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Economic analysis of ameliorating subsoil constraints using subsoil manure in a cropping system

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Abstract

To date, no studies have accounted for the effects of the yield and/or price risks that will occur over a run of years on the profitability of investing in ameliorating subsoil constraints within a cropping system. While addressing subsoil constraints is likely to increase grain yield, the key economic question for a grower is whether the income from extra grain produced covers the extra costs of ameliorating the subsoil.

The focus of this thesis was the likely profit and risk of investing in ameliorating subsoil constraints. Investment costs and annual activity gross margins for a set rotation were used to estimate the economic performance of subsoil amelioration. The marginal change to the gross margin as a result of subsoil amelioration was assessed using partial discounted cashflow budgets. Risk analysis was used to assess the effect of price and yield variability on the mean and variance of outcomes from an investment in ameliorating subsoil constraints in cropping.

This study shows an investment in subsoil amelioration was more profitable on average than an alternative investment earning 6% (real). The size of the expected extra yield benefits and longevity of these benefits are the most important factors for a grower to consider when assessing the likely merit (return and risk) of investing in subsoil amelioration in their own situations.

Declaration

This is to certify that:

i. the thesis comprises only my original work towards the Master of Philosophy except where indicated in the preface;

ii. due acknowledgement has been made in the text to all other material used, and

iii. the thesis is fewer than 50,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Sam Henty Date: 29-11-2019

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Table of contents

1 Introduction

Broadacre cropping is a major agricultural activity in Victoria. There were 3.5 million hectares of broadacre crops planted across Victoria in 2017-18, with a farm gate value of 2.2 billion dollars. In the past decade grain production has increased markedly in the Victorian high-rainfall zone (HRZ) (annual rainfall > 500 mm). In 2017-18, 8% of Victoria's broadacre cropping area was in the HRZ and it produced 16% of Victoria's total value of commodities produced from broadacre cropping (Figure 1.1)[1].

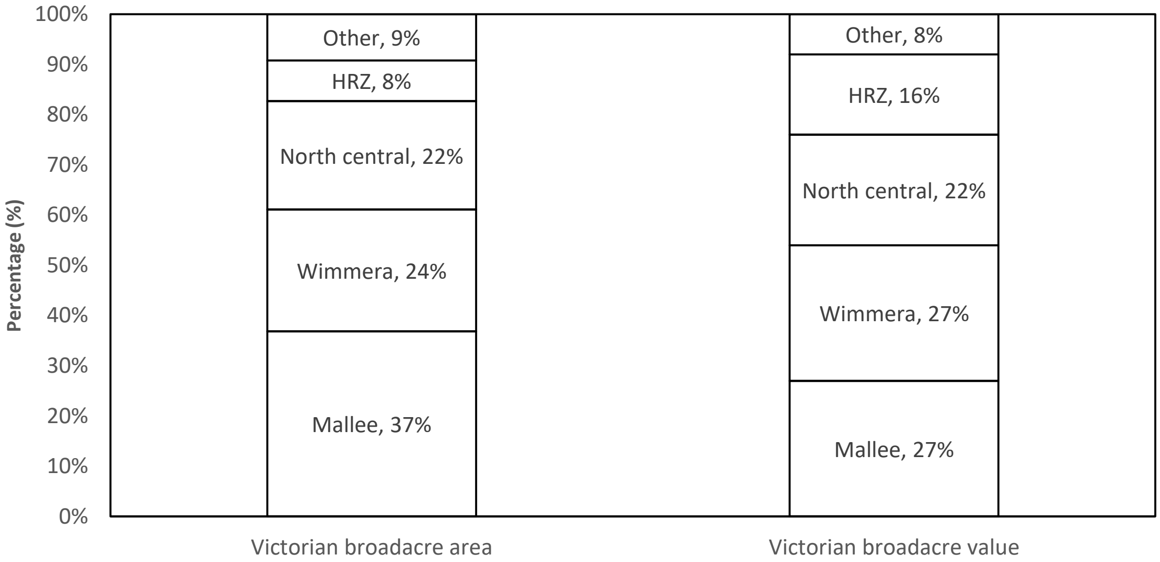

Figure 1.1. Percentage of total area planted and total value of commodities produced from broadacre crop for 2017-18 broadacre crops in different regions of Victoria. Data sourced for the Victorian high rainfall zone (HRZ) from the NRM regions: Glenelg Hopkins, Corangamite, Port Phillip/Western Port, Gippsland east, Gippsland west and the Hume SA4 region. (Source: ABS (2019a), ABS (2019b))

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[1] ABS (2019b) derived broadacre cropping value by the multiplication of price and quantity estimates of commodities produced from broadacre cropping.

Unconstrained yield potential for broadacre crops grown in the HRZ is higher than potential yields in low and medium rainfall regions. However, broadacre crop production in the HRZ of Victoria is limited by physicochemical constraints in the subsoil (Zhang *et al.* 2006, MacEwan *et al.* 2006, Adcock *et al.* 2007). Potential yield increases from improved varieties or agronomy is always constrained by subsoil properties, particularly soil characteristics that cause temporary waterlogging during wet periods, or cause water deficiencies in the dry times, such as lack of rooting depth (Belford *et al.* 1992, Nuttall *et al.* 2001, Nuttall *et al.* 2003, Dang *et al.* 2006, MacEwan *et al.* 2010, Christy *et al.* 2015). Research dating back to the 1990's has demonstrated that significant improvements in grain yields on soils containing physicochemical constraints can be achieved by placing organic matter and nutrients at depth in cropped soils. Growing crops using subsoil manure (SSM) is a technology that can enable large improvements in grain yields lasting several years. Subsoil manuring involves applying large quantities (up to 20 t/ha) of poultry litter in slots at depth in dense clay soils (Gill *et al.* 2008).

Despite the potential change in crop yields that can be achieved by SSM, there has been little analysis of farm-level economics of this innovation that investigates the economic merit of investing in SSM. While removing subsoil constraints is likely to increase grain yield, the key economic question for a crop farmer is whether the income from extra grain produced covers the extra costs of ameliorating the subsoil constraints. In this research the likely profit and risk of investing in SSM is investigated. The aim of this thesis is to develop a method for evaluating the economic merit of investing in SSM and for assessing how the risk associated with yield response and grain prices affects the profitability of investing in SSM. To this end, investment costs and annual activity gross margins for a set rotation are used to estimate the economic performance of SSM. Risk analysis is used to assess the effect of price and yield variability on the mean and variance of economic performance outcomes.

The research questions are:

1. What minimum extra benefits are required from an investment in subsoil manure to be competitive with alternative uses of capital over a 5-year and 10-year investment life?

2. How does the risk associated with yield response and grain prices affect the profitability of an investment in subsoil manure over a 5-year life of investment?

3. What effect does a decline in annual yield response have on return to investment in subsoil manure over a 10-year investment life?

Thesis outline

In Chapter 2, subsoil constraints, SSM technology and economic approaches used to analyse the adoption of SSM in a farm business are reviewed. In Chapter 3 the farm economic approach to analysing an investment in SSM is set out. Risk analysis using the marginal gross margin concept is demonstrated. In Chapter 4, results from the risk analysis are presented. Chapter 5 discusses the results and what the findings mean for those who are considering an investment in SSM. The thesis finishes with some concluding comments and suggestions for further research.

2 Literature review

2.1 Subsoil constraints

The subsoil is the soil below the cultivated layer, which in most grain farming systems does not exceed a depth of 15cms (Adcock *et al.* 2007). Constraints in subsoils occur because of poor soil structure. Poorly structured subsoils lack soil pore volume and space between soil particles. Subsoil constraints across the Victorian HRZ are exacerbated by clay dispersion in the subsoil. Dispersion of soil particles is a function of exchangeable cations (Rengasamy and Olsson 1991; Rengasamy and Marchuk 2011) and increases when there is a high percentage of exchangeable sodium ions (ESP) in the subsoil. Sodium ions weaken bonds between soil particles when wetted resulting in particle separation and dispersion. Upon drying the dispersed soil particles settle in pores and may seal the pathways for air and water (Rengasamy 1991). The nature and impact of subsoil constraints on crop productivity in SE Australia is well established (Zhang *et al.* 2007; Adcock *et al.* 2007; MacEwan *et al.* 2010). These subsoil constraints include high boron, transient salinity, acidity/alkalinity and sodicity. Most cropping soils across Australia contain one or more constraints (Figure 2.1). Soil constraints can affect crop development through restricted rooting depth, winter waterlogging and post-anthesis drought (Adcock *et al.* 2007; MacEwan *et al.* 2010; Robertson *et al.* 2016).

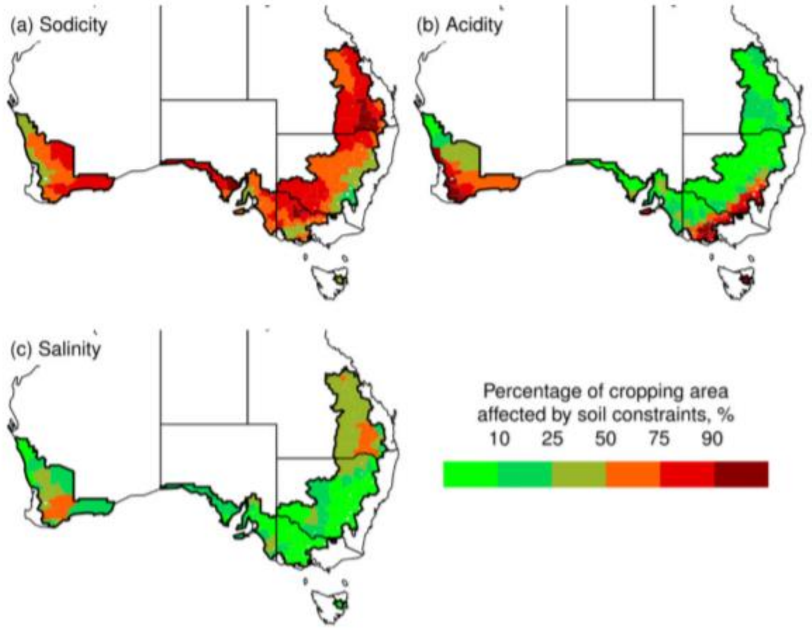

Figure 2.1 Areas of land, as a percentage of the cropping land, affected by (a) sodicity, (b) acidity, and (c) salinity (Source: Orton et al. 2018)

Root growth is restricted by poor aeration when the soil is wet and by inhibiting root penetration as the soil dries. Increasing root growth in subsoil layers to improve the crop’s access to water and nutrients has been suggested as a key area to increase crop productivity (Turner 2004; Zhang *et al.* 2006; Robertson *et al.* 2016).

2.2 Strategies to ameliorate subsoil constraints.

2.2.1 Gypsum

The application of gypsum to improve surface soil infiltration has a long history (Crocker 1922). Gypsum is used almost exclusively to topsoil (Loveday 1974) with subsoil application showing potential for short-term yield increases (Bridge and Kleinig 1986). Placing gypsum into a band in rip-lines in the subsoil is likely to restrict the amelioration to the soil within and adjacent to the rip-line, with minimal improvement in the subsoil matrix between the rip-lines (Gill *et al.* 2008; Armstrong *et al.* 2015). A more even distribution of gypsum on the soil surface, followed by deep ripping, may result in a more even distribution in the subsoil, but this will take time, would require sufficient rainfall and the benefits may be short-lived as improvements in the subsoil will stop when the dissolved gypsum is leached from the subsoil layers.

2.2.2 Deep Ripping

Deep ripping alone without a suitable ameliorant is unlikely to improve structure and crop productivity on poorly structured clay soils in the medium and high rainfall zones in the southern Region. Although deep ripping reduced soil strength in the ripped layers at 15 sites across southern NSW between 1980 and 2005, ripping only resulted in yield responses at a third of these sites (GRDC 2009). Similarly, where deep ripping was used on Chromosol, Calcarosol, Sodosol and Vertosol soils in the southern region, there was no benefit from the practice apart from small grain yield responses in the first year only at some sites (Gill *et al.* 2008; McBeath *et al.* 2010; Creelman and Celestina 2015). In many cases, deep ripping produced yield declines arising from bringing poorly structured sodic subsoil to the surface resulting in poor plant establishment. The disturbance of subsurface soil layers with ripping was not able to overcome the major subsoil factors limiting crop yields.

In contrast to the poor performance of deep ripping on the heavier-textured soils across south eastern Australia, deep ripping has produced much more promising results on the deep sandy soils of Western Australia. Deep ripping is very effective in ameliorating compacted soil layers, particularly those resulting from tillage practice, on soils from the sandplain areas (Jarvis 1986). Blackwell *et al.* (2015) reported how the disruption of the compacted subsurface layer by ripping enabled crop roots to grow faster and deeper and to access more subsoil water and nutrients, and this resulted in higher crop yields.

2.2.3 Primer plants

Primer plants have been used to modify the structure of deeper soil layers by extending their roots down into these layers, then dying and decaying, leaving pores or channels (Yunusa and Newton 2003). Primer crops can produce structural improvements to dense clay subsoils (McCallum *et al.* 2004), resulting in subsequent crops extracting more subsoil water (McCallum *et al.* 2004; Nuttall *et al.* 2008). Despite the potential structural improvements, evidence suggests that there is minimal improvement in the productivity of crops grown following the primer plant phase (McCallum *et al.* 2004; Nuttall *et al.* 2008; Ward *et al.* 2002*;* Yunusa *et al.* 2002) that could be attributed to improved subsoil structure.

One disadvantage of primer plants is the extended period of time required for the primer phase to improve subsoil structure. McCallum *et al.* (2004) reported that 10 years of a phalaris pasture and 3 to 4 years of lucerne were used in their study to generate improved macro-porosity in a dense B horizon in a Sodosol soil in central western NSW. This could have significant financial implications for many cropping businesses due to the opportunity costs of for-going cropping.

Another potential negative effect is that the primer plant might de-water the soil profile, resulting in less plant available water for following crops. Water deficits generated by the primer plants would be unlikely to be replenished before the following crop was grown, and this would limit any benefits from the amelioration of poorly structured subsoils in the first year (Angus *et al.* 1996; Hirth *et al.* 2001; Mele *et al.* 2001; Yunusa *et al.* 2002; Nuttall *et al.* 2008)

2.2.4 Deep placement of nutrients

Evidence from the last 50 years of research suggest that there is a high likelihood that deep nutrient application will lead to increased grain crop productivity. There are three identified cropping scenarios where deep nutrients are expected to increase crop yields (Ma *et al.* 2003; Dunbabin *et al.* 2009).

First, sands over clays on the Eyre and Yorke Peninsulas in South Australia. Researchers in this region developed a technology where liquid nutrients containing N, P and trace elements were injected at depths of 20-40 cm into deep infertile sands that overlie clay subsoils. Remarkably consistent and prolonged yield increases generally result from this practice (Adcock *et al.* 2005; Wilhelm 2005, McBeath *et al.* 2010). The deep nutrient response is attributed to the rapid drying of the infertile sandy surface soil in this semi-arid region with a Mediterranean-type climate with short, mild wet winters and long hot dry summers (Ma *et al.* 2003). Deep placement is believed to allow crop roots to access nutrients from the deeper layers where soil moisture is retained for longer periods than the surface soil.

Second, warm dry conditions of the northern Australia grains region occur during the vegetative growth of winter crops, so the crops rely heavily on subsoil moisture. When the topsoil dries with the warmer and drier conditions in the north, then nutrient supply from fertilisers that are banded at shallow depths become unavailable. A history of intensive cropping with limited application of fertilisers, has led to the depletion of nutrients in subsurface layers. Thus, in drier years, responses to deep nutrients occur (Singh *et al.* 2005, Bell *et al.* 2015). In contrast, in wetter years when roots can access nutrients in surface layers, there are no benefits from deep fertiliser placement (Bell *et al.* 2012).

Third, placement of phosphorus (P) fertiliser in bands below the seed, as opposed to placing it with the seed have been reported to significantly increase grain yield when the P status in the surface layer is low (Jarvis and Bolland 1990). In contrast, when the P status of the surface layer is adequate for crop growth, then there will no increase in grain yield with deep placement (Alston 1980; Bolland and Jarvis 1996; Scott *et al.* 2003). Crops can take up enough P from the fertile topsoil layers, before the soil surface dries off in the spring. However, if the soil surface P is low, plants are reliant on deeper subsurface layers for P uptake.

Sale *et al.* 2018 demonstrated that the deep placement of granular fertiliser was not as effective as applying the nutrient equivalent of poultry litter at the same depth on Sodosol and Chromosol soils in the Victorian HRZ. The granular fertiliser treatment yielded significantly less than the poultry litter treatment. Therefore, the deep nutrient treatment in this example was not able to deliver the same benefits as the incorporation of the nutrient-rich organic amendment in the subsoil. Under the conditions of these field experiments (heavy clay soils and with waterlogging in some years), the yield benefits from the deep placement of poultry litter could not be explained solely by the increase in nutrient supply in the subsoil.

Few studies have assessed whether physical properties in the subsoil will be improved with deep nutrient. In most cases the field trials focussed on crop performance with no measurements on subsoil physicochemical condition undertaken. Wilhelm (2005) indicated that the bulk of the benefit from deep nutrient additions to infertile sands over clay in South Australia, comes from the deep nutrients, with only ‘some benefit’ from the disturbance of the sand layer by the ripping process. The study by McBeath *et al.* (2010) however, reported reduced cone penetration resistance in the deeper sand layers in the first year, but that this had diminished by the 4th year. The authors suggest that repeated ripping may be required in the future. There were no reductions in bulk density or in the macro-porosity of the clay subsoil (McBeath *et al.* (2010).

2.2.5 Deep placement of organic material

Graham *et al.* (1992) demonstrated how high rates of organic amendment placed in the subsoil, resulted in large and long-lasting yield increases, across a variety of sites in the wheat belt of South Australia. The treatment involved digging out the soil profile and mixing in the amendment and was considered not practical or cost-effective for on-farm implementation. More recent field trials have tested the deep placement of organic matter and nutrients to ameliorate subsoil constraints and consistently produced large improvements in grain yields lasting several years (Gill *et al.* 2008, 2009, 2012; Espinosa *et al.* 2011; Peries 2014; Gourley and Sale 2014; Sale *et al.* 2013; Peries and Gill 2015; Sale *et al.* 2018). Poultry litter has become the organic amendment of choice for subsoil amelioration experiments and the practice was termed ‘subsoil manuring’. Poultry litter is a nutrient rich by-product of meat chicken production, it consists of bedding (usually sawdust or shavings, rice hulls or straw) and manure. Litter is typically purchased from contractors who clean commercial broiler sheds or bought directly from a broiler farm. Litter is low in moisture (20-26%) (Wiedemann 2015) and high in nutrients (Table 2.1). Subsoil manuring (SSM) involves a continual band of poultry litter, applied at 20 t/ha (fresh weight) at a depth of 30-40cm, at the base of a rip-line.

Table 2.1. Total nitrogen, phosphorus and potassium content of poultry litter applied at 20 t/ha

Nutrients	Amount of nutrient in 20 t/ha (kg/ha)	Nutrient concentration in poultry litter	Source
Nitrogen	594	3.0%	Celestina *et al.* 2018
Phosphorus	130	0.7%	Celestina *et al.* 2018
Potassium	266	1.3%	Celestina *et al.* 2018
Nitrogen	634	3.2%	Celestina *et al.* 2018
Phosphorus	295	1.5%	Celestina *et al.* 2018
Potassium	406	2.0%	Celestina *et al.* 2018
Nitrogen	640	3.2%	Sale *et al.* 2018
Phosphorus	360	1.8%	Sale *et al.* 2018
Potassium	400	2.0%	Sale *et al.* 2018

2.3 Crop responses to the subsoil application of organic amendments

Successful amelioration of subsurface soil layers with the addition of organic amendments, is deemed to have occurred when large yield responses occur in the 1st year and continue over the following 2-3 experimental years. This was the case for field trial results reported by Sale *et al.* (2018) and Gill *et al.* (2008) and Gill *et al.* (2009). Over the eight experimental years of these trials, the incorporation of 20 t/ha of poultry litter in the subsoil, resulted in average wheat yield increasing by 62% above the control.

