Government of South Australia
Department of Environment, Water and Natural Resources

RURAL SOLUTIONS SA
PIRSA

A review and summary of information pertaining to the modification of sandy soils in the broadacre agriculture zones of Southern Australia.

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PATHWAY TO IMPROVEMENT

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1. Acknowledgements

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2. Introduction

There are approximately 10.2 million hectares of land in South Australia cleared for agriculture (McCord and Payne 2004). Of this approximately 3.7 million hectares consist of deep sand (2 204, 000 ha) or sand over clay (1 403, 000 ha) soils (Hall et al 2009) Sandy soils create significant constraints to production in South Australia. Issues associated with sandy soils include;

- Poor inherent fertility
- Inherently prone to nutrient leaching
- Inherently prone to wind erosion
- Low moisture holding capacity
- High wind erosion risk
- Tendency to possess hydrophobic characteristics (non-wetting)
- Prone to acidification.

These constraints have been assessed to result in an estimated $791.8 million of foregone production lost annually in South Australia (Cann et al 2004).

However, with careful management using innovative soil amelioration techniques these soils also have significant opportunity for production gains. Non-wetting on sandy soils is considered an issue of moderate to high importance on 2.48 million hectares of cleared land with wind erosion also being a major issue on sandy soils (cleared area with moderate to severe wind erosion risk 2.4 million ha). (McCord and Payne 2004). Clay spreading and delving are currently the most widely used methods for the long term amelioration of non-wetting soils in South Australia.

3. Project Background

Initially broad scale work conducted on sandy soils in SA was in response to soil non-wetting characteristics. Recognised in many regions of the world, non-wetting soils are considered a serious problem across southern Australia with significant areas affected in South Australia, Victoria, and Western Australia. Caused by waxes from decaying organic matter these soils possess hydrophobic properties where water is slow to infiltrate and tends to bead on the soil surface. Ma'shum (1989) stated that the severity of water repellence is related directly to the concentration of organic waxes in the soil and has an inverse relationship with calculated surface area of the soils. This problem is mainly found in the surface horizons of sandy soils and once established appears to become a permanent feature of the soil.

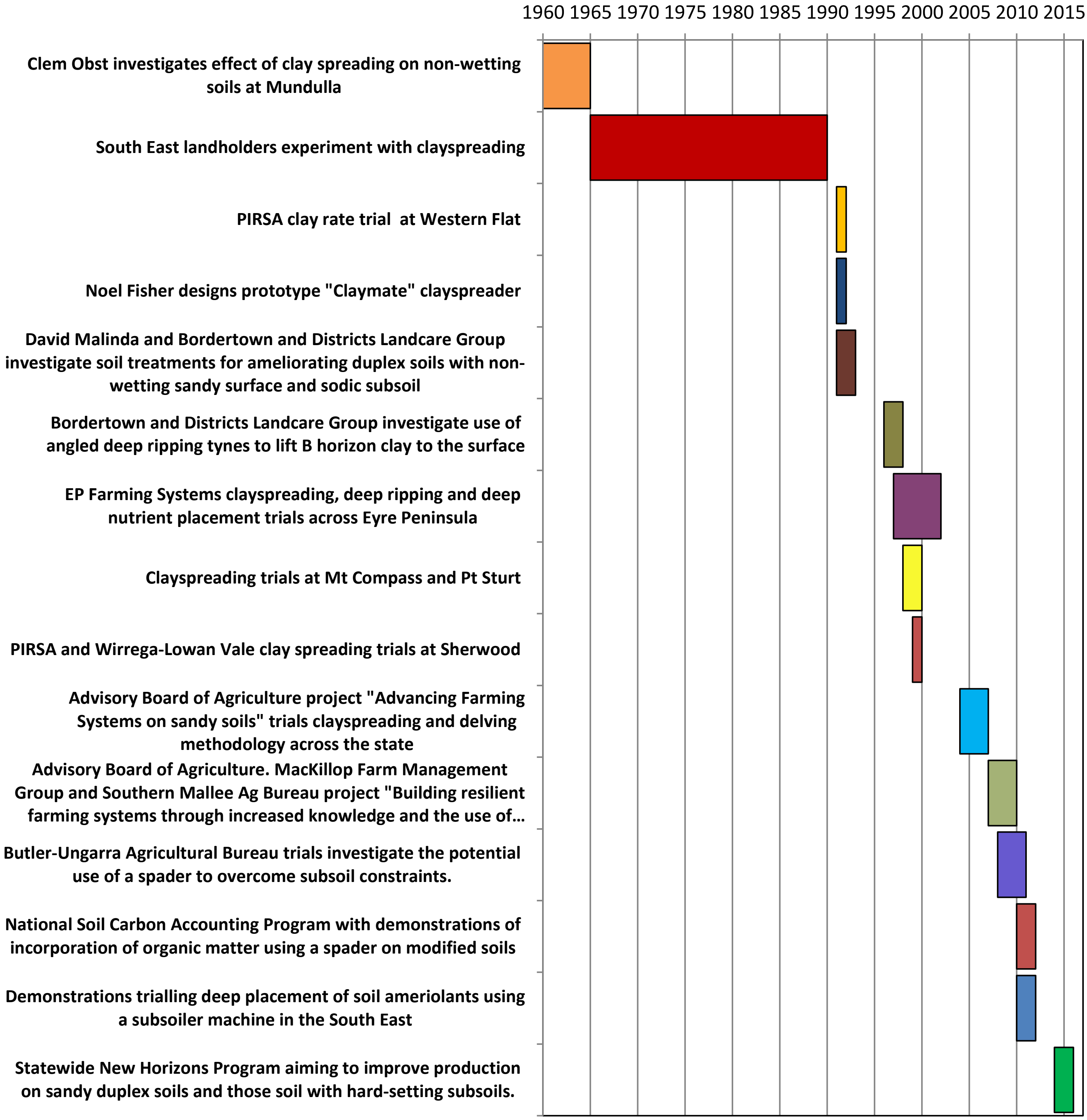
Michelsen (1990) states that by adding clay to a non-wetting soil the surface area is substantially increased and the water-repellence lowered. Clay spreading on a broad scale as a technique for overcoming water repellence on sandy soils was initially experimented with in 1968 by Mundulla farmer Clem Obst (Obst 1990). Clem's initial trials involved spreading a small amount of clay on a sandy rise and mixing it in. He noticed an immediate improvement to wetting ability of the soil. Subsequent trials by Clem involved using a road scraper to spread clay taken out of new dams onto sandy rises at 150 to 210 t/ha and incorporating the clay using a scarifier and railway iron. These trials discovered that spreading clay on the surface of these soils could increase crop yields and reduce the risk of degradation through:

- Eliminating soil hydrophobic (water repellent) properties
- Improving the overall fertility of sandy soils
- Reducing the inherent risk of wind erosion

Due to the capacity for significant reductions in the non-wetting nature of sands following clay spreading, landholders in other districts began to adopt the concept and began to investigate improved techniques for clay application.

The timeline below provides a summary of the major activities/projects which have been undertaken investigating the management of sandy soils in South Australia since Clem Obst's initial clayspreading. These activities and other soil modification work are further detailed as appendices to this report.

Figure 1. Timeline of major works undertaken to investigate the effect and best methodology of soil modification works in South Australia 1960 - 2014



4. Historic Information (Pre 2006)

4.1 Clay Spreading

Prior to 1990 the most common technique recommended for addressing water repellency on sandy soils included furrow sowing, cultivating in the rain, the use of press wheels on seeding equipment and applying wetting agents (Crabtree 1990). Crabtree also reports that landholders in the South East of South Australia had been experimenting with the application of Kaolin clays to the surface of non-wetting soils at rates of 25 to 250 t/ha.

Much of the research into best practice methods for clay spreading was conducted in the South East (Limestone Coast region) of South Australia by Agricultural Bureau and Landcare groups in the 1980's and 90's. A PIRSA experimental site was set up at Keith in 1988 to determine the effect of clay spreading on water repellence (Michelsen 1990). Clay rates of 0, 2.5, 5, 10 and 20 t/ha were applied to a deep non-wetting sandhill with the 20 t/ha recording a significant drop in water repellence (M.E.D 0.8). However subsequent sampling showed that M.E.D values had returned to above 2.0 within 2 years, suggesting that higher clay application rates are required for long term impacts on water repellence. Further trials sites were set up at Keith and Western Flat in 1989 to determine the effect of treatments including varying rates and types of clay as well as wetting agents on water repellence. The key findings of these trials were that;

- Low rates of locally sourced claying material were ineffective in overcoming water repellence with rates greater than 50 t/ha being required to make any significant difference
- Although commercial (high purity) kaolinite was very effective at lowering water repellency when applied at 8 t/ha, it had little effect on soil moisture
- Purity of clay used (% clay) is important when quoting claying rates
- The wetting agent treatment (at 25 L/ha and 50 L/ha) had no significant effect on water repellence or soil moisture.

The impact of clay application rates was further examined by PIRSA at a new trial site at Western Flat in 1991. The site was treated with 4 rates of clay (0, 50 t/ha, 100 and 150 t/ha) and monitored over seven years. Cann (2000) reports water repellence was halved on the treatments spread at 100 t/ha and 150 t/ha, with a less dramatic reduction on the 50 t/ha treatment. She stated that during the course of the monitoring there was a continued response to the 150 t/ha treatment with regard to water repellency. This lead the Bangham/Western Flat Ag Bureau to trial even higher rates of clay (up to 400 t/ha) in subsequent years. Cann (2000) reports that pasture production on the treatment spread at 160 t/ha was six times greater than that of the control and that yield responses plateaued at rates higher than this. It was also noted that the surface soil pH was increased after clay spreading.

Trials were also conducted in Western Australia. In one trial at Albany/Mt Barker in 1994 the application of kaolinite clay at rates of 100-150 t/ha saw yield increases of 80% (Murfitt 1994).

Research by McKissock (2000) indicated that despite its larger crystal size and smaller surface area kaolinite clays were better at overcoming water repellency than other clays (i.e. smectite and montmorillonite). McKissock suggested that this was less to do with dispersibility/sodicity than the higher capacity for kaolinite clays to remain coated onto the sand particles after a wetting and drying cycle. This is further described by Ward and Roper (2008) who suggest that, due to the much higher surface area of clay particles compared to sand, that an increase in the clay content of the soil by 2-3% is all that is required to overcome water repellence (approximately 30-40 t/ha of clay). They state that typically the amount of clay in B horizon materials are low (30-40% clay for a heavy clay textured soil) and therefore the effective application rates of this claying material are generally in excess of 150t/ha.

A key issue with early clay spreading was controlling clay application rate. Some of the earliest clay spreading machines used were heavy earthmoving equipment such as road scrapers. These machines spread clay onto the paddocks at rates much higher than 100 to 150 t/ha. This made incorporation difficult and resulted in issues such as surface sealing, compaction. Where high rates of calcareous clay were applied nutrient tie up was also an issue. Fertiliser spreaders have also been commonly used by landholders to apply clay to paddocks. These machines generally only had the capacity to spread light rates of clay (<30 t/ha) requiring at least two operations to ensure an adequate rate of clay was applied. In 1991 Noel Fisher, a landholder in the South East, designed a prototype machine specifically for clayspreading. A subsequent business venture manufactured the “Claymate” clayspreader. This machine was designed to rip the clay, pick it up, mix it in a rotary drum and spread it out in 10 m wide strips with minimal horsepower requirement.

By 1997 the significant production gains resulting from clay spreading sand over clay soils in the South East were well documented. This led landholders and researchers to trial how applicable the technique was on non-wetting sands in other districts including Eyre Peninsula, Yorke Peninsula and the Fleurieu Peninsula.

Clay spreading demonstration sites were established at Pt Sturt and Mt Compass on the Fleurieu Peninsula in 1998. The Pt Sturt site was located on a deep siliceous sand over sandy clay (Hughes 2001). Treatments consisted of a nil clay control, clay at 100 t/ha and clay at 200 t/ha. Plant counts at establishment recorded better germination (50%) of the barley crop on the 200 t/ha clay treatment. There was also much lower levels of manganese recorded in plant tissues tests where clay was applied at 100 t/ha and 200 t/ha. At Mt Compass clay was applied using the Claymate at a rate of 80 t/ha. There was no difference in pasture growth in 1999; however in 2000 there was an increase in pasture utilisation on the clayed area by 25% over the unclayed. In the winter of 2000 there was also a noticeable increase in the percentage of phalaris and subclover in the clayed area as opposed the onion weed and veldt grass in the unclayed.

A group on Southern Yorke Peninsula were involved in a trial using high purity clay (most local clay materials are only around 30% clay particles) from Mildura (Arumpo Bentonite) at low rates (0.5 to 2 t/ha). This was considered an option if local clay was unsuitable or unavailable. Trial results did not show significant yield increases as a result of the treatment and it was considered an uneconomic option (Hignett 2002)

Early trials on the Eyre Peninsula resulted in some issues not observed in the South-East. Solomon (1997) suggested that differences in subsoil soil clays in the region, particularly with regard to high levels of boron and carbonate may have some impact on crop response to claying (Solomon 1997). He noted that very high rates of clay in the South East (> 400 t/ha) had caused problems and recommended a rate of 100 to 200 t/ha for Eyre Peninsula applications. Analysis of tissue data from demonstrations conducted at Karkoo (Llewellyn date unknown) suggested that the use of calcareous clays resulted in manganese deficiency in subsequent crops. This was confirmed in trials at Edillilie (Davenport 2000) and at Wharminda (Malcolm et al 2003, Davenport 2004).

Significant trial work was undertaken on the Eyre Peninsula from 1997 to 2007 under the GRDC Eyre Peninsula Farming Systems Project (1997-2003) and Agricultural Bureaus of South Australia Project “Advancing Farming Systems on Sandy Soils” (2004-2007) to look at the impacts of clay spreading on local sandy soils.

