

Amelioration of hostile subsoils via incorporation of organic and inorganic amendments and subsequent changes in soil properties, crop water use and improved yield, in a medium rainfall zone of south-eastern Australia

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Key words

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Take home messages

- Deep placement of organic and inorganic amendments increased grain yield in the order of 20 to 50% for five successive years on an alkaline dispersive subsoil at Rand
- Deep placement of organic and inorganic amendments increased root growth and crop water use from the deeper clay layers during the critical reproductive stages of crop development
- Improvements in grain yield with deep placement of organic and inorganic amendments were associated with a reduction in subsoil pH and improvement in soil aggregation.

Background

Sodicity, salinity and acidity are significant surface and subsoil constraints that reduce crop productivity throughout the cropping regions of Australia (Sale *et al.*, 2021). The majority of cropping soils contain at minimum one, but more multiple constraints (McDonald *et al.*, 2013). The economic impact to Australian agriculture, expressed by the 'yield gap' between actual and potential yield, attributable to subsoil constraints was estimated to be more than A\$1.3 billion annually by Rengasamy (2002), and as much A\$2.8 billion by Hajkowicz and Young (2005). Of the 'three', sodicity is thought to be the most detrimental to productivity, resulting in the greatest yield gap. In Australian wheat-cropping regions alone, this 'gap' was estimated to be worth A\$1.3 billion per annum in lost income (Orton *et al.*, 2018), while close to 20% of Australia's land area is thought to be sodic.

Sodic soils, which are characterised by an excess of sodium (Na⁺) ions and classified as those with an exchangeable sodium percentage (ESP) greater than 6% (Northcote and Skene, 1972), are often poorly structured, have a high clay content, high bulk density, and are dispersive. These factors result in poor subsoil structure that can impede drainage, promote waterlogging (low water infiltration), and increase de-nitrification (nutrient imbalance), and soil strength (Orton *et al.*, 2018). These properties also impede the infiltration of water into and within the soil, reduce water and nutrient storage capacity, and ultimately the plant available water (PAW) content of the soil. Subsequently, root growth and rooting depth are impeded, as is crop ability to access and extract deeper stored water and nutrients (Passioura and Angus, 2010). This is particularly problematic in

environments characterised by a dry spring, where the reproductive phase often coincides with periods of water stress, and when the conversion of water to grain has the greatest effect both on yield (Kirkegaard *et al.*, 2007), and the likelihood and magnitude of a yield gap (Adcock *et al.*, 2007).

In southern NSW, winter crops commonly have sufficient water supply during their early growth stages either from stored soil water or rainfall. However, the reproductive phase is often affected by water stress or terminal drought and this is thought to be the major cause of variable grain yield (Farooq *et al.*, 2014). The effect of water stress in the reproductive phase is further impacted by shallow root depth induced by subsoil sodicity. Under such conditions, a key to improving crop productivity is to improve root growth in and through sodic subsoils to enable use of deep subsoil water later in the growing season. Water use at this late stage has a 2 to 3 fold greater conversion efficiency into grain yield (Kirkegaard *et al.*, 2007) than seasonal average based conversions efficiencies (e.g. 20 – 25 kg/mm verses 50 – 60 kg/mm).

While there are large advantages to be gained by improving the soil environment of sodic subsoils, the various amelioration approaches (deep ripping, subsoil manuring, applying gypsum, improved nutrition and use of ‘primer-crops’) have produced variable results (Adcock *et al.*, 2007; Gill *et al.*, 2008). Furthermore, the use of subsoil organic material is also impacted by limited local availability, the high cost of suitable organic ameliorants delivered in-paddock, the sometimes large quantities required, the lack of suitable commercial-scale machinery and the poor predictability of when and where the amelioration will benefit crop productivity (Gill *et al.*, 2008; Sale *et al.*, 2019).

Gypsum application has been the most widespread traditional approach used to correct subsoil sodicity. However, problems have included; surface application when the problem is evident in the subsoil, the large quantities of gypsum required to displace significant amounts of sodium and the somewhat low solubility of gypsum.

