Business case for investment in subsoil modification in the high rainfall zone of South west Victoria

SFS

Southern Farming Systems

This business case has been prepared by Cam Nicholson for Southern Farming Systems through funding from the Australian Government's National Landcare Programme. It forms part of a larger project (INNOV-108) that also involves the design and fabrication of machinery, development and testing of easy to use and cost effective amendments and on farm demonstration of the commercial machinery and products.

Significant contributions to this report were provided by Corinne Cellestina and Zoe Creelman.

Disclaimer

Southern Farming Systems
23 High Street
Inverleigh, VIC. 3321

January 2016

Contents

Executive Summary

Subsoil manuring is a practice that involves the incorporation of high rates of a fertile organic amendment into the subsoil layer in order to overcome soil constraints to production. A decade of research on hostile soils in the southern high rainfall zone has verified that this technology is capable of significantly and semi-permanently improving soil chemical, physical and biological properties and significantly increasing plant yields and biomass production.

Although expensive to implement (>$1000/ha), small plot trials indicate significant yield responses are possible, meaning the payback period for subsoil manuring can be as little as 1-2 years under favourable seasonal conditions, with internal rates of return of between 28% and 160%.

If implemented on responsive soil across the south west of Victoria, the regional impacts are significant, with an estimated average regional economic impact of $317.2 million per year. This comprises a direct farm impact (farm net profit increase) of $67.2 million per annum, along with a direct multiplier effect of $133.8 million per year and an additional $116.2 million through value adding (Nicholson et al. 2015). Overall employment would increase by 1,300 people, with 624 on farm jobs created and a further 677 full time jobs through post farm gate services. Importantly subsoil manuring had a proportionally greater benefit for all crops when yields were expected to be 'poor' (decile 1), helping to manage downside climatic risk.

Commercialisation of the concept remains the major barrier. The three greatest limitations to commercialisation are:

1. *Farmers having access to machinery that is cost effective and capable of treating large areas*. While valuable progress has recently been made in this area, there is still significant work to commercialise suitable machinery for on farm use.
2. *Access to suitable substrate at low cost*. Most trial work has been conducted with substrates that will be insufficient to meet expected demand and are likely to rise in price. Alternative products need to be found. Fodders grown and harvested in-situ show promise but require considerable research to determine the best products to use (quantity and quality). Further the product and incorporation costs must be reduced, as the economic analysis clearly shows the profitability of the practice depends on minimising this up-front cost.
3. *Identifying which locations will provide best return from investment in subsoil manuring.* While modelling and trial results indicate a wide range of responses, rainfall and soil type appear to have a big influence on the yield response to subsoil manuring and hence profitability of the practice.

Vision

Increased productivity, profitability and resilience of crop and livestock farmers in South West Victoria achieved through the improvement in subsoils that are limiting production.

The purpose of this business case

The business case is intended to provide sufficient evidence to support further investment in subsoil amelioration in the high rainfall zone of South West Victoria. Areas with similar cliamatic and soil constraints such as Tasmania and Southern NSW could also be considered.

The business case reviews the evolution of subsoil manuring, identifies soils that are likely to be most responsive to this practices and examines the productivity and profitability implications of the practice if adopted. Recommendations are made on where future investment should be directed.

Background and history

The concept of improving the subsoil through incorporation of organic material (subsoil manuring) has been investigated in South West Victoria since 2004. This region has led the thinking and application of this approach because while the region is considered to have reliable winter dominant growing season rainfall compared to other areas, current crop yields are only approximately 50% of the water-limited potential (Robertson et al, 2016). Unfavourable or 'hostile' subsoils have been identified as one of the major reasons for this sub optimal production (MacEwan et al, 2010, Zhang 2006).

Soil limitations

Hostile subsoils restrict plant root growth and the movement of air and water into the soil. The causes of this unfavourable environment are discussed in appendix 1, but essentially while the topsoil is reasonably good for plants (if fertiliser and lime is applied to rectify nutrient and acidity constraints), the deeper soil layers are restrictive. These restrictive layers are either 'bleached', with poor structure and devoid of nutrients, or are so dense that they limit the drainage of water and root penetration (figure 1).

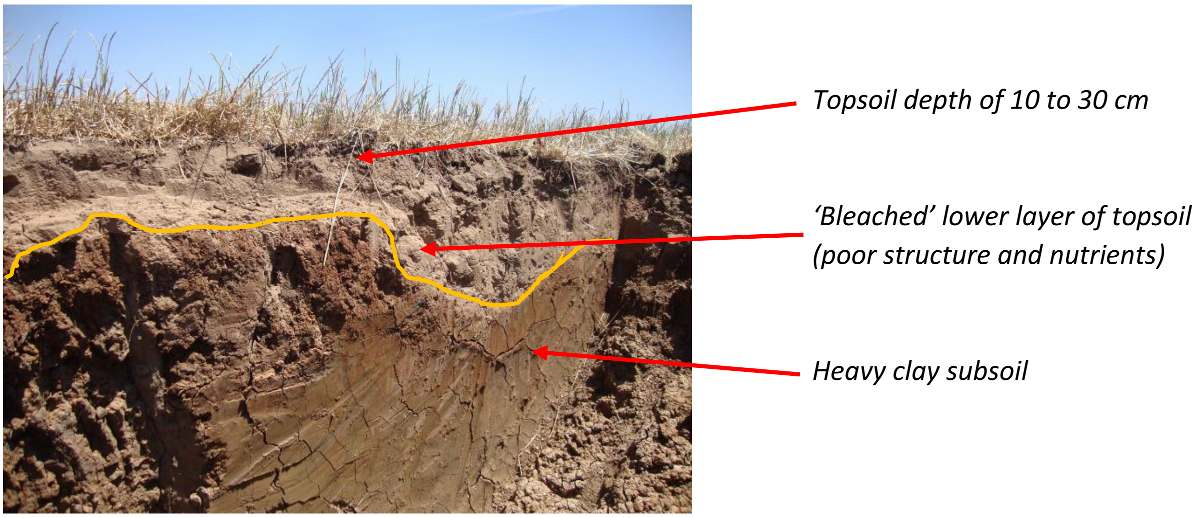

Figure 1: Contrast of typical duplex soil with shallow and variable depth topsoil, bleached layer and dense clay subsoil (Image: Corinne Celestina)

The contrasting topsoil and subsoil layers create two major problems for crop and pasture production. The first is the amount of rainfall that can be stored in the topsoil is limited by its depth. If winter rainfall events are large enough and the subsoil prevents draining, the topsoil quickly fills up and becomes saturated (waterlogged). This waterlogging has a negative impact on plant root growth and leads to a rapid loss of soil nitrogen. The second problem commonly occurs later in the season, during Spring, as soil temperature and plant growth increases. The topsoil is rapidly depleted of stored water however the plants have difficulty accessing water in the subsoil because they are unable to penetrate the bleached layer and/or clay layers (figure 2). Unless regular rainfall events occur, crops and pastures quickly become moisture stressed and production is compromised.

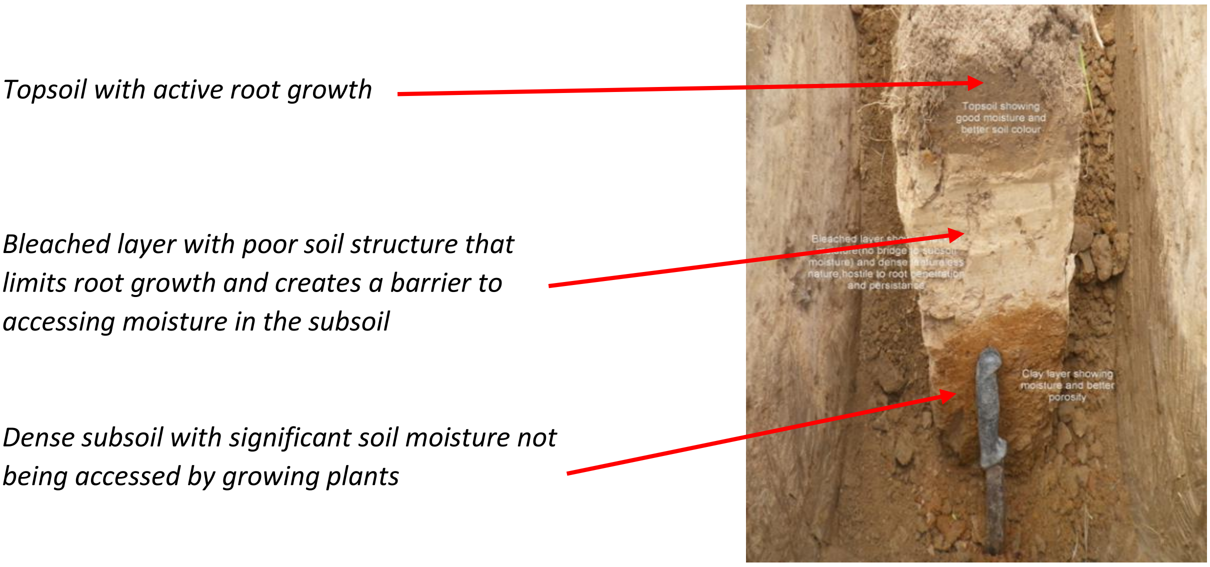

Figure 2: Contrasting topsoil, bleached horizon and dense subsoil still with moisture (Image: Simon Falkiner)

The capacity to store water in the soil is often referred to as the 'bucket size'. The simple reality for farmers in South West Victoria is the 'soil bucket' is often only the topsoil and is too small to match crop or pasture requirements from late season rainfall events. This moisture stress commonly over rides the other potential benefits that could be gained from improvements in farm practices.

A short literature review of the methods that have been tried to ameliorate these hostile subsoils is provided (appendix 2). In summary they have involved:

- Deep ripping to physically shatter the dense layer, however because of the chemical properties of the soil (sodicty), the benefits quickly disappeared (Clark et al. 2009).
- Using gypsum incorporated at depth to help improve the structure of the soil. The response was limited to only certain types of soil and even then the benefits were minimal (Gardner et al. 1992).

- Using plants with a strong taproot such as lucerne, forage crops and sunflowers to grow through the hostile soil and leaving channels for subsequent plants to exploit (figure 3). While this has shown some potential, only a small amount of the soil is modified.
- The incorporation of organic material through inversion of the soil (green manuring). While effective at placing organic material at depth, it also buries the nutrient rich topsoil and brings the poorer soil to the surface.

Figure 3: Channel through hostile subsoil created by lucerne (Image: Simon Falkiner)

Incorporation of organic material into the subsoil without inversion (subsoil manuring)

The placement of organic material at depth without soil inversion is a more recent development.

The first 'test' was undertaken with peat pellets and gypsum at the Southern Farming Systems site at Gnarwarre in 2004 (figure 4). This was followed by work conducted in 2005 at Ballan by Dr Peter Sale from Latrobe University, *Yaloak Estate* farm manager David Watson and Dr Renik Peries from the Department of Primary Industries (DPI). These initial investigations led to a series of trials across South West Victoria. Results were very promising and in some cases spectacular, with yields more than double compared to non-treated areas.

Figure 4: Dr Renick Peries (DPI), farmer David Langley and Bruce Wightman (DPI) conducting the first local trial of subsoil amelioration using organic material at the SFS research site at Gnarwarre.

A summary of the trial results are provided (appendix 3), along with expert opinion as to why the measured responses may be occurring (appendix 4). The general consensus is that subsoil manuring increases the size and number of soil pores, improves aeration, infiltration and water storage. It also has an initial short term fertiliser effect.

Positive results in replicated plot trials have been repeated by growers installing small trials of various sizes and layouts. Assessment of these on farm tests were often more subjective, relying on growers' observations and instincts rather than measured yields. Nevertheless, reported yield increases were in the range of 25% to 65% (Watson 2014).