Results across the region have been inconsistent due to variation in rainfall, clay type and carbonate content. Clay content in clay soils varies considerably from 16 % at Cleve to 56% at Wanilla. Carbonate content in clay varies considerably from 17 % at Kapinnie to 40 % at Karkoo (May 2006). Eyre Peninsula clays are often highly sodic with ESP at Kelly greater than 50%. In good rainfall years clay spread areas seemed to stay green longer than untreated areas. However the clay spread areas seemed to be the first to hay-off in low rainfall years.

A trial at Grund’s property at Kelly (near Kimba) was clay spread in 1997, with clay rates varying from 0 t/ha to 300 t/ha. In 1999, a year with a poor finish, higher yields occurred on the treatments with lower rates of clay. However, yields were much more even in 2000, a good year, with yields across all treatments significantly higher than the control (May 2000).

Further research on another site at Wharminda (Jones property) evaluated clay rate and incorporation depth to determine the most beneficial practice given lower rainfall conditions on Eyre Peninsula. Clay treatments were applied at rates varying from 0 t/ha to 250 t/ha. Results showed a significant yield increase where clay was applied at greater than 100 t/ha but that the economic advantage was reduced at rates greater than 150 t/ha. There was also a significant yield reduction where highly calcareous clay was applied at high rates (Doudle 1999).

Measurement of pasture growth in the second year of the Wharminda trial showed that where clay was spread at 150 t/ha the pasture dry matter production was double the control (Creeper and May 2000). This is consistent with pasture dry matter responses observed on clayed ground in Western Australia (Murfitt 1994)

By 2001 all treatments except for the 250 t/ha rate at this trial site had recouped the cost of the clayspreading. Yield results from this trial showed that in 2001 there was little yield benefit on the 50 t/ha treatment and that the gross margin increase plateaued at rates higher than 150 t/ha (Doudle 2001).

All treatments on the Wharminda trial site had recouped the cost of the operation treatment by 2002 (4 years after treating).The highest gross margins were recorded on the 50 to 100 t/ha treatments. The best yields were recorded at clay application rates of 100 to 150 t/ha with the 50 t/ha treatment showing little yield benefit over the control, Doudle (2002). Where high rates of clay (250 t/ha) had shallow incorporation, yields were poor in years where the crop suffered moisture stress late in the season.

These results were consistent with data from Sherwood in the South East where Cann (1999) reports that whilst you require at least 50 t/ha of clay to make a difference to water repellency, the best yield increases were recorded on treatments where clay was applied at 80 to 100 t/ha. There was a yield reduction at high rates of clay (> 100 t/ha where clay was incorporated with offset discs and 200 t/ha where a scarifier was used to incorporate the clay).

Work by Melissa Rebbeck and Chris Lynch in the South East in 2003 and 2004 revealed that soil modification by clay spreading and delving had potential to reduce the risk of severe frost damage to crops. Rebbeck and Knell (2007) state adding clay to sandy topsoils by clay spreading and delving can increase the night time temperatures in the crop canopy by around 1^{o}C as the it increases the capacity of the soil to store radiant heat during the day. In trials this lead to a reduction in frost damage on delved sites of up to 80%.

Rural Solutions SA and SARDI staff collaborated to bring together key points and case studies from clay spreading and delving trials across the region to develop a broadacre clay application manual for farmers, contractors and advisors (May 2006). This "Clay spreading and Delving on Eyre Peninsula" manual was published in 2006 as part of the Eyre Peninsula Farming Systems Project (funded by GRDC and NHT) and with the support of DWLBC (now Department of Environment, Water and Natural Resources).

The key points from this manual which can be applied to all regions are;

- Landholders should understand what clay they have and the nutritional issues that may arise following treatment and work out what they are trying to achieve by claying in order to determine rates and adequate incorporation methodology.
- Highly calcareous clay can lead to nutrient tie up when rates over 150 t/ha are used (no problem with higher rates on non-calcareous clays i.e. generally found on Lower Eyre Peninsula and the South East)
- Extra nutrition may be required to compensate for tie up in the first few years after spreading - particularly manganese.
- There can be compaction issues where there is poor incorporation of clay at rates greater than 150 t/ha)
- Depending on carbonate levels pH can stabilise at 0.5 to 1 unit higher than prior to spreading
- Clay must be incorporated well. Offset discs are able to effectively incorporate clay to 10 cm, whilst a wideline/scarifier can incorporate to 18 cm
- Clay spreading in 2004 cost $80 to $250/ha depending on application rate (approximately $1/t) whilst clay delving cost $130 to $160/ha. It cost at least as much to incorporate the clay as to spread/delve it.

4.2 Deep ripping and deep placement of nutrients.

Although it was found that clayspreading is able to overcome non-wetting characteristics and dramatically change the fertility of the soil in the top 10 cm (depth of incorporation), the low inherent fertility and water holding capacity of the underlying sand still causes significant constraints to root development and crop growth.

Supported by members of the Bordertown and District Landcare Group, Malinda (1995) investigated a range of techniques for ameliorating duplex soils with non-wetting sandy surface and sodic clay at Lowan Vale. Treatments included gypsum applications, deep ripping, organic matter and slotting (using a trench digger to remove the topsoil and part of the B horizon, mix the soil and back fill the trench). The highest yield was on treatments where a trench digger was used to remove the top 50 cm of soil. The clay and sand was then mixed together and used to backfill the trench. However despite the yield gains, at $8300/ ha this treatment was considered uneconomic.

In 2000 the Edillilie Landcare group with support from Rural Solutions SA used a Yeomans plow to place nutrients at different depths on a site spread with 150 t/ha of clay. Davenport (2000) reported; little yield increase over the control on treatments where nutrients were surface applied; deep ripping treatments gave a 60 % yield increase over the control; ripping combined with deep placement of nutrients resulted in yields double that of the control. It was difficult however to isolate whether the yield response on this plot was due to the ripping treatment or the nutrients place at depth.

John Masters, a land holder at Wharminda, used a single tyned ripper to rip to 40 cm on an area where he believed that clay was spread too thickly. He recorded a 25% yield increase along the rip line as opposed to between the rip lines (Masters 2001). This is consistent with the response from delving.

A summary of farmer demonstrations looking at the impact of deep ripping on soil compaction in 2003 showed that the response to deep ripping is unpredictable, often giving a yield increase in the first year but no long term benefit. The only treatment where there was a significant response was on a sand over clay soil at Koongawa which was delved to 80 cm bringing clay up to the surface (Doudle 2003).

Given the highly calcareous nature of some of the subsoil clays on Eyre Peninsula a number of landholders and researchers have investigated the effect of spreading calcareous clay on nutrient availability. Trials at Shane Malcolm’s Wharminda property in 2002 and 2003 showed that applying high rates of highly calcareous clays can induce a manganese deficiency, which is not able to be corrected by a single foliar application of manganese. This trial showed no significant yield difference where clay was applied at rates up to 100 t/ha however, grain analysis from these plots recorded low manganese levels. Where higher rates were applied (300 t/ha) there was a significant yield reduction (less than 50% of the unclayed control). Where nutrients were placed deeper than the clay layer yield was doubled compared to the control, (Malcolm et al 2003).

Increased yields where nutrients were placed below the clay layer were also observed in trials looking at subsoil nutrition and trace element application on clay spread soils at Kelly, Wharminda, Arno Bay and Pt Neill (Doudle and Wilhelm 2002, Wauchope 2005 and Telfer 2006).

4.3 Delving

Following the early Malinda trials the Bordertown and District Landcare group received funding in 1996 to experiment with using deep ripping tynes on duplex soils to lift clay up from the B horizon and bring it to the surface. The clay delving machine was specifically designed by the University of South Australia’s “South Australian Agricultural Machinery Research and Design Centre” with the tyne set at a 45 degree angle to the frame to allow the clay to slide up the tine from depths of up to 0.8 m to the surface (Desbiolles 1998). This was in contrast to machines used in the past to deep rip sodic subsoils where the tyne was set at 90 degrees to the frame. Howatson (1997) quoted Mr Groocock as saying that the angled “delving tine brings the soil to the surface whereas a ripper can push it sideways causing compaction”. Trials conducted on the properties of Wayne Dodd and Roger Groocock compared the effect of clay delving to a range of gypsum and deep ripping treatments. Desbiolles (1998) indicated that while there appeared to be some increase in yields from this technique, more investigation was required to further refine this process.

5. Sandy Soils Project (2004-2007)

Results from a survey of landholders (Cann 2002) report that by 2002 there had been 35,000 ha clay spread in the Upper South East with 6,500 ha delved and 1,700 ha deep ripped (Cann 2002). The key issues that landholders identified with regard to soil modification process were firstly, controlling the water repellence issue and secondly managing nutrition after claying. At this time farmers also wanted more information on clay types and rates, nutrition and delving.

An Advisory Board of Agriculture (ABA) project "Advancing Farming Systems on Sandy Soils" funded by NLP from 2004-2007 enabled extensive investigation on improving clay spreading and delving techniques across the state.

Considerable work looking at the main impacts of soil modification by delving was undertaken in the South East under this project. Eleven delving demonstration sites were established at locations ranging from Wirrega/Lowan Vale to Naracoorte. Where clay was brought up by the delving tynes fertility was increased in the A horizon (to the depth of incorporation 12 to 18 cm). Good root development was also found deep into the profile where clay lumps had been deposited, whereas in the undelved area root mass was concentrated in the A1 horizon. Where delving machines had been used that were less effective in mixing clay into the A horizons there was little change in soil fertility. (Bailey 2007)

Bailey (2007) noted that the Wattle Range the site prior to delving was infertile to 60 cm (low CEC) and that the highly bleached A2 horizon (25 to 35 cm) was likely to cause a barrier to root development due to very low nutrition. He noted that below 60 cm the B horizon clay was poorly structured with poor water infiltration. The delving process dramatically changed the soil profile. Although there was only a slight change in texture in the A1 horizon non-wetting had been addressed. In the A2 horizon the clay lumps (having a higher CEC) distributed throughout the profile provided sites of fertility and attracted root growth. Voids created from removing clay in the B horizon were filled by sand from the A2 resulting in an increase in the depth of water infiltration. The result was a 50 to 150 % increase in dry matter along the delve line as compared to the inter row.

Most of the delving machines used on these sites had delving tynes that were 10 to 15 cm wide and spaced between 1.5 and 1.8 metres apart. There is therefore a significant distance between delving tynes with only 20 to 40% of the soil profile being altered during the delving process. This is quite often reflected in greener and more vigorous growth being observed along the line where the delving tyne has ripped. Incorporation of clay following delving will change the surface soil of the inter row to the depth of incorporation however, there is still a significant proportion of the soil profile that has not been addressed. Monitoring of a number of delved sites in the South East indicated that in all cases where delving machines accessed clay, sufficient amounts were brought to the surface to ameliorate soil non-wetting properties and improve the nutrient status of the topsoils. However, it was also clear that the beneficial impact of delving on production extended beyond just addressing topsoil issues.

Summarising the results from trial work in the South East Bailey (2007) reported that:

- *Clay delving gave a greater response in sandy soils compared to clay spreading attributable to,*

a) Modification of bleached A2 horizons – soil analysis identified improved soil fertility of bleached horizons brought about by mixing A2 material with A1 and B material. The modified A2 had lower bulk density, improved root abundance, and increased potential to accumulate leached nutrients.
b) Mixing surface horizon sands into the tops of sodic, columnar clays at the interface with the sandy A2 horizon, increasing the potential for water infiltration and root penetration.

- *The response to clay delving varied with different machines and techniques.*

a) Machinery design appeared to have an influence on the amount of topsoil and clay incorporated into the A2 horizon.
b) Methodology – factors such as the timing of delving (spring, summer or autumn), depth and extent of incorporation and fertiliser management all may have some impact on plant growth.

Bailey indicated that further investigation was required to fine tune machinery configuration and delving methodology to achieve the best results and that delving contractors needed to be aware of the importance of distributing clay throughout the A horizons rather than just bringing clay to the surface or ripping through compacted layers in the A horizon.

May (2006) reported that monitoring of delved sites on Eyre Peninsula contained the same amount of microbial biomass in the profile as non-delved. However, on delved sites it was evenly distributed throughout the profile whilst on non delved sites it was concentrated in the 0 -10 cm layer.

In 2010 a survey of clayspreading and delving contractors and key landholders who had significant experience with claying sandy soils was conducted. The survey sought to determine the key information regarding best practice for clay spreading and delving and looked at machinery design, operation, clay incorporation and key tips for landholders. Twenty five contractors and landholders were invited to take part with nineteen responding. Key results from this survey are highlighted below (Masters 2010);

- Key design features looked for in clay spreading machines are the ability to control the rate of clay
- Key design features looked for in delvers are the ability to adjust the tyne angle depending on the depth to clay and the strength of the frame to withstand enormous pressure.
- Most contractors used a 3 tyned delver with tynes spaced 1.2 to 1.6 m apart. It was considered that the best spacing for rip lines is about 80 cm. With 1.6 m spacing this allow contractors to rip between lines to achieve optimum rip line spacing.
- Although some delving tynes can be inserted up to 2m deep, most contractors agreed that the maximum depth from which they could bring up clay was around 70 cm.
- Many contractors said that ideally they would have 3 different machines to use depending on depth to clay with a 3 tyned delver being most appropriate where clay is between 30 and 60 cm from the surface. Where clay is deeper a 1 tyned deep delver would be preferred. Where the clay is within 30 cm of the surface most contractors said a 9 tyned deep ripper is more appropriate so that too much clay is not bought to the surface.
- Some contractors use opening tynes to clear away vegetative residues allowing the clay to slide unhindered to the surface.
- Most tynes had a piece of smooth tempered steel (often a grader blade) welded to the tyne to allow to slide easily up the surface. They advised that whilst the cutting boot may be reinforced the main tyne needed to be smooth for the clay to slide effectively to the surface.
- Although it was possible to build a delver for under $20,000 around 10 years ago, recent increases in the price of steel and scarcity of suitable frames means that to build an adequate machine for contracting work today will cost in excess of $50,000.
- Cost of delving in 2010 was between $125 and $175/ha with clay spreading being double the cost of delving ($250 to $350/ha). However there is still a role for clay spreading on sites where clay is too deep to delve (> 70 cm from surface).
- Planning what the contractor will do in the paddock before they get there is vital to reduce time and thus cost of the operation.
- Changes in vegetation, (i.e. weeds) can be an indication of depth to clay, (i.e. Silvergrass/skeleton weed on deeper sands and clover/ryegrass where clay is shallower)
- Effective incorporation is paramount and usually costs at least as much as the clay application

6. "Building Resilient Farming Systems through improving knowledge and using innovative management techniques" Project (2006 – 2010)

The "Building Resilient Farming Systems" project funded through Caring for Our Country program and the South Australian Department of Environment and Natural Resources from 2006 to 2010 further increased understanding in soil modification practices resulting in the development of best practice guidelines.