This paper reports on the performance of a barley-wheat-canola-wheat rotation on a Sodosol (Isbell, 2002) soil two sites in Rand and Grogan in southern New South Wales in the five (Rand) and four (Grogan) years immediately following incorporation of a range of amendments, and the residual effects of ‘subsoil manuring’ on crop performance, soil physical properties, and access to PAW stored in the soil profile over subsequent seasons. A range of treatments comprising deep-ripping and subsoil incorporation of organic and inorganic amendments at a depth of 20–40cm were compared to, and contrasted with, surface applications, ripping-only and untreated controls. Amendments that could be easily procured or produced as part of a farming system were used in the trial. It is hypothesised that subsoil incorporation of organic or inorganic amendments will provide significant improvements in grain yield, which are associated with changes in the physical properties of the subsoil that result in improved root growth, and access to, and use of, deep soil water.

Method

Rand amendment site

The trial sites were located at Rand and Grogan in southern New South Wales in paddocks that had been under a continuous cropping (cereal-canola) for more than 50 years. The soil at both sites was a Sodosol with a texture-contrast profile increasing in clay content at depth, and with physical and chemical properties (Table 1.) unfavourable for root growth, including a high bulk density and low hydraulic conductivity.

Table 1. Chemical and physical properties of the soils at different depths at the Rand trial site

Depth (cm)	pH (H ₂ O)	EC (1:5) (μS/cm)	Nitrate N (mg/kg)	Exchangeable cations (cmol/kg)	Exchangeable sodium percentage (%)	Bulk density (g/cm ³)	Volumetric water content (θ _v)
0–10	6.6	132.1	20.6	16.1	3.8	1.40	0.120
10–20	7.8	104.0	5.8	22.6	7.3	1.52	0.163
20–40	9.0	201.5	4.1	26.7	12.5	1.50	0.196
40–50	9.4	300.5	3.0	27.5	18.1	1.48	0.232
50–60	9.5	401.3	3.0	28.8	21.8	1.53	0.237
60–100	9.4	645.0	2.9	29.7	26.4	1.55	0.218

The trials were established in February 2017 (Rand) and March 2018 (Grogan) as a randomised complete block with a range of treatments (Table 2) and four replicates. Experimental plots were arranged in two blocks (ranges) of 26 plots, separated by a 36m cropped buffer. Individual plots within each block were 2.5m wide (south-north) × 20m long (east-west), separated on their long sides by 2m buffers of uncultivated ground. Plots were ripped to a depth of 40cm, and amendments incorporated into the soil via a custom built 3-D ripping machine (NSW DPI), comprising a ‘Jack’ GM77-04 5-tyne ripper (Grizzly Engineering Pty Ltd, Swan Hill, VIC, Australia), configured to 500mm tyne spacings, and topped with a custom designed frame supporting two purpose built discharge hoppers (bins) and a 300L liquid cartage tank. The larger, ~1.6 cubic meter-capacity hopper was designed to deliver organic materials and can accommodate approximately 1000 kg of material, roughly equivalent to a standard ‘spout top, spout bottom’ bulk bag. The organic amendments were obtained in pellet form for ease of application and consisted of dried pea straw pellets (1.13% N, 0.05% P, 1.34% K; extrusion diam. 7–10mm, length 6–35mm), wheat stubble pellets (0.34% N, 0.15% P, 1.59% K; diam. 7–10mm, length 6–35mm), and dried poultry manure pellets marketed as Dynamic Lifter® (3% N, 2% P, 1.7% K; diam. 7–10mm, length 6–35mm). The amendments were applied three months prior to sowing the first season.

In 2017, experimental plots were sown to Barley (cv. LaTrobe[®]) on the 11th of May at a seeding rate of 70 kg/ha (target plant density 100 plants/m²). Monoammonium phosphate (MAP) was applied at 80 kg/ha as a starter fertiliser at sowing. The crop was sown after spraying with Boxer Gold® (800 g/L prosulfocarb + 120 g/L S-metolachlor), Spray.Seed® (135 g/L paraquat dichloride + 115 g/L diquat dibromide) and Treflan™ (480 g/L trifluralin). The crop was harvested on the 21st of November.

