Offsetting greenhouse gas emissions through increasing soil organic carbon in SA clay-modified soils: knowledge gap analysis

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2015 - Soil organic carbon in South Australia's agricultural soils. A review of the current status of and opportunities to increase stocks of soil organic carbon in the State's agricultural lands

2012 – Carbon program – clay modified soils

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Executive summary

The 2015 Paris Agreement includes a worldwide commitment to reduce greenhouse gas concentrations which was strongly supported by the South Australian Government. Agriculture contributed 13% of Australia's greenhouse gas emissions in 2015 and research is required to help industry reduce these levels. Two major opportunities for agricultural soils to contribute to South Australia's low carbon economy are soil organic carbon sequestration and emission abatement.

Agricultural soils are important not only for their contribution to the balance of greenhouse gas emissions but also their critical role securing global food supplies in a resource limited world (Hoyle *et al.* 2016). Globally, most agricultural systems have lost 40 to 70% of their natural soil carbon (Lal, 2004) and so it is critical to identify and implement practices that minimise or reverse the decline in soil carbon (Macdonald *et al.* 2013), whilst balancing economic sustainability and global food needs.

Sandy soils are important agricultural soils globally and cover approximately 2.6 million hectares of South Australia's agricultural region. However, low nutrient and water retention in these soils often occurs and is reflected with low plant productivity that makes it difficult to increase organic carbon (OC) content. Subsoil clay addition to sandy soil (clay modification) is a practice used in South Australia, Victoria and Western Australia to overcome water repellence and improve water retention, fertility and plant productivity. Clay modification has the potential to increase soil OC storage through increased plant growth (above and below ground) and increased capacity to store and stabilise the new OC by binding to clay clods. However, there is little information available about the potential of clay-amended soils to increase OC content and whether clay addition methods can be optimised to increase the OC storage capacity.

This project has been critical in collating and analysing existing South Australian information on soil organic carbon in clay-modified soil and comparing the results to unmodified sandy soil. Correlation of climatic, chemical and soil parameters with soil organic carbon stocks identified factors or practices that were driving these relationships in defined rainfall zones. In this analysis a soil OC stock increase of 4-8 tha^{-1} was attributed to clay-modification of soil. Further carbon sequestration is possible if key factors and practices that affect OC on different soil type and rainfall zones are recognised.

Factors that directly affect the soil organic carbon stock threshold in clay-modified soils include:

- rainfall, which governs the amount of above and below ground biomass that can be grown and ultimately contribute to OC;
- clay concentration, which determines the amount of OC that can be bound and protected and is governed by the amount of subsoil clay added to the sand; and
- depth to subsoil clay (soil type), which influences the movement of water and nutrients, with subsoil clay generally at depths greater than those modified by clay application.

Practices identified that improve the likelihood of creating a clay-modified soil that can achieve its OC sequestration potential were:

- clay clod distribution (depth of incorporation and clay source) especially for soil types where subsoil clay is greater than 70 cm depth;
- nutrient application matched to the new clay-modified regime to enable optimal biomass growth;
- farming system suited to soil type and rainfall zone;
- time since clay modification although this most likely reflects development of more effective clay modification practices over recent times; and
- clay clod size and effect on OC concentration.

Limitations to achieving the OC threshold in defined rainfall zones were identified as: those that affect input of OC (processes above ground, such as water use efficiency) in the <450 mm rainfall zone; and those that affect output of OC (processes below ground, such as those that influence rate of OC turnover) in the > 450 mm rainfall zone.

Driving factors and practice options that can help realise OC potential and their effect on OC stock in clay-modified soil. Arrows pointing up indicate an increase and arrows pointing down indicate a decrease. The number of arrows indicates the magnitude of the change and confidence in the effect is indicated, with * low confidence to * high confidence.**

Factor	Effect on OC stock	Confidence	Comment
An increase in factor that directly affects OC stock threshold			
Rainfall/water storage	↑↑	***	Determines the amount of biomass that can be grown
Temperature/evaporation	↓	***	Negative correlation – effect on soil microbes and plant physiology
Clay concentration	↑↑	***	Positive correlation to an upper limit of 20% clay. Minimal difference in OC stock between modified and unmodified soil where clay > 20% in 0-30 cm. Related to soil where subsoil clay within 30 cm (see below)
Depth to subsoil clay/soil type	↑	**	Clay modification best suited to sandy soil with subsoil clay > 30-40 cm (texture contrast soil). Greatest stock increase where subsoil clay > 70 cm (deep sand). Minimal difference in OC stock at depth < 30 cm (shallow texture contrast soil).
An increase in practice options that can realise the OC stock threshold			
Clay clod size	?	*	This study has no sites with OC data by clod size. However, other studies have demonstrated a negative correlation for OC concentration (Schapel *et al.* 2018 in press).
Depth of incorporation	↑	**	Deep incorporation (to 30 cm) is important where subsoil clay > 60 cm. Incorporating clay clods to 30 cm increases OC stock of the 10—30 cm depth when compared to unmodified soil.
Nutrient application	↑↑	**	Increased nutrition increases plant biomass = increased organic matter (OM) input into the soil. May also provide nutrients for microbes to cycle OM, that could in turn affect OC fractions
Time since modification	↑↓	**	Positive correlation to 10 years post modification for rainfall zones < 450 mm. Negative correlation for rainfall > 500 mm but thought to be due to changes in clay modification practices over time where younger sites have higher OC stock compared to older sites > 25 years
Addition of organic matter	-?	*	Unable to determine the effect of OM addition in this study. Addition of OM has been shown elsewhere to increase biomass production and hence OC concentration. However, it is unknown how increased microbial activity affects OC concentration. The addition of clay should provide greater protection to OC from microbial decomposition compared to sand alone.

Summary of identified key factors or practices that influence carbon stock and the primary limitation. Number of ticks indicates the level of influence on OC stock

	350-400 mm	400-450 mm	450-500 mm	>500 mm
Rainfall/water storage	✓✓✓	✓✓✓	✓	
Clay concentration		✓✓	✓✓✓	
Time since modification				✓
Nutrition	✓		✓✓✓	
Depth to subsoil clay/soil type	✓✓	✓✓	✓✓	✓
Limiting factor	**Inputs (above ground)**		**Outputs (below ground)**	

Evaluation of FullCAM identified that although it provided realistic modelling of soil OC levels, there were limitations such as the assumption that clay content is distributed evenly within the soil rather than in clods as occurs in clay-modified soil. There is no information on carbon pools in clay-modified soils and it is unknown how clay addition to sandy soil affects the transformation of OC inputs into more stable forms of OC. As carbon pools are relatively sensitive to changes in OC stocks, it is critical to ensure that the initial levels of the different pools are as accurate as possible.

Water balance modelling highlighted the importance of understanding the interaction between clay clod size and distribution, the impact of the nature of connected flowpaths on the migration of solutes and the impact on plant growth and yield.

Comparison of two nitrous oxide emission calculators against real time data from two properties on Eyre Peninsula indicated that calculated emissions are similar to those measured in real time. However, further comparison between nitrous oxide calculators and real time measurement of nitrous oxide emissions is recommended before final conclusions can be drawn. The effect of increasing soil OC through clay modification or addition of organic matter on nitrous oxide emissions are unclear. Further investigation is warranted despite the likelihood that nitrous oxide emissions will be relatively low for most clay-modified agricultural soils. This is particularly important when assessing the effectiveness of soil carbon sequestration in abating greenhouse gas emissions.

The literature review identified the potential for increased OC storage in clay-modified soil compared to unmodified sandy soil. There was variation in OC stock of both clay-modified and unmodified soil that has identified factors that influence OC storage in clay-modified soil. However, further research is required to:

- measure key parameters that have been identified as missing or inadequate in models (FullCAM, APSIM, HYDRUS and PHREEQC).
- utilise models to gain a greater understanding of the carbon sequestration mechanisms.
- verify outputs from models with targeted field sampling or laboratory experiments.
- identify rainfall zones and sandy soil types that have the greatest opportunity for increased OC storage.
- overcome the barriers for landholders to enter Emissions Reduction Fund soil carbon projects.

1 Introduction

Soil carbon sequestration is a priority area of interest recognised internationally in the 2015 Paris Agreement and supported by the South Australian Government. Two major opportunities for agricultural soils to contribute towards South Australia's low carbon economy are soil organic carbon sequestration and emission abatement. Validation of soil carbon sequestration opportunities and nitrous oxide (N_2O) reduction, and assessment of relevant models, will improve the knowledge base required for informed agricultural carbon offset policy and encourage adoption by landholders.

For South Australia to be Carbon Neutral by 2050, carbon emissions have to be reduced. Where emissions cannot practically or economically be reduced, offsets need to be secured by contracting carbon credits such as through implementation of Emissions Reduction Fund (ERF) projects.

However, before an ERF project can be implemented, interested parties need a clear understanding of what is required. A number of barriers have been identified that may prevent land holders engaging in a soil carbon project, including:

- A lack of understanding about suitable ERF methods
- Cost of implementing the soil carbon project
- Paperwork and time constraints
- Cost of verifying the organic carbon (OC) stock (soil sampling)
- A lack of information
  - Best practice implementation of eligible activities
  - Location of best return on farm
  - Eligible activities and their effect on soil OC and productivity
  - Emissions created by implementing an eligible activity
- Surety of return on investment
- Long time frame of 100 years permanence
- Clear, consistent government policy
- Uncertainty regarding the price of carbon
- Farming adaptations that are required for farmer's survival, especially those that address climatic conditions and increased plant production, may contradict soil carbon accounting rules
- Legal liability – will paddocks require encumbrances that restrict farming practice for the permanence period

These barriers need to be addressed and overcome before land holders will confidently engage in this process.

During 2016 and 2017, South Australian Government departments (PIRSA and DEW) liaised with the Commonwealth's Department of Environment and Energy to ensure that clay modification became an eligible activity in the 2018 ERF soil carbon methodology - Measurement of Soil Carbon Sequestration in Agricultural Systems. Clay modification of suitable soils can now create carbon credits for the State to purchase to offset greenhouse gas emissions. As with all soil carbon projects, clay modification must adhere to the rules of 'newness' and 'additionality' and must be conducted in accordance with the following rules to be eligible:

- Any soil is sourced from carbon estimation area that are part of the project
- Sampling is undertaken at a depth greater than the depth of any soil, sourced for the land management activities; added to the soil profile and incorporated through the soil profile; and
- The land where any soil is sourced is remediated as soon as is practical.

  Note: Remediation could involve returning sandy topsoil to a clay pit immediately after the clay is extracted.

A report commissioned in 2015 by DEW (formerly known as Department of Environment Water and Natural Resources DEWNR) assessed the status of soil organic carbon in South Australia's agricultural soils (Young *et al.* 2017) utilising data from DEW's State Land and Soil Information Framework (SL&SIF). Soils with the capacity to sequester carbon were identified and soils that could be modified through the addition of clay (clay-modified soil) were rated as having the highest theoretical sequestration potential.

The addition of subsoil clay to sandy topsoil (clay modification) can overcome water repellence and increase crop production, nutrient and water holding capacity and has the potential to increase organic carbon (OC) storage (Schapel *et al.*2017). Clay addition to sand has the potential to increase OC concentration through increased OC input from improved plant growth and stabilisation of OC by binding to clay and hence protection from microbial decomposition. Clay addition improves the inherent fertility of the soil due to the greater cation exchange capacity of clay therefore fertiliser efficiency should also increase, potentially decreasing emissions compared to an unmodified soil.

There are approximately 2.6 million hectares (Mha) of sandy soil under agriculture in South Australia with 2 Mha suitable for modification using clay (J. Hall 2011 pers. comm.). A feasible scenario over 25 years of modifying 1 Mha of suitable sandy agricultural soils with subsoil clay, assuming an average increase in carbon stock[1] of 7.5 tha^{-1}, can result in 7,500,000 $tCha^{-1}$ or 27,525,000 CO_2 emissions (CO_2-e) offset.

This project aimed to:

1) collate, review and reanalyse existing knowledge to conceptualise the carbon sequestration potential of South Australian clay-modified agricultural soils;
2) identify available carbon and nitrogen models and assess their applicability for clay-modified soils; and
3) identify gaps in current knowledge and provide a direction for supporting opportunities for carbon sequestration and nitrous oxide reduction.

Information from this project will provide a better understanding of the factors driving soil OC and the carbon sequestration potential of clay-modified soils. It will be used to inform agricultural carbon offset policy, determine further steps required to deliver a carbon offsets and emission reduction program specific to clay-modified soils in South Australia, and improve adoption of appropriate strategies by landholders.

Table 1. Summary of project objectives and task list

Task	Task Objective	Task list
1 - Data collation	To identify and collate previous research and available data on soil carbon status of South Australia soils. To identify knowledge gaps impacting on quantification of carbon offset opportunities in clay-modified agricultural soils through soil organic carbon sequestration and nitrogen emission abatement	Collate, review and re-analyse existing soil OC data sets Estimate of OC opportunity Identify gaps in knowledge
2 - Assessment of models	To identify and test models currently available to determine changes to soil OC stocks and nitrogen emission abatement following clay modification and changes to agronomic practice	Evaluate soil C (carbon) and N (nitrogen) models Support development of improved models Verification of C and N future benefit Identify gaps in knowledge
3 - Framework for future direction	To collate information to produce a conceptual model of important factors affecting carbon processes in clay-modified soils and provide a road map for a next steps process	Report of carbon sequestration opportunity and nitrous oxide emission abatement for SA agricultural soils Conceptual model Road map for future work
4 – Literature review and prioritisation of research	To review the knowledge gaps identified in the road map and prioritise research that is essential to progress clay modification as a viable option for soil carbon sequestration	Literature review of gaps identified in task 3 Identification of areas that require further investigation

[1] Average theoretical OC opportunity for clay modified soil identified in Young *et al.* (2017)

2 Collation, review and re-analysis of existing OC data

Objectives:

- *To identify and collate previous research and available data on soil carbon status of South Australia soils. To identify knowledge gaps impacting on quantification of carbon offset opportunities in clay-modified agricultural soils through soil organic carbon sequestration and nitrogen emission abatement*

Previous studies conducted by DEW and PIRSA made broad estimates of the potential to sequester organic carbon through modifying soils with clay. However, further investigation was required to provide a more detailed estimate of the potential for increasing soil organic carbon (SOC) in agricultural systems, and the combinations of soil and climate that provide the greatest opportunities.

