Fertiliser Strategies to Boost Crop Yield in Re-engineered Soil Profiles

Kanchana Wickramarachchi[*]and Gaus Azam

Department of Primary Industries and Regional Development, 75 York Road, Northam, WA 6401,
kanch.wickramarachchi@dpird.wa.gov.au

Abstract

Subsoil constraints such as compaction and acidity are prevalent in WA and hinder the development of deep root systems. Duplex soils, common in the region, exacerbate these challenges and lead to suboptimal yields. A field-based soil re-engineering experiment involving soil loosening and incorporation of ameliorants to a depth of 80 cm in a duplex soil profile with subsoil acidity and compaction, demonstrated that barley yields could be doubled by deep incorporation of lime, fertiliser, and clay compared to surface application of the same ameliorants. However, incorporating fertiliser to an 80 cm depth presents practical challenges to the annual replenishment of crop nutrients. To address this, two controlled environment experiments were conducted to develop fertiliser strategies for re-engineered soils based instead on surface banding and topdressing.

Results suggest that after increasing soil pH above the minimum target of 4.8 by incorporating lime and addressing soil compaction by loosening the soil, to 80 cm depth, barley yields of re-engineered soils can be maintained by surface application of inorganic fertiliser at increased rates. We found that 150 kg/ha of surface-applied N was enough to optimise barley grain yield, but higher barley protein could be achieved by applying more N. These findings help optimise fertiliser management practices of re-engineered soils, thereby contributing to the sustainability of broadacre cropping.

Keywords

Soil re-engineering, subsoil acidity, subsoil compaction, deep placement of fertiliser, incorporation of lime

Introduction

Half to two-thirds of Western Australian (WA) agricultural land is comprised of ‘texture contrast’ soils (sand over clay, hereafter duplex). Texture contrast soils in WA are often reported to have shallow crop roots (Siddique et al. 1990; Gregory and Eastham 1996). Only a small portion of roots grow in the B horizon due to a combination of chemical and physical limitations including subsoil compaction, poor soil fertility and acidity (Tennant et al. 1992), limiting root access to subsoil water and nutrients, leading to sub-optimal crop yields (Gregory 1997).

Deep tillage and/or deep incorporation of soil amendments, such as lime, inorganic and organic fertiliser (Fiskell and Calvert 1975; Gill et al. 2012) have been used to ameliorate subsoil constraints and increase rooting depth. However, most previous interventions were confined to a maximum depth of 40-50 centimeters. In 2021, a ‘blue-sky’ research project consisting of several field trials was established to treat multiple subsoil constraints by incorporating amendments and loosening compacted soil to a depth of 80 cm in different soil types across WA. The objective was to facilitate deeper root systems in annual crops to improve their capture of water (Materechera et al. 1993; Gregory 1997) and nitrogen (Dunbabin et al. 2003) from deep subsoil layers. Access to subsoil moisture and nutrients is particularly important in water-limited arid and semi-arid environments of WA, where crops depend completely on seasonal rainfall. The practice of rectifying multiple soil physical and chemical constraints to a depth of 80 cm has now been termed “soil re-engineering” (Azam et al. 2023).

One of the soil re-engineering experiments was conducted in Meenar, WA, on a duplex soil profile with several subsoil constraints including non-wetting topsoil and subsoil acidity and compaction. This soil was re-engineered by loosening the soil and incorporating different combinations of amendments, such as lime, clay, organic matter, and inorganic fertiliser, to a depth of 80 cm. Soil re-engineering reduced soil acidity, and compaction and increased water holding capacity within the whole soil profile almost instantly and the improvements prevailed to date. In this experiment, deep incorporation of a high rate of inorganic fertiliser, lime, and clay doubled the shoot biomass and grain yield of barley and canola compared to surface application of the same amendments in the two years following soil re-engineering intervention (Azam et al. 2023). However, annual replenishment of inorganic fertiliser to a depth of 80 cm of soil profile following re-engineering is not economically feasible. To address this, we conducted a series of soil column experiments to develop fertiliser strategies for re-engineered soils based on surface banding and topdressing. The first phase of this semi-controlled environment study, using reconstructed soil columns, investigated whether it was possible to achieve similar yields by surface application of a high rate of fertiliser compared to deep incorporation of a high rate of fertiliser. The second phase of the experiment investigated the effect of different rates of surface-applied nitrogen (with sufficient amounts of other nutrients) on barley crop growth and yield on the same soil.

