Optimising Irrigated Grains

Wednesday 13 October 2021

Finley Irrigated Research Centre, 2431 Newell Highway, Finley, NSW

Trial site courtesy of

Southern Growers

VISITOR INFORMATION

We trust that you will enjoy your day with us at the Finley Irrigated Research Centre. Your health and safety is paramount, therefore whilst on the property we ask that you both read and follow this information notice.

HEALTH & SAFETY

- COVID-19: Please ensure you practice social distancing rules and use the hand sanitiser provided.
- All visitors are requested to follow instructions from FAR Australia and Southern Growers staff at all times.
- All visitors to the site are requested to stay in your designated groups.
- All visitors are requested to report any hazards noted directly to a member of FAR Australia or Southern Growers staff.

FARM BIOSECURITY

- Please be considerate of farm biosecurity. Please do not walk into farm crops without permission. Please consider whether footwear and/or clothing have previously been worn in crops suffering from soil borne or foliar diseases.

FIRST AID

- We have a number of First Aiders on site. Should you require any assistance, please ask a member of FAR Australia or Southern Growers staff.

LITTER

- Please take your litter away with you, please do not dispose of any litter on site.

VEHICLES

- Vehicles will not be permitted outside of the designated car parking areas. Please ensure that your vehicle is parked within the designated area(s).

SMOKING

- There is No Smoking permitted on site.

Thank you for your cooperation, enjoy your day.

WELCOME TO THE FINLEY IRRIGATED RESEARCH CENTRE FIELD DAY

FEATURING OPTIMISING IRRIGATED GRAINS

On behalf of the project team, I am delighted to welcome you to the 2021 Finley Irrigated Research Site Field Day featuring 'Optimising Irrigated Grains'.

Today FAR Australia will showcase its field research site which has been set up in collaboration with Southern Growers as part of a GRDC funded Initiative "Optimising Irrigated Grains". The irrigated research site aims to assist NSW and Victorian growers in realising the genetic potential of irrigated grain crops grown under higher yield potential in the region. The research programme looks at crops grown under overhead irrigation and flood-based systems with the aim of covering the major irrigation types distributed across the Murrumbidgee and Murray Valleys of southern NSW. FAR Australia research staff Ben Morris and Tom Price are joined by Dr Eshan Tavakkoli and Alex Schultz from NSW DPI and Russell Ford, agronomist to provide you with a tour of the research trials and to talk about the trial objectives and inputs to date.

Today's topics will include:

- What is the effect of soil amelioration and soil amendments on canola?
- Growers and advisers will have the opportunity to look at the effects of irrigation systems 'surface' and 'overhead' on break crop (Chickpeas, canola and faba beans) canopy structure and disease.
- What are the optimum rates and timing of nitrogen applications for canola and is excess fertiliser carried over to the following crop?
- How do we keep cereal crops standing under irrigation? – Trials examine the effect of plant population, grazing and PGR's.
- Does European winter barley germplasm as opposed to spring germplasm e.g. RGT Planet have a place in irrigated farming systems in southern NSW?
- Getting the best out of your N application on durum wheat.
- How do Vetch Varieties respond to various irrigation strategies, and what is the optimum cutting time? (supported by Dairy Australia)
- Double Cropping with Rice in the rotation, Key Messages to optimise residual water, timing and rotation. (supported by Smarter Irrigation for Profit).
- Moisture monitoring, see various levels of probes in action (agrifutures).
- Whole Farm Irrigation Automation with Rubicon, see a hands-on practical demonstration of how we have fully automated our trial farm.

Should you require any assistance throughout the day, please don't hesitate to contact a member of the FAR or Southern Growers team who will be more than happy to help.

Thank you once again for taking the time to join us today; we hope that you find the trials tour and presentations useful, and as a result, take away new ideas which you can perhaps implement in your own farming business. Have a great day and we look forward to seeing you again at future project events.

I would like to thank the GRDC for investing in this research programme on display today and to Southern Growers as site host.

Nick Poole, Managing Director, FAR Australia

FAR1906-003RTX: Development and validation of soil amelioration and agronomic practices to realise the genetic potential of grain crops grown under a high yield potential, irrigated environment in the northern and southern regions is part of a wider GRDC funded project in irrigated grain production called “Optimising Irrigated Grains” involving a wide range of collaborators.

The season so far:

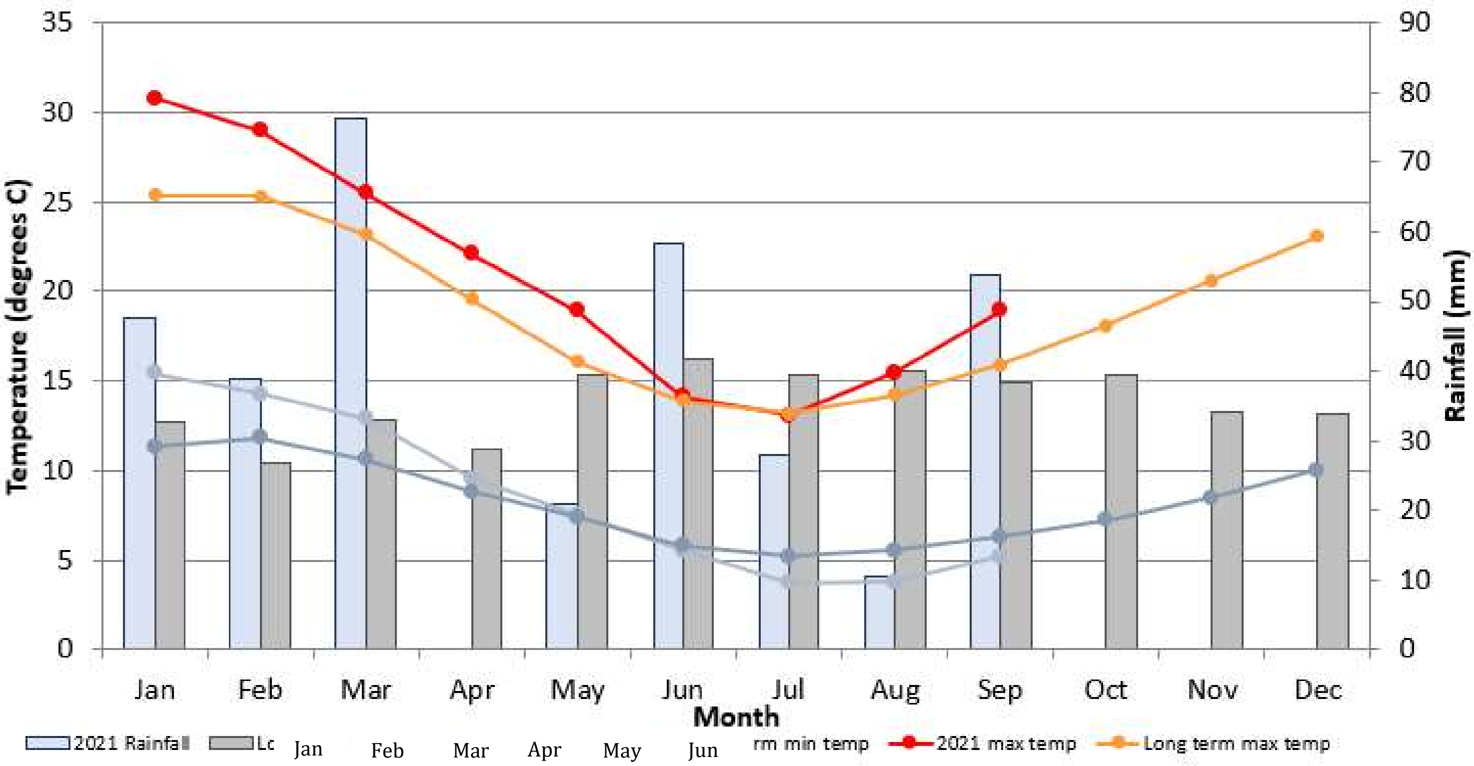


Figure 1. 2020 rainfall and long-term rainfall (1990-2021) (recorded at Finley), min and max temperatures and long-term min and max temperatures recorded at Tocumwal (1897-2021) for the year to date.
Rainfall for the growing season to date, April to September = 171.4mm.

