The resilience of re-engineered sandy soils in wet and dry seasons in Western Australia

Gaus Azam, Kanch Wickramarachchi, Hasin Rahman, Md Shahin Rahman, Chad Reynold, Glenn McDonald, Wayne Parker, David Hall, Craig Scanlan, Steve Davies, Chris Gazey

Department of Primary Industries and Regional Development, Perth, WA 6000, Email: gaus.azam@dpird.wa.gov.au

Abstract

Unpredictable climatic events such as wet winters and dry hot springs in the Mediterranean climate, are increasingly common, threatening the sustainability of the grains industry in southern Australia. Our previous research suggests that deep soil amelioration and re-engineering might double the grain yield and water use efficiency (WUE), particularly in more favourable seasons. However, the crucial question remains: will these enhancements endure during low decile seasons? To address this research question, we investigated four experiments for three seasons at Bolgart, Meenar, Badgin, and Tarin Rock in Western Australia (WA).

Estimated water-limited yield potentials (Yp) for cereals were 3.88, 3.63 and 2.29 t/ha in 2021, 2022 and 2023, respectively. The average paddock control yields were 1.75, 3.64 and 1.74 t/ha compared to the yields of best soil re-engineering treatment of 3.67, 6.26 and 3.44 t/ha during the same period across the four experiments. Yield gains of up to 2.2 t/ha for canola, 2.7 t/ha for wheat, and 2.7 t/ha for barley were achieved. WUE also increased by up to 16.5 and 15.1, and 18.7 kg/mm of effective rainfall for wheat, barley and canola, respectively. While yield enhancements were more pronounced during wetter seasons (2021 and 2022), WUE demonstrated higher performance during the drier season (2023). Our findings reveal that the improvements in soil properties persisted for three seasons and are expected to last longer.

Keywords

Soil re-engineering, interacting soil constraints, deep drainage, terminal drought, root architecture

Introduction

Multiple interacting soil constraints reduce plant-available water, crop productivity, water use efficiency (WUE) and long-term profitability across most of the 12 million hectares of sandplain cropping soils across the rainfall zones of the Western region of Australia (van Gool 2016). These soils typically have a low water and nutrient storage capacity and are often affected by soil acidification, subsoil compaction, soil water repellence and wind erosion (van Gool 2016). In addition to these constraints, texture contrast soils (sand over a clayey subsoil) can also have sodic, poorly structured clay-rich B-horizons. The B-horizons of texture contrast soils may be strongly alkaline, exhibit multiple chemical toxicities, and are often susceptible to transient waterlogging (Gregory 1997). Combined, these constraints result in a yield gap of 50% or more between actual and estimated water-limited yield potential (Yp) (Harries et al. 2022). Crop root development is often limited at soil depths below 20 cm and is largely restricted to the top 40 cm (Bowden and Jarvis 1985), which limits the volume of soil that crop roots can explore for water and nutrients (Azam and Gazey 2021). Consequently, crop yield does not reach Yp, and WUE remains low (for wheat, 10.7 kg/mm) despite the adoption of currently available agronomic practices, as reported in a recent study in Western Australia (WA) (Harries et al. 2022).

Current soil amelioration options (e.g., liming, claying, deep ripping, deep soil mixing and soil inversion) address one or more constraints to a depth of up to 40 cm. While initial research has demonstrated some benefits from managing multiple constraints (Davies 2019), these studies have not systematically determined the best combination, order, or timing of multiple amelioration practices to optimise the size and longevity of the benefit for specific soil type, constraint, and environment interactions. More recent studies in WA suggest the grain and WUE can be doubled by re-engineering soils in more favourable seasons (Azam et al. 2023). However, the crucial question remains: will these enhancements endure during low decile rainfall seasons? To address this research question, we investigated four experiments for three seasons across low to medium rainfall zones on deep sand and duplex soils in WA.