Watson (2014) interviewed farmers to understand how the concept proven at a small plot scale could be made a commercial reality. His key findings were:

- Farmers were mainly motivated to trial subsoil manuring by the desire to reduce reliance on inorganic fertiliser, improve water use efficiency and increase yields.

- They believe the ‘proof of concept’ with the technology has been achieved and if it could be adopted, would provide a major leap forward for agriculture.
- Most see amendments produced on farm as the best choice for substrate as the demand for and cost of bought-in amendments rises.
- Some growers are still seeking a more detailed understanding of the mechanisms by which subsoil manuring works, so continuing research in parallel to commercialisation efforts is critical.
- Adoption is limited by machinery to operate at a commercial scale.

Machinery development

The absence of machinery capable of treating farm scale areas was identified in the Watson report (2014) as a major barrier to adoption. The initial trial machine was small, relied on bought in amendment, lacked the capacity to accommodate large volumes or variable consistency of product and required considerable horsepower to pull (>200 HP). One farmer has replicated this design on a larger scale but has substantial private investment backing the development and application of the technology.

Based on the findings from Watson (2014) and with support from the University of Melbourne and the Australian Government’s National Landcare Programme, a functional prototype machine was designed, fabricated and tested in 2015 that attempted to address the barriers to commercial adoption (figure 5). The machine was constructed to meet the following design criteria:

- Capable of harvesting at least 6 t/ha DM of either a windrow or standing crop to a width of 2m.
- Capable of including additional products if required (lime, gypsum, manure).
- Deposit the harvested product into the soil in the same pass to a minimum depth of 250 mm, while ripping to a depth of 350 mm. This required a ripping, opening and closing mechanism
- Close over the ripped area leaving an acceptable surface finish.
- Be pulled with a tractor of < 150 HP.

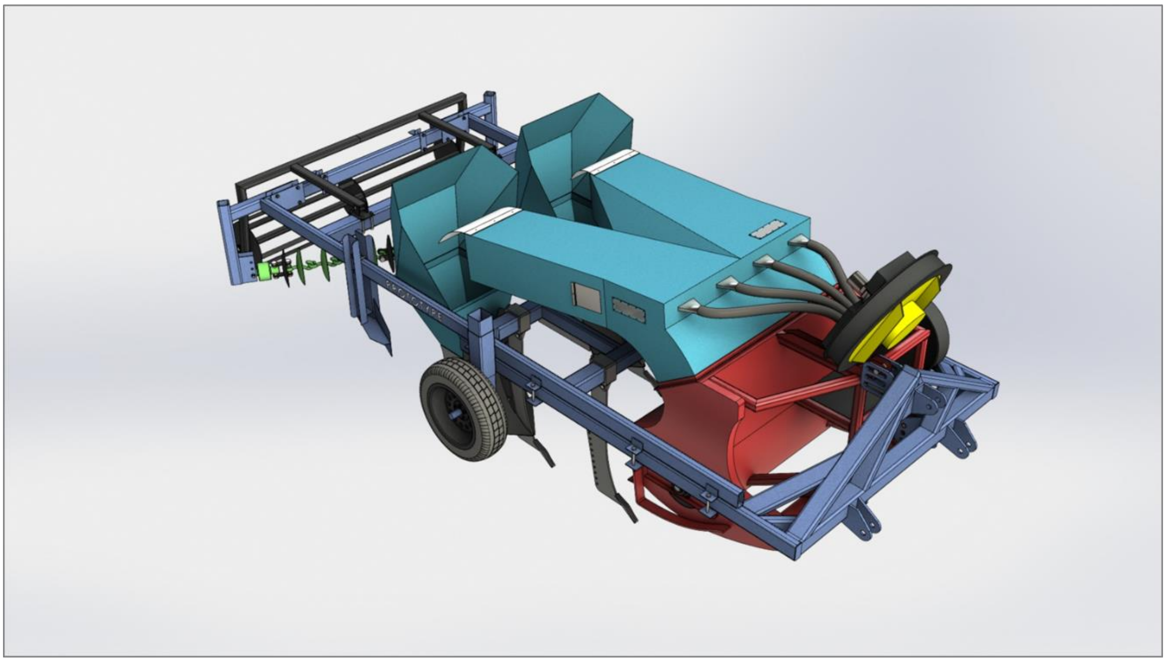

Figure 5: Final design of the in-situ subsoil manuring prototype (as manufactured) (Image: Domenic Germano)

A report on the development of the prototype has been prepared (Germano 2015) and provides a solid basis for further machinery development. The machine proved to be effective at harvesting and depositing organic material at depth (figure 6) and was used by SFS to establish 18 on farm sites using a range of materials in Spring 2015.

Topsoil

'Tubes' of fresh organic material placed into the poorly structured subsoil

Figure 6: Placement of in-situ harvested material (Image: Domenic Germano)

There is limited information on the yield response of fresh organic material compared to poultry manure. The first trial were established in 2014, however initial observations are promising (figures 7 & 8).

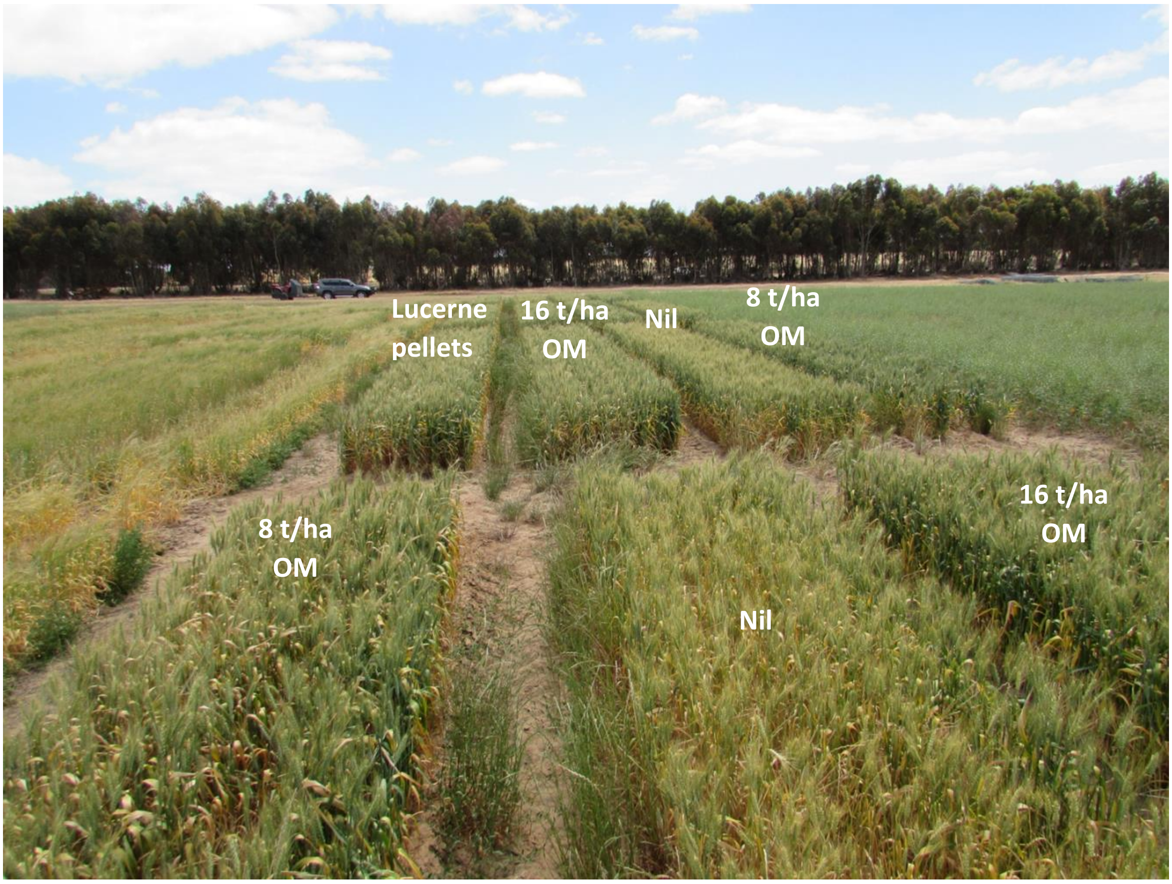

Figure 7: Visual differences in crop growth from varied rates of organic material (Image: David Watson)

Figure 8: Crop roots moving towards previously incorporated organic material (Image: Simon Falkiner)

Previous economic studies

Limited economic analysis has been done on subsoil manuring. Analysis of two field trials using poultry manure at 10t/ha and 20 t/ha showed subsoil amelioration was highly profitable due to the large yield increases that occurred (Peries 2014). This analysis has calculated the payback period for the investment to be just 1-2 years (Sale and Malcolm 2015), with rapid return to positive cash flow. However not all field trials have resulted in the same large increases in crop yields used in the economic analysis and farmer observations would suggest much lower yield responses. Also the ability to access large quantities of poultry manure may be problematic (see next section). Further it would be dangerous to assume the response across the entire region would be the same given the variability in soil type and climate.

A business case needs to justify any possible future investment in subsoil manuring in South West Victoria. This analysis needs to consider how consistent the pasture and crop yield response will be over time, the availability and suitability of organic products if the practice is widely adopted and the impact at a farm and regional level, given most properties are a mixture of cropping and livestock.

Business case

The business case analysis covers a region west of Melbourne to the South Australian border, an area of approximately 3.8 million hectares (figure 7). Not all land in this region is suitable for consideration, either because it is public land, is urbanised or has a land use other than broad-acre grazing and cropping e.g. dairying, horticulture, hobby farming.

Figure 7: Region considered in the scoping study

Farm land suitable for treatment

An extensive study was undertaken to identify land potentially suitable for the subsoil manuring (Celestina et al. 2015). This study identified three soils with duplex characteristics similar to figure 1 that are expected to be highly responsive to subsoil manuring. These soils cover approximately 2.17 million hectares or 57% of the region.

Land use and climate vary considerably across the 2.17 million hectares of suitable land. Nine locations were examined to reflect the diversity in farming systems across the region (table 1).

Table 1: Characteristics of locations examined

Location	Average annual rainfall 1962 - 2012 (mm/yr)	Farm size (ha)	Proportion crops (%)	Proportion grazing (%)	Long term average stocking rate (DSE/ha)[1]
Balliang (east)	509	1350	35	60	9.9
Birregurra	665	1000	0	95	18.6
Casterton	662	1150	5	90	16.5
Derrinallum	598	1200	15	80	14.1
Inverleigh	560	1200	20	75	13.3
Lake Bolac	563	1350	30	70	12.8
Mortlake	677	1150	15	80	17.2
Penshurst	725	1100	10	85	20.8
Winchelsea	579	1200	20	75	13.3

Detailed whole farm modelling was conducted using computer programs APSIM[2] and GrassGro[3] to calculate the variability in crop and pasture production with and without the permanent effects of sub soil amelioration (Nicholson et al. 2015). i.e. change in soil structure but ignoring the short term fertiliser effect. Fifty years of historic climatic data (1962 to 2012) was used in the analysis.

[1] Based on 85% of stocking rate predicted by French – Shultz water use efficiency model.

[2] APSIM (Agricultural Production Systems SIMulator) is an internationally recognised, highly advanced simulator of agricultural systems. It contains a suite of modules which enable the simulation of systems that cover a range of plant, animal, soil, climate and management interactions.

[3] GrassGro is a software tool developed by CSIRO Plant Industry to assist decision-making in grazing enterprises located in temperate southern Australia. GrassGro uses mathematical models to assess how weather, soils and management factors combine to affect productivity and profitability.

The results reveal two important points for consideration. Firstly there were large differences in yields *between* locations because of soil and climatic variability. Secondly there was considerable variability in yield response *within years* between untreated and treated crops and pasture at the same location because in some seasons the extra 'bucket size' was of little or no value. Examples of this variability is presented (figures 8 & 9).

