein contents below 10%, which at harvest is indicative of nitrogen deficiency (Unkovich et al., 2020). At grain protein concentrations less than approximately 11%, crop yields remain responsive to additional nitrogen (McDonald and Hooper, 2013; Unkovich et al.,2020). Only crops growing on plots with OM-based treatments are likely to have achieved their yield potential. Continued monitoring at this site over the next four years should further understanding of the treatment effects on WUE.

Wonwondah, Vic, broadacre crops trial

The selection of the amendments in this trial, how they were applied to the soil and rates of application were based on learnings derived from a range of recent research (co-funded by the GRDC and Agriculture Victoria). The physical and chemical nature of the different organic matter treatments vary depending on initial feed source. In addition to the several organic matter treatments, the use of gypsum, which is currently widely used commercially to mitigate soil sodicity/dispersion, and PAM, which has been used to reduce dispersion in the mine site rehabilitation and irrigation systems, were also assessed. Previous research (Armstrong et al., 2023) has shown the potential effectiveness of such amendments, whether they are organic or inorganic, in improving crop productivity will strongly depend on initial soil properties and seasonal conditions, especially water supply. In this case, the sodic Vertosol soil used in this trial is widely representative of large sections of the southern and western Wimmera and more broadly in western Victoria. Despite these considerations, this initial assessment, which was based on only two years of study and included an extremely wet growing season in the first year, suggests that ‘nutrient-rich’ organic matter, including high C:N materials such as cereal straw treated with supplementary fertiliser, was needed to produce a target stoichiometric C:N (and P and S) balance. This was just as effective as current high-priced alternatives, such as lucerne pellets.

Compared to 2022, where extremely wet (Decile 10) season conditions and extensive waterlogging during spring impeded faba bean growth and prevented any potential yield responses, 2023 was overall a much more favourable growing season. Furthermore, the initially good soil moisture conditions that were followed by dry spring conditions during the canola seed set provided the opportunity to investigate potential amelioration treatment effects on mitigating soil physicochemical constraints and crop subsoil water use.

Increases in canola crop biomass recorded during 2023, and a slight but non-significant increase in final canola yield in the deep ripping-only treatment, indicate that the Wonwondah site was responsive to deep ripping without the application of ameliorants, at least in the first two years post-treatment. Notably, the largest crop biomass and yield gain responses occurred when ‘nutrient-rich’ ameliorants were applied to the subsoil. These treatments were all stoichiometrically balanced to apply the equivalent amount of N, P, K and S as were applied in the 15 t/ha lucerne pellet treatment. While there were some biomass differences between these treatments during the growing season, they all produced the same amount of biomass (average of 15.9 t DM/ha, 28% greater than the untreated control) and canola yield (average of 4.54 t/ha, 42% greater than the untreated control) at harvest after the dry spring finish.

Assessment of volumetric water content down the profile and soil water usage showed that the WUE for these ‘nutrient-rich’ treatments was also consistent (apart from being slightly lower in the deep nutrients treatment at 12.6 kg grain/mm), despite some differences in the total amount of water used by these treatments. As with yield, canola WUE (as a function of total water used from rainfall and stored soil water) appeared to reach a ceiling of 14.0–14.4 kg grain/mm at the site, which was significantly more (P = 0.031) than in the untreated control (11.1 kg grain/mm). This level compares to other published values ranging from 4.6 in WA (Harries et al., 2022) to 13.4 kg/mm in southern NSW (Robertson and Kirkegaard, 2005).

Given the same yield response to the ‘nutrient-rich’ amelioration treatments in 2023, it could be presumed that crop nutrition, on top of the ripping effect, was the main driver of crop response to amelioration at the site. However, while these treatments were all stoichiometrically balanced, it would not be expected that they all decompose at the same rate, which would be expected to affect nutrient availability and therefore crop response. For example, the deep nutrient treatment consisted solely of inorganic and immediately available nutrients, compared to the lucerne pellet treatments, which would take considerably longer to break down in soil. Yet both treatments produced the same canola yield. Evidence of this nutrient availability difference was shown in the pre-sowing mineral N sampling that occurred in 2023, where much larger amounts of plant available mineral N were available in the deep nutrient treatment compared to the other ‘nutrient-rich’ treatments. Likewise, the deep UGW mulch + nutrients treatment produced an equally high yield to the other ‘nutrient-rich’ treatments, but the crop response to the UGW mulch only treatment was no different to deep ripping or applying deep gypsum alone. The lack of difference in pre-sowing mineral N in the deep UGW mulch treatment compared to the control also indicates that little decomposition of the material itself occurred since the application of the treatments in the previous year, leading to the conclusion that yield responses to the UGW mulch + nutrients treatment were driven by the added nutrients. During the root sampling in 2023, non-decomposed amendments were found in the soil cores collected in several plots. Non-decomposed amendments were also found in soil cores collected as much as six years after treatment application at other subsoil amelioration trial sites in the Wimmera district (e.g. DAV00149).

From the pre-sowing mineral N data, it was evident also that the wet conditions in 2022 resulted in some nitrate-N leaching down the soil profile, and potentially into constrained subsoil and below the rooting zone (maximum roots depths in ameliorated treatments at the site were 100–120 cm in 2023) where it will be inaccessible to crop roots.

This consistent crop response to the 'nutrient-rich' amelioration treatments, but different nutrient availability from each, suggests that the full potential and utilisation of the available nutrients from these treatments was not realised in 2023. This could be due a non-ameliorated constraint limiting the crops' ability to utilise available subsoil water, coupled with the dry spring conditions during seed set leading up to harvest. The consistent yield indicates the canola crop reached a limited yield governed by soil constraints; however, the 4.5 t/ha of canola yield at upwards of 45% oil and 29% protein in this environment is regarded as a high yield and good quality.

A generalised assessment of soil volumetric water content during each growing season showed that while the site suffered from waterlogging in the first year of the experiment, the deep application of the 'nutrient-rich' and the deep gypsum treatments facilitated greater infiltration of rainfall into the subsoil. This water was stored through the summer and was then available for use, but only in treatments where soil nutrition had been improved, by the canola crop during the dry finish in the second year of the experiment.

Kweda, WA, broadacre crops trial

Results from the large plot experiment in the first year of the trial indicated that treatments had a significant effect on grain yield, where gypsum was included, but this effect was not seen in the Iron Man Gypsum treatment in the small plots experiment in the same year. One of the limitations in the small plots experiment was that the control was the one treated with the Bednar plough, which was dissimilar to the control (untreated and unripped) of the large plots experiment. The gypsum treatments in the 2022 large plots yield data were separated more from that of the control (untreated and unripped), that is, showing a 15–16% increase relative to the nil control. If the gypsum treatments in the large plots experiment are compared with the Bednar treatment, the difference reduces to only a 7–8% increase. This implies that if a nil control had been used in the small plots experiment (unripped, untreated), a bigger difference between the Iron Man Gypsum and the small plot control (ripped, untreated) might have been seen.

Subsequently, there were few significant treatment differences found in the crop performance measurements. NDVI measurements on the lupin crop 11 weeks after sowing in 2023 in the small plots experiment did show significant treatment effects where compost was included in the amendment. Compost is known for improving the crop growth via enhancement of soil properties. For instance, Duong (2013) reported a significant increase in the availability and mobility of nitrogen and phosphorus in soil along with an increase in the soil cation exchange capacity. Similarly, Ngo and Cavagnaro (2018) reported an increase in wheat and tomato plant biomass in compost-treated soil. The authors partially attributed the increase in biomass to enhanced P availability regardless of the soil moisture conditions (wet or dry). This implies that compost might have enhanced nutrient availability to lupins despite the dry conditions, which might not be the case with other soil amendments. Surprisingly, crop yield was not influenced by the treatments despite the different NDVI. This might be either because of poor correlation between the NDVI and yield or the differential growth pattern of the crop in different treatments after 11 weeks (when NDVI was recorded), perhaps due to rainfall in August and September. There is a possibility that NDVI might have differed later in the growing season.

Several significant differences were seen in the soil chemistry data in 2024, as would be expected. These differences have not yet translated into effects on crop performance.

CONCLUSION

The mixed results from the four trial sites to date illustrate the challenges still faced when trying to gain a better understanding of the effectiveness of subsoil amelioration to address soil constraints. Variability in climatic conditions from year to year can play a significant role in determining whether amelioration effects will be seen or not. In dry conditions, at least in the early stages of amelioration, lack of soil moisture may mean that amendments are unable to function as designed so soil constraints are unaffected. In contrast, in wetter than average conditions, crops may not be water-limited and can effectively bypass the soil constraints.

In a much wetter than average first year in the Victorian trial in 2022, early faba bean biomass cuts indicated significant treatment differences were present. However, a very wet spring caused waterlogging at the site, which depressed grain yield, and no significant treatment differences were observed at harvest. Similarly, results from the Kweda site in WA may have been influenced by higher than average rainfall for the period of the trial, reducing the impact of the soil constraints on crop yield, and the same is possible for the first year of the Lockhart trial, where rainfall was also much higher than average.

Results on the heavy, dispersive, sodic soils in NSW and Victoria indicate that a range of subsoil amelioration treatments has potential to improve crop productivity in such soil types, provided that the amendment material contains a proportion of plant nutrients. Amendments where the plant nutrients, particularly nitrogen, are at least partially organically bound, from our results, appeared to have a more long-lasting impact on ameliorating subsoil constraints, being relatively protected from various loss pathways compared to mineral forms.

Currently, it is unclear whether the comparative effectiveness of these ameliorants in improving crop productivity is due to improved nutrition, better soil physicochemical conditions, or a combination of both mechanisms. Further study is required before questions around the mechanisms at play can be answered. The ongoing assessment in those sites that will be monitored over the longer term should provide more information to allow us to better understand the driving factors of crop responses to the different treatments over a wider range of seasonal conditions, supporting different crop types, and enabling appropriate economic analysis of the treatment options.

RECOMMENDATIONS

Long-term field trials are essential for understanding the effects of amelioration techniques on soil health and WUE. Soil amendments need time to change soil properties, and responses may vary from year to year due to changes in climate. One clear recommendation is to continue to monitor the sites over several more years, and it is opportune that three of the four trials will continue to be monitored under Soil CRC Project 4.2.006: Capitalising on established field trials for ameliorating (sub)soil constraints, and beyond that by the Department of Agriculture, Fisheries and Forestry (DAFF) Future Drought Fund, whereby several more years of data will be available for analysis. By extending this research, these projects will capture crop responses under more varying climate conditions, and by assessing the longevity of treatment effects enable improved economic analysis of outcomes for the amelioration strategies.

Yield responses to subsoil amelioration have been found to be very variable from site to site and are heavily dependent on rainfall and soil properties. Further research is needed to better understand what the drivers underlying the variable responses are. This and previous projects have found that OM-based treatments fortified with plant nutrients are typically the most effective amendment for reducing the impact of subsoil constraints. However, even with these amendments results have been variable and within-site replication has sometimes been poor, affecting the statistical analysis of data. Future research trials would benefit from having a more targeted experimental design focusing on those amendments that have been found to be more effective, examining different rates of application to better understand the economic viability of amelioration, and increasing the number of replicates to increase the statistical strength of the data analyses.