In 2018, wheat (cv. Lancer[®]) was sown on the 15th of May at a seeding rate of 80 kg/ha (target plant density 150 plants/m²). MAP was applied at 80 kg/ha as a starter fertiliser at the time of sowing. The crop was sown after spraying with Spray.Seed, Sakura® (850 g/kg pyroxasulfone), Logran® (750 g/kg triasulfuron) and Treflan. Urea (46% N) at 110 kg/ha (50.6 kg/ha N) was applied at 106 DAS. The crop was harvested on the 6th of December.

In 2019, Canola (Pioneer® 45Y92CL) was sown on the 10th of April at a seeding rate of 4.4kg/ha (target plant density 40 plants/m²). MAP was applied at 90 kg/ha (9 kg/ha N, 19.8 kg/ha P) as a starter fertiliser at the time of sowing. The crop was sown after spraying with Roundup® (360 g/L glyphosate, present as the isopropylamine salt in a tank mix with Kamba® 750 (750 g/L dicamba). Urea at 220 kg/ha (101.2 kg/ha N) was applied as a top-dressing at 119 DAS, and Prosaro® (210 g/L prothioconazole + 210 g/L tebuconazole) at 50% bloom as a preventative for Sclerotinia stem rot (132 DAS). The crop was harvested on the 30th of October.

In 2020, wheat (cv. Scepter[®]) was sown on the 16th of May at a seeding rate of 63 kg/ha (target plant density of 120 plants/m²). Diammonium phosphate (DAP) was applied at 78 kg/ha as a starter fertiliser at the time of sowing. The crop was sown after spraying with Spray.Seed, Roundup, Sakura and Treflan. Urea at 150 kg/ha (69 kg/ha N) was applied as a top-dressing 7 DAS prior to rain. The crop was harvested on the 7th of December.

The long-term average annual rainfall at the site is 553mm with a reasonably uniform average monthly rainfall. In 2017, in-season rainfall (April–November) totalled 329mm, while 244mm and 242mm, respectively, were recorded for the same period in 2018 and 2019. Rainfall in both 2018 and 2019 was approximately 25% less than that recorded for 2017, and approximately 65% of the long-term average seasonal rainfall. The long-term average monthly rainfall, and average monthly maximum and minimum temperatures, daily (bars) rainfall events and monthly rainfall at the Rand experimental site for the period 2017–2021 (Figure 1).