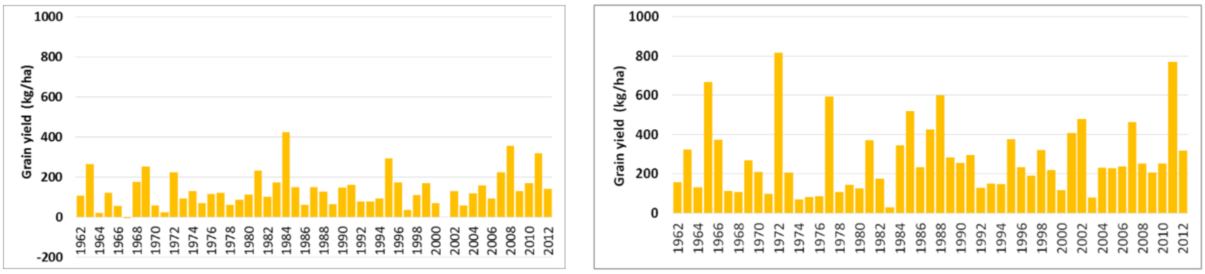

Figure 8: Difference in canola yields from subsoil amelioration at Lake Bolac (left) and Inverleigh (right).

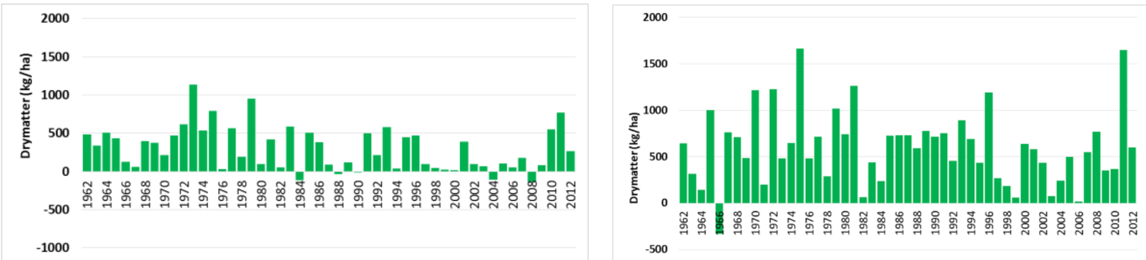

Figure 9: Difference in pasture production from subsoil amelioration at Inverleigh (left) and Mortlake (right).

The average yield response to subsoil amelioration for different crops and pasture are contained in the Nicholson et al. report (2015), with a summary in appendix 5. The results demonstrate most locations were more responsive in low production (decile 1) years and others in high production (decile 9) years. This resulted in high and low response locations. The high responsive locations represent approximately 950,000 ha or 44% of the potentially suitable land.

Supply and suitability of organic products

Supply constraints, handling logistics and product cost will impact on the likely adoption of subsoil manuring. Most of the initial trial work has been conducted with chicken manure, pelletised lucerne and Dynamic Lifter® applied at 20t/ha. Given the potential area of land suitable for treatment is 2.17 million hectares, 41 million tonnes of suitable product would be required if applied at 20 t/ha. If a 20 year time frame is considered to fully apply the technology, then more than 2 million tonnes of product would be required each year. Altering the time frame for amelioration and/or the amount of product applied changes the annual quantity required (table 2).

Table 2. Tonnes of organic product required each year to ameliorate all suitable crop and pasture areas in South West Victoria within a 10, 20 or 30 year time frame.

Product application rate (t/ha)	**Time frame for amelioration (yrs)**		
	10	**20**	**30**
10	2,070,000	1,034,000	690,000
15	3,104,000	1,552,000	1,034,000
20	4,139,000	2,070,000	1,380,000

There is insufficient poultry manure to meet potential demand. Current total Victorian supplies would only satisfy 12% of this requirement, assuming no other competing uses, and much of the product would have to be sourced from outside the region. If only the highly responsive locations are considered, the total amount available is 26%.

Alternative organic products are available that could be used, however some of these products have different composition to poultry manure[4] and have different costs. The availability of different products is summarised (table 3). Additional details on products and suitability are provided in appendix 6.

Table 3. Percentage of organic product currently available to undertake subsoil amelioration in South West Victoria within a 20 year time frame.

Organic amendment	**Quantity available (t DM/yr)**	**% of demand met by product (all areas)**	**% of demand met by product (high response areas only)**
Off-farm sources			
Poultry manure	250,000	12%	26%
Pig manure	170,000	8%	18%
Dewatered biosolids	95,000	5%	10%
Compost	380,000	8% - 16%	18% - 36%
Green waste	250,000	5% - 11%	12% - 24%
	1,145,000	**38% - 52%**	**84% - 114%**
On-farm sources			
Cereal crop stubble	1,800,000	89%	139%
Fresh pasture and fodder	8,450,000	409%	350%
	10,250,000	**498%**	**489%**

The results presented in table 3 suggests off farm sources will be insufficient to meet potential demand and that a combination of products and on farm sources will be required to provide the organic material for incorporation.

[4] Successful responses to subsoil amelioration with organic material has occurred by using high rates of organic amendments with a low C:N ratio (<25:1) and significant amounts of other nutrients critical for plant growth such as phosphorus, sulphur and potassium.

Economic analysis

Two types of analysis have been conducted. The first is a partial budget which examines the change in profit resulting from the investment in sub soil manuring (cumulative net cash flow, net present value and Internal Rate of Return). The second is a broader regional analysis of the changes in whole farm profit assuming subsoil manuring had been adopted across *all* the suitable area and a *permanent* change in soil condition had occurred.

Partial budget

Partial budget analysis has already been completed using poultry manure at two trial sites (Sale and Malcolm, 2015). The results were very favourable. However given the potential problem with accessing large quantities of poultry manure, further analysis was conducted to examine the feasibility of growing organic material in-situ and placing this at depth using machinery similar to the prototype developed by the University of Melbourne.

Details of the analysis are provided (appendix 7). The key points from the analysis were;

- Positive cash flow was achieved between two and four years depending on location.
- Cumulative net present value (NPV) @ 8% was between $549/ha and $2,485/ha nine years after subsoil manuring.
- An IRR from investment of between 28% and 104% depending on the location.

The analysis also highlighted the financial sensitivity around the yield response to subsoil manuring and the importance of trying to minimise the up-front cost of the practice.

Farm and regional analysis

Regional analysis was undertaken using nine farms representing a range of climatic conditions and farming systems in South West Victoria (Nicholson et al. 2014). It included mixes of cropping, cattle and sheep operations. Only soils thought to be potentially responsive to subsoil modification were included. The representative farms were then scaled up to provide a regional perspective.

The estimated average regional economic impact would be $317.2 million per year if subsoil manuring was adopted across all the potentially responsive soils. This comprises a direct farm impact (farm net profit increase) of $67.2 million per annum, along with a direct multiplier effect of $133.8 million per year and an additional $116.2 million through value adding (Nicholson et al. 2015). Overall employment would increase by 1,300 people, with 624 on farm jobs created and a further 677 full time jobs through post farm gate services.

Average increases in on farm production include an additional 38,400 tonnes of wheat, 10,200 tonnes of barley and 13,500 tonnes of canola. Changes in livestock numbers include an additional 43,900 cows, 817,000 prime lamb ewes and 415,000 merino ewes(Nicholson et al. 2015). These livestock changes do not include young animals.

An important insight from the modelling was the variability in response in 'poor', 'mid-range' and 'good' seasons. Subsoil modification had a proportionally greater benefit for all crops when yields were expected to be 'poor' (decile 1). In a 'middle' year the proportional benefits were less, especially with barley and canola, where yield increases were approximately half as much as 'poor' yielding years. In decile 9 yielding years, there was little benefit to canola production from subsoil modification, but a large benefit to barley. The benefits to wheat production were consistent across different yield conditions.

The overall increase in average annual net farm profit due to subsoil modification was 7.6%, however like the production variability, the economic response was of greater significance in extreme years. In the worst 10% of years, where total regional net farm profit was $314 million less than decile 5 profitability, the benefits accrued from subsoil modification were $62.3 million, only $5.0 million less than the net profit increase in an 'average' year. This equates to an 11.0% increase in net profit in much lower income years. In the best 10% of net profit years, the annual benefits from subsoil amelioration were $84.3M or 7.0% of total net profit.

The $62 million net farm profit in 'poor' years is arguably more valuable than the $67 million in an average year (even though every dollar is theoretically the same), because additional income in lower profit years can reduce the shortfall that may be experienced in meeting financing requirements and tax, thereby avoiding additional financing costs. Given the challenge of increasing climate variability in the future, subsoil modification may provide a useful foil in low profitability years.

The implications of both the production and profit results in extreme years has an impact on risk in the farming business. Downside risk in farming resides in the poor years, when yields and/or prices are well below average. The effect of subsoil modification in these poor years is to lift production and as a consequence net farm profit. In effect it reduces downside risk in the business. In the good year subsoil modification increases the chances of higher production and profit. It enables the business to make more when conditions are favourable. Both situations are positive for the farm business.

The difference in net farm profit was not the same at each of the nine locations modelled. In some locations, such as Balliang and Birregurra, the increase in net farm profit by subsoil manuring was large across 'poor', 'average' and 'good' years (as a % of total net farm profit). In contrast the response at Casterton were small, irrespective of the type of year. In other areas such as Derrinallum, the net farm profit increase were greatest in 'poor' years, whereas at Inverleigh the greatest benefits are in 'good' years. These impacts are summarised (table 4).

Table 4: Increase in farm profit from subsoil manuring in poor, average and good years (% change to total farm profit in brackets)

Location	'Poor' years	'Average' years	'Good' years
Balliang (east)	$ 47,000 (40%)	$ 57,000 (21%)	$ 69,000 (16%)
Birregurra	$ 48,000 (60%)	$ 46,000 (18%)	$ 43,000 (10%)
Casterton	$ 15,000 (6%)	$ 17,000 (4%)	$ 19,000 (4%)
Derrinallum	$ 20,000 (5%)	$ 16,000 (3%)	$ 14,000 (2%)

Inverleigh	$ 31,000 (8%)	$ 33,000 (6%)	$ 92,000 (13%)
Lake Bolac	$ 46,000 (12%)	$ 49,000 (8%)	$ 54,000 (7%)
Mortlake	$ 36,000 (8%)	$ 42,000 (7%)	$ 51,000 (6%)
Penshurst	$ 38,000 (8%)	$ 44,000 (7%)	$ 50,000 (6%)
Winchelsea	$ 30,000 (16%)	$ 32,000 (8%)	$ 35,000 (6%)

The variability in response needs to be investigated further, although climate, soil type and in the case of livestock differing pasture utilisation rates are the most likely explanations. However it does lead to the conclusion that identifying and targeting potentially high responsive areas first would give a greater return if only partial investment in subsoil modification was to be made.

Conclusion and recommendations

Subsoil manuring has the potential to greatly increase the productivity and profitability of mixed farms in the high rainfall zone of South West Victoria. There is sufficient evidence to indicate the placement of nutrient rich organic material into the hostile layers of subsoil will increase crop and pasture production, at least in the short term. Examination of the soil several years after treatment would suggest it will also have a long term impact on soil condition. Therefore we are convinced the proof of concept is strong in high rainfall environments.

Commercialisation of the concept remains the major barrier. The three greatest limitations to commercialisation are:

4. *Farmers having access to machinery that is cost effective and capable of treating large areas*. While valuable progress has recently been made in this area, there is still significant work to commercialise suitable machinery for on farm use.
5. *Access to suitable substrate at low cost*. Most trial work has been conducted with substrates that will be insufficient to meet expected demand and are likely to rise in price. Alternative products need to be found. Fodders grown and harvested in-situ show promise but require considerable research to determine the best products to use (quantity and quality). Further the product and incorporation costs must be reduced, as the economic analysis clearly shows the profitability of the practice depends on minimising this up-front cost.
6. *Identifying which locations will provide best return from investment in subsoil manuring.* While modelling and trial results indicate a wide range of responses, rainfall and soil type appear to have a big influence on the yield response to subsoil manuring and hence profitability of the practice.