There is a long history of clay application to sandy soils in South Australia. Clem Obst of Mundulla in the south east of SA, spread clay on a sand hill in 1968 to prevent it ‘blowing’ and started the practice of clay spreading. Delving was developed in 1992, where clay was within 60 cm of the sandy surface. Originally the focus of clay modification was to overcome water repellence and benefits to crop productivity were not actively sought until the late 1990’s. The importation of a machine known as a spader in 2008 was pivotal in realisation of further crop production increases, hypothesised to be due to deeper incorporation (to 30 cm) of clay and organic matter (OM).

In South Australia, the most common methods of clay modification are addition of subsoil clay to the surface of the sand (clay spreading) or elevation of *in-situ* subsoil clay (delving). Incorporation of the added clay can be shallow (10-15 cm) with discs, cultivators etc., or deep (15-40 cm), generally with a spader. These methods result in a mix of clay clods of varying size (1 mm to 200 mm Schapel 2017 pers. obs.) within a sand matrix. Betti *et al.* (2016) reported that clay clods remain distinct from the sand, creating a zone with bimodal soil physical properties rather than a uniform mix found in unmodified soils.

Sands often have low organic carbon (OC) concentration due to poor plant growth as a result of low nutrient and water retention capacity (Baldock and Skjemstad 2000). Sand grains are large, single particles with small surface area and few binding sites making OC vulnerable to microbial decomposition. Conversely, clay particles are small with large surface area and crystalline structure so can exchange cations and bind OC. OC binding to clay depends on clay mineralogy, sesquioxide and carbonate concentration (Fernández-Ugalde *et al.* 2011; Saidy *et al.* 2012). Clay decreases accessibility of OC to microbes by occlusion in aggregates (Tisdall and Oades 1982, Six *et al.* 2004) protecting OC from decomposition.

Addition of subsoil clay to sand (clay modification) has the potential to increase soil OC through increased OC input from improved plant growth (above and below ground), and stabilisation and protection of OC.

Factors that have been demonstrated to increase soil OC on agricultural land are:

- climate - rainfall, temperature, evaporation, vapour pressure deficit;
- farming system - specific agronomic management of crops or pastures, implementation of more pasture/livestock into cropping rotations, or conversion of cropping land to permanent pasture;
- time since implementation of management system; and
- clay concentration.

Hypothesised factors additional to those above that may affect OC stock in clay-modified soil include:

- size and distribution of clay clods;
- type of modification (spreading or delving);
- depth of incorporation (shallow or deep); and
- addition of organic matter.

A conceptual model of factors that influence soil organic carbon in clay-modified soil was developed (Figure 1) and demonstrates the complexity and often co-dependencies of numerous factors to increase OC stock.

A number of hypotheses were developed to guide the data analysis and enable a better understanding of the factors influencing OC in clay-modified soils.

Hypotheses:

1. Addition of clay subsoil to sand will increase OC stock
2. Higher rainfall will increase OC stock
3. Clay sourced from below (delving) will have higher OC stock than clay from above (clay spreading)
4. Deep incorporation of clay will increase OC stock compared to shallow incorporation
5. Addition of OM with clay will increase OC stock
6. Increased time since modification will increase OC stock

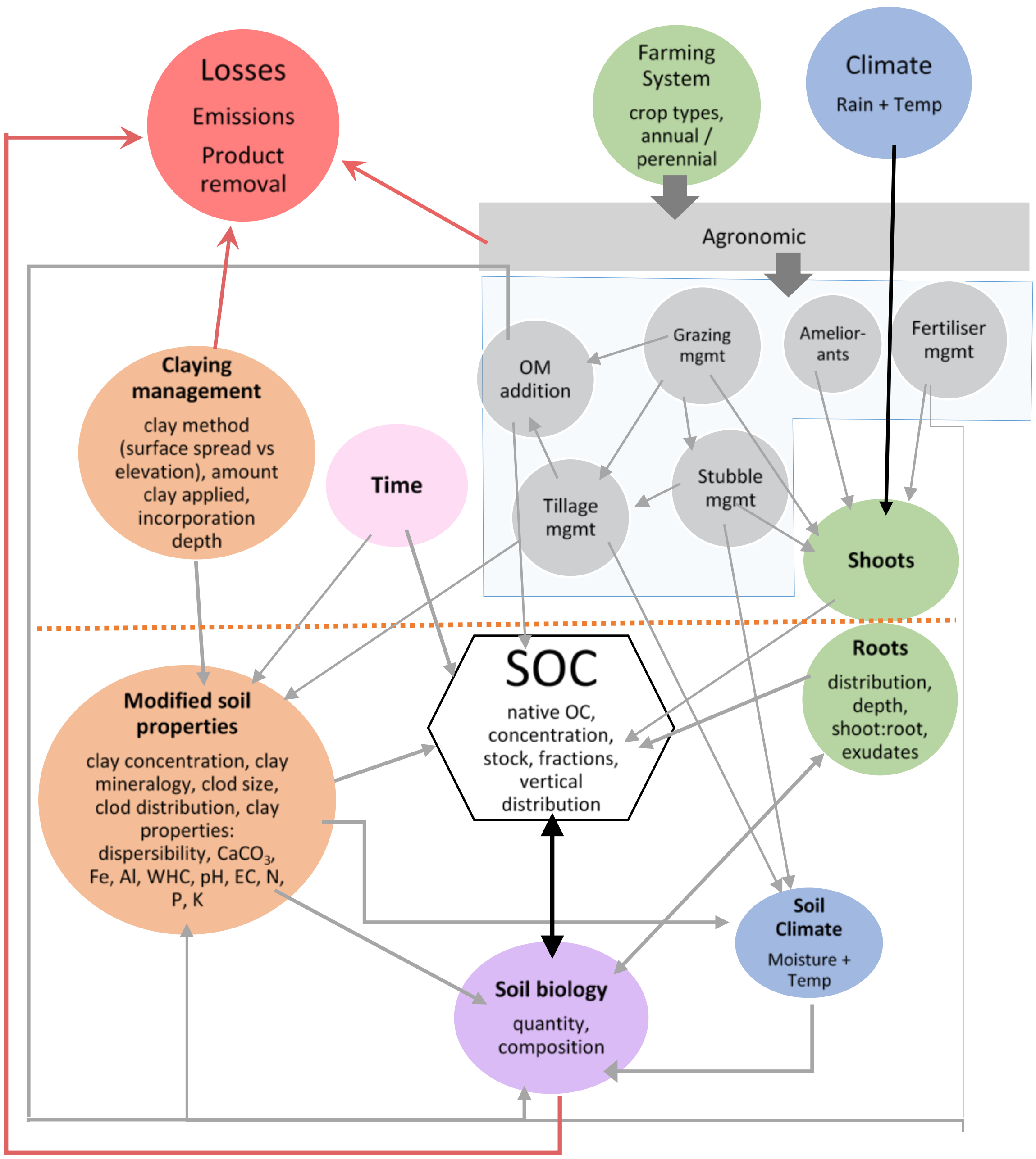

Figure 1. Conceptual model demonstrating the theoretical factors that influence soil organic carbon. Factors specific to clay modification are coloured brown. Abbreviations: mgmt. – management, OM – organic matter, D – delving, CS – clay spreading, temp – temperature, CaCO3 – calcium carbonate, Fe – iron, Al – aluminium, WHC – water holding capacity, EC – electrical conductivity, N - nitrogen, P – phosphorus, K – potassium.

2.1 Method

Exploratory and regression analysis of OC stock in the top 30 cm of soil was undertaken to determine factors influential in increasing OC in clay-modified soil. Sites were selected from three regions - South East, Murray Mallee and Eyre Peninsula. Over 200 clay-modified sites were identified in South Australia but the majority of these sites had been established to measure plant production rather than soil organic carbon. Only sites with: i) sufficient sampling intensity for accurate determination of OC concentration (Sanderman *et al.* 2011, Schapel *et al.* 2017); and ii) documented bulk density, soil description, soil chemical and management practices[2] were included in the dataset (Appendix A).

Forty-nine clay-modified and nine unmodified sites were suitable for inclusion in the analysis. To provide a comparable number of sites for exploratory analysis, additional unmodified sites were sourced. Forty sites were selected, 6 from trials or demonstrations and 34 from SL&SIF, based on OC concentration measured in 10 cm increments, bulk density values[3], similarity to soil type and distribution of rainfall zones with clay-modified sites.

OC stock was calculated for the 0-30 cm soil depth (fixed depth). To enable fair comparison across sites and clay-modification method, the OC stock of a standard soil mass for the 0-30 cm depth was used (90th percentile, 5000 tha^{-1}) and is known as OC stock equivalent soil mass (ESM) or OC stock $_{ESM}$. Further reference to OC stock in this report is to the OC stock $_{ESM}$.

Exploratory analysis of OC stock and concentrations using frequency distribution, minimum, maximum, average, standard error of the mean (SEM) and coefficient of variation (CV) was undertaken (Appendix B). A significant difference was considered when error bars from the standard error of the mean (SEM) did not overlap for the average OC stock for the parameter. This analysis was particularly useful in extracting OC information for parameters not suitable for regression analysis, text data or numerical data with limited options[4].

Exploratory analysis identified parameters and key groups to use as variates for regression analysis. Where additional unmodified sites did not have a record of management practices and data on a number of key soil parameters (predominantly clay concentration), they were excluded from the regression analysis. Regression analysis was conducted on 57 sites: 49 clay-modified and 9 unmodified. Significance for regression was p <0.05.

Simple linear regression was run on the whole data set to identify parameters that explained variance in OC stock (ESM 5000 tha^{-1}). To identify non-climatic factors, analysis was conducted within rainfall zones[5], 350-400, 400-450, 450-500 and 500-600 mm. Rainfall zones followed those in Young *et al.* 2017. Further scrutiny using linear regression within the rainfall zones, included groups: modified, clay source, incorporation depth, organic matter addition and time since modification (Table 2).

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[2] Collated parameters are listed in Appendix 1

[3] Bulk density values estimated by David Maschmedt for SA Soil groups for the National ASRIS (Australian Soil and Landscape Grid)

[4] For example, incorporation had limited numerical input; 10, 15 or 30 cm which was not appropriate for regression analysis

[5] Although there is a stronger regression relationship with rainfall from a coordinate based point source (C-Rainfall) compared to rainfall from the closest BOM weather station (average rainfall), the average rainfall grouping has been used for analysis due to the more even distribution of sites across rainfall zones and groups.

Table 2. Number of sites for key groups in the linear regression.

Key Groups	*n*
Rainfall zone	
350-400	13
400-450	17
450-500	17
500-600	11
Clay-modified	
No - unmodified	9
Yes – clay-modified	49
Clay source	
NA	9
Above (clay spreading)	33
Below (delving)	16
OM addition	
Unmodified - No	9
Clay modified - No	39
Clay modified - Yes	10
Time since modification (years)	
Unmodified - 0	9
< 5	19
5-10	19
10-15	7
15-25	3
25-45	1

2.2 Results

2.2.1 EXPLORATORY ANALYSIS

Frequency distribution of unmodified and clay-modified sites demonstrate a higher sample count with greater OC concentration in clay-modified samples, with the greatest change occurring in the 10-30 cm depth (Figure 2). A similar pattern is demonstrated in the frequency distribution for OC stock, with higher number of samples with higher OC stock in the clay-modified sites compared to the unmodified sites (Figure 3).

The box and whisker plot of unmodified and clay-modified sites for each rainfall zone (Figure 4) demonstrates less variance between the 25 and 75 percentile for clay-modified sites. Two outliers are identified for the clay-modified sites in the 350-400 mm and 400-450 mm rainfall zones. However, after checking the data these high points are considered valid to be included in the analysis.

There is a trend for increasing OC stock with increased rainfall. This is apparent for the unmodified sites although it is less defined in the clay-modified sites (Figure 4).