Methods

In Autumn 2021, four deep soil amelioration (re-engineering) experiments were established on deep yellow sand and duplex soils at four locations in WA (see more details in Table 1). The experiments were established using earthmoving equipment and physical labour. Soils were excavated layer by layer to 80cm depth before they were brought back at 10cm increments and incorporated with various soil amendments including lime, gypsum, clay, organic matter and inorganic nutrients.

There were four soil re-engineering treatments such as (i) loosening and liming, (ii) loosening, liming and claying (with gypsum), (iii) loosening, liming, claying (with gypsum) and adding organic matter, and (iv) loosening, liming, claying (with gypsum) and adding equivalent amount of available NPK in organic matter. All treatments were compared with an untreated control. Plots size was 20 m^2 and they were separated by buffers. All treatments were randomised using a complete randomised block design and replicated 3 or 4 times.

Soil samples were collected every year from all experiments at 10cm increments for testing various soil parameter. Crops, from all experiments, were hand harvested for measuring yield. Soil profile moisture content was measured in situ regularly using EnviroPro® capacitance probes (Entelechy Pty Ltd, Adelaide). Crop root architecture was also imaged repeatedly *in situ* using a Rhizotron set up (Azam and Gazey 2021). Yp and WUE were estimated using Oliver et al. (2009). A linear model was fitted to each of the measurements using the ANOVA procedure in GenStat 22nd Edition (VSN International Limited, United Kingdom) to compare the treatment effects on soil parameters, crop yield and WUE. Fisher's protected least significant difference (LSD) was applied at $P \leq 0.05$.

Table 1. Location, rainfall, soil types and soil constraints at four experimental sites.

Site (year)*	Coordinates (Lat, Long)	AR & GSR (mm)	Soil type and constraints
Bolgart (2021)	-31.3162, 116.5831	366 & 291	Deep yellow sand, Arenosol, severely repellent topsoil; low clay content throughout sandy profile with poor water and nutrient holding capacity; subsoil acidity at 15-45 cm, low SOC.
Badgin (2021)	-31.7879, 117.0111	409 & 320	Duplex (sand over clay), Kurosol, moderately acidic at 10–80 cm depth, compacted sand at 10–40cm with low water holding capacity, poorly structured dense clay in the subsoil below 40 cm depth, medium SOC.
Meenar (2021)	-31.6450, 116.8940	429 & 355	Duplex (loamy sand over clay), Kurosol, moderately acidic at throughout the profile, compacted loam at 10–40 cm with good water holding capacity, medium SOC.
Tarin Rock (2021)	-32.9905, 118.1787	323 & 215	Shallow duplex (sand over clay), Sodosol, severely repellent topsoil; moderately acidic at 10–30 cm depth, low compaction in top 30cm depth with low water holding capacity, low SOC.

Notes: Year in the parentheses represent the years of trial establishment, AR = annual rainfall, GSR = growing season (April-October) rainfall, SOC = soil organic carbon. Rainfall data represent the long-term average.

Results

Soil profile re-engineering through loosening, lime and clay incorporation rapidly overcame surface soil water repellence, subsoil acidity, compaction (bulk density) and nutrient status (Fig. 1). Re-engineering the soil profile to a depth of 80 cm also enabled crops to develop deeper root systems (Fig. 2), enhancing their access to water and nutrients and extending their growth period by up to three weeks during critical stages (data to be presented). The improvement in soil property have lasted for three years and may potentially persist for even longer.

The improvement in soil properties and enhanced uptake of water and nutrients have resulted in increased biomass, larger heads and pods, higher yields, and improved WUE. Overall, the control yielded 1.81 t/ha and there was a yield gap of 0.91 t/ha (n= 35) (Fig. 3a). By comparison the best soil re-engineering treatment yielded 3.43 t/ha surpassing the Yp by 0.71 t/ha (n = 35). Grain yield and WUE improvements ranged from 1.8-fold to 4.3-fold, depending on soil type, crop, and seasonal conditions. Yield increases were significant, particularly in duplex soils, with a 2.1-fold increase in canola, a 2.2-fold increase in wheat, and a 2.9-fold increase in barley.