Appendix 1: Further explanation on subsoil constraints in the high rainfall zone

Crop yields in the high rainfall zone (HRZ) of southern Australia (annual rainfall > 500mm) are often limited by subsoil constraints that occur on the duplex soils common to the region (Zhang et al. 2006). Duplex soils consist of a light surface soil overlying dense clay subsoil (Isbell 2002). These strong texture-contrast soils give rise to subsoil constraints including waterlogging, nutrient deficiencies, acidity and sodicity (Rengasamy 2002; Zhang et al. 2006) and are acknowledged to limit crop yields by restricting water movement and root growth (Belford et al. 1992; Rengasamy 2000).

Future yield improvements will require increasing root growth into the subsoil (Gardner et al.1992; Zhang et al. 2006) but conventional wisdom would hold that these hostile soils are too difficult to overcome or too costly to ameliorate (Sale 2010). Indeed, a quarter of a century of research has failed to find a suitable method of modifying these soils (Greenwood et al. 2006). Practices involving deep ripping, gypsum, underground drainage and primer crops, among others, have been used in attempts to ameliorate subsoil constraints with temporary and variable success (Adcock et al. 2007).

Subsoil constraints in duplex soils

Duplex soils, with a distinct texture contrast between the A and B horizons, are the dominant soil type across the HRZ of southern Australia (Zhang et al. 2006). These soils commonly have a number of subsoil constraints that limit crop yields, the key limitation being poor macroporosity and aeration that restricts normal root growth (Gill et al. 2009). Soils in the region are typically sodic and experience waterlogging; in drier areas the clay subsoils are sometimes saline but this is not generally the case in the HRZ (Rengasamy 2002; Sale 2010). The amelioration of subsoil constraints is intended to relieve these limitations by allowing crop roots access to water and nutrients at depth in the profile (Wong and Asseng 2007).

Physical and chemical constraints

High soil physical strength inhibits root growth into clay subsoils and restricts access to water and nutrients by reducing the soil volume accessible to the plant (Zhang et al. 2006). Dense B horizons are typically characterised by high bulk density and penetrometer resistance, low porosity and limited hydraulic conductivity (Zhang et al. 2006; Adcock et al. 2007). For example soil at a subsoil manuring trials sites in Ballan, Victoria had a bulk density in excess of 1.6 g/cm3 and percentage clay greater than 50% (Gill et al. 2008). Measures such as these indicate that soil strength and bulk density in duplex soils invariably exceeds the penetrative capacity of plant roots (Bengough et al. 1997).

Because roots are unable to penetrate deeper soil layers and extract water stored at depth in the profile, the subsoil remains wet (Gill et al. 2008). This inability to access stored soil water because of high mechanical impedance (Bengough et al. 1997) limits crop yields due to insufficient plant available water (small 'bucket size') in the profile (Gill et al. 2008).

Root growth can be affected both directly and indirectly by high soil strength: directly, by reducing access to extractable water and nutrients, and indirectly, by the effects of low porosity and waterlogging on roots (Adcock et al. 2007). In simple terms, the dense clay is either too hard when dry or too low in oxygen when wet to support root growth (Sale 2010).

Waterlogging

Rainfall in South West Victoria is commonly greater than 500 mm a year. Most falls over winter. When combined with shallow topsoils overlying impermeable clay, it results in restricted water movement and regular periods of waterlogging (Gardner et al. 1992; Zhang et al. 2006). These perched water tables on top of the B horizon are temporary but severe (Zhang et al. 2006) and occur when rainfall exceeds evapotranspiration and deep drainage through the subsoil (Gardner et al. 1992).

Consequences of waterlogging are limited aeration, nitrogen deficiency via denitrification (Gardner et al. 1992) and yield losses of up to 55% in wheat (Zhang et al. 2006) due to reduced crop growth and development (Jayawardane and Chan 1994).

Sodicity

The clay subsoils of duplex soils are often sodic with excessive concentrations of exchangeable sodium (Zhang et al. 2006). For example, exchangeable sodium percentage (ESP) in the subsoil below 40 cm at the Ballan trial site was greater than 20%, indicating significant subsoil sodicity (Gill et al. 2008). Sodicity causes a direct physical constraint to root growth by impeding root penetration (Adcock et al. 2007). The dispersive clay that characterises sodic soils results in severe structural degradation that inhibits water, nutrient and root movement (Zhang et al. 2006). Sodicity can also result in indirect effects on plant roots such as anaerobic conditions (Adcock et al. 2007).

Appendix 2: Review of subsoil amelioration techniques

Gypsum and deep ripping

Conventional amelioration of constraints to cropping in the HRZ has relied upon a combination of gypsum and deep ripping, with mixed results (Clark et al. 2009). Indeed, deep ripping accompanied by the application of gypsum and complete nutrients was found to increase grain yields and improve soil physical properties related to growth on a duplex sandy clay loam (Hamza and Anderson 2002). The amendments increased water infiltration, aggregation and cation exchange capacity and decreased soil strength and bulk density (Hamza and Anderson 2002). Similar positive effects on soil properties and/or crop yields from soil amendment using deep ripping and gypsum have been observed in other studies (Blackwell et al. 1991; Greenwood et al. 2006), yet in a recent trial Clark (2004, cited in Clark et al. 2009) found that gypsum and deep ripping failed to improve grain yields on a sodic dense clay subsoil. Other studies have also had limited success with the technique (Ellington 1986; Gardner and McDonald 1988). Although deep ripping and gypsum can improve structure and crop production on duplex soils, the effect is variable and not sustained in the long term (Eck and Unger 1985; Ellington 1986; Adcock et al. 2007; GRDC 2009). Subsequent management is required to preserve the beneficial effects and minimise compaction (Adcock et al. 2007).

Other traditional management strategies, including subsoil fertiliser, profile mixing, subsurface drainage and primer crops, have also had varying success (Mehanni 1974; Jayawardane and Chan 1994; Adcock et al. 2007). Primer crops such as lucerne (Medicago sativa) that achieve biological amelioration via the creation of biopores in the soil have shown promise as a strategy for improving growth of subsequent crops (Yunusa and Newton 2003); however this technique requires further testing in the field.

Organic material

A significant body of literature has proven the effectiveness of using organic amendments such as mulch, compost and manure to improve surface soil biological, chemical and physical properties (Baldock et al. 1994; Albiach et al. 2001; Bulluck et al. 2002; Ferreras et al. 2006; Ghosh et al. 2011) and to amend sodic surface soils (Hulugalle and Weaver 2005; Armstrong et al. 2007).

The incorporation of organic amendments into the subsoil is less well studied (Tarkalson et al. 1998; Olsson et al. 2002; Greenwood et al. 2006). Over two decades ago, Ellington (1986) proposed a technique for incorporating gypsum, lime and organic matter into the subsoil using a ripper in order to overcome the structural problems that constrain duplex soils. This method was adopted and trialled by Graham (1992, cited by Gill et al. 2008) who observed significant increases in plant growth as a result of deep placement of fertiliser and green manure.

Tarkalson et al. (1998) found that yields of beans and wheat were raised to similar levels as yields achieved on topsoil after application of manure. In a more recent study Olsson et al. (2002) modified subsoil by loosening and fragmentation and applied fertilisers and organic matter. As a result soil physical condition improved markedly but pasture yields were only sustained for the first year (Olsson et al. 2002). Greenwood et al. (2006) found that subsoil modification reduced soil strength and bulk density, improved aggregation and increased hydraulic conductivity, with results persisting for at least two years. Despite promising results from studies such as these, little progress has been made on the organic amendment of subsoils constraints until recently.

More recently, researchers at La Trobe University and the Victorian DPI have further developed this technique and have established a method of deep incorporation of organic materials into the subsoil, termed subsoil manuring (Sale 2010). Subsoil manuring field trials were established in 2005 at Yaloak Estate near Ballan in the southern Australian HRZ (Gill et al. 2008; Gill et al. 2009) and these were followed by a series of on-farm experiments on several sites across the Victorian HRZ since 2009 (Gill and Sale 2015, Peries 2014). In addition to field trials, laboratory experiments have also been conducted using soil collected from the trial sites (Clark et al. 2007; Clark et al. 2009). In the field the organic amendment is incorporated 30-40 cm deep in a rip line at the top of the clay subsoil using a prototype machine that utilises a pipe attached to a deep ripper (Gill et al. 2008). Two rip lines are placed 80-100 cm apart on a 1.7 m raised bed (Gill et al. 2008). Subsoil manuring on the dense, sodic clay subsoils that typify these sites has been tested using a range of organic amendments with significant success.

Poultry litter, pelletised lucerne and Dynamic Lifter at high rates (up to 20 t/ha fresh weight or 16 t/ha dry weight) have shown the most success in subsoil manuring trials. These products all have a very low C:N ratio (<15:1) and are highly fertile, containing 1-7% nitrogen, 1-5% phosphorous and 1-2% potassium (on a dry weight basis) (Clark et al 2007; Gill et al 2008). Depending on the amendment used they may also contain a whole suite of other macro and micronutrients necessary for plant growth and soil health: sulphur, calcium, magnesium, molybdenum, copper, boron, manganese, iron, chlorine and zinc.

Results from both field trials and laboratory experiments have shown that subsoil manuring is remarkably effective at overcoming subsoil constraints (Sale 2010). Organic amendments were found to promote biological activity, improve soil structure and chemical fertility, increase root growth and increase grain yield and quality and pasture and fodder production (Clark et al. 2007; Gill et al. 2008; Clark et al. 2009; Gill et al. 2009). Notably, subsoil manuring has also been able to increase bucket size – a colloquial term for plant rooting volume – thereby increasing water capture, storage and plant availability and increasing the volume of soil accessible to plant roots for nutrient uptake and proliferation (Peries 2014). The effects of subsoil manuring have been observed to last at least six years after the initial operation, suggesting at least a semi-permanent change to soil structure and function (Peries 2014) if not a permanent change.

Appendix 3: Results from experimental trials in South West Victoria

Significant increases in crop productivity have been observed following subsoil manuring (Gill et al. 2008). Results would indicate both a significant soil conditioner and fertiliser effect; improving soil physical, chemical and biological properties (Clark et al. 2007, Clark et al. 2009). There was found to be a significant correlation ($r>0.69$) between crop yield and deep root growth and changes in soil physical and chemical properties (Gill et al. 2009).

At Ballan and Penshurst subsoil manuring field trials doubled wheat biomass production and significantly increased grain yields to 11-13 t/ha; levels never before achieved for wheat crops in Australia (Gill et al. 2008). On average amended cereal plots produced more 55-60% more grain and often had higher grain protein concentrations (Gill et al. 2008). Similar results were found in canola trials (Gill et al. 2010) with increases of up to 115% compared to the control. Altogether, studies on a wider range of hostile subsoils across south-west Victoria have shown yield increases in the first few years after subsoil manuring of around 60% and improvements in soil water capture, storage and plant water uptake (Gill and Sale 2015; Sale 2010 (table A3.1).

These increases in crop productivity have occurred due to increased nutrient supply to the wheat plants from the ongoing mineralisation of organic matter, greater plant available water capacity in the profile due to improved structure and prolonged leaf greenness caused by reduced plant stress later in the growing season (Gill et al. 2008; Gill et al. 2010). The transformation of the soil physical properties by subsoil modification increased deep root growth and allowed enhanced uptake of water and nutrients (Gill et al. 2009). These changes permit continued extraction of subsoil water, ongoing mineralisation and uptake of nutrients and extended plant growth later in the growing season (Sale 2010).

