Subsoil manuring: an innovative approach to addressing subsoil problems targeting higher water use efficiency in Southern Australia

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Summary

Dense and impervious subsoils can be a major impediment to achieving potential water use efficiency (WUE) from cereal and canola crops grown in high rainfall Southern Australia. The placement of large volumes of organic matter within and above the heavy clay layers of the soil in a single deep ripping operation, referred to as subsoil manuring (SM), led to improvements in soil bulk density (25%) and a corresponding increase in soil macro porosity. This resulted in nearly a 37% increase in plant available water capacity (PAWC) that contributed to yield increases of between 27% and 96% across different soil types and rainfall regimes. The temporal change in soil physical properties with SM, of the otherwise hostile subsoil, led to capture and storage of summer rainfall (with a near doubling of the summer fallow efficiency) and made it available to crops during grain filling in the following spring when below average rainfall conditions existed. A collaborative research and extension programme since 2007 has looked at the technology, the resulting productivity increases and the economics of the practice. With the magnitude of yield increases obtained, it was found possible to recover the costs of the initial operation in under four years and the effect of a single intervention showed no signs of diminishing after four years. The emerging technology represents a powerful adaptive strategy to a warming and drying climate with the potential to double the crop yield in the region and revolutionise the farming system.

Introduction/ History

The agricultural regions of southern Australia, particularly the high rainfall zone (HRZ) have undergone significant land use change since about 1995 (ABS, 1994-2002). In regions receiving in excess of 550 mm of annual rainfall, cropping has increased in extent compared to traditional grazing because of the reliability of successful cropping with the long, cool season varieties (Zhang et.al., 2006). However, most clay and sodic subsoils in the region present a challenge to cropping (Gardner et.al., 1992) and these dense and low macro porosity soils (McEwan, 2006) often contribute to surface and sub-surface water-logging mainly during winter. A strategy to overcome this has seen the development of raised beds in broad acre, which on shrink-swell clay soils (Sarmah et.al., 1996) has contributed to changes in soil physical properties (Wightman et.al., 2005; Peries et.al., 2010) that aids greater root proliferation and assist crops to explore a larger volume of subsoil which was previously inaccessible to roots due to poor soil macro porosity. In other soils such as the grey Sodosol (Isbell, 2002; VRO, 1999) which predominates in the Victorian HRZ, improvement in subsoil structure is a very slow process with existing agronomic strategies.

The practice of subsoil manuring (SM) in the Victorian high rainfall zone (HRZ) has been trialled and evaluated since about 2003 (DPI, 2005). The practice involves the placement of large amounts (usually between 10 and 20 t/ha) of organic manure within the heavy (and dense) clay matrix of hostile duplex and/or gradational soils in a single ripping operation (Gill et. al., 2008). The soils studied so far are known to be very poor in their plant available water capacity (PAWC) because of poor macro and meso porosity (and aeration) and therefore are a major impediment to root growth and proliferation. They also typically have high levels of exchangeable sodium and are therefore prone to dispersion (VRO, 1999). The practice of SM encourages root development in the subsoils and with the extra nutrients and the suspected biological activity it encourages, leads to the aggregation of the dense clay matrix leading to a larger 'bucket size' (Gill et.al., 2009, 2012). In a warming and drying climate where crops often experience severe soil water deficit during grain-fill, this practice has shown great promise in sustaining growth and contributing to significant productivity benefits. For decades, growers in the HRZ were aware of the nature of their subsoils and their limitations and were keen to address this problem. However, the prevailing attitude was that "it was too

Improvised techniques involving manually slotting manure into a ripline.

expensive to ameliorate these hostile subsoils and so you just had to live with them". This paper draws on early experimental results (2005-2007), and summarises a series of recent experiments on SM conducted between 2009 and 2012, discussing the consistency of results over sites and seasons and argues for widespread use of the practice as a means of increasing water productivity as an adaptation strategy to a warming and drying climate.

