Can subsoil amelioration improve the productivity of grain production in medium-high rainfall environments?

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Abstract
The water limited yield of many grain crops growing on poorly structured subsoils in the medium-high rainfall zone of south eastern Australia falls far short of the full potential. Previous research has demonstrated that applying large quantities (> 10 t/ha) of organic matter, commonly referred to as subsoil manuring, can markedly improve grain yields for at least several years. A number of issues has limited the commercial implementation of this technology on-farm, including unpredictable yield responses, high upfront costs, the availability of suitable organic matter sources and the lack of commercially available machinery to apply the organic matter. Critically, the exact mechanisms underpinning the yield response and how this varies with the form and rate of organic matter used, soil type and seasonal conditions is unclear. We argue however that if these issues can be resolved, then there is the potential to significantly improve both the productivity and profitability of grain production in these cropping systems.

Keywords
Soil structure, yield potential, organic matter.

Introduction
The productivity of many cropping systems in Australia is limited by a range of subsoil physicochemical constraints that limit root growth and reduce water and nutrient-use efficiency (Adcock et al. 2007; Dang et al. 2010). In medium (375-500 mm annual rainfall) and high rainfall (>500 mm) environments of south eastern Australia up to 80% of cropping land is affected (GRDC 2016) by subsoil constraints. These include poor soil structure / high soil strength with potential for temporal water-logging, nutrient deficiencies and in some cases, acidity. Given the scale and impact of this problem, it is not surprising that a range of different approaches have been tried in order to ameliorate these subsoil constraint, especially over the past 30 years. Initially researchers considered that subsoil constraints were 'too deep and out of reach', and attempts to physically ameliorate them would be too expensive (Graham et al. 1986). A range of 'genetic solutions', where varieties with improved tolerances to one or more soil constraints were developed; the most successful examples included boron (B) tolerance in wheat and pulses such as lentils (e.g. Paull et al. 1988; Hobson et al. 2007). 'Genetic solutions' however resulted in relatively minor yield improvements as overcoming soil physical constraints were much more intractable than chemical toxicities, even when tolerances to multiple chemical toxicities (pyramiding) were employed (Nuttall et al. 2010). A major national research initiative funded by the GRDC from 2003-2007 (Project SPI08) examined a range of strategies designed to manage subsoil constraints. Amelioration attempts however met with little adoption on farms, in part reflecting the period of sustained low rainfall during the study period. The prevailing attitude then, at least for the heavier soils in south east Australia, was that 'amelioration strategies' often did not produce significant yield improvements, or when they did, these were not financially viable. Grain growers needed to *'live with the constraints'*. More recent assessments (Armstrong et al. 2015; Sale et al. 2014) have raised the possibility that 'amelioration', using organic and other amendments, may indeed by possible. In some cases, yield increases of more than 80% have been achieved (Final Report, GRDC Project ULA00008). However, adoption at a commercial scale has remained very low to date due to a combination of high upfront costs (up

to $1200/ha) to implement, variable yield responses and a number of logistical constraints such as the limited availability of suitable organic matter sources (Nicholson 2016) and access to appropriate machinery. This paper summarises key findings of a recent review (GRDC 2017) of knowledge gaps currently limiting the adoption of organic matter amelioration of soils by grain growers in south eastern Australia. The paper concludes by recommending a number of research priorities to overcome these gaps.

Overcoming barriers to commercial adoption of subsoil amelioration

Processes

A fundamental constraint to identifying potential strategies for overcoming the logistical constraints to the adoption of subsoil organic matter amelioration is that key mechanism/s behind the yield responses are unclear. Soil structure improvements, expressed as reduced bulk density, increased macro-porosity and saturated hydraulic conductivity are usually improved following amelioration (Clark et al. 2009). As a result, root growth is likely to improve and contribute to improved yields although indirect effects, such as minimising 'water-logging' are also likely to occur on certain soil types and environments. The improved soil structure is hypothesised to occur via enhanced 'biological activity' (from increased root growth and microbiological activity) and the release of exudates and mucilage leading to improved soil aggregation (Bronick and Lal 2005). A notable feature of this improved soil structure is the observation of the spread of this benefit beyond the immediate zone of application (normally applied as a band) of up to 25-30 cm both vertically and horizontally over a relatively short time span of 1 growing season (Gill et al. 2009). Other studies have demonstrated significant reductions in the soil exchangeable sodium percentage (ESP) in high sodic subsoils following the application of 20 t/ha of composed organic matter although the mechanism underpinning this change remains unknown (Armstrong et al. 2007).

Other factors however may also be in play. The physical disruption of poorly structured clay soils (whether they are sodic or not) by 'deep ripping' rarely produces positive crop responses, especially beyond the first season after application (McBeath et al. 2010) and in some cases can reduce yields. Most studies of organic amelioration have utilised organic matter sources including animal manures and lucerne pellets (Gill et al. 2008) or composted bedding straw (Armstrong et al. 2015) that are highly enriched with nutrients such as N, P, K and S. Other indirect evidence for the role of nutrients is the high variability in plant growth response to nonorganic ameliorants such as gypsum, which improve soil structure but do not contain nutrients, except S. It is unclear however whether the potential role of nutrients occurs via simulating microbial activity or root growth or via a direct effect on improved crop access to nutrients similar to the large yield responses to subsoil nutrient application recorded on well-structured Vertosol soils in the northern grains region (Bell et al. 2015).