This project allowed a number of sites to be established across different regions to further investigate the best techniques for modifying soils with significant production constraints using such technologies as clay delvers and "spaders". A spader is a machine somewhat like a large (3 to 4 m wide) rotary hoe which can be attached to the three point linkage of a tractor. Spaders have been used for many years in Europe in intensive agricultural production and were first imported into South Australia in 2007 by Bordertown farmer Roger Groocock. The spading operation has the capacity to mix the soil to 35 cm leaving an even seed bed in a single pass. This project has demonstrated the capacity of this machinery to improve clay incorporation on delved and clay spread sites and to allow assessment of mixing organic matter, gypsum, lime and other soil ameliorants into the soil profile.

In September 2011 a manual funded by the GRDC and Caring For Our Country "Building Resilient Farming Systems" Project entitled "Spread, Delve, Spade, Invert; a best practice guide for the addition of clay to sandy soils" (Leonard 2011) combined much of the current best practice information on clayspreading, delving and spading with a number of case studies into a manual for land managers interested in finding out more about soil modification.

The results from investigations conducted under this project in each region are summarised below.

6.1 Adelaide and Mount Lofty Ranges (Fleurieu Peninsula)

The Fleurieu Peninsula has an estimated 18,000 ha (18.5 % of agricultural land) of sandy soils (Harding and Dowie 2011). These soils are characterised as being generally low pH, water repellent and with moderate to high risk of wind erosion.

Trial sites were established on duplex soils at Waitpinga and Willow Creek (clay spreading), Back Valley and Inman Valley (delving and spading) and Myponga (spading). The soil profile of the Inman Valley trial site comprised a thick sandy A1 horizon with a strongly bleached A2 over coarsely structured mottled B horizon clay (Bailey et al 2010). The A2 horizon was described as being highly infertile due to leaching from water perched on the sodic subsoil. The trial combined a number of soil modification treatments with different lime application rates (nil, low 3 t/ha, high 6 t/ha). All soil modification treatments had significantly higher dry matter than the control in September (Control 1 t/ha, Spader only 2.6 t/ha, Delved only 3.25 t/ha and delved + spaded 4.5 t/ha). The lime treatments at this site outperformed the nil lime on all soil modification treatments (Tonkin 2011).

This response to liming was reflected at the site at Back Valley where there was an increase in dry matter production of 50 to 100% over the control on all treatments where lime was applied (Harding and Dowie 2011).

6.2 Eyre Peninsula

Eyre Peninsula has 841,000 ha (30 %) of cropping land which is at moderate or higher risk of wind erosion (Hall et al 2009). Morgan et al (2005) estimates that 445,000 ha is at risk of water repellence, (non-wetting). By 2004 approximately 100,000 ha (of the 450,000 ha of soils prone to water repellency) had been clay spread or delved. Modifying these soils through the use of clay spreading or delving has the potential to significantly improve production and reduce wind erosion risk.

6.2.1 Delving Sites

Under the "Building Resilient Farming Systems" project a number of clay delving sites were established and monitored at Warramboo, Kapinnie, Gum Flat and Rudall. Different local contractors were used to delve the sites and the site was incorporated by the landholder. Soil samples were taken prior to delving in March with follow up samples taken in September to assess changes as a result of the delving operation. Dry matter cuts and tissue tests were taken in September with cuts taken for yield in December. The results are detailed in the report "Eyre Peninsula Delving and Spading Demonstration Sites". (Masters 2010)

Results

Site 1. Kapinnie

Clay was within reach of the delving tyne (70 cm) and lumps were brought up to the surface. Soil analysis showed an increase in CEC, PBI and pH after delving. The site had a low initial starting pH at 5.3 (CaCl), after delving this had increased to 7.0 (CaCl). PBI rose from 6.3 to 39.

Dry matter production was 10% higher along the delve line as opposed to the inter-row (space between the rip lines). Root mass along the delve line was 35% higher along the delve line. The differences in plant growth were reflected in grain yield. Grain yield along the delve line was 56% higher than the inter-row (and 34% higher than the paddock average).

Site 2. Warramboo.

Soil analysis showed an increase in pH and CEC after delving. Grain yield along the delve line was 64% higher than the inter-row (and 21% higher than the paddock average).

Site 3. Gum Flat

Soil analysis showed a significant increase in pH after delving (increase from 4.8 (CaCl) to 6.0). There was also a reduction in the amount of available aluminium after delving. Dry matter cuts gave a much higher bulk of plant roots along the delve line (35% increase of the inter-row) and a 12% increase in dry matter produced. Grain yield at harvest was 56% higher than the inter-row (and 34 % higher than the paddock average)

Site 4. Rudall

Soil tests showed an increase in pH and CEC after delving. Unfortunately the sand was greater than 60 cm deep across a large proportion of the site and the crop did not establish well enough for cuts to be taken.

6.2.2 Spader Trials

In the years from 2008 to 2010 Rural Solutions SA consultants partnered with landholder groups including the Butler/Ungarra Agricultural Bureau, the Edillilie Landcare Group and the Lower Eyre Agricultural Development Association (LEADA) to investigate the effects of using a spader to incorporate soil ameliorants and mix the soil profile to 35 cm. Demonstration sites were established at Ungarra, Edillilie and Lipson. Funding support for these sites was obtained from the South Australian Government NRM Community Grants, EPNRM board Sustainable Agriculture Grants, LEADA's GRDC Managing Change project and the Advisory Board of Agriculture Caring for our Country project "Building resilient farming systems through increased knowledge and the use of innovative technologies".

Site 1. Ungarra (2008)

A spader was used to incorporate organic matter at a sand over clay site. Where the clay was at a depth of less than 30 cm clay was also brought to the surface and mixed through the A horizon. The results showed double the dry matter production on all treatments where the spader was used. Where clay was brought to the surface by the spader dry matter was tripled (Masters 2008). However, grain yields were only increased where either organic matter or clay was incorporated during the spading process. Grain yields were increased by 25% compared to the control where pea straw was incorporated and where clay was mixed through the profile by the spader grain yields were 50% higher than the control.

Site 2. Ungarra (2009)

The spader was again used to incorporate organic matter (lucerne hay 10 t/ha). On the northern site where the clay was too deep to be accessed by the spader there was a 15% reduction in yield (compared to the control) where the spader did not incorporate any soil ameliorant. However, where the spader was used to incorporate organic matter the grain yield was 15% higher than the control. (Masters 2009)

At the Southern site where clay was within reach of the spader yields were higher than the control on all treatments where the spader was used (this is likely to be due to the increased CEC resulting from a mixing of subsoil clay into the bleached A2 horizon). Despite a high incidence of fungal disease impacting the treatment the greatest yield increase occurred where lucerne straw was incorporated into the profile.

The spader was also used on 7 farmer demonstration sites around the district where grain yields were increased in excess of 12% on the spaded treatment as opposed to the unspaded control.

Site 3. Edillilie (2009)

A spader was used on a shallow ironstone sand over clay soil with a severely bleached A2 horizon at Edillilie in 2009. Treatments were the same as those used at the Ungarra site (nil treatment control, spaded only and spaded with 10 t/ha lucerne straw). On the northern end of the site the spading operation brought up a very high rate of clay causing some issues with surface sealing. The spaded only treatments at this location only yielded 65% of the control. Where hay was incorporated there was a 15% increase in grain yield over the control.

On the southern half of the site, where the clay was deeper in the profile, less clay was brought to the surface and surface sealing was not an issue. The spaded only treatment at this location yielded 25% higher than the control whilst the treatment which incorporated hay yielded 55% higher than the untreated control.

Site 4. Ungarra (2010)

A spader was used on a three replicated sites to trial the use of the spader to incorporate clay, organic matter and a range of fertiliser treatments. Treatments at the “Houston” site compared three different fertiliser treatments on unspaded, spring green manure (spaded) and autumn spaded plots. Plant emergence counts and plant tissue analysis were taken in early July with little difference between treatments (Davenport and Masters 2010). However, dry matter cuts in September recorded 200 to 500 kg more dry matter on the autumn spaded treatment when compared to the control. The spring spaded (green manure) treatments recording 600 to 1100 kg more dry matter than the control. Root DNA tests also showed double the root mass in the autumn spaded treatment compared to the control and triple the root mass in the spring spaded treatment.

These early differences in dry matter production did not result in higher yields and there was little difference in grain yield between treatments.

A spader was also used to incorporate clay on a clay spread and delved site. The delved site was so dominated by ryegrass that it was not possible to get yield data. On the “Snodgrass” clayspread site plant numbers on the unspaded control were on average 10% higher than that of the spaded treatments. Plant tissue tests at this time did not show any significant difference between the treatments. Dry matter cuts in September recorded twice the dry matter on the spaded treatments compared to the control. This significant increase in dry matter was reflected in grain yield data with increases up to 70% on the spaded treatment compared to the control.

6.3 Kangaroo Island

Between 2005 and 2007 a number of trials were implemented looking at the amelioration of sandy soils on Kangaroo Island. The first aimed to investigate the effect of deep ripping and nutrition on production at Stokes Bay and American River. Results from this trial indicated that surface applications of potassium and fertility enhancers had little effect on yield and that whilst deep ripping alone gave a 50% increase in yield, the most significant increases were where trace elements were placed by the ripper at depth. The deep ripping plus trace element treatment recorded two and a half times the yield of the control (Dohle 2005).

In 2006 further investigations were conducted at American River using a range of deep ripping, fertility enhancer and wetting agent treatments in order to overcome surface non wetting and boost subsoil fertility. During the season there was an increase in crop vigour observed where nutrients were placed deep into the subsoil. These differences were reflected in yield data where this treatment yielded five times that of the control. However, this treatment was at a cost of $600/ha. The wetting agents did not record any yield response (however 2006 was a wet season). The deep working by itself doubled the grain yield of the control (Dohle 2006). These results were supported by results from trials on intact cores taken from American River in 2007 where the deep ripping and nutrient placement at depth was the only treatment that delivered a significant response with a dry matter increase of 50% over the control (Dohle 2007).

6.4 SA Murray Darling Basin (Murray Mallee)

Delving trials in the Murray Mallee arose out of landholder interest in improving the productivity of soils constrained by a bleached A2 horizon. A key concern for landholders was the hostile B horizon clays that are present in this region which are not common in the South-East. With funding through the Sandy Soils project the Parilla Ag Bureau established a number of delving demonstration sites. A delver was used where the clay was deeper in the profile with a deep ripper being used where clay was less than 50 cm below the soil surface (Eldridge 2007). Treatments included shallow and deep incorporation. Grain yields on the delved treatments were in excess of double those of the undelved control. The trial also compared the impact of varying the spacing of the delving tynes. Grain yields increased as tyne spacing decreased, however the cost of the delving operation also increased with narrower tyne spacings. Monitoring of this trial for a second year showed a continuing yield benefit from the delving operation with the delved treatments 20% higher yields than the untreated control (Tonkin 2011).

Tonkin (2012) states that although the clay spreading treatment overcomes the non-wetting characteristic at the surface there is no noticeable increase in yield from clay spreading. Yield data from the Parilla clay spreading trial showed increased yields only on treatments where clay rates above 180 t/ha were used. (Tonkin 2011) The Parilla delving trial suggests that where clay is within reach of the delving tyne not only is the water repellence addressed but crop yields also increased on the delved treatments. The data show increased yields on all delved treatments, with delving at 0.7 m tyne spacing recording twice the yield of the control in 2011. However the report states that the yield benefit from the 0.7 m tyne spacing was variable with seasonal conditions. This tyne spacing appears to give a yield benefit in better than average seasons but not in poorer season whilst wider tyne spacings give better yields in below average seasons but do not offer a yield advantage in good seasons. The most consistent yield benefit across varying seasonal conditions came from the modified grizzly plough at 1.0 m tyne spacing. There was no significant difference in yield between the shallow and deep incorporation treatments. Yield results on the delving and spader trial were more variable with the main yield benefit appearing to result from the delving treatment rather than the incorporation method. This is consistent with the results recorded at the Mt Hill trial site on Eyre Peninsula in 2011 (Masters and Davenport 2011).

Tonkin et al (2012) also looked at the impact of soil modification on clay content, CEC and organic carbon levels stating that spading and spading plus delving treatments produce the most significant changes increasing the clay content in the 0-10 and 10-20 layers to up to double that of the unmodified soil. The soil modification treatments lead to an initial decrease in the organic carbon levels in the 0-10 cm layer however increased the organic carbon percentage deeper in the soil profile as a result of the soil mixing process. CEC values correspond directly to clay content of the soil and it is predicted that increased CEC will lead to increased organic carbon content over time due to the increased capacity to hold onto nutrients.

6.5 Northern and Yorke Agricultural Districts

Woodard and Harding (2010) report that there is approximately 223, 000 ha of sandy soil in the Northern and Yorke Districts cleared for agricultural production. These soils are at moderate to high risk of wind erosion and water repellence. Of this 173, 000 ha is suitable for clay spreading (predominately in the Minlaton, Arthurton and Port Broughton districts) with approx 46, 400 ha suitable for delving (predominantly in the Pt Wakefield, Nantawarra, Moonta, Stow, Port Vincent, Bowilla and Avon district).