Research, Development and Extension on subsoil manuring

The first research trials for the evaluation of SM was carried out on a Sodosol at Yaloak estate in Ballan, Victoria from 2005-2007 where the average annual rainfall is around 570 mm and winter dominant. It was a small plot trial (5 m long on 1.7 m raised beds) in a randomised block design with four replicates. The amendments were applied manually with an improvised implement that was pulled behind a single ripper to a depth of 30-40 cm. Two rip lines were made on each 1.7 m bed, 75 cm apart. The treatments included a control, a deep rip only treatment, lucerne and Dynamic Lifter at the rate of 20 t/ha and other treatments and treatment combinations with sand, gypsum and MAP fertilizer. Treatments such as deep ripping plus gypsum had in the past been used in the amelioration of hostile subsoils with a varying degree of success (Jayawardene and Chan, 1994; Jayawardene et.al., 1995). Crops were managed to best practice guidelines for the region.

The prototype 'blue machine' developed for use in subsoil manuring trials..

Based on the encouraging results from the above trials, five validation trials were installed in 2009 to test the broad acre applicability of the practice of SM across sites and seasons. In all these trials, poultry manure was used as the ameliorant at rates of 10 and 20 t/ha. In addition to a control and deep ripping treatment, there was also an inorganic treatment (to match the nutrients in 20 t/ha poultry manure) and a treatment of 10 t/ha manure supplemented with inorganic nutrients (to match the nutrients of 20 t/ha poultry manure). Again the trials were in a randomised block designs with four replicates. One of the sites (Stewarton) in high rainfall Northern Victoria had an additional treatment of 20 t/ha manure applied on the surface. All trial sites were sown by commercial machinery by the farmers or contractors of the property and managed to best practice guidelines for the region. Grain yield, grain protein and profile water use was monitored over four growing seasons to 2012. Soil water was measured using a Neutron Moisture Meter (NMM).

Results and Discussion

From the initial research trials at Ballan, grain yields in the order of 11.5 to 13.2 t/ha were obtained from treatments with organic amendments compared to control (7.6 t/ha) and deep rip plus gypsum (8.5 t/ha) treatments (Gill et.al., 2008). The higher yield with organic amendments was associated with higher grain number per head, grain size and number of heads produced per unit area. The higher yields were also accompanied by higher harvest indices (63 to 69%) compared to control (48%), deep ripping (55%) and deep ripping with gypsum (62%).

However, equally or more important were the temporal changes to soil physical properties as a result of the amendment within the heavy clay matrix of the soil. Measurements made at a midpoint between the two rip lines showed a 25% decrease in soil bulk density and a corresponding increase in macro porosity from 8% to over 18% (Gill et.al., 2009). The increase in porosity contributed to additional PAWC. A lowering of the wilting point in soil (the lower limit of plant available water) also contributed to the increased PAWC. These soil processes along with 'suspected' soil biological activity, aided by crop root activity, caused aggregation of the soil, thereby breaking down the heavy clay matrix and increasing the 'bucket size' of the otherwise hostile and dense clay. The changed aggregate structure of the soil was visually observed 24 months after the amendment was placed within the clay matrix. The root length density at depth of the wheat crops grown increased significantly with the SM treatment. The improvement in soil hydraulic conductivity was also substantial in response to SM. In shallower layers there was a 6-fold increase, while at 30-40 cm depth the increase was almost 50-fold (Gill et al., 2009).

The changed aggregate structure of the otherwise dense clay then contributed to the capture, storage and use of more soil water in 2005 and 2006 (Table 1). During the summer fallow period, SM plots accumulated almost three times the soil water compared with the control, thus contributing to the summer fallow efficiency (Gill et al., 2012). The additional water stored and used in the subsequent seasons contributed to the significantly high grain yields in these trials.

Table 1. The accumulation and use of soil water in the profile to 80 cm depth by wheat crops in the 2005 and 2006 seasons at Ballan in South West Victoria measured using a NMM.

Water Use 2005 (mm)		Water Use 2006 (mm)		Accumulation of water in the profile, 2006 (mm)	
Control	Manured	Control	Manured	Control	Manured
57	123	57	136	45	125

Table 2 summarises the yield of wheat and canola from a range of trials conducted between 2005 and 2011. The increases attributed to SM were consistent across sites and seasons with the magnitude of such differences dependent on either the soil condition or the rainfall distribution during the season. Also important to note is the duration of the effect. Data on Table 2 shows that three years after manuring, canola (Ballan) and wheat (Penshurst) crops were still yielding significantly higher (56% and 66% respectively than the corresponding control treatments.