The successful amelioration of subsoils resulted in a marked increase in aggregation of the clay subsoil. The basis for this increased aggregation is attributed to enhanced biological activity occurring when nutrient-rich organic amendment was placed in or mixed with soil. Biological activity is thought to be increased in soil with added organic amendment and in the presence of active crop roots. The aggregation effect from increased biological activity was able to negate the effect of high exchangeable sodium that would normally lead to the dispersion in sodic subsoils (Gill *et al.* 2009; Clark *et al.* 2009; Sale *et al.* 2011). A continuing supply of water, nutrients, and oxygen supplied from the soil results in vigorous and continuing root growth in the treated subsoils. Crops can extract more water from the subsoil layer, during critical stages which is thought to be the reason for the large grain yield responses. However, it is not fully understood how the application of high rates of nutrient enriched organic matter and associated increased root activity and soil biota can increase aggregation of a sodic clay soil. Nor are the processes understood that are responsible for the lateral spread of the soil aggregation effect beyond the rip lines.

2.3.1 Rainfall effects on yield response

Across the experimental sites and years where large crop responses occurred, rainfall ranged from decile 3 to 9. Taken collectively these results show how yield increases occurred with organic amendments, when they were added to heavier-textured sodic soils in the HRZ of Victoria, in years when the annual rainfalls ranged from just-below-average to above average. Yield responses in these years occurred across a range of crop types including wheat, barley, canola and faba beans.

However, at several experimental sites the subsoil application of poultry litter failed to produce a grain yield response above that of the control treatment (Gill *et al.* 2012; Creelman and Celestina 2015; Celestina *et al.* 2016; Celestina *et al.* 2018; Sherriff and Trengrove 2018). The lack of grain yield responses to deep incorporation of organic amendments coincided with years of very low rainfall (annual rainfall decile 1 or 2). In many instances there were significant vegetative growth responses, but these did not translate into increases in grain yield. One explanation for lack of yield response in very dry years is depleted soil water availability during the crops' grain filling stage because of rapid early plant growth (Gill *et al.* 2012). The size and distribution of rainfall seems to have a marked bearing on the effectiveness of the organic matter amelioration to improve crop growth and facilitate beneficial soil function. However, the relationship between amelioration process and water availability remains unknown.

2.4 Project DAV00149

The Grains Research and Development Corporation (GRDC) project DAV00149 - Understanding the amelioration processes of the subsoil application of amendments in the Southern Region, is a collaborative project comprising GRDC, Agriculture Victoria, PIRSA/SARDI, NSW Department Primary Industries, University of Tasmania , LaTrobe University, University of South Australia, University of Melbourne and Southern Farming Systems. The project aims to provide grain growers and their advisers in south-eastern Australia (South Australia, Victoria, southern NSW and Tasmania) with cost-effective techniques to ameliorate poorly structured subsoils and increase crop production and profitability through the incorporation of organic matter and/or other amendments.

GRDC (2018) page 20, details the findings from the first year of experimentation. The key points are summarised below:

> *Preliminary results from experimentation across the country has shown that some organic amendments can increase grain yields, even in seasons where rainfall is significantly below average. In the first year following treatment, surface applications were more effective but as the soil consolidates following initial disturbance (which can markedly reduce crop establishment and early growth), placing amendments in the subsoil appears more effective. Crop*

response to amendments is strongly linked to soil water dynamics in the (potential) root zone. Largest yield responses in 2018 to organic matter amelioration were recorded at the High Rainfall Zone sites with little or negative responses at the Medium Rainfall Zone sites (but this was under seasonal conditions where Growing Season Rainfall was at Decile 1).

2.5 Farm management economic assessments of applying organic matter to the subsoil

Multiple studies have attempted economic assessments of removing subsoils constraints using biophysical models to derive crop yield response data (Abadi Ghadim *et al.* 1991, Wong and Asseng 2007, Farre *et al.* 2015, Zull *et al.* 2016, Ward *et al.* 2018). In all cases the subsoil constraints were different to those experienced in the HRZ of Victoria. As a result, the amelioration practices that have been evaluated and the associated costs and benefits used in these studies are not applicable to this analysis. Nicholson *et al.* (2015) used a modelling approach in conditions and practices relevant to this study and is discussed in more depth later in section 2.5.

There are few studies that have attempted to assess whether applying organic matter to the subsoil is a profitable investment in broadacre cropping. Trengrove and Sheriff (2018) estimated the extra income and costs from the applying poultry litter to a depth of 30-40cm to ameliorate deep sandy subsoil constraints in South Australia. The authors estimated an investment cost of

$900/ha to apply 20t/ha of poultry litter to the subsoil; no detail was provided about the components that made up the total cost of applying the ameliorant. Despite dry growing conditions, the 20t/ha SSM treatment ranked highly according to the ‘Return on Investment’ performance criteria. ‘Return on investment’ was ill-defined as the cumulative extra nominal net revenue divided by the cumulative extra nominal variable and capital costs over three years of the experiment. No attempt was made by the authors to include the opportunity cost of the capital required for investment.

Nicholson *et al.* (2015) modelled expected SSM soil conditions and their subsequent crop yields in Victoria’s HRZ. Probability distributions were developed from the modelled yield data and historic grain price data and applied to a profit budget to account for variability in profit. The cost of undertaking SSM was not included in the profit budget. An investment analysis is not complete without considering all benefits and costs, including estimating the total investment cost and the opportunity cost of the total investment cost.

To date, Sale and Malcolm (2015) is the only study that conducts a farm-level SSM investment analysis. The costs and benefits of achieving the grain yield responses reported in Sale *et al.* (2018) over four consecutive crops were used to determine if a farm business would be better off cropping using SSM or by using the conventional cropping methods. Included was a saving, or the cost of annual fertiliser inputs not required for each of the first three years as a result of the high nutrient load contained in the deeply placed poultry litter amendment in year one. The construction of the SSM machine was estimated to cost $170,000 and the work rate of the machine was 0.5ha/hr. The authors estimated that using the machine to incorporate 20 t/ha of poultry litter cost between $1244 and $1345/ha (depending on location). The purchase, handling and transport of the poultry litter made up 70% of the total cost. Discounted partial cash flow analysis was used to estimate the Net Present Value (8% nominal) and Modified Internal Rate of Return of growing crops using SSM. The authors concluded that based on the experimental results, SSM was a highly profitable investment, resulting in an extra annual net return of $419 or $546/ha. This return represents a return to the extra capital invested above a cost of capital of 8% nominal per annum. The authors also conducted a threshold analysis and found that given the cost, an extra 0.8 and 1.03 rotational (wheat and canola) t/ha were the threshold yields required to return the 8% return on investment. The investment remained profitable when investments costs doubled, and when the opportunity cost/discount rate was increased to 20%. The *ex-post* analysis conducted by Sale and Malcolm (2015) was limited to the variability in actual yields and prices that were recorded over the four years of the experiment. No attempt was made by the authors to investigate the implications of yield and price variability on the performance of the investment in SSM

To date, no studies have accounted for the effects of the yield and/or price risks that will occur over a run of years on the profitability of investing in SSM in a cropping system.

2.6 Farm management economic evaluation methods

2.6.1 Activity gross margin analysis

Activity gross margin provides an estimate of the potential revenue, expenses and profit for a single activity or enterprise. Each crop or type of livestock that can be grown is an activity (Kay *et al.* 2004). Activity gross margins can be created for different levels of production and are often used to evaluate the economic benefits of new technologies at the farm-level. The base unit for activity gross margins is typically one hectare for crops (Kay *et al.* 2004). Activity gross margin analysis has been reviewed extensively by Makeham and Malcom (1993), Barry *et al.* (2000), Kay *et al.* (2004), Malcolm *et al.* (2005) among others. The advantages of using activity gross margins are the simplicity of development and the relative ease of incorporating sensitivity analysis to investigate the impact of risk on the budget outcome.

2.6.2 Partial budgets

A common technique used for evaluating changes to parts of the whole-farm business is the partial budget. A partial budget is used to assess a proposed change in the plan and thus it shows only the extra expenses and the extra revenue resulting from the change (Makeham and Malcolm, 1993). Ferris and Malcolm (1999) state that where the initial investment has been made and the concern is to increase productivity, the appropriate method to use should be marginal analysis – using partial budgeting not whole farm budgeting. The partial budget approach to analysing an investment involves defining the costs of investment as the extra capital required and defining annual benefits as the difference between whole-farm profit with and without the change. The partial approach can be used to determine whether the investment represents a good use of capital. Where time is important, discounting needs to be applied to properly compare benefits and costs occurring at different times and over time.

2.6.3 Whole-farm analysis

The whole farm approach to analysing farm systems and conducting farm systems research is well-established and documented, see Heady (1948, 1950, 1952), Kay *et al.* (2004), Malcolm 2004a,b).

The whole farm approach to research examines significant input-output relations and the interrelationships between component parts of the system that are important to the question(s) under scrutiny (Bachman 1950). The approach gathers key economic, financial and technical information and uses a range of techniques, predominantly budgeting and simulation to analyse the information. More recently Malcolm *et al. (*2012) outlines the role of the whole farm approach in dynamic farm systems research, emphasising the role of information about response functions, risk and time. Malcolm *et al. (*2012) highlights that the challenge with the whole farm approach is to select the key aspects of the operation of the whole farm system and study their contribution to problems farmers have in achieving their goals. The confounding challenge is that analysing questions about the farm system requires analysis of most other aspects of the farm business because of important interrelationships.

Because the science is not settled, there are implications for the economic analysis used in this research and the definitiveness of conclusions made.

2.7 The effects of crop rotation

There is limited detail in the literature on methods to account for the effect of crop sequences on farm management economic evaluations. Helmers *et al.* (1986) summarises that when analysing a crop rotation, it is important to separate the stabilizing effect of the rotation as such from the effect of growing more than one crop at a time. When analysing the rotational effect on long-term cropping systems, the method employed by Stranger *et al.* (2008)

ensured each crop phase of the rotation was represented in each year of the analysis. Malcolm *et al.* (2005) page 100 sets out a method to account for the effects of crop rotations on the profitability of different farms;

> *The expected gross margins of individual phases of crop sequences are not adequate information on which to base decisions. The way activities are analysed depends on why they are being analysed. The relative lengths of alternative crop sequences, and the size and timing of gross margins of each phase of a sequence, have to be considered to validly evaluate alternatives. The effects of one crop in one year on another crop in another year have to be taken into consideration. These effects might be of benefit, such as providing a disease break or nitrogen. Or, they could be harmful, such as depleting nitrogen, or adding to yield-reducing or cost increasing populations of disease-causing organisms, weeds or crop re-growth. The GM of a crop activity is specific to the land area under consideration and is affected by the history of that piece of land. In comparing the profitability of different farm plans involving different crop and livestock combinations, returns from entire sequences are compared, not individual segments of a sequence. If a long fallow is used to grow crops, the land has to be set aside for six months or more without producing anything except perhaps some short periods of grazing of unwanted grasses and other weeds. This means that the GM per hectare devoted to crop has virtually to be halved – that is, one fallow hectare and one crop hectare are needed to produce each crop. If it is assumed that each segment of each sequence will be present*

> *on the farm in each year, then the annual total gross margin per sequence-hectare is the figure to use to compare with alternative rotations.*

2.8 Risk and Uncertainty

Hardaker *et al (*2015) page 4, define the terms risk and uncertainty as:

> *Risk is imperfect knowledge where probabilities of possible outcomes are known, and uncertainty exists when these probabilities are not known.*

In farm management economics, risk is part of the consequence of decisions made within the business and relates to the volatility of potential outcomes. Risk can be classified into two types: business risk and financial risk. Business risk is the risk any business faces no matter how it is financed. It come from production and price risk, uncertainty and variability. Financial risk is the increase in the variability in returns to the business owners as a result of using debt. The amount of debt used by a business affects the cost of debt leading to larger financing requirements and extra finance costs (Makeham and Malcolm 1993).

Managing risk is about gathering relevant information, weighing it judiciously and acting accordingly (Malcolm *et al.* 2005). A good decision is a considered choice based on rational interpretation of the available information. Bad decisions are those that have no hope of successful outcomes, even if favourable conditions prevailed. Whether such a decision turns out right or wrong is partly a matter of luck and in any case can never be determined until after the event (Dillon *et al.* 1977). Analysing changes and making decisions requires considering the volatility of potential outcomes. The method for doing this requires the use of information from investigation of 'what if' scenarios using budgets (models) built into spreadsheets and weigh up how likely they are to happen (Malcolm *et al.* 2005).

Stochasticity means variation caused by the random events. In this analysis the random events are prices and yields occurring in any production year. Riskin this work is defined as volatility of annual profit or net cash flow around the mean over the life of the investment. The volatility is measured using the standard measures of variance around the mean, the standard deviation and the coefficient of variation.

2.8.1 Subjective and objective probabilities

Historical frequency of events occurring can be expressed as objective probabilities. Objective probabilities are not relevant to decision making about a changed future. Subjective probabilities are the only relevant probability estimates to use in decision-analysis (Anderson *et al.* 1977). In this research the probability distributions of prices are subjective probabilities about the prices of wheat and canola in the future, formed using information about past and forecast prices. The subjective probability distribution of yields is based on the actual yields that have been achieved in past research, but the probability is subjective in that a judgement is imposed that these past yields are likely to be achieved again in the future.

2.8.2 Stochastic simulation

Stochastic simulation can be used to explicitly represent unpredictable variables in the value of benefits generated by the investment. Stochastic simulation involves solving a farm model using different possible individual values for each of the stochastic variables in the model. These values are drawn from probability distributions which represent the stochastic variables. Each time the model is solved, an individual value for the variable of interest – the annual benefit is calculated. This is known as an iteration. By performing thousands of iterations, a probability distribution of annual benefits is obtained. In turn, the probability distribution of annual benefits is then used as an input to stochastic simulation of a discounted cash flow analysis to obtain a probability distribution of the net present values of the pasture investments (Hardaker *et al.* 2015).

There are many examples where stochastic simulation has been used to evaluate risky farm investment decisions. Relevant to this study is the work of Heard *et al.* (2012), Ho *et al.* (2013) and Lewis *et al.* (2018). These studies investigated how changing an operating system effects farm profit and risk. Experimental data and stochastic simulation were used to create probability distributions for farm profit that represent the risky prospects evaluated.

2.8.3 Attitude to Risk

An individual's attitude towards risk can be categorized into five general types: highly risk preferring, risk preferring, neutral, risk averse and highly risk averse (Hardaker 2000). Risk averters are prepared to sacrifice income for a reduced likelihood of lower income or losses. Risk preferers, favour more risky investments where the chance of higher gains exists, along with the chance of lower income or losses. Risk neutral decision makers select the highest anticipated return, regardless of the associated probabilities of loss or gain (Boehlje and Eidman 1984).

Given these observations, the question arises as to whether a farmer's risk aversion needs to be considered in farm investment decisions. Hardaker and Lein (2005), summarise that farmers are highly risk averse, even for marginal decisions. Pannell *et al.* (2000) demonstrates that farmers in developed countries appear to have relatively low levels of risk aversion, especially in relation to investments involving a relatively small proportion of total wealth. Consistent this argument other studies conclude that the cost of ignoring risk aversion may be less than what is commonly thought. The phenomenon of flat payoff functions described by Pannell (2006) means that the effects upon the outcomes of the analysis entailed by including risk aversion are likely to be very small.

2.8.4 Mean – Variance analysis

The mean-variance analysis (also known as the *E,V* efficiency rule) is a simple method of ranking risky choices. As described by Hardaker *et al.* (2015), the analysis is based on the proposition that if the expected value (mean or median) of alternative A is greater than alternative B and the variance (standard deviation) of A is less than the variance of B, then alternative A is the preferred choice. The limited information required (mean and variance of a distribution of outcomes) for this approach is its biggest advantage and the reason for its popularity (Hardaker *et al.* 2015). However, this is also a limitation of the approach as it means that alternative risky prospects are not compared in terms of the full distribution of outcomes.

2.8.5 Stochastic Dominance

Stochastic dominance is a method of risk analysis used to make convenient observations about risky choice when an absence of specific knowledge about a farmer’s attitude towards risk (utility function) exists. Described by Hardar and Russell (1969), the method for identifying risky choice is based on the cumulative probability of the risky prospects being considered. A Cumulative Distribution Function (CDF) is a method of deriving continuous probability distributions (Anderson *et al.* 1977).

Using CDF’s and the assumption that an individual prefers more wealth to less, First-order Stochastic Dominance (FSD) is the simplest and most universally applicable criteria to rank different probability distributions (Barry 1984) When two CDF’s are compared and weighted, FSD is reached when the CDF of the preferred alternative is always less than that of the inferior prospect up to any payoff. Graphically, FSD means that the CDF of the dominant distribution must never lie above the CDF of the dominated distribution (Hardaker *et al.* 2015). In some cases, application of FSD may not be able to discriminate between alternatives sufficiently, in the sense that it is judged that there are still too many choice alternatives in the efficient set. In this case, more discriminating methods such as second- and third-degree stochastic dominance and stochastic efficiency with respect to function may be considered (Hardaker *et al.* 2015)

3 Method

The focus of this thesis is the likely profit and risk of investing in subsoil manuring (SSM). Investment costs and annual activity gross margins for a set rotation are used to estimate the economic performance of SSM. Risk analysis is used to assess the effect of price and yield variability on the mean and variance of outcomes from investing to ameliorate subsoil constraints to crop production. The research method is summarised in the schematic diagram in Figure 3.1.

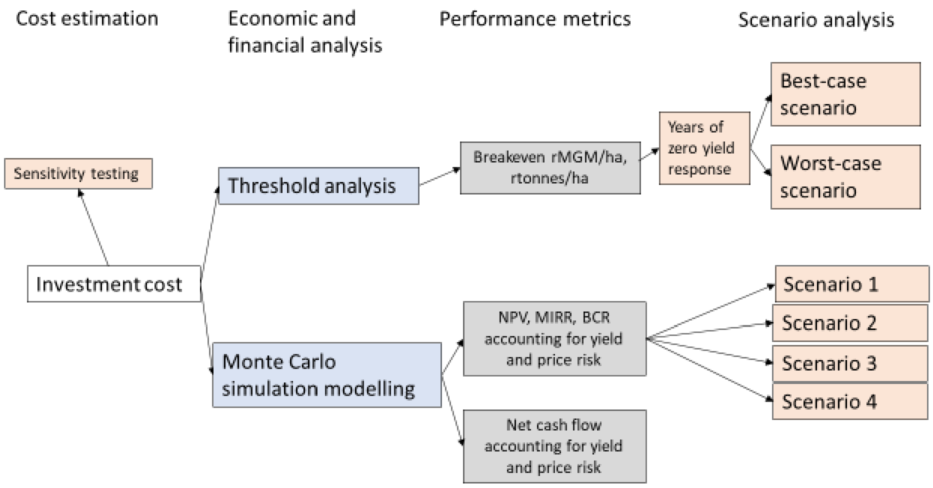

Figure 3.1. A schematic representation of the method used in this research.

3.1 Economic Analysis

The economic effects of the using subsoil manure in a farm system are assessed using partial discounted cash flow budgets over five and ten-years. The approach is standard farm management economics, as described in Malcolm *et al.* (2005).

3.1.1 Rotational Marginal Gross Margin

Activity gross margins are estimated as the gross income minus variable expenses for an activity. Each crop that can be grown is an activity and the base unit for activity gross margin is one hectare (Kay *et al.* 2004; Malcolm *et al.* 2005).

The PIRSA crop gross margin guide (PIRSA 2019) provides a series of representative crop gross margins which itemise the most likely yield and variable costs for the major crops across rainfall zones. An investment in SSM to increase crop yields has associated extra variable costs for the extra yield resulting from the intervention. The PIRSA estimates of crop activity gross margins for the high rainfall (>400mm) zone were used in this research as the basis for estimates of the annual activity variable costs which related to the yields of the crops grown. The PIRSA estimates are based on southern cropping conditions and applicable to this research.