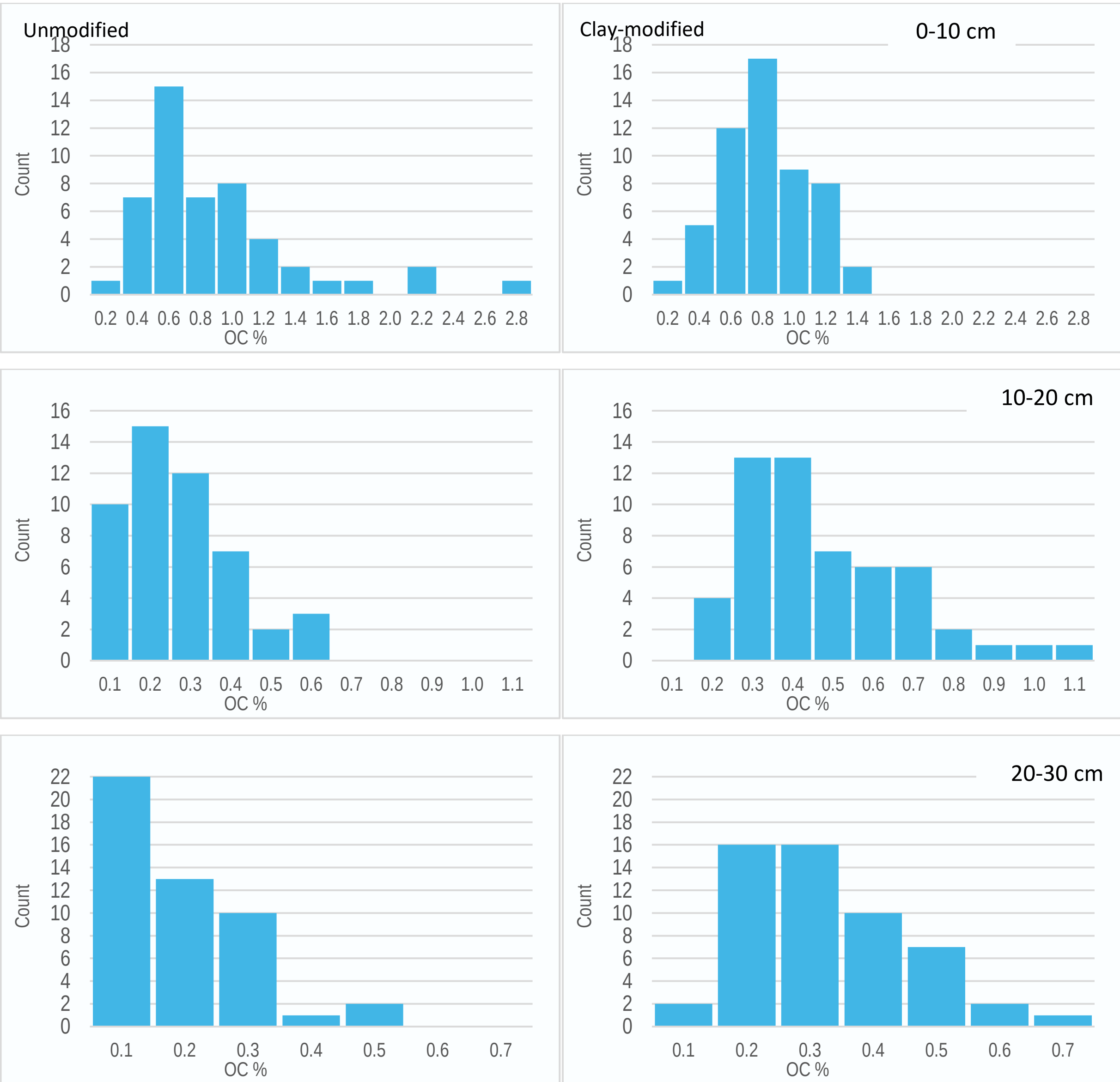

Figure 2. Frequency distribution for OC concentration for the 0-10, 10-20 and 20-30 cm depth for unmodified (left) and clay-modified (right) sites.

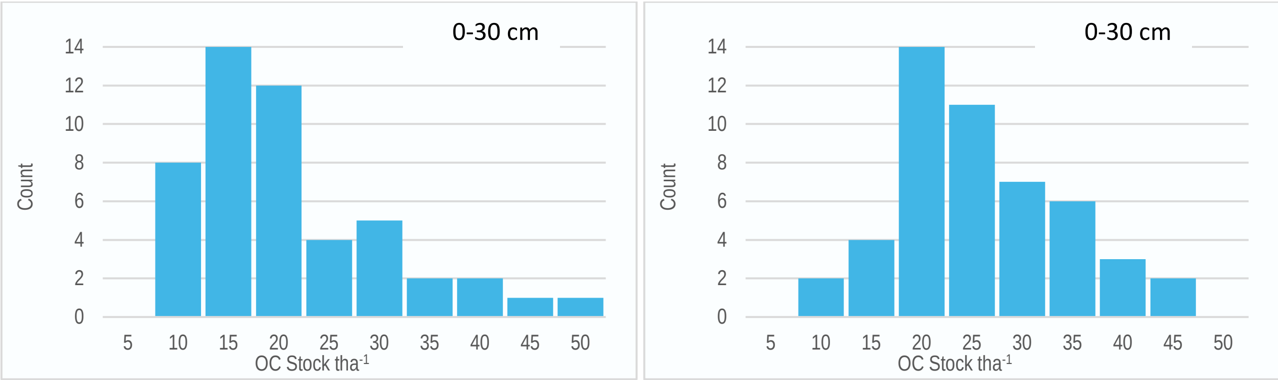

Figure 3. Frequency distribution for OC stock (0-30 cm) for unmodified (left) and clay-modified (right) sites.

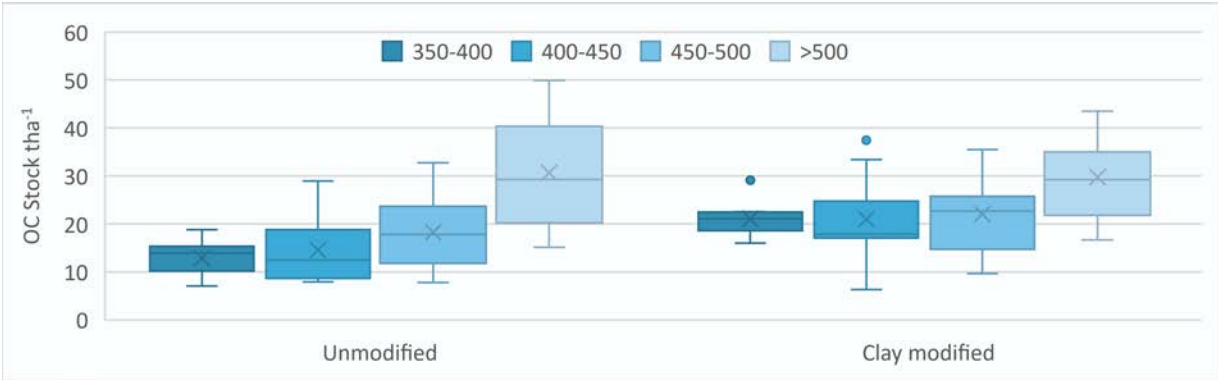

Figure 4. Box and Whisker plot displaying the distribution of OC stock values with a rainfall zone for unmodified (no) and clay-modified (yes) sites. Symbols: X represents the average, the line the median, the box is the quartiles, bars are the 5% and 95% and the dot is data considered to be an outlier.

Overall, there is a 4.9 tha^{-1} increase in OC stock with clay modification compared to unmodified sites (Figure 5). There is a positive correlation between OC stock and rainfall with a significant increase (10-13.5 tha^{-1}) in OC stock in the > 500 mm rainfall zone compared to those < 500 mm (Figure 5). However, there is no difference between clay-modified and unmodified OC stock in >500 mm zone but there is a significant difference between unmodified and clay-modified sites (5-8 tha^{-1}) for the 350-400 and 400-450 mm rainfall zones (Figure 6).

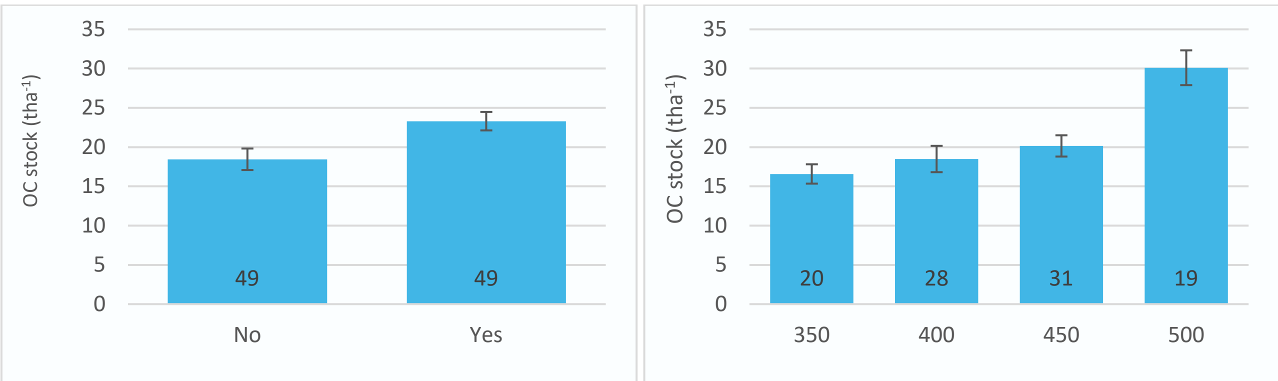

Figure 5. Average OC stock (tha^{-1}) by clay-modified (Yes) or unmodified (No) sites (left) and rainfall zone (right). Error bars denote SEM and numeric labels are number of samples for each category.

Separating the clay-modified sites by clay source (i.e. above (clay spread) and below (delved)) identifies a significant increase between unmodified and clay sourced from below for rainfall zones 350 to 500 mm (5-11 tha^{-1}), and 350-400 mm (10 tha^{-1}) for clay sourced from above (Figure 6). There is a significant difference between clay source for 350-400 mm (clay above > clay below) and 400-450 mm (clay below > clay above) zones. Across all rainfall zones, there is an increase in OC stock of 4.4 to 5.7 tha^{-1} for clay-modified sites, sourced from above and below, compared to unmodified sites.

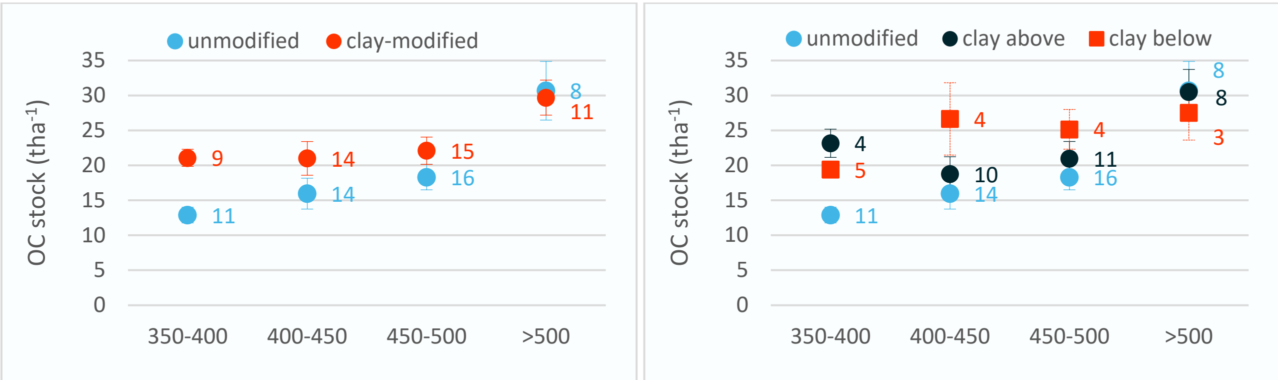

Figure 6. Average OC stock (tha^{-1}) separated into rainfall zones for: unmodified and clay-modified sites (left); and clay sourced above, clay sourced below or unmodified. Error bars denote SEM and numeric labels are number of samples for each category.

Incorporating clay increases OC stock 4.3 tha^{-1} for shallow and 5.3 tha^{-1} for deep incorporation. There is a significant difference between unmodified and deep incorporation for rainfall zones less than 500 mm, and 350-400 mm for shallow incorporation. There is no significant difference between incorporation depth (shallow and deep) for any rainfall zone however, deep incorporation in deep sands significantly increased OC stock by 20 tha^{-1} over shallow incorporation and unmodified sites (Figure 7).

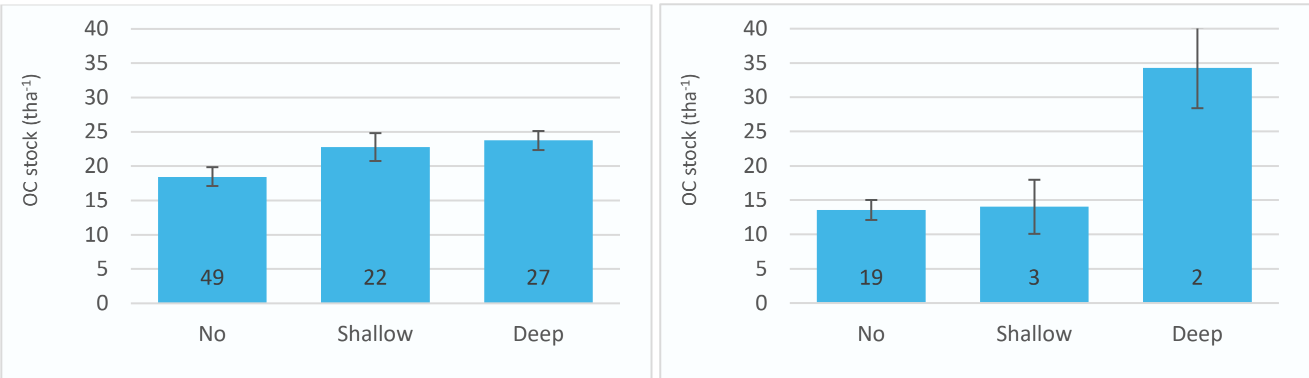

Figure 7. Average OC stock (tha^{-1}) for unmodified (No) and clay-modified sites with shallow and deep incorporation for the whole dataset (left) and for soil type deep sand (right). Error bars denote SEM and numeric labels are number of samples for each category.