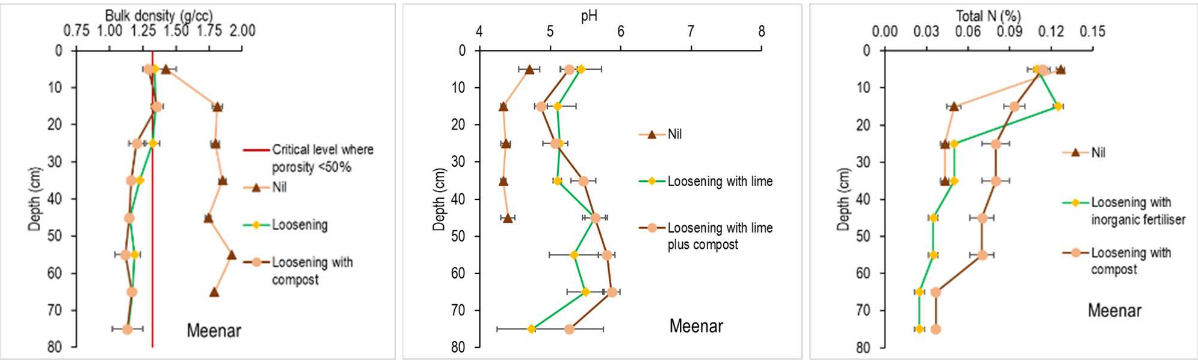

Figure 1. Soil bulk density, pH and nitrogen level in selected treatments at Meenar sites. Measurements were taken two months after the experiment was established. Horizontal bars represent the standard errors.

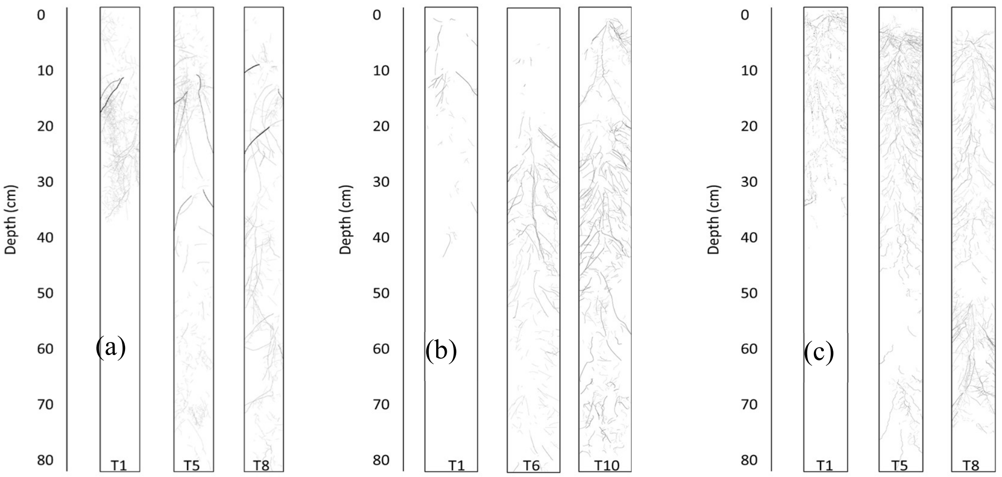

Figure 3: Images of (a) wheat (Badgin), (b) barley (Tarin Rock) and (c) canola (Meenar) roots T1 = control, T5 and T6 = Loosening & lime and T8 and T10 = Loosening & lime & clay & organic matter.