When a change is made to a farm system, it is the marginal changes that matter. In this case, the focus is on the marginal change to crop activity gross margin as a result of SSM. Marginal Gross Margin (MGM) is an estimate of the extra yield-related income and variable costs associated with the extra yield produced because of SSM. The extra variable costs such as levies, harvest costs and freight costs associated with extra yield are the relevant marginal changes with an investment in SSM. It is assumed that the variable costs of cultivation, sowing and spraying are costs that vary with hectares covered, not with tonnes of output, so will not change directly with yield increases. Seeding rates are not increased with SSM, so seeding costs remain unchanged as yield increases. No extra machinery or equipment is needed during the years after SSM (Table 3.1). Extra yield implications for extra fertilizer are captured in the initial investment in manure to ameliorate subsoil condition.

Table 3.1 Marginal Gross Margin

Extra Income ($/ha) = extra yield (t/ha) x price ($/t)	
Extra variable costs	
Wheat	**Canola**
GRDC Levy ($/t.ha) = 1% of extra income ($/ha)	**GRDC Levy ($/t.ha)** = 1% of extra income ($/ha)
EPR and State Levies($/t.ha) = $3.50 x extra yield (t/ha)	**EPR and State Levies ($/t.ha)**= $0.50 x extra yield (t/ha)
Harvesting ($/t.ha) = $20 x extra yield (t/ha)	**Harvesting ($/t.ha)** = $41 x extra yield (t/ha)
Freight ($/t.ha) = $20 x extra yield (t/ha)	**Freight ($/t.ha)** = $25 x extra yield (t/ha)
Marginal Gross Margin ($/ha) = Extra income – Extra variable costs	

Wheat and canola are the dominant crop types used in the SSM field trial data. Wheat and canola are grown as part of a sequence of crop activities (rotations) over time in crop farms in the Victorian high rainfall zone (HRZ) (Robertson *et al.* 2016). Rotating crops in sequence reduces variability of yields compared with monoculture practices and provides agronomic benefits for subsequent crops in the rotation (Helmers *et al.* 1986). The expected MGM of an individual phase of a wheat or canola rotation does not provide enough information on which to base a decision. The performance of crop activities can only be assessed in terms of the sequence or rotation in which they are grow, i.e. crops are not grown as 'standalone' activities. The 'Rotational Gross Margin' is the metric to assess the economic performance of crop activities. Hence, in this analysis, Rotational Gross Margin is used evaluate the performance of all crops grown in the analysis of crop rotation. To capture the impacts on crop yields of seasonal variability at a time and over time, the crop activities and crop rotations are analysed as though each component of the rotation is present on the land area in each year (Malcolm *et al.* 2005). Again, the marginal effects are the relevant effects to analyse a change in a farm system. Thus, the rotational Marginal Gross Margin per hectare (rMGM/ha) is the measure used. This is derived by estimating the rMGM per hectare of wheat and canola activities components on the cropland. for example, a two-hectare crop rotation comprising a hectare of wheat and a hectare of canola on a farm in a year, alternating through time, is estimated as:

$$rMGM(\$/ha.yr) = \frac{MGMwheat + MGMcanola}{2} \tag{1}$$

3.2 Data

3.2.1 Investment Cost

The assumption was that the farm has a 430-horsepower tractor that normally works 800 hours/year with 5 years of ownership remaining. It will now be used for an additional 200 hours per year placing chicken litter in the subsoil. The tractor initially cost $300,000 and after 10 years will have a salvage value of $62,000 in nominal dollars. The SSM implement cost $100,000 to construct, has a salvage value of $30,000 in nominal dollars after 10 years. The implement work rate is 3.5 km/hr or 1.2 ha/hr assuming a 70% field efficiency (Hanna 2016) to apply 20t/ha of chicken litter to a subsoil depth of 30-40 cm. The cost of owning the tractor, after allowing for depreciation, interest on capital, insurance and shedding is $29 per treated ha. The operating cost of the tractor is $68/treated ha. The total cost of owning and operating the implement, allowing for depreciation, interest on capital, repairs and maintenance (at 5% of the purchase price per year) that are allocated to the subsoil manure activity comes to $68 per treated hectare. The labour cost to operate the tractor and subsoiling implement is $28 per treated ha. The machinery costs are provided in Table 3.2.

Table 3.2 Estimated costs per hectare of applying 20/t chicken litter at 30-40cm subsoil depth

Chicken litter application rate (t/ha)	20
Implement work rate (ha/hr)	1.2
Distance from litter source (km)	180
Chicken Litter cost	
Purchase ($/ha)	263
Delivery ($/ha)	471
Handling ($/ha)	80
Labour ($/ha)	49
Chicken litter cost – Total ($/ha)	863
Subsoil application cost	
Tractor - owning and operating ($/ha)	98
Implement - owning and operating ($/ha)	68
Subsoil application – Total ($/ha)	166
Total Cost ($/ha)	1029

The cost of the chicken litter from a broiler farm in Bendigo Victoria was $6/m^3 or $13/t, assuming 450 kg/m^3. The freight costs were $0.13/t/km, based on a truck capacity of 60 m^3 or 27 tonnes of litter, with a one-way delivery rate of $3.50/km (Hazeldene's pers. comm.). The site of the subsoil amelioration was assumed to be at Westmere in South-Western Victoria, which is 180 km. from the broiler farm. The chicken litter handling costs of Sale and Malcolm (2015) were used, adjusted to 2018 dollars. These costs included $80 per treated hectare to screen the litter and an extra labour unit at $35/hour or $49 per treated hectare was required to reload (assuming it take 30 mins to load and reload) the implement with chicken litter.

3.2.1.1 *Investment cost sensitivity analysis*

The sensitivity of total SSM investment cost to variation in key inputs from the values assumed in section 3.2.1 (base values). The inputs analysed were application rate (t/ha), distance from litter source (km), cost of litter ($/t), operational speed (km/hr) and number of treated hectares per year (ha/yr). All inputs remained at base values while a 50% increase and decrease in each key input was tested independently. Variation in inputs was assessed according to the impact on the total SSM investment cost ($/ha).

3.2.2 Grain yield response to SSM

Yield data for wheat and canola were collated from SSM field trials in the HRZ of Victoria, Australia (Table 3.3). The minimum criteria for the data to be used was:

(i) Trial sites were located in the high rainfall zone of Victoria.

(ii) The trial sites were constrained by a subsoil thought to be responsive to SSM.

(iii) The method used in SSM treatments was consistent across all sites and involved a continual band of chicken litter, applied at 20 t/ha (fresh weight) at a depth of 30-40cm, at the base of a rip-line.

(iv) The chicken litter was applied in the first year of each of the respective trials and not applied again.

(v) Data has been published in peer-reviewed journals.

Yield data from the control treatments at each trial was collected. Control treatments represented the commercial practise of farmers in the region; the control treatments were sown with minimal soil disturbance and this was the only difference from the SSM treatment. Yield response was measured as the difference between SSM and control treatments.

Table 3.3 Summary of SSM field trials undertaken in the high rainfall zone of Victoria to ameliorate constraints in poorly structured subsoils.

Year	**Crop**	**Field trial location**	**Control yield (t/ha)**	**SSM yield (t/ha)**	**Yield response (t/ha)**	**Yield response (%)**	**Reference**
2015	Wheat	Westmere	3.67	2.77	-0.9	-25%	Celestina *et al.* 2018
2006	Wheat	Ballan	3.6	3	-0.6	-17%	Gill *et al.* 2012
2006	Wheat	Ballan	3.6	5.6	2	56%	Gill *et al.* 2012
2011	Wheat	Derrinallum	5	7.4	2.4	48%	Sale *et al.* 2018
2010	Wheat	Wickliffe	9.1	11.6	2.5	27%	Sale *et al.* 2018
2009	Wheat	Penshurst	4.8	7.6	2.8	58%	Sale *et al.* 2018
2012	Wheat	Derrinallum	6.3	10.4	4.1	65%	Sale *et al.* 2018
2011	Wheat	Penshurst	6.8	11.3	4.5	66%	Sale *et al.* 2018
2005	Wheat	Ballan	7	11.6	4.6	66%	Gill *et al.* 2008
2009	Wheat	Derrinallum	5	9.8	4.8	96%	Sale *et al.* 2018
2005	Wheat	Ballan	7.6	13.2	5.6	74%	Gill *et al.* 2008
2014	Canola	Westmere	2.25	2.23	-0.02	-1%	Celestina *et al.* 2018
2007	Canola	Ballan	1.6	2.3	0.7	44%	Gill *et al.* 2012
2007	Canola	Ballan	1.6	2.4	0.8	50%	Gill *et al.* 2012
2010	Canola	Penshurst	0.8	2	1.2	150%	Sale *et al.* 2018
2012	Canola	Penshurst	2.4	4.3	1.9	79%	Sale *et al.* 2018

3.3 Key performance measures

Investment costs, avoided fertiliser costs and rMGM were used in partial development budgets. The partial development budget results showed the expected change in marginal gross margin per hectare for each component and year of the rotation. The annual marginal changes in rotation gross margin as a result of SSM were adjusted to investment net present values using discounted cash flow budgets. This was done for two possible lives of the investment: five and ten years. A 6% (real) discount rate was used to discount the future benefits and costs to present values of the alternative investments. The 6% real discount rate represents a real risk-free opportunity cost of uses of marginal capital in many farm systems and for off farm investments.

The key measures of profitability and economic performance were:

- Net present value (NPV). NPV reflects the rMGM over the life of the investment converted into equivalent present value at the start of the investment. For this analysis, 6% and 10% (real) discount rates was used to compare the NPV of the project to alternative investments.
- Modified internal rate of return (MIRR). This is the return on investment, considering the finance rate for the cost of the investment (6%) and the interest received on reinvestment of cash surpluses (5%) through the life of the investment.

- Benefit-cost ratio (BCR). BCR is the sum of the streams of extra investment benefits and extra costs (annual and capital), discounted at 6% real and expressed as a ratio.

3.4 Risk Analysis

3.4.1 Breakeven (Threshold) Analysis

The additional costs of SSM are known better than the expected extra benefits and risks. A breakeven analysis was conducted using the partial budget model to solve for the minimum extra rMGM/ha per year required to return a NPV equal to zero (i.e. earning 10% return on marginal capital) over the two lives of investment (5 years and 10 years), given the initial capital invested. A salvage value of the initial capital invested of zero was assumed at the end of both time periods and the benefits of avoided fertiliser costs were not included. These conservative assumptions have the effect that the estimated extra net benefits required to ‘breakeven’ with alternative uses of the capital is a maximum extra net benefits required. The associated extra yield required is thus a maximum extra yield required from using SSM, for SSM to be a better use of scarce capital than alternative uses. The unit price received for wheat and canola was held constant at 25-year average prices (real) of $324/t and $578/t respectively to ensure the analysis was evaluating only the effect of SSM economic outcomes, not distorted by effects of unusually high or low grain prices.

3.4.1.1 *Sensitivity Testing*

The sensitivity analysis involved looking at the effects of years in which zero net benefits and the associated zero extra yield (defined as a poor year) were achieved from SSM on the breakeven extra net benefits and associated extra yield required. Discrete scenarios were developed to test different numbers of consecutive years in which zero extra yield (poor year) was achieved, in the five and ten-year analysis period.

Two scenarios were tested in the five-year analysis period: (i) one consecutive poor year; (ii) two consecutive poor years. Four scenarios were tested in the ten-year analysis period: (i) one consecutive poor year; (ii) three consecutive poor years; (iii) five consecutive poor years; and (iv) seven consecutive poor years.

In each scenario the minimum extra rMGM/ha (above the control case) required to return NPV equal to zero at 10 per cent real discount rate, was estimated. The longer a farmer waits for future net benefits of SSM, the less those benefits are worth. The timing of the consecutive poor years was analysed to assess the true economic effects on required future gross margins. Poor year scenarios were tested as occurring consecutively, either early or late in the life of the investment. If the poor years scenario occurred early in the analysis period, a farmer would have to wait longer for the net benefits. This represented the ‘worst’ case for that scenario. If the poor years scenario occurred late in the analysis period, the farmer would not have to wait as long for the net benefits. This represented the ‘best’ case for that scenario. For example, in a ten-year analysis, the scenario with three consecutive poor years – the ‘best’ case – had zero extra yield above the control case in years eight, nine and ten and the ‘worst’ case had zero extra yield in years one, two and three.

3.4.2 Profit and Risk Analysis

Business risk is the volatility of annual operating profit, resulting from volatility of yields and prices. The risk analysis quantified and tested the effects of the effect of added business risk that might result from using SSM. Business risk is risk independent of how a business is financed, called financial risk.

The farm management methods for economic and risk assessments follow from Makeham and Malcolm (1993). Stochastic simulation was carried out on the partial budget model using @Risk (Palisade Corporation, Ithaca, NY, USA), an add-in package to Microsoft Excel, which allows uncertain variables to be defined by probability distributions. The Monte Carlo simulation approach randomly selects sets of input parameters based on the specified probability distributions and a possible outcome is estimated. Each outcome from a random set of inputs is called an iteration. When more iterations are run, the output distributions generated become more stable in the sense that the summary statistics change less, this is called convergence. Convergence in all economic performance outcome distributions was established when 100,000 iterations was used. The standard deviation of the outcome represented the amount of variation around the mean of net returns, or the risk. An alternative measure of risk is the coefficient of variation, which scales the variance by the mean to provide a relative measure of risk that accounts for differences in means (Goodwin and Ker 2002).

To account for the risk of the key variables, input probability distributions were developed for grain price and SSM yield response. Note: in the risk analysis, both price and yield risk are included, compared with the threshold analysis in which only yield was variable.

Risk free discount rate

The risk of yield and price volatility around the mean is included in the discounted cash flow analysis of SSM by using distributions of yields and of prices for the crops involved. Each year of the life of the investment, yield and price points are sampled from the distributions of yield and prices. The resulting 5-year estimates of NPVs are accordingly also presented as distributions. With much of the risk of the investment encapsulated in the analysis in this manner, the discount rate used in calculating the NPV can be a (relatively) risk-free rate. To use a discount rate adjusted for the risk of yield and price volatility, and then also include the risk of yield and price volatility in the analysis by sampling from distributions of these variables to estimate a distribution of NPVs would be to effectively ‘double-count’ or ‘double -adjust’ for these risks. For this reason, the discount rate used in estimating the NPV is a real risk-free rate of return on capital, real opportunity cost of capital, that is available in the economy. A guide to risk-free rates of return on capital available in the economy is the Federal Government 10-year bond rate. This has ranged from 2% real p.a. to 6% real p.a. over the past century. In this analysis, 6% real opportunity cost of capital is used as the risk-free discount rate and the risk surrounding yields and prices is incorporated in the numbers by using distributions of yields and prices.

3.4.3 Profit and Risk Scenarios

Four scenarios were tested within this framework. Each scenario was designed examine different levels of extra net benefits from an investment in SSM.

3.4.3.1 *Scenario 1.*

Grain price

International supply and demand for wheat and canola and currency exchange rates are the key determinants of wheat and canola prices in Victoria.

Australian annual average prices for both crops came from the ABARES annual commodity statistics, converted into 2018 dollars (Figure 3.2). Using @Risk, probability distributions were developed by fitting positively skewed Lognorm distributions to the price data (Table 3.4).

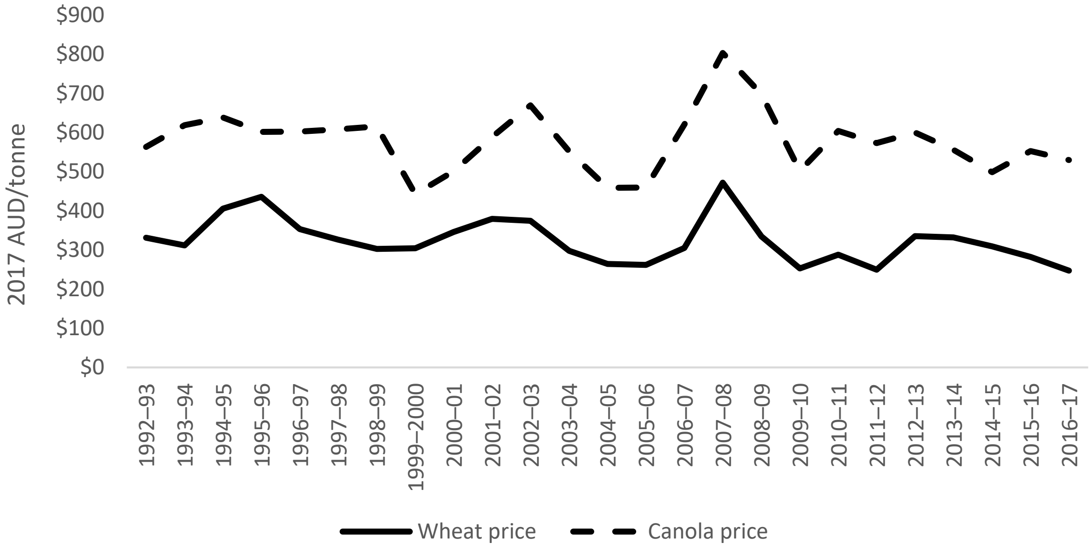

Figure 3.2 Average yearly wheat and canola prices received per tonne in Australia in 2017 dollars (ABARES commodity statistics)

Table 3.4 Type and key percentiles (P) of the grain price distributions used in the analysis.

Variable	Distribution type	P1	P5	P25	P50	P75	P95	P99
All scenarios.								
Wheat price ($/t)	Lognorm	236	252	283	313	353	434	512
Canola price ($/t)	Lognorm	424	461	523	572	627	717	790

SSM yield response

There remains a lack of demonstrated scientific understanding of the mechanisms underpinning crop responses to SSM throughout the life of the investment. Yield response data from SSM field trials (Table 3.3) were used to develop probability distributions for future SSM yield response. At each field trial location, the control and SSM were treated with the same controlled variables (crop variety, seed quantity, herbicides and insecticides) and measurable uncontrolled factors (soil type, initial soil fertility and soil moisture content). The uncertainty in SSM yield response most likely arises from the influence of climatic variables that are random and uncontrollable. Given this assumption, the gross approach to developing yield response probability distributions was used. As described by Anderson *et al.* (1977), the gross approach compounds the climatic variation into the yield response results without identifying the effect of the source of variation. The assumption with this approach is that the available yield response data was from a time span of a length that captured the yield response variability from conditional climatic variables and reflects SSM yield response risk.

As only limited yield response data was available, and the effects of climatic stochastic factors cannot be identified, sparse data techniques described by Anderson (1973) were adopted. Probability distributions were fit using the alternative parameter functions (ALT) in @Risk. The ALT function allows the entry of percentile parameters for specific percentile locations of an input distribution as opposed to the traditional arguments used by the distribution.

The distribution type and the 0.05, 0.50 and 0.95 percentiles were specified. The median of the field trial data for each crop type were selected as the 0.50 percentile. PERT distributions were selected as the most appropriate distribution type to simulate yield response because of the distribution shape. PERT distributions are beta so can account for the skewness and/or kurtosis in the yield data (Goodwin & Ker 2002). Given the percentiles specified, @RISK then used a process of successive approximations from the parameters of a standard Pert distribution to produce the remaining percentiles for the PertALT distributions (Table 3.5).

Table 3.5 Type and key percentiles (P) of the experimental yield response distributions used in scenario 1 and 2.

Variable	Distribution type	P1	P5	P25	P50	P75	P95	P99
Scenario 1 and 2.								
Experimental wheat yield response (t/ha)	PertALT	-2.1	-0.9	1.3	2.8	4.2	5.6	6.2
Experimental canola yield response (t/ha)	PertALT	-0.2	-0.02	0.4	0.8	1.2	1.9	2.3

Avoided fertiliser cost

The high nutrient content of the chicken litter meant a saving can be assumed for the annual use and cost of fertiliser inputs on SSM land. Sale *et al.* (2018) observed that the 20t/ha of poultry litter supplied superior nutrition for the crops. There was higher nitrogen uptake rates and grain protein concentrations in wheat grown in the SSM treatments, compared to conventional crops. These benefits persisted for three years. This meant that expenditure on fertiliser could be avoided for the first three years of the analysis. The PIRSA high rainfall crop gross margin guide provided fertiliser rates and costs per rotational hectare (Table 3.6). These formed the basis for the estimates of fertilizer costs avoided in the first three years of the SSM regime. All investment costs were assumed to be incurred in year one and the benefits from the avoided fertiliser costs were assumed to occur only in first three years of the analysis, regardless of the amount extra yield grown.

Table 3.6 Benefits received from the avoided fertiliser cost in the first three years of the analysis period.