Significantly, subsoil manuring has been able to overcome barriers to root growth in the subsoil and increase bucket size (Sale 2010). The amended soils were able to capture and store more water in the soil profile and, as a result of enhanced root proliferation in deep soil layers, the extraction of subsoil water by crops in the 40-80 cm layer was increased by as much as 60 mm in some years (Gill et al. 2008; Gill et al. 2009). These advancements in water extraction and transpiration efficiency occurred late in crop development when transpiration efficiency is maximised (Kirkegaard et al. 2007; Passioura and Angus 2010; Peries and Gill 2010).

In some years due to waterlogging, poor weed control or adequate growing season rainfall, less impressive results were observed (Gill and Sale 2015). Greenwood et al. (2006) consider that the response to soil modification may be less than satisfactory when subsoil constraints are compensated for by other factors. In this case, the response to subsoil manuring was reduced or nullified by significant growing season rainfall. Similarly, studies by Eck (1977) and Kelly (1985) found no crop response to soil amendment when frequent irrigation was used. In addition, subsoil manuring is able to alleviate waterlogging in the short term due to the increased bucket size but if rainfall is substantial and sufficient to fill the profile, waterlogging will still occur in the next horizon down (Clark et al 2007).

For a summary of a range of trial results refer to Table A3.1.

Table A3.1. Summary of results of a selection of small-plot subsoil manuring trials conducted across south western Victoria. Subsoil manured plots received 20 t/ha fresh weight (16 t/ha dry weight) poultry litter or equivalent. (Gill and Sale 2015, Gill et al 2008, Gill et al 2009, Nicholson 2012, Peries 2014, Sale at al 2012)

Trial site and soil type	Year	Crop	Seasonal conditions	Commercial crop yield (t/ha)	Subsoil manured yield (t/ha)	Increase in yield (t/ha)	Percentage increase (%)	Comments
Ballan	2005	Wheat	Average	7.6	12.5	5.3	70%	
	2006	Wheat	Drought. 55% of average rainfall	3.6	5.6	2.0	55%	
	2007	Canola	Wet autumn, dry spring	1.6	2.5	0.9	56%	
Winchelsea	2009	Barley	Heat wave Nov	4.4	7.7	3.5	77%	
Derrinallum	2009	Wheat	Heat wave Nov	5.0	9.8	4.8	96%	
	2010	Canola	Waterlogging, GSR 913mm	0.5	0.8	0.3	60%	Plant losses at establishment due to waterlogging
	2011	Wheat	Average	5.0	7.4	2.4	48%	
	2012	Wheat	Dry finish	6.3	10.4	4.1	65%	
Penshurst	2009	Wheat	Heat wave Nov	4.8	6.8	2.0	42%	
	2010	Canola	Waterlogging, GSR 840mm	0.8	2.0	1.2	67%	Plant losses at establishment due to waterlogging
	2011	Wheat	Average	6.8	11.3	4.5	66%	
	2012	Canola	Average	2.3	2.9	0.6	26%	
Wickliffe	2010	Wheat	Waterlogging, GSR 836mm	9.1	11.6	2.5	27%	
	2011	Wheat	Average	5.3	4.9	-0.4	-8%	Poor establishment and weedy
	2012	Faba Bean	Dry finish	3.6	6.3	2.7	75%	
Stewarton	2011	Wheat	Above average	5.7	8.1	2.4	42%	
	2012	Wheat	Dry finish	4.9	9.4	4.5	92%	
Birregurra	2011	Wheat	Average	4.1	5.7	1.6	39%	
	2012	Ryegrass	Average	5.3	6.5	1.4	23%	Ryegrass silage in 2012

Appendix 4: Review of the effects of subsoil amelioration with organic matter

The physical, chemical and biological basis for the plant response to subsoil manuring
The ability of subsoil manuring to improve soil properties and hence crop growth is dependent upon complex processes that underlie its success. Addition of nutrient-rich organic matter to soil alters the biological, physical and chemical properties of that soil (Quilty and Cattle 2011). Changes to soil properties are mediated by soil microbes, fungi and plant roots that act in concert to bring about changes in the bulk soil (Bronick and Lal 2005). Improvements in soil properties result from biological activity stemming from mineralisation of organic amendments and exudates from deep penetrating roots (Gill et al. 2009). Plant yield responses occur in turn due to both the soil conditioner and fertiliser effect of subsoil manuring.

Changes in soil properties following incorporation of organic matter
Subsoil manuring results in significant changes to soil physical properties in the 20-40 cm layer of sodic soil following deep incorporation of organic amendments (Gill et al. 2009). The key change was an increase in pore space resulting from improved soil aggregation (Gill et al. 2009). In addition to improvements in macroporosity from 10% to >18%, subsoil manuring also reduced bulk density and volumetric water content and increased 50-fold the hydraulic conductivity on the soil (Gill et al. 2009).The changes in turn contributed to the subsequent increases in plant available water capacity or bucket size (Peries 2014). The ability of nutrient-rich organic amendments to improve aggregation results from their ability to stimulate the activity of microbes, fungi and plant roots in the soil (Clark et al. 2009).

Aggregate formation was observed to take place in two phases (Gill et al. 2009), illustrating the dynamic nature of soil aggregation (Bronick and Lal 2005). In the first phase, organic residues stimulated intensive microbial activity, leading to the production of extracellular polysaccharides (Clark et al. 2009). These extracellular polysaccharides lead to rapid but transient aggregate stabilisation (Chaney and Swift 1986; Chenu 1993; Amellal et al. 1999; Alami et al. 2000; Watts et al. 2001). In the second phase, microbial activity was reduced and the formation of aggregates was mediated by fungal activity (Clark et al. 2009). Although slower to commence (Clark et al. 2009), fungal activity formed somewhat more resistant and stable aggregates by binding soil particles with hyphae (Tisdall and Oades 1982; Dorioz et al 1993; Tisdall 1997).

These improvements in soil aggregation and porosity were found to have a positive feedback effect on plant roots, whereby increased root growth and activity in the subsoil – namely the production of root mucilages and exudates in the rhizosphere (Redi and Goss 1981; Czarnes et al. 2000' Milleret et al. 2009) – further stimulated microbial activity and extracelluar polysaccharide production (Gill et al. 2009). These mucilages and polysaccharides are the cementing agents that stabilise aggregates and enhance soil structure (Gill et al. 2009). These results are in agreement with the model of biologically-mediated aggregation in soils via these processes (Tisdall and Oades 1982; Dorioz et al. 1993; Six et al. 2004; Huang et al. 2005).

Up to 30% of the organic carbon that enters the soil as part of the subsoil manuring process will be sequestered as long-term carbon forms such as humus and glomalin (GRDC 2013; Dairy Australia 2010). It is highly likely that deep incorporation of organic amendments may provide a more stable environment for soil C sequestration due to the sustained aerobic conditions (Clark et al 2007).

Subsoil manuring has both a soil conditioner and fertiliser effect
Subsoil manuring has both a soil conditioner and fertiliser effect; that is, it is capable of improving soil properties and also increasing soil fertility, both mechanisms which can act to increase plant yields. Although the semi-permanent changes in soil physical and biological properties are heavily document, the more transient effect of nutrition is significant and not be to be discounted.

Organic amendments such as animal manures and plant biomass essentially act as slow release fertilisers as not all the nutrients contained in the matter are immediately available for plant growth (FSA Consulting 2007). The conversion of organic nutrients such as N to inorganic forms suitable for plant uptake is a biological process mediated by soil moisture and temperature (GRDC 2010) associated with the mineralisation or decomposition of organic matter (GRDC 2013). This allows one application to provide nutrients for several seasons. Importantly, organic matter is more than just N, P and K – depending on the product, it also contains high rates of other macro and micronutrients such as calcium which is critical for alleviating sodicity and improving structural integrity of sodic soils (FSA Consulting 2007; RIRDC 2013).

The availability of nutrients in the first few years after application can vary greatly depending on the nutrient and the rate of mineralisation of organic matter but generally speaking, the effect of increased fertility on plant yields will be greatest for the first few years after subsoil manuring, with diminishing returns as time goes on (Griffiths 2004; GRDC 2010). This is distinct to the changes in soil physical properties that are observed under subsoil manuring, which are slower to occur but are understood to be semi-permanent or permanent (Peries 2014) (Figure A4.1).

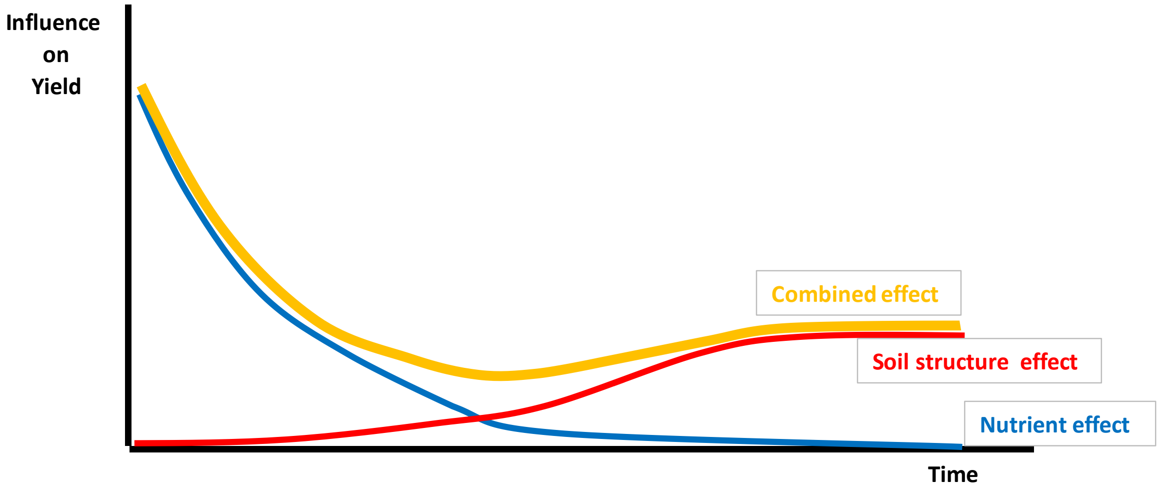

Figure A4.1: Visual representation of the permanent soil conditioner effect and temporary soil fertility effect from poultry manure

Effect of residue quality on decomposition and aggregation
The dynamics of aggregate formation and mineralisation are linked with the type and quality of organic residue incorporated into the subsoil (Clark et al. 2009). Formation of macroaggregates was found to be fastest with green plant material, whereas stubbles and chicken manure were slower to achieve similar levels of aggregation (Clark et al. 2009). This is due to differences in the provision of suitable substrates for bacterial and fungal activity (Clark et al. 2009).

In the earlier stage of aggregate formation, conditions are more favourable for microbial activity due to the low C/N ratio of the green plant residues (Clark et al. 2009). In comparison, higher C/N ratios in the later phase of aggregation favour fungal activity for decomposing more resistant organic material (Clark et al.2009). Increasing maturity of the organic amendment was associated with lower initial stimulation of microbial activity due to a decline in labile organic C and readily degradable organic material (Clark et al. 2007). Similar effects related to residue quality have been found in other trials (Puget et al. 2000; Eiland et al. 2001; Hulugalle and Weaver 2005; Rousk and Baath 2007). These results favour the incorporation of green crop residues (or amendments with high labile C and N) as they are able to rapidly form stable aggregates and provide favourable nutrients to the crop (Clark et al. 2007; Clark et al. 2009).