Prior to 2006 there was limited clay spreading/delving occurring in the Northern and Yorke districts (Woodard 2009). In 2006 a trials were established on sites of sandy soils at Bute, Bowmans and Wanderah using a Claymate to spread treatments at 80 t/ha and 160 t/ha. In 2008 landholders trialled clay delving at Bismarck Valley, Nantawarra and Lochiel. Around 1300 ha were delved on 13 properties in these districts. Early observations were of better crop growth on delved sites, but results were variable. It was noted that the best results were on the side of dunes rather than on top of the dune where the delving tyne was able to reach the clayey sand at depth and mix it through the profile. There was no response to delving where there was no texture change.

By 2010 Woodard and Harding report that around 4000 ha of sandy soils in the region had been clay spread or delved (most of the work had been done around the Stansbury, Nantawarra and Bowmans districts).

Presuming clay materials contain around 30% clay recommended rates for clay spreading in the region are in the range of 80 t/ha to 150 t/ha, depending on rainfall. When delving, it is recommended that only 50 t/ha to 80 t/ha be brought to the surface (Woodard and Harding 2010).

Woodard (2011) considers that the reasons for the low uptake of clay spreading and delving technologies to date compared with other regions has been a lack of knowledge on the techniques by local landholders and contractors and some poor results on sites where highly calcareous clays were used. Under the "Improving soil health by modification of sandy soils" project claying workshops were conducted in the Linwood, Halbury and Alford districts to discuss best practice soil modification strategies. With the support of the Northern and Yorke Districts NRM board 6 sites were established in the Linwood and Halbury districts to further demonstrate the benefits of modifying sandy soils in the region.

6.5.1 Stockport and Linwood Soil Modification Demonstration Sites.

Demonstration Site 1.

An initial soil survey of the paddock was conducted to determine the depth to clay and decide on an appropriate soil modification treatment. Depth to clay ranged from 300 to 800 mm. Where clay was between 300 and 600 mm delving was considered a potential treatment option. Where clay was greater than 600 mm below the surface the area would be clay spread. Considerable increases in soil pH and CEC were observed in the delved areas. There was also a reduction in water repellence at the surface on the delved treatments and where rates of 100 -200 t/ha of clay were applied.

Demonstration Site 2.

This site had been clayspread at a high rate with poor incorporation of the clay. A spader was used to incorporate the clay and soil chemical measurement taken to quantify the effect of the spading treatment. The clay spreading treatment saw a large increase in the pH CEC over the unmodified soil in the 0-10 cm layer. The spading treatments distributed clay and nutrients deeper into the profile than traditional incorporation technologies are able to.

Demonstration Site 3.

This site demonstrated delving and spading technology as a means of addressing production constraints and land degradation issues on sandy texture contrast soil. The clay at this site was uniformly between 300 and 350 mm below the soil surface. The site was first delved and then levelled and incorporated using a spader. Analysis from soil samples showed an increase in CEC resulting from the delving process. They also showed a higher percentage of sand particles and lower clay percentage in the 0-10cm layer of the area that was "double spaded" compared to the area that only had one pass with the spader, suggesting more thorough mixing from the double operation. However there was little significant difference in the soil chemistry between the single and double spader operation.

Demonstration Site 4.

This site was initially sampled to determine the area that may benefit from soil modification and the depth to clay. It was determined that the northern area of the paddock had sufficient clay not to be water repellent and that only southern side of the dune would require treatment. On the area considered suitable a clayey sand was present within 300 mm from the soil surface. The site was delved and worked using a disc machine. It was then spaded at a 45 degree angle to the delve line. Soil analysis showed little change in chemical attributes of the soil. However the delving increased the clay content of the 0-10 cm layer by 3% which was sufficient to bring the clay content at the surface of the site above 5% and address the water repellency.

6.5.2 Other Soil Modification Demonstration Sites.

Demonstration Sites 5 to 7.

Further demonstration sites were established at Halbury, Alford and Whitwarta with and recorded similar changes in soil physical attributes and chemistry.

6.6 Limestone Coast (South East)

Through the "Building Resilient Farming Systems" project and with the support of the South East NRM board's Healthy soils program the MacKillop Farm Management Group looked at the effect of using the spader machine on seven sites in the region. Five of these sites were sandy soils that had been clayed or delved; two were heavier loam over clay soils. The Jaeschke site at Sherwood showed increases in the production of vegetative dry matter where the spader was used; however there was no significant increase in grain yield (McFarlane 2010). This lack of grain yield response despite large increase in dry matter is consistent with results from Eyre Peninsula.

Other pasture production sites at Western Flat and Willalooka showed significant increases in dry matter production on the spaded treatments in the winter and early spring cuts but by October there was little difference between the treatments.

The MacKillop Farm Management Group also established a trial site under this project to investigate, quantify and promote the benefits of deep ripping. The trial site was located at Frances on a loam over clay soil. Sodicity was highly variable across the site changing considerable over short distances. Treatments included a range of gypsum applications with a range of deep ripping and mixing treatments. Potter (2011) reported that, over a three year period the treatment where gypsum was applied after ripping recorded on average a 16% increase in grain yield, and the treatment where gypsum was mixed in with a spader produced a 19% increase in yield.

7. Building on the "Building Resilient Farming Systems" project (2011-2014)

A number of new projects since 2010 have built on the knowledge gained through the "Building Resilient Farming systems through improved knowledge and innovative management techniques" project. These projects have enabled further investigation of the potential gains in production that may result from the modification of sandy soils, particularly with respect to deep placement of soil ameliorants such as organic matter. The results of these projects are outlined below.

7.1 Building Living Soils Project (Eyre Peninsula 2011)

Further demonstrations of the benefits of soil modification using spading and delving technology were established in 2011 at Lock, Mt Hill and Cummins. A range of different treatments, including the use of the spader to incorporate clay and organic matter were trialed; with plant establishment counts, dry matter, root DNA and crop yield taken. Results from spading sites at Lock, Pillanna and Edillilie (Masters and Davenport 2011) support earlier work indicating that whilst, the addition of clay can increase production on sandy soils, these benefits can be further increased by the addition of clay and organic matter.

Masters and Davenport (2011) report that on the Lock site, there was much higher dry matter production and yield than the control where the spader had been used to incorporate barley straw and even higher dry matter production and crop yield where canola hay was incorporated. These results raise further questions regarding the use of different forms of organic carbon and their impact on soil microbial processes. The Mt Hill site showed significant increases in dry matter over the control for all soil modification treatments. However the best grain yield increases were those in which the spader was used in combination with a delving treatment.

7.2 Continuous Improvement of soil management to support resilient farming systems (MacKillop Farm Management Group, South East 2011-2012)

The spader and deep ripping trials sites established by the MacKillop Farm Management group have continued to be monitored since the end of the “Building Resilient Farming Systems” project in 2010. The clayspread and delved sites at Groocock, Jaeschke, and Lilliecrapp have also been sampled according to soil organic carbon sampling methodology as part of the ABA20:20 Challenge project “Increasing soil carbon by modifying duplex sandy soils”.

On Clothier’s spading and subsoiler trial on sand over clay at Woolumbool there was a pasture yield deficit from the spading treatments compared to the unmodified control in 2012. Apart from the spader plus sheep manure treatment, the other spader and organic matter treatments grew around half of the dry matter of the control. (note, this site was not re-sown so the control had better existing pasture cover compared with any spaded treatments) In 2013 the spade plus organic matter treatments grew around the same amount of dry matter as the untreated control, whilst the treatments where animal manure was incorporated using the spader had larger dry matter production that the control. The treatments where the subsoiler was used to place organic matter deeper into the soil profile did not have any increased dry matter production compared to the control. However placing animal manure at depth using the subsoiler did seem to result in an increase in dry matter. On the deep sand site sown to lucerne, the spaded manure treatments gave the best yield.

Yield measurements taken in 2012 on Jaeschke’s Sherwood site have shown an increase in grain yield on the spaded treatments above the control on all spaded plots. However where the spader was used to mix hay to depth the yield increase was the highest (4.2 t/ha compared to 3.1 t/ha for the control). Where the subsoiler machine was used to deep rip the plot there was an increase in grain yield over the control. However the yield response was greater where the subsoiler was used to place a soil ameliorant at depth. The highest yields were on the plots where the subsoiler was used for the deep placement of pig manure (Hughes and Fraser 2014). This reflects similar responses seen at the Woolumbool site.

At the Mil-El delving site (established with support from South East NRM) there was a small increase in pasture dry matter growth where additional fertiliser was applied the site compared to the untreated control (6.0 t/ha vs 5.2 t/ha). However the delving treatments had a much greater response (8.5 to 9.0 t/ha) than surface applied fertiliser alone. There was little difference between the delving only and the delving with additional fertiliser treatments.

At Lillecrapp’s subsoiler demonstration site in 2013 there was a large increase in the spring pasture dry matter production compared to the control where the subsoiler was used to place chicken manure at depth (5.3 t/ha compared to 4.1 t/ha). These responses were still evident in 2014.

7.3 Karoonda and Districts Agricultural Bureau – Improving Land Management through Soil Modification. (SAMDB 2010 - 2012)

The Karoonda & Districts Agricultural Bureau and Rural Solutions SA developed a project in 2010 to further investigate the potential for increasing crop yield by modifying sandy soils in the district. The key investigations of this project were to trial the benefits of a number of different soil modification processes including; clayspreading, delving and spading (a newly developed soil modification technique capable of mixing and incorporating clay and organic matter down to 30-40 cm). Demonstration sites were established by landholders in the Karoonda and Districts Ag Bureau at a number of locations in the Karoonda area looking at the effect of delving (farmer incorporated), spading, delved (spader incorporated) and clay spreading at a light and heavy rate. The results of these trials showed that soil modification treatments such as delving, spading or a combination of the two can all be used to modify soils to improve production and change soil characteristics. (Tonkin 2013) Where delving did not bring up any clay there was no yield benefit however, where clay was brought up by a delver, yield increases of 40 to 60% were observed compared to the control. Similar yield increases were experienced where a spader was able to bring up clay from the B horizon. A combination of delving and spading further increased yields on two of the sites (Tonkin 2011).

Results from the trial indicate that the response from the soil modification treatments will depend upon the soil type. For example the Wood site has responded better to spading then delving, however the delving treatment gave a better response than spading on the Loller site. These trials also indicated that in the low rainfall district around Karoonda low to medium rates of clay (70-140 t/ha) were adequate to overcome water repellence and increase production.

Tonkin (2011) also reports that soil modification treatments were effective in increasing root density at Wood's trial site with a small increase in root density over the control in the 0-10 cm resulting from delving but a much larger increase (up to 3 times that of the control) where a spader was used.

Similar increases in root density in the 0-10 cm layer were seen resulting from clay application on sandy texture-contrast soils at Pope's. This site also indicated that the spading treatment, despite having lower overall root densities than the unspaded plots, encouraged better root development further down the profile to 30 cm than simply clay spreading alone. The treatments are expected to provide continued benefits over time and monitoring will be required to further understand the effects of the soil modification process.

A small trial was conducted at Ettrick to test the effectiveness of two soil wetter products on sandy sites without access to appropriate clay for spreading or delving. There was no noticeable effect on crop emergence or growth for either product when applied as a broadacre surface spray prior to seeding. Whilst there may be some option to further investigate the effectiveness of these products applied in-furrow at seeding it was concluded that there was no role for broadacre application of these products. (Tonkin 2013)

7.4 ABA 20:20 Challenge project – Improving soil carbon levels through modification of sandy soils. (Eyre Peninsula and South East 2012)

Soil sampling using SCARP sampling protocols was undertaken in 2012 to investigate the potential to increase soil organic carbon levels by modifying duplex sandy soils. A summary of the results of analysis of these samples by Schapel and Davenport (2012) states that the modified claying treatments had generally;

- Decreased bulk density when compared to unmodified soils
- Decreased soil organic carbon (SOC) concentrations in the 0-10 cm layer. However there is a significant increase in SOC in the other soil layers (particularly in the 10-20 cm layer (the historical bleached A2 horizon)
- Higher carbon stocks to 30 cm depth compared to unmodified soils.

However, the increases in carbon stocks were not uniform across rainfall zones or modification techniques. At the Bordertown sites the clay spread and delved treatments had the highest carbon stock whilst the spaded treatments had the highest carbon stocks at Ungarra. It was also noted that due to the lack of uniformity on duplex sandy sites sampling according to SCARP methodology may not be appropriate, particularly on delved sites where variations in depth to clay may result in a high degree of variability in the impact of the soil modification treatments.

As part of this project there were also a number of demonstration sites established on modified sandy soils on Eyre Peninsula as well as continuing investigation on sites in the South East. At Karkoo on the Eyre Peninsula two demonstration sites were established on clayspread paddocks. A spader was used to incorporate the clay and added organic matter (10 t/ha of lupin grain) to depth. Results from these sites showed little difference in dry matter production between the untreated control and the treatment where a high rate of clay had not been incorporated into the soil. This supports the observation that high rates of clay that have not been effectively incorporated can form hardsetting layers at the soil surface. In contrast, where a spader had mixed the soil to a depth of 30 cm dry matter production was much higher than the control (Masters 2012).

Spading also resulted in 17 to 40% higher yields compared to the control. All clay spread treatments had higher grain yields than the control with the addition of organic matter providing a greater yield benefit to clayspreading or clayspreading with deep incorporation.

7.5 New Horizons Project – Releasing the productive potential across 40% of South Australia. (State-wide 2014)

Analysis of results from soil organic carbon sampling under the SCARP (red brown earth) and ABA20:20 Challenge (modified sand over clay) projects showed large variations in carbon stocks on these soil types which are not directly linked to rainfall zones. This suggests that there is potential to increase the soil organic carbon levels on poorly structured low fertility sandy soils and those soils with poorly structured clay subsoils by using soil modification techniques to address production constraints. It is estimated that these soil types comprise 40% of cropping soils in South Australia.