A significant factor restricting grower adoption of subsoil organic matter amelioration is the variable crop response, especially given the very high initial upfront costs of amelioration. There is a strong relationship between the amount and distribution of rainfall and the relative response of crops to subsoil amelioration. For example Sale (2014) reported that large yield responses occurred over a 4-year period between 2009 and 2012 in the Victorian High Rainfall Zone (HRZ) where rainfall ranged from Decile 3 to 9. However, in the drier seasons of 2014-2015 (rainfall was Decile 1 to 2), no yield responses were recorded. Similarly, consistently large yield responses (up to 40%) have been recorded on sodic clay soils in the medium rainfall zone of the Wimmera during growing season rainfall of Decile 3 to 5 (Armstrong et al. 2015) whereas in a run of drier seasons (Decile 1 - 4), no yield responses were recorded on a similar clay soil. Although subsoil constraints have no effect in the absence of subsoil water (Nuttall and Armstrong 2010), it remains unclear whether soil water availability affects crop response by directly limiting the yield potential of the crop, or by indirectly affecting other processes such as the microbial decomposition of the organic matter and associated nutrient release, the improvement in soil structure, and/or the effect of poor soil structure *per se*, e.g. temporal water logging. As an analogy to nutrient management, it is likely that the timing of rainfall will be as important, if not greater, than the total amount of rainfall recorded.

The form, rate and position of organic matter applied

Most of the studies undertaken to date in subsoil amelioration of dryland cropping systems have utilised either nutrient-enriched animal manures or composted organic matter applied at relatively large rates (10 – 30 t/ha). The widespread use of these manures will not be sustainable in the long-term because of limited supply and increasing cost (both of the product and transport to the paddock), and this has created interest in identifying more cost-effective amendments based on readily available farm-grown biomass materials.

Recently, the Southern Farming Systems Group has trialled the use of 'green chop' materials such as vetch that are grown, harvested and injected into the subsoil *in-situ*. Cereal stubbles are the largest source of organic matter grown on farm. However, the stoichiometric ratio (C:N:P:S) has been shown to be an important determinant of soil C decomposition (Kirkby et al. 2011) and may be important in both soil structure stabilisation as well as mineralisation and immobilisation of soil nutrients. Given that the high C:N of cereal stubble would result in immobilisation of nutrients, , a strategy where-by nutrients could be added to ensure a C:N of less than 25:1 may overcome this limitation (Paul and Clark 1989), although costs would need to be considered. Despite the potential to use alternative sources of organic matter, the research to date suggests that relatively high rates of organic matter are required to drive significant (and long lasting) productivity improvements. Uncertainty exists about the best position in the soil to apply the organic matter. Most studies undertaken by the La Trobe University and the Victorian State Agencies in the Victorian HRZ have placed the organic matter in a band at depths of 30 to 40 cm (Gill et al. 2008, 2009). However studies on sodic clay soils in the medium rainfall Wimmera region of Victoria (Armstrong et al. 2007, 2015) top-dressed the organic matter still recorded significant yield responses. In contrast studies in South Australia on sandy soils found that top dressing was ineffective (D Davenport, pers. comm.). This issue needs addressing as even small increases in placement depth involve significant increases in draft (and therefore energy costs). It has been hypothesised that the optimum depth for placing organic amendments in the soil, to improve the condition of the deeper soil profile for cropping, will be site- and season-specific. The benefits of deep placement are more likely to be apparent in the high rainfall regions where the additional rainfall can be captured and held in ameliorated subsoil layers, and then used by crops. Alternatively, other studies with nutrients alone (e.g. Dunbabin et al. 2009) suggest that maximum plant response occurs when there is a spatial synchronisation between nutrients, crop roots and water availability.

Suitable machinery
The availability of commercial scale machinery to effectively apply organic matter remains a key constraint to the widespread adoption of subsoil amelioration (Nicholson 2016). A major barrier to the development of this machinery in part reflects uncertainty by manufacturers as to the form of organic matter, the rates required, and depth and row spacing of the placement (i.e. issues identified earlier). This situation is complicated by the range of environments (varying in soil type and yield potential) underpinning grain production in south eastern Australia, as the optimum tyne type, row spacing and depth will most likely vary accordingly. The occurrence and severity of subsoil physicochemical constraints exhibits wide spatial variability within paddocks (Armstrong et al. 2009). The effectiveness of any strategy designed to ameliorate these constraints, including the application of organic matter into the subsoil, will therefore vary accordingly. The availability of rapid (and relatively inexpensive) soil mapping technology such as EM38 and 'variable rate' application provides the opportunity to both identify where these constraints occur and reduce overall application costs.

Conclusions
The use of organic matter to ameliorate poorly-structured soils in the medium and high-rainfall zone of south eastern Australia has the potential to significantly improve grain productivity. Although a number of logistical constraints currently limit adoption of this management strategy by growers, there is a reasonable likelihood that an appropriately designed research, development and extension program can lead to practices that will overcome these constraints.

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