Appendix 5: Summary of APSIM and GrassGro modelled pasture and crop yield responses to sub soil modification by location

Location	Pasture response	Crop response
Balliang (east)	Highly variable, with average yield increase less than 200 kg/ha. Many unresponsive year, some large negative years, and a few high responses (~1500 kg/ha or 20%) corresponding to well above average rainfall in spring and early summer.	Consistent increase in canola yields (~9%) and wheat (~15%) across above and below average rainfall, although wheat response was more variable. Barley yields were more erratic, with negative responses recorded on a third of all years and an average yield increase of only 165 kg/ha (5.9%). Most negative barley results occurred with below average rainfall.
Birregurra	Very responsive. Average yield increase of 10.9%, with some years 20% to 30% greater. High responses consistently recorded even in years of 100mm below average annual rainfall	Not applicable
Casterton	Modest but consistent yield response (~400kg/ha), with only a few years with large responses (~1000 kg/ha).	Small yield increases for all crop types. Canola yields were small but consistent, wheat and barley more variable, including a number of negative response years.
Derrinallum	Little or no response in most years. Only in 14% of years was the response above 500 kg/ha.	Variable yield response across all crop types (including negative results), with a small yield increase from canola, only 3.3% increase for wheat and no increase with barley. Larger yield increases for wheat and canola in below average rainfall years.
Inverleigh	Positive but small response in about half of years (~500 kg/ha), but for other years little or no yield difference. Most positive responses in average to above average rainfall years.	Yield response in canola and wheat was small but consistent (+8.4%), wheat (6.4%), with positive responses more pronounced in low yielding years. Barley yields were highly variable, with more negative yielding years than positive yielding years.
Lake Bolac	Variable but generally positive response (ave ~400 kg/ha). Few years of negative or no response. Most positive responses (>500 kg/ha) in average to above average rainfall years.	Yield response in canola was small but consistent (3.7%), wheat and barley responses were more variable but usually positive (3.9% and 9.7% respectively).
Mortlake	Responses in most years, with increases around 600 kg/ha on average. The variability was lower compared to other sites. Responses across different amounts of annual rainfall	Yield response in canola was small and variable (+5.2%), both wheat and barley yields were inconsistent, with minimal average yield increase and about one third of all results giving a negative yield response.
Penshurst	Responsive site in most years. Average yield increase was ~600 kg/ha (5.7%), with one quarter of all years above 10000 kg/ha. Large responses occurred across a range of rainfalls.	Yield response for all crops was small and variable (canola 4.9%, wheat 1.9% and barley 2.4%). The average yield increases were only less than 150 kg/ha for both cereals.

Winchelsea	Highly variable, with approximately half the years recording minor or negative yield responses. Average response was ~200kg/ha, but this was the results of some extreme high and negative yielding years.	There was minimal yield response in canola. Wheat yields were marginally more responsive but also more variable and barley yields were even more erratic.

Appendix 6: Summary of on and off-farm organic products potentially available for subsoil amelioration.

NB: All amounts and quantities stated are on a dry weight basis.

Organic amendment	Source	Volume available	Cost	Composition and quality	Comments on suitability and effectiveness	References
Poultry litter	Broiler and layer operations located around Nagambie, Bendigo, Geelong, West Gippsland and the Mornington Peninsula.	250,000 t/yr. Available year-round.	$16-30/m^3 or $40-70/t delivered and spread depending on source.	Composition similar to other animal manures and depends on production system and manure management practice. C:N 5-15:1, moisture 15-30%, density 2.5m^3/t. Highly fertile. Typically: 1-7% N, 1-5% P, 1-2% K plus a wide range of macro and micronutrients.	Generally lower moisture content and higher density than pig litter but may require drying or composting. Risk of heavy metal (Cu, Zn) accumulation or salinity at high application levels. May contain pathogenic microorganisms or weed seeds. Odorous.	GRDC (2010), RIRDC (n.d.), RIRDC (2013), RIRDC (2014)
Piggery litter	Piggeries concentrated in the Loddon, Goulburn, Wimmera, Mallee and South West.	170,000 t/yr. Available year-round.	$40-70/t delivered and spread depending on source.	Composition similar to other animal manures and depends on production system and manure management practice. C:N 10-20:1, moisture 30-60%. Highly fertile. Typically: 1-7% N, 1-5% P, 1-2% K plus a wide range of macro and micronutrients.	Can be high moisture/low density and requires either drying or composting. Risk of heavy metal (Cu, Zn) accumulation at high application levels. May contain pathogenic microorganisms or weed seeds. Odorous.	APL (2012), APL (2013), Craddock & Wallis (2013), FSA Consulting (2007), GRDC (2010).
De-watered biosolids	Waste water treatment plants in Camperdown, Hamilton, Geelong and Werribee.	95,000 t/yr. Available year-round.	$65-500/t delivered and spread, depending on grade and source.	C:N , moisture 80% before dewatering and 5% dried. Highly fertile. Typically: 5-7% N, 1-4% P, 1-0.5% K plus a wide range of macro and micronutrients.	Market risk. Requires extensive processing. Treatment and use is governed by strict regulations and QA systems. May contain pathogenic microorganisms, contaminants and heavy metals (Zn, Cu, Cd, Pb, Hg).	EPA Victoria (2004), GRDC (2010), McLaughlin & Filmer (2008),

					Dewatered to minimise volumes, higher bulk density so easier and cheaper to transport and spread.	SEWPAC (2012)
Compost	Private companies across the state including Camperdown	340,000 t/yr.[5] Available year-round.	$15-60/m³ delivered depending on source. $42/t made on site.	C:N 10-40:1, moisture content 25-40%. May contain wide range of macro and micronutrients. Highly variable composition depending on source and processing but generally significantly lower nutrient availability and slower release than other organic amendments: 0.5-2% N, 0.1-1.5% P, 0.1-1% K.	Treatment and use is governed by strict regulations. Improved consistency and uniformity of product aids in spreading. Can reduce weed seed densities and eliminate some pathogens. May contain pathogenic microorganisms, contaminants and heavy metals.	Compost Victoria (2010), Compost Victoria (2014), FSA Consulting (2007), ROU (2012)
Green waste	Downstream processors in Melbourne, Dandong, Traralgon, Bacchus Marsh, Camperdown and Shepparton.	380,000 t/yr (fresh) or 225,000 t/yr[6] (composted). Available year-round	$17-20/m³ or $40-50/t depending on source.	As per compost: composted product of highly variable quality. C:N 10-40:1. Moderate fertility but nutrient levels vary: 1-3% N, 0.1-1.5% P, 0.8-1.0% K. Contains wide range of macro and micronutrients.	Should not be used uncomposted; therefore, same caveats apply as for compost. May contain pathogenic microorganisms, contaminants, heavy metals, weed seeds and decomposables.	Biala & Wynen (1998), RDV (2012), SESL (n.d.), Sustainability Victoria (2013).
Cereal crop stubble	Primary producers across the south west region	1,850,000 t/yr. Available year round either	$95[7]/t on farm.	C:N 120:1, moisture <10%. Carbon rich and nutrient poor: 0.5% N, 0.05% P, 1.3% K.	Very low moisture and bulk density. May contain weed seeds.	GRDC (2013), Midwood et al (2011),

[5] Based on 850,000m^3/yr at 2.5m^3/t

[6] Based on: 62,000 t/yr (south west) and 320,000 t/yr (metropolitan = 382,000 t then composted so the totoal volume is 20-60% lower: 150,000-300,000 t/yr
Average 225,000

[7] 80% of sale price for cereal straw

		after harvest (summer) or baled and stockpiled.				Vadakattu et al (2011).
Pastures and fodders	Primary producers across the south west region	8,500,000 t/yr. Available primarily in spring depending on species.	$350/ha to grow a pasture or fodder.	C:N 15:1, moisture 45-90%. Moderate fertility, nutrient levels vary depending on species and growth stage. 2-5% N, 0.15% P, 2% K plus a wide range of macro and micronutrients.	Moisture and bulk density varies depending on growth stage and management/timing of cutting. May contain weed seeds.	GRDC (2013), Vadakattu et al (2011).

Appendix 7: Partial budget analysis of using in-situ fodder for subsoil manuring

Technical details

Eight locations were examined to provide a geographic spread of locations. It was assumed a cropping phase would immediately follow subsoil manuring, to reflect the potential higher returns that could be realised compared to grazing. The winter crop rotation was typical of the region, namely canola followed by wheat then barley. This three year cycle was repeated three times, resulting in a nine year cropping phase.

Crop yields

APSIM was used to generate crop yields over a nine year period. The years 2002 to 2010 were selected as this represented a drought and favourable years (table A7.1). The APSIM parameters used at each location are described in Nicholson et al. 2015.

Table A7.1: Modelled crop yields without subsoil manuring at eight locations (2002 – 2010)

Location	2002 (canola)	2003 (wheat)	2004 (barley)	2005 (canola)	2006 (wheat)	2007 (barley)	2008 (canola)	2009 (wheat)	2010 (barley)
Inverleigh	2.9	5.0	4.2	3.9	1.2	4.4	1.4	4.0	6.6
Lake Bolac	2.5	4.8	3.9	3.6	1.1	1.4	2.1	4.1	3.0
Penshurst	4.5	7.4	4.3	4.5	4.7	5.7	4.1	5.3	5.8
Winchelsea	4.2	4.1	4.3	4.4	1.2	3.7	1.9	2.8	4.2
Mortlake	4.0	6.7	6.5	4.7	1.8	5.0	2.0	5.3	5.8
Derrinallum	3.8	5.6	3.0	4.5	1.5	4.7	1.9	4.9	2.1
Casterton	4.3	7.1	5.9	4.5	2.2	4.0	3.4	5.5	4.8
Balliang (east)	1.0	3.9	3.1	1.8	1.4	1.9	0.5	3.2	4.1

Organic amendment

The organic material used was in-situ fodder grown for the express purpose of subsoil manuring and was sown and grown in place of a grain crop (wheat). An opportunity cost was calculated for the foregone grain crop using APSIM yields for the 2001 season.

The selection of fodder species aimed to maximise dry matter production and ensure a C:N ratio of approximately 15:1. In this example a peas and oats mixture was sown. 10 t/ha of dry matter was assumed available for incorporation from the in-situ fodder. No grazing was included in the year the in-situ fodder was grown.

Response to subsoil manuring

There is no local data to determine the yield response to fodder material buried at depth. To overcome this, three generic yield response curves were created to represent the effect of subsoil manuring on grain yield. The response curves endeavoured to mimic the initial short term yield increase due to improved fertility and the longer term permanent effect on soil structure i.e. increase in water holding capacity or 'bucket size' (figure A7.1). Results from only the high response curve has been presented, with the moderate and low response discussed in the sensitivity analysis.

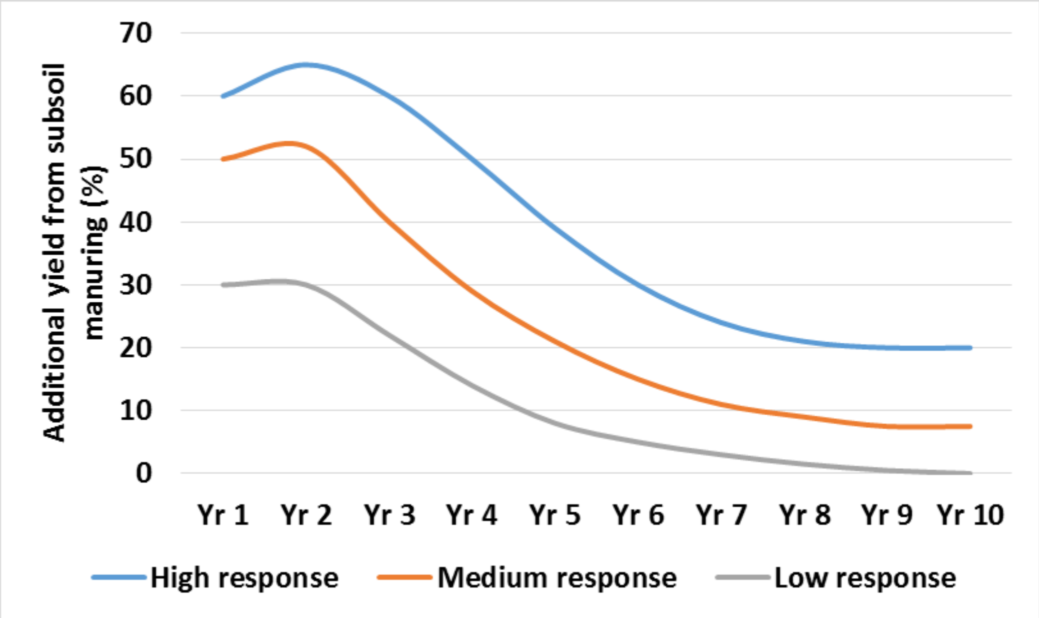

Figure A7.1: Additional yield for high, medium and low response from subsoil manuring

There was no reduction in fertiliser use with subsoil manuring, as the nutrient from the organic material was assumed to be consumed in increased crop yields.