	Fertiliser price ($/kg)	Wheat Rate (kg/ha.yr)	Canola Rate (kg/ha.yr)	Wheat Cost ($/ha.yr)	Canola Cost ($/ha.yr)	**Rotation Avoided cost ($/ha.yr)**
Urea (46:0:0)*	$0.48	160	150	$77	$72	**$74**
DAP (18:20:0)	$0.66	80	75	$53	$50	**$51**
SOA (21:0:24)	$0.43		100		$43	**$22**

*The number parenthesis represents the percentage of Nitrogen: Phosphorus: Sulphur in each fertiliser

Salvage Value

The salvage value of SSM is unknown. The extra benefits from a transformed subsoil may dissipate over time or may be changed to a form that could be maintained over time: a form that is superior to the state of the soil at the start of the investment. Currently no data exists to quantify the proportion of the initial investment remaining, or the residual crop benefits, after a 5 and 10-year period. The uncertainty regarding the amount of the initial capital that could be 'recouped' at the end of 5 and 10-years life of investment meant a salvage value of $0 was assumed for both analysis periods.

Correlation

In the risk analysis, correlation coefficients were defined for yield response and grain price probability distributions to ensure existing relationships were maintained when simulating these variables (Table 3.7). Because crop activities were analysed as though they were present on the same land area in each year, it was assumed that both crop types would respond similarly in a given year. A correlation coefficient of 0.7 was assumed for wheat and canola yield response distributions. The strong correlation meant that if a high yield was selected from a wheat distribution it was very likely that a high yield would be selected from the canola distribution. Similarly, price risk tends to be systemic so strong correlations between prices of different crops are assumed. Changes in yield that affect the aggregate production can impact market prices, therefore the average correlation between crop yield and price is negative (Kimura *et al.* 2010). For this analysis it was assumed to be a moderate negative correlation between the yield response and grain price distributions for each crop type. Although the samples drawn from the distributions were correlated, the integrity of the original distributions was maintained. The resulting samples for each distribution reflect the distribution function from which they were drawn.

Table 3.7 Correlation coefficient matrix for the input distributions used in this analysis.

	Wheat yield response (t/ha)	Canola yield response (t/ha)	Wheat price ($/t)	Canola price ($/t)
Wheat yield response (t/ha)	1			
Canola yield response (t/ha)	0.7	1		
Wheat price ($/t)	-0.3	-0.3	1	
Canola price ($/t)	-0.3	-0.3	0.6	1

3.4.3.2 *Scenario 2*

The sensitivity of excluding all the benefits of avoided fertiliser costs was examined. All avoided fertiliser costs were removed from the partial budget model over the five-year investment life.

3.4.3.3 *Scenario 3*

The sensitivity of a decreased yield response on farm compared with the trial results was examined. Davidson *et al.* (1965, 1967) found that in unfavourable years the average yield of commercial crops was approximately equal to the yields obtained under experimental conditions. In good seasons, commercial yields did not rise as dramatically as experimental yields. Davidson *et al.* (1965) established that in Victorian conditions the average commercial yield was 57% lower than an experimental yield. To account for this relationship the wheat and canola yield response distributions were fitted again using the same method, described in 3.4.1.2, except the experimental data used for the 0.5 and 0.95 percentiles was decreased by 50% (Table 3.8).

Table 3.8 Type and key percentiles (P) of the reduced yield response distributions used in the analysis.

Variable	Distribution type	P1	P5	P25	P50	P75	P95	P99
Scenario 3.								
Reduced wheat yield response (t/ha)	PertALT	-2.1	-1.1	0.4	1.4	2.2	2.8	3.0
Reduced canola yield response (t/ha)	PertALT	-0.2	-0.08	0.2	0.4	0.6	1.0	1.1

In addition to the reduced yield response, declining benefits of avoided fertiliser costs were also tested by decreasing the avoided costs by 50% in year two and then a further 50% in year three (Table 3.9). The adjusted distributions and avoided costs were applied to the partial budget model over the five-year investment life.

Table 3.9. Benefits received from declining avoided fertiliser costs in the first three years of the analysis period.

	Rotation Year 1 ($/ha.yr)	Rotation Year 2 ($/ha.yr)	Rotation Year 3 ($/ha.yr)
Urea (46:0:0)*	74.4	37.2	18.6
DAP (18:20:0)	51.2	25.6	12.8
SOA (21:0:24)	21.5	10.8	5.4

*The number the parenthesis represents the percentage of Nitrogen: Phosphorus: Sulphur in each fertiliser

3.4.3.4 *Scenario 4*

Currently no experimental data exist to quantify the relationship of time and yield response. In scenarios 1- 3, the same probabilities of yield responses were applied to each year of the five years of investment life, and there is no 'salvage value' of the initial investment. This approach does not account for the expected decay in the potential yields from the initial application of SSM as the poultry litter nutrients are depleted. Nor does it capture likely, and possibly medium-term, positive benefits of higher yields in the future on SSM treated areas compared with the untreated or *status quo* situation, from continued increased availability of plant-available water as a result of the subsoil changes created by the ameliorant.

Scenario 4 is set up to shed light on the investment if the case was that potential yields decline after year 5. Declining potential yield responses from year 6 effects the profitability of the SSM investment over a 10-year life. The assumption in Scenario 4 is that the range and likelihood of the initial advantages of SSM begin to diminish after year 5 so by year 10 the most likely extra yield response is zero, i.e. back to the *status quo* case. A decay rate in the extra yield that result from the SSM in years 1-5, of 60% per year, was applied from year 6 to year 10. This resulted in a median extra yield response of close to zero in year 10. It was assumed that the SSM experimental yield responses for wheat and canola (Table 3.5) were on offer in years 1 - 5. Values in the extra wheat and canola yield response probability distributions in year 6 were reduced by 60% from year 5, year 7 extra yields were reduced by 60% from year 6, year 8 extra yields were reduced by 60% from year 7 and the method continued for every subsequent year up to year 10 (Table 3.10).

Table 3.10 Type and key percentiles (P) of the decayed yield response distributions used in scenario 4.

Variable	Distribution type	P1	P5	P25	P50	P75	P95	P99
Scenario 4								
Yr 6 canola yield response (t/ha)	PertALT	-0.08	-0.01	0.16	0.32	0.50	0.76	0.91
Yr 7 canola yield response (t/ha)	PertALT	-0.03	0.00	0.06	0.13	0.20	0.30	0.37
Yr 8 canola yield response (t/ha)	PertALT	-0.01	0.00	0.03	0.05	0.08	0.12	0.14
Yr 9 canola yield response (t/ha)	PertALT	0.00	0.00	0.01	0.02	0.03	0.05	0.06
Yr 10 canola yield response (t/ha)	PertALT	0.00	0.00	0.00	0.01	0.01	0.02	0.02
Yr 6 wheat yield response (t/ha)	PertALT	-0.85	-0.35	0.51	1.12	1.68	2.26	2.47
Yr 7 wheat yield response (t/ha)	PertALT	-0.34	-0.14	0.20	0.45	0.67	0.90	0.99
Yr 8 wheat yield response (t/ha)	PertALT	-0.13	-0.06	0.08	0.18	0.27	0.36	0.39
Yr 9 wheat yield response (t/ha)	PertALT	-0.06	-0.02	0.03	0.07	0.11	0.14	0.16
Yr 10 wheat yield response (t/ha)	PertALT	-0.02	-0.01	0.01	0.03	0.04	0.06	0.06

3.4.4 Additional testing

The magnitude of the likely SSM yield responses and how long SSM yield responses persist remain unknown. Because of the lack of understanding there are many alternate future scenarios that could be tested. The assumptions and the scenarios in this research were formed by current scientific hypotheses and expert opinion. To help understand the results presented above further sensitivity testing was undertaken within the scenarios used in this research. This investigative testing mostly examined assumptions relating to the investment life and the experimental yield/commercial yield penalty. The results of this testing will not be presented in detail.

3.4.5 Financial analysis

Finance is concerned with the flows of cash in and out over the life of the investment. (Note: the economic analysis has the implicit assumption that all annual cash deficits can be financed at the going market rate of interest, which is also the opportunity cost (in a perfect capital market), and all annual cash surpluses earn the going market rate of interest or opportunity cost). In practice financial considerations are often paramount. Provided the economic returns look like they will be adequate, the cash in and cash out story is often a key determinant of whether the potential investor will adopt the change.

Financial risk analysis was also conducted. This involved comparing the rotational annual net cash flows from the control (no SSM) area of crops on the cropping land with the rotational annual net cash flows from the SSM area crops on the same cropping land, over the life of the investment. The variability in average annual net cash flow from the control and SSM scenarios was compared over a five- year investment life.

Stochastic simulation was conducted using the Monte Carlo approach described in 3.4.1. The standard deviation and coefficient of variation represent the amount of variation in average annual cash flow, or the financial risk.

3.4.5.1 *Control crop rotational net cash flow*

Control crop rotational nominal net cash flow was estimated using income and costs for a wheat/canola rotation on non-SSM land (Table 3.11). Control yield probability distributions (Table 3.10) were developed from experimental control data (Table 3.3) and variable costs were taken from the PIRSA crop gross margin guide for high rainfall areas.

Table 3.10 Type and key percentiles (P) of the control yield distributions used in the financial analysis.

Variable	Distribution type	P1	P5	P25	P50	P75	P95	P99
Control yield								
Control wheat yield (t/ha)	PertALT	2.5	3.6	5.2	6.3	7.4	9.0	10.1
Control canola yield (t/ha)	PertALT	0.6	0.8	1.2	1.6	1.9	2.4	2.6

Table 3.11 Annual rotational net cash flow for control crop.

Income Gross Income ($/ha)	Control yield (t/ha) x price ($/t)	
	Wheat	Canola
Costs		
GRDC Levy	1% of gross income ($/ha)	1% of gross income ($/ha)
EPR and State Levies	$3.50 x yield (t/ha)	$0.50 x yield (t/ha)
Seed and treatment ($/ha)	$51	$50
Fertiliser ($/ha)	$130	$165
Herbicide ($/ha)	$118	$93
Fungicide ($/ha)	$25	$5
Insecticide ($/ha)		$67
Grain and fert Freight ($/t)	$50	$55
Contract Operations ($/ha)	$185	$289
Net cash flow ($/ha)	Gross income – Variable costs	

3.4.5.2 *SSM crop rotational net cash flow*

SSM crop rotational net cash flow was estimated by adding the rotational marginal gross margins described in Section 3.1.1 to the control rotational net cash flow (Table 3.12), net of annualised SSM investment costs. The annual cost of the SSM investment was estimating using the annuity (at 6%) of the capital invested over a five-year life. Separate yield probability distributions were used for control and SSM response. Yield probability distributions were not correlated.

Table 3.12 Annual rotational net cash flow for control crop.

Marginal gross margin ($/ha)	Extra income - extra costs
Control net cash flow ($/ha)	Gross income – Costs
SSM investment cost Annualised capital cost ($/ha)	5-year life $271/ year
SSM annual net cash flow ($/ha)	Marginal rotational gross margin + Control rotational net cash flow - Annualised capital cost ($/ha)

4 Results

4.1 Cost sensitivity

The sensitivity of total SSM investment cost to a 50% variation in litter application rate, distance from litter source and cost of litter was tested. The key inputs were tested independently while all other inputs remained constant.

Changes to application rate had the largest impact on total SSM cost. A 50% variation in application rate resulted in a 38% change in total SSM cost (Table 4.1, Figure 4.1). A 50% change in the distance poultry litter was transported effected the total cost by 23%. When the price of poultry litter per tonne was varied by 50%, the total cost of SSM changed by 13%.

Table 4.1 Effect on total SSM cost when litter application rate, distance from litter source and cost of litter were varied by 50% from the base values while all other variables remain constant.

	Minimum			**Maximum**			
	Total SSM cost			**Total SSM cost**			
Input	**Cost ($)**	**Change (%)**	**-50% base value**	**Cost ($)**	**Change (%)**	**+50% base value**	**Base Input value**
Application rate (t/ha)	$638	-38%	10	$1,420	38%	30	20
Distance from poultry litter source (km)	$793	-23%	90	$1,265	23%	270	180
Cost of poultry litter ($/t)	$898	-13%	6.5	$1,160	13%	19.5	13

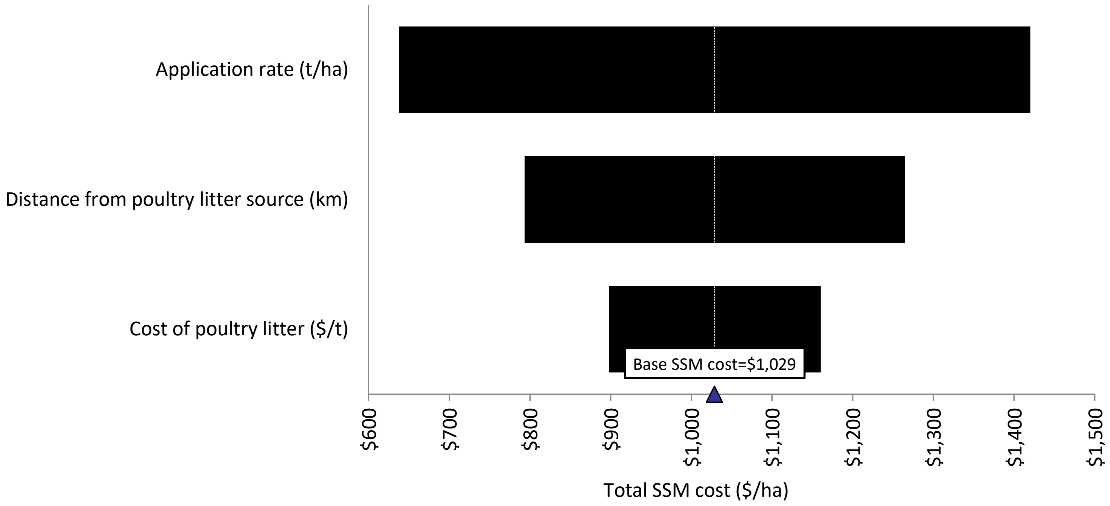

Figure 4.1. Effect on total SSM cost when litter application rate, distance from litter source and cost of litter were varied by 50% from the base values while all other variables remain constant.

4.2 Threshold analysis

Under the assumptions described in 3.2.1, Tables 4.2 and 4.3 show the maximum requirements from an investment in subsoil manuring (SSM) to be competitive with an alternate use of scarce capital earning 10% real. The net benefits to earn the required return on capital increased as years with zero SSM benefits increased. The proportional increases in required extra rotation marginal gross margin (rMGM) and rotation tonnes were the same for each of the zero response year scenarios. The threshold extra requirement in rMGM and rotation tonnes was higher in all scenarios when no SSM yield benefits occurred at the beginning of the investment. The results at 10% are insensitive to risk premium. A lower threshold earning rate, decreases the extra benefits required from the investment but the rankings and conclusions do not change.

Table 4.2. Summary of threshold analysis results: required extra rotation dollars per hectare per year. The number of zero response years was tested for early and late in the investment period representing the 'worst' and 'best' case respectively.

Number of zero response years	0	1	3	5	7
Five-year extra rotation $/ha/yr required					
'Best' case	247	295	539		
'Worst' case	247	325	717		
Ten-year extra rotation $/ha/yr required					
'Best' case	152	162	192	247	376
'Worst' case	152	179	256	397	733

Table 4.3 Summary of threshold analysis results: required extra rotation tonnes per hectare per year. The number of zero response years was tested for early and late in the investment period representing the 'worst' and 'best' case respectively.

Number of zero response years	0	1	3	5	7
Five-year extra rotation tonnes/ha/yr required					
'Best' case	0.77	0.92	1.68		
'Worst' case	0.77	1.01	2.24		
Ten-year extra rotation tonnes/ha/yr required					
'Best' case	0.47	0.51	0.60	0.82	1.17
'Worst' case	0.47	0.56	0.80	1.10	2.28

4.2.1 Five-year investment life

An extra rMGM of $247 per year or 0.77 rotation tonnes per hectare per year was required when the SSM yield benefits occurred in all five years (Table 4.1, Figures 4.2 and 4.3). The required net benefits increased to $295/ha/yr or 0.92 t/ha/yr (+20% compared to SSM benefits in all five years) when no SSM yield benefits occurred in the last year of the five-year investment period ('best' case). The requirements increased further to $325/ha/yr or 1.01 t/ha/yr (+32% compared to SSM benefits in all five years) when no SSM yield benefits occurred in year one of five (‘worst’ case). The extra requirements were highest when no SSM yield benefits occurred in year three of the five years. An extra rMGM of $539 or 1.68 rotation tonnes per hectare per year (+118% compared to SSM benefits in all five years) was required when no SSM yield benefits occurred in the last three years of the investment period (‘best’ case). A rMGM of $717 or 2.24 rotation tonnes per hectare per year (+191% compared to SSM benefits in all five years) was required when no SSM yield benefits occurred in the first three years (‘worst’ case). This threshold was the largest for the five-year investment.

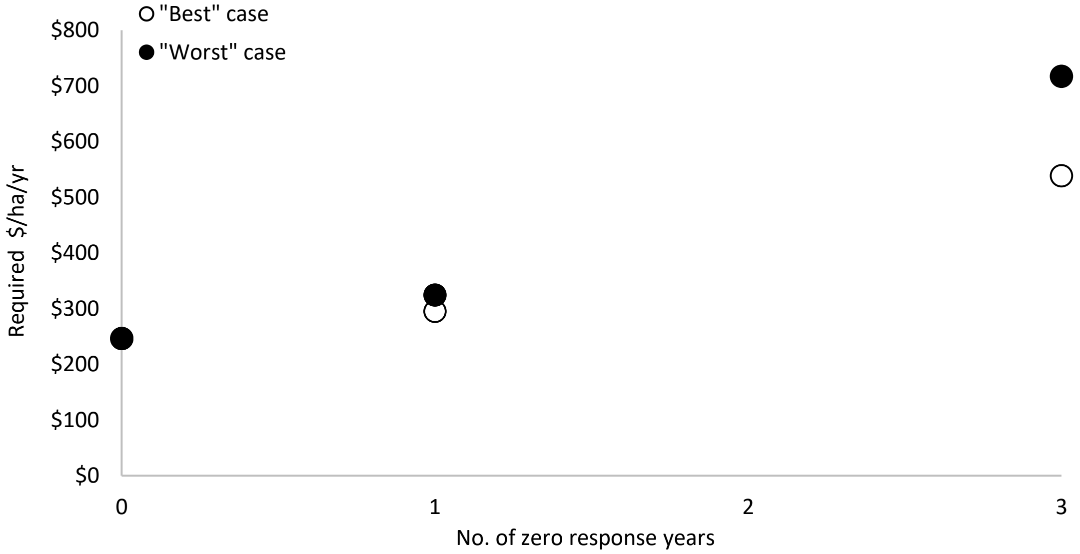

Figure 4.2. Required extra rotation marginal gross margin per hectare ($/ha/yr) to be competitive with alternative investments earning 10% (real) over five years ($324/t wheat, $578/t canola, zero salvage value, zero avoided fertiliser benefit). Discrete scenarios on the x-axis represent different numbers of consecutive years in which zero extra yield (poor years) was achieved. The poor years were tested early and late in the investment period representing the ‘worst’ and ‘best’ case respectively for that scenario.