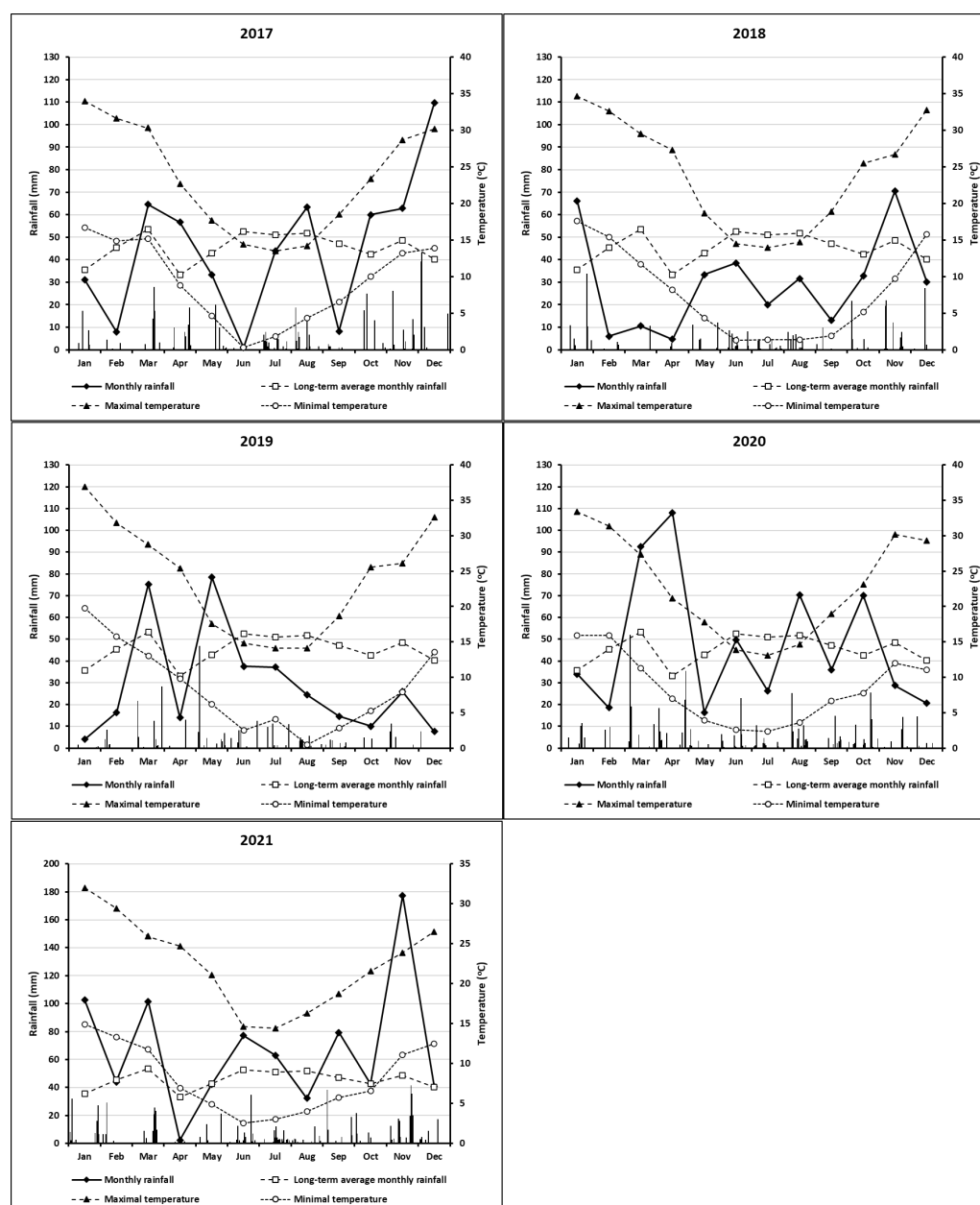


Figure 1. Long-term average monthly rainfall, and average monthly maximum and minimum temperatures, daily (bars) rainfall events and monthly rainfall at the Rand experimental site located at Urangeline East, NSW.

Table 2. Description of the treatments and organic and inorganic amendments used in the trial.

Treatment	Description	Amount of amendment added
1	Control	Direct sowing
2	Deep gypsum	5 t/ha, incorporated to depth of 20-40 cm
3	Deep liquid NPK	Incorporated to depth of 20-40 cm, the amount of NPK added was matched to NPK content of chicken manure
4	Deep chicken manure	8 t/ha, incorporated to depth of 20-40 cm
5	Deep pea straw	15 t/ha, incorporated to depth of 20-40 cm
6	Deep pea straw +gypsum+NPK	12 t/ha, 2.5 t/ha, incorporated to depth of 20-40 cm,
7	Deep pea straw+NPK	15 t/ha, incorporated to depth of 20-40 cm
8	Deep wheat stubble	15 t/ha, incorporated to depth of 20-40 cm
9	Deep wheat stubble +NPK	15 t/ha, incorporated to depth of 20-40 cm
10	Ripping only	To depth of 40cm
11	Surface gypsum	5 t/ha, applied at soil surface
12	Surface chicken manure	8 t/ha, applied at soil surface
13	Surface pea straw	15 t/ha, applied at soil surface

At late flowering soil coring was completed using a tractor-mounted hydraulic soil-coring rig and 45 mm diameter soil cores. The break core method was used to estimate rooting depth and exposed roots were recorded at the following depths 0 - 10, 10 - 20, 20 - 40, 40 - 60, and 60 – 100 cm. Quadrat samples of 2m² were taken at physiological maturity to measure plant biomass and grain yield.

