Australian Farm Business Management Journal
2022, Volume 19, Paper 3
ISSN: 1449-7875

Economic Analysis of Ameliorating Sub-soil Constraints using Sub-soil Manure in a Cropping System[1]

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Abstract

In the high-rainfall zone of south-eastern Australia, yields of broadacre crops are constrained by physical and chemical characteristics of the sub-soil. Scientific research is being conducted into ameliorating these physical and chemical sub-soil constraints by using organic amendments that have high levels of nitrogen. This paper is about the results of economic research into the net benefits and risk of ameliorating sub-soil constraints by applying sub-soil amendments such as chicken manure to cropland in the high rainfall zone. The key economic question for a grower is whether the extra benefits of ameliorating sub-soil constraints and increasing the yields of crops are greater than the extra costs of doing so, considering risk. The aim of this research was to determine the effects of yield and price risks over a run of years on the profitability of making such soil amendment investments. Investment costs and annual activity gross margins for a crop rotation were used to estimate the economic performance (NPV, IRR and BCR). Risk analysis was used to assess the effect of price and yield variability on the mean and variance of outcomes. It was found that an investment in sub-soil amelioration which lasted for five years was more profitable than conventional cropping, at an average annual required rate of return of 6 per cent p.a. real, before tax. The size of the expected extra yield benefits above the yields of conventional cropping, and the longevity of the effects of the amendment and yield benefits, are the most important factors for a crop farmer to consider when assessing the option of investing in sub-soil amelioration to grow better crops in the high rainfall zone.

Keywords: sub-soil amelioration, sub-soil manure, risk and return

Introduction

Broadacre cropping is a major agricultural activity in Victoria. There were 3.5 million hectares of broadacre crops grown in Victoria in 2017-18, with a farm gate value of $2.2 billion. In the past decade grain production has increased markedly in the Victorian high-rainfall zone (HRZ) (annual rainfall > 500 mm). In 2017-18, 8 per cent of Victoria's broadacre cropping area was in the HRZ, producing 16 per cent of the total value of commodities produced from broadacre cropping in Victoria (Figure 1)[2].

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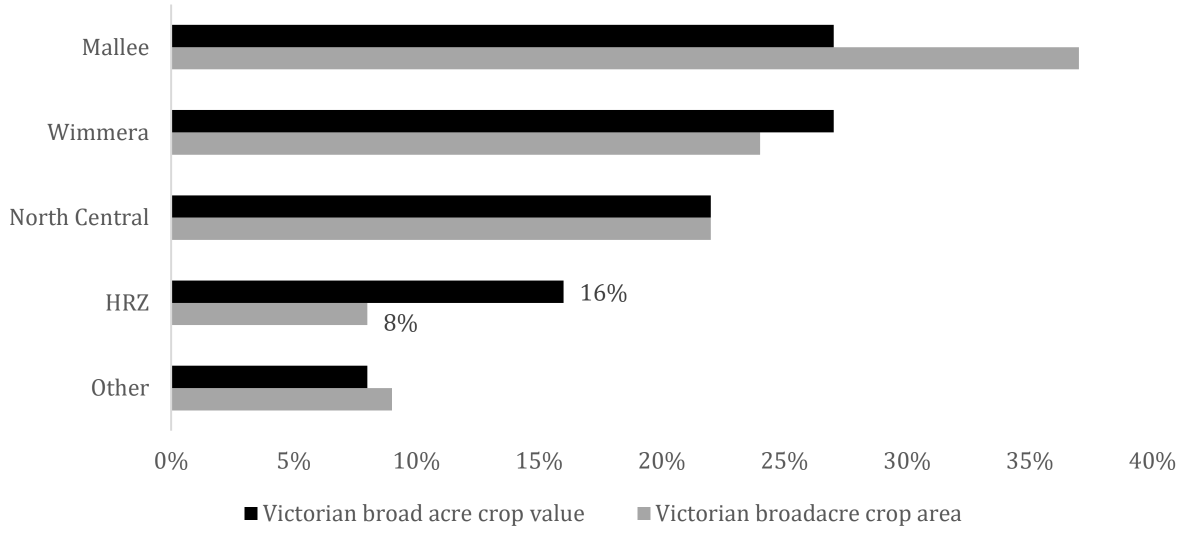
[1] This research was funded by the Grains Research and Development Corporation.

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

Figure 1. Percentage of total area planted and total value of commodities produced from broadacre crops for 2017-18 in different regions of Victoria

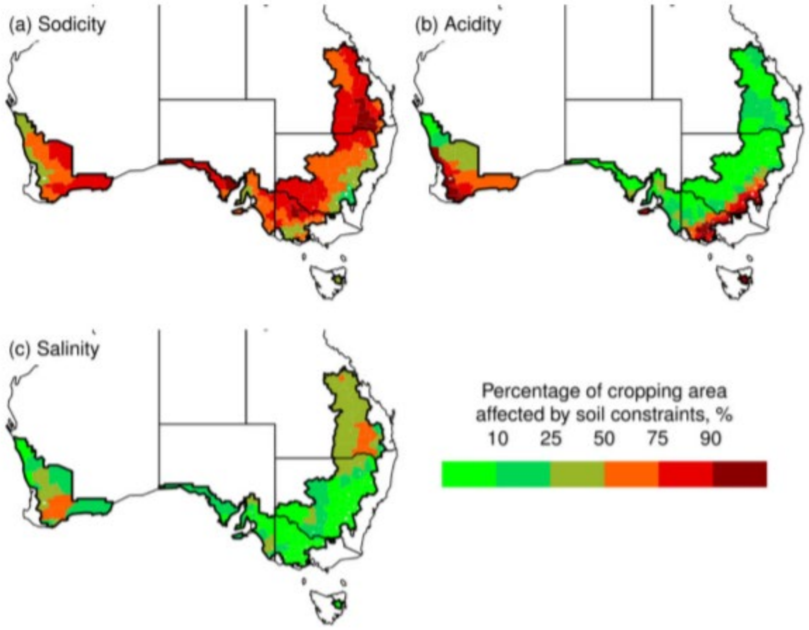


Source: ABS (2019a), ABS (2019b). Data sourced for the Victorian high rainfall zone (HRZ) was from the following NRM regions: Glenelg Hopkins, Corangamite, Port Phillip/Western Port, Gippsland east, Gippsland west and the Hume SA4.