Autumn Irrigation
Overhead – 1st May 20mm applied to canola, faba beans and chickpeas after sowing. 10mm applied to Durum.
Flood – 3rd May 100mm applied to canola and faba beans on surface irrigation after sowing.

Spring Irrigation
Flood – 100mm applied to All flood bays 18th and 19th September
Overhead – 3 applications of 15mm on Durum 17th and 20th September 4th October. 4 applications of 15mm on canola, fabas and chickpeas 18th and 19th September 5th and 7th October.

Canola

HyTTec® Trophy, 45Y28, Diamond & Bonito - Sown 30th April

- Optimum Plant Population Under Overhead and Flood Irrigation
- Nitrogen Use Efficiency – N Rates
- Nitrogen Use Efficiency – N Timing
- Fungicide Management Strategies
- Plant Growth Regulation

Faba Beans

Amberley, Fiesta, Bendoc & Samira - Sown 30th April

- Optimum Plant Population Under Overhead and Flood Irrigation
- Rhizobium Inoculation
- Disease Management Strategies
- Plant Growth Regulation

Barley

Cassiopee & Planet - Sown 29th April and 12th May

- Nitrogen Use Efficiency – N Rates
- Nitrogen Use Efficiency – N Timing
- Plant Growth Regulation

Durum

Aurora & Vittaroi - Sown 12th and 20th May

- Optimum Plant Population Under Overhead and Flood Irrigation
- Influence of Faba Cultivation on Durum Wheat Yield and Profitability
- Nitrogen Use Efficiency – N Rates
- Nitrogen Use Efficiency – N Timing
- Germplasm and Disease Management Interaction
- Disease Management – Products, Rates & Timings
- Plant Growth Regulation

Chickpeas

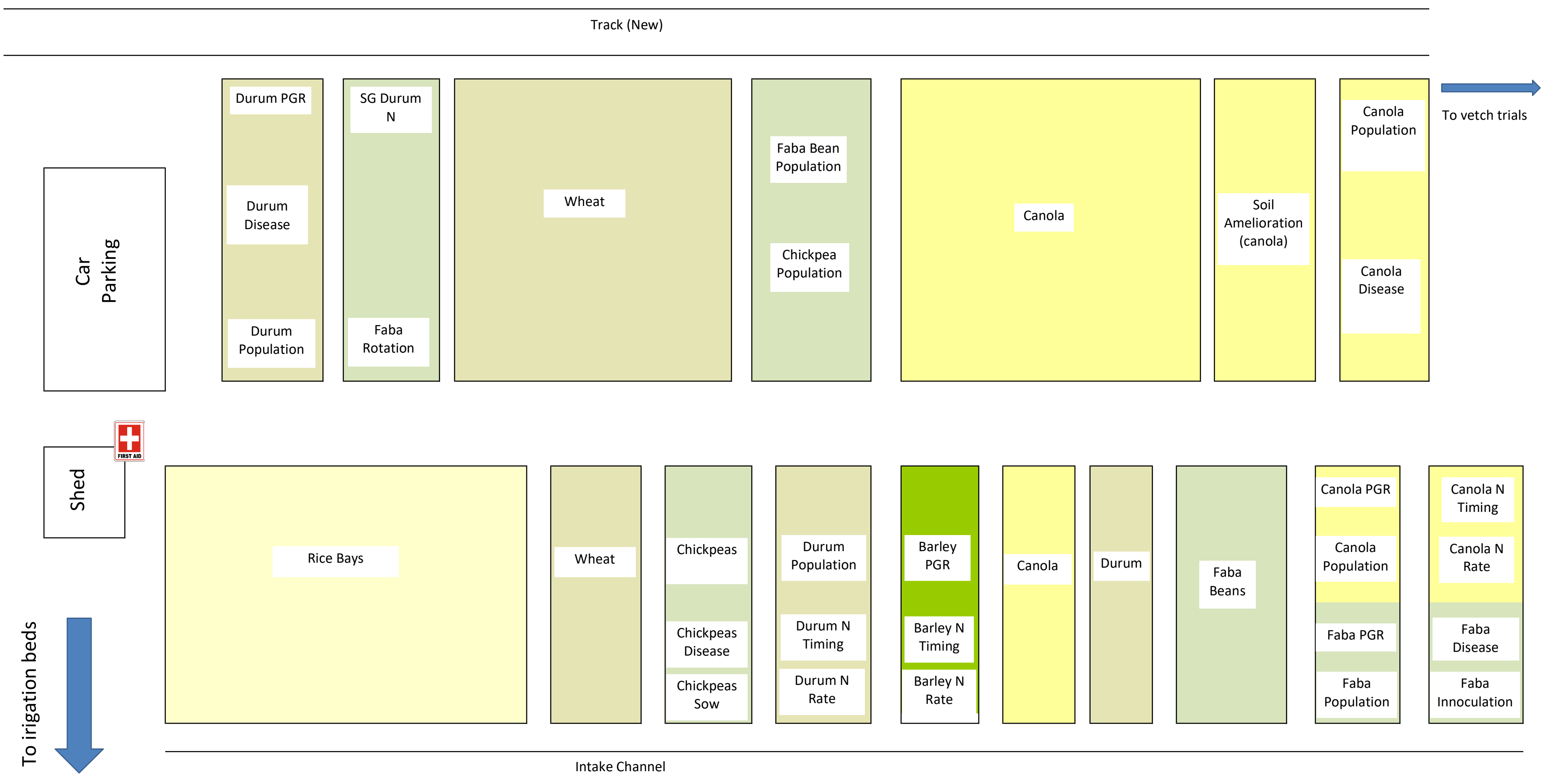
Genesis 090 & PBA Monarch - Sown 29th April

- Optimum Plant Population Under Overhead and Flood Irrigation
- Disease Management Strategies

Soil Amelioration Trial

Canola - Truflex Condor - Sown 17th May

FINLEY IRRIGATED RESEARCH CENTRE
SITE PLAN 2021



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OPTIMISING IRRIGATED GRAINS

BACKGROUND
Optimising Irrigated Grains is a three-year GRDC investment which commenced in spring 2019 in order to develop and evaluate the effectiveness of novel soil management technologies and crop specific agronomic management practices in irrigated environments on system profitability.

Crop specific agronomic practices are focussed on maximising system profitability through:

1. Optimising the return on nitrogen through improved nitrogen use efficiency;
2. improving the understanding of N-form, timing and rate in the context of irrigation timing and inter-related agronomic decisions; and
3. understanding how to consistently optimise yield (in the context of water price, input costs and commodity price) for the crops where gaps are most apparent.

Soil management technologies have been focussed on improving soil structure, infiltration and moisture retention on (i) shallow and poorly structured red duplex soils (ii) sodic grey clays prone to dispersion and waterlogging at Finley, NSW and Kerang, VIC.

Which Crops?
The crops researched as part of the project are:

i) Faba bean (the pulse crop seen with the most potential for irrigated systems); ii) chickpea (an emerging high value pulse, important in crop sequences to provide a cereal disease break); iii) durum (the major option to increase the profitability of the cereal phase under irrigation); iv) canola (higher yields provide scope for significant increase in profitability and potential break effect); and v) **maize (the summer crop with the greatest scope to improve returns under a double cropping system).**

In tendering for the project, the project team added a sixth crop which is barley. This is based on spring sown barley in Tasmania and winter barley where appropriate on the mainland.