Methods

Construction of soil columns for re-engineering

Bulk soil was used for the experiment, excavated from three depths (topsoil, 0-10 cm; midsoil, 10-40 cm; and subsoil, 40-80 cm) within the above-mentioned farmer field in Meenar, WA. The soil was acidic throughout the profile (pH 4.2-4.5), with about 8% clay in the top sandy layer (0-40 cm). Topsoil had medium organic carbon (1.3%). The subsoil had 38% clay content which was very densely packed (bulk density 1.8 g/cm^3, soil strength >5 MPa). The soil was air dried and ameliorated with the respective amendments and repacked into PVC columns (diameter 15 cm and height 85 cm) at 1.5 g/cm^3 bulk density, simulating the re-engineered soil profiles in the field trial.

Experimental Design – Phase I

The experimental design of the Phase-I was a factorial combination of four levels of amendments and three levels of fertiliser treatments with three replications. The amendment treatments were (i) loosening soil to 80 cm with no amendments (ii) loosening soil and liming (1g lime/kg soil) to 80 cm depth (iii) loosening soil to 80 cm depth and adding clay (5%) to the top sandy 40 cm of the soil profile (iv) loosening soil to 80 cm depth, liming to 80 cm plus adding clay to top 40 cm (combination of amendment treatments ii and iii). The three fertiliser treatments were (i) topdressing at a low rate, F1: NPK 27.0, 13.1, 21.4 kg/ha soil (ii) topdressing at a high rate, F2: NPK 54.0, 26.2, 42.8 kg/ha and (iii) deep incorporation at re-engineering rate, F3: NPK rates for 0-10 cm 27.0, 13.1, 21.4 kg/ha; for 10-40 cm 81, 40, 64 kg/ha and for 40-80 cm depth 107, 52, 85 kg/ha. The re-engineering fertiliser rate F3, incorporated deeply, was equivalent to the rate used in the re-engineering field study.

A barley crop (cv. Maximus) was grown for a period of 75 days. The crop was irrigated to 80% field capacity and the moisture level was maintained to meet the evapotranspiration demand of the crop. The crop was harvested at 75 days after seeding (DAS). At harvest, shoots were clipped to determine shoot biomass and the soil column was then sliced into six depth increments (0-10, 10-20, 20-30, 30-40, 40-60 and 60-80 cm). After recovering some soil for analyses, roots were washed from each depth increment and scanned for root growth parameters using the software WINRHIZO™.

Experimental Design – Phase II

The experimental design of the Phase-II was a factorial combination of two levels of amendments (based on the results from Phase-I, the clay amendment was eliminated) and four levels of N fertiliser with three replications. The amendment treatments were (i) loosening soil to 80 cm with no lime, and (ii) loosening soil and liming (1g lime/kg soil) to 80 cm depth. The four N levels applied in the form of urea were (i) 0 (ii) 75 (basal) (ii)150 (basal and 1 split at Z22, and (iv) 225 (basal and 2 splits at Z22 and Z30) kg N/ha. In this experiment, three intact soil cores (diameter 15 cm, height 83 cm) were excavated from the field and used as a paddock control representing compacted field conditions. A barley crop (cv. Maximus) was grown for 156 days before it was harvested to measure shoot biomass, grain yield and other yield parameters. Immediately after harvest, soil columns were processed as per Phase-I for soil and root parameters. The crop was irrigated as per Phase-I, however, no irrigation was applied from 125 DAS onwards to induce a terminal drought during grain filling (and match the seasonal forecast for the 2023 season).

Results

Phase I

There was no significant (P>0.05) interaction between the amendment and the fertiliser treatments, however, there were significant main effects (P<0.001) of the amendment and the fertiliser treatments in increasing tiller number, shoot biomass, rooting depth and root length density. Root growth was mainly improved due to lime incorporation with some additional effect from F3 (data to be presented). Doubling the rate of fertiliser applied as a top dressing (F2) significantly increased the tiller number by 1.4 times, while incorporating the re-engineering rate of fertiliser into the soil profile (F3) significantly boosted the number of ears by 1.6 times compared to the lower rate of top dressing (F1) (Image 1, Table 1). Adding clay to the soil profile did not improve any plant growth parameters. Loosening and liming resulted in a 2-fold increase in the number of tillers compared to loosening the profile alone (Table 2).