The validation trials conducted between 2009 and 2012 were designed to test the above results under general farmer management. Deep litter poultry manure (dry) was selected as the preferred organic amendment (3.2%N; 1.5%P and 1.3%K approximately with about 40% total C in the litter). While most sites consistently produced significantly higher yields with SM compared to the control, we will discuss results only for two sites in this paper: the sites of Penshurst (near Hamilton in Western Victoria) and Derrinallum (also in the Western District) with contrasting soil and rainfall conditions. These two sites were also used in an economic analysis of the practice of SM because of noteworthy differences in the cost of manuring. The soil at Derrinallum was a Grey Sodosol (Isbell, 2002) with a prominent and wavy layer of ironstone ("buckshot") that often sets hard when dry. The wavy nature of this layer also dictated the depth of the topsoil that was variable across the site. In contrast the soil at Penshurst was a gradational basalt (Black Sodosol) soil (VRO, 1999) with a soil bulk density of 1.5-1.6 g cm-3 at 20-50 cm depth in the profile. It was also the wettest site in Victoria with an average annual rainfall of 720 mm, but a site also recognised for its low water use efficiency (WUE) in a recent benchmarking survey (Peries and Gill, 2010). This suggests that despite the relatively high rainfall, there is significant and unproductive loss of water from the system that could otherwise be used in production if it can be captured and stored in the profile.

Table 2. Summary of crop yields for commercial and subsoil-manured crops, at sites across the HRZ in Victoria, from 2005-2011.

Year	Site	Crop number following treatment	Grain Yield (t/ha)			Percent increase
			Commercial crop	Subsoil manured [1]	Increase in yield	
Wheat						
2005	Ballan	Wheat (1st crop)	7.6	12.5	5.3	70 %
2009	Derrinallum	Wheat (1st crop)	5.0	9.8	4.8	96 %
2009	Penshurst	Wheat (1st crop)	4.8	7.6	2.8	58 %
2010	Wickliffe	Wheat (1st crop)	9.1	11.6	2.5	27 %
2011	Stewarton	Wheat (1st crop)	5.7	8.1	2.4	42 %
2006	Ballan	Wheat (2nd crop)	3.6	5.6	2.0	55 %
2011	Derrinallum	Wheat (3rd crop)	5.0	7.4	2.4	48 %
2011	Penshurst	Wheat (3rd crop)	6.8	11.3	4.5	66 %
Barley						
2009	Winchelsea	Barley (1st crop)	4.4	7.7	3.4	77 %
Canola						
2007	Ballan	Canola (3rd crop)	1.6	2.5	0.9	56%

[1] Plots received 20 t/ha (fresh weight with less than 20% moisture) of organic amendment that was incorporated into the subsoil.

Penshurst site in SW Victoria

Table 3 shows grain yield and grain protein from the Penshurst site for the four years since the SM treatment was applied. Consistently higher grain yields of wheat and canola were obtained in all four years but the difference in yield was not significant with canola in 2010 (a decile-9 year) being a very wet season with 530 mm of growing season rain. Of this, 230 mm of rain fell in the grain filling period and there was water-logging throughout the growing season. The story with wheat indicates when and where the benefits of SM are best realised. The year of manuring (2009) was only relatively wet with a grain filling period rainfall of 135 mm where the yield difference from manuring was only 2.8 t/ha. In contrast, there was only 59 mm of rainfall during grain filling in 2011, where the SM treatment produced a yield advantage of 4.5 t/ha.

These yield differences in response to seasonal rainfall distribution were associated with the extraction of subsoil water. Table 4 shows the profile soil water extraction from the subsoil (50-100 cm depth) in years 2010 to 2012. All crops extracted significantly greater amounts of water from depth in the subsoil manured treatment compared to the commercial crop (control). Despite only receiving 59 mm of rainfall during the grain filling period in 2012, the canola crop, which was the fourth crop since the SM treatment was applied, still showed significant extraction of 'stored' soil water from depth to produce a yield advantage of 2 t/ha.

Table 3. Grain yield and grain protein for treatments at Penshurst from 2009 to 2012.