How are the project objectives being achieved?
The objectives of the project, now in its second year, are underpinned by approximately 65 - 70 field trials conducted annually at five Irrigated Research Centres (IRCs). The principal Research Centres at Kerang and Finley will cover all five autumn sown crops (faba beans, chickpeas, durum, barley and canola) with the addition of maize sown in the spring on commercial farms. Satellite centres have been established in Frances, Griffiths and Tasmania with a smaller number of trials per annum. The soil amelioration research has been established in collaboration with NSW DPI and is based on two large block research trials at Kerang (Grey Clay under surface irrigation) and Finley (Red Duplex under overhead irrigation). Different soil amelioration treatments were established at these research sites in March 2020 and results of the first-year experiments (faba beans at Finley and oats at Kerang) were reported in the Provisional Winter Crop report in February 2021.

Summary of Findings

<u>Finley, NSW</u>

Grain yields and harvest dry matter production under the two irrigation systems
Though not statistically comparable, surface irrigation trials that received more water (484mm compared to 369-394 mm for the lateral overhead) through the growing season were in general higher yielding than identical trials grown under an overhead irrigation system. Of the crops evaluated, all gave higher yields in identical plant population trials (sown on the same day) on the surface irrigation bays with canola yields peaking at 4.91t/ha (cv 45Y28), durum at 8.2t/ha (cv Vittaroi) and fabas at 7.45t/ha (cv PBA Amberley). Compared to peak yields in the overhead irrigation trials of 4.27t/ha with canola, 7.25t/ha with durum and 5.17t/ha with faba beans using the same cultivars.

Water Use Efficiency (WUE)
In most cases at Finley although the yields were invariably higher where more water was applied with surface irrigation, in general water use efficiency measured as kg mm/ha tended to be higher where crops were grown under overhead

(again remembering that identical trials on both systems could not be directly compared within the same trial). One of the largest differences in yields between the two irrigation systems was with faba beans where there were differences of approximately 2t/ha in favour of surface irrigation (Table 1 & 2). In these trials higher WUE was recorded with the surface irrigation system.

Table 1. *Grain yield (t/ha) of four seed rates (plant populations) with two different cultivars grown under overhead irrigation (sown on the same day as the trial in Table 2 on the same site).*

		Yield t/ha					
Plants/m^2(actual)		**PBA Amberley**		**Fiesta VF**		**Mean**	
Amberley	**Fiesta**	**Yield t/ha**		**Yield t/ha**		**Yield t/ha**	
10	11	3.00	-	3.31	-	**3.15**	**b**
16	16	4.50	-	4.93	-	**4.72**	**a**
23	31	4.83	-	4.84	-	**4.84**	**a**
32	45	5.17	-	5.15	-	**5.16**	**a**
Mean		**4.38**	**-**	**4.56**	**-**		
LSD Seed Rate p = 0.05		0.49		**P val**		<0.001	
LSD Cultivar p=0.05		ns		**P val**		0.343	
LSD Seed Rate x Cultivar.		ns		**P val**		0.719	

Total water available (GSR + Irrigation) 394mm

Table 2. *Grain yield (t/ha) of four seed rates (plant populations) with two different cultivars grown with surface irrigation.*

		Cultivar					
Plants/m^2 (actual)		**PBA Amberley**		**Fiesta VF**		**Mean**	
Amberley	**Fiesta**	**Yield t/ha**		**Yield t/ha**		**Yield t/ha**	
11	13	6.28	-	6.12	-	**6.20**	**b**
20	25	7.45	-	6.75	-	**7.10**	**a**
31	27	7.33	-	7.06	-	**7.19**	**a**
26	31	7.15	-	6.92	-	**7.04**	**a**
Mean		**7.05**	**-**	**6.71**	**-**		
LSD Seed Rate p = 0.05		0.35		**P val**		<0.001	
LSD Cultivar p=0.05		0.42		**P val**		0.083	
LSD Seed Rate x Cultivar.		ns		**P val**		0.381	

Total water available (GSR + Irrigation) 484mm

Nutrition

The research site was characterised by high levels of soil available nitrogen (N) at the start of the season with estimates of over 200kg N/ha at sowing on 0 – 90 cm following the fallow. This resulted in crops of canola and cereals being at their most profitable with lower and or the lowest levels of applied nitrogen fertiliser. In addition to available soil mineral N at sowing there was evidence in durum of 70kg N/ha becoming available through mineralisation during the course of the season. High fertility and N mineralisation were mirrored in results observed with canola nutrition trials (following wheat stubble rather than fallow). Canola yields varied from 3.91 – 4.71t/ha based on 0 to 320kg N/ha of applied N with an optimum of 160kg N/ha applied N fertiliser (Table 3) and 129 kg N/ha soil available N (0 – 90cm). Differences in oil content were small but significant with a 1.2% oil content decline covering N rates between 80 – 320 N applied.

Table 3. *Influence of applied nitrogen fertiliser rate (split 50:50) at six leaf (6L) & Green bud (GB) on seed yield (t/ha) and oil content (%).*

Nitrogen Treatment Rate & Timing		**Total**	**Grain yield and quality**			
		Nitrogen	**Yield**		**Oil**	
		N/ha	**t/ha**		**%**	
1.	0kg N/ha	0	3.91	d	43.0	ab
2.	40kg N/ha@6L & 40kg N/ha@GB	80	4.30	c	43.3	a
3.	60kg N/ha@6L & 60kg N/ha@GB	120	4.41	bc	42.0	d

4.	80kg N/ha@6L & 80kg N/ha@GB	160	4.55	ab	42.4	bcd
5.	100kg N/ha@6L & 100kg N/ha@GB	200	4.59	ab	42.4	bcd
6.	120kg N/ha@6L & 120kg N/ha@GB	240	4.62	a	42.8	a-d
7.	140kg N/ha@6L & 140kg N/ha@GB	280	4.71	a	42.9	abc
8.	160kg N/ha@6L & 160kg N/ha@GB	320	4.71	a	42.1	cd
	Mean		**4.475**		**42.6**	
	LSD		0.19		0.84	
	P val		<0.001		0.032	

N applied as prilled Urea (46% N content)

A common theme from both winter and summer crop results so far is that frequently higher yielding irrigated crops (canola, grain maize and durum) will remove much larger quantities of nitrogen from the soil than the crop has the ability to respond to in that season. In grain maize crops in 2019/20 similar findings were noted, with grain maize crops not responding to more than 250kg N/ha applied fertiliser yet observed N offtakes at harvest were between 300 – 450kg N/ha at harvest with two thirds of the N in the grain.

Crop structure and lodging

Higher plant populations and associated problems with lodging was a primary constraint to yield observed in both winter barley and durum wheat. The highest yields of durum wheat under a surface irrigation system were observed with a plant population of just less than 100 plants/m^2, despite a mid-May sowing date. Higher durum populations resulted in lower yields as a result of higher levels of crop lodging, particularly in the surface irrigation trials. In barley a comparison of winter and spring germplasm showed that RGT Planet (spring barley) was higher yielding (mean 7.27t/ha in PGR trial) and less dependent on plant growth regulation than Cassiopée (winter barley) (mean 6.13t/ha). The fertility of the research site and earlier sowing (April 24) did not favour barley productivity and overall barley yields were disappointing, although lower fertility scenarios may produce better results. The results served to illustrate the value of canopy management in irrigated cereals, illustrating that frequently crops that are sown too thick (with no regard to planting by seed number) and fail to deliver higher yields, particularly if they lodge.

Chickpea sowing date

Under overhead irrigation two identical chickpea trials were set up to look at yield performance from an April and May sowing. The spatially separate trials were not statistically comparable however both trials gave similar peak yields if population was adjusted. Chickpeas sown 27 April gave an average yield of 3.32t/ha (with a peak yield 3.59t/ha cv Genesis090) compared to 19 May sowing with an average yield of 2.88t/ha (with a peak yield 3.41t/ha cv Genesis090). The optimum plant populations being approximately 30 plants/m^2 with the later sowing and approximately 20 plants/m2 with the earlier sowing. In both trials where plant population fell below the optimum at 10 plants/m^2, yields were reduced to 3.1t/ha and 2.39t/ha for early and late sowing respectively.