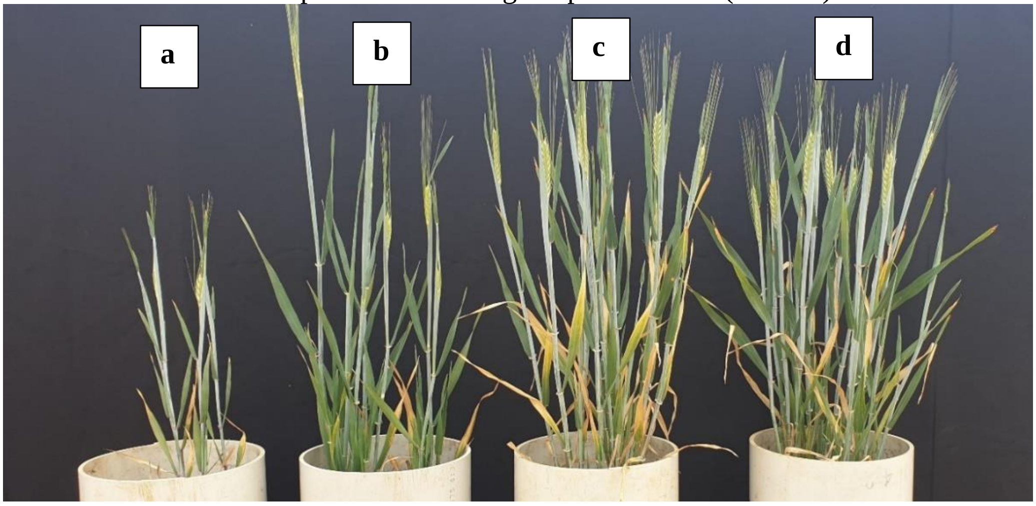

Image 1. Barley crop growth (71 DAS) in soil columns with different re-engineering treatments: (a) soil loosening to 80 cm with a top-dressing of the low rate of fertiliser application; (b) soil loosening + lime incorporated to 80 cm depth and a top dressing of the low rate of fertiliser application; (c) soil loosening + lime incorporated to 80 cm and a top dressing with a high rate of fertiliser application; and (d) soil loosening + lime + fertiliser incorporated to 80 cm.

Table 1. Above-ground biomass and number of ears per column (g) as influenced by fertiliser treatment applied. Means followed by the same letter for a given data raw are not significantly different (l.s.d. at *P* = 0.05).

	Fertiliser treatment			l.s.d.
	Top dress low	Top dress high	Deep incorporated re-engineering rate	(p=0.05)
Above-ground biomass per column (g)	5.39 a	8.02 b	9.63 b	1.67
Number of ears per column	6.67 a	9.0 b	10.42 b	1.69

Table 2. Above-ground biomass and number of ears per column (g) as influenced by re-engineering treatment applied. Means followed by the same letter for a given data raw are not significantly different (l.s.d. at *P* = 0.05).

	Re-engineering treatment				l.s.d.
	Loosening	Loosening + Clay	Loosening + Lime	Loosening + Lime +Clay	(p=0.05)
Above-ground biomass per column (g)	3.46 a	4.32 a	11.16 b	11.78 b	1.91
Number of ears per column	5.44 a	5.89 a	11.56 b	11.89 b	1.95

Deep incorporation of lime to a depth of 80 cm raised the soil pH from below the critical threshold of 4.8 to above 5.2 at all depths (data to be presented). Consequently, the extractable aluminium concentration dropped below 1 ppm at all depths below the top 10 cm, significantly reducing it to levels well below toxicity (2-5 ppm for sensitive species). In contrast, the pH of treatments without lime incorporation remained below 4.8 at every depth and extractable aluminium concentration stayed far above toxic levels in the subsoil.

Phase II

In the intact core with no nitrogen fertiliser, 93% of roots were confined to the top 10 cm, and the maximum rooting depth was 20-30 cm (data to be presented). Soil loosening to 80 cm depth alone had only 48% of roots in the top 10 cm and the rooting depth was increased to 60-80 cm. Soil re-engineering treatments of loosening and lime incorporation to 80 cm depth generated greater (expressed in root length density) and deeper barley root systems (Image 2). There were significant main effects of the amendments and the N levels (P<0.001) on above-ground biomass, tiller number, grain yield and protein yield; however, the interactions were not significant ((P>0.05). In the absence of lime, 75 kg/ha N was enough to optimise shoot biomass and grain yield. In the presence of lime, increasing the amount of N increased shoot biomass, grain and protein yields (Table 3). There was no difference between the two higher levels of N (150 and 225 kg/ha) in biomass and grain yield, however, 225 kg/ha increased protein yield compared to 150 kg/ha.