The unconstrained yield potential for broadacre crops grown in the HRZ is higher than potential yields in low and medium rainfall regions. Broadacre crop production in the HRZ of Victoria is limited by physical and chemical constraints in the sub-soil (Adcock *et al*., 2007; MacEwan *et al.,* 2006; Zhang *et al.,* 2006). The sub-soil is the soil below the cultivated layer. In most grain farming systems, the sub-soil does not exceed a depth of 15 cms (Adcock *et al*., 2007). Constraints in sub-soils occur because of poor soil structure. Poorly structured sub-soils lack volume of soil pores and space between soil particles. Sub-soil constraints across the Victorian HRZ are exacerbated by clay dispersion in the sub-soil. 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 sub-soil. 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 and Olsson, 1991). The nature and impact of sub-soil constraints on crop productivity in South East Australia is well established (Adcock *et al*., 2007; MacEwan *et al*., 2010; Zhang *et al*., 2007). These sub-soil constraints include high boron, transient salinity, acidity/alkalinity and sodicity. Most cropping soils across Australia contain one or more constraints (Figure 2). 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).

Potential yield increases from improved varieties or agronomy is always constrained by sub-soil 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). Root growth is restricted by poor aeration when the soil is wet and inhibited root penetration as the soil dries. Increasing root growth in sub-soil 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).

Figure 2. Areas of land, as a percentage of the cropping land, affected by (a) sodicity, (b) acidity, and (c) salinity, Australia



Source: Orton et al. (2018)

Strategies to Ameliorate Sub-soil Constraints

The strategies that have been used to ameliorate sub-soil constraints include: the application of gypsum; deep ripping; use of primer plants; deep placement of nutrients; and deep placement of organic material.

The application of gypsum to improve surface soil infiltration has a long history (Crocker, 1922). Gypsum is applied almost exclusively to topsoil (Loveday, 1974) with sub-soil application showing potential for short-term yield increases (Bridge and Kleinig, 1986). Placing gypsum into a band in rip-lines in the sub-soil is likely to restrict the amelioration to the soil within and adjacent to the rip-line, with minimal improvement in the sub-soil matrix between the rip-lines (Gill *et al.,* 2008; Armstrong *et al.,* 2015). An even distribution of gypsum on the soil surface, followed by deep ripping, may result in an even distribution in the sub-soil, but this takes time, requires rainfall and the benefits dissipate as the dissolved gypsum leaches from the sub-soil layers.

Deep ripping without a suitable soil ameliorant is unlikely to improve structure of the soil and crop productivity on clay soils that have poor structure in the medium and high rainfall zones in the southern Region. While deep ripping reduced soil strength in the ripped layers at 15 sites across southern NSW between 1980 and 2005, this 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 at a few sites (Gill *et al.,* 2008; McBeath *et al.,* 2010; Creelman and Celestina, 2015). In many cases, deep ripping produced yield declines as a result of bringing poorly structured sodic sub-soil to the surface which contributed to poor plant establishment. The disturbance of sub-surface soil layers with ripping was not able to overcome the major sub-soil factors limiting crop yields. In contrast to the poor performance of deep ripping on the heavier-textured soils across south eastern Australia, deep ripping produces more promising results on the deep sandy soils of Western Australia. Deep ripping is highly effective in ameliorating soil layers that are compacted, particularly where compaction is the result of tillage practice, on soils from the sandplain areas (Jarvis, 1986). Blackwell *et al.* (2015) reported that disruption of the compacted sub-surface layer by ripping enabled crop roots to grow faster and deeper and to gain access to increased amounts of sub-soil water and nutrients, which produced crop yields higher than in soils that were not deep ripped.

Evidence from research suggests that there is a high likelihood that applying nutrients at depth to crops increases yields of grain. Three cropping scenarios have been identified where placing nutrients deep in soil profiles are expected to increase yields of crops (Ma *et al.,* 2003; Dunbabin *et al.,* 2009).

- First, in soils that consist of sands over clays on the Eyre and Yorke Peninsulas in South Australia; researchers developed a technology where liquid nutrients containing Nitrogen (N), Phosphorus (P) and trace elements were injected at depths of 20-40 cm into deep infertile sands that lie over clay sub-soils. Remarkably consistent and prolonged increases in yields generally resulted from this practice (Adcock *et al.,* 2007; McBeath *et al.,* 2010; Wilhelm, 2005). This yield response to deep-placed nutrients may have occurred in part because the soils in the Eyre and Yorke Peninsulas, with their Mediterranean-type climate with short, mild wet winters and long hot dry summers, have low fertility and dry rapidly (Ma *et al.,* 2003).

- Second, warm dry conditions of the northern Australia grains region occur during the vegetative growth of winter crops, which means crops in this region rely heavily on sub-soil moisture. When the top-soil dries with the warmer and drier conditions in the north, nutrients from fertilizers that are banded at shallow depths become unavailable. A history of intensive cropping with limited application of fertilizers has led to the depletion of nutrients in sub-surface layers. Thus, responses to deep nutrients occurred in dry years (Singh *et al.,* 2005; Bell *et al.,* 2015). In contrast, in wet years when roots could obtain access to nutrients in surface layers, there was no benefit from deep fertilizer placement (Bell *et al.,* 2012).

- Third, placement of phosphorus (P) fertilizer 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, there was no increase in grain yield with deep placement of P (Alston, 1980; Bolland and Jarvis, 1996; Scott *et al.,* 2003). Crops can take up the P they need from the fertile top-soil layers before the soil surface dries off in the spring. If the soil surface P is low, plants rely on deep sub-surface layers for the P they require.