Although an increase in OC stock was demonstrated for sites with added organic matter (OM), analysis of only clay-modified sites showed no significant differences in OC stock with and without OM addition (Figure 8).

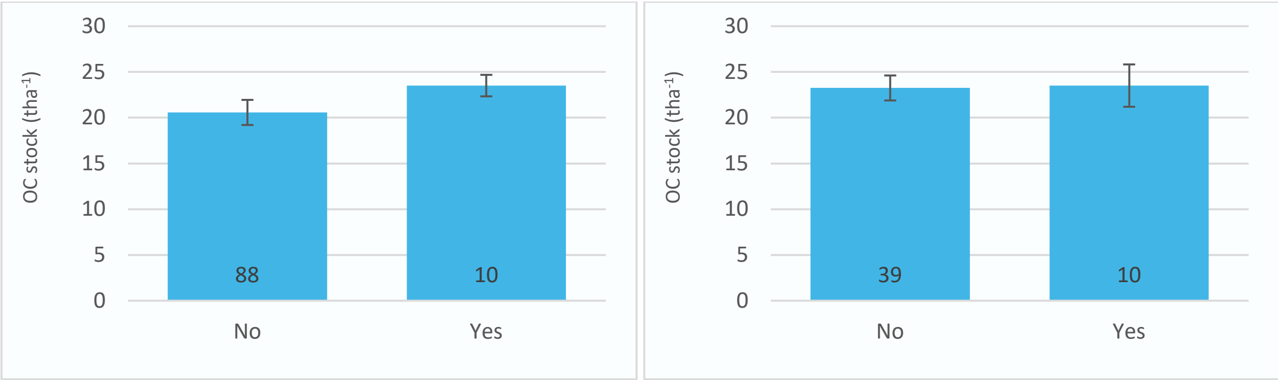

Figure 8. OC stock with OM addition for all sites (left) and clay-modified sites only (right). Error bars denote SEM and numeric labels are number of samples for each category.

A significant increase in OC stock (7-8 tha^{-1}) occurred on clay-modified sites treated less than 10 years from sampling, compared to unmodified sites for rainfall < 450 mm. The OC stock of the oldest clay-modified site in the State (45 years) is less than the unmodified and other clay-modified sites in the 500 mm rainfall zone (Figure 9).

A significant increase in OC stock (3 tha^{-1}) was observed under low-intensity pasture (grazing) management on clay-modified soil compared to unmodified soil. There was no difference in continuous cropping or crop-pasture/grazing systems. In clay-modified soils, there was no significant difference in OC stock between farming systems (Figure 9).

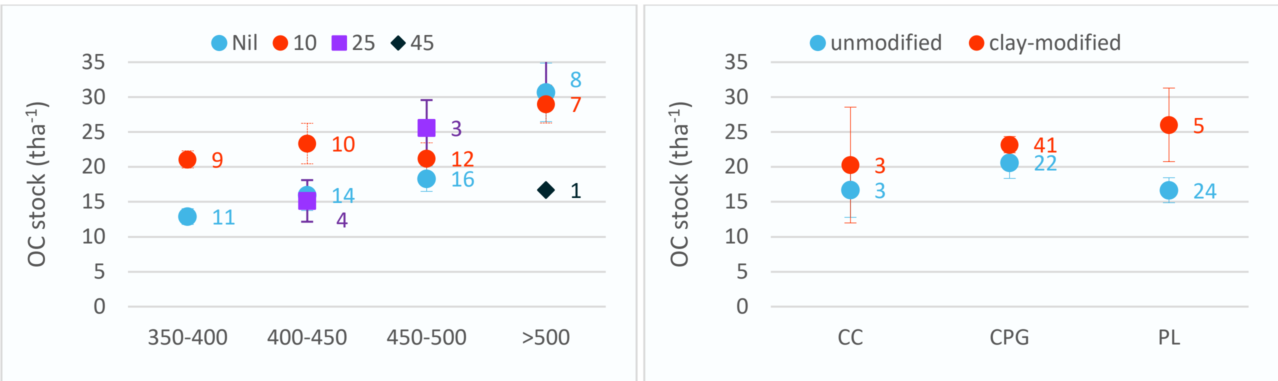

Figure 9. OC stock of unmodified (Nil) and time since clay modification (years) for rainfall zones (left) and unmodified (No) and clay-modified for land-use management system. Abbreviation: CC – continuous cropping, CGP – crop/pasture with grazing, PL – pasture low intensity system (right). Error bars denote SEM and numeric labels are number of samples for each category.

There is a significant decrease in OC stock in unmodified soil with soil depth, but this trend is not observed in clay-modified soil types (Figure 10). There is a significant increase in OC stock (8 tha^{-1}) in clay-modified compared to unmodified deep sands where subsoil clay is greater than 70 cm from the soil surface. There is minimal difference in OC stock between unmodified and clay-modified for shallow texture contrast soil where subsoil clay is within 30 cm of the surface.

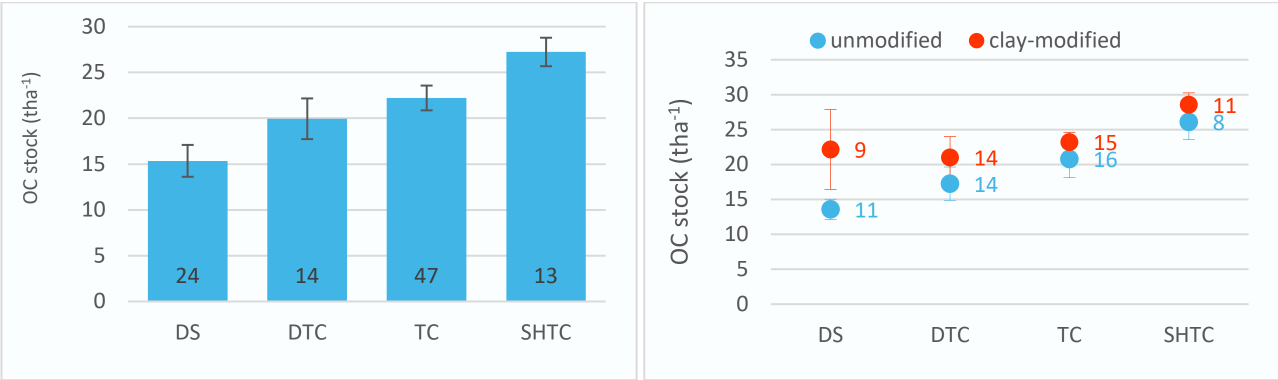

Figure 10. OC stock for soil types (left) and separated into unmodified (No) and clay-modified (Yes) for soil type. Abbreviations: DS – deep sand (subsoil clay > 70 cm), DTC – deep texture contrast (subsoil clay 50-70 cm), TC – texture contrast (subsoil clay 30-50 cm), SHTC – shallow texture contrast (subsoil clay < 30 cm). Error bars denote SEM and numeric labels are number of samples for each category.

Table 3. Change in OC stock$_{ESM}$ (tha^{-1}) of clay-modified compared to unmodified and sites for key parameters by rainfall zone. Bolded values denote significant difference of clay-modified to unmodified sites. CC – continuous cropping, CGP – crop/pasture rotation with grazing, PL – pasture low intensity DS – deep sand (subsoil clay > 70 cm), DTC – deep texture contrast (subsoil clay 50-70 cm), TC – texture contrast (subsoil clay 30-50 cm), SHTC – shallow texture contrast (subsoil clay < 30 cm)

		Rainfall zones (mm)				
Modification	Clay-modified	**4.9**	**8.2**	**5.0**	3.8	-1.0
Soil type	DS	**8.6**	*	-4.4	5.1	2.4
	DTC	3.8	*	**9.0**	0.3	11.9
	TC	2.4	**4.9**	**5.9**	0.5	-8.5
	SHTC	2.5	*	*	3.8	*
Clay source	Clay above	**4.4**	**10.3**	2.8	2.7	-0.2
	Clay below	**5.7**	**6.5**	**10.7**	**6.8**	-3.2
Incorporation depth	Shallow	**4.3**	**9.6**	4.9	2.8	-2.4
	Deep	**5.3**	**7.8**	**5.2**	**4.6**	0.2
Time since modification	10	**4.7**	**8.1**	**7.4**	2.9	-1.7
(years)	25	**6.0**	*	-0.8	7.3	5.0
	45	-1.7	*	*	*	**-14.0**
Farming system	CC	3.6	*	*	**5.2**	*
	CPG	2.6	**7.2**	3.3	-3.4	**-14.7**
	PL	**9.4**	**10.6**	-19.4	*	3.3

** indicates ≤ 1 sample. There are a number of large OC stock difference that cannot be denoted as significant due to no SEM for either clay-modified or unmodified.*

2.2.2 LINEAR REGRESSION

Regression was utilised to identify key parameters that influence OC stock. Simple regression of the whole data set (all rainfall zones) identified the following key variables and the percentage variance they explain (Table 4):

- climatic factors (rainfall, temperature and evaporation);
- clay concentration;
- nutrients (nitrogen, phosphorus, potassium, sulphur);
- OC stabilisation (Calcium and Iron);
- boron;
- water holding capacity and;
- average grain yield.

Regression of OC stock with groups by rainfall zone (Table 4) identified:

- Climatic factors were related with a (significant decrease in OC stock for 350-400 mm rainfall zone (for clay source only) with increases in temperature or evaporation
- Clay concentration is significant for 400-500 mm and in the 10-20 cm depth for 500 mm with increasing variance associated with increasing rainfall, but with no significant difference in the 350-400 mm rainfall zone
- Depth to subsoil was significant for rainfall zones 350-400 and 450-500 mm
- Depth of incorporation was not significant unless analysed as a group within the regression
- Time since modification was not significant unless analysed as a group with the regression in rainfall zone > 500mm ($p < 0.1$) with a significant positive response for 10 and 15 years
- Nutrition showed significant positive responses for rainfall zones 350-400 mm (modified group only) and 450-500 mm
- OC stabilisation, calcium and iron Fe gave significant positive responses for rainfall zones 350-400 mm (modified group only) and 450-500 mm
- Soil properties (cation exchange capacity, electrical conductivity, pH) showed significant positive responses for some rainfall zones.

Table 4. Summary of simple linear regression of OC stock for whole data set by rainfall zone with a significant response. Values denote percentage of variance explained, text denotes depth or group with significant response. Abbr: sig – significant, IS – insufficient samples for analysis, CS – clay source, Mod – modified, N – nitrogen, P – phosphorus, K – potassium, S – sulphur, Ca - calcium, Fe – iron, CEC – cation exchange capacity, EC – electrical conductivity, WHC – water holding capacity

		All rainfall zones	350-400 mm	400-450 mm	450-500 mm	>500 mm
Climate	Average rainfall	23				
	Temperature	20	79 (CS)	44		
	Evaporation	25	79 (CS)	37		Clay source
Clay	Clay concentration	17		56	67	30 (10-20cm)
	Time since modification					
Nutrition	N, P, K, S	25-60	80-85 (Mod)		40-80	IS
OC stability	Ca, Fe	40-50	30-40 (Mod)		40-70	IS
Soil	CEC	8 (20-30 cm)	40 (Mod)		36	IS
	pH	6	82 (CS)			
	EC	8 (20-30 cm)		24	30	
	Boron	27				
	WHC	28				
	Subsoil depth		39		35	
Yield	Grain yield	37				

2.3 Discussion

The addition of subsoil clay to sand increased OC stock compared to unmodified sandy soil. There are however many variables that either directly or indirectly affect the storage of soil organic carbon. The regression analysis identified key variables that explained significant variance and determined the upper (threshold) and lower limits of OC stock within the dataset. The exploratory analysis quantified the OC stock differences between unmodified and clay-modified soil. A number of key variables have been identified that influence OC stock in clay-modified soils (Table 5).

Factors that directly affect the soil OC stock threshold in clay-modified soils are:

- Rainfall
- Amount of clay applied (clay concentration)
- Depth to subsoil clay (soil type)

Practices that improve the probability of creating a clay-modified soil can reach its OC threshold are:

- Clay clod distribution (depth of incorporation and clay source)
- Nutrient application
- Farming system
- Clay clod size[6]

Rainfall determines the biomass that can be grown and ultimately controls organic matter input into the soil. In the 350-450 mm rainfall zone, a gradient of OC stock identified that there are practices that can increase inputs into the system, such as increased water use efficiency.

Clay concentration defines how much OC can be stored in the soil. Adding subsoil clay to sand permanently increases clay concentration. OC bound to clay is protected from microbial decomposition, whereas OC unbound in sand is vulnerable to decomposition. Increases in OC stock are expected as a result of clay addition to sand due to improved plant growth (above and below ground) and stabilisation and protection of OC. This study identified no difference in OC stock between unmodified and clay-modified soil when there was an average clay concentration above 20% within the 0-30 cm depth. This indicates a threshold value of 20% clay concentration in clay-modified soil for carbon sequestration.

This limit to the amount of OC stock may also be determined by subsoil clay within 30 cm of the surface. At this depth, no significant difference in OC stock between unmodified and clay-modified soil was identified. Depth to subsoil clay may affect a number of variables such as water holding capacity, access to stored moisture (plant available water), cation exchange capacity and nutrients available to plants. For soils with subsoil clay between 30-70 cm depth, a significant difference in OC stock was identified for rainfall zones below 450 mm. Although a significant difference in OC stock was observed in the deep sand (subsoil clay > 70 cm), this was not identified in specific rainfall zones and may be driven by other factors such as clay source or depth of incorporation.