Grogan subsoil amelioration experiment

In 2018 an experiment was conducted near the township of Grogan in southern NSW, which included 27 amendments in a row column design with four replicates. The soil profile was slightly acidic in the top 10cm (pH_{1:5 water} 5.9) and pH dramatically increases with depth (Table 3). The changes in soil sodicity (exchangeable sodium percentage, ESP) followed a similar trend of soil pH with exchangeable sodium percentage (ESP) at 10.5% in the topsoil and increasing up to 40% in the subsoil (Table 3).

Table 3. Site characterisation for the Grogan experimental site. Values are means (n=5).

Soil depths (cm)	EC (µs/cm)	pH (1:5 water)	Colwell-P (µg/g)	CEC (cmol(+) /kg)	Exchangeable sodium percentage
0-10	309.40	5.87	58.80	16.66	10.53
10-20	133.00	7.65	7.40	22.06	11.97
20-30	136.90	8.76	2.62	24.53	15.94
30-40	207.66	9.12	2.50	25.55	20.12
40-60	338.94	9.60	1.34	27.17	26.27
60-80	530.40	9.53	1.00	31.63	36.68
80-100	897.20	9.43	1.48	34.07	40.25
100-120	1148.20	9.38	1.50	35.28	40.35

The agronomic management of the trial was similar to Rand site as outlined above. However, the effect of several additional treatments including elemental sulphur, and lucerne hay was investigated.

Results

Rand and Grogan amendment trial

The one-off application of various amendments (Table 2) significantly affected the crop grain yield over 5 consecutive years at the Rand site. For example, in 2021, canola grain yield (relative to control) increased following the deep placement of wheat stubble, wheat stubble + nutrient and manure by 15-12% ($P < 0.001$) (Figure 2). At the Grogan site, canola grain yield (relative to control) increased following the deep placement of manure, lucerne hay and gypsum + pea hay+ nutrient by 45, 42 and 39% respectively ($P < 0.001$) (Figure 2). The variations in yield in response to surface application of amendments or ripping only was not significantly different from the control at both sites.

At the Rand site, a multi-year cumulative analysis of grain yield response (2017-2021) indicated that deep placement of plant-based stubble, gypsum and their combination resulted in significant and consistent improvements in crop yield (Table 4). A preliminary cumulative gross return is also presented in Table 4.