Deep placement of organic material, rather than nutrients alone, is showing promise for ameliorating sub-soil constraints for the Victorian HRZ. Poultry litter is a nutrient-rich by-product of meat chicken production, consisting of bedding (usually sawdust or shavings, rice hulls or straw) and manure. Litter is low in moisture (20-26 per cent) (Wiedemann, 2015) and high in nutrients (Table 1). Litter is typically purchased from contractors who clean commercial broiler sheds or bought directly from a broiler farm. Sale *et al.* (2021) showed how the structure of dense clay subsoils can be improved by deep banding of nutrient-rich organic amendments, followed by the growth of crop roots in the subsoil. Sale *et al.* (2018) demonstrated that deep placement of granular fertilizer was not as effective as applying its nutrient equivalent as poultry litter at the same depth on Sodosol and Chromosol soils in the Victorian HRZ. The granular fertilizer treatment yielded significantly less grain. 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 sub-soil. Graham *et al.* (1992) found high rates of organic amendment placed in the sub-soil resulted in large and long-lasting yield increases across a variety of sites in the wheat belt of South Australia. Since the treatment involved digging out the soil profile and mixing in the amendment, it is not practical on farm. Recent field trials that have tested deep placement of organic matter and nutrients to ameliorate sub-soil constraints have consistently produced large improvements in grain yields lasting several years (Espinosa *et al.,* 2011; Gill *et al.,* 2008, 2009, 2012; Peries, 2014; Peries and Gill, 2015; Sale *et al.,* 2013; Sale *et al.,* 2018). Poultry litter has become the favoured organic amendment for sub-soil amelioration experiments; the practice is termed 'sub-soil manuring'. Sub-soil manuring (SSM) involves placing a continuous band of poultry litter, applied at 10 t/ha or 20 t/ha (fresh weight) at a depth of 30-40 cm, at the base of a rip-line.

Table 1. Total nitrogen, phosphorus and potassium content of poultry litter applied at 20 t/ha, across three experiments

Nutrients	Amount of nutrient in 20 t/ha (kg/ha)	Nutrient concentration in poultry litter (per cent)	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)

Amelioration of sub-surface soil layers by adding organic amendments is deemed to be successful when yield responses occur, usually in the first year and continuing over the following 2-3 experimental years. This was the case for field trial results reported by Sale *et al.* (2018), Gill *et al.* (2008) and Gill *et al.* (2009). Over the eight experimental years of these trials, incorporating 20 t/ha of poultry litter in the sub-soil increased average wheat yield by 62 per cent above the control. The amelioration of sub-soils resulted in a marked increase in aggregation of the clay sub-soil. 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 sub-soils (Gill *et al*., 2009; Clark *et al*., 2009; Sale *et al*., 2011). A continuous supply of water, nutrients, and oxygen from the soil results in vigorous and continuing root growth in the treated sub-soils. Crops can extract more water from the sub-soil layer, during critical stages which is thought to be the reason for the large grain yield responses. It is not fully understood how applying high rates of nutrient enriched organic matter and associated increased root activity and soil biota increases aggregation of a sodic clay soil. The processes that are responsible for the lateral spread of the soil aggregation effect beyond the rip lines is not yet well understood either.

Interestingly, at several experimental sites, sub-soil application of poultry litter failed to produce a grain yield response above that of the control treatment (Celestina *et al.,* 2016; Celestina *et al.,* 2018; Creelman and Celestina, 2015; Gill *et al.,* 2012; Sherriff and Trengrove, 2018). The lack of grain yield responses to deep incorporation of organic amendments coincided with years of 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. Across the experimental sites and in 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. One explanation for lack of yield response in dry years is depleted soil water availability during the grain filling stage of the crop, caused by rapid early plant growth (Gill *et al.,* 2012). The size and distribution of rainfall seems to have a marked bearing on the effectiveness of sub-soil amelioration to improve crop growth and improve soil functions (Sale *et al.,* 2021). However, the relationship between the amelioration process and water availability remains unknown.

Farm Management Economic Assessments of Applying Organic Matter to the Sub-soil

The research reviewed above has demonstrated that growing crops using sub-soil manure (SSM) is a technology that can enable large improvements in grain yields lasting several years. Despite the potential change in crop yields that can be achieved by SSM, there has been little analysis of the economic merit at farm level of investing in SSM. Numerous studies have attempted economic assessments of removing sub-soil constraints using biophysical models to derive crop yield response data (Abadi Ghadim *et al.,* 1991; Farre *et al.,* 2015; Ward *et al.,* 2018; Wong and Asseng, 2007; Zull *et al.,* 2016). In all these studies, the sub-soil constraints were different to those of 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 region.

Nicholson *et al.* (2015) modelled expected SSM soil conditions and their subsequent crop yields in Victoria's HRZ. They applied probability distributions, developed from the modelled yield data and historic grain price data, to a profit budget to account for variability in profit, but 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.

A few other studies have attempted to assess whether applying organic matter to the sub-soil is a profitable investment in broadacre cropping. Trengrove and Sheriff (2018) estimated the extra income and costs from applying poultry litter to a depth of 30-40 cm to ameliorate deep sandy sub-soil constraints in South Australia. The authors estimated an investment cost of $900/ha to apply 20 t/ha of poultry litter to the sub-soil; no detail was provided about the components that made up the total cost of applying the ameliorant. Despite dry growing conditions, the 20 t/ha SSM treatment ranked highly according to an average 'Return on Investment' performance criterion, defined as being the cumulative extra nominal net revenue divided by the cumulative extra nominal variable and capital costs over three years of the experiment.

Sale and Malcolm (2015) is the only study that has conducted a farm-level SSM investment analysis. The costs and benefits of achieving the grain yield responses 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 (the cost of annual fertilizer inputs not required) for each of the first three years because of the high nutrient load contained in the deeply placed poultry litter amendment in year one. The SSM machine had a capital value of $170,000 and the work rate of the machine was 0.5 ha/hr. The authors estimated that using the machine to incorporate 20 t/ha of poultry litter cost between $1244/ha and $1345/ha (depending on location). The purchase, handling and transport of the poultry litter made up 70 per cent of the total cost. Discounted partial cash flow analysis was used to estimate the Net Present Value (8 per cent 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 represents a return to the extra capital invested above a cost of capital of 8 per cent 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 8 per cent return on investment. The investment remained profitable when investments costs doubled, and when the opportunity cost/discount rate was increased to 20 per cent. Risk analysis conducted by Sale and Malcolm (2015) was limited to the variability observed from four years of yield and price data. No attempt was made by the authors to investigate the implications of a range of potential yield and price scenarios 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. This research sought to start to fill that knowledge gap. The aim is to investigate the risk and return of investing in sub-soil manuring (SSM). The specific research questions were:

1. What minimum extra benefits are required from an investment in sub-soil 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 sub-soil manure over a 5-year life of investment?
3. What effect does a decline in annual yield response have on return to investment in sub-soil manure over a 10-year investment life?