Clay sourced from below the soil surface by delving is distributed as clay clods throughout the whole soil profile, increasing OC distribution to depths greater than 30 cm. Clay applied from above (clay spreading), increases stock if depth to subsoil clay is within 30-70 cm. However, below 70 cm, a negative correlation of declining OC stock with increasing depth to subsoil, can occur. Closer inspection of the data identified that deep incorporation (to 30 cm) can increase OC stock in this soil type compared to shallow incorporation or unmodified soil. Reported increases in production with deep incorporation may be strongly influenced by clay clod size and distribution throughout the soil profile. The impact of these variables on OC, water dynamics and nutrition requires further investigation.

Clay modification increases OC distribution in the 10-30 cm depth of soil compared to unmodified soils (Appendix C). There is often a decrease in OC concentration in the surface 10 cm in clay-modified soil. This could be due to a number

[6] Although clod size was not measured in this study, water dynamic modelling work by Dirk Mallants and other studies by Schapel and Marschner (unpub) have demonstrated clod size as an important factor influencing OC concentration and stock

of factors, including but not limited to: increased microbial decomposition resulting from increased, favourable moisture and temperature conditions; increased decomposition of OC in the sand component due to elevated microbial activity; and dilution of OC resulting from re-distribution deeper in the soil profile as a result of incorporation.

There was no evidence of increased OC stock with the addition and deep incorporation of organic matter in this study. This may be because the majority of clay-modified sites with organic matter additions were less than four years since modification so have not reached their OC potential and require more time to do so. Alternatively, incorporating organic matter increased microbial activity. This could create a 'healthier', more productive soil but might not result in increased soil OC due to a higher turnover rate.

Time since implementation of a management change is regarded as a primary factor driving OC stock change in unmodified soils. However, in clay-modified soils this has been shown to be the case only where rainfall is above 500 mm. In this zone, rainfall does not appear to limit OC stock with no significant difference between clay-modified and unmodified soils and biomass production and OC stock are not limited by inadequate nutrition. Regression analysis identified a positive correlation for time since clay modification, where OC stock at 15 years is greater than 10 years (there is no data for 25 years). It is important to note that the oldest clay-modified site in the state has the lowest OC stock result in this rainfall zone. This may be due to a number of factors such as clay concentration; depth to clay subsoil; incorporation depth; and applied nutrition. This reflects the change in practice of clay modification over time.

The addition of clay to sand creates a new nutritional threshold, increasing the cation exchange and water holding capacity of the soil. However, some sites do not reach their OC potential as adequate nutrition to support higher biomass growth is not provided. Application of sufficient nutrients for plant and microbial growth is a practice that can influence OC and was identified as a limiting factor in the 450-500 mm rainfall zone. However, there is uncertainty whether the strong positive correlation between OC stock and soil chemical properties (nutrition/OC stability) is solely a result of higher fertility due to applied nutrients as it is also likely to reflect chemical properties that are introduced due to the addition of subsoil clay to sand. Further investigation is required to separate the measured soil chemical changes into those attributed to the addition of clay and those to the addition of nutrients from applied fertiliser or other practices.

Although there were no significant OC stock differences between land-use systems in clay-modified soils there was a significant difference between clay-modified and unmodified soils under low intensity pasture management. In this system, the addition of clay to sand increased OC stock, probably through increased biomass production.

Data analysis for sites considered in this study have provided answers to the hypotheses, as outlined below.

Hypotheses		Finding
1	Addition of clay subsoil to sand will increase OC stock	True
2	Higher rainfall will increase OC stock	True
3	Clay sourced from below (delving) will have higher OC stock than clay from above (spreading)	True for rainfall zones 350 to 450 mm
4	Deep incorporation of clay will increase OC stock compared to shallow incorporation	True when depth to subsoil clay > 70 cm
5	Addition of OM with clay will increase OC stock	Uncertain - further work required
6	Increased time since modification will increase OC stock	True for rainfall > 500mm

This study has highlighted the many interactions that result in an increase in OC stock. There are very few examples of singular 'if, then' rather many, multi-faceted 'if, and/or, then' determinations that are overlain by constraints that could be due to climatic, soil, machinery or management factors. A summary of the factors that drive soil OC or the practices that can realise its OC potential and the associated effect on OC stock for clay-modified soil is detailed in Table 5. A summary of key factors or practices that influence OC stock and the primary limitation by rainfall zone is detailed in Table 6. Limitations are divided into factors that affect either the input of OC into the soil (above ground) or the output of OC due to the turnover rate or stabilisation of OC (below ground).

Table 5. Driving factors and practice options that help realise soil OC potential and their effect on OC stock in clay-modified soil. Arrows pointing up indicate an increase and arrows pointing down indicate a decrease. The number of arrows indicates the magnitude of the change and confidence in the effect is indicated, with * low confidence to * high confidence.**

Factor	Effect on OC Stock	Confidence	Comment
An increase in factor that directly affects OC stock threshold			
Rainfall / Water storage	↑↑	***	Determines the amount of biomass that can be grown
Temperature/Evaporation	↓	***	Negative correlation – effect on soil microbes and plant physiology
Clay concentration	↑↑	***	Positive correlation to an upper limit of 20% clay. Minimal difference in OC stock between modified and unmodified soil where clay > 20% in 0-30 cm. Related to soil where subsoil clay within 30 cm (see below)
Depth to subsoil clay / soil type	↑	**	Clay modification best on sandy soil with > 30-40 cm to subsoil clay (texture contrast soil). Greatest stock increase where subsoil clay > 70 cm (deep sand). Minimal difference in OC stock at depth < 30 cm (shallow texture contrast soil).
An increase in practice options that can realise the OC stock threshold			
Clay clod size	?	*	This study has no sites with OC data by clod size. However, other studies have demonstrated a negative correlation for OC concentration (Schapel *et al.* 2018 in press).
Depth of incorporation	↑	**	Deep incorporation (to 30 cm) is important where subsoil clay > 60 cm. Incorporating clay clods to 30 cm increases OC stock of the 10—30 cm depth when compared to unmodified soil.
Nutrient application	↑↑	**	Increased nutrition increases plant biomass = increased OM input into the soil. May also provide nutrients for microbes to cycle OM, that could in turn affect OC fractions
Time since modification	↑↓	**	Positive correlation to 10 years post modification for rainfall zones < 450 mm. Negative correlation for rainfall > 500 mm but this is due to changes in clay modification practices over time where younger sites have higher OC stock compared to older sites > 25 years
Addition of organic matter	-?	*	Unable to determine the effect of OM addition in this study. Addition of OM has been shown elsewhere to increase biomass production and hence OC concentration. However, it is unknown how increased microbial activity affects OC concentration. The addition of clay should provide greater protection to OC from microbial decomposition compared to sand alone.

Table 6. Summary of identified key factors or practices that influence carbon stock and the primary limitation primary limitation. Number of ticks indicates the level of influence on OC stock.

	350-400 mm	400-450 mm	450-500 mm	>500 mm
Rainfall / Water storage	✓✓✓	✓✓✓	✓	
Clay concentration		✓✓	✓✓✓	
Time since modification				✓
Nutrition	✓		✓✓✓	
Depth to subsoil clay / soil type	✓✓	✓✓	✓✓	✓
Limiting factor	**Inputs (above ground)**		**Outputs (below ground)**	

A report commissioned by DEW (Young *et al.* 2017) identified that clay-modified soils were rated as having the highest theoretical sequestration potential[7]. OC stock opportunity was calculated as the difference in clay-modified site stock values between the 75th and 25th percentile, using data from the SL&SIF. The theoretical OC stock opportunity is compared to measured field data collated for this project (Table 7).

Table 7. OC stock opportunity (tha^{-1}) in clay-modified soil by rainfall group for the theoretical and measured data.

	Rainfall zone (mm)			
	350-400	400-450	450-500	>500
*Opportunity**				
Theoretical	5.0	7.5	10.0	12.5
Measured data	9.1	4.3	9.5	10.8
Difference	*+4.1*	*-3.2*	*-0.5*	*-1.7*
Maximum - minimum				
Measured data	13.0	31.2	25.8	26.7

*Opportunity was calculated as the difference between the 75 and 25 percentile

There is a difference in OC opportunity between theoretical and measured data. The assumptions made for increases in OC stock for theoretical, were based on 'best practice' clay modification with few limitations. Conversely, the measured data is based on a wide range of clay modification practices, some with large limitations to increasing OC stock as highlighted by the large difference between the maximum and minimum OC stock.

This suggests that either the OC stock of the theoretical data is over-estimated or the OC stock determined from the measured data indicates limitations to achievement of OC potential. Further work is required to refine the measured dataset investigating the OC stock opportunity of sites that have had management in the best practice (i.e. few limitations similar to the theoretical data).

[7] The theoretical calculations for clay modified soils for individual soil sub-groups were determined with an assumed increase in C stock ranging from 130% for the < 300 mm up to 200% for the > 650 mm rainfall zone. These assumptions were guided by the greatest OC stock opportunity of 22 t ha^{-1} (Schapel *et al.* 2017) and this value was used as the upper limit for a doubling (200%) of OC stock in clay modified compared to unmodified soil.

3 Assessment of models

Objective: To identify and test models currently available to determine changes to soil OC stocks and nitrogen emission abatement following clay modification and changes to agronomic practice

Clay-modified soils differ to unmodified soils due to the uneven distribution of clay (subsoil clay clods of varying size in a sand matrix) that affects soil water dynamics, temperature and chemical properties.

A review of soil carbon models was undertaken (Table 8 with full report in Appendix D) to identify and test soil carbon models for sensitivity and relevance (applicability) to clay modification for carbon sequestration. The models reviewed were:

- Century, Agricultural Production System sIMulator (APSIM), Rothamsted soil carbon turnover (Roth-C; English and Australian versions):
    - The Roth-Cmodel was developed from long term rotation trials at Rothamsted, United Kingdom.
    - The APSIM was developed in Australia as a crop production modelling shell and also has the capability to simulate soil carbon dynamics. However, no clay-modified soil has been characterised for the database, consequently predictions may not be accurate for these soils. APSIM can be used to model crop production.
    - Century model was developed in the United States and simulates carbon, nitrogen, phosphorus and Sulphur dynamics through an annual cycle over time scales of centuries and millennia.
- The Full Carbon Accounting Model (FullCAM), which was developed in Australia and extensively tested and verified for Australian conditions:
    - The model has been widely used for simulating soil and biomass carbon dynamics at project level and nationally.
    - FullCAM is the model required for national soil C (carbon) accounting.
- Hydrus (HPx) model is a reactive transport model with a flexible framework able to define reaction networks, including soil organic matter (SOM) degradation.
    - Mallants *et al.* (2017) highlighted the potential of Hydrus 2D to model the impact of water movement in clay modified soils.

As FullCAM is used to model carbon stock change and emissions by the National Carbon Accounting System, it was decided to use it to model changes in carbon stocks in South Australian clay-modified soil. APSIM was considered but the soil module is difficult to change and as no clay-modified soil has been characterised in the APSIM program, the model predictions are unlikely to be accurate.

3.1 FullCAM evaluation in clay-modified soil

The Full Carbon Accounting Model (FullCAM)[8] is the model used to construct Australia's national greenhouse gas emissions account for the land sector and must be used to model carbon stock change and emissions for some Carbon Farming Initiatives methodology determinations. FullCAM includes the Roth-C model described in Jenkinson *et al.*, (1987, 1991) and Jenkinson (1990). During the development of FullCAM, a research project was commissioned by the Australian Greenhouse Office to calibrate the Rothamsted soil carbon turnover model (Roth-C version 26.3) for Australian conditions (Skjemstad and Spouncer, 2003; Skjemstad *et al.*, 2004). The model parameters derived from this calibration activity were incorporated into FullCAM.

[8] FullCAM is a result of continuous work and contributions from a range of organisations, made up of both data providers and IT service providers. To view the FullCAM institutional arrangements relating to the collection and preparation of input data for FullCAM, refer Volume 1 of the 2013 National Inventory Report (Section 1.2). The development of FullCAM and its component models is described in Volume 2 of the 2013 National Inventory Report (Appendix 6B).

Janik *et al.* (2002) found the most sensitive variables are: resistant plant material (RPM) pool size and decomposition rate; and variables associated with plant inputs. Annual rainfall variability is also highly sensitive in some regions where occasional high rainfall events occur. Variables of moderate sensitivity are the humic acid (HUM) decomposition rate, the size of the inert organic matter (IOM) pool and a number of climate variables. Other variables have relatively low sensitivity.

Roth-C has been assessed for Australian conditions and the default figures have been adjusted accordingly, however the model itself has been largely incorporated into FullCAM.

3.1.1 METHOD

FullCAM was evaluated to determine the sensitivity of parameters for clay-modified soils. The "Configuration" of agricultural soil was chosen rather than agricultural system, to simplify the process. Real data from the New Horizon trial sites at Karoonda and Brimpton Lake were used (Fraser *et al.* 2017). Site information regarding average rainfall, pan evaporation and average air temperature were sourced from Bureau of Meteorology (http://www.bom.gov.au/climate/data/).

Agricultural soil inputs were determined from biomass cuts conducted at the New Horizon trial sites. Dry matter was assumed to contain 40% carbon with above ground (tops) dry matter measured (no below ground (roots) dry matter measurements were taken). A range of seasons were used for plant residue inputs – dry, average and wet, rather than just an average season. It was assumed that the majority of carbon inputs occurred in late spring, summer and autumn with low levels in winter and early spring.