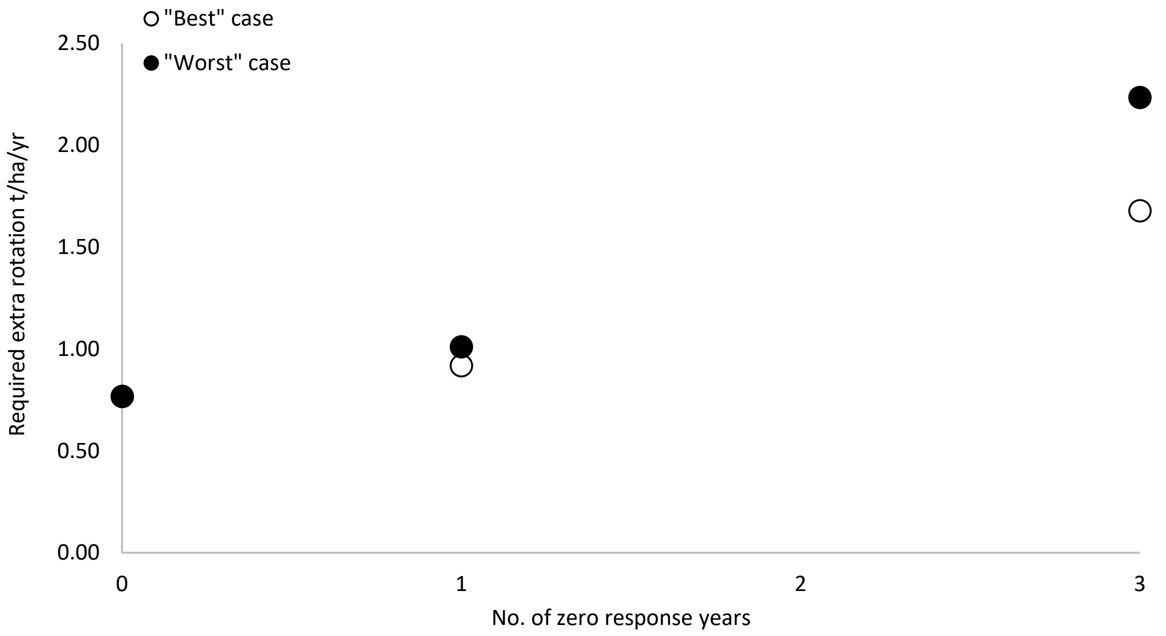

Figure 4.3. Required extra rotation tonnes per hectare per year to be competitive with alternative investments earning 10% (real) over five years ($324/t wheat, $578/t canola, zero salvage value, zero avoided fertiliser benefit). Discrete scenarios on the x-axis represent different numbers of consecutive years in which zero extra yield was achieved. The poor years were tested early and late in the investment period representing the 'worst' and 'best' case respectively for that scenario.

4.2.2 Ten-year investment life

An extra rMGM of $152 or 0.47 rotation tonnes hectare was required when the SSM yield benefits occurred in all ten years (Table 4.1, Figures 4.4 and 4.5). The threshold (extra yield and rMGM required for investment to earn opportunity cost of capital) increased by +7% (compared to SSM benefits in all ten years) when no SSM benefits occurred in the last year of the investment period ('best' case). The 'best' case threshold was larger when no SSM benefits occurred in the last three years (+26%); the last five years (+62%) and the last seven years (+147%) of the ten-year investment period. The threshold increased by +17% (compared to SSM benefits in all ten years) when no SSM benefits occurred in the first year of the investment period (‘worst’ case). The ‘worst’ case threshold further increased when no SSM benefits occurred in the first three years (+68%); the first five years (+161%) and the first seven years of the investment.

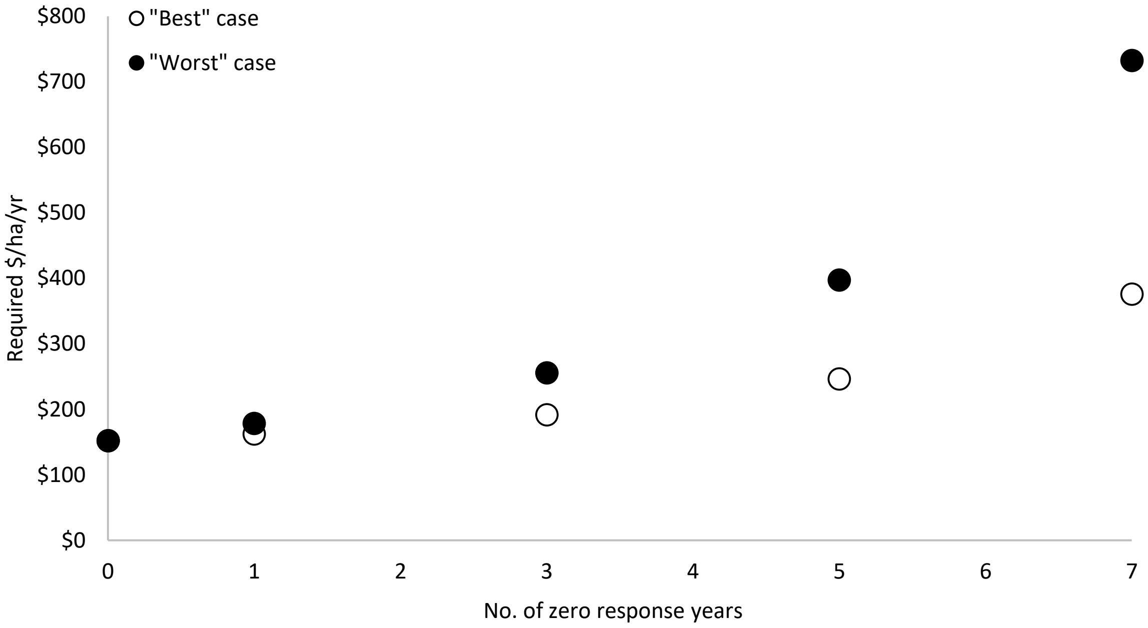

Figure 4.4. Required extra rotation marginal gross margin per hectare ($/ha/yr) to be competitive with alternative investments earning 10% (real) over ten years ($324/t wheat, $578/t canola, zero salvage value, zero avoided fertiliser benefit). Discrete scenarios on the x-axis represent different numbers of consecutive years in which zero extra yield was achieved. The poor years were tested early and late in the investment period representing the ‘worst’ and ‘best’ case respectively for that scenario.

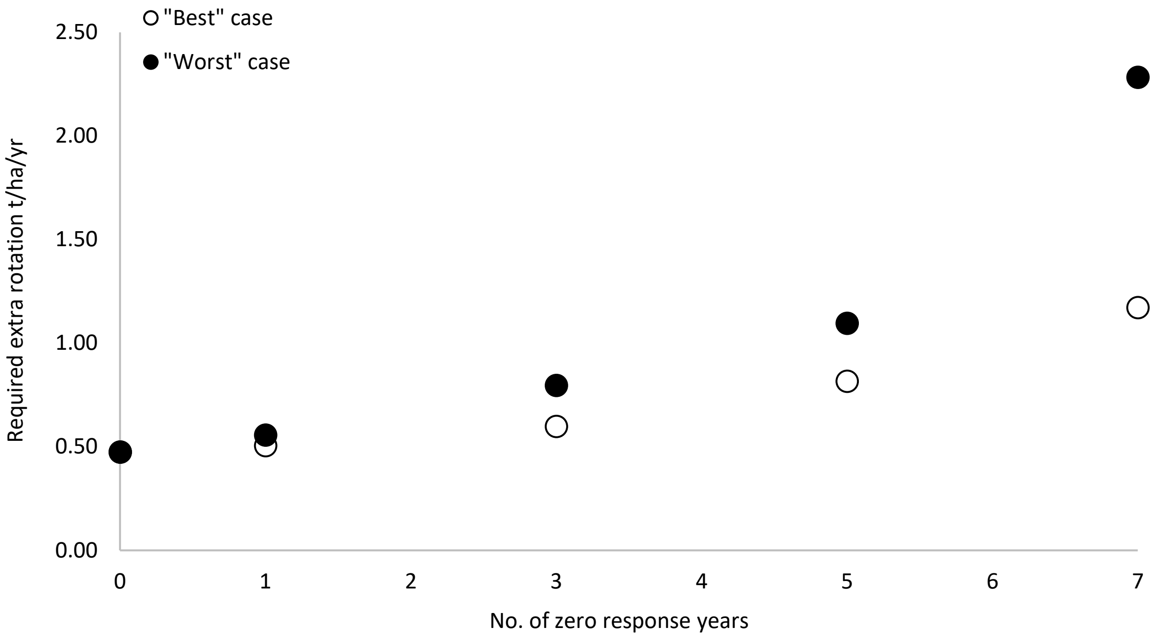

Figure 4.5. Required extra rotation tonnes per hectare per year to be competitive with alternative investments earning 10% (real) over ten years ($324/t wheat, $578/t canola, zero salvage value, zero avoided fertiliser benefit). Discrete scenarios on the x-axis represent different numbers of consecutive years in which zero extra yield was achieved. The poor years were tested for occurring early and late in the investment period representing the 'worst' and 'best' case respectively for that scenario.

4.3 Profit and risk results

In this section, the experimental SSM yields that have been produced are modelled and estimates are made of the performance of the investment if these yields were achieved. Performance is judged using the criteria of NPV, MIRR and BCR. A positive NPV on investment represents the addition to wealth that would result, above what would be earned in the alternative investment earning 6% on capital. If the BCR is greater than 1, the investment is earning more than the required 6% return.

The investment analysis gives results as net present value at a real risk-free discount rate of 6%; a benefit cost ratio of the streams of benefits and costs discounted at the 6% real risk free opportunity cost rate; and a modified internal rate of return which too is a risk free measure as the volatility of yields and prices are included in the yields and prices used in the analysis. Interpreting these NPV, BCR and MIRR results means comparing the probabilities of achieving positive NPVs, BCR and MIRRs greater than 6%. For example, if NPV was positive at every combination of yield and price at 6% discount rate then this would mean the investment earns more than the risk-free rate of return at every possible yield and price. Or if the BCR was greater than one 80% of the time, this means that 80% of the time the investment earns more than the opportunity cost. Or, if the MIRR is greater than 6% in 90% of the iterations of the investment budget, this means that 9 times out of 10 the investment earns more than the risk-free rate of return on capital.

The probability that the MIRR of investing in SSM exceeding the risk-free rate of return on capital, and by how much, could be compared to the probability of alternative uses on the farm of capital, which had similar price and yield risk to that of the SSM investment, earning more than the 6% risk-free rate of return.

Profit and risk scenario results

Over a range of combinations of conditions, and over a run of five and ten years, all SSM scenarios were more profitable on average than an alternative investment earning 6% (real). (Table 4.4, Table 4.5). Profitability is indicated by the stream of annual benefits and costs having a positive NPV or a BCR above 1 at the required rate of return of 6% real p.a. The average return on the SSM investment is indicated by the MIRR.

Table 4.4. Mean, standard deviation (s.d.) and coefficient of variation (c.v) of net present value (NPV), modified internal rate of return (MIRR) and benefit cost ratio per hectare over five year investment life for each scenario: experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

Economic performance measure	5-year Scenario 1	5-year Scenario 2	5-year Scenario 3
Mean NPV (6% real) ($/ha)	1,343	1,040	50
s.d. ($/ha)	716	663	444
c.v (%)	53%	64%	881%
Mean MIRR (%)	23%	20%	6%
s.d. (%)	8%	9%	9%
c.v (%)	36%	43%	147%
Mean BCR (6% real)	1.9	1.6	1.0
s.d.	0.5	0.3	0.4
c.v (%)	23%	22%	36%

In scenario 1 experimental yield response and three years of avoided fertiliser costs was examined, producing a mean NPV of $1,346 per hectare and a mean BCR of 1.9. The removal of the avoided fertiliser benefits in Scenario 2 reduced the mean BCR and NPV to 1.6 and $1,040 per hectare respectively. A reduced experimental yield response and reduced avoided fertiliser benefit (Scenario 3) further decreased the mean NPV to $52 per hectare and the BCR to 1.0.

An experimental yield response and three years of avoided fertiliser (Scenario 1) costs had a mean MIRR of 23%. Excluding the extra benefits of avoided fertiliser costs (Scenario 2) resulted in a small decrease in mean MIRR (3% units). A reduced experimental yield response and reduced avoided fertiliser benefit (Scenario 3) further decreased mean MIRR to 6% (75% decrease from scenario 1).

Variation in the return on extra capital was measured by the standard deviation (the range 33% above and below the mean) and the coefficient of variation (the ratio between the standard deviation and the mean) (Table 4.4). In Fig. 4.6, 4.8 and 4.11, the mean is represented by the line in the middle of the box. The size of the box is an indication of the variability or risk associated with each scenario and measures the spread of the middle 50% of data. The whiskers extending from the boxes represent 40% of the data that falls outside the middle 50%, such that 90% of all observations are incorporated in the box plots. Over 5-years for each scenario the standard deviation of the NPV increased as the mean increased and there was little difference in the standard deviation in BCR and MIRR. In Scenario 1 and 2 there was only small differences in the coefficient of variation of each performance measure. Scenario 3 had the largest coefficient of variation in each performance measure. The coefficient of variations for the NPV was 881%, MIRR was 147% and BCR was 36%.

The likelihood of earning 6% real from the SSM if the investment lasted 5-years is shown in Figure 4.10. Removing any benefit from avoided fertiliser costs (Scenario 2) resulted in only small differences in the likelihood that the required rate of return will be earned between Scenario 1 and 2 in the five-year life. A reduced experimental yield response and decay in the rate of avoided fertiliser benefits (Scenario 3) resulted in a 45% chance the investment would return 6% or less over a five-year investment life.

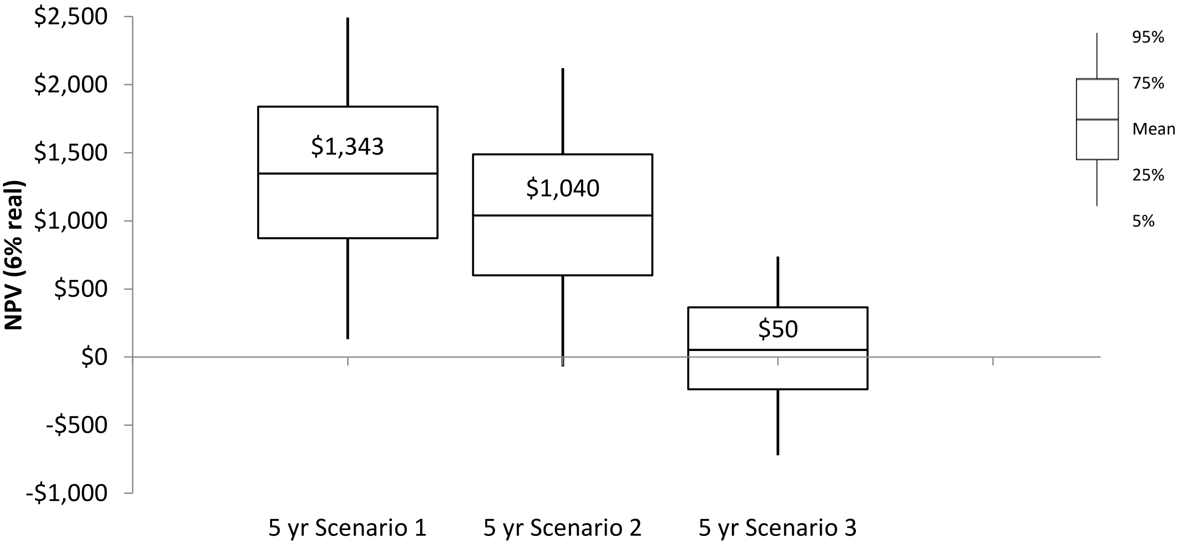

Figure 4.6. Median and key percentiles of NPV per hectare at 6% real discount rate in a five-year investment life for each scenario: experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

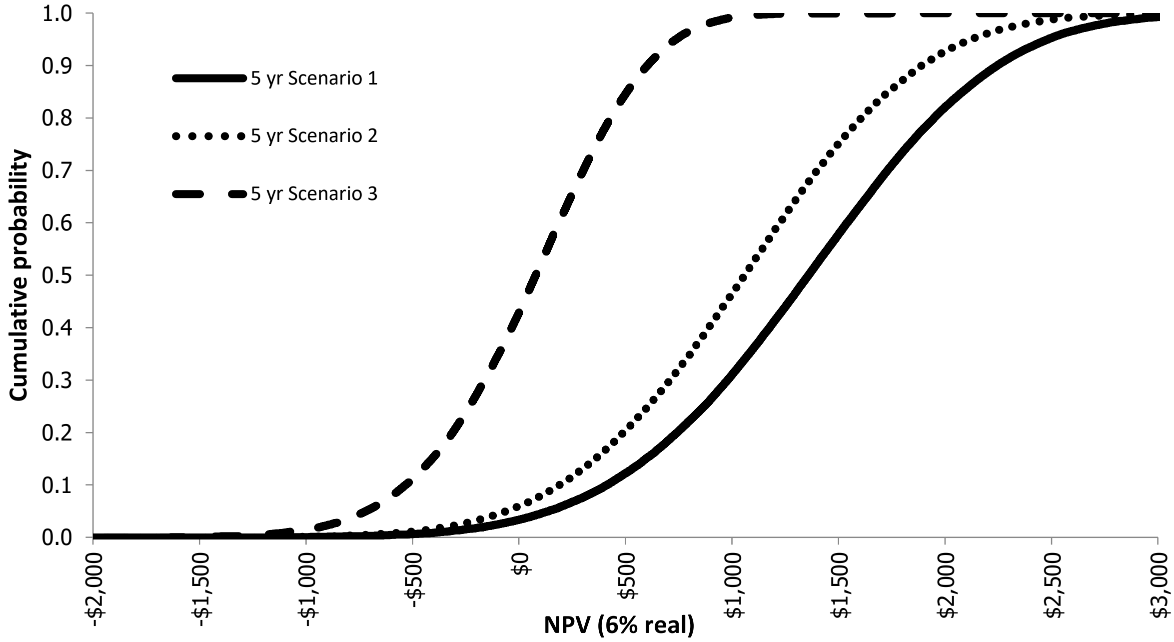

Figure 4.7. All possible NPV outcomes for each scenario and the probability that each NPV outcome, or one with a lower value will occur. Scenarios are defined as: Experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

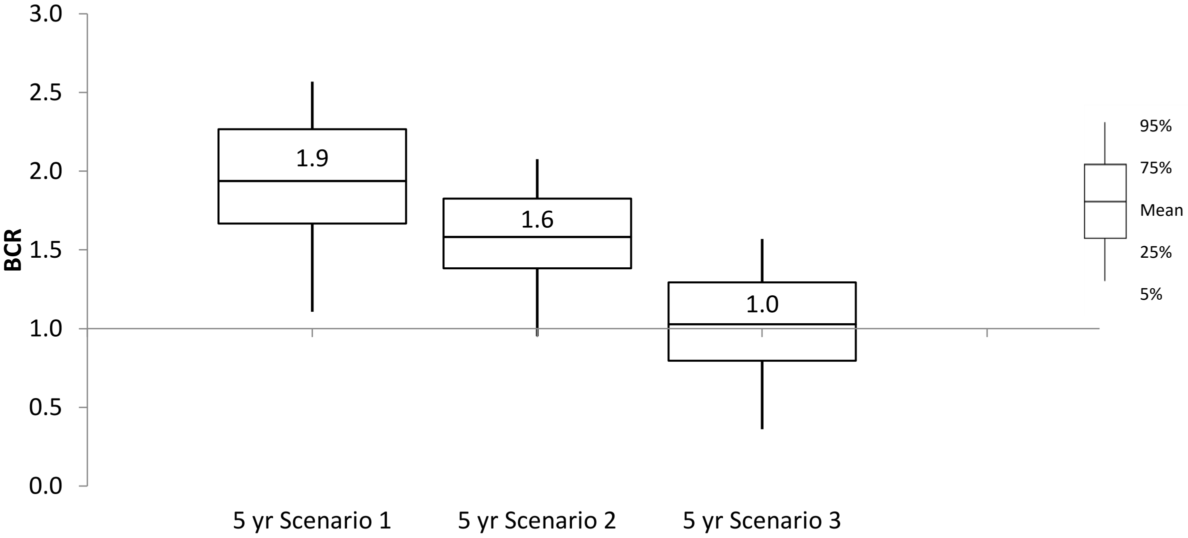

Figure 4.8. Median and key percentiles of the benefit costs ratio per hectare per year in a five-year investment period for each scenario: experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