Method – Economic Analysis

The research questions were answered using farm economics, as described by Malcolm *et al.* (2005). A partial discounted cash flow budget over a 5-year and a 10-year planning horizon was the framework to evaluate these questions. The key measures to assess sub-soil manure as a management strategy to ameliorate sub-soil constraints were:

- Net present value (NPV). For this analysis, two discount rates (6 per cent p.a. real and 10 per cent p.a. real) were 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 per cent p.a.) and the interest received on reinvestment of cash surpluses (5 per cent p.a.) 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 per cent p.a. real and expressed as a ratio.

This research is part of a larger research project (GRDC project DAV00149 - Understanding the amelioration processes of the sub-soil application of amendments in the Southern Region). Data from the field trials of the larger research project were used in this research. 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). There is limited detail in the literature on methods available to account for the effect of crop sequences on farm management economic evaluations. Helmers *et al.* (1986) note that, when analysing a crop rotation, it is important to separate the stabilising effect of the rotation 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) set 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 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 (p.100).

Thus, the performance of crop activities can only be assessed in terms of the sequence or rotation in which they are grown, i.e. crops are not grown as 'stand-alone' 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 to 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).

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 income and variable costs associated with the extra yield produced because of SSM. In Table 2, the calculation of MGM as a result of SSM is summarised. 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, and are thus excluded as they will not change directly with yield increases. Seeding rates are not increased with SSM, so seeding costs also remain unchanged as yield increases. It is assumed that no extra machinery or equipment is needed during the years after SSM. Extra yield implications for extra fertilizer are captured in the initial investment in manure to ameliorate sub-soil condition.

Table 2. Marginal Gross Margin

<table>
<tr><td colspan="2">Extra Income ($/ha) = extra yield (t/ha) x price ($/t)</td></tr>
<tr><td colspan="2">Extra variable costs</td></tr>
<tr><td>Wheat</td><td>Canola</td></tr>
<tr><td>GRDC Levy ($/t.ha) = 1 per cent of extra income ($/ha)</td><td>GRDC Levy ($/t.ha) = 1 per cent of extra income ($/ha)</td></tr>
<tr><td>EPR and State Levies ($/t.ha) = $3.50 x extra yield (t/ha)</td><td>EPR and State Levies ($/t.ha)= $0.50 x extra yield (t/ha)</td></tr>
<tr><td>Harvesting ($/t.ha) = $20 x extra yield (t/ha)</td><td>Harvesting ($/t.ha) = $41 x extra yield (t/ha)</td></tr>
<tr><td>Freight ($/t.ha) = $20 x extra yield (t/ha)</td><td>Freight ($/t.ha) = $25 x extra yield (t/ha)</td></tr>
<tr><td colspan="2">Marginal Gross Margin ($/ha) = Extra income – Extra variable costs</td></tr>
</table>

As previously explained, the expected MGM of an individual phase of a wheat or canola rotation does not provide enough information on which to base a decision. Thus, the rotational Marginal Gross Margin per hectare (rMGM/ha) is the measure used. This is derived by estimating the rMGM per hectare of the wheat and canola activities 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:

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

The 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. The PIRSA (2019) 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 (2019) estimates are based on southern cropping conditions and applicable to this research.

Assumptions and data

Yield data for wheat and canola were collated from SSM field trials in the HRZ of Victoria (Table 3). The minimum criteria for the data to be used were:

(i) Trial sites were located in the high rainfall zone of Victoria.
(ii) The trial sites were constrained by a sub-soil 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 have been published in peer-reviewed journals.

Yield data from the control treatments at each trial were collected. Control treatments represented the commercial practice 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.

The SSM investment cost was based on the farm having a 430-horsepower tractor that normally worked 800 hours/year with 5 years of ownership remaining. It would now be used for an additional 200 hours per year placing chicken litter in the sub-soil. The tractor initially cost $300,000 and after 10 years has 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 per cent field efficiency (Hanna, 2016) to apply 20 t/ha of chicken litter to a sub-soil depth of 30-40 cm. The cost of owning the tractor, after allowing for depreciation, interest on capital, insurance and shedding is $29/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 per cent of the purchase price per year) that are allocated to the sub-soil manure activity comes to $68/treated hectare. The labour cost to operate the tractor and sub-soiling implement is $28/treated ha. The machinery costs are provided in Table 4.

The cost of the chicken litter from a broiler farm in Bendigo Victoria was $6/m^3 or $13/t, assuming 450 kg/m3. The freight costs were $0.13/t/km, based on a truck capacity of 60 m3 or 27 tonnes of litter, with a one-way delivery rate of $3.50/km (Hazeldene's pers. comm.). The site of the sub-soil 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/treated hectare to screen the litter and an extra labour unit at $35/hour or $49/treated hectare was required to reload (assuming it take 30 mins to load and reload) the implement with chicken litter.

Table 3. Summary of SSM field trials undertaken in the high rainfall zone of Victoria to ameliorate constraints in poorly structured sub-soils

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)

Method - Risk Analysis

In farm economics, risk is part of the consequence of decisions made within the business and relates to the volatility of potential outcomes. Hardaker *et al. (*2015, p. 4), define the terms risk and uncertainty as:

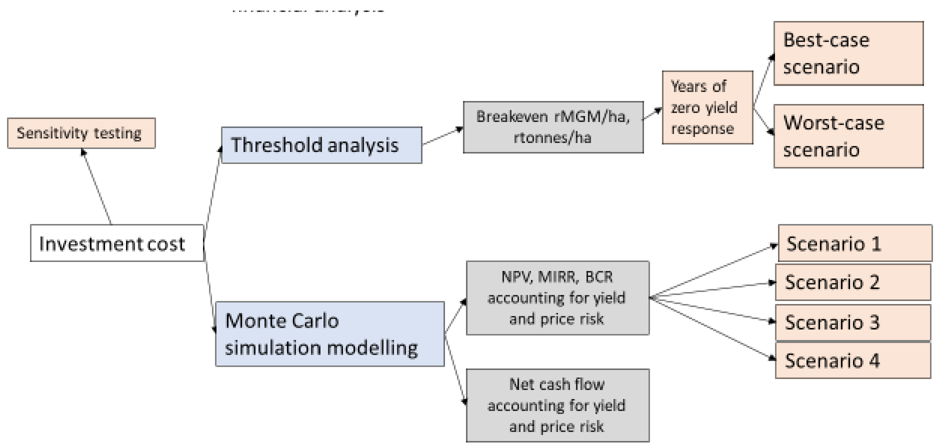
> Uncertainty is imperfect knowledge and risk is uncertain consequences, particularly possible exposure to unfavourable consequences.