There is an estimated 2.8 million hectares of sandy soils in South Australia's cropping zone. It is estimated that crops grown on these soils are only achieving 40 to 50% water use efficiency. Soil modification techniques have the potential to address production constraints on these soils with demonstrated yield increases of around 70% on average. The main mechanism for increasing yield on these soils is by increasing crop root exploration throughout a greater proportion of the soil profile resulting in increased water use efficiency (Hughes and Fraser 2014).

It is estimated that 1.7 million hectares of cropping soils in SA comprise soils with poorly structured subsoil layers (Hughes and Fraser 2014). The addition of gypsum and organic matter can help to improve soil structure on these soils. However, the challenge is to apply treatments to the layers in the soil profile which constrain production.

Under the PIRSA's New Horizons project funded by the Government of South Australia replicated trials have been established in 2014 in three NRM regions; South East, SA MDB and Eyre Peninsula with treatments including clayspreading, deep incorporation of clay and organic matter and deep placement of nutrition.

8. Future Directions

Future research priorities for managing production and soil conservation issues on sandy soils may include new soil modification practices or the addition of ameliorants during the soil modification process.

8.1 Soil Modification

8.1.1 Deep Ripping (where sodic B horizon clays at less than 40 cm depth)

Other soil modification techniques are being trialled which may have some benefit in increasing production in sandy soils. There is a number of researchers who are further investigating the benefits of deep ripping (soil disturbance at depths of 40 cm without inverting soil GRDC 2009) with nutrient placement at depth. McBeath (2010) described increases in yield by 15 to 120% at Stansbury and Crystal Brook where soils were ripped to 50 cm with large tines, and gypsum and nutrients added at the working depth. These yield responses were even recorded in dry years and are attributed to an increase in crop water use efficiency by overcoming soil compaction. She states however that treatments on trials from 2004 have shown minimal residual benefit from ripping and that the benefit may last 2 to 3 years at most if alternative methods to stabilise the subsoil structure are not used.

These observations are supported by Hall et al (2010) who reports that in Victorian trials, despite initial increase in crop yield by 0.1 – 0.5 t/ha, recompaction of the subsoil was observed after 2 years and that after 8 years the only treatment that remained more profitable than the control were clay spreading at rates greater than 100 t/ha.

A GRDC fact sheet (2009) on deep ripping concluded that deep ripping is ineffective on sodic subsoils in Southern Australia unless combined with gypsum and that even on responsive soils there is a decline in the benefit of deep ripping over time. Also, that there is little impact on yield if there are other subsoil constraints. The fact sheet notes that the best yield responses result from significant changes in water infiltration and seem to occur in areas with greater than 325 mm rainfall. The New Horizon project as well as a number of smaller projects including the; Crossville Ag Bureau CFOC project (Addressing subsoil constraints on the Hardsetting Soils of Eastern Eyre Peninsula) and the EPNRM CFI Action on the Ground Project (Managing subsoil constraints to sequester carbon in soils of Eyre Peninsula) all have components looking at deep ripping and deep placement of soil ameliorants to overcome subsoil constraints to plant growth.

8.1.2 Subsoil Manuring

Considerable work has been done in Victoria looking at the benefits of subsoil manuring (incorporating organic amendment at depths of 30 to 40 cm). Gill et al (2009) reported yield increases in excess of 60% over the control where poultry manure or lucerne hay was incorporated at 20 t/ha. However the cost of treatment to achieve these responses was $750 to $850 /ha depending on incorporation costs. Some of results of preliminary trial work with this machine in the South East has been described in the document. There is a great deal of interest from the farming community in deep placement of nutrients and soil ameliorants as a means of overcoming subsoil constraints. Trial work using the subsoiler machine is continuing with continued monitoring of demonstration sites in the South East and Kangaroo Island and new demonstrations sites being established in the Northern and Yorke Agricultural Districts in 2014. The is also trials being conducted on the Eyre Peninsula in 2014 looking at deep ripping and incorporation of gypsum and organic matter to ameliorate poorly structured subsoils.

8.1.3 Soil inversion

Nicholls (2010) described a process being trialled in Western Australia where a mouldboard plough is being used as a once off operation to invert the top 30 cm of soil. Early results indicate that it can reduce compaction, increase water infiltration and aid the control of herbicide resistant weeds. The has been some demonstration work undertaken by individual landholders using mouldboard ploughs to ameliorate water-repellent surface soils in the South East and Eyre Peninsula. On duplex sandy soils with highly bleach A2 horizons and low clay percentages in the subsurface layers the risk of wind erosion may be increased following this operation. The sandy soil types on which mouldboard ploughing is likely to present the best opportunities is likely to be those sands which contain some clay in the subsurface layers i.e. Moornaba sands. Thus when inverted, the higher nutrient/organic matter A1 provides sites for plant root exploration whilst the erosion risk on the inverted A2 is minimised due to the clay percentage

8.1.4 Addition of Amelioration Products

Improving the effectiveness of soil modification by incorporating amelioration products into the soil profile during the soil modification operation. Amelioration products may include but are not limited to;

- biochar
- smaller quantities of pure clays such as bentonite or zeolite as a soil additive in place of high rates of localised claying materials
- Using waste products such as composts, green waste, biosolids as soil amendments
- Incorporating clays and organic matter
- Green manuring and summer crops/pastures

8.2 Soil Amelioration/Management Practices

Where claying of sandy soils is not an option, then changes to current technologies or development and use of new ameliorant products may be required to overcome productions constraints. Such changes to technologies or ameliorants may include (Tonkin 2012);

- New wetter/water absorbing products
- Tine configuration/Seed placement/Press wheels
- Product delivery/placement innovation
- Wetter/water absorbing product placement
- Crop rotations for best root use of the soil volume
- Plant breeding for greater root volume in infertile sands.

9. Conclusions and Recommendations

Clayspreading is well established in the Limestone Coast (South East), Eyre Peninsula districts and SAMDB (Murray Mallee) regions (and has increasing uptake in the SAMDB and NYAD) as a means of overcoming water repellence on sandy soils. Trials have discovered that clay rates as low as 50 t/ha will have some effect on addressing non-wetting. However, it has been observed that for this effect to have long term benefits with significantly increased crop yield, rates greater than 100 t/ha are required. In lower rainfall districts crops have been observed to "hay off" in seasons with a dry finish on areas where clay rates greater than 150 t/ha have been applied. Significant yield reductions have also been observed where highly calcareous clays have been applied at rates greater than 100 t/ha, due to trace element tie up. Whilst clay spreading is effective in overcoming water repellency on sandy soils crop yield is generally still limited by low fertility in the subsurface layers.

Clay delving is able to increase both the surface and subsurface CEC and moisture holding capacity by bringing up clay from the B horizon and depositing it throughout the A horizon. This enables crop roots to crop deeper in the soil profile which increases crop water use efficiency. Soil modification in this way has led to significant increases in dry matter and grain yield (70% on average across the trials). Clay delving is a cost effective operation when compared to clay spreading (around $125 to $175/ha in 2010 as opposed to $250 to $350/ha for clayspreading). However, there is little long term benefit from delving where B horizon clay is too deep to be able to be brought into the A horizon by the delving tyne (around 65 cm with current delving machines). Clay spreading should be considered where clay is located deeper than this.

Effective incorporation of the soil ameliorant is vital in achieving the best results from soil modification. Traditional incorporation techniques such as disc or tyned cultivators are usually able to only incorporate clay to a maximum depth of 15 cm. whereas "spaders" are effective at mixing the soil profile to 35 cm. Landholders need to plan how they will incorporate the clay when clay spreading and delving and adjust clay rates on the incorporation depth that they can achieve.

Significant increases in dry matter production have been achieved through using a spader on sandy soils. However, in seasons with dry finishes unless the spader has been used to incorporate other soil ameliorants, such as clay or organic matter, the increased in dry matter have rarely translated into increase in yields. Where a spader has been used to incorporate clay or organic matter there have been yield increases beyond the benefit seen by shallow mixing (traditional incorporation techniques) of clay alone.

Soil carbon sampling on modified sands has shown reduced soil bulk density (compaction) and increased soil organic carbon stocks to 30 cm when compared to unmodified soils. However these increases in yield and soil organic carbon do not seem to be consistent to particular soil modification treatments. Further trials are being undertaken within the New Horizons project to determine the best combination of clay application, incorporation and deep mixing of nutrients and organic matter to improve water use efficiency and production on sandy soils.

Deep ripping sodic soils to overcome compaction does not have a long term benefit unless other steps are taken to stabilise structure, (such as the addition gypsum or organic matter). However, there may be potential to use a combination of deep ripping and deep placement of ameliorants to overcome sodic subsoils.

10. Abbreviations used in this document

ABA – Advisory Board of Agriculture
CEC - Cation Exchange Capacity
DEWNR – Department of Environment, Water and Natural Resources
DWLBC – Department of Water Land and Biodiversity Conservation (now DEWNR)
EPNRM - Eyre Peninsula Natural Resource Management Board
ESP - Exchangeable Sodium Percentage
GRDC - Grains Research and Development Corporation
LEADA – Lower Eyre Agricultural Development Association
M.E.D – Molarity of Ethanol Droplet (a method for assessing water repellence)
NHT - Natural Heritage Trust
NLP – National Landcare Program
NRM – Natural Resource Management
NYAD – Northern and Yorke Agricultural Districts
PBI – Phosphorus Buffering Index
PIRSA - Primary Industries and Regions SA
SARDI – South Australian Research and Development Institute
SAMDB – South Australian Murray Darling Basin NRM District
SCARP – Soil Carbon Accounting Research Program.
SOC – Soil Organic Carbon Stock

11. References

Bailey, G. (2007) "2007 Sandy Soils Project: Clay Delving". Information booklet. Rural Solutions SA

Bailey, G., Hughes, B., Tonkin, R and Watkins, N. (2010) Gross soil modification of duplex soils through delving and spading. In: "Proceedings 19th World Congress of soil science, *Soil Solutions for a changing world*. 1-6 August 2010", Brisbane, pp. 26-27

Cann, M.A. (1999) "Sherwood Clay Spreading Field Day". Workshop Proceedings. PIRSA

Cann, M.A (2001) "Clayspreading on Water Repellent Sand", Project Results and Summary, Bangham- Western Flat Ag Bureau

Cann, M.A. (2000) Clay spreading on water repellent sands in the south east of South Australia – promoting sustainable agriculture. *Journal of Hydrology*, **231-232**, pp. 333-341.

Cann, M.A. (2002) "Upper South East clay spreading and delving survey results". Draft Report. PIRSA

Cann, M. A. Davenport, D. Bright, M. Young, D. Wheeler, S. (2004), Sandy Soils in South Australia, A situation Analysis, DWLBC.

Carter, D. and Hetherington, R. (1997) Claying water repellent soils. Farmnote 14/97. Department of Agriculture, Western Australia.

Crabtree, W. (1990) Managing water repellence in sandy soils. Farmnote 55/90. Department of Agriculture. Western Australia.

Creeper, I and May, R. (2000) Clay spreading and the effect on pastures. In: "Eyre Peninsula Farming Systems 2000 Summary ". EPARF pp. 107-108

Davenport, D (2000) Edillilie clay spreading trial. In: "Eyre Peninsula Farming Systems 2000 Summary". EPARF p. 106

Davenport, D. and Masters, B. (2010) Modification of sandy subsoils on EP. In: "Eyre Peninsula Farming Systems 2010 Summary". EPARF, pp. 154-157.

Dohle, L. (2005) Sandy soils on Kangaroo Island. In: "KI Agricultural Trials and Demonstration Booklet 2005". Rural Solutions SA.

Dohle, L. (2006) Soil amendments on a deep sand at American River. In: "KI Agricultural Trials and Demonstration Booklet 2006". Rural Solutions SA.

Dohle, L. (2007) American River Intact core trial. In: "KI Agricultural Trials and Demonstration Booklet 2005". Rural Solutions SA.

Doudle, S. (1999) Understanding clay spreading on Eyre Peninsula. In: "Eyre Peninsula Farming Systems Summary; 1999" pp. 74-76

Doudle, S. (2001) Clay spreading trial. In: "Eyre Peninsula Farming Systems 2001 Summary". EPARF pp. 117-118

Doudle, S. (2002) Clay spreading at Wharminda. In: "Eyre Peninsula Farming Systems 2002 Summary". EPARF p. 133

Doudle, S and Wilhelm, N. (2002) Trace element application methods on clay. In: "Eyre Peninsula Farming Systems 2000 Summary ". EPARF p. 127

Eldridge, R (2007) "Clay Delving at Parilla", Project Report. Rural Solutions SA

Gill, J.S, Sale, P.W.G, Peries, R.R, and Tang, C. (2010) Changes in soils physical properties and crop root growth in dense sodic subsoil following incorporation of organic amendments. *Field Crop Research.* **114,** 137-146

GRDC (2009) "Deep ripping not appropriate for all soil types" Fact Sheet, GRDC

Hall, D.J.M, Jones, H.R, Crabtree, W.L and Daniels, T.L (2010) Claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in Southern Western Australia. A*ustralian Journal of Soil Research,* **48,** 178-187

Hall, J., Maschmedt, D and Billing, B. (2009) "The Soils of Southern South Australia". Department of Water, Land and Biodiversity Conservation.

Harding, A. and Dowie, R. (2011) "Best practice management manual for the management of sandy soils on the Southern Fleurieu Peninsula". Final Report. Rural Solutions SA

Hignett, C (2002) Effect of Arumpo bentonite clay on non-wetting sands. In: "Southern Yorke Peninsula Alkaline Soils Group Trial Summary; 2002".

Howatson, R. (1997, June 5) SA farmers lead clay lifting work on non-wetting sands. *Stock Journal,* pp. 25-26.