Treatment	Grain Yield (t/ha)				Grain protein (%)	
	2009 Wheat	2010 Canola	2011 Wheat	2012 Canola	2009 Wheat	2011 Wheat
Commercial crop	4.8	0.8	6.8	2.3	13.3	9.3
Deep ripped only	4.5	1.2	7.4	2.0	13.3	9.6
Subsoil Manuring (20 t/ha)	7.6	2.0	11.3	4.3	15.8	10.7
Subsoil Manuring (10 t/ha)	6.8	1.4	10.0	2.9	13.6	10.0
Fertiliser nutrients (DAP/Urea)	6.0	1.3	7.7	1.9	15.8	10.6
½ Fertiliser + 10 t Manure	5.7	1.2	6.8	3.2	15.7	10.8
LSD $_{(P=0.05)}$	**1.6**	**NS**	**2.1**	**0.7**	**3.0**	**1.3**
Significance	**0.001**	**0.20**	**0.001**	**0.02**	**0.007**	**0.13**

Table 4. Extraction of subsoil water (mm) between anthesis and maturity, from the 50-100 cm deep subsoil layer, at Penshurst from 2010 to 2012.

Treatment	Change in profile water content (mm) in the 50-100 cm subsoil layer, between anthesis and maturity		
	2010 Canola	2011 Wheat	2012 Canola
Commercial crop	- 2.2	30.3	14.8
Deep ripped only	16.6	13.8	29.8
Subsoil Manuring (20 t/ha)	40.4	47.1	45.8
Subsoil Manuring (10 t/ha)	24.2	33.1	24.4
Fertiliser nutrients (DAP/Urea)	24.8	14.1	12.4
LSD $_{(P=0.05)}$	**24.1**	**5.6**	**16.1**
Significance	**0.026**	**0.001**	**0.004**

This clearly indicates that the effect of SM showed no signs of diminishing in the fourth year from application. The length of time that the beneficial effects of SM will persist cannot be predicted. However, the expectation is that since the observed and measured changes to soil physical properties in the subsoil are 'suspected' to be biologically driven, the effect is unlikely to disappear in the short-term provided there is no major modification of the farming system.

Derrinallum site in SW Victoria

The three wheat crops grown at Derrinallum in 2009, 2011 and 2012 all produced significantly high grain yields with the full rate of subsoil manuring (20 t/ha) compared to control (Table 5). The magnitude of the yield response was again related to the rainfall during the grain filling period from October to November. The large grain yield increases in wheat in 2009 (4.8 t/ha) and 2012 (4.1 t/ha), occurred with 104 and 109 mm of grain filling period rainfall. In both years the subsoil manuring treatment also yielded significantly more than the full nutrient treatment. However in 2011, the more modest yield increase of 2.4 t/ha of wheat was achieved, and this grain filled with 120 mm of rainfall in the October to November period. In this year there was no difference in grain yield between the subsoil-manured and full nutrient treatment.

Table 5. Grain yield and grain protein for treatments at Derrinallum from 2009 to 2012.

Treatment	Grain Yield (t/ha)				Grain protein (%)		
	2009 Wheat	2011 Wheat	2012 Wheat		2009 Wheat	2011 Wheat	2012 Wheat
Commercial crop	5.0	5.0	6.3		11.5	10.3	10.6
Deep ripped only	4.5	5.5	6.9		11.7	11.0	11.3
Subsoil Manuring (20 t/ha)	9.8	7.4	10.4		12.9	11.6	10.6
Subsoil Manuring (10 t/ha)	6.8	6.9	8.8		12.1	10.9	11.3
Fertiliser nutrients (DAP/Urea)	6.0	7.3	7.9		12.7	13.0	11.9
½ Fertiliser + 10 t Manure	5.7	7.1	8.8		12.7	11.4	11.3
LSD $_{(P=0.05)}$	**1.6**	**1.8**	**1.1**		**1.0**	**1.6**	**1.8**
Significance	**0.001**	**0.046**	**0.001**		**0.067**	**0.053**	**0.57**

The canola crop at Derrinallum in 2010 failed because of water-logging (Tables 5,6). This decile-9.5 year received 929 mm of annual rainfall, which greatly exceeded the 653 mm of average rainfall for this site. There was 555 mm of growing season rainfall and 164 mm of grain-filling rainfall at the site. Overall, there was an extra 63 mm of annual rainfall at Derrinallum than at Penshurst, and 17 mm more of growing season rainfall. Given that the subsoil at the Derrinallum was 'more hostile' with a denser clay and ironstone gravel layers, it was not surprising that the water-logging stress at Derrinallum exceeded that at Penshurst, resulting in the failure of the canola crop.