The economic benefit from conducting subsoil amelioration is a critical component of translating research outcomes into practical, on-farm solutions. Economic sensitivity analysis of costs/benefits influencing the net present value of soil amelioration in the DAV00149 project found that the cost of amendment used was the largest factor contributing to profitability, followed by the size of yield response (t/ha) and then residual value, that is, the length of time benefits persist. Future research should, where possible, include amendments based on readily available and comparatively inexpensive materials, such as local crop stubble or green-waste compost, with additional mineral nutrients added as required, to broaden the scope to determine what treatments are economically as well as agronomically feasible at a commercial scale.

Some farmers have been sufficiently convinced by existing trial results to begin applying subsoil amelioration at a commercial scale. Tools are available to help with the decision-making process for growers thinking about whether subsoil amelioration would work on their farm, for example, Agriculture Victoria's decision support guide (https://agriculture.vic.gov.au/crops-and-horticulture/grains-pulses-and-cereals/decision-support-for-grain-growers). Data from this project and its extensions will continue to be fed into Soil CRC Project 4.3.005: Diagnosis frameworks for multiple and complex soil constraints, and Project 4.3.006: Optimising soil constraint management through computer-based learning and modelling. These aim to produce a knowledge-guided machine-learning modelling framework that uses scientific understanding and learns from existing data to predict which combinations of soil management will work best for a particular soil affected by multiple constraints under specific conditions. When released, growers and advisers will be able to utilise this tool to better inform decisions around addressing subsoil constraints.

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ANNEXURE A: INTEGRATED SOLUTIONS FOR UNDERPERFORMING CONSTRAINED SOILS: ACCESSING SOIL MOISTURE – QUEENSLAND SITE REPORT

Performance through collaboration

Integrated solutions for underperforming constrained soils: Accessing soil moisture

Final report for research project 4.2.004

M18.1 Project Output 7: Final Report Annexure – Qld Site

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November 2025

PROJECT PARTICIPANTS

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DISCLAIMER

PEER REVIEW STATEMENT

The Soil CRC recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The author(s) confirm(s) that this document has been reviewed and approved by the project's steering committee and by its program leader. These reviewers evaluated its:

- originality
- methodology
- rigour
- compliance with ethical guidelines
- conclusions against results
- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2018), and provided constructive feedback which was considered and addressed by the author(s).

KEYWORDS

Subsoil constraints; sugarcane; subsoil amelioration; novel amendments.

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EXECUTIVE SUMMARY

OBJECTIVES

Aim 1: To establish an on-farm field experiment to assess the long-term effectiveness of new practices and products to ameliorate multiple soil constraints in a key soil type that supports the sugarcane industry.

Aim 2: To quantify the effectiveness of different amelioration strategies to increase soil water storage and crop water use efficiency.

Aim 3: To assemble datasets for use by next users in calibration and validation of hybrid biophysical modelling to develop frameworks and tools for diagnosing and ameliorating multiple soil constraints.

RESULTS

Aim 1: A new field trial site was successfully established on a working farm near Clare, Queensland (Qld) on a heavy sodic clay soil of the Burdekin River Irrigation Area. Due to the length of sugarcane crop growth cycles, the Qld trial was established later than the other sites and has only recently completed its second year.

Aim 2: Results from the first two years of the trial have not shown any significant treatment effects on sugarcane production. This may mean the soil is unresponsive to amelioration, or it may be related to the wetter than average seasons possibly enabling the sugarcane to effectively bypass the subsoil constraints due to sufficient plant available water present in the upper soil layers to support the crop's growth cycle.

Aim 3: Data from the trial site was supplied to the Agricultural Systems and Catchment modelling team in the University of Southern Queensland's Centre for Sustainable Agricultural Systems. The modelling team are using the Agricultural Production Systems sIMulator (APSIM) model to assess the impact of subsoil constraints on water use efficiency and crop production (Soil CRC Projects 4.3.005; 4.3.006).

NEXT STEPS	TIMING
The Qld site will continue to be monitored under Soil CRC project 4.2.006 - Capitalising on established field trials for ameliorating (sub)soil constraints.	2025–27.

INTRODUCTION

The overall purpose of the project was to achieve reliable and profitable crop productivity responses on soils with multiple constraints, and to close the gap between current on-farm production and the rainfall-limited yield potential in key soil types in Victoria (Vic), New South Wales (NSW), Qld and Western Australia (WA). Using knowledge recently developed across a range of projects (Soil CRC, GRDC and AgriFutures funded), field-based studies were undertaken to quantify the effects of promising amelioration strategies on soil water storage and supply, rooting depth, and function and crop productivity. This project combined approaches of crop physiology and soil amelioration innovation to improve the cost effectiveness of addressing subsoil constraints. Whereas previous research considered constraints individually, the approach in this project was to focus on soils with multiple constraints. The combination of constraints considered varied between the clay-textured soils in Vic, NSW and Qld compared to sands in WA.

1.1 PROJECT AIMS

1.1.1 Specific aims of the overall project

1. To establish four on-farm field experiments to assess the long-term effectiveness of new practices and products to ameliorate multiple soil constraints in key soil types that support the grains and sugarcane industries. The key constraints were poorly structured dispersive alkaline subsoils in Vic and NSW, dense sodic subsoils in Qld, and low water holding capacity and water repellent sands in WA.
2. To quantify the effectiveness of different amelioration strategies to increase soil water storage and crop water use efficiency.
3. To assemble datasets for use by next users in calibration and validation of a hybrid biophysical modelling to address Milestones 4.3.2 and 4.3.4 on the development frameworks and tools for diagnosing and ameliorating multiple soil constraints.

The longer-term objective of this research was to reduce the yield gap between current water limited potential and realised yields associated with multiple soil constraints in Australia, thus delivering economic and sustainability benefits to farmers. The means to achieve this was by utilisation of the most effective amelioration strategies tailored to specific soil types and region. The project aims to quantify the multi-year soil and crop responses to these management practices to enable sustained increases in agricultural productivity on key soils in four cropping regions (Vic, NSW, Qld and WA).

1.1.2 Queensland site annexure

This report specifically focuses on the Queensland component of Project 4.2.004, from inception to completion of the 2025 harvest. A full description of the other sites' results, and the Qld site up to that date, are presented in the full final report for Project 4.2.004 (at the beginning of this document).

BACKGROUND

A contract variation was enacted for the commencement date of the Qld component of the project to be moved from November 2021 to November 2022, and therefore the conclusion date for the North Queensland (Burdekin Productivity Services) component of this project was to be delayed by one year. This change allowed for the project to investigate findings appropriately by ensuring that there was time to source treatments for subsoil amendments and harvest the sugarcane crop following application.

The reasoning for this change was that the original timelines did not fit in with the sugarcane cropping system. The typical crop cycle involves the commencement of fallow around November, where treatments need to be applied prior to sowing a legume rotational crop. Then cane is typically planted in March, directly following harvest of the legume. At the time of variation submission, amendments could not be sourced for the 2021 fallow, so they were applied at the end of 2022, cane was planted in March 2023 and first harvested around July 2024. Under the original project timelines, the project would have been completed before a second sugarcane crop could be harvested.

This report covers the activities, data and results of the subsoil amendment trial established in the Burdekin in 2022, to the end of season in 2025.

METHODOLOGY

This trial aimed at ameliorating poor subsoil conditions with varying soil ameliorants under sugarcane. The trial site was established on a grower's irrigated property in the Clare region of the Burdekin. The grower had previously voiced concerns about subsoil conditions. Soil tests and soil pits showed a structureless heavily compacted clay to depth, being sodic and magnesic below 20 cm.

The block was EM mapped in Nov 2022 to determine the paddock variability and establish a location within the block with the least variation. Once the location was selected, the old cane crop was ploughed out (multiple offset discings and rippings), and the block laser levelled. Then baseline soil samples were collected, with three samples per plot at increments 0–10, 10–20, 20–50 and 50–100 cm depth.

3.1 TRIAL PLAN

The trial was set up using a randomised block design with eight subsoil amendment treatments including a control, with four replications across the block (Figure 1). Each plot was three rows wide and 45 m long, allowing for the middle row to be the designated sampling row. Laneways of 1 m were placed between plots by spraying out cane when it was young. This enabled easy distinction between plots when sampling.

3.2 LEAF SAMPLING

The sugarcane crop was planted in March 2023, and third leaf samples were taken in November 2023.

3.3 HARVESTING YEAR 1

The harvest data collected was tonnage per hectare and sugar content (CCS) for each plot. The data was taken from row 2 of each plot to minimise potential effects from neighbouring treatments.

Tonnes of cane were measured using the Sugar Research Australia (SRA) weigh truck, which collected and weighed all cane cut by the harvester that was in row 2 (Figure 2A).

Before the harvester entered each plot, six randomly selected intact sticks were sampled from row 2 for CCS. This was done by hand cutting and bundling with plot labels (Figure 2B). CCS readings were determined using the SRA SpectraCane mill.

Figure 1. Sugarcane trial layout and treatments.

Figure 2. (A) Sugarcane harvest with the Sugar Research Australia weigh truck; (B) hand cutting randomly selected intact sticks for CCS content measurement.

3.4 SOIL SAMPLING YEAR 1

After harvesting, soil core samples were taken of each plot of Treatments 1, 2, 3, 4 and 8, and sent to NSW DPI for chemical and biological analysis. Three cores were sampled per plot from 0–20 cm and 20–40 cm (Figure 3).

Figure 3. Soil core subsampling for chemical and biological analysis.

3.5 DRONE FLIGHTS

In July of the trial's second year (2025), the trial was monitored using drone and Normalised Difference Vegetation Index (NDVI) imagery (Figure 4). No visual differences could be seen in crop health between plots. The entire trial site was representative of the rest of the untreated block.

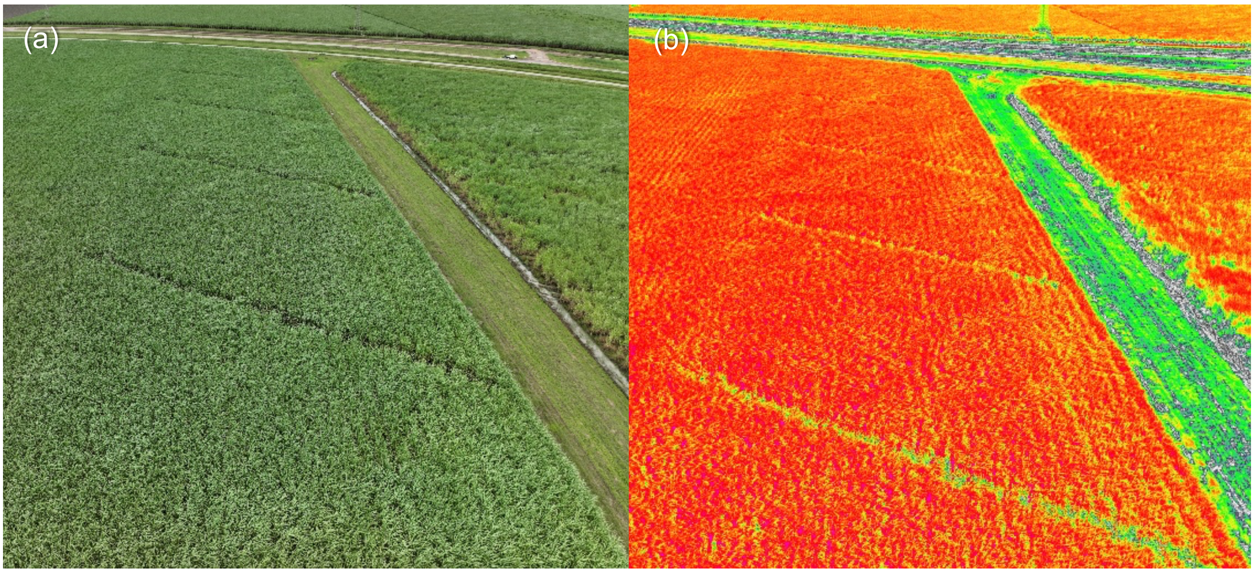

Figure 4. (A) Overhead drone photo; (B) NDVI image of trial site, when the crop was ten months old.