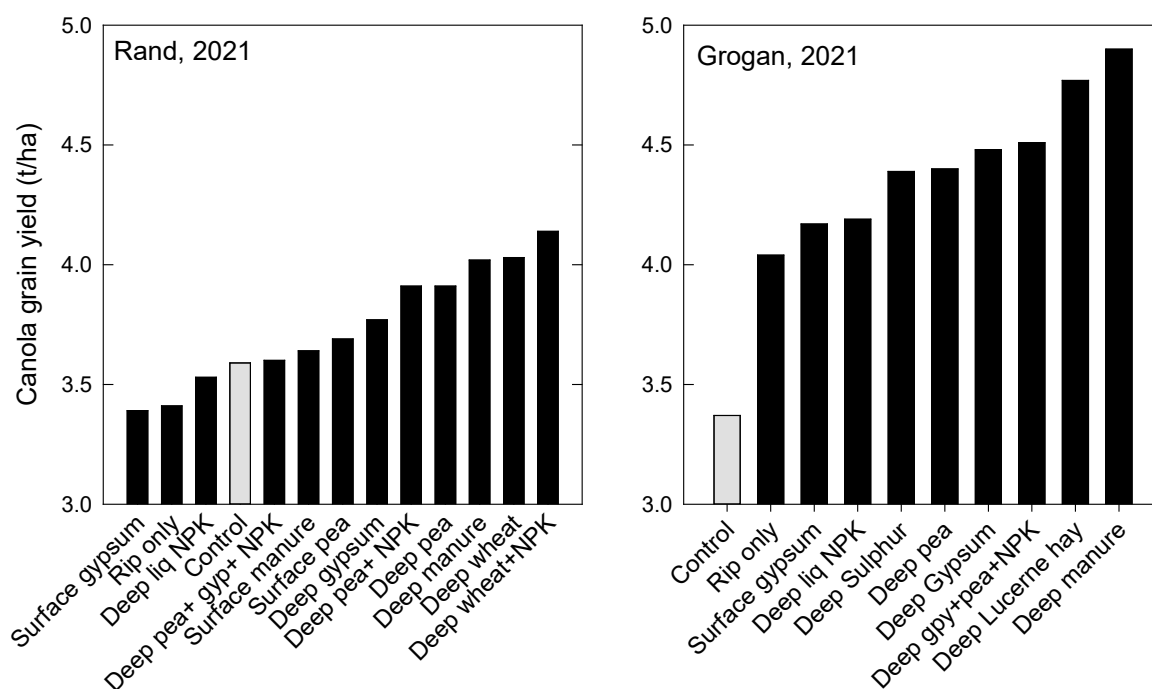


Figure 2. The mean effect of surface or deep-placed amendments on grain yield of canola (cv. Dimond) grown in an alkaline dispersive subsoil at Rand (left) and Grogan (right), NSW in 2021. Values are mean (n=4). LSD_{0.05} = 0.28 (left) and 0.78 (right).

Table 4. Cumulative grain yield (2017-2020) and cumulative gross return (\$) for barley (2017; \$220/t), wheat (2018; \$250/t), canola (2019; \$600/t) and wheat (2020; \$250/t), canola (2021; \$800/t) at Rand.

Treatment	Yield (t/ha)		\$	
Rip only	19.3	a	7465	a
Control	19.3	a	7497	a
Surface gypsum	19.1	ab	7550	ab
Deep liq NPK	20.6	ab	7671	ab
Surface pea	19.7	bc	7769	ab
Surface manure	20.6	bc	7981	bc
Deep pea+gyp+NPK	23.0	cd	8577	cd
Deep wheat	22.3	cd	8614	cd
Deep pea	22.7	cd	8635	d
Deep manure	22.3	d	8645	cd
Deep pea+NPK	22.3	d	8682	d
Deep wheat+NPK	22.6	d	8698	d
Deep gypsum	22.7	d	8700	d

*Results with the same letter after them are not significantly different $P < 0.05$

Over the course of this study several key measurements of soil and crop parameters were made to investigate the impact of various amendments on soil: plant interactions. Selected data from the Rand trial is reported below.

The number of visible roots in the amended subsoil layer (20 – 40cm depth) were significantly ($P < 0.05$) affected by different amendments (Figure 3). Deep placement of both manure and pea hay increased the number of visible roots by more than 3-fold. Neutron probe readings taken in September also indicate that the highest root counts were associated with the driest soil water profile (Figure 4). Variation in soil pH measured at the amended layer is shown in Table 5. Compared to the control, deep placement of gypsum reduced the soil pH by 0.86 units (8.99 to 8.13) at 20 – 40cm depth. However, pH was not affected by other treatments.