Risk was accounted for in this analysis using both discrete and stochastic analysis. In Figure 3 a schematic representation of how risk was incorporated into this research is presented. A number of different approaches were used to explore risk associated with the application of sub-soil manure to ameliorate sub-soil constraints.

Table 4. Estimated costs per hectare of applying 20/t chicken litter at 30-40cm sub-soil 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 ($/ha)	863
Sub-soil application cost	
Tractor - owning and operating ($/ha)	98
Implement - owning and operating ($/ha)	68
Sub-soil application – Total ($/ha)	166
Total Cost ($/ha)	1029

Figure 3. A schematic representation of how risk was incorporated in this research



Sensitivity analysis of investment cost

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

Breakeven (threshold) analysis

Since there is less certainty about the extra benefits from SSM, a breakeven (threshold) analysis was conducted to solve for the minimum extra rMGM/ha per year required to return a NPV equal to zero (i.e. earning 10 per cent p.a return on marginal capital) over a 5-year planning horizon and a 10-year planning horizon), given the initial capital invested. The assumptions behind this analysis were:

- The salvage value of capital invested was zero.
- 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.
- The benefits of avoided fertilizer costs were not included.

This breakeven analysis was explored using several different discrete scenarios. 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. 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.

Monte Carlo simulation modelling

The simulation modelling quantified and tested the effects of the effect of added business risk that might result from using SSM. The @RISK (Palisade Corporation, Ithaca, NY, USA) add-in package to Microsoft Excel was used. The @RISK program 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. In the Monte-Carlo simulation modelling, both price and yield risk are included, compared with the threshold analysis in which only yield was variable.

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, the 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 per cent real p.a. to 6 per cent real p.a. over the past century. In this analysis, 6 per cent p.a. 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. Interpreting these NPV, BCR and MIRR results means comparing the probabilities of achieving positive NPVs, BCRs greater than one and MIRRs greater than 6 per cent. For example, if NPV was positive at every combination of yield and price at 6 per cent 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 per cent of the time, this means that 80 per cent of the time the investment earns more than the opportunity cost. Or, if the MIRR is greater than 6 per cent in 90 per cent 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 per cent risk-free rate of return.

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

Each scenario had a probability distribution for commodity price. Probability distributions for wheat and canola prices were developed by fitting positively skewed Lognorm distributions to ABARES price data (Table 5).

Table 5. Type and key percentiles (P) of the grain price distributions used in the analysis, all scenarios

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

Source: ABARES (2019)

Scenario 1 – experimental yield response with three years of maximum benefits from avoided fertilizer

Yield response data from SSM field trials (Table 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 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 were 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 was 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 distributions, 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 6).

Table 6. 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
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

Correlation coefficients were defined for yield response and grain price probability distributions to ensure existing relationships were maintained when simulating these variables (Table 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. Based on the assumptions reported by Kimura *et al.* (2010), a correlation coefficient of 0.7 was applied to 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 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

The high nutrient content of the chicken litter meant a saving can be assumed for the annual use and cost of fertilizer 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 fertilizer could be avoided for the first three years of the analysis. The PIRSA (2019) high rainfall crop gross margin guide provided fertilizer rates and costs per rotational hectare. These formed the basis for the estimates of fertilizer costs avoided in the first three years of the SSM regime (Table 8). All investment costs were assumed to be incurred in year one and the benefits from the avoided fertilizer costs were assumed to occur only in the first three years of the analysis, regardless of the amount of extra yield grown.

Table 8. Benefits received from the avoided fertilizer cost in the first three years of the analysis period

	Fertilizer 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 numbers in parenthesis represents the percentage of Nitrogen: Phosphorus: Sulphur in each fertilizer

The salvage value of SSM after a period of elapsed time is unknown. The extra benefits from a transformed sub-soil 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.

Scenario 2 – experimental yield response with no benefits of avoided fertilizer

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

Scenario 3 – 50 per cent reduced experimental yield response with decayed benefits of avoided fertilizer

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 per cent 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 earlier, except the experimental data used for the 0.5 and 0.95 percentiles were decreased by 50 per cent (Table 9).

Table 9. Type and key percentiles (P) of the reduced yield response distributions used in scenario 3

Variable	Distribution type	P1	P5	P25	P50	P75	P95	P99
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 fertilizer costs were also tested by decreasing the avoided costs by 50 per cent in year two and then a further 50 per cent in year three (Table 10). The adjusted distributions and avoided costs were applied to the partial budget model over the five-year investment life.

Table 10. Benefits received from declining avoided fertilizer 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 numbers in parenthesis represents the percentage of Nitrogen: Phosphorus: Sulphur in each fertilizer

Scenario 4 – extra yield from SSM declines after year 5

Currently no experimental data exists 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 because of the sub-soil changes created by the ameliorant.

Scenario 4 explores the effect of potential yield 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 that, 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 results from the SSM in years 1-5, of 60 per cent 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 6) were on offer in years 1 – 5; then from year 6 onward the extra wheat and canola yield response probability distributions were reduced at a declining amount (Table 11).

Method - Financial Analysis

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. Finance is concerned with the flows of cash in and out over the life of the investment. 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 therefore 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.

Table 11. 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
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

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 above. The standard deviation and coefficient of variation represent the amount of variation in average annual cash flow, or the financial risk.

Control crop rotational nominal net cash flow was estimated using income and costs for a wheat/canola rotation on non-SSM land (Table 12). Control yield probability distributions (Table 13) were developed from experimental control data and variable costs were taken from the PIRSA (2019) crop gross margin guide for high rainfall areas.

Table 12. 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 per cent of gross income ($/ha)	1 per cent of gross income ($/ha)
EPR and State Levies	$3.50 x yield (t/ha)	$0.50 x yield (t/ha)
Seed and treatment ($/ha)	$51	$50
Fertilizer ($/ha)	$130	$165
Herbicide ($/ha)	$118	$93
Fungicide ($/ha)	$25	$5
Insecticide ($/ha)		$67
Grain and fertilizer freight ($/t)	$50	$55
Contract Operations ($/ha)	$185	$289
Net cash flow ($/ha)	Gross income – Variable costs	

Table 13. 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

The SSM crop rotational net cash flow (Table 14) was estimated by adding the rotational marginal gross margins (rMGM) described earlier to the control rotational net cash flow, net of annualised SSM investment costs. The annual cost of the SSM investment was estimating using the annuity (at 6 per cent real interest rate) 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 14. 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)

Results

Sensitivity analysis of investment cost

The sensitivity of total SSM investment cost to a 50 per cent 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 (Table 15).