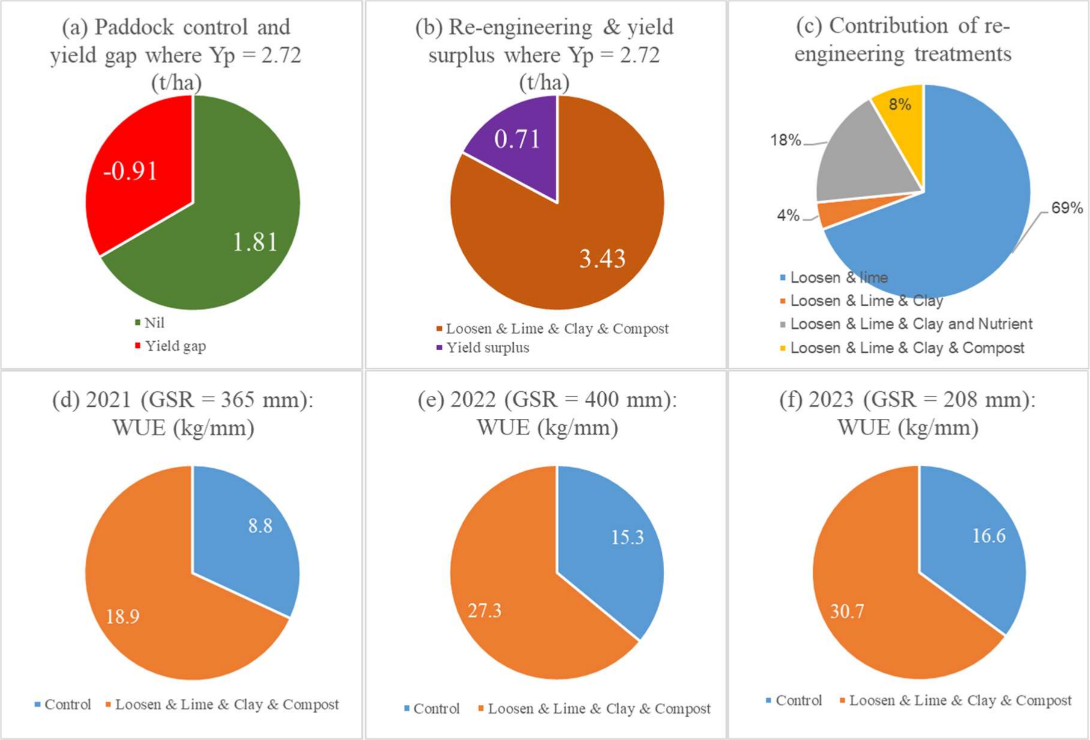

Figure 3: (a-c) Grain yield gaps, impact of various soil re-engineering treatments, and (d-f) seasonal differences in grain yield and WUE in the best soil re-engineering treatments and the control.

Nearly 70% of the yield response was related to deep loosening and lime incorporation in these four trials (n=35) (Fig. 3c). Clay addition resulted in an additional 4% yield increase over the loosening and lime incorporation treatment. Deep incorporation of nutrients further increased yield by 18% compared to the loosening plus lime plus claying. Overall, incorporation of organic matter added 8% more yield compared to the loosening plus lime plus clay plus inorganic nutrient.

The WUE increased by up to 16.5 and 15.1 and 18.7 kg/mm in wheat (n=9), barley (n = 7) and canola (n=12), respectively. While yield enhancements in more pronounced during wetter seasons (2021–2022), WUE demonstrated higher performance during the drier season (2023). Overall, the WUE increased by 10.1, 12.0 and 14.1 kg/mm in 2021, 2022 and 2023 seasons, respectively (Fig. 3d-f).

Conclusion

Our study demonstrated that grain yields and WUE can be increased by up to 2–4 times on sand and texture-contrast soils by re-engineering soils. These gains were achieved through rapid and complete removal of multiple interacting soil constraints. The improvements in soil persisted for three seasons and are expected to last longer. Overall soil re-engineering set a new rainfall-limited yield potentials at selected sites by surpassing the traditional Yp. While yield enhancements were greater wetter seasons of 2021 and 2022, the WUE was greater during the drier season of 2023. It is anticipated that upon adoption by grain growers, the insights gained from soil re-engineering research will unlock the potential for achieving a new frontier in grain yield and WUE in WA.

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