The wetter finish for the wheat crop at Derrinallum in 2011, was associated with a modest 2.4 t/ha wheat yield increase with full subsoil manuring over the control treatment. It also resulted in a lack of treatment differences in the extraction of deep soil water by the crops in 2011 (Table 6). However, in the drier finish in 2012, when there was a 4.1 t/ha yield increase in wheat with the full subsoil manuring treatment, there was also a very large, significant increase in the deep water extraction between the full manuring treatment and all other treatments.

Table 6. Extraction of subsoil water (mm) between anthesis and maturity, from the 50-100 cm deep Subsoil clay layer, at Derrinallum from 2010 to 2012.

Treatment	Change in profile water content (mm) from the subsoil 50-100 cm layer, between anthesis and maturity		
	2010 Canola	2011 Wheat	2012 Wheat
Commercial crop	-	27.2	12.0
Deep ripped only	-	33.2	4.2
Subsoil Manuring (20 t/ha)	-	18.0	26.7
Subsoil Manuring (10 t/ha)	-	22.6	4.5
Fertiliser nutrients (DAP/Urea)	-	38.2	2.7
LSD $_{(P=0.05)}$	**-**	**21.2**	**2.3**
Significance	**-**	**0.31**	**0.001**

Large, consistent and recurring crop yield increases occurred on subsoil-manured plots, at the two field sites at Penshurst and Derrinallum described above between 2009 and 2012. These were achieved when successful commercial crops were established without the adversity of water-logging. The magnitude of the yield increase with subsoil manuring appeared to depend on the seasonal conditions during the grain-filling period. The larger yield responses mainly occurred with dry finishes to the growing season. The association between dry finishes and increased yield responses, occurred at Penshurst where there was a modest yield increase of 2.8 t/ha wheat in 2009 with 135 mm of grain-fill rain, while the large increase of 4.5 t/ha wheat occurred with 59 mm of grain-fill rainfall. Similarly at Derrinallum there was a 4.8 t/ha wheat yield increase with 104 mm of grain-fill rain in 2009, compared to the 2.4 t/ha wheat with 120 mm of grain-fill rain in 2011. Thus the basis for these large yield responses to subsoil manuring in years with a dry finish relates to the fact that the control yield is constrained by water deficit during the grain filling period, whereas there is less yield constraint from water deficit on manured subsoil.

A key finding from this research is that subsoil manuring increases the availability of deep subsoil water, and this enables the crops to avoid water deficit during the grain-filling period. Earlier work has shown how subsoil manuring was able to almost double the macro-porosity of the upper clay layers of the Sodosol soil from less than 10% to more than 20% of the soil volume (Gill et al. 2009). This no doubt resulted from the increased aggregation of the clay layer that was illustrated by Sale et al. (2011). A macro-porosity of less than 10% is likely to limit root growth (Glinski and Lipiec, 1990; Engelaar and Yoneyama, 2000) and therefore the change would enhance the root growth in the clay subsoil during crop growth, resulting in extra soil water being extracted from the clay subsoil. It follows that in dry springs, the crop roots are able to extract extra subsoil water that has been replenished by the rain that has fallen during the previous year. This was demonstrated consistently in this work, as in practically every case where large grain yield responses were recorded with the subsoil manuring treatment (Gill et al., 2012). There was also a significant increase in the volume of soil water that was extracted from subsoil at 50-100 cm depth.

The increased PAWC with subsoil manuring, was documented at another site (Stewarton) during this work (data not shown) in 2012 following the second successive crop of wheat that was grown following the subsoil intervention. An additional 78 mm of plant available water in the 40-100 cm depth was measured when the soil profile was at its drained upper limit. It is likely that a significant proportion of this extra subsoil water below 40 cm would be used by the crop after anthesis. Given that crops use water so much more efficiently after anthesis (Passioura 1976; Kirkegaard et al. 2007), then large increases in wheat yield (in excess of 4 t/ha) that have been reported here are indeed possible.

Apart from the increased use of subsoil water in dry springs, it is likely that there are two other factors contributing to the grain yield increases with subsoil manuring. The first of these is the response to the increased nutrient supply in the subsoil resulting from the nutrients added in the poultry litter that was incorporated in the clay subsoil. The quantity of added nutrients in 20 t/ha of poultry manure was substantial. They amounted to 530 kg of total N, 315 kg of total P, and 330 kg of total K per hectare. So the response to subsoil manuring at Derrinallum in the wet spring of 2011, could be explained in part by the extra nutrients that were available to the crops, given that there was no soil water deficit during the grain filling period. A second factor that most likely contributed to the increased grain yield with subsoil manuring, particularly in wet years, was some alleviation of water-logging stress in the subsoil, due to the increased macro-porosity within the clay.