3.6 HARVEST YEAR 2 (2025 FIRST RATOON)

The trial was harvested the same way as year one, hand cutting six sticks of cane from row 2 of each plot and using the weigh truck to measure tonnage from row 2 of each plot.

Figure 5. (A and B) Sugarcane harvest in Year 2 with the SRA weigh truck.

3.7 SOIL SAMPLING YEAR 2

Soil cores were also sampled post-harvest in year 2. Samples were taken from treatments 1, 2, 3, 4, and 8 (Figure 6). Four cores were taken from depths of 0–10cm and 20–40cm per sampled plot. This enabled adequate samples for both chemical and biological testing.

Figure 6. Soil coring for chemical and biological analysis.

3.8 SOIL TEST ANALYSES

3.8.1 Soil pH, TC, TN and GRSP quantification

Total soil carbon and total soil nitrogen were quantified on a 0.2 g subsample of dried, ground soil using a LECO TruMac Analyser (LECO Corporation, MI, USA). Soil pH was measured on 1:5 soil:water and soil:0.01M $CaCl_2$ slurries (Rayment and Lyons, 2011) by an automated electrode system. Glomalin-related soil protein (GRSP) was measured as using the method described in Hurisso et al. (2018). In brief, the GRSPs were extracted from technical duplicates by autoclave-citrate extraction and quantified using bovine serum albumin as the standard curve.

3.8.2 DNA extraction, PCR and sequencing

Soil DNA (five treatments, four replicates) was extracted using a DNeasy PowerSoil kit as per the manufacturer's instructions. Two universal primer sets were used to amplify full-length phylogenetic marker regions: the 16S rRNA gene (~1.5kb) was targeted using primers 5'-AGRGTTYGATYMTGGCTCAG-3' (forward) and 5'-RGYTACCTTGTTACGACTT-3' (reverse), and the fungal ITS-28S region (~1.8 kb) was amplified with primers 5'-ACCWGCGGARGGATCATTA-3' (forward) and 5'-TCCTGAGGGAAACTTCG-3' (reverse).

PCR amplicons were prepared for sequencing with the Kinnex 16S rRNA library preparation kit and sequenced using a PacBio Revio sequencer at the Australian Genome Research Facility (AGRF, Qld). PacBio HiFi reads for full-length 16S and ITS rRNA regions were quality-filtered and denoised using QIIME2 coupled with DADA2, implemented within a PacBio Nextflow pipeline, to generate high-resolution amplicon sequence variants (ASVs). Bacterial ASV taxonomy was assigned using SILVA138, while fungal ASV taxonomy was assigned using UNITE10. Long read amplicon sequences were rarefied to achieve equal sampling depth using the 'rrarefy' function in the vegan R package in preparation for downstream analyses.

3.8.3 **Statistical analyses**

Boxplots of soil pH, total carbon and total nitrogen by treatment were generated using the *ggplot2* R package. Analysis of variance (ANOVA) was used using 'treatment' as the predictor term to determine significant differences. Alpha diversity metrics were calculated based on the rarefied ASV frequency datasets using the R *vegan* package. Permutational analysis of variance (PERMANOVA) and ANOVA were performed to test whether community compositions were significantly different using treatment as the predictor term. Comparison of bacterial and fungal community compositions by treatment were visualised by plotting a redundancy analysis (RDA) using *ggplot2*. High-level community composition bar charts were generated by aggregating ASV relative abundances at the phylum-class level, filtering to classes present at more than 1% in any treatment and plotted using a custom script. Relative abundance heatmaps were generated by filtering the ASV frequency tables to genera present at more than a threshold of 1% relative abundance and plotting using the 'heatmap' function in base R. Heatmaps were square root-transformed and row-scaled. The most abundant strains within these genera were then presented alongside. All figures were polished in Inkscape (v.0.92).

3.9 INDUSTRY ENGAGEMENT AND COMMUNICATION

In May 2023 a soil health bus trip for local growers and advisers was organised. This bus trip's final and major site visit was the CRC trial site. A soil pit that was dug showed the challenging nature of the soils (limited structure, compaction and wet profile beyond 20 cm deep), as well as some of the treatments could be seen in their applied bands. Growers walked down into the pit to observe (Figure 7). A demonstration was also set up at the trial site to explain how simple tests, such as pH, dispersion and slaking, could be undertaken to understand basic soil properties (Figure 8). During the bus tour, many aspects of the Soil CRC and various projects and activities were discussed. Excellent feedback was received from all who attended, which included 17 growers, six industry advisers and four BPS staff.

An industry leader bus trip was organised in 2024, which covered promotion of projects and activities that BPS was involved with and one of the key sites was this project site. There was a lot of interest from grower representatives that sit on political organisations, and positive feedback about not only being involved with the Soil CRC but addressing local soils issues.

School bus trips were organised in each year of the project (2023, 2024, 2025) with Year 9 students. The visits included discussion around soil constraints, soil properties and reuse of waste products (mill mud/ash, compost) and means by which industry can reuse these products to overcome soil constraints and improve productivity.

Discussions of the trial site, treatments, soil constraints and plant cane harvest results were held at 13 grower shed meetings in early 2025, with around 200 growers attending in total.

Figure 7. Soil pit being examined by visiting growers.

Figure 8. Demonstration of simple soil tests at the Clare Soil CRC trial site.

RESULTS

4.1 Baseline soil characteristics

Average baseline soil chemistry characteristics for the trial site are shown in Table 1. Results showed that the site had alkaline soil throughout the profile, with low salinity and moderately high CEC. Exchangeable magnesium (Mg) was quite high throughout the profile, and the exchangeable sodium percentage (ESP) was above the threshold of 6% below 20 cm depth, indicating that the subsoil was sodic. The subsoil was also moderately dispersive between 20–50 cm depth, and very dispersive between 50–100 cm depth (Figure 9).

Table 1. Basic trial site soil characteristics at the start of the experiment.

Depth (cm)	pH_w	EC (µS/cm)	Colwell P (mg/kg)	eCEC (cmol(+)/kg)	Exch. K^+ (cmol(+)/kg)	Exch. Ca^{2+} (cmol(+)/kg)	Exch. Mg^{2+} (cmol(+)/kg)	Exch. Al^{3+} (cmol(+)/kg)	ESP (%)
0-10	7.81	67.53	19.5	30.09	0.36	16.02	12.72	0.1%	3.1%
10-20	8.02	81.96	15.7	29.91	0.30	15.35	12.90	0.1%	4.4%
20-50	8.57	170.23	4.0	30.26	0.26	13.39	13.57	0.1%	10.0%
50-100	8.61	220.56	2.4	30.15	0.24	11.46	14.04	0.1%	14.5%

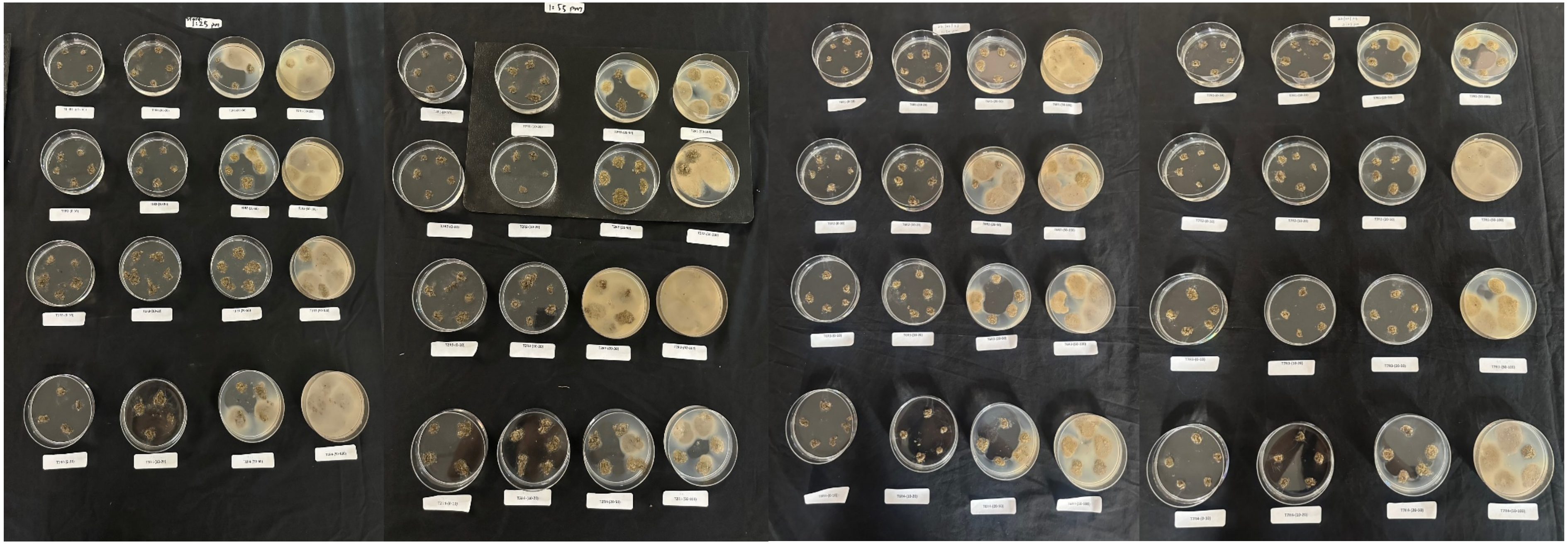

Figure 9. Selected example soil aggregate dispersion tests.

4.2 LEAF SAMPLE NITROGEN

No significant differences in third leaf nitrogen were observed between treatments in the first year (Figure 10). It was interesting that all treatments were below the critical value for nitrogen percentage (orange dashed line), while the harvest results showed no loss in yield or performance. Thus, the crop did not seem to have suffered from a lack of nitrogen.