Soil cover was estimated from biomass production at the sites, taking into account management and natural degradation. The "whole plot clay content" in the model was varied to determine the impact of claying from 3% for unmodified sand to 9% for clayed soils[9]. It is assumed that good incorporation of the clay to a depth of 30 cm has been undertaken.

The "initial soil" conditions were assumed to contain 13 $tCha^{-1}$ (average OC stock content of deep sand – unmodified soil). In lieu of measured data, carbon masses outlined for SOC pool values within FullCAM for Australian soils (Janik *et al.* 2007) were used —1%, 20%, 2%, 0.2%, 60%, 17% for DPM (degradable plant material), RPM (resistant plant material), BIOF (biomass fast), BIOS (biomass slow), HUM (humic acid), and IOM (inert organic matter), respectively. Janik *et al.* (2002) report that errors in estimates of the IOM, HUM, and RPM pools contribute to uncertainty in the modelled total soil carbon, with the RPM pool demonstrating most sensitivity in model outputs.

Water moisture deficit was estimated at 10 mm/10 cm soil for sand (3% clay) and 15 mm/10 cm soil for sandy loam (9% clay).

3.1.2 RESULTS

Initial testing of the model indicated that it has potential to simulate changes in carbon stock in South Australian modified soils (Figure 11).

[9] Soil clay contents of 5-9% have been measured in the 0-30 cm in productive systems after soil modification (Schapel pers comm).

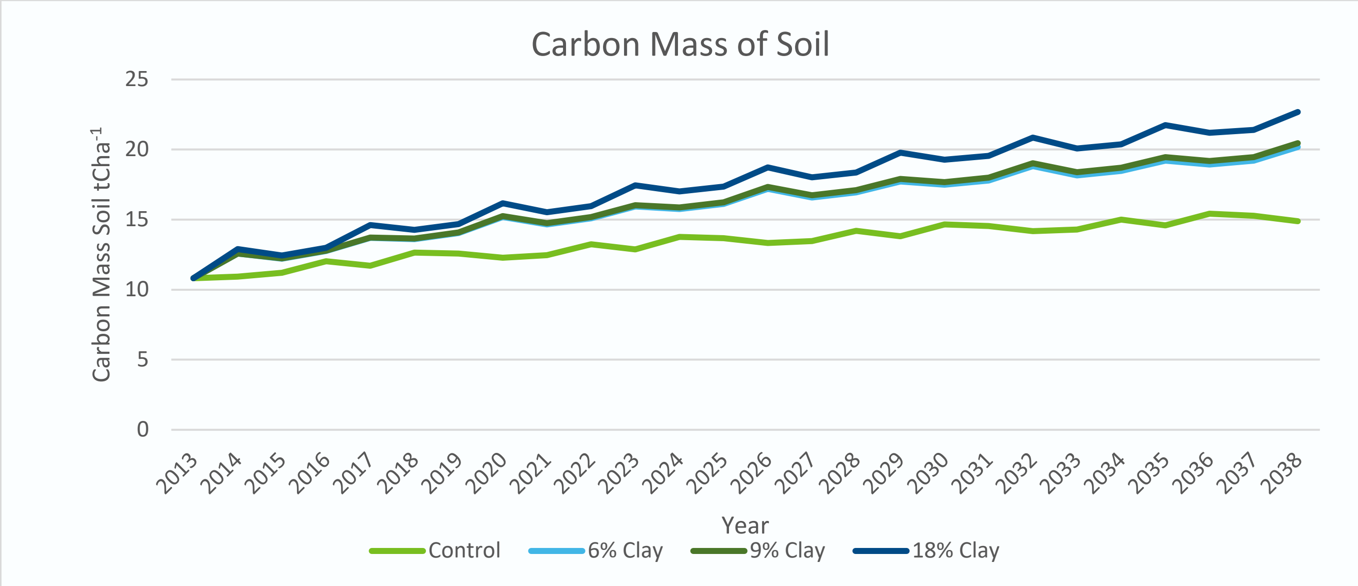

Figure 11. Modelled carbon mass of soil following modification by clay minimum (6% clay) and target (9% clay) at a low rainfall site (370 mm annual rainfall).

For example, at a low rainfall site (370 mm annual rainfall) the carbon stocks increased from the original 10.8 $tCha^{-1}$ to 14.9 t C ha^{-1} for 3% clay, 20.2 t C ha^{-1} for 6% clay and 20.5 t C ha^{-1} for 9% clay after 25 years. This gave an increase of 4.1 t C ha^{-1} at 3% clay, 9.4 t C ha^{-1} for 6% clay and 9.7 t C ha^{-1} for 9% clay over this period. The largest change in carbon is driven by the increase in biomass returned with only a relatively small difference between the 6% and 9% clay.

Increasing the clay content to 18% would increase carbon stocks to 22.7 t C ha^{-1}, 11.9 t C ha^{-1} above the original levels. However, clay rates this high have been shown to have a negative effect on production and be uneconomical (Schapel pers. obs).

Rainfall had a minor impact on OC stocks with the major effect being the changes in biomass produced as a result of the rainfall rather than the rainfall itself.

3.1.3 DISCUSSION

Findings from FullCAM regarding clay-modified soils has indicated:

- it provides a realistic modelling of soil OC levels;
- limitations of the model are that clay content assumes even distribution within a soil;
- soil OC pools and the amount of biomass input are both sensitive to increasing carbon OC stocks; and
- there is limited information regarding the level of carbon stored in the different soil OC pools in South Australian sandy soils.

Carbon pools are relatively sensitive to OC changes in OC stocks, therefore it is critical to ensure that the starting levels of the different pools are as accurate as possible. This appears to be the largest gap in South Australian current knowledge with only limited information available about different carbon pools for the state's sandy soils. Currently data from Western Australia is used (Janik *et al.* 2007).

Fractionation of the different carbon pools on a range of South Australian soils is a high priority, however the cost of doing this is relatively high.

Additional analysis using FullCAM is required to further assess the impact of rainfall and biomass input from various sites throughout South Australia on OC stocks.

Table 8. Summary of main components of reviewed soil carbon models.

Model	Model origin	Time step	Model modules/sub models	Missing model	Model parameters
APSIM	Australia	Daily	Modules include a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls. Crop growth Water budget Nitrogen budget Soil organic matter budget	Clay content	Drained Upper and lower soil limit – depend on bulk density and clay concentration Soil organic carbon content SOIL N is the module that simulates the mineralisation of nitrogen and thus the nitrogen supply available to a crop from the soil and residues/ roots from previous crops. Soil nitrogen content – impact on C Temperature, evaporation and rainfall
Century	United States	Monthly	Soil organic matter Nitrogen, phosphorus and sulphur dynamics Water budget Grassland/crop Forest production		Generalised plant-soil ecosystem model that simulates plant production, soil carbon dynamics, soil nutrient dynamics, and soil water and temperature. Soil nutrient cycling and soil organic matter dynamics are represented in great detail, while plant growth is represented using relatively simple sub-models. The major input variables include: 1) monthly precipitation, 2) monthly average maximum and minimum air temperature, 3) soil texture, 4) lignin, nitrogen, sulphur and phosphorus content of plant material and 5) soil and atmospheric nitrogen inputs.
Roth-C	United Kingdom	Monthly	Turnover of organic carbon Clay content Temperature Moisture content	Crop growth	Clay content – has little impact on OC stocks Biomass production – increases with increasing clay content, which has a large impact on OC stocks
FullCAM	Australia	Monthly	CAMFor – OC mass and transfer in forests CAMAg – impact of management on OC accumulation and pools Roth-C. – calibrated for Australian conditions	Crop growth and yields	
HPx	Belgium/USA	Daily	HYDRUS 2D/3D– flow transport PHREEQC-3 - biogeochemistry		Rainfall, temperature and evaporation Nitrogen Microbial activity Organic carbon The Flow equation incorporates a sink term to account for water uptake by plant roots. Inputs - unsaturated soil hydraulic properties comprising the water retention curve (or soil moisture characteristic) and the hydraulic conductivity function The Heat transport equation considers conduction as well as convection with flowing water. The Solute transport equations consider advective-dispersive transport in the liquid phase, and diffusion in the gaseous phase. The transport equations also include provisions for nonlinear and/or nonequilibrium reactions between the solid and liquid phases, Inputs - dispersivities, diffusion coefficients in the liquid and gaseous phases) and reaction (sorption and degradation) parameters

3.2 HYDRUS

The effect of clay clod size on productivity of sandy soils has received little attention in the literature, although it can be reasonably assumed that water and temperature distribution, water holding capacity, root growth and fertiliser delivery to roots, and organic carbon turnover all depend to some degree on the size of clay clods. Jacques *et al.* (2017), used a coupled multi-component reactive transport model and demonstrated strong seasonal fluctuations in various pools of soil organic matter and biomass across a soil profile due to variations in soil water contents and temperatures. Because of the large differences in soil hydraulic functions and heat transfer properties between clay and sand, the water and temperature distribution in a soil with large textural contrasts will likely be large too.

The objective of this study was to numerically simulate the soil water balance components for vegetated soil where clay amelioration has occurred (to a depth of 40 cm) using two sizes of clay clods 5 and 10 cm. These simulations were to illustrate whether or not the size of clay clods has any material effect on the water balance component, and in particular on crop transpiration and therefore crop yield.

3.2.1 METHOD

Numerical modelling using HYDRUS (2D/3D) was used to provide insight into the interrelationship between soil water redistribution following rainfall, soil evaporation and root water uptake of a sandy profile into which clay clods had been incorporated. A two-dimensional variably-saturated flow model was used with two clod sizes (5 and 10 cm-diameter) incorporated in the top half of the soil profile, with identical cross-sectional area occupied by the small (44 in total) and large (11 in total) clods (Figure 12).

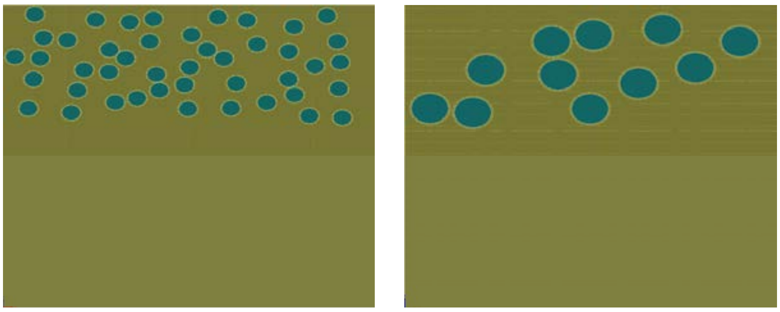

Figure 12. Soil model with 44 5-cm-diameter (left) and 11 10-cm-diameter (right) clay clods randomly distributed in the top of a 1×1 m2 sandy soil.

Two soil hydraulic functions were used, one for sand and one for clay (Table 9). The sand represents the top soil while the clay is used to represent clay clods that were added to the top soil layer to improve the soil water holding capacity. The hydraulic parameters were based on data reported by Betti *et al.* (2016) that focused on how the size of subsoil clods affect the soil-water availability in sand-clay mixtures.

Calculations were based on one dry and one wet climatological year. Based on the Mount Gambier Aero Climate station, the year 2015 was chosen as the dry year and 2016 as the wet year[10].

Simulations were carried out for a total of 365 days, where each clod size model considered two different top boundary conditions (dry and wet). i.e. with an infiltration rate of 50 and 400 mm/year.

[10] Note that (1) 2015 was a very dry year with total annual rainfall slightly higher than the 5th percentile (512 mm), and (2) 2016 was a very wet year, with total annual rainfall slightly higher than the 95th percentile (901 mm) based on a time series from 1942 till 2017 (Bureau of Meteorology 2017)

Table 9. Soil hydraulic properties for sand and clay soil.

Material	Soil	θs [cm³/cm³]	θr [cm³/cm³]	α [1/cm]	n [-]	Ks [cm/day]	l [-]
1	Sand	0.0430	0.354	0.0287	2.664	449	0.5
2	Clay	0.250	0.551	0.0284	2.689	0.0613	0.5

3.2.2 RESULTS

Under the wet climatic conditions, characterised by a total annual rainfall of 907 mm and potential evapotranspiration of 1302 mm, both small and large clay clods display a low pressure head that was sufficient to cause the root water uptake to become virtually zero. This means that water uptake by plant roots only occurs in the sandy soil. A larger number of smaller zero-uptake zones is thought to have a less negative impact on plant growth and yield than fewer larger-scale zero-uptake zones typical of large clay clods. In such soil, pore-water velocities display a characteristic pattern, with heterogeneities in the flow field that are more localised for the large clods whereas they are more uniformly distributed for the small clods. The calculated water balance components, such as actual transpiration and drainage, are very similar for a sandy soil with small or large clay clods.

Under a dry climate, characterised by a total annual rainfall of 527 mm and potential evapotranspiration of 1305 mm, the general pressure head pattern for both small and large clods is similar: a dry sandy soil with a relatively uniform pressure head of approximately -110 cm. The equilibrium pressure head h adjusts until the unsaturated hydraulic $K(h)$ conductivity equals the infiltation rate i, while pressure head further adjusts according to the root water uptake. The clay clods have a significantly lower pressure head, with minimal values in the range -8,000 to -10,000 cm. Under such conditions, the root water uptake function in the all clay clods is effectively zero. The main differences between the two clods sizes is that there are more connected flowpaths exhibiting higher velocities for the small clods than for the large clods.

3.2.3 DISCUSSION

The simulated pressure head pattern for both small and large clods was similar: a dry sandy soil with a relatively uniform pressure head, with the clay clods having a significantly lower pressure head, with minimal values in the range -8,000 to -10,000 cm.