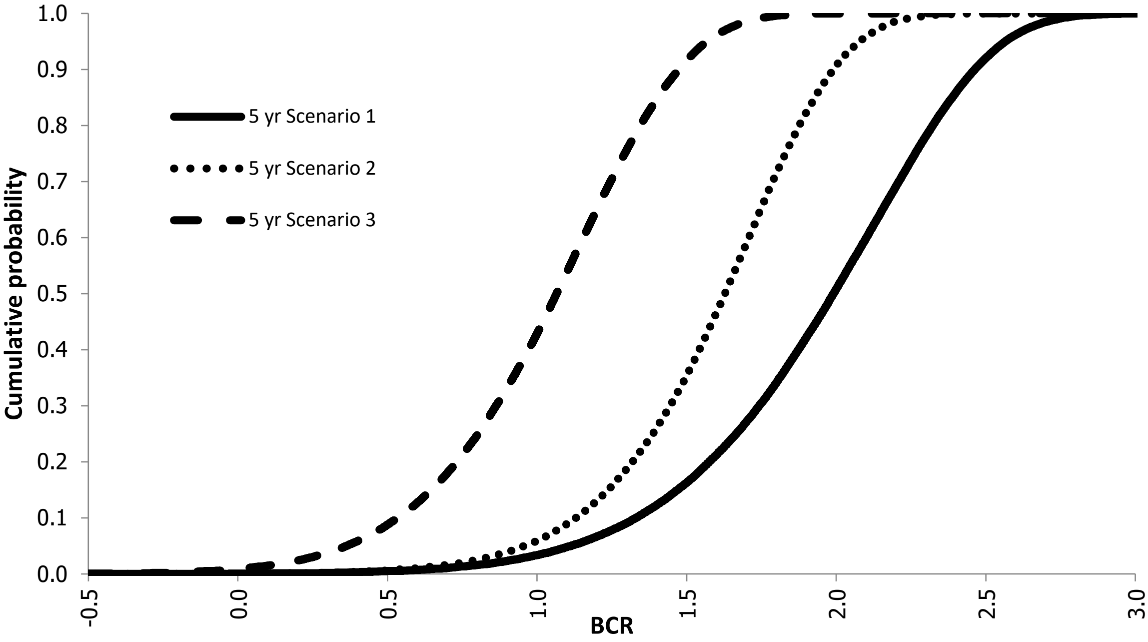

Figure 4.9. All possible BCR outcomes for each scenario and the probability that each BCR outcome, or one with a lower value will occur. Scenarios are defined as: Experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

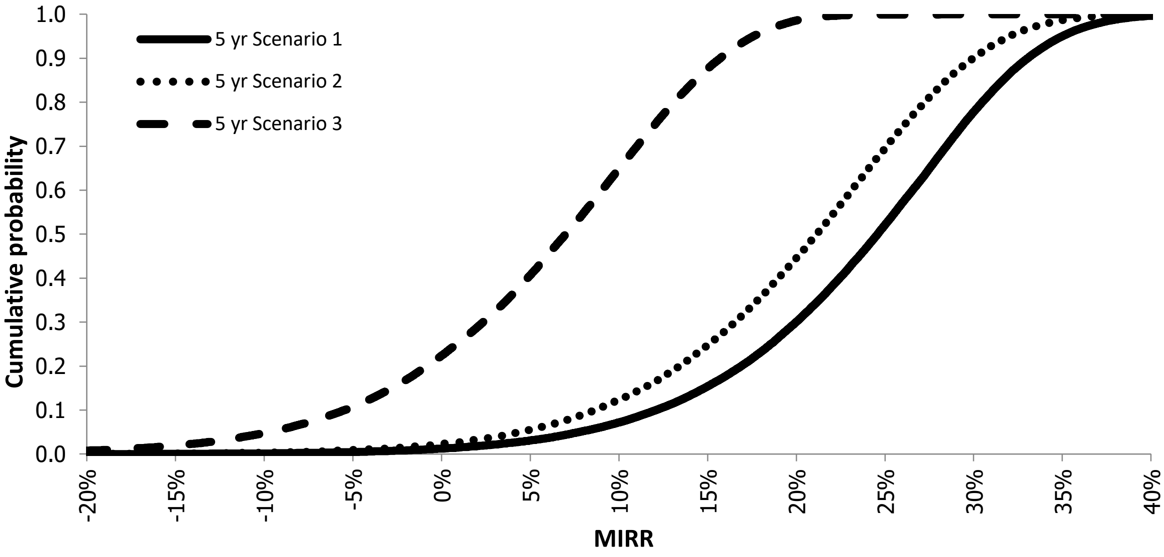

Figure 4.10. All possible MIRR outcomes for each scenario and the probability that each MIRR outcome, or one with a lower value will occur. Scenarios are defined as: Experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

If the range and likelihood of the initial yield benefits begin to diminish after 5-years so by year 10 the most likely yield response is zero (Scenario 4), on average the investment remained more profitable than the opportunity cost rate of 6% (Table 4.5). There was a 96% chance that over a 10-year life the investment in SSM would earn above 6% real MIRR (Figure 4.11).

Table 4.5. Mean, standard deviation (s.d.) and coefficient of variation (c.v) of net present value (NPV), modified internal rate of return (MIRR) and benefit cost ratio per hectare over ten-year investment life for scenario 4;

Economic performance measure	10-year Scenario 4
Mean NPV (6% real) ($)	1,267
s.d. ($)	670
c.v (%)	53%
Mean MIRR (%)	13%
s.d. (%)	4%
c.v (%)	28%
Mean BCR (6% real)	1.7
s.d.	0.3
c.v (%)	19%

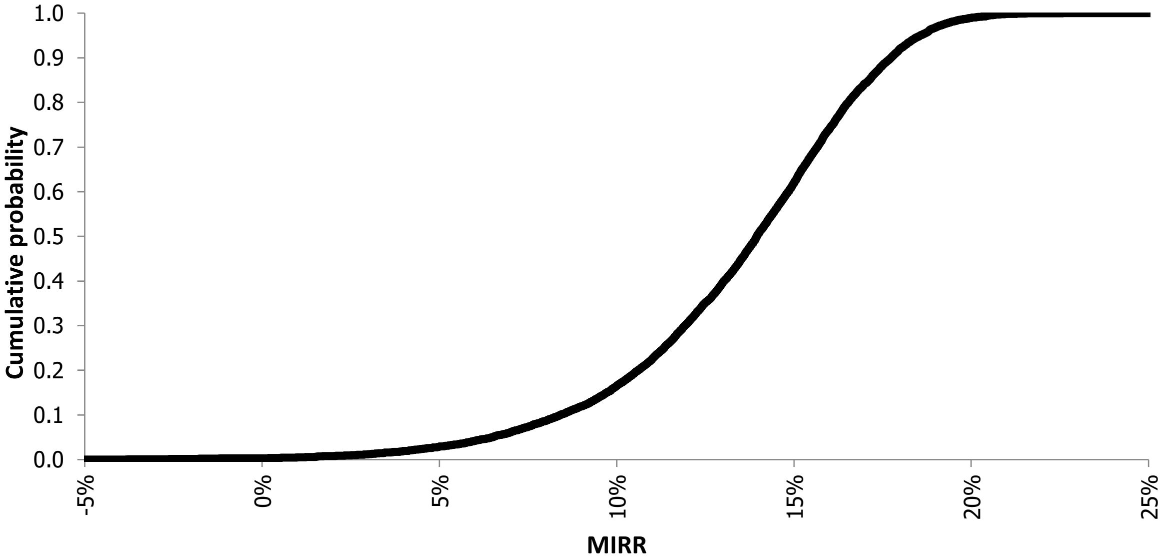

Figure 4.11. All possible MIRR outcomes for Scenario 4 and the probability that each MIRR outcome, or one with a lower value will occur. Scenario 4 is defined as: 10-year investment life, experimental yield response range and likelihood begin to diminish after 5-years so by year 10 the most likely yield response is zero.

Additional testing

Investment Life

When the assumptions used in Scenarios 1-3 were applied to an investment life longer than 5-years, SSM was a more profitable investment. Profitability decreased when the investment life was less than 5-years.

Yield penalty

In scenario 3, when the penalty was decreased from 50% to 25% reduction in experimental yield response, the investment was more profitable. When the yield penalty was increased to a reduction of 75% of experimental yield response, the investment was less profitable than a penalty of 50%.

4.4 Financial Analysis

The variability in annual net cash flows from the control (no SSM) and the SSM scenarios were compared. Investing in SSM resulted in more variable annual cashflow than the control.

Table 4.6 Standard deviation (s.d) and coefficient of variation (cv) of net cash flow over five and ten year investments for each scenario: experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

Parameter	5-year Control	5-year Scenario 1	5-year Scenario 2	5-year Scenario 3
s.d. ($/ha)	154	251	243	196
c.v (%)	25%	27%	28%	32%

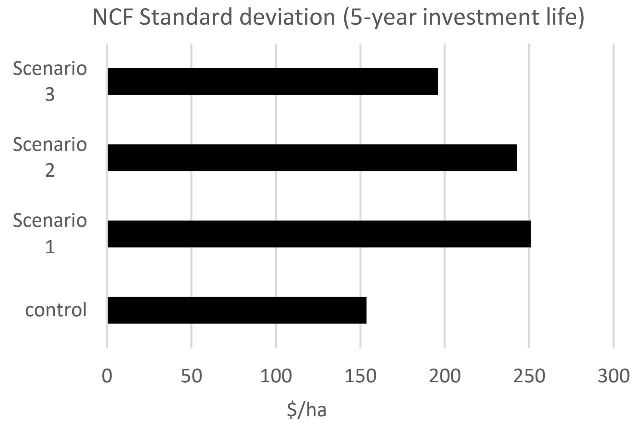

Figure 4.12 Standard deviation of average annual net cash flow (NCF) for the control and each SSM scenario over a five-year investment life. Scenario 1: experimental yield response with three years of maximum benefits from avoided fertiliser. Scenario 2: experimental yield response with no benefits of avoided fertiliser. Scenario 3: 50% reduced experimental yield response with decayed benefits of avoided fertiliser

5. Discussion

Increasing information is being discovered about ameliorating soil conditions using subsoil manuring (SSM) in cereal, grain legume and oilseed cropping on sodic soils in regions of low, medium and high rainfall. However, there remains a lack of demonstrated scientific understanding of the mechanisms underpinning the likely additional yields that are possible and the duration of the investment.

In the face of unknowns and uncertainties about extra benefits of an investment, the approach in farm economics is to use 'Threshold Analysis'. This technique involves estimating the extra benefits per year, and sometimes the life of the investment, that would be required to be achieved for an investment to earn a return on capital that is better than the opportunity cost of the capital, risks considered. The focus in this discussion is on the results of this type of farm economic analysis of the results available about extra yields resulting from SSM trials and experiments, and what the results might mean for farmers weighing up the decision to invest in ameliorating subsoil constraints to production using subsoil manure.

Research questions

1. What minimum extra benefits are required from an investment in subsoil manure to be competitive with alternative uses of capital over a 5-year and 10-year investment life?

2. How does the risk associated with yield response and grain prices affect the profitability of an investment in subsoil manure over a 5-year life of investment?

3. What effect does a decline in annual yield response have on return to investment in subsoil manure over a 10-year investment life?

While the main objective of this research project was to answer the research questions about the economics of investing in SSM to ameliorate soil constraints to yields in high rainfall cropping regions, a subsidiary aim was to test and develop theoretically sound approaches to answering the research questions. Various approaches were considered; some approaches were found wanting, some approaches passed the tests of farm economic theory and farm decision analysis practicality to give convincing conclusions. The findings from applying these sound economic farm economic analytical methods to experimental results about ameliorating subsoil constraints to yields are discussed below.

5.1.Threshold Analysis

A method for estimating the cost of implementing subsoil manuring (SSM) on a farm is well established (Malcolm and Sale 2015). In contrast, less is known about the possible annual benefits and the duration of these annual benefits, from changing the state of cropping soils using SSM. A threshold analysis was used to examine extra net benefits required from the SSM investment to be competitive with an alternative use of scarce capital, over two possible lives of an investment in SSM (five years duration and ten years duration).

In the analysis the initial SSM cost and the required rate of return on marginal capital was the same regardless of the length of the investment life. Annual net benefits needed to earn the required return on capital were higher in the five-year period compared to the ten-year period. The shorter investment life had less time to achieve the threshold earning rate and therefore required larger annual extra net benefits to do so.

Scientific understanding of the mechanisms underpinning crop responses to SSM remains uncertain and the frequency of years producing SSM yield response is unknown. Gill *et al.* (2012) and Celestina *et al.* (2018) found that at several experimental sites SSM failed to produce a grain yield response above that of the control: the traditional cropping system. To account for years in which SSM does not increase grain yields above the yields that would be achieved by usual cropping methods, discrete scenarios were developed to test different numbers of consecutive years in which zero extra yield (defined as poor years) was achieved in the five and ten years life of the investment. An increase in the number of poor years in an investment life resulted in fewer years returning a positive annual marginal gross margin. Therefore, the annual net benefits to earn the required return on capital increased as years with zero SSM benefits increased and years with positive annual extra gross margin decreased. Scenarios defined as ‘Poor year scenarios’ were tested for the scenario where the years of poor performance occurred consecutively, early or late in the life of the investment. If the consecutive poor years scenario occurred early in the life of the investment, a farmer would have to wait longer for the cumulative net benefits to be positive. This represented the ‘worst’ case for the investment in SSM. If the consecutive poor years scenario occurred late in life of the investment, the farmer would not have to wait as long for the positive cumulative net benefits. This represented the ‘best’ case for the investment.

The required extra net cumulative benefits were the highest in all the ‘worst’ case scenarios (Table 4.2 and 4.3). The present value of future SSM net benefits depends on the discount rate and the number of years before the net benefits are received. The process of finding present values involves discounting future value of the SSM net benefits to equivalent present value to account for the time value of money. The discount occurs because the farmer must wait to receive the future net benefits and cannot invest it in an alternative investment which earns the opportunity discount rate (Barry *et al.* 2000, Kay *et al.* 2004, Malcolm *et al.* 2005). This result highlights that the longer a farmer waits for future net benefits of SSM, the less those benefits are worth in equivalent present value terms. The assumption underlying the threshold analysis was that in poor years there was zero extra net benefits from the SSM investment. There is a possibility that a paddock treated with SSM could perform worse than the control in some years. This would result in a negative annual extra net benefit from the investment in SSM. A negative extra net benefit has not been accounted for in this threshold analysis. With poor years defined as delivering yields equal to the control, yields in some years that were worse than the control would mean the threshold extra annual required yields to make SSM a good investment would be even higher than estimated for the scenarios that have poor years.

5.2. Profit and Risk Analysis

5.2.1. Method and assumptions summary

The marginal change to a crop activity gross margin as a result of SSM was assessed using partial discounted cash flow budgets over five years. The partial budget results showed the expected change in extra benefits and extra costs for each component and year of the set rotation. The analysis assumed extra benefits from two sources:

i) The marginal grain income received as a result of extra yield produced. The annual marginal grain income was calculated using annual SSM yield response probability distributions and annual grain price probability distributions.

ii) The high nutrient content of the chicken litter meant a saving was assumed for the total annual use and cost of fertiliser inputs on SSM treated land.

The sensitivity to changes in the magnitude and frequency of yield response and avoided fertiliser costs were examined using three discrete scenarios:

Scenario 1**:** Yield response data from SSM field trials (Table 3.3) were used to develop probability distributions to estimate future SSM yield response. The PIRSA high rainfall crop gross margin guide provided fertiliser rates and costs per rotational hectare. These formed the basis for the estimates of annual fertiliser costs avoided. The annual avoided costs were assumed to apply in each of the first three years of the investment.

Scenario 2: Yield response assumptions were the same as scenario 1 and there were zero benefits from avoided fertiliser costs.

Scenario 3: Yield response probability distributions were fitted again using the same method, described in section 3.4.1.2, except the experimental data used for the 0.5 and 0.95 percentiles were decreased by 50%. In addition to the reduced yield response, declining benefits of avoided fertiliser costs were also tested by decreasing the avoided costs by 50% in year two and then a further 50% in year three.

Scenario 4: Scenario 4 investigates how a declining yield response effects the profitability of the SSM investment over a 10-year life. The assumption is that the range and likelihood of the initial advantages of SSM begin to diminish after year 5 so by year 10 the most likely yield response is zero.

The key measures of profitability and economic performance were:

- Net present value (NPV). NPV reflects the rMGM over the life of the investment converted into equivalent present value at the start of the investment. For the profit and risk analysis, a 6% (real) discount rate was used to compare the NPV of the project to alternative investments.
- Modified internal rate of return (MIRR). This is the return on investment, considering the finance rate for the cost of the investment (6%) and the interest received on reinvestment of cash surpluses (5%) through the life of the investment.
- Benefit-cost ratio (BCR). BCR is the sum of the streams of extra investment benefits and extra costs (annual and capital), discounted at 6% real and expressed as a ratio.

The standard deviation and the coefficient of variation represent the amount of variation around the mean, or the risk.

5.2.2. Summary of profit and risk results

Investments are assessed in terms of returns and risk. In this analysis the extra returns were the addition to farm profit resulting from extra yields from using SSM. Risk analysis was used to assess the effect of the inevitable variability of commodity prices and yields on the mean and variance of the return on capital from investing in SSM. Considering risk, using SSM in a cropping system in all scenarios tested were profitable, as defined by an opportunity cost of capital of 6% real p.a. Profitability was assessed as being highest in the scenarios based on achieving the yield responses from SSM field experiments that have been reported hitherto (Scenario 1 and 2 - Table 5.1).

Table 5.1. Mean, standard deviation (s.d.) and coefficient of variation (c.v) of net present value (NPV), modified internal rate of return (MIRR) and benefit cost ratio per hectare over five year investment life for each scenario: experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

Economic performance measure	5-year Scenario 1	5-year Scenario 2	5-year Scenario 3
Mean NPV (6% real) ($)	1,343	1,040	50
s.d. ($)	716	663	444
c.v (%)	53%	64%	881%
Mean MIRR (%)	23%	20%	6%
s.d. (%)	8%	9%	9%
c.v (%)	36%	43%	147%
Mean BCR (6% real)	1.9	1.6	1.0
s.d.	0.5	0.3	0.4
c.v (%)	23%	22%	36%

If the range and likelihood of the initial yield benefits begin to diminish after 5-years so by year 10 the most likely yield response is zero (Scenario 4), the investment was still profitable at the opportunity cost rate of 6% (Table 5.2)

Table 5.2. Mean, standard deviation (s.d.) and coefficient of variation (c.v) of net present value (NPV), modified internal rate of return (MIRR) and benefit cost ratio per hectare over ten-year investment life for scenario 4;

Economic performance measure	10-year Scenario 4
Mean NPV (6% real) ($)	1,267
s.d. ($)	670
c.v (%)	53%
Mean MIRR (%)	13%
s.d. (%)	4%
c.v (%)	28%
Mean BCR (6% real)	1.7
s.d.	0.3
c.v (%)	19%

5.3. What do these findings mean for a farm decision-maker

5.3.1. Required benefits.

The information from this threshold analysis is intended to support a discussion about the magnitude of the benefits required from the investment to be competitive with an alternative use of scarce capital and to assess the implications of variation in extra yield responses for the decision to ameliorate soil status.

The required benefits need to be considered in the context of existing physical and managerial constraints on the proposed treated area. For example, if the crop land is in a region where it is probable that water (only) limited yield potential (French and Schultz 1984) is lower than the required SSM break-even yield, it is unlikely that the benefits of alleviating subsoil constraints using SSM will be achieved. Alternatively, if the crop land is in a region where the required yield benefits are deemed to be achievable but the topsoil fertility is currently poorly managed, the ability to achieve the required benefits of SSM will be constrained by the current management practice and the most profitable use of the capital required for SSM is likely to be elsewhere.

5.3.2. Risk

5.3.2.1. Profit

If a farmer cannot achieve yield responses consistent with the yields responses achieved in experiments when implementing SSM on a commercial scale (Scenario 3), and achieves only 50% of the experimental yield responses, then over a 5-year investment life there is a high chance (44%) that the investment would achieve a return equal to or lower than the required 6% (Figure 5.1).

A farmer who would only invest in SSM if the life of the investment is somewhat longer than 5 years, lasting even 10-years, needs to consider a scenario where the expected yield response will decline over time (Scenario 4). Despite the conservative decay assumptions used in Scenario 4, there is 96% chance that over a 10-year life the investment in SSM would earn above 6% real return on capital (Figure 4.11). The probability that an investment in SSM exceeds the risk-free rate of return on capital, and by how much, can be compared to the probability of alternative uses of on the farm of capital, which have similar price and yield risk to that of the SSM investment, earning more than the 6% risk-free rate of return.