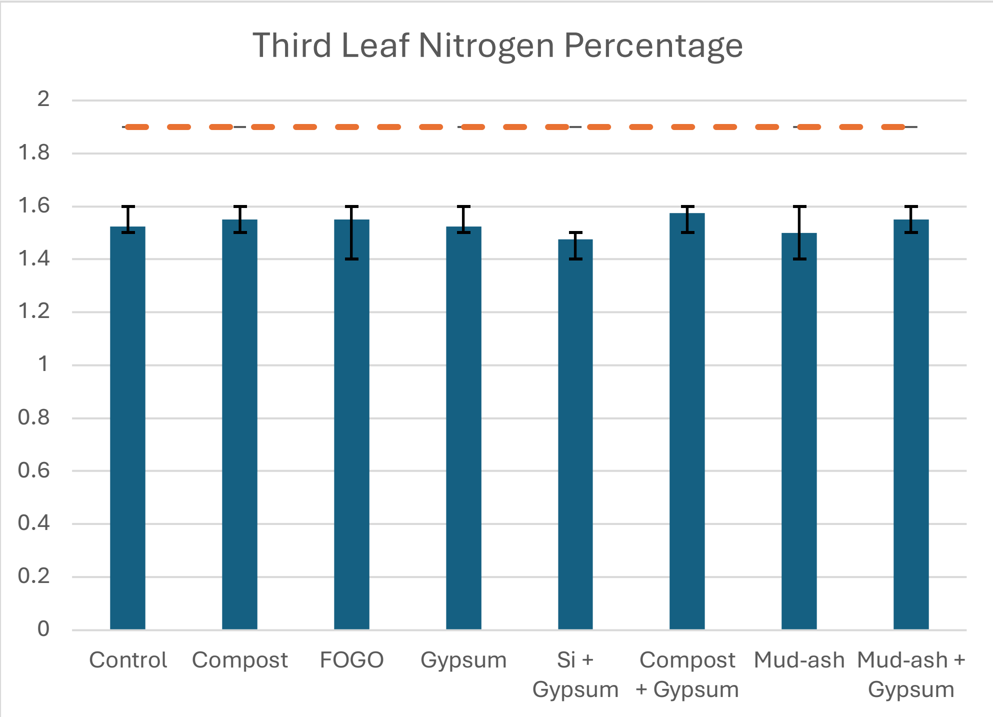

Figure 10. Third leaf nitrogen percentage by treatment, November 2023. Orange dashed line indicates the critical leaf nitrogen value for sugarcane at eight months.

4.3 HARVEST RESULTS YEAR 1 (2024 PLANT CROP)

Yield per hectare and CCS were obtained to ascertain crop performance in each plot. Tonnes of sugar yield were derived from the cane yield and CCS content.

No significant differences were found between treatments for any of the performance parameters (Figures 11–13). The plant crop was high yielding, with high CCS across the entire trial generally. It was suspected the high performance, which is usual for a sugarcane crop, particularly on this farm, may have masked any treatment differences. Hence it was hoped the following year would see some treatment effects. Note that in the CCS results spectra cane results were higher than commercial due to sound sticks being selected by hand for analysis. The results show readings of CCS around 18% (Figure 12). In a commercial context, CCS would be around 16.5%.

There were no trends across the paddock or within replicate blocks (Figure 17A), indicating the plots' placement in the paddock did not skew the results.

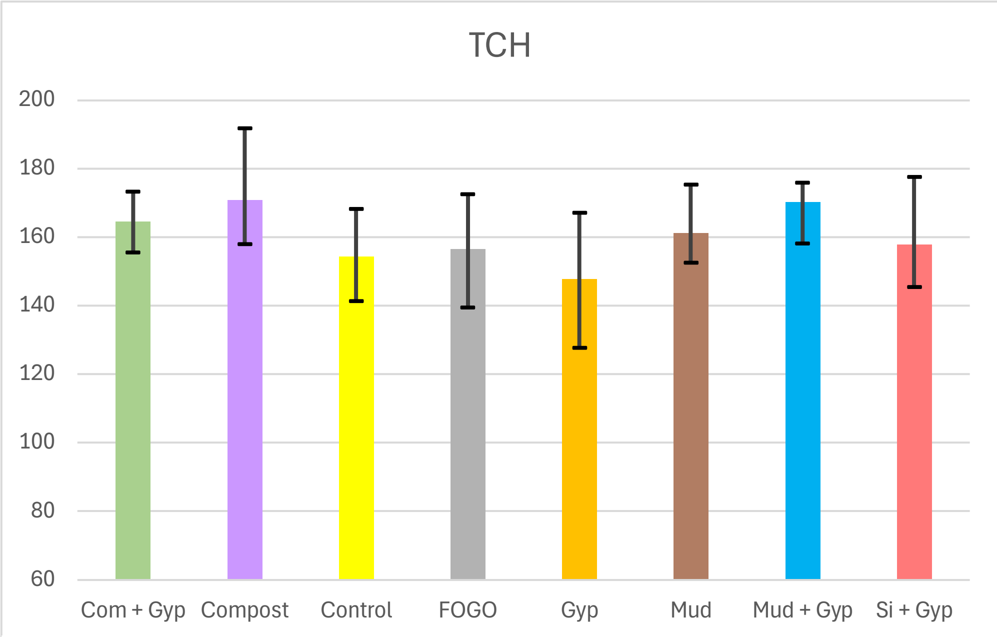

Figure 11. Tonnes of cane per hectare (TCH) by treatment in year 1. Black range bars indicate minimum to maximum tonnes spanning four replications per treatment.

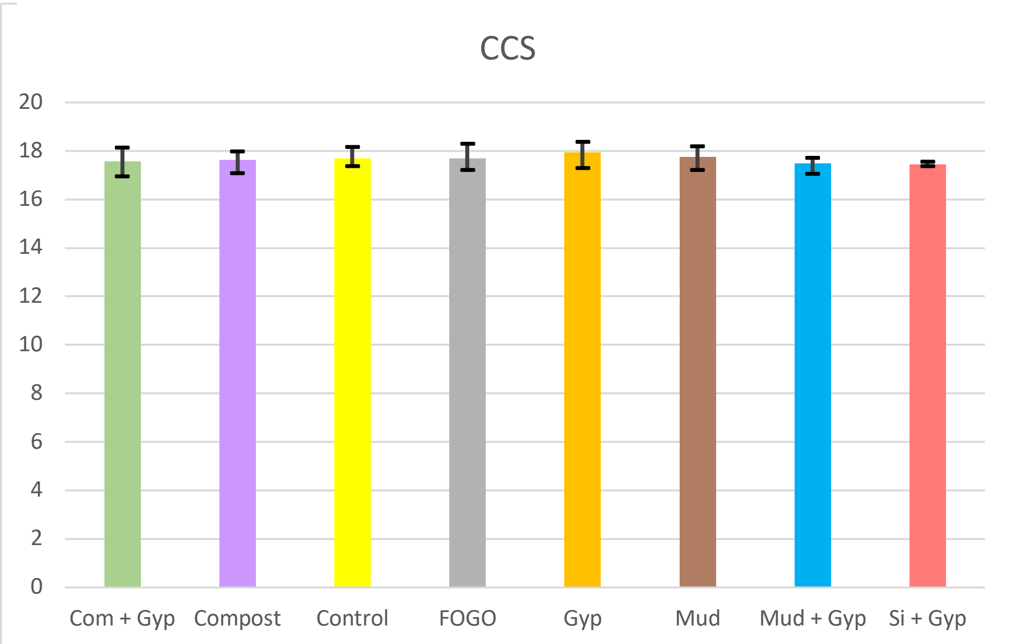

Figure 12. Commercial cane sugar content (CCS) by treatment in year 1. CSS incorporates brix, pol, and fibre content and is expressed as a percentage.

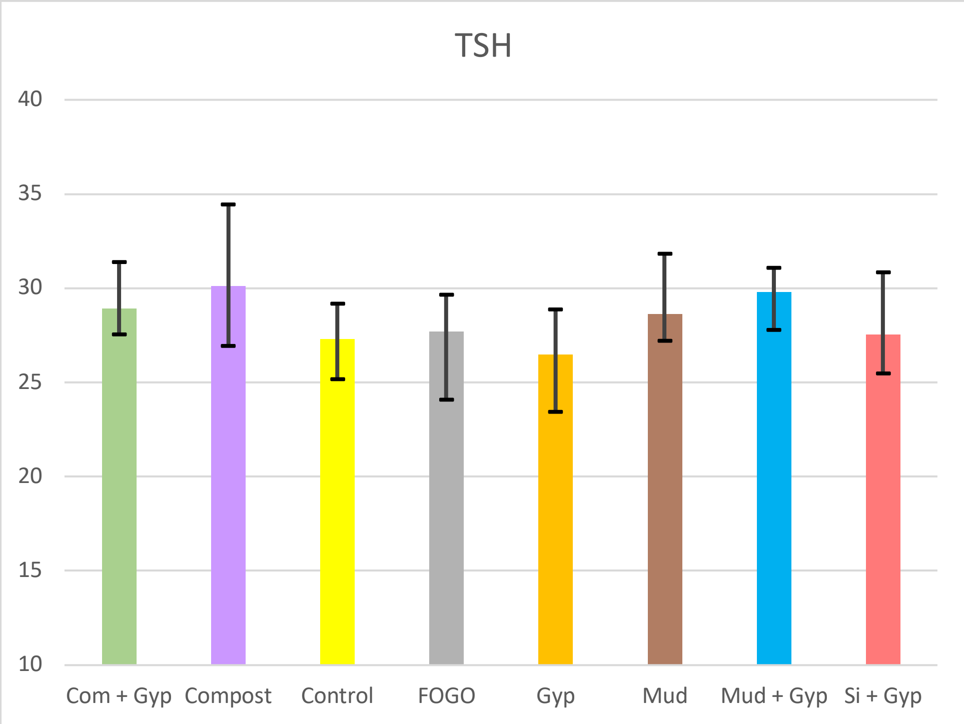

Figure 13. Tonnes of sugar per hectare by treatment in year 1. This incorporates cane yield and CCS to produce sugar yield.

4.4 HARVEST RESULTS YEAR 2 (2025 FIRST RATOON)

Again, no significant differences were seen between treatments for cane yield (tonnes per hectare), CCS, or tonnes of sugar per hectare (Figures 14–16).

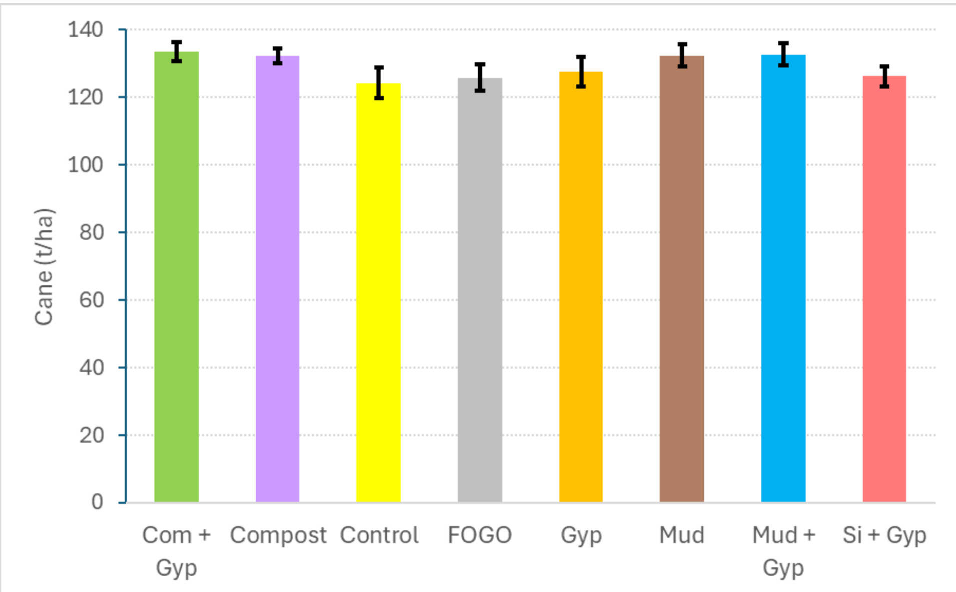

Figure 14. Tonnes of cane per hectare by treatment, first ratoon crop results, 2025. Treatment differences not statistically significant ($P = 0.232$). Bars indicate standard error of the means.