Hughes, B. (2001) Point Sturt and Mt Compass clay spreading demonstration. Draft Report – unpublished internal. Rural Solutions SA

Hughes, B and Fraser, M (2014) "SE Soils A snapshot of some projects focusing on acid soils and soil modification", Presentation to SE NRM, 8^{th} April 2014.

Leonard, E (Ed.) (2011) "Spread, Delve, Spade, Invert – a best practice guide to the addition of clay to sandy soils" Manual, GRDC.

M., Oades, J.M. and Tate, M.E. (1989) The use of dispersible clays to reduce water repellency of sandy soils. *Australian Journal of soil research*, **27**, 797-806

McBeath, T.M., Grant, C.D., Murray, R.S and Chittleborough, D.J. (2010). Effects of subsoil amendment on soil physical properties, crop response and soil water quality in a dry year. *Australian Journal of Soil Research,* **48,** 140-149

McCord, A and Payne, R. (2004) "Report on the condition of agricultural land in South Australia". Report, Department of Water, Land and Biodiversity Conservation.

McFarlane, J. (2008) "Quantify and promote the benefits of deep ripping". Project Report. MacKillop Farm Management Group.

McFarlane, J. (2010) "Building resilient farming systems". Final Project report. MacKillop Farm Management Group.

McKissock, I., Walker E.L., Gilkes, R.J and Carter, D.J. (2000) The influence of clay type on reduction of water repellency by applied clays: a review of some West Australian work. *Journal of Hydrology* **231–232**, pp. 323–332.

Malcolm, S., Davenport, D. and Doudle, S (2003) Clay spreading with highly calcareous clays". In: "Eyre Peninsula Farming Systems 2003 Summary". EPARF p. 126

Malinda, D. (1995) Ameliorating a soil with a non-wetting sandy surface and a sodic clay subsoil. *Australian Journal of Soil and Water Conservation,* **Vol 8. Issue 1,** 36-41

Masters, B. (2008) Overcoming soil constraints using the spader machine. In: "Lower Eyre Agricultural Development Association Trial Results Summary; 2008". LEADA.

Masters, B. (2009) Addressing fertility and other rootzone constraints on duplex soils. In: "Lower Eyre Agricultural Development Association Trial Results Summary; 2009". LEADA.

Masters, B. (2010) "Best practice clayspreading and delving- a summary of responses to a survey of clayspreading and delving contractors". Final Report. Rural Solutions SA.

Masters, B. (2010) "Eyre Peninsula delving and spading demonstration sites". Final Report. Rural Solutions SA

Masters, B and Davenport, D (2011). Addressing production constraints through the modification of sandy soils. In "Eyre Peninsula Farming Systems Summary 2011". EPARF pp. 166-172

Masters, B (2012). Deep incorporation of organic matter to improve crop production on modified duplex sandy soils. In "Eyre Peninsula Farming Systems Summary 2012". EPARF pp.

Masters, J. (2001) Deep ripping of clay spread areas. In: "Eyre Peninsula Farming Systems 2001 Summary". EPARF pp. 119-120

May, R. (2000) Clay spreading at Kelly. In "The Eyre Peninsula Farming System Summary; 2000" PIRSA, p. 108

May, R and Doudle, S. (2003) Eyre Peninsula clay spreading and delving survey – a summary of results to date. In: "Eyre Peninsula Farming Systems 2003 Summary". EPARF pp. 123-125

May, R (2006) "Clay Spreading and Delving on Eyre Peninsula – A broadacre clay application manual for farmers, contractors and advisors". (Eds. D. Davenport, N, Wilhelm and S. Doudle) GRDC. Government of South Australia

Michelsen. P (1990) Dispersible sodic clay application to water repellent soils in the South East of South Australia. In: "Water Repellency in Soils, National Workshop Proceedings. April 1990".

Morgan, S.J, Nichols, C.W and Payne. R.A (2005) "Soil Conservation and Land Management Directions for the Agricultural Lands of South Australia". Department of Water, Land and Biodiversity Conservation

Murfitt, C. (1994) Claying lift yields on non-wetting soils. In: Farming Ahead, **34**, October 1994 Kondinin, pp. 2-3

Nicholls, C. (2010) Inversion turns the tables on soils constraint. In: Farming Ahead, **227,** December 2010. Kondinin, p40-41

Obst, C (1990) Non-Wetting Soils: Management Problems and Solutions at "Pine View", Mundulla. In: "Water Repellency in Soils, National Workshop Proceedings. April 1990".

Potter, T (2011) Unpublished trial data, SARDI

Rebbeck, M.A and Knell, G.A. (2007) "Manging Frost Risk; A guide for Southern Australian Grains". Manual, GRDC/SARDI

Solomon, A. (1997) Clay spreading on Water repellent sands. In: "Harvest and Livestock report 1997" Department of Agriculture. South Australia.

Schapel, A and Davenport, D. (2012) "Carbon Program- Clay modified Soils" Report to DEWNR, Rural Solutions SA

Telfer, J. (2006) Subsoil nutrition on clay spread soils. In: "Eyre Peninsula Farming Systems 2006 Summary". EPARF p. 163

Tonkin, R. (2011) "Acidity Trials Summary July 2011". Summary Report. Rural Solutions SA.

Tonkin, R. (2011) "Soil Modification Trials at Karoonda", Draft Report. Rural Solutions SA.

Tonkin, R. (2011) "Root Density Measurements- Clayspread/Spaded trial, S. Pope – September 2011". Short Report, Rural Solutions SA

Tonkin, R. (2011) "Root Density Measurements- Delve/Spade trial, N. Wood- October 2011". Short Report, Rural Solutions SA

Tonkin, R. (2011) "Parilla Clay spreading and Delving Trials, Harvest results 2011" Trial Results. Rural Solutions SA

Tonkin, R. (2011) "Improving Land Management through Soil Modification, Harvest Report 2011-2012" Project Report, Karoonda and Districts Agricultural Bureau:

Tonkin, R., Davenport, D. and Schapel, A. (2012) "Soil Modification effects on clay, CEC and organic carbon content using delving and spading on a sandy texture-contrast soil in the South Australian Mallee" Draft paper for the Soil Science Australia National Conference Dec 2012.

Tonkin, R (2013) "A Review of Information on Managing Sandy Soils - With particular reference to the South Australian Murray-Darling Basin NRM Region", Project Report, Rural Solutions SA.

Ward, P. and Roper, M. (2008) Clay addition to non-wetting sands: What does it do to the soil? In "ABB Grain 10th Annual SANTFA No-Till Conference Proceedings, 2008". SANTFA

Woodard, D. (2009) "Discussion paper on nutrition issues with delving". Project report. Rural Solutions SA.

Woodard, D and Harding, A (2010) "Improved soil protection by clay spreading/delving sand in the Northern and Yorke Region" Project Report. Rural Solutions SA

Woodard, D. (2011) "Reducing Erosion and Improving Soil Health by Soil Modification of Sandy Soils – Linwood and Halbury areas" Project report, Rural Solutions SA.

Wauchope, K. (2005) Subsoil nutrition on clay spread soils. In: "Eyre Peninsula Farming Systems 2005 Summary". EPARF p. 128

12. Appendices

Appendix 1: Timeline of activities undertaken to investigate the effects of soil modification on production in South Australia and the best methodology for such practices in different regions.

Years work undertaken	Description of Work	Trial Site Location	Proponent/Group	Region	Reference
1968	Initial clayspreading trials	Mundulla	Clem Obst - landholder demonstration	Limestone Coast (South East)	Obst (1990)
1988	Clayspreading trials at rates to 20 t/ha	Keith and Western Flat	PIRSA	Limestone Coast (South East)	Michelsen (1990)
1989	Clayspreading and soil amendment trials	Western Flat	PIRSA	Limestone Coast (South East)	Michelsen (1990)
1991	Clayspreading to overcome water repellence trial	Western Flat	PIRSA/ Bangham-Western Flat Ag Bureau	Limestone Coast (South East)	Cann (2000)
1991	"Claymate" clayspreader designed		Noel Fisher	Limestone Coast (South East)	
1991	Soil treatments for ameliorating duplex soils with non wetting sandy surface and sodic subsoil	Lowan Vale	Bordertown and Districts Landcare Group/David Malinda	Limestone Coast (South East)	Malinda (1995)
1996	Deep ripping duplex soils to lift B horizon clay to the surface	Lowan Vale	Bordertown and Districts Landcare Group	Limestone Coast (South East)	Howatson (1997) Desbiolles (1998)
1997-2000	Clayspreading rate for low rainfall district trials	Kelly	Kelly Landcare Group/EP Farming Systems	Eyre Peninsula	May (2000)
1998-2000	Clayspreading trials at Mt Compass and Pt Sturt	Mt Compass/Pt Sturt	PIRSA	Fleurieu Peninsula	Hughes (2001)
1999	Clayspreading rate trials	Sherwood	PIRSA	Limestone Coast (South East)	Cann (1999)
1999-2002	Understanding Clay on Eyre Peninsula	Wharminda	Wharminda Agricultural Bureau/EP Farming Systems	Eyre Peninsula	Doudle (1999, 2001,2002) Creeper and May (2000)
2000	Deep placement of nutrients on clay spread soils	Edillilie	Edillilie Landcare Group/Rural Solutions SA	Eyre Peninsula	Davenport (2000)

2001	Deep ripping heavily clayed soils	Wharminda	John Masters - landholder demonstration	Eyre Peninsula	Masters (2001)
2002	Clayspreading using low rates of Arumpo Bentonite	Southern Yorke Peninsula	Southern YP Alkaline Soils Group/Cliff Hignett	Northern and Yorke Agricultural Districts	Hignett (2002)
2002	Trace element application methods on clayed soils	Kelly	Kelly Landcare Group/EP Farming Systems	Eyre Peninsula	Doudle and Wilhelm (2002)
2002-2003	Clayspreading with highly calcareous clays	Wharminda	Wharminda Ag Bureau/EP Faming Systems/Rural Solutions SA	Eyre Peninsula	Malcolm et al (2002, 2003)
2003	Deep ripping/working farmer demonstrations	Buckleboo, Ceduna, Koongawa	EP Farming Systems, Buckleboo Farm Improvement Group, Goode Agricultural Bureau, Central Eyre Agricultural Bureau	Eyre Peninsula	Doudle (2003)
2004-2007	Advancing Farming Systems on Sandy Soils	Statewide	Agricultural Bureaus of South Australia/Rural Solutions SA	Statewide	Bailey (2007)
2005	Subsoil nutrition on clayspread soils	Wharminda, Arno Bay,	Eastern and Lower Eyre Soil Conservation Boards/Rural Solutions SA	Eyre Peninsula	Wauchope (2005)
2005	Deep ripping and nutrition	Stokes Bay, American River	KIAg/Rural Solutions SA/ Agricultural Bureaus of South Australia	Kangaroo Island	Dohle (2005)
2006	Subsoil nutrition on clayspread soils	Port Neill	Dutton and Driver River Catchment Groups Agricultural Bureaus of South Australia /Rural Solutions SA	Eyre Peninsula	Telfer (2006)
2006	Clayspreading trials	Bute, Bowmans, Wanderah	Agricultural Bureaus of South Australia /Rural Solutions SA	Northern and Yorke Agricultural Districts	Woodard (2009)
2006	Use of deep ripping, fertility enhancers and wetting agents to overcome constraints and boost fertility on sandy soils.	American River	KIAg/Rural Solutions SA/ Agricultural Bureaus of South Australia	Kangaroo Island	Dohle (2006)
2006	Publication of "Clayspreading and delving on Eyre Peninsula"	Multiple sites	EP Farming Systems/Rural Solutions SA	Eyre Peninsula	May (2006)
2007	Intact core trial	American River	KIAg/Rural Solutions SA/ Agricultural Bureaus of South Australia	Kangaroo Island	Dohle (2007)
2007-2010	Delving demonstration sites	Kapinnie, Warramboo, Gum Flat, Rudall	Agricultural Bureaus of South Australia /Rural Solutions SA	Eyre Peninsula	Masters (2010)
2008-2010	Clay spreading and delving trials	Karoonda, Parilla	Southern Mallee Ag Bureau/ Agricultural Bureaus of South Australia /Rural Solutions SA	Murray Mallee	Tonkin (2011)

2008	Spading demonstration	Ungarra	EPNRM/Butler-Ungarra Agricultural Bureau/Rural Solutions SA	Eyre Peninsula	Masters (2008)
2008	Clay delving demonstration sites	Bismarck Valley, Nantawarra, Lochiel	Agricultural Bureaus of South Australia /Rural Solutions SA	Northern and Yorke Agricultural Districts	Woodard and Harding (2010)
2009	Overcoming subsoil constraints using a spader	Ungarra, Edillilie	Butler-Ungarra Agricultural Bureau/LEADA/Edillilie Landcare Group/Rural Solutions SA	Eyre Peninsula	Masters (2009
2010	Spader trials	Sherwood, Willalooka, Western Flat	MacKillop Farm Management Group/ Agricultural Bureaus of South Australia /Rural Solutions SA	Limestone Coast (South East)	McFarlane (2010)
2010	Deep ripping trials	Frances	MacKillop Farm Management Group/ Agricultural Bureaus of South Australia /Rural Solutions SA	Limestone Coast (South East)	Potter (2011)
2010	Using spader to overcome issues on sandy soils	Ungarra	Butler-Ungarra Agricultural Bureau/ Agricultural Bureaus of South Australia Rural Solutions SA	Eyre Peninsula	Davenport and Masters (2010)
2010	Soil modification trials	Waitpinga, Willow Creek, Back Valley, Inman Valley, Myponga	Agricultural Bureaus of South Australia /Rural Solutions SA	Fleurieu Peninsula	Bailey (2010) Tonkin (2011)
2011	Addressing production constraints through the modification of sandy soils	Lock, Mt Hill, Ungarra, Edillilie	DENR/EPNRM Board/LEADA/Rural Solutions SA	Eyre Peninsula	Masters and Davenport (2011)
2011- 2013	Soil modification trials	Karoonda and Parilla	DENR/Southern Mallee Ag Bureaus/Rural Solutions SA	Murray Mallee	Tonkin (2011) Tonkin (2012)
2011	Publication of "Spread, Delve, Spade, Invert – a best practice guide for the addition of clay to sandy soils"	Statewide	Emma Leonard – AgriknowHow (Ed.) for GRDC/DENR/Agricultural Bureaus of SA/Rural Solutions SA	Statewide	Leonard (Editor) 2011
2012	ABA20:20 Challenge – Increasing soil carbon on sandy soils through soil modification	Karkoo/Wanilla/Edillilie/Sherwood	Agricultural Bureaus of South Australia/DEWNR/Rural Solutions SA	Eyre Peninsula and South East	Schapel (2012)
2010-2013	Improving production on sandy soils through deep placement of soil ameriolants (Subsoil manuring)	Lucindale/Struan/Mil-El	SENRM board/MacKillop Farm Management Group/Agricultural Bureaus of South Australia/Rural Solutions SA	South East	
2014	New Horizons – Increasing production on sandy duplex soils and soils with poorly structured subsoils in South Australia	Cadgee, Karoonda and Brimpton Lake	Government of South Australia/Mallee Sustainable Farming Systems/MacKillop Farm Management Group/Southern Mallee Agricultural Bureau/Lower Eyre Ag Development Assc./Uni of South Australia/Adelaide University	South East/SAMDB and Eyre Peninsula	Davenport and Schapel (2014)

Appendix 2: Index of Soil Modification Resources and Information.