As a result, the root water uptake function in the all clay clods is effectively zero. The main differences between the two clods sizes is that there are more connected flow-paths exhibiting higher velocities for the small clods than for the large clods. Water balance components transpiration and drainage are similar for both small and large clods.

Further research is required to assess the impact of the nature of connected flowpaths on the migration of solutes (e.g. fertilisers or pesticides) within the soil profile and whether clod size affects the efficacy of such agrochemicals. Also, boron-containing clay clods may release boron over time which may affect plant health; the rate at which this occurs is currently unknown, but can be readily evaluated with the HYDRUS (2D/3D) model developed here. Finally, both soil temperature and soil water availability affect organic carbon turnover. The effect of clay addition on soil temperature distribution warrents further investigation, with a need to couple the carbon cycle with the spatio-temporal distribution of soil temperature and water content in a 2D model. The coupled HYDRUS (2D/3D) - PHREEQC model is currently the only existing model that is able to simulate these coupled processes

3.3 Nitrous Oxide Models

Nitrous oxide (N_2O) is a greenhouse gas with over 300 times the global warming potential of carbon dioxide. Around 60% of Australia's total nitrous oxide emissions come from soils associated with agricultural production (Department of Agriculture 2013). The primary sources of nitrous oxide emissions from agriculture are associated with the use of nitrogen and urea based fertilisers and intensive livestock production systems. Nitrous oxide from the agricultural sector represents around 80% of Australia's total greenhouse gas inventory and of this, 73% is emitted from agricultural soils (Dala *et al.* 2003). Dala *et al.* (2003) states that nitrous oxide emissions from agricultural soils come from nitrogen fertilisers (32%), soil disturbance (38%) and animal waste (30%).

Minimising nitrous oxide emissions from farms is critical to: i) conserve as much nitrogen in the farming system as possible (for plant growth); and ii) limit contribution to greenhouse gas emissions.

Nitrous oxide emissions from soils can be measured in a number of different ways, including through the use of open path lasers, flux towers, automated or on-ground continuous flow atmospheric monitoring systems and non-automated chambers or 'manual chambers'. However these methods are often very expensive (e.g. open path lasers, flux towers) and/or labour intensive (e.g. nonautomated chambers). Other methods to determine nitrous oxide emissions from soils include the use N_2O emission models or calculators.

The use of calculators to determine nitrous oxide emissions may present an opportunity to determine emissions with reduced capital expense and labour intensity compared to 'real time' measurements. A comparison of calculated data with 'real time' data is required to verify apparent usefulness. This report presents these comparisons for two farming properties on Eyre Peninsula.

Following determination of the merit of using calculators to determine nitrous oxide emissions, their apparent usefulness can be determined in situations where clay modification may occur, and be compared to other findings.

3.3.1 NITROUS OXIDE CALCULATOR COMPARISON

A number of N_2O emission calculators have been developed:

- Farming Enterprise Greenhouse Gas Emissions Calculator (Queensland University of Technology) – developed for use only in Queensland.
- United States Cropland Greenhouse Gas Calculator (Michigan State University Board of Trustees 2017) - developed for use in the United States of America.
- Global Nitrous Oxide Calculator (European Union 2014) – developed for calculation of emissions globally.
- Grains Greenhouse Accounting Framework v 9.1 (Eckard and Taylor 2016) – developed for calculating of emissions in Australia.

The first two emission calculators were not investigated further as they have limited relevance to South Australian scenarios. The last two nitrous oxide emission calculators -were compared in May-June 2017.

Global Nitrous Oxide Calculator (GNOC)

This web-based tool allows calculation of soil N_2O emissions from locations globally. The tool was designed for default emissions from biofuel crops but has been used in analysis of data from soil modification trials on Eyre Peninsula (Eyre Peninsula NRM Board 2017). GNOC allows the user to select the exact site using either co-ordinates or a global map and has default environmental and management data for the selected location. However, these parameters can be changed if local data is available (see Table 10 for overview). Emissions are calculated for Total soil N_2O emissions and a range of other parameters (Table 10).

Greenhouse Accounting Framework (GAF)

The Greenhouse Accounting Framework[11] (GAF) (Greenhouse in Agriculture 2017) uses the Australian National Greenhouse Gas Inventory method to predict the magnitude and sources of Greenhouse gases from a farm for diary, beef, sheep, feedlots or grain farms. For this discussion paper, only the Grains/Cropping Accounting Framework (G-GAF) (Eckard and Taylor 2016) was considered.

The G-GAF calculates greenhouse emissions of carbon dioxide, methane and nitrous oxide for a whole, grain-producing farm. This model appears to be simpler than the GNOC model but does not allow for modification of climate, soil type or organic carbon level variables (see Table 10 for overview). However, the G-GAF does account for energy use from diesel, natural gas and electricity in accordance with Australian National Greenhouse Gas Inventory method.

Table 10. Comparison of parameters and outputs from Global Nitrous Oxide Calculator (European Union 2014) and Grains Greenhouse Accounting Framework (Eckard and Taylor 2016) N_2O emission models.

Parameter	Global Nitrous Oxide Calculator	Grains Greenhouse Accounting Framework
Location	Actual location can be entered	Region based by state and zone based on rainfall
Crop type	Up to 16 available, however some parameters have limited application in Australia e.g. oil palm fruit with soya beans being the only pulse crop option	Up to 16 crop types available
Crop Area	Per hectare	Actual area of each crop grown
Soil type	Options: organic; mineral	Not available
Irrigation	Options: yes; no	Options: Non-irrigated crop; Irrigated crop
Biomass	Actual measurement can be entered	Not available
Grain yield	Not available	Actual measurement can be entered
Mineral fertiliser	Actual measurement can be entered	Actual measurement can be entered
Manure	Actual measurement can be entered	Not available
Soil pH	3 options: <5.5; 5.5-7.3; >7.3	Not available
Soil Organic C (%)	3 options: <1; 1-3; >3	Not available
Soil Texture	3 options: Coarse; medium; fine	Not available
Leaching	Options: Yes/No	Not available
Outputs	Total soil N_2O emissions Direct N_2O emissions from fertiliser application Direct N_2O emissions from drain/managed organic soils Indirect N_2O emissions produced from leaching and runoff from fertiliser application Indirect N_2O emissions producer from atmospheric deposition of N volatized N_2O Above-ground residue dry matter Annual amount of N in crop residue N input from sugarcane vignasse [a product of ethanol production] and filtercake [a byproduct of sugar cane processing] Direct N_2O emissions from N in crop residues Indirect N_2O emissions produced from leaching and runoff N in crop residues	CO_2 -Energy CO_2 -Lime CO_2 - Urea Application CH_4 - Field Burning CH_4 - Energy N_2O - Fertiliser N_2O - Crop residues N_2O - Atmospheric deposition N_2O - Leaching and Runoff N_2O - Field Burning N_2O - Energy

[11] Greenhouse Accounting Frameworks have been developed for Australian Dairy, Sheep, Beef or Grain Farms

Calculator comparison example 1 – Cockaleechie

For this example, a 1000 ha cropping property situated on Lower Eyre Peninsula in ~550 mm rainfall area was used. A summary of factors used in the nitrous oxide calculator are summarised in Table 11. A comparison of nitrous oxide emissions calculated are summarised in Table 12.

Total nitrous oxide emissions, calculated using GNOC and G-GAF, differed by ± 2.06 t CO_2-e/ha. The GNOC estimated a total crop emissions of 2.71 t CO_2-e/ha, compared with the G-GAF calculator which estimated total crop emissions of 0.65 t CO_2-e/ha.

The calculated nitrous oxide emissions for Cockaleechie, are comparable to the results from trials in wheat grown in rotation with canola, pulses and legume pastures on Eyre Peninsula (SARDI 2015), where emissions ranged from 2.25-5.7 N_2O-N/ha/day (equivalent to 0.38-0.97 t CO_2-e/ha).

Calculator comparison example 2 – Kyancutta

The property is a 3500 ha mixed wheat/sheep property on Central Eyre Peninsula in 310 mm rainfall area. A summary of factors used in the nitrous oxide calculator are summarised in Table 13. A comparison of nitrous oxide emissions calculated are summarised in Table 13.

Table 11. Summary of factors used in nitrous oxide emission calculators for property at Cockaleechie. Information sourced from landholder and peak biomass crop cuts.

Crop type	Area of crop (ha)	Crop yield (t/ha)	Crop peak biomass (t/ha)	Nitrogen fertiliser application (kg N/ha)
Wheat	300	3.5	8.75	120
Barley	300	4.0	10.00	127
Canola	150	1.6	5.33	12
Pulses	150	1.5	5.00	9

Table 12. Comparison of calculated nitrous oxide emissions for property at Cockaleechie

Global Nitrous Oxide Calculator	Grains Greenhouse Accounting Framework
Wheat = 1.76 kg N_2O-N /ha Barley = 1.90 kg N_2O-N /ha Canola = 1.72 kg N_2O-N /ha Pulses = 0.46 kg N_2O-N/ha	Emissions not calculated for individual crop types
Total N_2O crop emissions 2.71 t CO_2-e/ha	Total N_2O crop emissions 0.65 t CO_2-e/ha

Total nitrous oxide emissions, calculated using GNOC and G-GAF returned similar values. The GNOC estimated a total crop emissions of 0.27 t CO_2-e/ha, compared with the G-GAF calculator which estimated total crop emissions of 0.10 t CO_2-e/ha.

Table 13. Summary of factors used in nitrous oxide emission calculations for property at Kyancutta. Information sourced from landholder and peak biomass crop cuts.

Crop type	Area of crop (ha)	Crop yield (t/ha)	Crop peak biomass (t/ha)	Nitrogen fertiliser application (kg N/ha)
Wheat	1450	1.5	3.75	30
Barley	350	1.5	3.75	30

Table 14. Comparison of calculated nitrous oxide emissions for property at Kyancutta

Global Nitrous Oxide Calculator	Grains Greenhouse Accounting Framework
Wheat 0.29 kg N_2O-N/ha Barley 0.30 kg N_2O-N/ha	Emissions not calculated for individual crop types
Total N_2O crop emissions 0.27 t CO_2-e/ha	Total N_2O crop emissions 0.10 t CO_2-e/ha

The calculated nitrous oxide emissions for Kyancutta are comparable to those of Ferrier and Wallace (2014), who reported peak emissions ranging from 2-3 g N_2O-N/ha/day (equivalent to 0.34-0.51 t CO_2-e/ha) from barley crops north of Booleroo Centre (annual average rainfall 320 mm pers. comm M Wurst August 2017); and results in wheat grown in rotation with canola, pulses and legume pastures at Minnipa (annual rainfall 285 mm) where 0.5-1.34 g N_2O-N/ha/day (equivalent to 0.09-0.23 t CO_2-e/ha) were recorded. These measurements were aimed to capture maximum N_2O-N emissions, being conducted immediately following nitrogen application and rainfall, therefore average emissions are likely to be much lower.

Summary

Comparison of the calculators with real time data from two properties on Eyre Peninsula has shown that calculated emissions are similar to those measured in real time. However, further comparison between nitrous oxide calculators and real time measurement of nitrous oxide emissions is warranted before final conclusions can be drawn.

Limitations/unknowns of calculators

Soil modification scenarios

Calculators do not have parameters for clay percentage, however GNOC has soil texture which could be used as a surrogate. The parameters are however unlikely to be small enough to allow for clay modification.

Where calculating N_2O emissions as a result of clay modification plus the incorporation of organic matter, the calculators are limited in the following ways:

- Nitrogen ratio in organic matter – if samples of organic matter are not tested for nitrogen content before incorporation, the nitrogen ratio of the organic matter needs to be determined based on feed test data which has been published such as *Feeding Sheep in Dry times* (State of Western Australia 2006)
- Following the incorporation of organic matter, the period of time for the material to break down is generally unknown, in many circumstances it can be assumed that the period for fine materials is less than 12 months.
- The depth to which organic matter is incorporated is an important factor, particularly if organic matter does not break down before the following years seeding operations. The organic matter incorporation depth is important as subsequent seeding operations may disturb organic matter thus releasing N_2O emissions.
- The GNOC model is reliant on 'peak biomass' measurements, therefore timing of biomass cuts are critical, otherwise estimations of peak biomass will need to be determined through programs such as Pastures from Space (CSIRO 2014) or similar.

Pasture phases

Both models do not easily account for crops with a pasture phase, however GAF does have models for Australian dairy, sheep and beef.

Other factors

Other considerations:

- GNOC does not calculate CH_4, CO_2 emissions
- G-GAF model is very sensitive to annual rainfall particularly at <600 or >600 mm
- GNOC has limited crop types relevant to Australian conditions

3.3.2 CALCULATING NITROUS OXIDE EMISSIONS FOLLOWING SOIL CLAY-MODIFICATION

Comparisons of the two nitrous oxide calculators GNOC and G-GAF in Table 10, ascertained that neither calculator had a parameter to account for changes in clay percentage. Only the GNOC has a parameter for soil texture which may be used as a surrogate for clay percentage.

The calculator has three options: coarse (< 18% clay), medium (18 to 35% clay) and fine (> 35% clay), and a corresponding effect value summarised in Table 15. An example of the effect of soil texture parameters on nitrous oxide emissions from a wheat crop grown (as summarised in 'Calculator comparison example 2 – Kyancutta'), and employing the three parameter classes for soil texture is presented in Table 16.

Following clay-modification activities where soils result in $\geq$18% clay (classed as medium soil texture), the change in nitrous oxide emissions is a small reduction (-0.11 t CO_2-e/ha) (Table 16). It is highly unlikely that the soils would achieve >35% clay, and this scenario is not further explored.