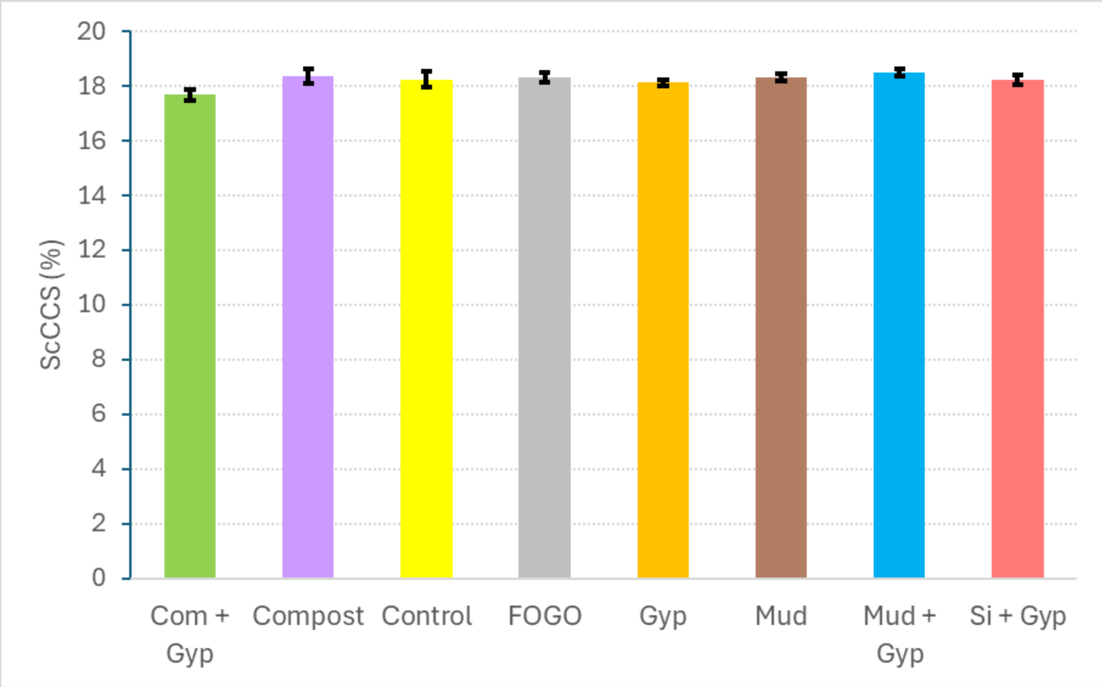

Figure 15. Spectra Cane NIR Commercial cane sugar (%) by treatment, first ratoon crop results, 2025. Treatment differences not statistically significant (*P* = 0.164). Bars indicate standard error of the means.

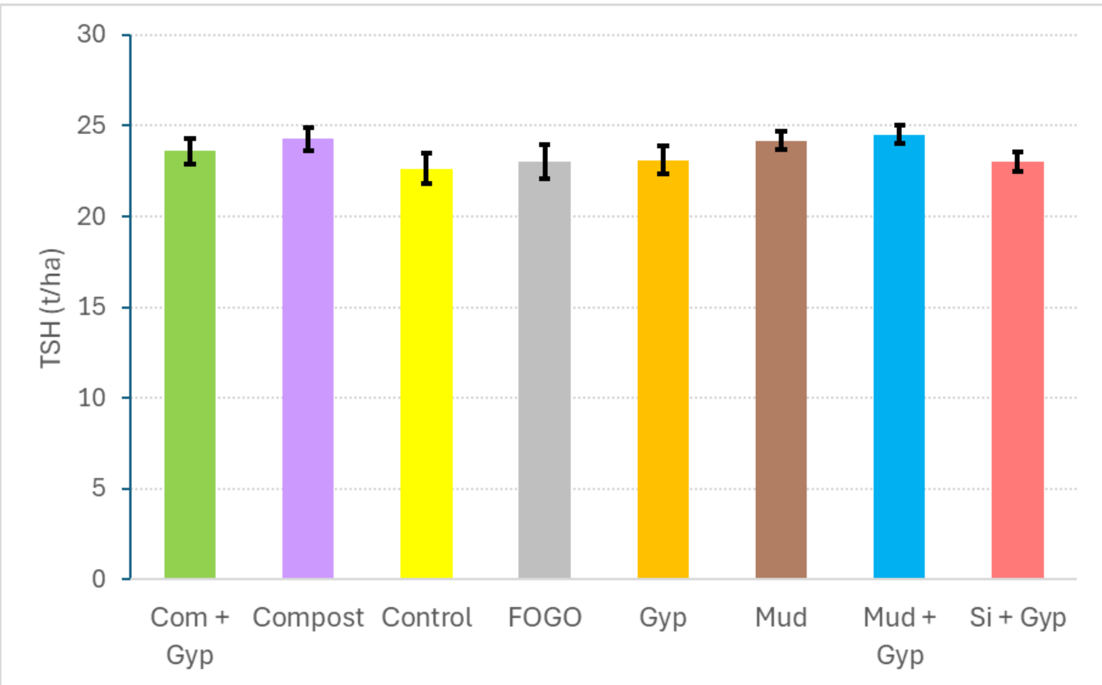

Figure 16. Tonnes of sugar per hectare by treatment, first ratoon crop results, 2025. Treatment differences not statistically significant (*P* = 0.228). Bars indicate standard error of the means.

Sugarcane biomass tonnage was higher in Year 1 with greater range between plots compared to Year 2. The decrease in yield is most likely due to very wet and cloudy conditions at the start of the 2025 season, resulting in less solar radiation and some waterlogging, along with an expected yield drop in the second year of the crop cycle.

CCS was similar between the two years, sitting around the 18% mark, which is a relatively high in comparison to district averages.

Due to lower tonnages in the second year, tonnes of sugar for 2025 were also lower than in 2024, with 2024 also having greater range across replicates, that is, more variable yield within treatments (Figure 17).

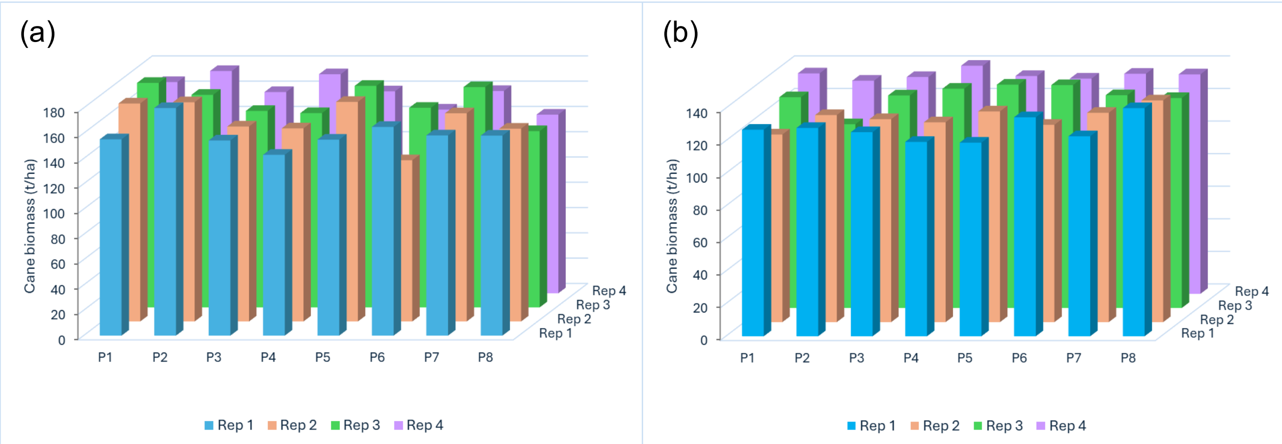

Figure 17. Tonnes of cane/ha (treatment × replicate block) in (A) 2024; (B) 2025.

4.5 SOIL TEST RESULTS

4.5.1 Year 1

Soil chemical characteristics at the end of Year 1 for the control, gypsum, mud/ash, compost and FOGO treatments at the two sample depths are shown in Table 2. Soil pH, total carbon and total nitrogen varied by sampling depth ($P < 0.001$), with no significant differences observed by treatment within each depth (Figure 18A–C). Soil pH was significantly lower in the topsoil (0–20 cm) versus the subsoil (20–40 cm). Total carbon and nitrogen decreased with depth ($P > 0.05$), with no significant treatment differences ($P < 0.001$). GRSP in the 0–20 cm range did not differ by treatment (Figure 18D).

Microbial sequencing depth was standardised 11,836 bacterial sequences and 17,003 fungal sequences (Figure 19). Bacterial and fungal α-diversity metrics (Sobs, Shannon, Simpson) showed no treatment effects, with all treatments yielding similar richness, diversity and evenness (Figure 20).

Redundancy analysis (RDA) ordinations constrained by treatment revealed that, while there were some compositional differences associated with treatment, overall community compositions did not significantly differ by treatment ($P > 0.05$, Figure 21). Phylum-class relative abundances were largely consistent among treatments for both bacteria and fungi, with the exception of Sordariomycetes. This class of fungi was more dominant in compost and mud/ash treatments, followed by gypsum and FOGO treatments than the control ($P < 0.001$, Figure 22).

High-resolution taxonomic profiling identified nine dominant bacterial strains that significantly differed by treatment ($P < 0.001$, Figure 23). Among the dominant fungal populations, two fungal genera and one fungal taxon significantly differed among treatments (Figures 23 and 24).