Disease Management

Disease management was a key component to maximising yields on the Finley IRC site in chickpeas and durum. April sown chickpeas produced significant increases in seed yield and margins from disease management strategies based on three fungicide applications in 2020. Yields were higher with newer chemistry based on QoI (strobilurins) and SDHI chemistry and the advantage over a chlorothalonil based strategy was statistically significant (1.15t/ha response v 0.83t/ha - average of two cultivars). In canola good visual differences in upper canopy blackleg infection did not result in significant yield differences over the untreated. This would indicate that we need more data on irrigated canola responses to upper canopy blackleg before we adopt prophylactic fungicide strategies for this issue. However, it should be pointed out that no Sclerotinia was observed in the 2020 Finley canola trials, a disease where there is more evidence to suggest a yield response when crops are infected.

Soil Amelioration (in collaboration with NSW DPI)

Following soil amelioration treatments being established by NSW DPI in March 2020 the large block trial area was sown with a commercial seed drill to faba beans on 19 May. The mixture of deep ripping, gypsum and organic amendment treatments produced significant yield increases of between 0.66 – 1.22t/ha over the untreated control but there were no significant yield differences amongst the soil amelioration treatments. Of the treatments it was noted that surface applied organic amendment (15t/ha Lucerne pellets) alone also produced a significant yield increase (0.66t/ha).

Caution: Please note that this article is based on the first-year results from the project. If you like a more in-depth analysis of the results generated in the first year of field trials at all sites, please contact Ben Morris, FAR Australia (ben.morris@faraustralia.com.au)

GRAIN MAIZE RESULTS SUMMARY – YEAR 2 (2020 – 2021)

10 irrigated grain maize trials were established at two locations in northern Victoria. The primary focus of this second year of field research was to look at the influence of higher levels of nitrogen (N) input on harvest dry matter, grain yield, harvest index, nitrogen offtake and profitability. In addition, the research programme also examined the influence of plant population, row spacing and disease management. At the main research sites in Peechelba East and Kerang, irrigation was provided by overhead pivot and surface irrigation (Flood - border check) respectively. Total irrigation quantities applied were as follows, Peechelba East (Pivot 5.1 Mega L/ha applied) and Kerang (Surface irrigation border check 11.6 MegaL/ha). All research was conducted using the Pioneer Hybrid P1756, the same hybrid used in year one of the programme. To ensure soil type consistency between seasons the principal trials were conducted at the same field research sites (different parts of the paddock) as 2019/20. At Peechelba East on a commercial farm (red loam over clay) the research was conducted under the same pivot as 2019/20 (not on the same area under the pivot) with all trials established into grain maize residues from the previous season, compared to grain maize following oaten hay stubble in the first year of research. At Kerang (self-mulching grey clay) in both years maize research has been conducted following grass dominant pasture.

Grain yields and nutrition

Grain maize crops yielding 16 -19t/ha with dry matters of 33 - 35t/ha commonly remove 400kg N/ha from the soil, but in results generated over the last two years these crops do not respond significantly to N fertiliser inputs greater than approximately 250kg N/ha. Of the nitrogen removed by the crop canopy at harvest approximately 30 – 35% of the N is returned to the soil as stover residues, so based on a 400kg N offtake approximately 120 - 140kg N/ha is returned to the soil as harvest residues. Applications of nitrogen in excess of 250kg N/ha with up to 550kg N/ha experimented upon in the project have been largely uneconomic in the season; these applications lost up to $400/ha depending on the price of N fertiliser and the exact rates of N applied. With applications of N fertiliser commonly applied at levels of 300 – 450kg N/ha on farm for irrigated grain maize it has not been possible to illustrate that such high levels of N input are the route to higher grain yields in this crop. Whilst in an irrigated system it is unclear how much of the excess N is available the following season, research conducted indicates that we need to rethink the profitability of such large doses or at a minimum take account of soil mineralisation for nitrogen applications in irrigated summer crops. At both research sites supply of nitrogen from the soil has been responsible for supplementing fertiliser N in the production of large crop canopies and grain yields in excess of 16t/ha. **Whilst we cannot mine our soils without regard to this contribution, the research has illustrated that in-crop mineralisation in the summer months is an extremely significant contributor to the N budget calculations under irrigation.** Whilst over fertilising can be claimed to be beneficial for following crops it is important to recognise that this research has failed to generate any evidence to suggest that grain maize crops can respond (with statistical significance) to more than 250kg N/ha. Clearly, the level of organic carbon in the soil will vary and contribute different amounts of soil N supply through the course of a season, however the key finding has been our inability to generate significant yield responses up to the levels of fertiliser being applied on farm. At Peechelba East in 2021 the research was conducted in a maize-on-maize scenario in order to test whether economic responses could be secured from higher amounts of N compared to 2020 when maize was grown following oaten hay. Overall grain yields were lower yielding at 16 - 17.5t/ha in 2021 and although 17t/ha crops were achieved with N rates above 250kg N/ha, the economics were marginal - in some cases slightly positive (Trial 1) and in other cases negative (Trial 3). In no cases at this site over the last two years were statistically significant yield increases achieved with N rates above 250kg. These results have been generated in commercial situation where 200 – 230kg N/ha has been applied as fertigation with applications from V4, V8 and pre VT (tasselling). In 2020 at this site the highest grain yields recorded (machine harvested plots) were 18 - 19t/ha; these were produced on crop canopies fertilised with approximately 250kg N/ha (50N as pre drill urea and the remaining 200N as fertigation).

N timing has failed to generate significant yield effects but for the second year there has been some evidence to suggest split applications, with an emphasis on later applications (up to tasselling), has been associated with higher grain protein. In addition, if large applications were made at sowing as single doses there was evidence to suggest nitrification inhibitors (eNpower) have a role, but yield increases were not statistically significant.

Plant population and row spacing

Over two years plant population and row spacing have been noted to have significant effects on dry matter production and grain yields. Optimum plant populations at Peechelba East maize on maize were lower than those observed following oaten hay in 2020 when yields were higher (18 - 19t/ha). At yields of 16 - 17t/ha when maize followed maize, an economic optimum of 80,000 plants/ha was established compared to 92,000 plants/ha with the same hybrid P1756. Although there was evidence that higher plant populations respond to higher N input, **the best margins ($/ha) from the**

Peechelba East site in 2021 were generated with 230kg N/ha (applied as fertigation) applied to 80,000 plants/ha. At Kerang there was no yield advantage associated with higher plant populations (105 -107,000 plants/m2) of hybrid P1756 compared to 83 - 84,000 plants/m2. Spatial configuration of the low plant populations is an important consideration from results generated so far, with data suggesting that narrower row spacing combined with lower plant populations may offer higher productivity than the traditional 750mm row spacing. **In 2021 at Kerang the combination of 500mm row spacing and lower plant population generated the highest grain yields on the research site.** At Boort in 2020 decreasing row spacing from 750mm (approx. 30 inch) to 500mm (approx. 20inch) significantly increased grain yield with a 3.46 t/ha yield increase (trials hand harvested). This will be a major emphasis of the final year of research in 2021/22 as it has been one of the few factors, other than overall N input, to significantly influence maize grain yield. Poorer establishment in that trial resulted in no significant differences due to plant population.

Foliar nutrition

The project with the assistance and support of industry evaluated a number of different foliar applications of both macro and micronutrients in 2021. At Peechelba East these liquid fertilisers (based on calcium nitrate and Natures K) were applied as supplement applications on top of a standard N fertigation strategy (based on 230N) and a higher N input of 420kg N/ha at V5, V7 and up to V9. There were some interesting interactions and significant effects on total dry matter produced but no statistically significant yield responses over the standard N controls. Potassium levels in the newest tissue were shown to be low at this site when assessed at tasselling, but none of the treatments were seen to significantly increase K concentration in the upper leaves relative to the untreated crops. At Kerang an application of Spraygro Complete K (an NPK trace element liquid) applied at silking and 14 days after silking had no impact on yield. Monitoring of tissues at Kerang revealed tissue levels of key elements to be sufficient when assessed at silking, apart from N concentration. In this first year of evaluation the significance of the results generated did not live up to the level of discussion that generated the research programme. Work in this area will continue in 2022.