Table 15. Effect on total SSM cost when litter application rate, distance from litter source and cost of litter were varied by 50 per cent 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 per cent	10	$1,420	38 per cent	30	20
Distance from poultry litter source (km)	$793	-23 per cent	90	$1,265	23 per cent	270	180
Cost of poultry litter ($/t)	$898	-13 per cent	6.5	$1,160	13 per cent	19.5	13

Breakeven (threshold) analysis

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. For example, if SSM had a 5-year life on the investment, 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, whereas an extra rMGM of $717, or 2.24 rotation tonnes per hectare per year, was required when no SSM yield benefits occurred in the first three years ('worst' case) (Table 16 and Table 17). Similarly, if SSM had a 10-year life, an extra rMGM of $152, or 0.47 rotation tonnes hectare, per year was required when the SSM yield benefits occurred in all ten years whereas, when no SSM benefits occurred in the first five years, the threshold increased by +161 per cent (Table 16 and Table 17).

Table 16. Required extra marginal gross margin per hectare ($/ha/yr) to be competitive with alternative investments earning 10 per cent p.a. (real) over five years ($324/t wheat, $578/t canola, zero salvage value, zero avoided fertilizer benefit)

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

*Best case: zero response years occurred late in the analysis period

** Worst case: zero response years occurred early in the analysis period

The proportional increases in required extra rMGM and rotation tonnes were the same for each of the zero response year scenarios for the five- and ten-year rotations (Table 16 and 17).

Table 17. Required extra rotation tonnes per hectare per year to be competitive with alternative investments earning 10 per cent p.a. (real) over five years ($324/t wheat, $578/t canola, zero salvage value, zero avoided fertilizer benefit)

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

*Best case: zero response years occurred late in the analysis period

** Worst case: zero response years occurred early in the analysis period

A lower threshold earning rate decreases the extra benefits required from the investment but the rankings and conclusions do not change.

Monte Carlo simulation modelling

The four scenarios evaluated were:

- Scenario 1 – experimental yield response with three years of maximum benefits from avoided fertilizer,
- Scenario 2 – experimental yield response with no benefits from avoided fertilizer,
- Scenario 3 – 50 per cent reduced experimental yield response with decayed benefits from avoided fertilizer,
- Scenario 4 –extra yield from SSM decline after year 5 of a 10-year planning horizon.

Over a range of combinations of conditions, and over a run of five and ten years, all SSM scenarios analysed were more profitable on average than an alternative investment earning 6 per cent (real) (Table 18 and 19).

Table 18. Mean and standard deviation of net present value (NPV), modified internal rate of return (MIRR), and benefit cost ratio (BCR) per hectare over 5-year investment life for scenarios 1-3

Economic performance measure	Scenario 1	Scenario 2	Scenario 3
Mean NPV (6% real) ($/ha)	1,343	1,040	50
Standard deviation ($/ha)	716	663	444
Mean MIRR (%)	23	20	6
Standard deviation (%)	8	9	9
Mean BCR (6% real)	1.9	1.6	1.0
Standard deviation	0.5	0.3	0.4

The likelihood of earning 6 per cent p.a. real from the SSM if the investment lasted 5-years is shown in Figure 4. Removing any benefit from avoided fertilizer 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 fertilizer benefits (Scenario 3) resulted in a 45 per cent chance the investment would return 6 per cent or less over a five-year investment life.

The range of likely returns is different for each scenario analysed (Figure 5).

If the outcomes from SSM were as described in scenario 1 or 2, the benefit cost ratio is likely to be greater than 1, 95 per cent of the time. However, if the outcomes from SSM were as described in scenario 3, then there is only a 60 per cent chance of the benefit cost ratio being greater than 1 (Figure 6). 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.

If the range and likelihood of the initial yield benefits begin to diminish after 5 years, so that 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 per cent (Table 19). There was a 96 per cent chance that over a 10-year life the investment in SSM would earn above 6 per cent real MIRR (Figure 7).

Figure 4. Cumulative distribution of NPV for scenarios 1-3 with a 5-year investment life

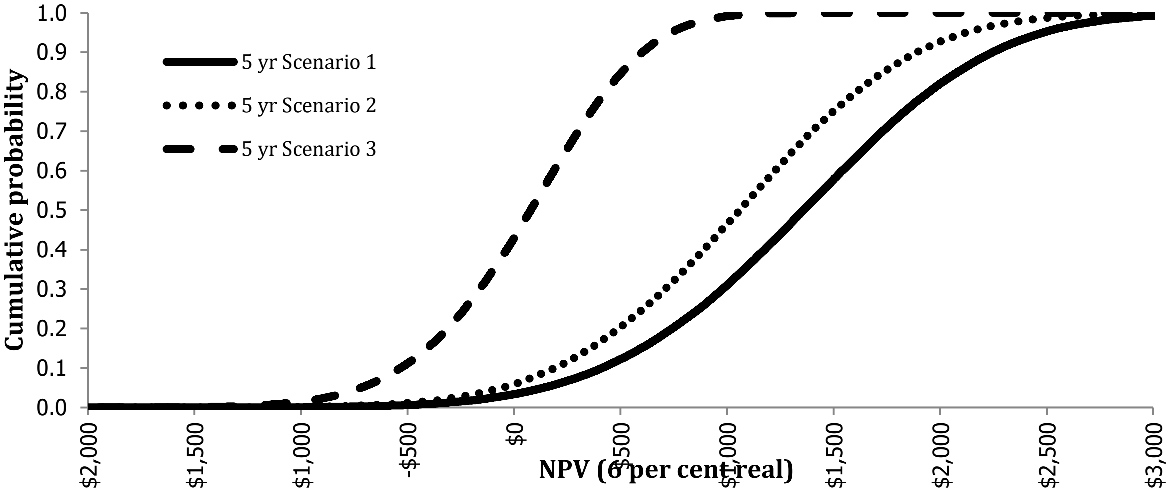


Figure 5. Cumulative distribution of MIRR for scenarios 1-3 with a 5-year investment life