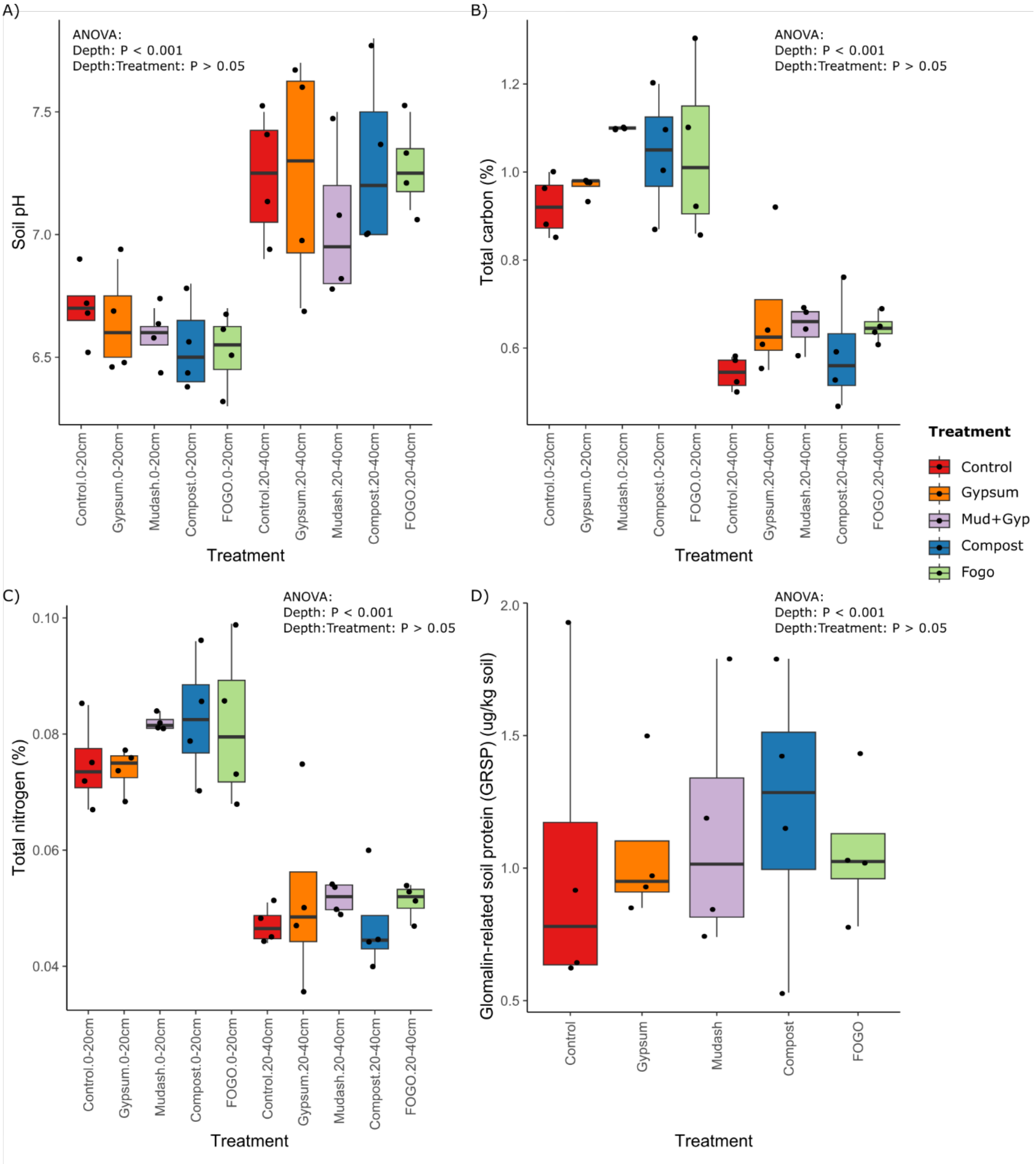

Figure 18. (A) Soil pH; (B) total carbon (%); (C) total nitrogen (%) by treatment by depth; and (D) glomalin-related soil protein (GRSP) content by treatment within 0–20 cm.

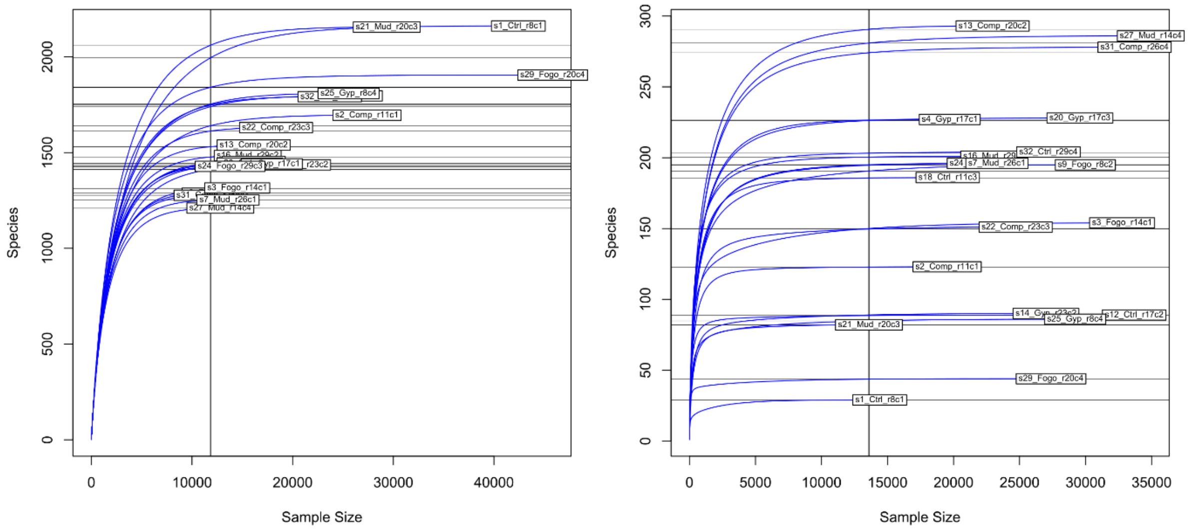

Figure 19. (A) Bacterial sequences were rarefied to 11,836 sequences per sample; (B) fungal sequences were rarefied to 17,003 sequences per sample.

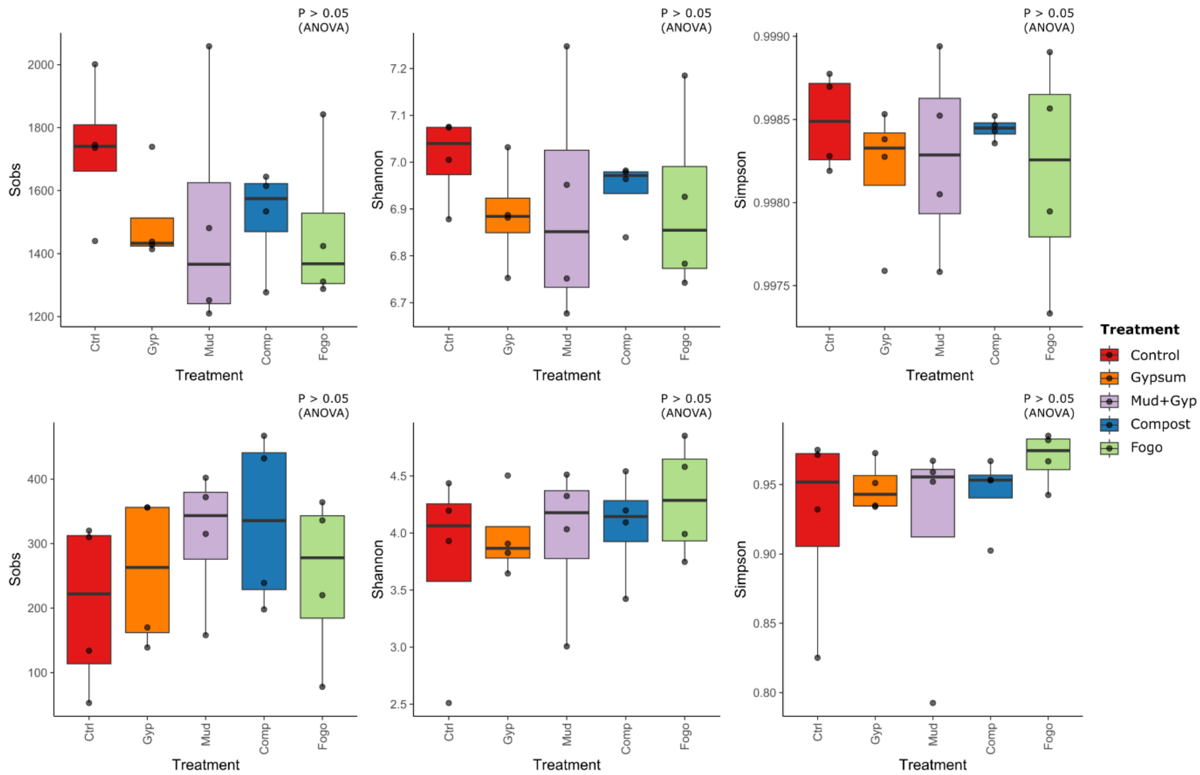

Figure 20. Alpha diversity metrics of bacterial (top row) and fungal (bottom row) communities by treatment: observed number of taxa (Sobs, left), Shannon diversity (middle), and Simpson diversity by treatment (right).

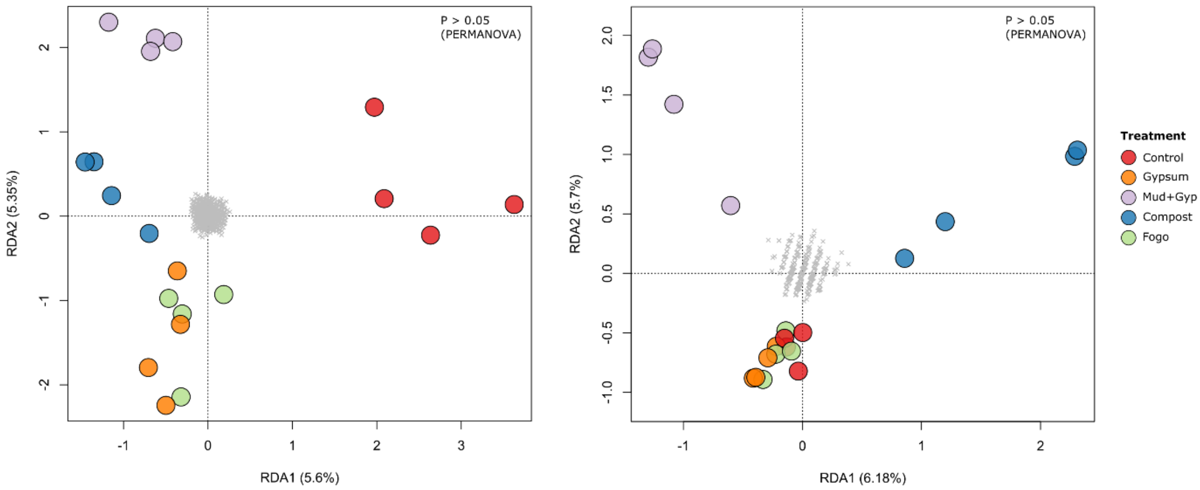

Figure 21. Redundancy analysis (RDA) of bacterial (left); and fungal composition (right) by treatment.