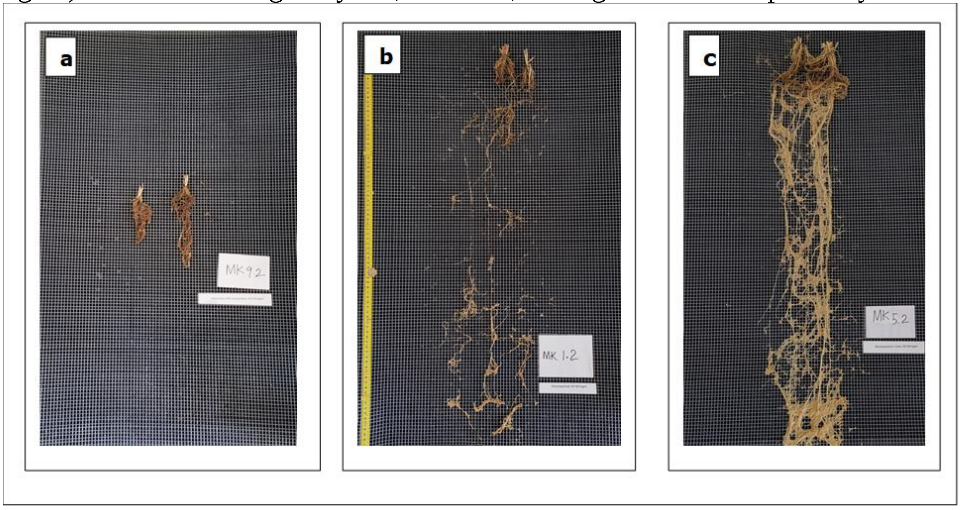

Image 2. Root system profiles of a barley crop (156 DAS) with (a) no nitrogen fertiliser applied, grown in intact core, (b) soil loosening to 80 cm depth, and (c) soil loosening plus lime incorporation to 80 cm depth.

Table 3. Mean grain, above-ground biomass and protein yields per column (g) as influenced by N level applied. Means followed by the same letter for a given data raw are not significantly different (l.s.d. at *P* = 0.05).

	N Level (kg/ha)				l.s.d
	0	75	150	225	(p=0.05)
Grain yield (g)	10.89 a	16.62 b	17.8 bc	19.8 c	2.85
Above-ground biomass yield (g)	18.23 a	30.51 b	35.12 bc	37.31 c	5.75
Protein yield (g)	0.83 a	1.23 b	1.56 c	1.87 d	0.21

Conclusions

After increasing the soil pH and reducing the compaction of the soil profile by deep incorporation of lime to 80 cm depth, barley yield can be maintained by surface application of inorganic fertiliser at increased rates. Our study shows that 150 kg/ha N was required to optimise the barley grain yield, but higher barley protein could be achieved with more N applied.

References

Azam G, Wickramarachchi K, Davies S, Clausen J, Reynolds C, Isbister B, Hall D, Parker W, McDonald G, Rahman H, Rahman M, Van Burgel A, Gazey C (2023) Doubling grain yield and water use efficiency by reengineering sands and texture contrast soils in Western Australia. Paper presented at the National Soil Science Conference, Darwin, Australia,

Dunbabin V, Diggle A, Rengel Z (2003) Is there an optimal root architecture for nitrate capture in leaching environments? Plant, Cell & Environment 26 (6):835-844. doi:https://doi.org/10.1046/j.1365-3040.2003.01015.x

Fiskell JGA, Calvert DV (1975) EFFECTS OF DEEP TILLAGE, LIME INCORPORATION AND DRAINAGE ON CHEMICAL PROPERTIES OF SPODOSOL PROFILES. Soil Science 120 (2)

Gill JS, Clark GJ, Sale PW, Peries RR, Tang C (2012) Deep placement of organic amendments in dense sodic subsoil increases summer fallow efficiency and the use of deep soil water by crops. Plant and Soil 359 (1):57-69. doi:10.1007/s11104-012-1126-6

Gregory PJ (1997) Alternative crops for duplex soils: growth and water use of some cereal, legume, and oilseed crops, and pastures. Australian Journal of Agricultural Research 49 (1):21-32. doi:https://doi.org/10.1071/A97053

Gregory PJ, Eastham J (1996) Growth of shoots and roots, and interception of radiation by wheat and lupin crops on a shallow, duplex soil in response to time of sowing. Crop & Pasture Science 47:427-447

Materechera SA, Alston AM, Kirby JM, Dexter AR (1993) Field evaluation of laboratory techniques for predicting the ability of roots to penetrate strong soil and of the influence of roots on water sorptivity. Plant and Soil 149 (2):149-158. doi:10.1007/BF00016604

Siddique K, Belford R, Tennant D (1990) Root: Shoot ratios of old and modern, tall and semi-dwarf wheats in a Mediterranean environment. Plant and Soil 121:89-98. doi:10.1007/BF00013101

Tennant D, Scholz G, Dixon J, Purdie B (1992) Physical and chemical characteristics of duplex soils and their distribution in the south-west of Western Australia. Australian Journal of Experimental Agriculture 32 (7):827-843