Historical Information on managing water repellent sands and soil modification (pre 2006)								
Title	**Region**	**Soil Modification Treatment**	**File Type**	**File Name**	**Document Type**	**Author**	**Publisher**	**Date**
The use of dispersible clays to reduce water repellency of sandy soils.	Statewide	Clay spreading	.pdf	Mashum_Dispersible_clay_AustJSoilRes_27.pdf	Published Scientific Paper	Ma'shum et al	Australian Journal of soil research 1989, 27, 797-806	1989
Dispersible sodic clay application to water repellent soils in the South East of South Australia	South East	Clay Spreading	.pdf	Michelsen_clay_spreading90.pdf	Workshop proceedings	P. Michelsen	Water Repellency in Soils, National Workshop Proceedings. April 1990.	1900
Non-Wetting Soils: Management Problems and Solutions at "Pine View", Mundulla.	South East	Clay Spreading	.pdf	Obst_clayspreading_Pineview.pdf	Workshop proceedings	Clem Obst	Water Repellency in Soils, National Workshop Proceedings. April 1990.	1990
Managing water repellence in sandy soils	Western Australia	Clay spreading	.pdf	CRABTREE_Managing_water_repellence.pdf	AgNOTE Fact Sheet No 55/90	Bill Crabtree Doug McGhie	AgWA	1990
Claying of Water Repellent Soils on the South Coast of Western Australia for Profit.	Western Australia	Clay spreading	.pdf	Carter_Claying_water_repellent_soils_WA.pdf	Published Scientific Paper	Carter and Hetherington	GRDC	
Effect of clay mineralogy and exchangeable cation on water repellency in clay amended sandy soils	Statewide	Clay spreading	.pdf	Ward_effect_clay_mineralolgy_water_repellent_sands_AustJSoilRes_31.pdf	Published Scientific Paper	P. Ward and J.M. Oades	Australian Journal of soil research 1993, 31, 351-64	1993
Claying lifts yields on non-wetting soils	Statewide	Clay spreading	.pdf	Kondinon_clay_lifts_yields.pdf	Article	Claire Murfitt	Farming Ahead No 34 - October 1994	Oct-94

Ameliorating a soil with a non wetting sandy surface and sodic clay subsoil	Statewide	Clay spreading	.pdf	MALINDA_ameliorating_non_wetting_AusJSoil.pdf	Published Scientific Paper	David Malinda	Aust Journal Soil Water Cons Vol 8 No 1	Feb-95
SA Farmers lead clay lifting work on non wetting sands	South East	Delving	.pdf	SJ_SA_Farmers_lead_claying.pdf	Stock Journal article	Rohan Howatson	Stock Journal	Jun-97
Clay spreading on water repellent sands	Eyre Peninsula	Clay spreading	.pdf	SOLOMON_clayspreading_water_repellent_Sands.pdf	Harvest report	Andrew Solomon	Harvest and Livestock report 1997	1997
Claying water repellent soils	Western Australia	Clay spreading	.pdf	CARTER_Claying_water_repellent_AGNOTE1497.pdf	AGNOTE Fact Sheet No 14/97	Carter et al	AgWA	1997
Claying for Profit on Sandy Soils.	Western Australia	Clay spreading	.pdf	Carter_Claying_for_profit.pdf	Aust. Grain article	Carter and Hetherington	Australian Grain June/July 1997	1997
Understanding clay spreading on Eyre Peninsula	Eyre Peninsula	Clay spreading	.pdf	EPFS99_Understanding_clay.pdf	EPFS Summary 1999	Samantha Doudle	EP Farming Systems	1999
Sherwood Clay spreading field day	South East	Clay spreading	.pdf	Sherwood_clay_spreading_FD1999.pdf	Handout	Mel Cann	PISA	1999
The role of Clayspreading in the Reduction of Groundwater Recharge	South East	Clay spreading	.pdf	Bruce_role_reduction_recharge.pdf	Published Scientific Paper	Bruce and Cann	PIRSA	1999
Claymate Clay Spreader	Statewide	Clay spreading	.pdf	Claymate_spreader.pdf	Product brochure		Claymate	1999
Clay spreading to control water repellence on sand - the "Pine View" experience	South East	Clay spreading	.pdf	CSS_Clayspreading_obst.pdf	Crop science society newsletter	Clem Obst	Crop Science Society.	2000
Water repellency bibliography	Australia	Clay spreading	.pdf	Water_repellency_bibliography.pdf	Published Scientific Paper	DeBano and Dekker	Journal of Hydrology 231-232 (2000) 409-432	2000
Clay spreading on water repellent sands in the south east of South Australia - promoting sustainable agriculture	South East	Clay spreading	.pdf	Cann_clay_Spreaing_water_repellent_JrnlHydrology_231.pdf	Published Scientific Paper	Mel Cann	Journal of Hydrology 231-232 (2000) 333-341	2000

A multivariate framework for interpreting the effects of soil properties, soil management and landuse on water repellency.	Western Australia	All	.pdf	Harper_multivariate_analysis_water_repellence_JrnlHydrology.pdf	Published Scientific Paper	Harper et al	Journal of Hydrology 231-232 (2000) 371-383	2000
The influence of clay type on reduction of water repellency by applied clays: a review of some West Australian work	Western Australia	Clay spreading	pdf	McKissock_Clay_type_reductions_repellency_JrnlHydrology_231.pdf	Published Scientific Paper	McKissock et al	Journal of Hydrology 231-232 (2000) 323-332	2000
The reduction of water repellency by added clay is influenced by clay and soil properties	Western Australia	Clay spreading	.pdf	McKissock_Clay_type_reductions_repellency_Appliedclayscience_20.pdf	Published Scientific Paper	McKissock et al	applied clay science 20 (2002) 225-241	2002
Upper South East Clay Survey Results	South East	Clay spreading	.pdf	USE_clay_survey_results.pdf	Survey results	Mel Cann	Rural Solutions SA	2002
Evaluation of different clay minerals as additives for soil water repellency alleviation	Europe	Clay spreading	.pdf	Lichner_evaluation_different_clay_AppliedClaySc_31.pdf	Published Scientific Paper	Lichner et al	Applied clay science 31 (2006) 238-248	2005
Effect of clay amendment on adsorption and desorption of copper in water repellent soils.	Europe	Clay spreading	.pdf	Xiong_Clay_effect_copper_AustJSoilRes_43.pdf	Published Scientific Paper	Xiong et al	Australian Journal of soil research, 2005, 43, 397-402	2005
Clay addition to non-wetting sands: What does it do to the soil?	Statewide	Clay spreading	.pdf	Ward_Roper_Clayspreading.pdf	Conference Proceedings – SANTFA 2008	Phil Ward and Margaret Roper.	ABB Grain 10th Annual SANTFA No-Till Conference Proceedings, 2008”. Pp 74-76	2008

Clay Spreading trials Eyre Peninsula (2000-2005)								
Edillilie Clayspreading Trial	Eyre Peninsula	Clay spreading	.pdf	EPFS_Edillilie_Clayspreading_trial.pdf	EPFS Summary 2000	David Davenport	EP Farming Systems	2000
Clay spreading and the effect on pastures	Eyre Peninsula	Clay spreading	.pdf	EPFS_Clayspreading_effect_pasture.pdf	EPFS Summary 2000	Ian Creeper Rachel May	EP Farming Systems	2000
Clay Spreading at Kelly	Eyre Peninsula	Clay spreading	.pdf	EPFS00_Clayspreading_Kell.pdf	EPFS Summary 2000	Rachel May	EP Farming Systems	2000
Clay Spreading Trial	Eyre Peninsula	Clay spreading	.pdf	EPFS01_Clayspreading_trial.pdf	EPFS Summary 2001	Samantha Doudle	EP Farming Systems	2001
Deep ripping of clay spread areas	Eyre Peninsula	Clayspreading and delving	.pdf	EPFS01_Deep_ripping_clayspread_areas.pdf	EPFS Summary 2001	John Masters	EP Farming Systems	2001
Clay spreading at Wharminda	Eyre Peninsula	Clay spreading	.pdf	EPFS_Clayspreading_Wharminda.pdf	EPFS Summary 2002	Samantha Doudle	EP Farming Systems	2002
Clay spreading with highly calcareous clays	Eyre Peninsula	Clay spreading	.pdf	EPFS02_Clayspreaing_highly_calcareous.pdf	EPFS Summary 2002	Malcolm et al	EP Farming Systems	2002
Trace element application method on clay	Eyre Peninsula	Clay spreading	.pdf	EPFS02_Trace_element_on_clay.pdf	EPFS Summary 2002	Samantha Doudle/ Nigel Wilhelm	EP Farming Systems	2002
Clay spreading with highly calcareous clays	Eyre Peninsula	Clay spreading	.pdf	EPFS03_Clayspreading_highly_calcareous.pdf	EPFS Summary 2003	Malcolm et al	EP Farming Systems	2003
Deep ripping/Working Farmer Demos	Eyre Peninsula	Delving	.pdf	EPFS03_Deep_ripping.pdf	EPFS Summary 2003	Samantha Doudle	EP Farming Systems	2003
Eyre Peninsula Clayspreading and delving survey- a summary of results to date	Eyre Peninsula	Clayspreading and delving	.pdf	EPFS03_Deep_ripping.pdf	EPFS summary 2003	Rachel May/ Samantha Doudle	EP Farming Systems	2003
Subsoil nutrition on Clay spread soils	Eyre Peninsula	Clay spreading	.pdf	EPFS05_Subsoil_nutrion_clayspread.pdf	EPFS summary 2005	Kieran Wauchope	EP Farming Systems	2005
Compaction and deep ripping - Some FAQs	Eyre Peninsula	Delving	.pdf	EPFS_compaction_deep_ripping.pdf	EPFS summary 2005	Doudle et al	EP Farming Systems	2005
Other Soil Modification Trials 2000-2005								

Effect of Arumpo bentonite clay on non wetting sands	Northern and Yorke	Clay spreading	.pdf	cliffhignett_clay_nonwetting.pdf	Trial Results	Cliff Hignett	Soil Water Solutions	2002
Realising potential by modifying sandy soil	South East	All	.pdf	Nuffield_Steven_jaeschke_report.pdf	Nuffield Scholarship report	Steven Jaeschke	Meat and Livestock Australia	2004
Sandy Soils and Building Resilient soils trials (2006-2010)								
Statewide information								
Clay spreading and delving on Eyre Peninsula- A broadacre clay application manual for farmers, contractors and advisors.	Statewide	Clay spreading		Clay spread man.pdf	Manual	Rachel May	Rural Solutions SA	2006
Clay spreading – Best Practice	Statewide	Clay spreading	.doc	Clay spreading FS.doc	Fact Sheet		ABA	
Delving – Best practice	Statewide	Delving	.doc	Delving FS.pdf	Fact Sheet		ABA	
Modification of bleached horizons in sandy duplex soils	Statewide	Delving	.doc	SSPdelvpost.doc	Poster	Glenn Bailey David Davenport	Rural Solutions SA	
Making Sandy soils more profitable	Statewide	Clayspreading and delving	.doc	Paskepost 1.doc	Poster	Glenn Bailey David Davenport	Rural Solutions SA	
Advancing farming systems on sandy soils	Statewide	Delving	.doc	SSPintropost.doc	Poster	Glenn Bailey David Davenport	Rural Solutions SA	
Soil modification contractors	Statewide	All	.xls	Clay_spreading_delving_contractors_221210.xls	Contacts list	Brett Masters	Rural Solutions SA	Dec-10
Best practice clay spreading and delving – A summary of contractors survey responses.	Statewide	Clayspreading and delving	.pdf	Survey_of_delving_contractors_Final_Dec 2010.pdf	Report	Brett Masters	Rural Solutions SA	Dec-10
Spread, Delve, Spade, Invert – a best practice guide to the addition of clay to sandy soils	Statewide	All	.pdf	6476_Spread_delve_invert.pdf	Manual	E. Leonard (Ed.)	GRDC	Dec-10