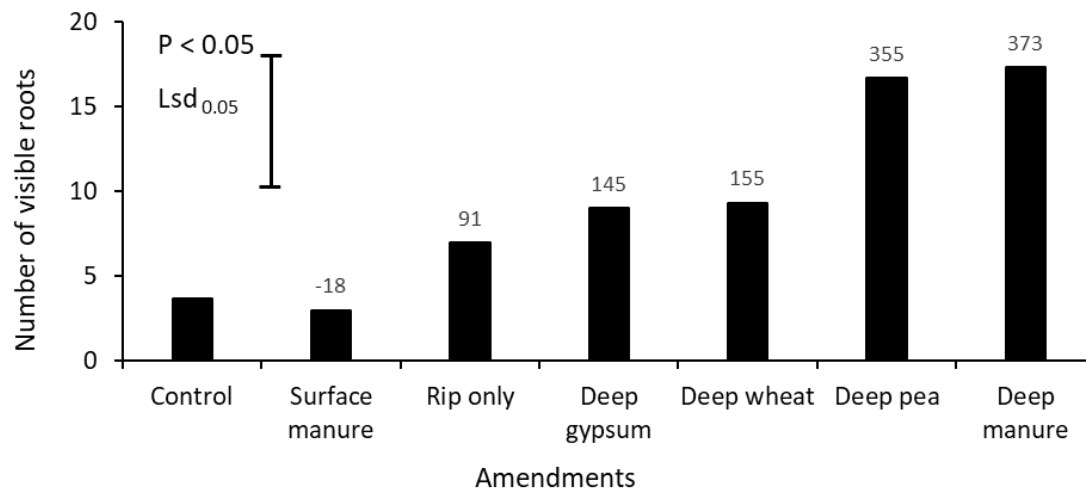


Figure 3. The mean effect of surface or deep-placed amendments on the number of visible roots at 30cm at late flowering of canola (cv. Pioneer 45Y91CL) grown in alkaline dispersive subsoil at Rand, SNSW in 2019. Values on the top of each bar represents the percent change of visible roots compared to control.

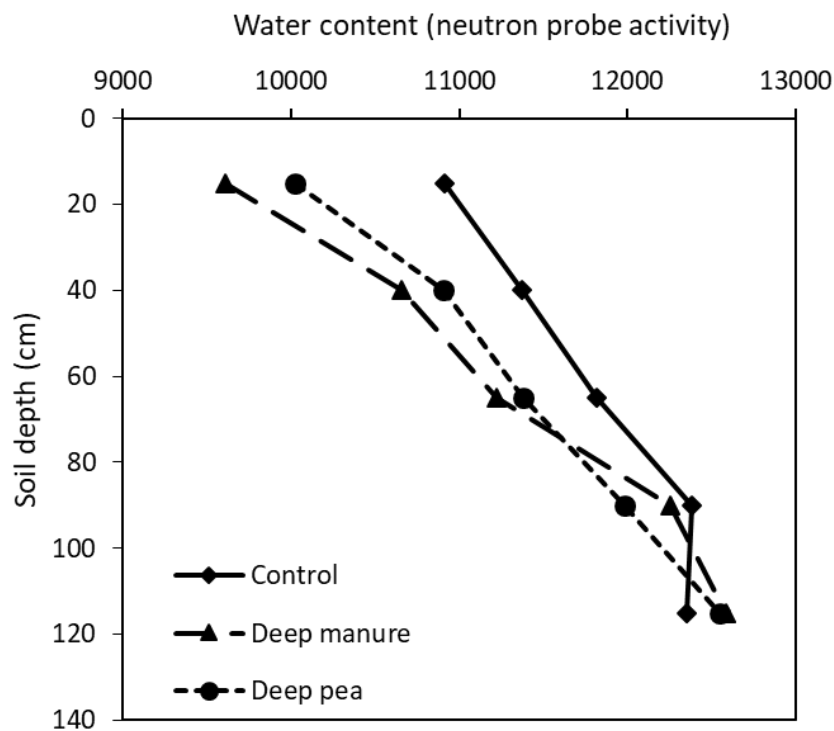


Figure 4. Neutron probe readings taken in September at the Rand amendment site for contrasting treatment comparisons. Results are based on the neutron activity (raw data) where higher values represent higher water content in the soil profile. Values are averages ($n = 4$).

Table 5. Mean soil pH (20-40 cm) in selected treatments at the Rand site. Samples were collected in May 2020. $LSD_{0.05} = 0.27$.