The magnitude of expected extra yield benefits and number of years the extra benefits can be achieved are the most important factors for a farmer to consider when assessing the likely merit (return and risk) of investing in SSM in their own situations. The expectations of the extra annual yield from crops grown on SSM treated land needs to be considered in the context of the farmers preparedness and willingness to bear additional risk. As risk-aversion increases, the decision maker would be increasingly less comfortable adopting SSM if the yield response is less than what has been achieved in experiments.

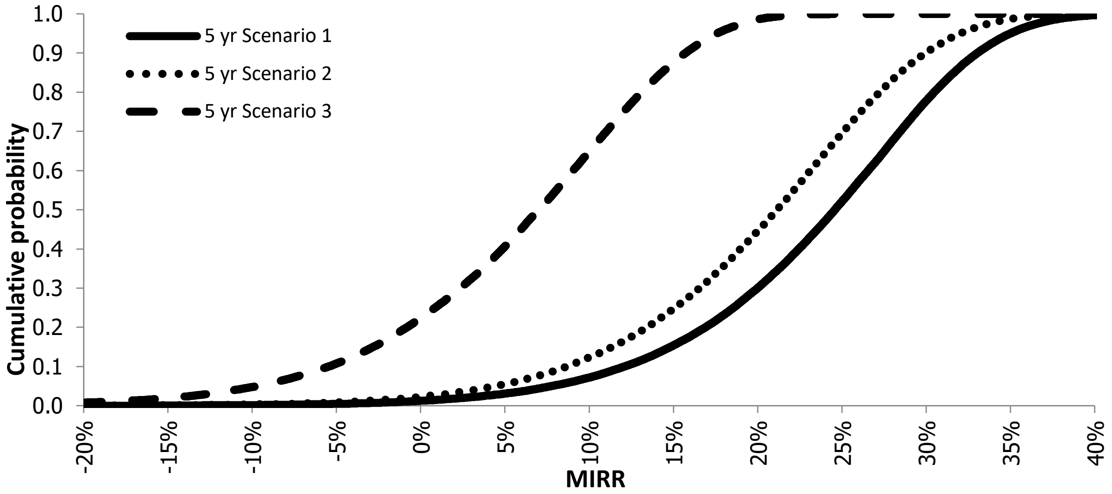

Figure 5.1. All possible MIRR outcomes for each scenario and the probability that each MIRR outcome, or one with a lower value will occur. Scenarios are defined as: Experimental yield response with three years of maximum benefits from avoided fertiliser (Scenario 1); experimental yield response with no benefits of avoided fertiliser (Scenario 2); 50% reduced experimental yield response with decayed benefits of avoided fertiliser (Scenario 3).

5.3.2.2. Financial risk

A farmer considering investing in SSM with 5-years of net benefits would need to be prepared to accept that there will likely be more volatility in annual net cash flow (NCF) than with the *status quo* (Figure 5.2). Considering the capital cost of SSM, a farmer may need to increase debt to undertake the investment which has implications for the balance sheet and annual debt servicing capacity. More variable annual cash flow could increase the financial risk of the business by limiting the ability to service debt in some years.

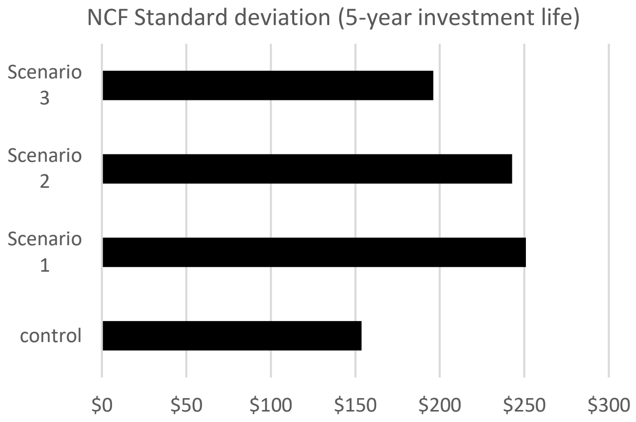

Figure 5.2. Standard deviation of average annual net cash flow (NCF) for the control and each SSM scenario over a five-year investment life. Control: income and costs for a wheat/canola rotation on non-SSM land. Scenario 1: experimental SSM yield response with three years of maximum benefits from avoided fertiliser. Scenario 2: experimental SSM yield response with no benefits of avoided fertiliser. Scenario 3: 50% reduced experimental SSM yield response with decayed benefits of avoided fertiliser.

5.3.2.3. Future work

In some years it's expected that a crop grown with SSM will fail to produce a grain yield above a crop grown without SSM. One explanation for lack of extra yield response is depleted soil water availability during grain filling because of rapid early plant growth from high nitrogen availability (Gill *et al.* 2012). The risks associated with grain filling are irrelevant for a farmer who is only concerned with harvesting the plant biomass produced by a crop (eg. For fodder or grazing). The magnitude of the plant biomass response and corresponding income benefits from SSM may be less than the potential of a grain response and income (Lin *et al.* 2016). Future SSM research could investigate the expected net benefits from using SSM in pasture and fodder production systems.

5.3.3. Implications of applying high rates of nutrients

Poultry litter is a by-product of meat chicken production and has become the organic amendment of choice for SSM experiments. Poultry litter contains high concentrations of nutrients critical to crop growth and grain production. Large quantities of nutrients are applied to the soil when poultry litter is incorporated at 20t/ha (Table 2.1). In this research a saving in the annual use and cost of fertiliser inputs on SSM land (Scenario 1) was examined. The cost-saving was assumed to apply in each of the first three years after poultry litter incorporation.

Annual and cumulative profits were reduced when there were no benefits included from saved annual fertiliser costs (Scenario 2) compared to when the cost-saving was included (Scenario 1). The small difference in profit between the two scenarios (Table 5.1) indicates that the benefits of forgone fertiliser costs were minor compared to the benefits of extra yield. A farmer considering SSM would be prudent to not rely exclusively on fertiliser cost-saving for the investment to be profitable.

The excess application of nutrients through widespread adoption of SSM could lead to contamination of waterways or soil imbalances through nutrient run-off and accumulation (Reddin and Wallis 2015). Currently there is no law or regulation of the application of poultry litter to agricultural land in Australia. The Queensland government has legislated nutrient application on some agricultural land to protect waterways from nutrient run-off caused by excess fertiliser application by farmers (Chapter 4A of the Environmental Protection Act 1994). An understanding of the environmental impacts of large-scale adoption of the subsoil application of high rates of poultry litter is required before promoting the practice to industry.

5.3.4. Application rate

Transport and handling costs of SSM amendments are significant. The estimated cost of applying 20 t/ha of chicken litter to a depth of 30-40cms on a farm located 180 km from the poultry litter source, was $1,029 per hectare. The main component of this total cost was the costs of delivering poultry litter to the paddock. Almost 84% of the total cost went towards the purchase ($263 ha), transport ($471 ha) and handling ($129 ha) of the litter prior to its incorporation in the soil. This finding is consistent with Sale and Malcolm (2015) who reported that poultry littler costs made up approximately 70% of total SSM cost. High investment cost is one of the major barriers to widespread commercial adoption of the SSM (Nicolson 2016, Armstrong *et al. 2017)*. Results from this research demonstrate that changes to application rate have the largest impact on total SSM cost (Figure 4.1). A 50% reduction in application rate resulted in a 38% reduction in total SSM cost. A lower investment cost would reduce the required extra benefits from the investment to be competitive with an alternative use of capital.

There is positive but limited evidence of the impact on yield response from application rates lower than 20 t/ha of poultry litter. Sale *et al.* (2018) reported significant increases in yield from poultry litter applied at 10t/ha compared to conventional practices. Despite the lower rate of litter application, the practice remained profitable (Sale and Malcolm 2015). The aims of SSM field research have been broadly limited to showing that there is a statistically significant relationship between amendment and yield response rather than quantifying the relationship over a range of different applications rates. A farm decision-maker is concerned with making a profit among other goals, given limited resources (Lloyd 1958). The decision rule to make as much profit as possible from using a variable input, such as poultry litter, is to apply the input up to where the extra grain income from an extra tonne of amendment applied just exceeds the extra cost of applying the extra tonne (Dillon & Anderson 1990). Decreasing the application rate of the amendment could be an effective method of decreasing the extra cost of SSM, though without information on yield responses to a range of SSM application rates the extra grain income cannot be estimated. Future SSM research ought to include crop response functions to application rate to equip farmers with the information needed to make rational investment decisions.

5.3.5. Access to appropriate machinery

Access to appropriate machinery has also been previously reported as a barrier to commercial adoption of the SSM (Armstrong *et al. 2017)*. The machine used as the basis of this analysis was custom designed to conduct SSM on a commercial scale. The field capacity of the machine was estimated to be 1.2 ha/hr based on an average speed of 3.5km/ha, operating width of 5 metres and accounting for time delays including turning and refilling the machine with litter. The field capacity therefore represents the number of hectares that can be treated in one hour. Using these findings, it's possible to estimate the maximum number of hectares one SSM machine can treat annually [2]. Assuming the SSM treatment window is 120 days between January to April and the contractor runs the SSM machine for 10 hours a day for 6 days a week over this period, possible treatment hours would amount to 7,200. Based on these best-case assumptions, one machine could treat 8,820 ha per year. Approximately 3,618,000 ha of Victorian cropping area is constrained by sodic subsoils (Orton *et al.* 2018). The lack of commercially ready SSM machinery is a

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[2] The machine used in this analysis is the only known SSM machine available in Victoria for contracting on a commercial scale. Other SSM machines exist but are either not available for contracting or are only suitable for experimental areas.

current impediment to ameliorating subsoil constraints using SSM, though one which commercial interests would likely rectify if demand grew.

5.3.6. Limitations of poultry litter as an amendment.

Incorporating of high rates of poultry litter has successfully subsoil ameliorated conditions. Previous studies have identified that there is insufficient poultry litter produced in Victoria to meet the demand of ameliorating the area of subsoil constraints likely to be responsive to SSM intervention. (Armstrong *et al. 2017,* Nicolson 2016). The findings from this research demonstrate possible further limitations to using poultry litter as a SSM amendment.

5.3.6.1. Source location

The distance the SSM treated land is from the source of the poultry litter has a large impact on the total cost of SSM (Figure 4.1). Chicken meat farms are the main source of chicken litter in Australia (Weidermann 2015). Chicken meat farms are generally aggregated within 100km of meat processing plants (Watson and Weidermann 2019) which are located at a limited number of locations around Australia (Figure 5.3). The soils likely to be responsive to SSM are located well beyond the chicken meat production regions, transport costs of ameliorant will likely be high for a large proportion of farmers considering SSM.

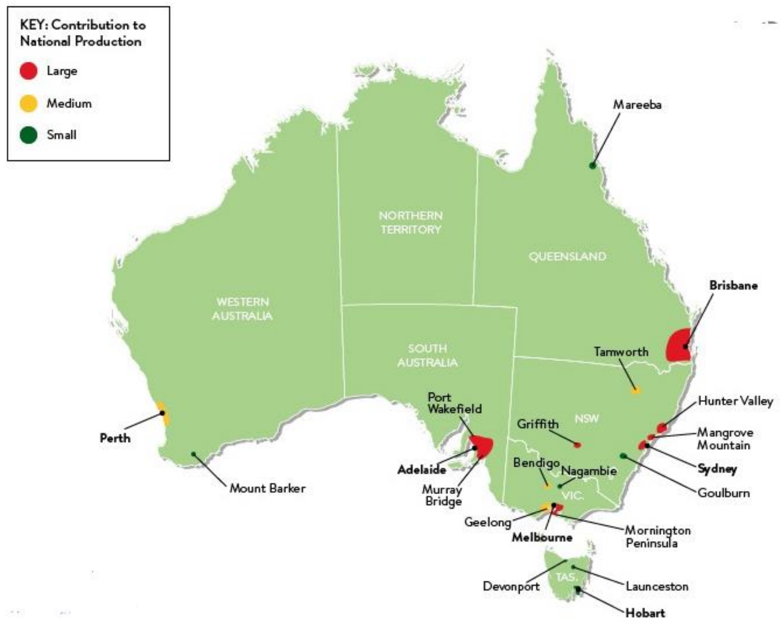

Figure 5.3. Chicken meat producing regions in Australia (Source: ACMF 2019).

5.3.6.2. Competition and price

The Australian chicken meat industry estimates that 1,801,384 m^3 of poultry litter is produced annually (Watson and Weidermann 2019). This is equivalent to approximately 810,000 tonnes of litter based on a bulk density of 450kg/m^3. Poultry litter is commonly used as fertiliser replacement on agricultural land. In 2016-17, 700,000 tonnes of litter were applied to land in Australia (Table 5.4).

Table 5.4. Poultry litter application by state. (Source: ABS 2018)

State	Poultry litter applied to land (t)
New South Wales	375,917
Queensland	85,405
Victoria	130,580
WA/SA/TAS	109,989
Australia	701,891

A farmer considering SSM would be entering into a competitive market for poultry litter. Widespread adoption of SSM could create additional demand for an already scarce resource. Findings from this research show that an increase in the price per tonne of poultry litter can have large effects on the total investment cost (Figure 4.1). If the extra demand for poultry litter leads to an increase in the cost of poultry litter, SSM investment costs could continue to increase as practice adoption becomes more widespread. Quantifying the extra demand for poultry litter is a more complex task than is appropriate for this research. Extra demand could be affected in-part by; the frequency SSM needs to be undertaken, the price of synthetic nutrients, whether SSM will be undertaken by current users of poultry litter.

5.3.6.3. Alternative materials

Once the mechanisms underpinning crop responses to SSM are understood, amendments without the limitations of poultry litter may be an option for SSM. One objective of current SSM research (GRDC project DAV00149) is to develop an understanding of SSM amendments based on farm-grown biomass materials. Farm-grown biomass has the potential to produce an amendment with lower transport costs and without the worry of purchasing an amendment in a competitive market. Farm grown biomass amendment will have costs and risks that would not be incurred when using poultry litter. Some foreseen costs associated with farm grown biomass amendment include:

- The opportunity cost of growing a crop specifically to be an amendment
- Lost production of the amendment crop due to poor seasonal conditions (yield risk) or management errors
- Additional costs of getting a crop or crop stubble into a form that is suitable for the SSM machine.

A detailed investigation of the costs and risks associated with farm grown biomass amendment using the frame work of Johnson and Hardin (1955) is warranted before these options are promoted as cost-effective alternatives to poultry litter.

5.3.7. Capital appreciation of SSM treated land

An alternative scenario associated with investing in SSM may also warrant consideration. This is the case where at the end of the life of the initial investment, either five or ten years, the soil has been transformed in a medium to long term manner into something different and better than was the case at the start of the life of the investment. If this was the situation, remembering that the value of an asset is the capitalised value of expected future net earnings, then the productivity and profitability per hectare of the crop land would have been permanently increased. This would represent an increase in the economic value of the land. If this was the case, the land at the end of the investment would have an extra value above the control case. In this situation the salvage value of the land is positive, representing the improved profit prospects of the land. The assumption can be made that a subsequent buyer of the land after the SSM investment would pay more for it than they would have paid for the land before the investment in the SSM. In this scenario, the required extra net benefits and extra yield to make the initial investment in SSM worthwhile, and the return from the initial investment, would be higher than that calculated assuming zero end of life benefits from the initial investment.

5.3.8. Experimental data for on-farm decisions

Experimental yields were reduced by 50% (Scenario 3) to account for the well-established relationship between experimental yields and farm-scale yields (Davidson & Martin 1965, Davidson *et al.* 1967, Swanson 1957, Dillon & Anderson 1990). Future SSM research should include paddock-scale trials to quantify crop response when the management area is similar to commercial conditions. Recommendations such as this one are not new (Lloyd 1958, Skerman 1958, Kanel 1975, Byerlee *et al.* 1979, Just 2003). Candler (1962) surmises the issue by stating that;

> *Without an attempt to apply the results of agricultural production experimentation to the farms which they are thought to be applicable, the experimental research is merely the formulation of a hypothesis about the production relations in the research plot being studied.*

Trials conducted on-farm are considered by farmers to be sources of high-quality information. On-farm trials provide the most information to farmers about whether or not a new innovation is suitable for a particular farm as they possess the key characteristics of being local and credible (Jackson 2013). Accordingly, SSM researchers, SSM contractors and industry promoters could increase the rate of adoption of SSM by facilitating on farm trials. This could be done by providing farmers with access to SSM machinery to trial on paddocks with responsive soil types.

5.3.9. Misrepresenting farm-level risk

The data used in this analysis were aggregated from various experimental sites in the high rainfall cropping zone in Victoria. Using region-wide data could underemphasise farm-level variation while emphasising region-wide random effects (Just and Weninger 1999). Just and Weninger (1999) demonstrate that region-wide yield variation may be from widespread weather and pest conditions. Farm-specific yield randomness may be caused by errors in management, farm-specific resource constraints, and farm-specific weather and pest conditions. Therefore, farm-level variability, the crucial level for analysing investment under uncertainty, could be mischaracterised in this analysis. The economic framework in this research has been developed so that when paddock-scale SSM yield response data is produced, it can be incorporated to more accurately represent farm-level risk.

6 Conclusion

Changes to poultry litter application rate have the largest effect on total SSM cost. A 50% reduction in application rate reduces the total cost by 38%. Reducing the application rate from 20t/ha could be an effective method of decreasing the cost of using SSM, depending on the related soil and yield effects.

Threshold analysis indicated that over a 10-year investment life additional yield of 0.47 tonne per ha per annum of wheat and canola in a wheat-canola rotation was required to deliver 10% real return on capital p.a. Note: the 10% return on capital includes a risk premium. A 5-year investment required an additional 0.77 tonnes per ha of wheat and canola to deliver 10% return on capital p.a. The number of responsive years over the investment life and the timing of when the responsive years occur influences the magnitude of extra yields required per year. A worst case was where all the additional yield occurred late in the life of investment and the farmer waits longer for the benefits of SSM to be received.

Simulation analysis over a 5-year life with yield response occurring in a stochastic manner above the counterfactual case of the *status quo*, with and without benefits of saved annual fertilizer, SSM in a wheat-canola rotation had 50% chance of earning returns on capital above 20% p.a. with one standard deviation around this mean of plus or minus 8% return. A worst case where only half the experimental yields were achieved and initial fertilizer savings rapidly decayed, had a 50% chance of earning a return above 6% p.a. with one standard deviation around this mean of plus or minus 9%.

An investment in SSM was more profitable on average than an alternative investment earning 6% (real) despite the conservative assumption of not valuing the likely enduring improvements in soil productivity subsequent to the assumed investment life.

Further research

This investigation has unearthed areas and questions that would be promising for further research activities:

- Quantify the yield response relationship over a range of different SSM applications rates.
- The climatic conditions required for yield responses from SSM amelioration of soil constraints
- The expected duration of soil and yield benefits from SSM amelioration of soil constraints
- The time decay rate of yield benefits from SSM amelioration of soil constraints
- Crop response of SSM treatment for areas treated at farm size and managed under farm conditions
- Extent and duration of an annual fertiliser replacement (saving) effect.
- Using SSM in pasture and fodder production systems
- Environmental impacts of applying high rates of nutrient-rich organic matter to the subsoil.

In sum, on the evidence, ameliorating constraints to yields of sodic subsoils used for cropping is an innovation with great potential to raise the productivity of crop production in some parts of Australia’s southern cropping regions.

References

ABS (2018), Australian Bureau of Statistics, Land Management and Farming in Australia 2016-17, Cat. No. 4627.0, Canberra

ABS (2019a) Australian Bureau of Statistics, Value of Agricultural Commodities Produced 2017-18, cat. no. 7503, Canberra.

ABS (2019b) Australian Bureau of Statistics, Agricultural Commodities 2017-18, cat. no. 7121, Canberra.

ACMF (2018) The Australian Chicken Meat Federation. https://www.chicken.org.au/structure-of-the-industry/

Adcock D, McNeill AM, McDonald GK, Armstrong RD (2007) Subsoil constraints to crop production on neutral and alkaline soils in Southern Australia: a review of current knowledge and management strategies. *Australian Journal of Experimental Agriculture* **47**, 1245-1261.