Among the largest yield responses that occurred at the Penshurst and Derrinallum sites in south west Victoria in 2012, there was an extra 2 t/ha of canola produced at Penshurst and 4.1 t/ha of extra wheat at Derrinallum. These crops were the 4th successive crops grown at these sites following the subsoil manuring intervention in 2009. This then raises the issue as to how long the yield-promoting benefits from subsoil manuring will last? This remains to be seen, and these two sites will be monitored over time to answer this question. However, we suspect that the continuing root activity in the subsoil layers, with each successive crop, will continue to provide microbial substrates in the form of decaying roots, mucilages and root exudates. These will stimulate microbial activity to release the extra-cellular polysaccharides that will in turn maintain the cohesiveness of the clay aggregates that have been observed in the treated clay layers, and create the extra macro-porosity that enables root occupation in the subsoil. It is possible then that the benefits will continue with continual cropping, where the crop roots are able to regularly grow and proliferate in the treated clay layers (Sale et. al., 2013).

Economics of subsoil manuring:

The Penshurst and Derrinallum site data were used in an economic analysis (Sale and Malcolm, 2013) to determine whether using large amounts of manure in a deep ripping operation was affordable and profitable to farmers. As far as possible, real costs were used in the analysis. The source of poultry manure was closer to Derrinallum than to Penshurst which increased the freight costs in the Penshurst operation. The analysis determined that there was a higher total cost of operation at Penshurst ($1345/ha) compared to Derrinallum ($1244/ha) at the 20 t/ha application rate. Ripping and application costs were based on the costs incurred by the first ever commercial subsoiling machine developed by a private operator in the Western District of Victoria.

The analysis used the actual grain yields harvested from control versus manured plots at each site over four consecutive years. Fuel and operator costs were taken into consideration based on the different speed of travel of the tractor to deliver 10 and 20 t/ha manure in a single deep ripping operation.

Given the magnitude of yield responses with SM and their continuation over time, the practice was found to be very profitable. The preliminary results indicate that the investment in the high rate of manure incorporation (20 t/ha) resulted in an annual increase in wealth (each year for the next 4 years) that exceeded $500/ha at Penshurst, and $400/ha at Derrinallum, over and above an investment earning 8% per annum. This annuity was less at Derrinallum due to crop failure (through water-logging) in the second year following the SM intervention.

Conclusions/ Future of subsoil manuring

Subsoil manuring resulted in consistent grain yield increases across the network of sites in the HRZ of Victoria. In years with drier finishes, the yield of the commercial control crop was constrained due to water deficits during grain filling, while the subsoil manured crops were able to access additional subsoil water. Thus, these crops were not constrained and significantly higher yields were achieved.

In wet years with wet finishes to the season, we suspect that the yield increases result from both an increase in nutrient supply in the subsoil and to some alleviation in water-logging stress that may develop in the soil profile.

The plant available water capacity (PAWC) in the soil profile was measured to 100 cm in the trials, and as a result of the subsoil manuring intervention, the PAWC was increased from 60 to 138 mm between 50 and 100 cm. This more than doubling of PAWC represents an invaluable result for the yield- potential of the treated land. The ability of the soil to capture and store greater amounts of rainfall will increase, meaning crops will have access to larger amounts of water during later growth stages, which will result in large increases in crop yield. Such results will increase the resilience of a cropping system on these Sodosol soils, as we encounter increasing climate variability in the future.

The future of SM will depend on the adoption of this technology by growers. Currently there is limited access to machinery for farmers interested in testing the technology under their field conditions. There is also the need to look at options in terms of material other than poultry manure which has been tested in broad acre. In 2014, we embark on a journey to develop a suitable machine that is robust enough to handle the range of soil conditions that might respond to SM. In parallel there are also SM demonstrations being set up across different parts of Victoria and the search continuing through research and development to identify the range of materials (both on-farm and off-farm) that could provide a more economical form of amendment that will have a similar effect to the materials that have already been tested.

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