Rotation Position

To better understand the effect of previous crop the research at Peechelba East took quadrat cuts out of an adjacent crop of P1756 that was grown following a crop of faba beans that was terminated in October. Although results are not statistically comparable using equivalent N input from research conducted with maize on maize, the comparison revealed greater overall DM production and grain yield (18.17t/ha) where maize followed a terminated faba bean crop compared to 16.59t/ha following maize (note yields are expressed at 0% moisture in this case).

Disease Management

Two trials looking at experimental treatments based on triazole (Group 3 DMIs) and strobilurin (Group 11 QoI) fungicides produced no economic response to application and no evidence of increased green leaf retention in the maize canopy. Other than low levels of common rust *(Puccinia sorghi)* little foliar disease was observed in these trials. This two-years' of research work examining this aspect of agronomy research will now be discontinued and greater emphasis placed on row spacing, population and nutrition for 2022. In the maize-on-maize scenario at Peechelba East a low frequency of blackened plants was identified in the trials, but the foliar fungicides had no impact on the level of these blackened plants.

ACKNOWLEDGEMENTS

FAR Australia would like to place on record their grateful thanks to the Grains Research and Development Corporation (GRDC) for providing the majority investment in particular, we would like to thank Kaara Klepper (GRDC) for her input and support in the oversight of the project.

In addition, we would like to acknowledge the collaborative support of our trials research partner Irrigated Cropping Council (ICC) and extension grower group partner the Maize Association of Australia (MAA), in particular Charlotte Aves, Damian Jones and Rohan Pay at ICC and Liz Mann at MAA.

Initiatives such as this only work if you have the full collaboration of the land owner and we have been fortunate to have the support of Southern Growers for supplying the research site at Finley, Neale and Daniel Coulthard in providing the research site at Peechelba Colin and Geoff Gitsham at Kerang, and Campbell Dalton at Yenda Hopefield. I would also like to thank all the local cropping community and industry in the region for getting the research and their support of the various field days held at the research sites.

Finally, can I place on record my thanks for my own trials team for bringing this research programme through to harvest, in particular Ben Morris, Tom Price and Kat Fuhrmann. I would like to thank Sharon Nielsen from SAGI for all of her input to the analysis of the results. ***Nick Poole, Managing Director, FAR Australia.***

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
dispersive alkaline subsoils**,** amendments, soil pH, exchangeable sodium percentage, root growth, grain yield
GRDC code
DAV00149 & UA00159

Take home messages

- Deep placement of organic and inorganic amendments increased grain yield in the order of 20 to 50% for four 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
- Genotypic variability in grain yield response of wheat cultivars grown on alkaline dispersive subsoils has identified varieties and associated traits for enhanced performance and future breeding.

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). Thisis 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 either from stored soil water or rainfall during the early growth stages. 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.
Genetic improvement is also frequently advocated as an avenue for improving crop productivity and adaptation under different hostile soil conditions (McDonald et al., 2012; Nuttall et al., 2010). Little is known about genetic variation for tolerance of subsoil constraints and how they relate to different plant traits such as elemental toxicity tolerance, canopy cover, rooting depth and harvest index and the integration of these factors in yield response of different genotypes. This limited knowledge is also due to the practical difficulties in measuring dynamic and variable soil constraints under field conditions.

This paper reports on the performance of a barley-wheat-canola-wheat rotation on a Sodosol (Isbell, 2002) soil at a site in the Riverina town of Rand in southern New South Wales in the four years immediately following incorporation of a range of subsoil 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 site was located at Rand, in the Riverina region of southern New South Wales in a paddock that had been under a continuous cropping (cereal-canola) for more than 50 years. The soil 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 trial site.*

Depth (cm)	pH (H_20)	EC (1:5) (μS/cm)	Nitrate N (mg/kg)	Exchangeable cations (cmol/kg)	Exchangeable sodium percentage (%)	Bulk density (g/cm^3)	Volumetric water content (θv)
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 trial was established in February 2017 as a randomized complete block with 13 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/m^2). 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/m^2). 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/m^2). 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® M (340 g/L MCPA present as the dimethylamine salt + 80 g/L dicamba present as the dimethylamine salt). 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/m^2). 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 2017–2020 (Figure 1).

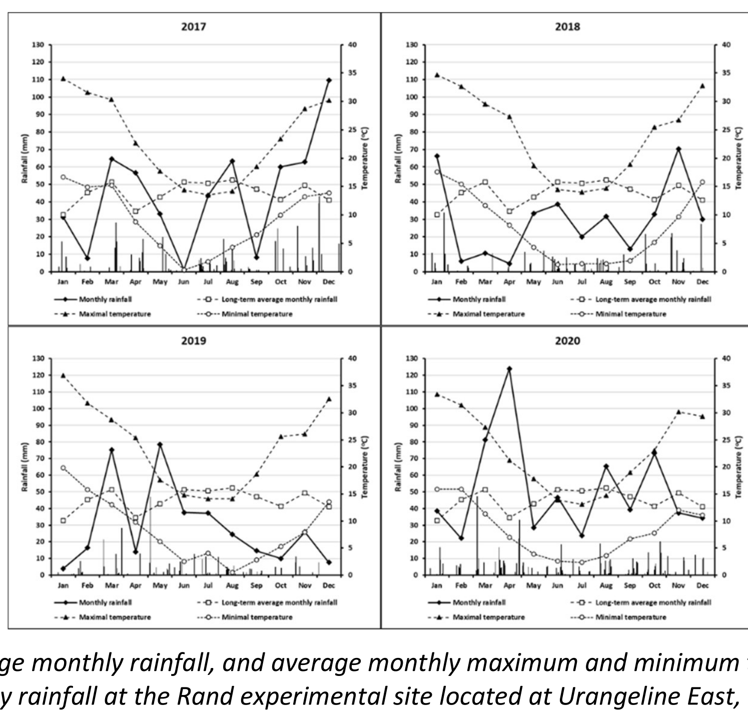

Figure 1. *Long-term average monthly rainfall, and average monthly maximum and minimum temperatures, daily (bars) rainfall events and monthly rainfall at the Rand experimental site located at Urangeline East, NSW.*

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, N to match 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 2m^2 were taken at physiological maturity to measure plant biomass and grain yield.

Grogan genotypes screening experiment
In 2019 an experiment was conducted near the township of Grogan in southern NSW, which included 17 commercial wheat genotypes 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 1). The changes in soil sodicity (exchangeable sodium percentage, ESP) followed a similar trend of soil pH with ESP at 10.5% in the topsoil and increasing up to 40% in the subsoil (Table 1).

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 experiment was sown on 17 May 2019 using a direct sown drill with DBS tynes spaced at 25cm. At sowing 90 kg MAP (20kg P/ha and 9kg N/ha) was drilled in all plots and 75 kg N/ha was surface applied just prior to stem elongation. Mean plant density as measured by seedling counts at four weeks after sowing was 116 ± 1.6 (mean ± SE of 68 plots) plants m^{-2}. At different growth stages multispectral images (MicaSense RedEdge-MX) were collected using drone technology to determine different vegetation indices such as normalised differences in vegetation index (NDVI) and leaf chlorophyll index (LCI) as a surrogate of canopy attributes and plant physiological processes (Liu et al., 2019; Satir and Berberoglu, 2016; Zhang et al., 2019). Quadrat samples of $1m^2$ area were taken at physiological maturity to measure plant biomass and grain yield. Harvest index was calculated as grain yield divided by biomass.