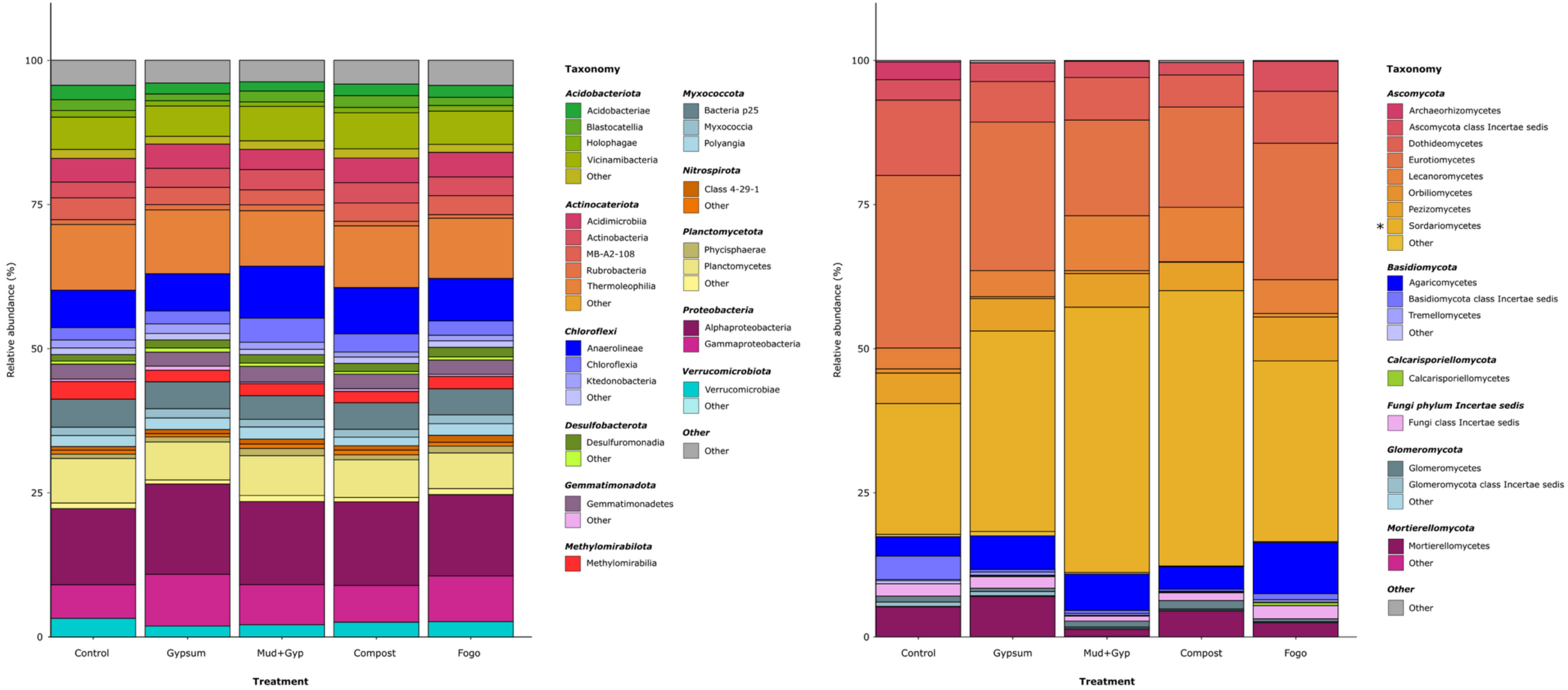

Figure 22. Stacked phylum-class level community barcharts of dominant (> 1%) (A) bacterial; and (B) fungal phyla by treatment using the average relative abundances. Phyla present at less than 1% were grouped into ‘Other’. The presence of an asterisk indicates classes that significantly differ by treatment.

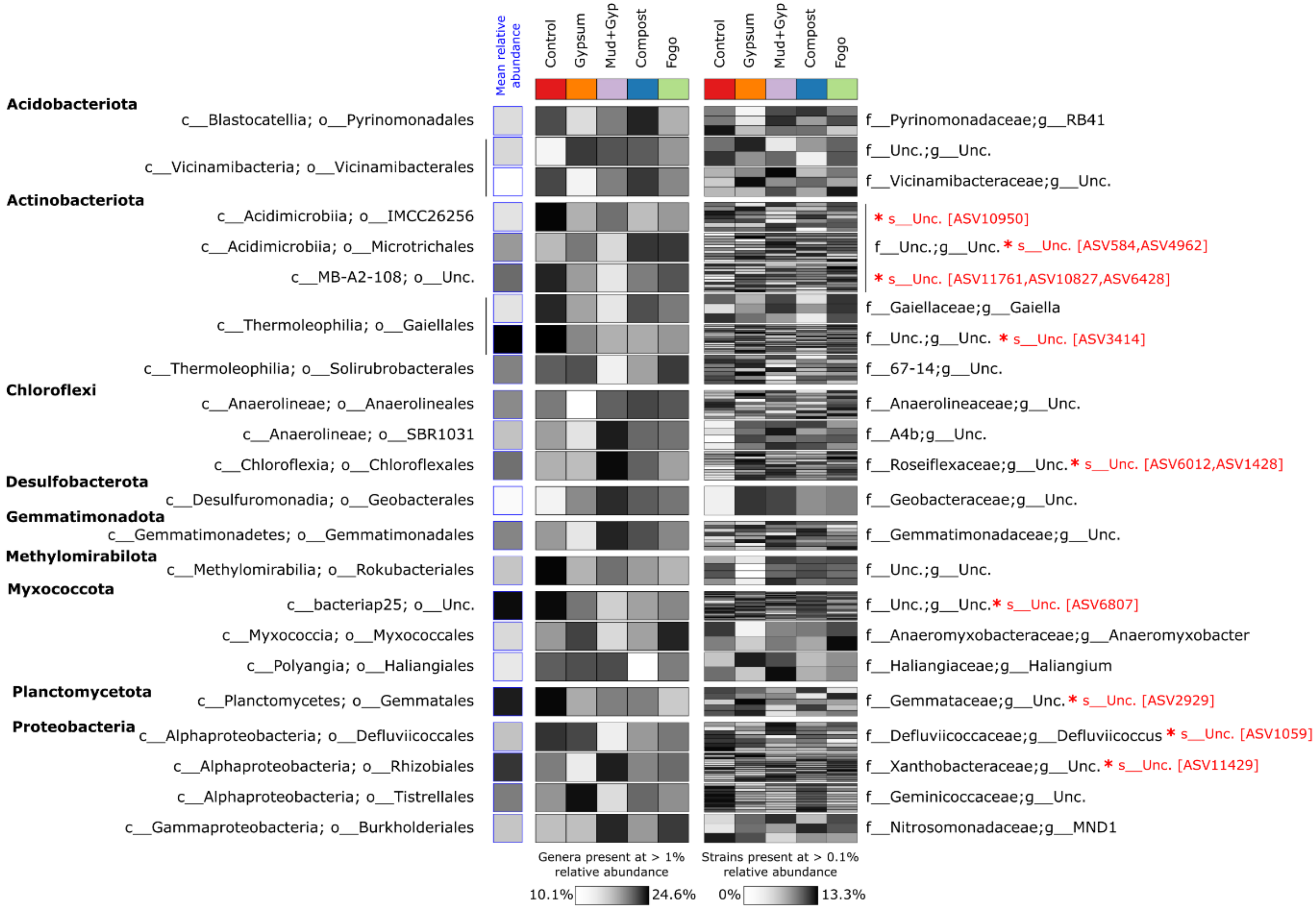

Figure 23. Relative abundance heatmap of dominant (genera relative abundance > 1%) bacterial populations by treatment at the genus and strain level. Blue boxes indicate the mean abundance of each population across all samples to give context of their d dominance relative to other community members. Strains that significantly differ by treatment are featured in red.

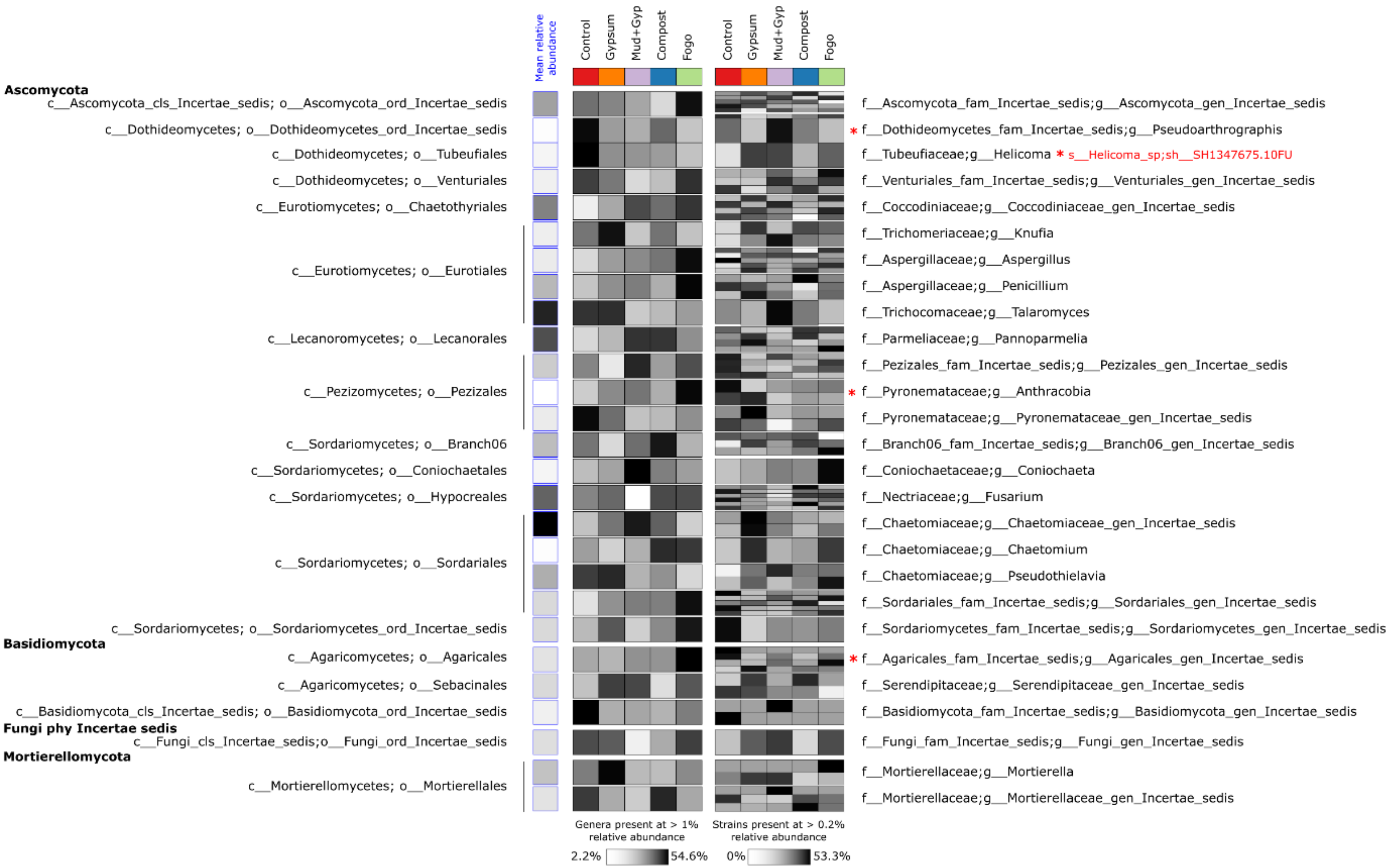

Figure 24. Relative abundance heatmap of dominant (genera relative abundance > 1%) fungal populations by treatment at the genus and strain level. Blue boxes indicate the mean abundance of each population across all samples to give context of their dominance relative to other community members. The presence of an asterisk indicates genera that significantly differ by treatment. Strains that significantly differ by treatment are featured in red.

Table 2. Summary mean soil chemical characteristics of the selected treatments post-harvest Year 1.