Eyre Peninsula								
Subsoil nutrition on Clay spread soils	Eyre Peninsula	Clay spreading	.pdf	EPSF06_Subsoil_nutrition_clayspread.pdf	EPFS Summary 2006	Joshua Telfer	EP Farming Systems	2006
Ungarra spader soil profiles 2008	Eyre Peninsula	Spading	.pdf	Ungarra_spaded_profile.pdf		Brett Masters	Rural Solutions SA	2008
Overcoming soil constraints using the spader	Eyre Peninsula	Spading	.pdf	BUAG_spader_handout_2008.pdf	Handout	Brett Masters	Rural Solutions SA	Sep-08
Overcoming soil constraints using the spader	Eyre Peninsula	Spading	.pdf	LEADA_spaders (2).pdf	Trial Results	Brett Masters	LEADA trial results booklet	Dec-08
Turning to Better soils	Eyre Peninsula	Spading	.pdf	SJ09_spading_edilillie.pdf	Stock Journal article	Paula Thompson	Stock Journal	June 18, 2009
Spading yields benefits	Eyre Peninsula	Spading	.pdf	Sjcropping_051109_Spading_yields_benefits.pdf	Stock Journal article	Liz Guerin	Stock Journal	Nov 5, 2009
Addressing fertility and other root zone constraints on duplex soils.	Eyre Peninsula		.pdf	LEADA_spader_edililie_ungarra.pdf	Trial Results	Brett Masters	Rural Solutions SA	2009
Investigation into the use of spader technology to overcome soil constraints	Eyre Peninsula	Spading	.pdf	BUAG_2009_Final_report.pdf	Report	Brett Masters	Rural Solutions SA	Apr-10
Butler Ungarra Trial Handout 2010	Eyre Peninsula	Spading	.pdf	Buag_handout10.pdf	Handout	Brett Masters	Rural Solutions SA	Sep-10
EP delving and spading demonstrations	Eyre Peninsula	Delving	.pdf	EP_delving_report_2010.pdf	Report	Brett Masters	Rural Solutions SA	2010
Modification of sandy soils on EP	Eyre Peninsula	Spading	.pdf	EPFS_Soil_modification10.pdf	Trial Results	Brett Masters	EP Farming Systems Summary 2010	2010
Addressing production constraints through the modification of sandy soils	Eyre Peninsula	All	.pdf	Masters2011_EPFS2011_Addressing_soil_constraints.pdf	Trial Results	Brett Masters and David Davenport	EP Farming Systems Summary 2011	2011

Fleurieu Peninsula								
Pt Sturt and Mt Compass Clayspreading trials	Fleurieu Peninsula	Clay spreading	.pdf	Pt_sturt_clayspreading.pdf	Draft report- unpublished internal	Brian Hughes	Rural Solutions SA	2001
Gross modification of sandy duplex soils	Fleurieu Peninsula	All	.pdf	Bailey_gross_modification_duplex.pdf	Published scientific paper	Bailey et al	Rural Solutions SA	2010
Clay made to pay	Fleurieu Peninsula	Spading	.pdf	SJCropping_15109_Clay_made_to_pay.pd f	Stock Journal article	Paula Thompson	Stock Journal	October 15, 2009
Best practice management of sandy soils on the Southern Fleurieu	Fleurieu Peninsula	All	.pdf	Southern Fleurieu sandy soils report.pdf	Report/Manual	Andrew Harding / Rod Dowie	AMLR NRM Board	2011
AMLR NRM Board - Potential for clay delving	Fleurieu Peninsula	Delving	.pdf	Fleurieu_clay_delving.pdf	Map		DWLBC 2007	
Acidity trials summary - July 2011	Fleurieu Peninsula	Delving	.pdf	acidity_trials_summary_Jul~1.doc	Trial results	Rebecca Tonkin	DWLBC 2007	2011
Kangaroo Island								
Soil amendments on deep sands at American River	Kangaroo Island	Deep ripping	.pdf	Soil amendments on deep sands at American River.pdf	Trial Results	Lyn Dohle	Rural Solutions SA	2007
Sandy Soils of Kangaroo Island	Kangaroo Island		.pdf	5. Sandy soils.pdf	Report	Lyn Dohle	Rural Solutions SA	2007
American River In-tact core trial	Kangaroo Island	Deep ripping	.pdf	American River In-tact core trial.pdf	Trial Results	Lyn Dohle	Rural Solutions SA	2007
SA Murray Darling Basin								
Clay delving at Parilla	SAMDB	Delving	.pdf	Eldridge_delving_2007.pdf	Report	Rod Eldridge	Rural Solutions SA	
Soil modification for increased productivity	SAMDB		.pdf	MFSP_Karoonda_booklet_2010.pdf	Karoonda Trial Site Walk handout 2010	Rebecca Tonkin	Mallee Sustainable Farming Project.	2010
Increase yields with clay	SAMDB	Delving	.pdf	Sjcropping_110310_Increase_yields_clay. pdf	Stock Journal article	Alisha Fogden	Stock Journal	March 11, 2010
Soil Modification Trials at Karoonda (DRAFT)	SAMDB	Clay spreading, delving, spading	.doc	Karoonda_results_field_day.doc	Field Day handout	Rebecca Tonkin	Rural Solutions SA	Aug-11

Root Density Measurements – Clayspread/Spaded trial. S. Pope – Short Report, September 2010	SAMDB	Clayspreading and Spading	.doc	Short report Pope root density Oct 2010.docx	Report	Rebecca Tonkin	Rural Solutions SA	September 2011
Root Density Measurements – Delve/Spaded Trial – Short Report, October 2011	SAMDB	Delving and Spading	.doc	Short report Wood root density Oct 2010.docx	Report	Rebecca Tonkin	Rural Solutions SA	October 2011
Parilla Clay Spreading and Delving trials. Harvest Results, 2011	SAMDB	All	.doc	SMAB harvest report 2011.docx	Trial Results	Rebecca Tonkin	Rural Solutions SA	December 2011
Soil modification effects on clay, CEC and organic carbon content using delving and spading on a sandy texture-contrast soil in the South Australian Mallee	SAMDB	All	.doc	RTonkin_soil_mod_final.docx	Scientific Paper	Rebecca Tonkin. David Davenport and Amanda Schapel	Rural Solutions SA	April 2012
Northern and Yorke								
A discussion paper on nutrition issues with delving	Murray Mallee	Delving	.doc	Nutrition in delving Sept 07.doc	Discussion Paper	David Woodard	Rural Solutions SA	Sep-07
Delving sandy soils	Northern and Yorke	Delving	.pdf	Delving sandy soils.pdf	Fact Sheet	Andrew Harding	NYAD NRM	Mar-10
Clay spreading on sandy soils	Northern and Yorke	Clay spreading	.pdf	Clay spreading on sandy soils.pdf	Fact Sheet	Andrew Harding	NYAD NRM	Mar-10
NYNRM Potential for Clay Delving	Northern and Yorke	Delving	.pdf	Northern_yorke_delving.pdf	Map			
Improved soil protection by clayspreading and delving sands in the Northern and Yorke Agricultural Districts	Northern and Yorke	Clay spreading and delving	.pdf	3. Clay spreading report.pdf	Report	David Woodard and Andrew Harding	Rural Solutions SA	2010
Reducing Erosion and Improving Soil Health by the Modification of Sand Soils – Linwood and Halbury Districts	Northern and Yorke	Clay Spreading and Delving	.pdf	RSSA_report_soils_Lower_North.pdf	Report	David Woodard	Rural Solutions SA	2011

Limestone Coast (South East)								
2007 Sandy Soils Workshop – Clay Delving	Limestone Coast (South East)	Delving	.pdf	SSP delving handout 290407_GB.pdf	Handout booklet	Glenn Bailey	Rural Solutions SA	Apr-07
Delving for Maximum pasture production	Limestone Coast (South East)	Delving	.doc	SSP_template.doc	Poster	Glenn Bailey David Davenport	Rural Solutions SA	2007
Soil Data Sheets -South East Delving project	Limestone Coast (South East)	Delving	.doc	Delving best practice.doc	Data Sheets	Glenn Bailey	Rural Solutions SA	2007
Delving for maximum pasture production	Limestone Coast (South East)	Delving	.doc	Delving pasture edit.doc	Handout	Glenn Bailey David Davenport	Rural Solutions SA	2007
Rotary spader takes years of soil restructure	Limestone Coast (South East)	Spading	.pdf	GRDC08_spader.pdf	Ground Cover article		Ground cover issue 77 Nov/Dec 2008	Nov/Dec 2008
Deep ripping Trial - Final Report December 2008	Limestone Coast (South East)	Subsoil manuring, deep ripping and soil inversion	.pdf	MFMG_deep_ripping_trial.pdf	Trial results	Jock McFarlane	MacKillop Farm Managemen t Group	Dec-08
Building resilient farming systems - Final Report Harvest 2010	Limestone Coast (South East)	All	.pdf	MacKillop_ABA_Building_resilient_soils_re port_2010.pdf	Final report	Jock McFarlane	Rural Solutions SA	2010
The Soil Book - Representative soils of the Upper SE	Limestone Coast (South East)	All	.pdf	MFMG_the soil_book.pdf	Information booklet	Glenn Bailey	Rural Solutions SA	2010
Results of soil treatments at the Pannell's Farm	Limestone Coast (South East)	Delving	.pdf	SENRM_FS_Pannell_Farm.pdf	Fact Sheet	Johanna Cross	SENRM Board	
Results of soil treatments at the Pridham's Farm	Limestone Coast (South East)	Delving	.pdf	DEMONSTRATION_SENRM_FS_Pridham _Farm.pdf	Fact Sheet	Johanna Cross	SENRM Board	

Recent Work in Modifciation of Sandy Soils.								
SE Soils A snapshot of some projects focusing on acid soils and soil modification	Limestone Coast (South East)	All	.pdf	SE_soils_pres_Final_April8.pdf.	Presentation to SE NRM, 8th April 2014.	Brian Hughes/Mel Fraser	SENRM Board	April 2014
Karoonda and Districts Agricultural Bureau Project Report – Improving land management through soil modification. Harvest Report 2011-2012	SAMDB	All	.doc	Karoonda_trial_harvest_report_2012.docx	Project Report	Rebecca Tonkin	Rural Solutions SA	December 2011
Carbon Program – Clay Modified Soils	Statewide	All	.doc	Draft clay modified soils report V4.pdf	Report	Amanda Schapel and David Davenport	Rural Solutions SA	June 2012
Deep Incorporation of organic matter to improve crop production on modified duplex sandy soils.	Eyre Peninsula	All	.doc	Leada_12_Modra_Karkoo.doc	Report	Brett Masters	EPARF	2012
A review of information on managing sandy soils – Particularly with respect to the SAMDB Mallee	SAMDB	All	.doc	A_review_of_infomation_on_Managing_Sandy_Soils.doc	Report	Rebecca Tonkin	SAMDB NRM board	2013
Future directions in Soil Modification (Subsoil Manuring, Soil Inversion)								
Ameliorating hostile subsoils in South West Victoria	Victoria	Subsoil manuring, deep ripping and soil inversion	.pdf	GRDCFS_subsoil_amelioralition.pdf	Fact sheet		GRDC	Sep-05
Deep ripping not appropriate for all soil types	Statewide	Subsoil manuring, deep ripping and soil inversion	.pdf	GRDCFS_deep_ripping.pdf	Fact sheet		GRDC	2009
Changes in soil physical properties and crop root growth in dense sodic subsoil following incorporation of organic amendments	Victoria	Subsoil manuring, deep ripping and soil inversion	.pdf	Gill_Changes_soil_physical_props_FieldCropRES114.pdf	Published Scientific Paper	Gill et al	Field crops research 114 (2009) 137-146	2009
Subsoil manuring: Do the benefits warrant the costs.	Victoria	Subsoil manuring, deep ripping and soil inversion	.pdf	Sale_subsoil_manuring.pdf	Published Scientific Paper	Peter Sale	Grassland society of Southern Aust. Conference	2010

							proceedings	
Claying and deep ripping can increase crop yields and profits on water repellent sands with marginal fertility in southern Western Australia	Western Australia	Clayspreading and delving	.pdf	Hall_Claying_deep_ripping_crop_yields_AustJSoilRes_48.pdf	Published Scientific Paper	Hall et al	Australian journal of Soil research 2010, 48 178-187	2010
Spader generates interest	Western Australia	Spading	.pdf	WANTFA2010_Spader_generates_interest.pdf	Farm Weekly Article		WANTFA	March 4, 2010
Impact of soil inversion, soil dilution and claying on non-wetting sandplain soils	Western Australia	Subsoil manuring, deep ripping and soil inversion	.pdf	AgribusinessCU10_Impact_soil_inversion.pdf	Published Scientific Paper	Davies et al	GRDC Agribusiness Crop Updates WA	2010
Inversion turns the tables on soil constraints.	Western Australia	Subsoil Manuring, deep ripping and soil inversion	.pdf	FA227_Soil _inversion.pdf	Farming Ahead article	Catriona Nicholls	Farming Ahead December 2010 No. 227	Dec-10
Mouldboard ploughing could help lift yields in sandy soils	Western Australia		.pdf	GRDC_mouldboard_plough.pdf	Ground Cover article	Nicole Baxter	Ground Cover issue 87 - Jul/Aug 2010	July/Aug 2010
Subsoil Manuring: Expensive but worth it.	Victoria	Subsoil manuring, deep ripping and soil inversion	.pdf	GRDC_subsoiling.pdf	GRDC article		GRDC	November 4, 2010
Effect of subsoil amendments on soil physical properties, crop response and soil water quality in a dry year.	Statewide	Subsoil manuring, deep ripping and soil inversion	.pdf	McBeath_Subsoil_amendments_AustJSoilRes_48.pdf	Published Scientific Paper	Macbeth et al	Australian Journal of Soil research 2010, 48 140-149	
Treating hostile subsoils	Victoria	Subsoil manuring, deep ripping and soil inversion	.doc	GRDC_subsoil_manuring.doc	Published Scientific Paper	Sale et al	GRDC	
Spading: Improving non-wetting sands	Western Australia	Spading	.pdf	Esperance_spader_trial.pdf	Trial Results	Quenten Knight	Precision Agronomics Australia	