Results

Rand amendment trial

The one-off application of various amendments (Table 2) significantly affected the crop grain yield over 4 consecutive years. For example, in 2020, wheat grain yield (relative to control) increased following the deep placement of wheat stubble, wheat stubble + nutrient and gypsum by 21%, 20 and 18% 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. A multi-year cumulative analysis of grain yield response (2017-2020) 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.

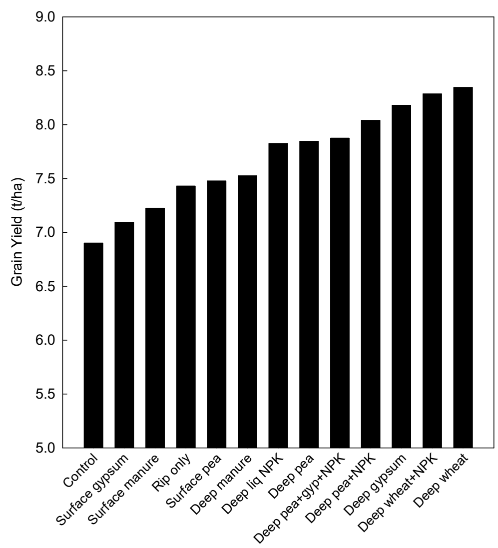

Figure 2. *The mean effect of surface or deep-placed amendments on grain yield of wheat (cv. Scepter⑪) grown in an alkaline dispersive subsoil in Rand, SNSW in 2020. Values are mean (n=4).* $LSD_{0.05} = 0.67$.

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) at Rand.*

Treat	Yield (t/ha)		$	
Control	15.3	a	4517	a
Surface gypsum	15.5	a	4576	a
Rip only	15.9	ab	4737	ab
Surface pea	16.00	ab	4817	ab
Deep liq NPK	17.1	bc	4847	ab
Surface manure	17.1	bc	5104	bc
Deep wheat	18.2	cd	5388	cd
Deep manure	18.3	cd	5428	cd
Deep pea+NPK	18.4	cd	5557	d
Deep wheat+NPK	18.5	d	5383	cd
Deep pea	18.7	d	5507	d
Deep gypsum	18.9	d	5684	d
Deep pea+gyp+NPK	19.4	d	5699	d

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.

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.

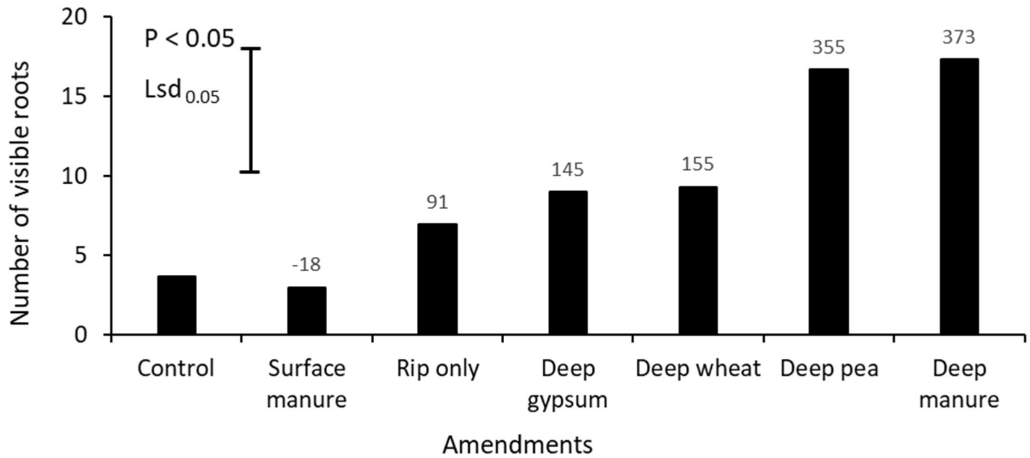

Figure 3. *The mean effect of surface or deep-placed amendments on the number of visible roots at 30cm at late flowering of canola (cv. Pioneer® 45Y91CL) grown in alkaline dispersive subsoil in Rand, SNSW in 2019. Values on the top of each bar is representing percent change of visible roots compared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

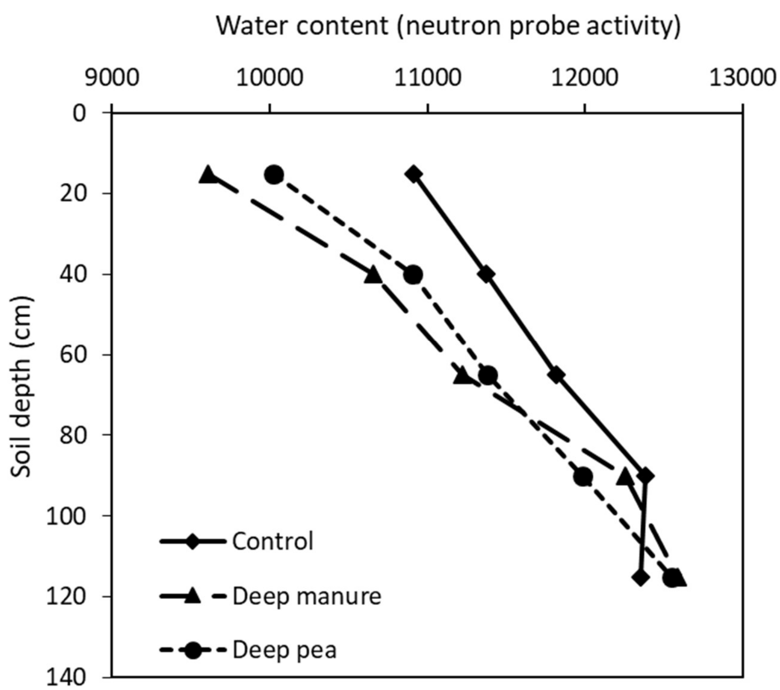

Figure 4. *Neutron probe readings taken in September at the Rand amendment site for contrasting treatment comparisons. Results are based on the neutron activity (raw data) where higher values represent higher water content in the soil profile. Values are averages (n = 4).*

Table 5. *The changes in 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	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

Grogan genotypes screening trial

Significant (P < 0.001) genotypic variation occurred in grain yield among the genotypes and ranged from only 0.57 t/ha (Gregory⑪) to 2.0 t/ha (Scepter⑪, Emu Rock⑪ and Mace⑪; Figure 5). Biomass at final harvest did not significantly differ among the genotypes (data not shown; P = 0.11) and there was no significant (P = 0.09) correlation between grain yield and biomass at final harvest (Figure 6).

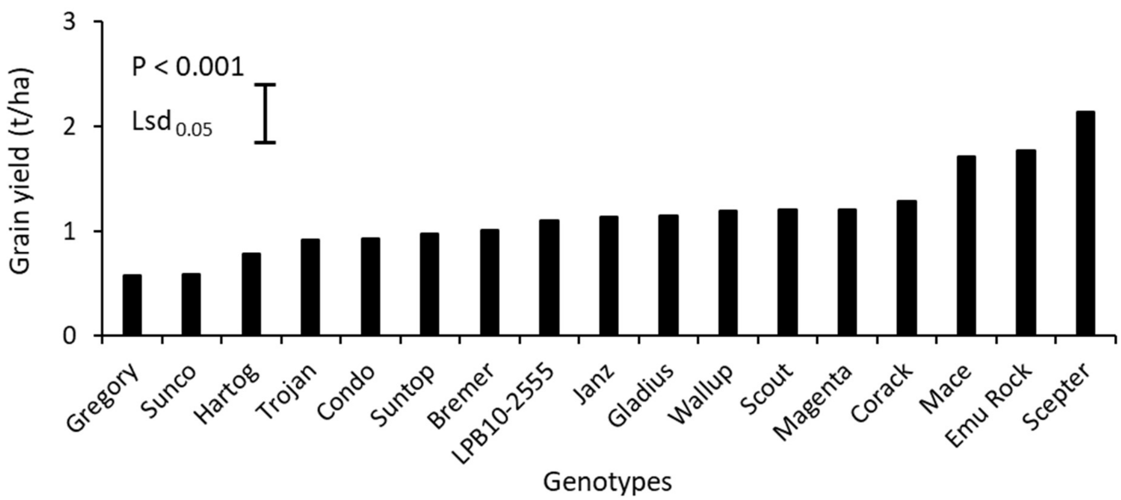

Figure 5. *Variations in grain yield of 17 wheat genotypes grown in alkaline sodic dispersive subsoil in Grogan, SNSW in 2019. Each data point is mean values of n = 4.*
(Varieties Gregory, Trojan, Condo, Suntop, Bremer, Gladius, Wallup, Scout, Magenta, Corack, Mace, Emu Rock and Scepter are protected under the Plant Breeders Rights Act 1994)

Significant variation was observed in harvest index (data not shown; P < 0.001), which ranged from 0.08 (Gregory⑪) to 0.26 (Scepter⑪). A significant (P < 0.001) and positive correlation between harvest index and grain yield is observed among the studied genotypes (Figure 6).