Depth (cm)	Treatment	pH_w	TC (%)	TN (%)	Exch. Ca^{2+} (cmol(+)/kg)	Exch. Mg^{2+} (cmol(+)/kg)	Exch. K^+ (cmol(+)/kg)	Exch. Na^+ (cmol(+)/kg)	eCEC (cmol(+)/kg)	Exch. Ca (% eCEC)	Exch. Mg (% eCEC)	ESP (%)
0–20	Control	6.70	0.92	0.075	14.00	10.00	0.36	0.94	25.00	54.50	40.50	3.73
	Gypsum	6.65	0.97	0.074	14.25	9.75	0.35	0.82	25.25	56.25	38.75	3.25
	Mud/ash	6.58	1.10	0.082	14.25	10.25	0.36	0.84	25.50	55.75	39.75	3.17
	Compost	6.55	1.04	0.083	14.50	9.97	0.36	0.85	25.75	56.00	39.00	3.30
	FOGO	6.53	1.04	0.082	14.50	9.95	0.38	0.78	25.75	56.00	39.25	3.05
	***P*-value**	**0.584**	**0.246**	**0.458**	**0.752**	**0.195**	**0.566**	**0.455**	**0.499**	**0.495**	**0.295**	**0.249**
20–40	Control	7.22	0.54	0.047	12.25	10.50	0.31	2.17	25.00	48.00	42.25	8.55
	Gypsum	7.25	0.68	0.052	13.50	11.25	0.32	2.08	27.50	50.25	41.00	7.70
	Mud/ash	7.05	0.65	0.052	12.75	10.50	0.30	1.92	25.50	49.75	41.50	7.60
	Compost	7.30	0.59	0.047	12.50	10.35	0.30	2.05	25.25	50.00	40.50	8.03
	FOGO	7.25	0.65	0.051	13.00	10.47	0.32	2.10	26.25	50.25	40.25	8.07
	***P*-value**	**0.852**	**0.323**	**0.850**	**0.675**	**0.280**	**0.337**	**0.793**	**0.156**	**0.719**	**0.516**	**0.726**

4.5.2 **Year 2**

Soil chemical characteristics at the end of Year 2 for the control, gypsum, mud/ash, compost and FOGO treatments at the two sample depths are shown in Table 3. As in Year 1, soil pH, total carbon and total nitrogen varied by sampling depth (P < 0.001), with no significant differences observed by treatment within each depth for pH, TC and ESP (Figure 25). Soil pH was significantly lower in the topsoil (0–20 cm) versus the subsoil (20–40 cm), as was TC (P < 0.001), with no significant treatment differences (P > 0.05). However, total nitrogen values were significantly different in the 20–40 cm depth, where the compost and FOGO treatments had statistically greater nitrogen content than the other treatments (P = 0.013). Exchangeable sodium percentage increased significantly with depth (P < 0.001), but not between treatments (P > 0.05).

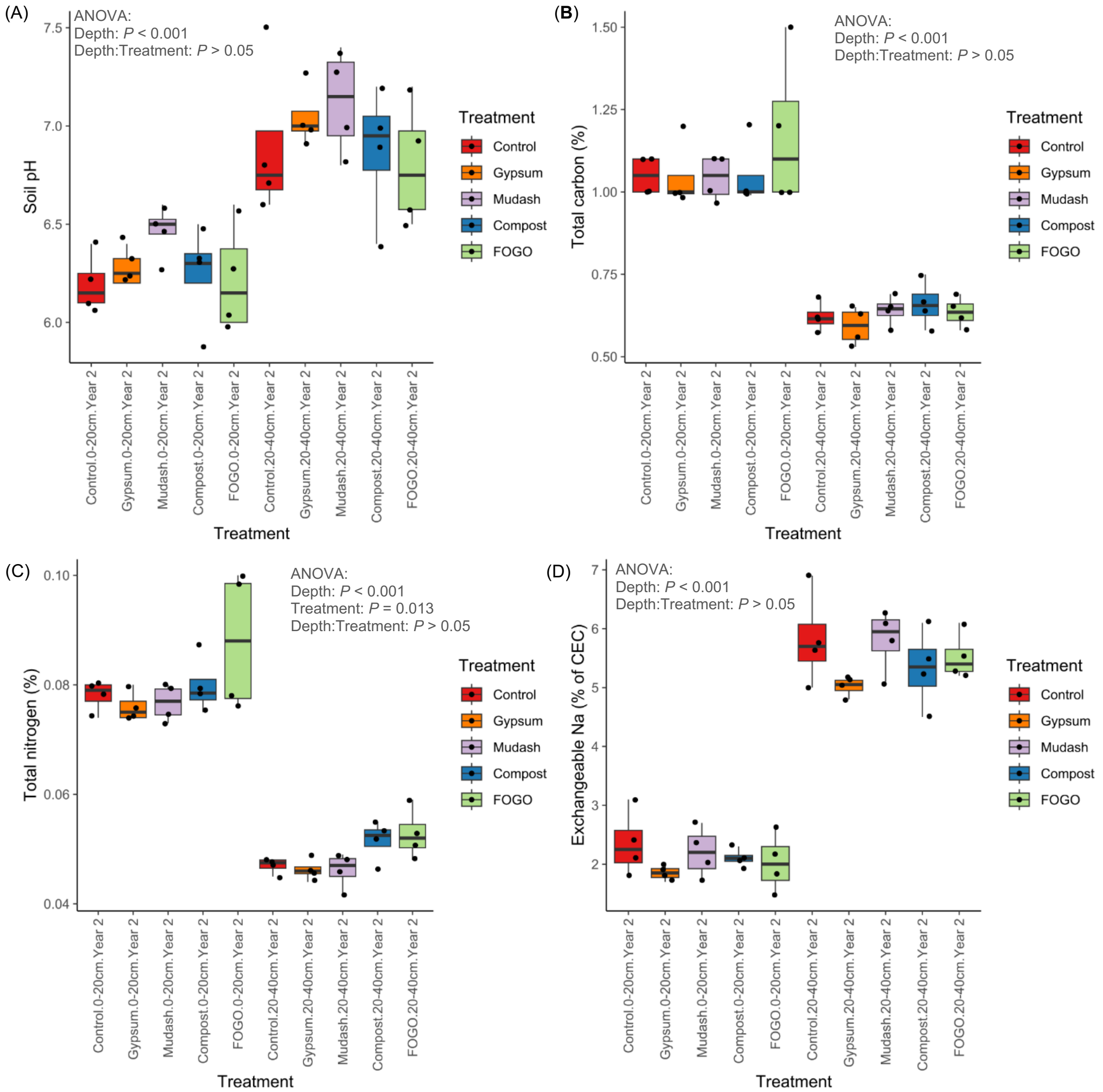

Figure 25. (A) Soil pH; (B) total carbon (%); (C) total nitrogen (%); and (D) exchangeable sodium percentage, by treatment and depth.

Table 3. Summary mean soil chemical characteristics of the selected treatments post-harvest Year 2.

Depth (cm)	Treatment	pH_w	TC (%)	TN (%)	Exch. Ca^{2+} (cmol(+)/kg)	Exch. Mg^{2+} (cmol(+)/kg)	Exch. K^+ (cmol(+)/kg)	Exch. Na^+ (cmol(+)/kg)	eCEC (cmol(+)/kg)	Exch. Ca (% eCEC)	Exch. Mg (% eCEC)	ESP (%)
0–20	Control	6.20	1.05	0.078	16.00	11.00	0.45	0.66	28.00	56.50	39.50	2.35
	Gypsum	6.28	1.04	0.076	16.50	10.50	0.47	0.52	28.00	58.50	37.50	1.85
	Mud/ash	6.47	1.04	0.077	16.50	11.25	0.47	0.64	29.00	57.25	39.25	2.20
	Compost	6.25	1.05	0.080	16.25	10.75	0.46	0.60	28.00	57.25	39.00	2.10
	FOGO	6.22	1.18	0.088	16.25	11.00	0.46	0.57	28.25	57.50	38.50	2.02
	***P*-value**	**0.327**	**0.553**	**0.144**	**0.840**	**0.154**	**0.650**	**0.442**	**0.498**	**0.361**	**0.130**	**0.486**
20–40	Control	6.90	0.62	0.047	14.00	11.00	0.38	1.60	27.00	51.50	41.25	5.83
	Gypsum	7.05	0.59	0.046	15.00	11.50	0.40	1.42	28.00	53.25	40.25	5.03
	Mud/ash	7.12	0.64	0.046	15.00	12.00	0.38	1.70	29.00	51.25	41.25	5.82
	Compost	6.88	0.66	0.052	14.25	11.50	0.40	1.48	28.00	52.25	41.25	5.33
	FOGO	6.80	0.64	0.053	14.75	11.50	0.39	1.57	28.25	52.25	41.00	5.53
	***P*-value**	**0.586**	**0.504**	**0.013**	**0.599**	**0.252**	**0.833**	**0.586**	**0.547**	**0.277**	**0.712**	**0.246**

DISCUSSION

The lack of statistically significant results from this trial raises questions about the efficacy of applying subsoil ameliorants in this soil type and farming system over a two-year period. The inability to see differences between treatments in the first two years of the crop cycle may mean that ameliorants may take longer than two years to be effective. There are also questions about adequate rates of ameliorants applied and whether the farming system itself has an impact, particularly being an irrigated system. It has been found in other subsoil amelioration trials that treatment effects are not seen in wetter years (Arslan et al., 2026), whereby plant roots are able to access enough soil water to support the crop during the growing season from the upper soil layers and soil constraints are lessened or altogether absent. Another factor may be that the amendments, being placed at around 25 cm depth, were not situated where the subsoil constraints were severe. The soil at 20–50 cm depth was typically only moderately and intermittently dispersive (Figure 9), and the exchangeable sodium percentage at the depth of placement was not particularly high (Tables 1, 2). With both years of the trial having wetter than average rainfall, these combined factors may mean that the sugarcane crops were able to circumvent the subsoil constraints present, negating any influence on plant growth that the amendments might have had.

The four amendment treatments (compost, mud/ash, gypsum, and FOGO) generally had no significant effect on fundamental soil chemical properties compared to the nil control. Soil pH, total carbon and total nitrogen varied significantly by sampling depth but not by treatment within each depth, except for TN in Year 2. The TN in the 20–40 cm depth in the compost and FOGO treatments was significantly greater than that of the other treatments, albeit the actual values and relative differences were small. This suggests that the organic N in these amendments was less susceptible to leaching compared to the other amendments, given that no differences in TN were observed in Year 1. GRSP content in the topsoil layer in Year 1 also showed no treatment differences. This indicates that the amendments did not substantially alter the bulk chemical environment of the soil. Results for most measured soil characteristics were significantly different between the two sample years, which can be ascribed to seasonal variation, probably related to the high precipitation which is likely to have caused some cation leaching.

Both bacterial and fungal communities showed no treatment-induced changes in alpha diversity metrics. Observed richness (Sobs), Shannon diversity, and Simpson diversity were similar across all treatments for both bacteria and fungi. Additionally, redundancy analysis revealed that community compositions did not significantly differ by treatment for either bacteria or fungi. This indicates that the amendments have not significantly altered microbial community composition, richness or evenness.

Despite the lack of broad-scale community shifts, high-resolution community profiling revealed treatment-specific responses at finer taxonomic levels. The fungal class Sordariomycetes was significantly more dominant in compost and mud/ash treatments, followed by gypsum and FOGO, compared to the control. The enrichment of Sordariomycetes – copiotrophic saprotrophs with high cellulolytic activity (Miao et al., 2022; Clocchiatti et al., 2021) – likely reflects the availability of labile carbon in the compost and mud/ash amendments, though functional validation through metagenomics or enzyme assays would be required to confirm their metabolic activities in these amended soils. At the strain level, nine dominant bacterial strains differed significantly by treatment, along with two fungal genera and one fungal taxon. These findings suggest that while overall community structure remains stable, organic amendments can selectively influence specific microbial populations that may play distinct functional roles in soil processes.

In summary, targeted responses in specific microbial taxa were observed despite stability in bulk soil properties and overall community diversity, potentially indicating early-stage biological shifts preceding measurable changes in soil chemistry.

CONCLUSION

Overall, this trial has ascertained that none of the subsoil ameliorants applied to a heavy clay with sodic and magnesic subsoil had a measurable impact on sugarcane performance within a two-year period. Though this marks the end of this project, the site will continue to be monitored by BPS to assess any potential impacts the treatments may have in the third and fourth year of the crop cycle.

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