Alston AM (1980) Response of wheat to deep placement of nitrogen and phosphorus fertilizers on a soil high in phosphorus in the surface layer. Australian Journal of Soil Research **31**, 13-24

Anderson JR (1973) Sparse data, climatic variability, and yield uncertainty in response analysis. *American Journal of Agricultural Economics* **55,** 77-82.

Anderson JR, Dillon JL, Hardaker B (1977) Agricultural Decision Analysis. Iowa State University Press.

Angus JF, Peoples MB, Gault RR, Gardner PA, Howe GN (1996) Improved pastures and their effects on subsequent crops. Proceedings of the 8th Australian Agronomy Conference, Toowoomba

Armstrong RD, Eagle C, Matassa V, Jarwal SD (2007) Application of composted pig bedding on a Vertosol and Sodosol soil. 1. Effect on crop growth and soil water. Australian Journal of Experimental Agriculture **47**, 689-699.

Armstrong RD, Eagle C, Flood R (2015) Improving grain yields on a sodic clay soil in a temperate, medium-rainfall cropping environment. *Crop and Pasture Science* **66**, 492-505.

Armstrong R, Sale P, Tavakkoli E, Wilhelm N, Davenport D, Dean G, Malcolm B, Midwood J, Rengsamy P, Grant C, O'Leary G. (2017) Can subsoil amelioration improve the productivity of grain production in medium-high rainfall environments? Proceedings of the 18th Australian Agronomy Conference, Ballarat, Victoria, Australia pp. 1-4.

Bachman KL (1950) Relation of economic theory to the analysis of empirical data in farm management research. J. Farm Econ. **32**, 1159-1168

Barry PJ (1984) Risk Management in Agriculture. Iowa State University Press. Ames, Iowa

Barry PJ, Ellinger PN, Hopkin JA, Baker CB (2000) Financial Management in Agriculture. Sixth Edition. (Interstate Publishers INC)

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.

Bell M, Lester D, Smith L, Want P (2012) Increasing complexity in nutrient management on clay soils in the northern grain belt – nutrient stratification and multiple nutrient limitations.

Bell M, Sands D, Lester D, Norton R (2015) Response to deep placed P, K and S in central Queensland. Proceedings of the 17th Australian Agronomy Conference, Hobart, September.

Bell M, Hochman Z, Whish J, Zull A, de Voil Peter (2016) Optimising Performance of Current Northern Cropping Farming Systems. GRDC Grains Research Updates.

Blackwell P, Bakker D, Davies S, Isbister B (2015) Deep ripping for soil compaction. https://www.agric.wa.gov.au/soil-compaction/deep-ripping-soil-compaction.

Blackwell P, Isbister B, Riethmuller G, Barrett-Lennard E, Hall D, Lemon J, Hagan J, Ward P. (2016) Deeper ripping and topsoil slotting to overcome subsoil compaction and other constraints more economically: way to go. GRDC Grains Research Updates

Boehlje MD, Eidman VR (1984) Farm management. John Wiley & Sons

Bolland MDA, Jarvis RJ (1996) Effectiveness of different methods of applying superphosphate for lupins grown on sandplain soils. Australian Journal of Experimental Agriculture **36**, 707-715

Bridge BJ, Kleinig CR (1986) The effect of gypsum on the water storage in a sandy loam soil under irrigated pasture. Transactions of the 9th International Congress of Soil Science **1**, 313-323

Byerlee D, Biggs S, Collinson M, Harrington L, Martinez JC, Moscardi E, Winkelmann D (1979) On-Farm Research to develop technologies appropriate to farmers. Paper presented at the Conference of the International Association of Agricultural Economists, Banff, Canada, September 1979.

Candler W (1962) Production economics and problems of animal production. Proceedings of the New Zealand Society of Animal Production **22**, 142-158

Celestina C, Midwood J, Franks A, Hunt J (2016) Nitrogen fertility drives the microbial and crop response to subsoil manuring. Southern Farming Systems Trial Results Book 2016. pp 97-100

Celestina C, Midwood J, Sherriff S, Trengove S, Hunt J, Tang C, Franks A (2018). Crop yield responses to surface and subsoil applications of poultry litter and inorganic fertiliser in south-eastern Australia. Crop and Pasture Science, **69**, 303-316.

Chisholm AH, Dillon JL (1971) Discounting and Other Interest Rate Procedures in Farm Management. Professional Farm Management Guidebook No. 2. Agricultural Business Research Institute (ABRI), University of New England: Armidale, NSW.

Christy B, Clough A, Riffkin P, Norton R, Midwood J, O'Leary G, Stott K, Weeks A, Potter T (2015) Technical report: Managing crop inputs in a high yield potential environment – HRZ of southern Australia. The State of Victoria Department of Economic Development, Jobs, Transport & Resources.

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

Creelman Z, Celestina C (2015) Subsoil manuring: what is important in getting it 'right'? Southern Farming Systems Trial Results Book 2015. pp 142-149.

Crocker W (1922) History of the Use of Agricultural Gypsum. Gypsum
Industries Association, Chicago.

Dang YP, Dalal RC, Buck SR, Harms B, Kelly R, Hochman Z, Schwenke GD, Biggs AJW, Ferguson NJ, Norrish S, Routeley R, McDonald M, Hall C, Singh DK, Daniells IG, Farquharson R, Manning W, Speirs S, Grewal HS, Cornish P, Bodapati N, Orange D (2010) Diagnosis, extent, impacts, and management of subsoil constraints in the northern grains region of Australia. *Australian Journal of Soil Research* **48**, 105-119.

Dang YP, Dalal RC, Routley R, Schwenke GD, Daniells I (2006) Subsoil constraints to grain production in the cropping soils of the north-eastern region of Australia: an overview. Australian Journal of Experimental Agriculture **46**, 19-35.

Davidson BR, Martin BR, Mauldon RG (1967) The application of experimental research to farm production. *Journal of Farm Economics* **49,** 900-907.

Davidson BR, Martin BR (1965) The relationship between yields on farms and in experiments. *Australian Journal of Agricultural Economics* **9**, 129-140.

Dillon C (2003) A Framework for Economic Analysis of Cropping Systems: Profitability, Risk Management, and Resource Allocation, Journal of Crop Production, **9**, 409-432

Dillon JL, Anderson JR (1990) 'The Analysis of Response in Crop and Livestock Production. Third Edition' (Pergamon Press)

Dunbabin VM, Armstrong RD, Officer SJ, Norton RM (2009) Identifying fertiliser management strategies to maximise nitrogen and phosphorus acquisition by wheat in two contrasting soils from Victoria Australia. Australian Journal of Soil Research **47**, 74-90.

PIRSA (2019) Primary Industries and Regions South Australia, Farm Gross Margin Guide. https://pir.sa.gov.au/consultancy/farm_gross_margins_and_enterprise_planning_guide

Espinosa D, Sale PW, Tang C (2011) Changes in pasture root growth and transpiration efficiency following the incorporation of organic manures into a clay subsoil. Plant and soil **348**, 329-343.

Farre I, Bowden B, Davies S, van Gool D. (2015) Removal of a subsoil constraint–When does it pay. In Proceedings of the 15th Australian Agronomy Conference, Christchurch, New Zealand.

French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean-type environment: 1. The relationship between yield, water use and climate. Australian Journal of Agricultural Research **35**, 743-764.

Ghadim AK, Kingwell R, Pannell D (1991) An economic evaluation of deep tillage to reduce soil compaction on crop-livestock farms in Western Australia. Agricultural Systems. **37** 291-307

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.

Gill JS, Sale PWG, 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, Clark GJ, Sale PW, Peries RR, Tang C (2012) Deep placement of organic amendments increases fallow efficiency and the use of deep soil water by crops. *Plant and Soil* **359**, 57-69.

Goodwin BK, Ker AP (2002) Modelling price and yield risk. A comprehensive assessment of the role of risk in US agriculture. Springer: Boston, MA. 289-323

Graham RD, Turner NC, Ascher JS (1992) Evidence for subsoil constraints and potential benefits from amelioration. Proceedings of the National Workshop on Subsoil Constraints to Root Growth and High Soil Water Use by Plants, Tanunda, South Australia

GRDC (2009) Deep Ripping Fact Sheet. https://grdc.com.au/Resources/Factsheets/2009/06/Deep-ripping-not-appropriate-for-all-soil-types, assessed October 2019.

GRDC (2018) Annual Results Report: Understanding the amelioration processes of the subsoil application of amendments in the Southern Region.

Hadar J, Russell WR (1969) Rules for ordering uncertain prospects. The American economic review. **59** 25-34.

Hanna M (2016) Estimating the field capacity of farm machines. Ag Decision Maker. Iowa State University.

Hardaker JB (2000) Some Issues in Dealing with Risk in Agriculture, Working Paper Series in Agricultural and Resource Economics.

Hardaker JB and Lien G (2005) Towards Some Principles of Good Practice for Decision Analysis in Agriculture. Norwegian Agricultural Economics Research Institute, Working Paper

Hardaker JB, Lien G, Anderson JR, Huirne RB (2015) Coping with risk in agriculture: Applied decision analysis. CABI

Hardin LS, Johnson GL (1955) Economics of forage evaluation. Journal of Farm Economics. **5** 1457-1459.

Heady EO (1948) Elementary models in farm production economics research, Journal of Farm Economics **30** 201-226.

Heady EO (1950) Applications of recent economic theory in agricultural production economics, Journal of Farm Economics Proceedings **32** 1125-1139.

Heady EO (1952) Economics of Agricultural Production and resource Use, Iowa University Press.

Heard JW, Leddin CM, Armstrong DP, Ho CK, Tarrant KA, Malcolm B, Wales WJ (2012) The impact of system changes to a dairy farm in south-west Victoria: risk and increasing profitability. Animal Production Science. **52** 557-565.

Helmers GA, Langemeier MR and Atwood J (1986) An Economic Analysis of Alternative Cropping Systems for East-Central Nebraska. *Journal of Alternative Agriculture* **1**, 153-158.

Hirth JR, Hainse PJ, Ridley AM, Wilson KF (2001) Lucerne in crop rotations on the Riverine Plains. 2. Biomass and groin yields, water use efficiency, soil nitrogen, and profitability. Australian Journal of Agricultural Research **52**, 279-293.

Ho CK, Malcolm B, Doyle PT (2013) Potential impacts of negative associative effects between concentrate supplements, pasture and conserved forage for milk production and dairy farm profit. Animal Production Science. **53** 437-452.

Jackson T (2013) Pasture investment decisions: returns, risk and time. In Melbourne School of Land and Environment, Doctor of Philosophy Melbourne: University of Melbourne.

Jarvis RJ (1986) Crop response to deep tillage. In ‘Review of Deep Tillage Research’. Western Australian Department of Agriculture, Division of Plant Research, Technical Report 3.

Jarvis RJ, Bolland MDA (1990) Placing superphosphate at different depths in the soil changes its effectiveness for wheat and lupin production. Fertilizer Research **22**, 97-107

Just RE, Weninger Q (1999) Are Crop Yields Normally Distributed? American Journal of Agricultural Economics **81**, 287-304

Just RE (2003) Risk research in agricultural economics: opportunities and challenges for the next twenty-five years. Agricultural systems **75**, 123-159

Kay RD, Edwards WM, Duffy PA (2004) 'Farm Management' (Mcgraw-Hill Companies)

Kanel D (1957) Relative Roles of Survey and Experiment in Farm Management. Journal of Farm Economics **39**, 1451-1454

Kimura S, Antón J, LeThi C (2010). Farm Level Analysis of Risk and Risk Management Strategies and Policies: Cross Country Analysis, OECD Food, Agriculture and Fisheries Papers, No. 26, OECD Publishing, Paris.

Lewis CD, Ho CK, Jacobs JL, Malcolm B (2018) Benefits and costs of grazing various proportions of perennial ryegrass and chicory for dairy production. Animal Production Science. **58** 1423-1431.

Lin Y, van Santen E, Watts D (2016). The effect of poultry litter application on agricultural production: a meta-analysis of crop yield, nutrient uptake and soil fertility. Annual Conference on Applied Statistics in Agriculture.

Lindner R, Fischer A, Pardey P (1979). The time to adoption. Economics Letters, **2**, 187-190.

Lloyd AG (1958) Agricultural experiments and their economic significance. Review of Marketing and Agricultural Economics **26**, 185-209

Loveday J (1974) Recognition of gypsum-responsive soils. Australian Journal of Soil Research **12**, 87-96.

Ma Q, Rengel Z, Rose T (2003) The effectiveness of deep placement of fertilisers is determined by crop species and edaphic conditions in Mediterranean-type environments: a review. Australian Journal of Soil Research **47**, 19-32

MacEwan RJ, Crawford DM, Newton PJ, Clunec TS (2010) High clay contents, dense soils, and spatial variability are the principal constraints to cropping the higher rainfall land in south-eastern Australia. *Australian Journal of Soil Research* **48**, 150-166.

MacEwan RJ, Crawford DM, Newton PJ, Clune TS (2006) Subsoil Constraints to Cropping in the High Rainfall Zone of South East Australia – a scoping study. Department of Primary Industries, Primary Industries Research, Victoria, Bendigo.

Makeham JP, Malcolm LR (1993) The Farming Game Now. Cambridge University Press

Malcolm B. (2004a). Farm Management analysis: a core discipline, simple sums, sophisticated thinking. Agricultural Economics, **21**, 570-586.

Malcolm B. (2004b). Where's the economics? The core discipline of farm management has gone missing!*. Australian Journal of Agricultural and Resource Economics, **48**, 395-417.

Malcolm B, Makeham J, Wright V (2005) 'The Farming Game - Agricultural Management and Marketing.' (Cambridge University Press: Melbourne)

Malcolm B, Ho CK, Armstrong DP, Doyle PT, Tarrant KA, Heard JW, Leddin CM, Wales WJ. (2012) Dairy directions: a decade of whole farm analysis of dairy systems. Australasian Agribusiness Review **20** 39-58.

McBeath TM, Grant CD, Murray RS, Chittleborough DJ (2010) Effects of subsoil amendments on soil physical properties, crop response, and soil water quality. *Australian Journal of Soil Research* **48**, 140-149.

McCallum MH, Kirkegaard JA, Green TW, Cresswell HP, Davies SL, Angus JF, Peoples MB (2004) Improved subsoil macro porosity following perennial pastures. Australian Journal of Experimental Agriculture **44**, 299-307.

Mele PM, Yunusa IAM (2001) Cereal yields associated with changes in soil characteristics following six years of acacia. Proceedings of the 10th Australian Agronomy Conference, Hobart.

Nicholson C, Creelman Z, Celestina C (2015). Increased farm productivity through injection of organic wastes into subsoils. Part 2. Southern Farming Systems

Nicholson C (2016). Business case for investment in subsoil modification with organic material. Prepared for Southern Farming Systems, as part of the National Landcare Project, INNOV-108.

Nuttall JG, Armstrong RD, Connor DJ (2001) Understanding subsoil water-use by cereals on southern Mallee soils: II. Crop response. In Proceedings of the 10th Australian Agronomy Conference 28

Nuttall JG, Armstrong RD, Connor DJ (2003) Evaluating physicochemical constraints of Calcarosols on wheat yield in the Victorian southern Mallee. Australian Journal of Agricultural Research **54**, 487–498.

Nuttall JG, Davies SL, Armstrong RA, Peoples MB (2008) Testing the primer-plant concept: wheat yields can be increased on alkaline sodic soils when an effective primer phase is used. Australian Journal of Agricultural Research **59**, 331-338.

Orton TG, Mallawaarachchi T, Pringle MJ, Menzies NW, Dalal RC, Kopittke PM, Searle R, Hochman Z, Dang YP (2018) Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat. Land Degradation & Development **11,** 3866-3875.

Pannell, D. (2006). Flat Earth Economics: The Far-reaching Consequences of Flat Payoff Functions in Economic Decision Making. Review of Agricultural Economics 28(4): 553-566.

Pannell D, Malcolm B and Kingwell R (2000). Are we risking too much? Perspectives on risk in farm modelling? Agricultural economics **23** 69-78.

Peries R, Gill JS (2015) Subsoil manuring in the high rainfall zone: a practice for ameliorating subsoils for improved productivity InProc. 17th ASA Conference, 20-24 September 2015. Hobart, Australia.

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

Redden P, Wallis B (2015) Chicken litter as fertiliser for broad-acre grain crops-a user's guide. Rural Industries Research and Development Corporation and Rural Directions Pty Ltd. Canberra, Australia.

Rengasamy P, Marchuk A (2011) Cation ratio of soil structural stability (CROSS). *Soil Research* **49**, 280-285.

Rengasamy P, Olsson KA (1991) Sodicity and soil structure. *Australian Journal of Soil Research* **29**, 935-952.

Robertson M, Kirkegaard J, Peake A, Creelman Z, Bell L, Lilley J, Lawes R. (2016) Trends in grain production and yield gaps in the high-rainfall zone of southern Australia. *Crop and Pasture Science* ***67***, 921-937.

Sale P, Gill J, Peries R, Tang C (2011) Treating hostile subsoils. GRDC Update for Advisers. Ballarat, Victoria. pp. 105–109.

Sale P, Peries R, Gill J, Malcolm B, Tang C (2013) Subsoil manuring to ameliorate dense sodic-clay subsoils – the process, agronomic results and economics. GRDC Update, Griffith and Moama 2013

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

Sale PW, Gill JS, Peries RR, Tang C (2018) Crop responses to subsoil manuring. I. Results in south-western Victoria from 2009 to 2012. Crop and Pasture Science. **70,** 44-54.

Scott BJ, Carpenter DJ, Braysher BD, Cullis BR, Evans CM (2003) Phosphorus fertiliser placement for lupins in southern New South Wales. Australian Journal of Experimental Agriculture **43**, 79-86.

Sherriff S, Trengrove S (2018) Subsoil amelioration – four years on. Hart Field-Site Trial Results 2018. 71-80.

Singh DK, Sale PWG, Routley RR (2005) Increasing phosphorus supply in subsurface soil in northern Australia: rationale for deep placement and the effects with different crops. Plant and Soil **260**, 35-44.

Skerman PJ (1958) Agricultural Experiments and Their Economic Significance (I). Australian Journal of Agricultural Economics. **2**, 24-32

Stanger TF, Lauer JG, Chavas JP (2008) The profitability and risk of long-term cropping systems featuring different rotations and nitrogen rates. Agronomy Journal **100,** 105-113.

Swanson ER (1957) Problems of Applying Experimental Results to Commercial Practice. Journal of Farm Economics **39**, 382-389

Trengove S, Sherriff S (2018), Amelioration of Sandy Soils - Opportunities for Long Term Improvement. GRDC Grains Research Updates, Adelaide, South Australia.

Turner NC (2004) Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. Journal of Experimental Botany. **55,** 2413-2425.

Ward PR, Dunin FX, Micin SF (2002) Water use and root growth by annual and perennial pastures and subsequent crops in a phase rotation. Agricultural Water Management **53** 83-97.

Ward P, Oliver Y, Hall D (2018) How often does subsoil amelioration pay the bills? GRDC Grains Research Updates, Perth, Western Australia.

Watson K, Wiedemann SG (2019). Review of Fresh Litter Supply, Management and Spent Litter Utilisation. AgriFutures, Canberra, Australia.

Wiedemann SG (2015). Land application of chicken litter: a guide for users. Rural Industries Research and Development Corporation, Canberra, Australia.

Wilhelm N (2005) Deep placement of nutrients – few excuses let not to recommend it. Eyre Peninsula Farming Systems 2005 Summary. 126-127.

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

Yunusa IAM, Mele PM, Rab MA, Schefe CR, Beverly CR (2002) Priming of soil structural and hydrological properties by native woody species, annual crops and permanent pasture. Australian Journal of Soil Research **40**, 207-219.

Yunusa IAM, Newton PJ (2003) Plants for amelioration of subsoil constraints and hydrological control: the primer-plant concept. Plant and Soil **257**, 261-281

Zhang H, Turner N.C, Poole M.L, Simpson N (2006) Crop production in the high rainfall zones of southern Australia — potential, constraints and opportunities. Aust. J. Exp. Agric. 46, 1035–1049.

Zull A, Bell M, Cox H, Gentry J (2016) A bioeconomic framework for phosphorus deep-placement decisions. Contributed presentation at the 60th AARES Annual Conference, Canberra.