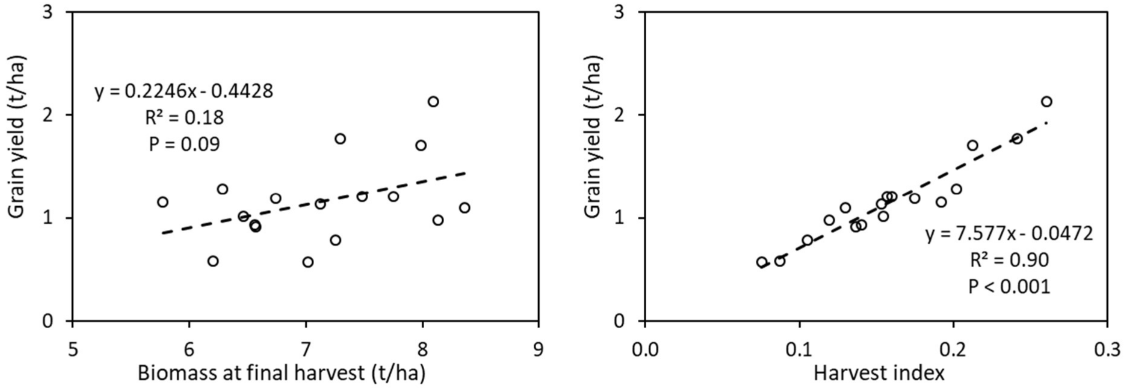

Figure 6. *Linear regressions between grain yield and biomass at final harvest (left) and harvest index (right) of 17 wheat genotypes grown in alkaline sodic dispersive subsoil at Grogan, SNSW in 2019.*

All the non-destructive vegetation indices, i.e. NDVI ($P < 0.01$), NDRE ($P < 0.001$) and LCI ($P < 0.001$) measured at stem elongation showed significant and positive correlation with biomass at anthesis (Figure 7).

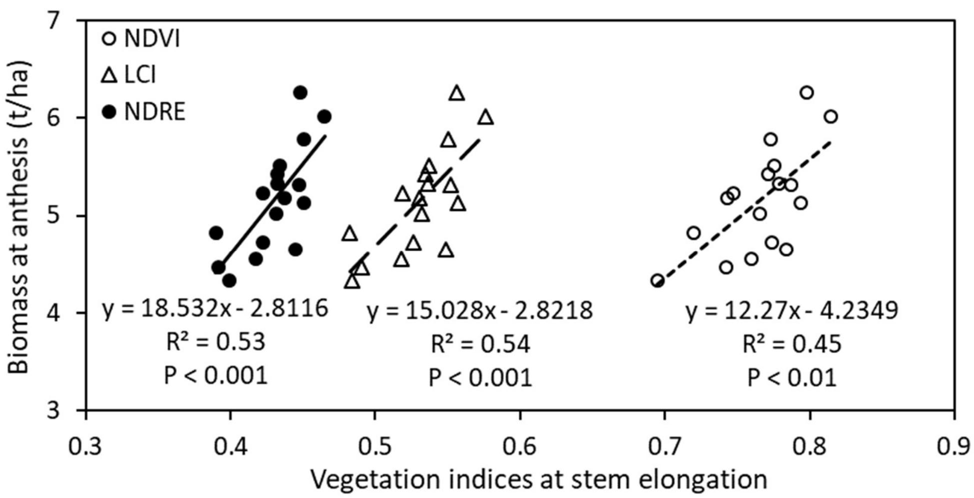

Figure 7. *Linear regressions between vegetation indices (measured at stem-elongation) and anthesis biomass of 17 wheat genotypes grown in alkaline sodic dispersive subsoil at Grogan, SNSW in 2019. NDVI = normalised differences in vegetation index; LCI = Leaf chlorophyll index; NDRE = Normalised difference red edge.*

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 and wheat were grown in 2017–2020, respectively, under increasingly dry conditions. 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 where the 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.

Despite, demonstrating significant improvement in grain yield with subsoil incorporation of organic and inorganic amendments, the widespread adoption of these practices are still limited by their cost effectiveness. Identifying traits associated with the superior tolerance to different soil constraints may be a low cost technique to tackle this issue (McDonald et al., 2012). Given the intensive drought condition in the study year, considerable genotypic variation was observed with some varieties having 3- fold higher grain yield than other varieties. Based on controlled-environment studies, the high yielding varieties at Grogan, 'MaceΦ and Emu RockΦ,' are moderately tolerant to tolerant to high pH and have roots that can grow relatively well through soils of high bulk density, whereas low yielding varieties such as GregoryΦ, Hartog and Sunco, are more sensitive to one or both of these stresses. The very low harvest index in the trial suggests that there was severe stress around flowering to reduce grain set, as well as during grain filling. Results suggest that the ability to maintain root growth hay have helped to alleviate stress in varieties like Emu RockΦ and Mace Φ. Furthermore, different traits associated with this greater yield performance of wheat genotypes are crucial aspects of future breeding programs.

Conclusions
The findings from the current field studies demonstrate initial but promising results of ameliorating alkaline dispersive subsoils in medium and high rainfall zones of southern NSW. Deep placement of organic and inorganic amendments resulted in significant yield improvement in four successive years at Rand where subsoil water was present. 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. In addition to soil management, genotypic variability in grain yield of wheat cultivars observed and their associated traits identified in the current study can be used for improving wheat germplasm through future breeding programs.

References
Adcock, D., McNeill, A. M., McDonald, G. K., and Armstrong, R. D. (2007). Subsoil constraints to crop production on neutral and alkaline soils in south-eastern Australia: a review of current knowledge and management strategies. *Australian Journal of Experimental Agriculture* **47**, 1245-1261.
Fang, Y., Singh, B. P., Collins, D., Armstrong, R., Van Zwieten, L., and Tavakkoli, E. (2020a). Nutrient stoichiometry and labile carbon content of organic amendments control microbial biomass and carbon-use efficiency in a poorly structured sodic-subsoil. *Biology and Fertility of Soils* **56**, 219-233.
Fang, Y., Singh, B. P., Farrell, M., Van Zwieten, L., Armstrong, R., Chen, C., Bahadori, M., and Tavakkoli, E. (2020b). Balanced nutrient stoichiometry of organic amendments enhances carbon priming in a poorly structured sodic subsoil. *Soil Biology and Biochemistry* **145**, 107800.
Farooq, M., Hussain, M., and Siddique, K. H. M. (2014). Drought stress in wheat during flowering and grain-filling periods. *Critical Reviews in Plant Sciences* **33**, 331-349.
Gill, J. S., Sale, P. W. G., and Tang, C. (2008). Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research* **107**, 265-275.