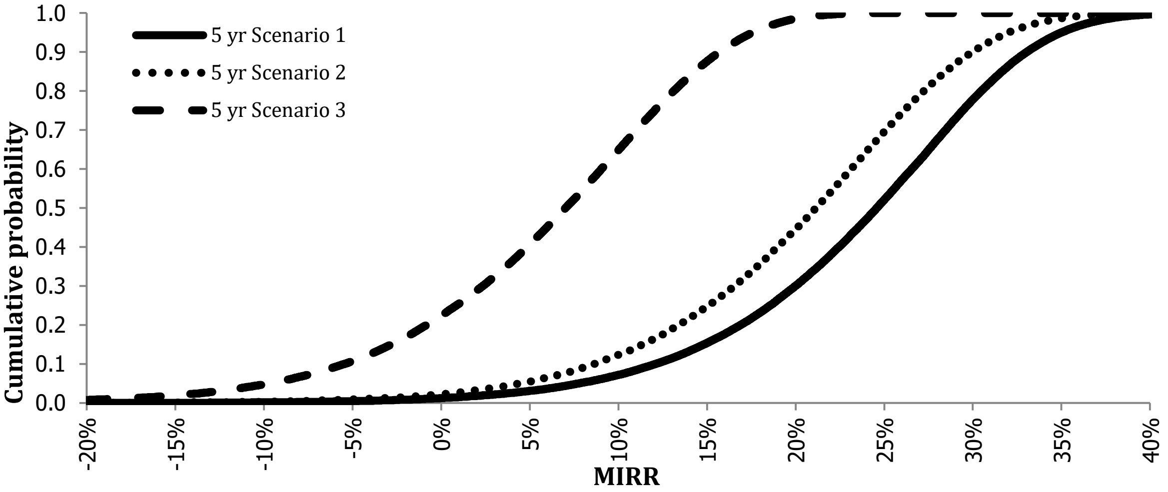


Figure 6. Cumulative distribution of BCR for scenarios 1-3 with a 5-year investment life

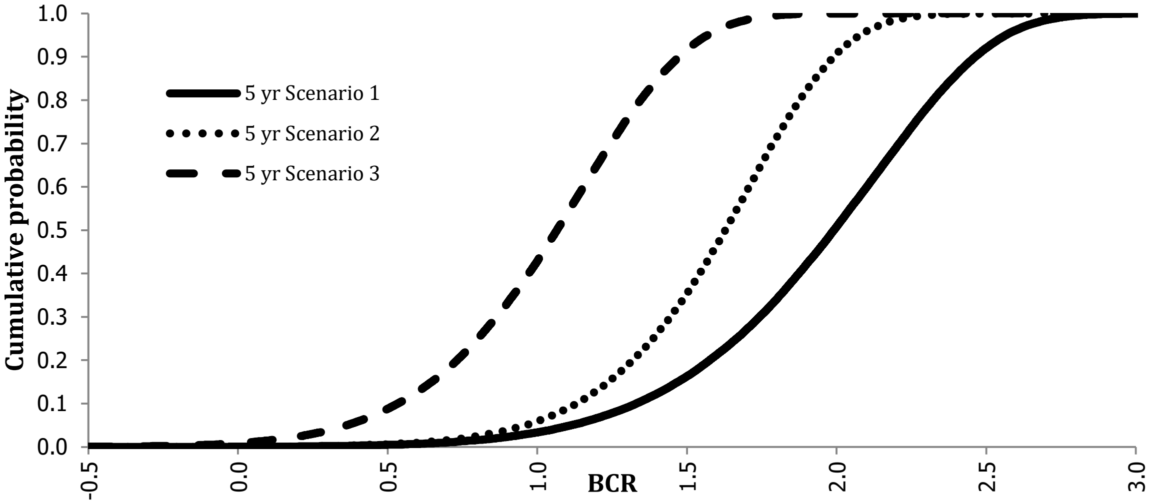
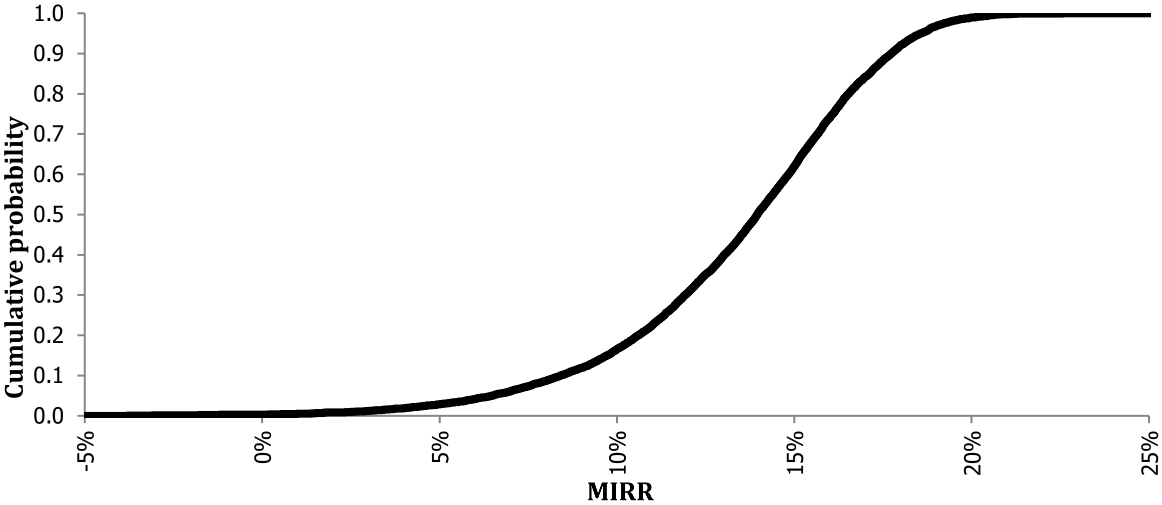


Table 19. Mean and standard deviation of net present value (NPV), modified internal rate of return (MIRR) and benefit cost ratio (BCR) per hectare over 10-year investment life for scenario 4

Economic performance measure	10-year Scenario 4
Mean NPV (6% real) ($)	1,267
Standard deviation ($)	670
Mean MIRR (%)	13
Standard deviation (%)	4
Mean BCR (6% real)	1.7
Standard deviation	0.3

Figure 7. Cumulative distribution of MIRR over 10-year investment life for scenario 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, as seen by a higher standard deviation (Table 20).