Prices

Grain prices were the average for January each year at Geelong Port immediately after harvest i.e. Jan 2002 prices for 2001 grown crop (table A7.2). (www.agprice.grainandgraze3.com.au). It was assumed the additional nitrogen from the organic material would result in feed quality barley. Otherwise there was no adjustment in price for changes in grain quality.

Table A7.: Average crop prices (Jan 1 to Jan 31) at Geelong port (2002 – 2011)

Crop year	Crop	Price ($/t)
2001	Wheat (APW)	$ 170
2002	Canola	$ 400
2003	Wheat (APW)	$ 179
2004	Barley (feed)	$ 158
2005	Canola	$ 312
2006	Wheat (APW)	$ 283
2007	Barley (feed)	$ 343
2008	Canola	$ 567
2009	Wheat (APW)	$ 212
2010	Barley (feed)	$ 207

Amendment costs were based on growing a peas and oat fodder. Minimal herbicides were used and fertiliser applied to maximise dry matter production. 2015 prices were initially used to determine variable costs but then discounted (deflated) based on CPI to reflect likely costs in 2001 (table A7.3). It was assumed fodder costs were the same at each location.

Table A7.3: Variable cost for in-situ fodder production

	Cost	Units	Quantity	TOTAL
Herbicides				
Pre sowing	$ 8.50	l	1.5 l	$ 12.75
Seed				
Peas	$ 0.35	kg	80 kg	$ 28.00
Oats	$ 0.20	kg	80 kg	$ 16.00
Fertiliser				
MAP	$ 700	t	80 kg	$ 56.00
Urea	$ 600	t	100 kg	$ 60.00
Sowing				
Fuel & oil	$ 18.50	ha	1	$ 18.50
R&M	$ 20.00	ha	1	$ 20.00
		2015 total		**$ 211**
		CPI adjustment		-$ 63
		2001 total		**$ 148**

Incorporation costs for subsoil manuring are taken from Celestine et al. (2015) appendix 4. Key figures are (in 2014 dollars):

- Overhead costs of $69/ha
- Operating costs of $62/ha
- Repairs and maintenance of $31/ha
- Labour of $26/ha
- Total machinery costs of $188/ha

Incorporation costs using 2014 figures were initially used to determine incorporation costs but then discounted (deflated) based on CPI to reflect likely costs in 2001. It was assumed incorporation costs were the same at each location.

The only variable costs adjusted because of the potential yields increase from subsoil manuring was additional freight associated with larger grain yields. Transport costs of $15/t were used for 2010 and discounted each year in line with CPI. Harvest costs remained the same irrespective of additional yield.

Economic and financial analysis

There were differences in cumulative net cash flow, net present value (NVP) and internal rate of return (IRR) at each location (table A7.4). Positive cash flow was achieved at most sites within 2 to 3 years. Balliang (east) was the exception, taking 4 years reach positive cash flow. NPV (@8%) of more than $2,000/ha was recorded at three locations and IRR above 50% at six of the eight locations.

Table A7.4: Time to positive cash flow, NPV (@8%) and IRR assuming high response to subsoil manuring

Location	Years to +ve cash flow	NPV @8% after 9 yrs	IRR
Inverleigh	3	$1,324	45%
Lake Bolac	3	$1,119	46%
Penshurst	2	$2,485	81%
Winchelsea	2	$1,846	104%
Mortlake	3	$2,042	69%
Derrinallum	3	$1,637	64%
Casterton	2	$2,240	83%
Balliang (east)	4	$549	28%

Sensitivity analysis

Analysis using more conservative responses to subsoil manuring were undertaken. Results clearly show the influence a less favourable or long lasting result from subsoil manuring has on investment (figure A7.2).

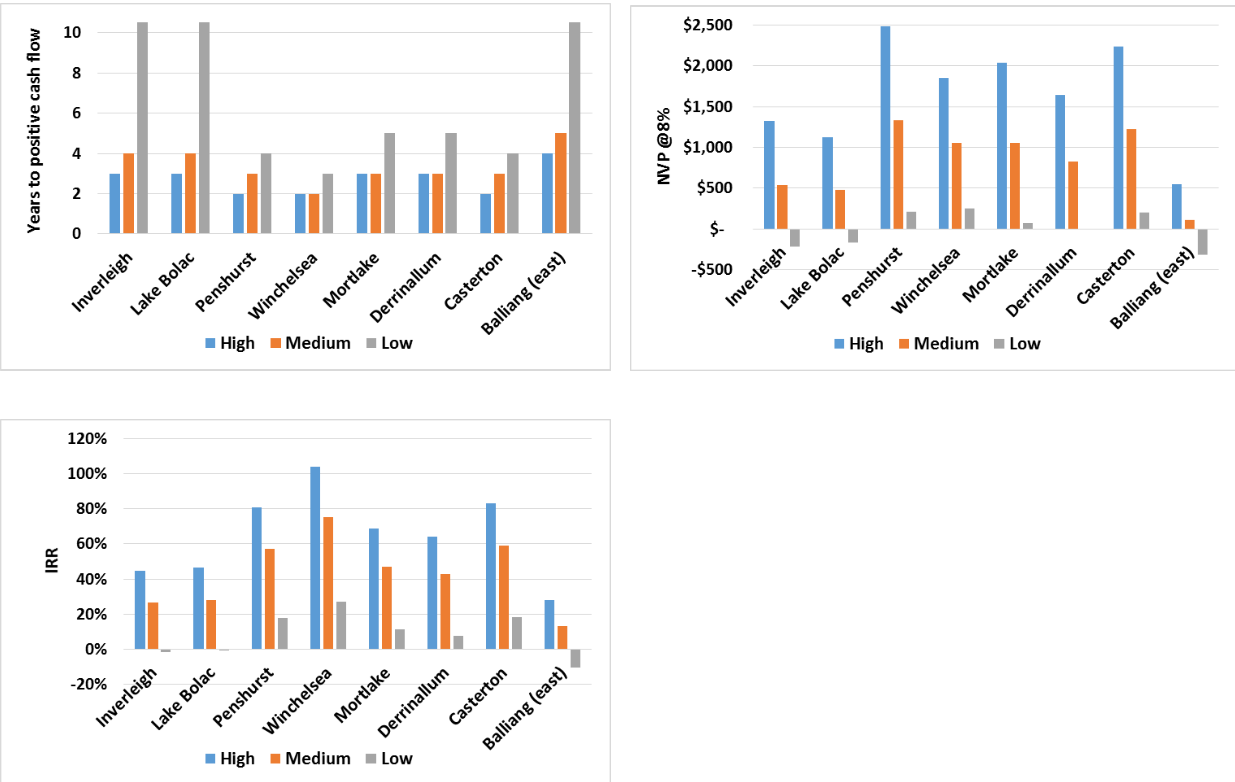

Figure A7.2: Years to positive cash flow, cumulative net present value and internal rate of return nine years after sub soil manuring (with high, medium and low response to amelioration).

Discussion

Subsoil manuring would appear to be sound investment at all locations if high response rates after treatment are achieved. The most profitable response (based on NPV and IRR) and the shortest period to positive cash flow is achieved in the higher rainfall locations (figure A7.3). This is to be expected as rainfall influenced the modelled yields from APSIM however it does suggest the importance achieving high yields has on the profitability of the practice.

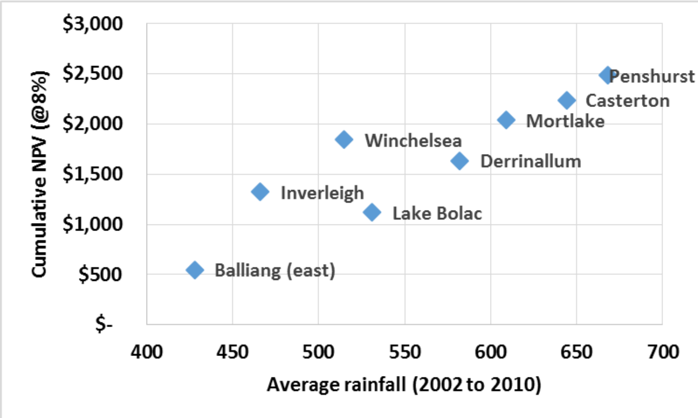

Figure A7.3: Cumulative NPV (@ 8%) for high response to subsoil manuring at 8 locations against average rainfall.

Results clearly show the strong correlation between average rainfall from 2002 to 2010 and the cumulative NPV. Using more conservative yield responses to subsoil manuring dramatically reduced returns. Under the low response to subsoil manuring three locations recorded a NVP below 8%.

The significant up-front costs of growing a dedicated fodder for subsoil manuring and the income foregone from the crop that could have been sown instead of the fodder significantly affects returns. While the costs in this analysis may have been over exaggerated by very high modelled yields in 2001, the results show the importance of minimising the fodder production phase. Alternatives such as using paddocks that may contain herbicide resistant weeds, where crop production would be compromised if sown, or using crops that may be frosted could provide options with lower opportunity costs. For example a 50% reduction in up-front costs at Inverleigh improved the IRR on the low responsive yield from -2% to +32%.

References

ABARES data for the Barwon and Western district statistical divisions from surveys in 1993/94, 2000/01, 2006/07 and 2010/11.

Adcock D, McNeill AM, McDonald GK, Armstrong RD (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.

Alami Y, Achouak W, Marol C, Heulin T (2000) Rhizosphere soil aggregation and plant growth promotion of sunflowers by an exopolysaccharide-producing rhizobium sp. strain isolated from sunflower roots. *Applied and Environmental Microbiology* **66**, 3393-3398.

Albiach R, Canet R, Pomares F, Ingelmo F (2001) Organic matter components and aggregate stability after the application of different amendments to a horticultural soil. *Bioresource Technology* **76,** 125-129.

Amellal N, Bartoli F, Villemin G, Talouizte A, Heulin T (1999) Effects of inoculation of EPS-producing Pantoea agglomerans on wheat rhizosphere aggregation. *Plant and Soil* **211**, 93-101.

Armstrong RD, Eagle C, Jarwal SD (2007) Application of composted pig bedding litter on a Vertosol and Sodosol soil. 2. Effect on soil chemical and physical fertility. *Australian Journal of Experimental Agriculture* **47**, 1341-1350.

Baldock JA, Aoyama M, Oades JM, Susanto, Grant CD (1994) Structural amelioration of a South Australian red-brown earth using calcium and organic amendments. *Australian Journal of Soil Research* **32**, 571-594.

Belford RK, Dracup M, Tennant D (1992) Limitations to growth and yield of cereal and lupin crops on duplex soils. *Australian Journal of Experimental Agriculture* **32**, 929–945.

Bengough AG, Croser C, Pritchard J (1997) A biophysical analysis of root growth under mechanical stress. *Plant and Soil* **189**, 155-164.

Blackwell PS, Jayawardane NS, Green IW, Wood JT, Blackwell K, Beatty HJ (1991) Subsoil macropore space of a transitional red-brown earth after either deep tillage, gypsum or both. 1. Physical effects and short-term changes. *Australian Journal of Soil Research* **29**, 123-40.