Hajkowicz, S., and Young, M. (2005). Costing yield loss from acidity, sodicity and dryland salinity to Australian agriculture. *Land Degradation & Development* **16**, 417-433.
Isbell, R. F. (2002). "The Australian Soil Classification.," CSIRO, Melbourne.
Kirkegaard, J. A., Lilley, J. M., Howe, G. N., and Graham, J. M. (2007). Impact of subsoil water use on wheat yield. *Australian Journal of Agricultural Research* **58**, 303-315.
Liu, C., Liu, Y., Lu, Y., Liao, Y., Nie, J., Yuan, X., and Chen, F. (2019). Use of a leaf chlorophyll content index to improve the prediction of above-ground biomass and productivity. *PeerJ* **6**, e6240-e6240.
McDonald, G. K., Taylor, J. D., Verbyla, A., and Kuchel, H. (2012). Assessing the importance of subsoil constraints to yield of wheat and its implications for yield improvement. *Crop & Pasture Science* **63**, 1043-1065.
McDonald, G. K., Taylor, J. D., Verbyla, A., and Kuchel, H. (2013). Assessing the importance of subsoil constraints to yield of wheat and its implications for yield improvement. *Crop and Pasture Science* **63**, 1043-1065.
Northcote, K. H., and Skene, J. K. M. (1972). "Australian Soils with Saline and Sodic Properties," CSIRO, Melbourne, Australia.
Nuttall, J. G., Hobson, K. B., Materne, M., Moody, D. B., Munns, R., and Armstrong, R. D. (2010). Use of genetic tolerance in grain crops to overcome subsoil constraints in alkaline cropping soils. *Australian Journal of Soil Research* **48**, 188-199.
Orton, T. G., Mallawaarachchi, T., Pringle, M. J., Menzies, N. W., Dalal, R. C., Kopittke, P. M., Searle, R., Hochman, Z., and Dang, Y. P. (2018). Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat. *Land Degradation & Development* **29**, 3866-3875.
Passioura, J. B., and Angus, J. F. (2010). Chapter 2 - Improving Productivity of Crops in Water-Limited Environments. *In* "Advances in Agronomy" (D. L. Sparks, ed.), Vol. 106, pp. 37-75. Academic Press.
Rengasamy, P. (2002). Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* **42**, 351-361.
Rengasamy, P., Tavakkoli, E., and McDonald, G. K. (2016). Exchangeable cations and clay dispersion: net dispersive charge, a new concept for dispersive soil. *European Journal of Soil Science* **67**, 659-665.
Sale, P., Tavakkoli, E., Armstrong, R., Wilhelm, N., Tang, C., Desbiolles, J., Malcolm, B., O'Leary, G., Dean, G., Davenport, D., Henty, S., and Hart, M. (2021). Chapter Six - Ameliorating dense clay subsoils to increase the yield of rain-fed crops. *In* "Advances in Agronomy" (D. L. Sparks, ed.), Vol. 165, pp. 249-300. Academic Press.
Sale, P. W., Gill, J. S., Peries, R. R., and Tang, C. (2019). Crop responses to subsoil manuring. I. Results in south-western Victoria from 2009 to 2012. *Crop and Pasture Science* **70**, 44-54.
Satir, O., and Berberoglu, S. (2016). Crop yield prediction under soil salinity using satellite derived vegetation indices. *Field Crops Research* **192**, 134-143.
Tavakkoli, E., Rengasamy, P., Smith, E., and McDonald, G. K. (2015). The effect of cation–anion interactions on soil pH and solubility of organic carbon. *European Journal of Soil Science* **66**, 1054-1062.
Tavakkoli, E., Weng, Z. H., Tahmasbian, I., Uddin, S., Poile, G., Oates, A., Xu, B. B., Sandral, G., Fang, Y., and Armstrong, R. (2019). Understanding the amelioration processes of the subsoil application of amendments. 18 - 19 February 2019, GRDC Grains Research Update (Wagga Wagga).
Wasson, A. P., Richards, R. A., Chatrath, R., Misra, S. C., Prasad, S. V. S., Rebetzke, G. J., Kirkegaard, J. A., Christopher, J., and Watt, M. (2012). Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. *Journal of Experimental Botany* **63**, 3485-3498.
Zhang, K., Ge, X., Shen, P., Li, W., Liu, X., Cao, Q., Zhu, Y., Cao, W., and Tian, Y. (2019). Predicting rice grain yield based on dynamic changes in vegetation indexes during early to mid-growth stages. *Remote Sensing* **11**, 387.

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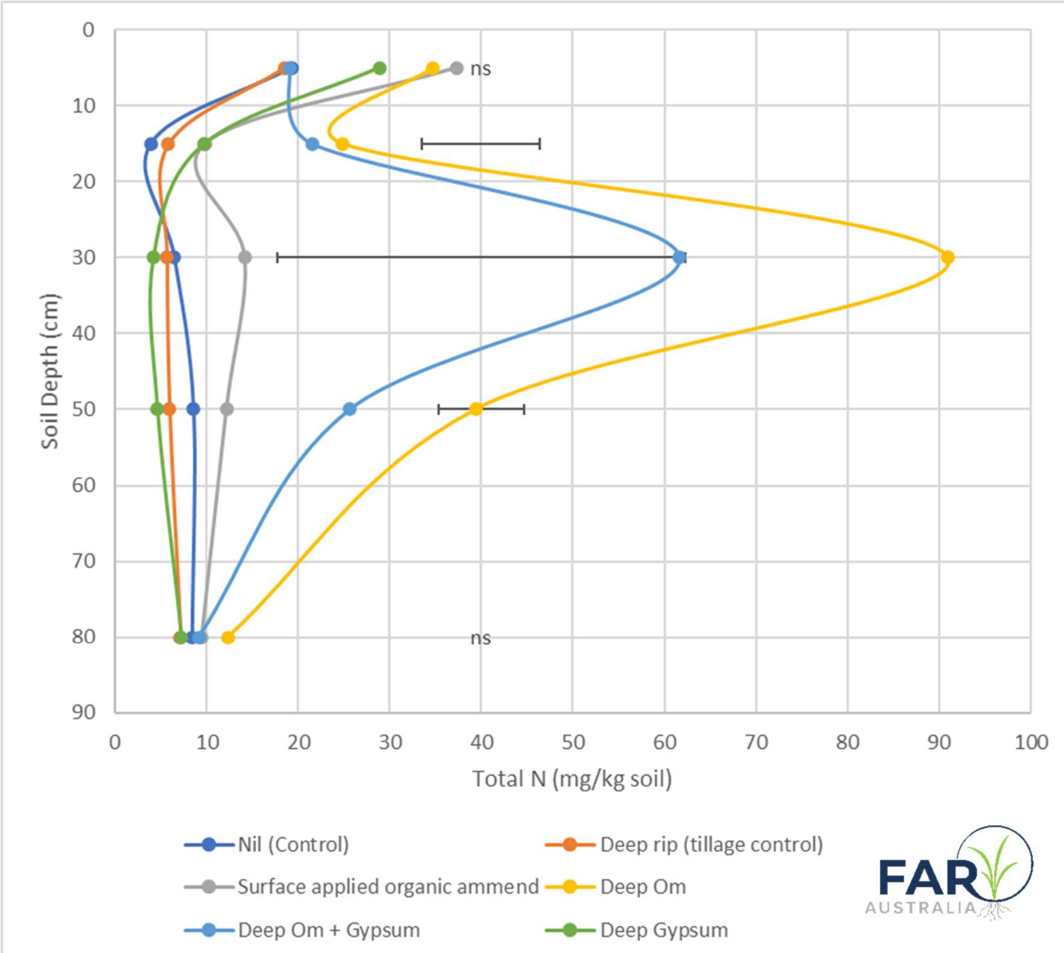

Figure 1. *Chart showing total nitrogen (NH4+NO3, mg/kg) at various soil depths following Amelioration treatments, 17th March 2020. Soil testing courtesy of NSW DPI, 15th Feb 2021. Analysis by FAR Australia. Error bars represent LSD, P value 0.05, ns=not significant.*

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