Amendment	Predicted mean	Significant difference group
Control	8.99	a
Deep liq NPK	8.96	a
Rip only	8.94	a
Deep wheat+NPK	8.93	ab
Surface gypsum	8.92	ab
Deep pea	8.87	ab
Deep wheat	8.83	ab
Deep manure	8.60	bc
Deep pea+gyp+NPK	8.52	c
Deep gypsum	8.13	d

Discussion

In Alkaline dispersive soils, several properties of subsoils including, high pH, high levels of soluble carbonate species, poorly structured dense clay, and dispersion together with overall poor chemical fertility, represent a hostile environment for crop roots. Here we demonstrate the impact of various amendments on these properties and the potential to re-engineer these hostile subsoils for improved crop performance.

Barley, wheat, canola, wheat and canola were grown in 2017–2021, respectively. Growing season rainfall (April to November total) was average in 2017 (decile 5), and declined in 2018 (decile 1.5), with still drier conditions in 2019 (decile 1.0), when only 45 mm of rain (decile 0) fell during the spring months from September to November. This improved in 2020 and 2021 where the Rand trial received > 401 mm during growing the season. The amendments that consistently resulted in significant yield increases above the control, were the deep-placed combination of pea straw pellets, gypsum and liquid fertilizer nutrients, and the deep-placed gypsum and deep placed pea straw (Table 4). Improvements in subsoil structure were measured in the winter of 2019. The deep crop residue amendments significantly increased macro aggregation, as measured on the rip-line at a depth of 20-40 cm. Similarly, deep gypsum and the deep gypsum/pea straw/nutrient combination markedly increased water infiltration into the soil profile, with higher saturated hydraulic conductivities measured on the rip-line. Our results to date indicate that independent modes of action of various amendments (e.g., crop residue vs gypsum) are required in the amendment mix, in order to ameliorate these subsoils. For example, adding gypsum reduced pH in the amended subsoil to below 8.5 (Table 5). This indicates that significant changes in soil pH can occur with realistic application rates of gypsum in subsoil. Given high alkalinity also increases negative charges on the surfaces of clay particles (Rengasamy *et al.*, 2016), which increases clay dispersion, a reduction in pH following gypsum application also resulted in significant improvement (reduction) in soil dispersion (Tavakkoli *et al.*, 2015). In alkaline sodic soils, high ESP and high pH are always linked together and it is difficult to apportion their effects on the resulting poor soil physicochemical conditions and consequently on crop growth.

The addition of pea straw and nutrients provides substrate for enhanced biological activity resulting in increased macro aggregation and improved subsoil structure. When combined together, organic

and inorganic amendments may result in additive effects to improve soil physical and chemical properties (Fang *et al.*, 2020a; Fang *et al.*, 2020b).

In a year of intensive drought like 2019, the grain yield improvements at Rand may be attributed to the additional root growth in the amended subsoil layer (Figure 3), which facilitated the use of extra subsoil water (Tavakkoli *et al.*, 2019 and Figure 4). Under dryland conditions, water captured by roots in the subsoil layer is extremely valuable as its availability coincides with the grain filling period and has a very high conversion efficiency into grain yield (Kirkegaard *et al.*, 2007; Wasson *et al.*, 2012). A major focus of this current research is to understand the amelioration processes of the subsoil application of organic and inorganic amendments. A tentative, but promising, finding from our field and controlled environment trials, is that farm grown products like wheat and pea stubbles when mixed with nutrients improve soil aggregation, root growth, water extraction and grain yield and these treatments are comparable to animal manures and gypsum. If confirmed, this means that grain growers have a potentially large supply of relatively inexpensive organic ameliorants already available in their paddocks, which will increase the application options and viability of correcting subsoil sodicity.

Conclusions

The findings from the current field studies demonstrate promising results of ameliorating alkaline dispersive subsoils in medium rainfall zones of southern NSW. Deep placement of organic and inorganic amendments resulted in significant yield improvement in successive years at Rand and Grogan. This yield improvement was facilitated by a reduction in soil pH and ESP% and increased microbial activity that can lead to improved soil aggregation. Furthermore, deep placement of organic and inorganic amendments increased root growth, which in turn increased soil water use from the deeper clay layers during the critical reproductive stages of crop development, thereby increasing grain yield.

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