Bulluck LR, Brosius M, Evanylo GK, Ristaino JB (2002) Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. *Applied Soil Ecology* **19**,147-160.

Bronick CJ, Lal R (2005) Soil structure and management: a review. *Geoderma* **124**, 3-22.

Chaney K, Swift RS (1986) Studies on aggregate stability. 1. Reformatiom of soil aggregates. *Journal of Soil Science* **37**, 329-335.

Celestina C, Creelman Z, Nicholson C (2015) Feasibility and logistics of subsoil manuring in South West Victoria – a report for the Department of State Development, Business and lnnovation, Victoria. Southern Farming Systems Inverleigh.

Chenu C (1993) Clay- or sand-polysaccharide associations as models for the interface between micro-organisms and soil: water related properties and microstructure. *Geoderma* **56,** 143-156.

Clark GJ, Dodgshun N, Sale PWG, Tang C (2007) Changes in chemical and biological properties of a sodic clay subsoil with addition of organic amendments. *Soil Biology and Biochemistry* **39**, 2806-2817.

Clark GJ, Sale PWG, Tang C (2009) Organic amendments initiate the formation and stabilisation of macroaggregates in a high clay sodic soil. *Australian Journal of Soil Research* **47**, 770-780.

Czarnes S, Hallett PD, Bengough AG, Young IM (2000) Root- and microbial-derived mucilages affect soil structure and water transport. *European Journal of Soil Science* **51**, 435-443.

Dairy Australia (2010) Soil Carbon Sequestration under Pasture in Australian Dairy Regions. McKenzie soil Management. Orange NSW.

Department of Primary Industries (DPI) (2006) Subsoil Constraints to Cropping in the High Rainfall Zone of South East Australia. DPI, Bendigo, VIC.

Dorioz JM, Robert M, Chenu C (1993) The role of roots, fungi and bacteria on clay particle organization. An experimental approach. *Geoderma* **56**, 179-194.

Eck HV, Martinez T, Wilson GC (1977) Alfalfa production on a profile-modified slowly permeable soil. *Soil Science Society of America Journal* **41**, 1181–1186.

Eck HV, Unger PW (1985) Soil profile modification for increasing crop production. *Advances in Soil Science* **1**, 65–100.

Eiland F, Klamer M, Lind AM, Leth M, Baath E (2001) Influence of initial C/N ratio on chemical and microbial composition during long term composting of straw. *Microbiology and Ecology* **41**, 272-280.

Ferreras L, Gomez E, Toresani S, Firpo I, Rotondo R (2006) Effect of organic amendments on some physical, chemical and biological properties in a horticultural soil. *Bioresource Technology* **97**, 635-640.

FSA Consulting (2007) Making the most of animal by-products: fact sheet series workbook. FSA Consulting, Toowoomba, QLD.

Gardner WK, Fawcett RG, Steed GR, Pratley JE, Whitfield DM, van Rees H (1992) Crop production on duplex soils in south-eastern Australia. *Australian Journal of Experimental Agriculture* **32**, 915-927.

Gardner WK, McDonald GK (1988) Responses by wheat to lupin, soil amelioration and fertiliser treatments in a solodised solonetz soil. *Australian Journal of Experimental Agriculture* **28**, 607-615.

Germano, D (2015) *In-situ Subsoil Manuring: Prototype Design Report*. Melbourne School of Engineering, University of Melbourne. Parkville.

Ghosh S, Lockwood P, Daniel H, Hulugalle N, King K, Kristiansen P (2011) Changes in Vertisol properties as affected by organic amendments application rates. *Soil Use and Management* **27**, 195-204.

Gill JS, Sale P (2015) Subsoil manuring. La Trobe University, Melbourne. Retrieved from: http://www.latrobe.edu.au/agribio/research/specialisations/subsoil-manuring

Gill JS, Sale P, Peries RR, Tang C (2009) Changes in soil physical properties and crop root growth in dense sodic subsoil following incorporation of organic amendments. *Field Crops Research* **114**, 137-146.

Gill JS, Sale PWG, 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.

Greenwood KL, Mundy GN, Kelly KB, Dellow KE, Austin SM (2006) Improved soil and irrigation management for forage production 1. Site establishment and soil physical properties. *Australian Journal of Experimental Agriculture* **46**, 307-317.

Griffiths N (2004) Best practice guidelines for using poultry litter on pastures. NSW DPI.

Gill JS, Byrne J, Sale P, Tang C (2010) Subsoil manuring with different organic manures increased canola yield in a dry spring. In 'Proceedings of the 19th world congress of soil science: soil solutions for a changing world'. pp. 165-168. (International Union of Soil Science: Brisbane, Qld)

Grains Research and Development Corporation (GRDC) (2009) Deep ripping. GRDC, Kingston, ACT.

Grains Research and Development Corporation (GRDC) (2013) Managing Soil Organic Matter: A Practical Guide. GRDC, Kingston, ACT.

Hamza MA, Anderson WK (2002) Improving soil physical fertility and crop yield on a clay soil in Western Australia. *Australian Journal of Agricultural Research* **53**, 615-620.

Huang PM, Wang MK, Chiu CY (2005) Soil mineral–organic matter–microbe interactions: Impacts on biogeochemical processes and biodiversity in soils. *Pedobiologica* **49**, 609-635.

Hulugalle NR, Weaver TB (2005) Short-term variations in chemical properties of Vertosols as affected by amounts, carbon/nitrogen ratio, and nutrient concentration of crop residues. *Communications in Soil Science and Plant Analysis* **36**, 1449-1464.

Isbell RF (2002) The Australian Soil Classification: Revised addition. CSIRO Publishing, Clayton, VIC.
Jayawardane NS, Chan KY (1994) The management of soil physical properties limiting crop production in Australian sodic soils – a review. *Australian Journal of Soil Research* **32**, 13-44.

Kelly KB (1985) Effects of soil modification and treating on pasture growth and physical properties of an irrigated red-brown earth. *Australian Journal of Agricultural Research* **36**, 799–807.

Kirkegaard JA, Lilley JM, Howe GN, Graham JN (2007) Impact of subsoil water use on wheat yield. *Australian Journal of Agricultural Research* **58**, 303-315.

Lawson P (2010) Taking the trouble out of stubble management. *Farming Ahead* November 2010, **226**, 26-45.
MacEwan, R.J., Crawford, D.M., Newton, P.J., Clune, T.S., 2010. High clay contents, dense soils, and spatial variability are the principal subsoil constraints to cropping the higher rainfall land in south-eastern Australia. Aust. J. SOIL Res. 48, 150–166. doi:10.1071/sr09076

Mehanni AH (1974) Short term effect of some methods for improving soil structure in red-brown earth soils of the northern irrigation areas, Victoria. *Australian Journal of Experimental Agriculture and Animal Husbandry* **14**, 689-693.

Midwood J, Birbeck P, Whitlock A, McCallum M (2011) Managing Stubble. GRDC. Kingston, ACT.

Milleret R, Le Bayon RC, Lamy F, Gobat JM, Boivin P (2009) Impact of roots, mycorrhizas and earthworms on soil physical properties as assessed by shrinkage analysis. *Journal of Hydrology* **373**, 499-507.

Nicholson C (2012) Subsoil manuring trial: Birregurra. Woady Yaloak Catchment Group, VIC. Unpublished report.

Nicholson C Creelman Z, Celestina C, (2015) Production and economic impact of subsoil modification on broad acre grazing and cropping – a report for the Department of State Development, Business and Innovation, Victoria. Southern Farming Systems Inverleigh.

Olsson KA, Dellow KE, Hirth JR, Kelly KB, Greenwood KL, Blaikie SJ (2002) Application of composted pig bedding litter on a Vertosol and Sodosol soil. 2. Effect on soil chemical and physical fertility. *Australian Journal of Experimental Agriculture* **42**, 453-463.

Passioura JB, Angus JF (2010) Improving the productivity of crops in water-limited environments. *Advances in Agronomy* **106**, 37-75.

Peries R (2014) Subsoil manuring: an innovative approach to addressing subsoil problems targeting higher water use efficiency in Southern Australia. Southern Farming Systems 2013 Growing Season Trial Results. Southern Farming Systems, Inverleigh, VIC.

Peries R, Gill JS (2010) Improving crop water use efficiency in high rainfall zone (HRZ) Victoria, through appropriate practice change to overcome subsoil limitations. In 'Proceedings of the 15th agronomy conference: food security from sustainable agriculture.' (Agronomy Society of Australia: Lincoln, NZ)

Puget P, Chenu C, Balesdent J (2000) Dynamics of soil organic matter associated with particle-size fractions of water-stable aggregates. *European Journal of Soil Science* **51**, 595-605.

Reid JB, Goss MJ (1981) Effect of living roots of different plant species on the aggregate stability of two arable soils. *Journal of Soil Science* **32**, 521-541.

Rengasamy P (2000) Subsoil constraints and agricultural productivity. *Journal of the Indian Society of Soil Science* **48**, 674–682.

Rengasamy P (2002) Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: a review. *Australian Journal of Experimental Agriculture* **42**, 351-361.

Robertson M, Kirkegaard J, Peake A, Creelman Z, Bell L, Lilley J, Midwood J, Zhang H, Kleven S, Duff C, Riffken P (2016) Trends in grain production and yield gaps in the high rainfall zone of southern Australia. Draft submitted to *Australian Journal of Experimental Agriculture* for publication

Rousk J, Baath E (2007) Fungal and bacterial growth in soil with plant materials of different C/N ratios. *FEMS Microbiology and Ecology* **62**, 258-267.

Sale, P (2010) Subsoil manuring: do the benefits warrant the costs? In 'Proceedings of the 51st annual conference of the Grassland Society of Southern Australia Inc.' pp. 71-78. (The Grassland Society of Southern Australia: Wangaratta, Vic)

Sale P, Gill JS, Peries R, Tang C (2012) Taming hostile subsoils for production. GRDC Media Centre. Retrieved from: www.grdc.com.au

Sale P, Malcolm B (2015) Amending sodic soils using sub-soil manure: economic analysis of crop trials in the high rainfall zone of Victoria. *Australian Farm Business Management Journal* **12**, 22-31.

Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil and Tillage Research **79**, 7-31.

Tarkalson DD, Jolley VD, Robbins CW, Terry RE (1998) Mycorrhizal colonization and nutrition of wheat and sweet corn grown in manure-treated and untreated topsoil and subsoil. *Journal of Plant Nutrition* **21**, 1985-1999.

Tisdall (1997) Aggregation of soil by fungal hyphae. *Australian Journal of Soil Research* **35**, 55-60.

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. *Journal of Soil Science* **33**, 141-163.

Quilty JR, Cattle SR (2011) Use and understanding of organic amendments in Australian agriculture: a review. *Soil Research* **49**, 1-26.

Watson D (2014) Subsoil manuring: farmer perspectives and case studies. AgVise Services, VIC. Unpublished report.

Watts CW, Whalley WR, Longstaff DJ, White RP, Brooke PC, Whitmore AP (2001) Aggregation of a soil with different cropping histories following the addition of organic materials. *Soil Use and Management* **17**, 263-268.

Wong MTF, Asseng S (2007) Yield and environmental benefits of ameliorating subsoil constraints under variable rainfall in a Mediterranean environment. *Plant Soil* **297**, 29-42.

Yates. Technical Data Sheet: Dynamic Lifter. Retrieved from: http://yatesau-production.s3.amazonaws.com/assets/3892/DL_Tech_Data_Sheet.pdf

Zhang H, Turner NC, Poole ML, Simpson N (2006) Crop production in the high rainfall zones of southern Australia —potential, constraints and opportunities. *Australian Journal of Experimental Agriculture* **46**, 1035-1049.