Table 20. Standard deviation of net cash flow over five and ten year investments for scenarios 1-3

Parameter	5-year Control	5-year Scenario 1	5-year Scenario 2	5-year Scenario 3
s.d. ($/ha)	154	251	243	196

Discussion

In this research, the likely profit and risk of investing in SSM was investigated. While the main objective 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. The findings from applying these sound farm economic analytical methods to experimental results about ameliorating sub-soil constraints to yields are discussed below.

The minimum extra benefits required for an investment in sub-soil manure to be competitive with alternative uses of capital over a 5-year and 10-year investment life was investigated using threshold analysis. A threshold analysis was used to examine the 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. This is important as 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. Threshold analysis indicated that over a 10-year investment life, an additional yield of 0.47 tonne per ha per annum of wheat and canola in a wheat-canola rotation was required to deliver 10 per cent real return on capital p.a. If the SSM only had a 5-year life, then an additional 0.77 tonnes per ha of wheat and canola was required to deliver 10 per cent p.a. real return on capital. The number of responsive years[3] over the investment life and the timing of when the responsive years occur influence the magnitude of extra yields required per year. These could range from an extra 0.77 t/ha per annum to 2.24 t/ha per annum for a 5-year project life, or from 0.47 t/ha per annum to 2.28 t/ha per annum for a 10-year project life. The 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. 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.

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-limited yield potential (French and Schultz, 1984) is lower than the required SSM break-even yield, it is unlikely that the benefits of alleviating sub-soil constraints using SSM will be achieved. Alternatively, if the crop land is in a region where the required yield benefits are achievable but the topsoil fertility is currently poorly managed, the ability to generate 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.

Simulation analysis over a 5-year life indicated that the benefits of SSM in a wheat-canola rotation depends on the yield response. If there is a yield response occurring in a stochastic manner above the counterfactual case of the *status quo*, with and without benefits of saved annual fertilizer, then there is a 50 per cent chance of earning returns on capital above 20 per cent p.a. with one standard deviation around this mean of plus or minus 8 per cent return. Thus, it is likely that an investment in SSM would increase a farmer’s wealth (the NPV is likely to be positive at a 6 per cent discount rate). However, a worst-case scenario, where only half the experimental yields were achieved and initial fertilizer savings rapidly decayed, had a 50 per cent chance of earning a return above 6 per cent p.a. with one standard deviation around this mean of plus or minus 9 per cent. 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 capital on the farm, which have similar price and yield risk to that of the SSM investment, earning more than the 6 per cent risk-free rate of return. An investment in SSM was more profitable on average than an alternative investment earning 6 per cent (real) despite the conservative assumption of valuing at zero the likely enduring improvements in soil productivity subsequent to the assumed investment life.

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[3] A responsive year is one where there is extra yield from SSM.

The magnitude of expected extra yield benefits and the number of years the extra benefits can be achieved are the most important factors for a farmer to consider when assessing the likely merit of investing in SSM in their own situation. The expectations of the extra annual yield from crops grown on SSM-treated land needs to be considered in the context of the farmer's 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. For example, if a farmer cannot achieve yield responses consistent with the yield responses achieved in experiments when implementing SSM on a commercial scale, and achieves only 50 per cent of the experimental yield responses, then over a 5-year investment life there is a high chance (44 per cent) that the investment would achieve a return equal to, or lower than, the required 6 per cent.

A farmer considering SSM would be prudent to not rely exclusively on fertilizer cost-saving for the investment to be profitable. The small difference in profit between scenarios analysed in this research indicates that the benefits of forgone fertilizer costs were minor compared to the benefits of extra yield.

A farmer considering investing in SSM with 5 years of net benefits would also need to be prepared to accept that there will likely be more volatility in annual net cash flow (NCF) than with the *status quo*. 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.

Experimental yields were reduced by 50 per cent (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). Under this scenario, the expected return was significantly lower. 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) summarises 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 (p.149).

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 an 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.

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 is possible to estimate the maximum number of hectares one SSM machine can treat annually[4]. 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. However, approximately 3,618,000 ha of Victorian cropping area is constrained by sodic sub-soils (Orton *et al.,* 2018). The lack of commercially-ready SSM machinery is a current impediment to ameliorating sub-soil constraints using SSM, though one which commercial interests would likely rectify if demand grew.

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 were 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 were 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.

Poultry litter as an amendment – limitations and alternatives

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 per cent 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 per cent 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. A 50 per cent reduction in application rate resulted in a 38 per cent 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.

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. 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 application 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

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[4] 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.

amendment could be an effective method of decreasing the extra cost of SSM although, 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.

Previous studies have identified that there is insufficient poultry litter produced in Victoria to meet the demand of ameliorating the area of sub-soil 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. The distance the land that is being treated with SSM is from the source of the poultry litter has a large impact on the total cost of SSM. Chicken meat farms are the main source of chicken litter in Australia (Weidermann, 2015). Chicken meat farms are generally aggregated within 100 km of meat processing plants (Watson and Weidermann, 2019), which are located at a limited number of locations around Australia. The soils likely to be responsive to SSM are located well beyond the chicken meat production regions, so transport costs of ameliorant will likely be high for a large proportion of farmers considering SSM.

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 fertilizer replacement on agricultural land. In 2016-17, 700,000 tonnes of litter were applied to land in Australia (Table 21).

Table 21. Poultry litter application by state

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

Source: ABS (2018)

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. 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 the practice 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 of when SSM needs to be undertaken, the price of synthetic nutrients, and whether SSM will be undertaken by current users of poultry litter.

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 fertilizer application by farmers (Chapter 4A of the Environmental Protection Act 1994). An understanding of the environmental impacts of large-scale adoption of the sub-soil application of high rates of poultry litter is required before promoting the practice to industry.

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 framework of Hardin and Johnson (1955) is warranted before these options are promoted as cost-effective alternatives to poultry litter.

Final Thoughts

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 fertilizer replacement (saving) effect;
- Using SSM in pasture and fodder production systems;
- Environmental impacts of applying high rates of nutrient-rich organic matter to the sub-soil.

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

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