Table 15. The parameter class and definitions (based on topsoil properties: 0 – 30 cm depth) and effect values for soil texture.

Parameter class	Effect value
Coarse - sands, loamy sands and sandy loams with less than 18 percent clay and more than 65 percent sand	0
Medium - sandy loams, loams, sandy clay loams, silt loams, silt, silty clay loams and clay loams with less than 35 % clay and less than 65 % sand; the sand fraction may be as high as 82 percent if a minimum of 18 percent of clay is present.	-0.1583
Fine - clays, silty clays, sandy clays, clay loams and silty clay loams with more than 35 percent clay.	0.4312

Table 16. Effect of soil texture parameter class on nitrous oxide emission calculations for a wheat crop grown at Kyancutta.

Parameter class	Total N_2O crop emissions (kg N_2O-N/ha)	Total N_2O crop emissions (t CO_2-e/ha)
Coarse	1.76	0.82
Medium	1.53	0.71
Fine	2.62	1.22

The changes in nitrous oxide emissions following activities aiming at increasing soil organic carbon through clay-modification or addition of organic matter, have had limited focus in Australia, particularly in the temperate cropping regions. One such study near Dalwallinu, Western Australia (annual rainfall 291 mm), Barton *et al.* (2016) found cumulative soil nitrous oxide emissions from a coarse-textured soil (free draining sand), increased by at least 10-fold as a result of increasing soil organic matter, which was consistent with the results from other climates. e.g. Stehfest and Bouwman (2006) and Lehtinen *et al.* (2014). However, these findings are in contrast to calculated nitrous oxide emissions which found a small reduction in nitrous oxide emissions as a result of changing clay percentages in soils. The two differing approaches to increasing soil carbon may account for this discrepancy.

Increasing soil organic matter and percentage clay also increases the availability of nitrogen and carbon to soil microorganisms that carry out the denitrification process. However, the levels of emissions are likely to be relatively low for most modified agricultural soils, for example at Buntine, Wester Australia (0.0.2-0.16 kg N_2O-N/ha/year) (Barton *et al.* 2016).

Summary

Initial investigations into the effect of increasing soil organic carbon through clay-modification or addition of organic matter on nitrous oxide emissions are unclear. Further investigation is recommended despite the likelihood that nitrous oxide emissions will be relatively low for most modified agricultural soils. This is particularly important when assessing the effectiveness of soil carbon sequestration to abate greenhouse gas emissions.

4 Gap Analysis and recommendations

Objective: To collate information to produce a conceptual model of important factors affecting carbon processes in clay-modified soils and provide a road map for a next steps process

This project has identified that the addition of subsoil clay to sandy topsoil increased soil organic carbon stock when compared to unmodified sandy soil. Important factors and processes were identified that can maximise OC stock in clay-modified soil. The comparison of theoretical OC stock opportunity against measured data highlights the need to refine the measured dataset to sites with best practice management to refine estimates of OC stock opportunity. This will enable identification of rainfall zones and soils with the greatest opportunity for increased OC stock with the additions of clay.

The project compared sites with substantial variation in factors such as subsoil clay properties, clay application methods, management practices (such as crop rotation, fertiliser application) and seasonal influences that were not possible to capture in this analysis but likely to affect OC stock. To confidently monitor OC stock over time, comparisons ideally would be made on sites that have been treated in the same way with replication and repeated measurements over time. However, there are very few established clay-modified sites with multiple treatments that also include an unmodified ‘nil’ for comparison. Such sites were sampled during 2015 and 2016 and their data included in this project[12], although it is difficult to calculate temporal changes in OC stock as these sites have only been sampled twice. This lack of temporal OC data also makes it difficult to determine if clay-modified sites have reached OC equilibrium or are able to store additional OC.

The analyses of existing carbon data and evaluation of carbon models highlight the importance of understanding clay clod size and distribution within the profile, and the impact on factors affecting soil OC and plant growth. Factors of interest that require further investigation include impact of clay clod on soil temperature, moisture, nutrient, biological activity and rate of turnover of OC. There is a critical lack of knowledge regarding the effect of clay modification on OC pools and decomposition rate which are essential for accurate carbon modelling using FullCAM. Both direct measurement and modelling (using HYDRUS (2D/3D) - PHREEQC to couple the carbon cycle with spatio-temporal distribution of soil temperature and water content) of these factors are essential. Modelling may also distinguish measured soil chemical changes in clay-modified soil into those attributed to the addition of: i) chemicals with the subsoil clay; and ii) those from applied fertiliser or other practice due to increased cation exchange capacity.

There is uncertainty as to the magnitude of emissions resulting from clay modification with or without organic matter or how these emissions will be assessed in the new ERF agricultural soils method. The new method allows for the use of proximal sensors instead of laboratory analysis which could make OC verification more economic and likely to be adopted. However, proximal sensors would need to be tested and verified in clay-modified soils prior to widespread use to ensure the reliability of OC predictions.

Gaps in knowledge identified in this project are summarised in Figure 13.

[12] With the exception of the PIRSA/DEW/GRDC New Horizons Sandy Soil trial sites. The sites have been sampled for OC at the implementation of the project in 2014 and are anticipated to be re-sampled in late 2018 or early 2019, five growing seasons after clay modification. The unmodified Nils have been included in this project.

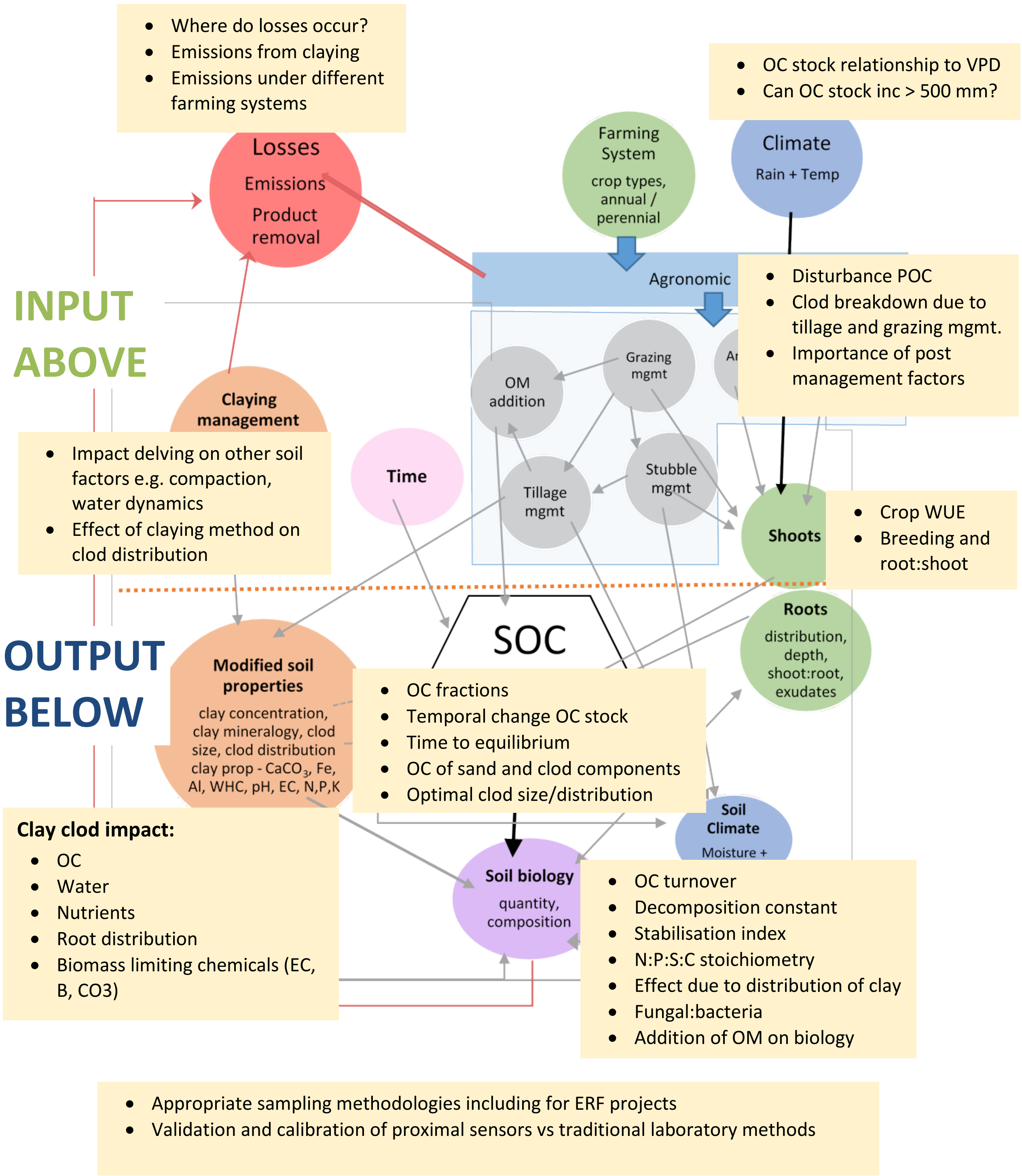

Figure 13. Gaps in analysis overlaying the conceptual model for processes that affect soil OC in clay modified soils. Gaps in analysis highlighted in yellow boxes. The full conceptual model is shown as Figure 1.

5 Literature review

5.1 Background

Organic carbon (OC) is essential for a number of soil physical, chemical and biological processes (Baldock and Skjemstad 1999) and is strongly associated with soil health and plant productivity (Hoyle 2013). Soil OC also plays a role in offsetting atmospheric carbon dioxide (CO_2) emissions that are contributing to climate change (IPCC 2001). Soils are recognised as the largest terrestrial sink for carbon, holding three times the amount stored in vegetation and twice as much as that present in the atmosphere (Batjes 1996). For carbon sequestration to occur, there needs to be transfer and storage of carbon from the atmosphere to the soil. Soil can act as both a sink and source of OC. Agricultural management disrupts the natural soil OC and nutrient cycling balance causing a decline in the OC of agricultural soil (Lal 2004). The potential of agricultural soils to sequester OC has been widely debated with concern about the: ability to store additional OC (Powlson *et al.* 2011); rate at which soil OC can accumulate (West and Post 2002); concept of OC saturation (Canadell *et al.* 2007) and equilibrium (Jenny *et al.* 1949); and longevity of OC sequestered in soil (Johnston *et al.* 2009).

Globally, most agricultural ecosystems have lost 40 to 70% of their natural soil OC (Lal 2007). It is crucial to identify and implement practices that minimise or reverse the decline in soil OC (Macdonald *et al.* 2013), whilst balancing economic sustainability and global food needs. Restoring some of this OC is an opportunity for sequestration (McCarl *et al.* 2007) and under intensive agricultural practices, sequestration rates of 0.3 - 0.5 t C ha^{-1} yr^{-1} of OC are possible (Lal 2007). It is estimated that cropped soils will take 20-30 years before OC saturation occurs and a new equilibrium is reached (Minasny 2017, Sommer and Bossio 2014).

Given the highly weathered soils and often harsh and dry climate across much of Australia's cropping region, findings from more temperate northern hemisphere trials should be viewed with caution (Kirkegaard 1994). A review by Sanderman *et al.* (2010) established that under Australian conditions, conversion of native land for agriculture has resulted in 40 to 60% loss of soil OC. Under improved management of cropland (such as improved rotation, adoption of no-till or stubble retention) compared to conventional management, sequestration rates of 0.2-0.3 t C ha^{-1} yr^{-1} can be expected. Furthermore, Sanderman *et al.* (2010) state that the greatest theoretical potential for carbon sequestration within existing agricultural systems will likely come from large additions of organic materials (manure, green wastes, biochar), maximising pasture phases in mixed cropping systems, shifting from annual to perennial species in permanent pastures, with the greatest gains expected from more radical management shifts, such as conversion from cropping to permanent pasture and retirement and restoration of degraded land.

The addition of clay to sandy soils also has the potential to increase soil OC storage through improved plant growth (above and below ground) and increased stabilisation by binding to clay.

This literature review discusses factors that affect OC storage in agricultural soil, identifies those that are important under Australian conditions and the influences these have on soil OC. Comparison of sandy soil and sandy soil with subsoil clay addition properties leads to a discussion of the OC and clay content and distribution in clay-modified soils, and the factors that influence OC storage in these soils. Research gaps are identified and next steps are outlined.

5.2 Factors affecting soil OC storage – existing literature

Soil carbon is present in both inorganic (IC) and organic (OC) forms in soil. IC is mineral-based, derived from lithogenic and pedogenic processes, relatively stable and with the exception of liming, not strongly influenced by land management practices. IC is not included in calculations for carbon sequestration. OC is the carbon associated with soil organic matter (OM) and ranges between 40-60% of OM by weight (Chan 2008). Soil OM includes all living and non-living organic material in the soil (Baldock and Skjemstad 1999) such as plants, soil fauna, microbial biomass and plant residues. OC can be influenced by land management practices and is the form of carbon used to calculate sequestration.

OC plays a critical role in the soil, creating aggregates of soil particles, stabilising structure, increasing water infiltration and overall water holding capacity, storing and releasing nutrients and improving cation exchange and buffering capacity (Baldock 2007, Hoyle 2013, Krull *et al.* 2004). Accordingly, increasing soil OC is not only important for carbon sequestration but also for improved land management, fertility, water use efficiency, productivity (Chan *et al.* 2003, Lal 2004, Liddicoat *et al.* 2010, Sanderman *et al.* 2010), reduced erosion and increased resilience against the impacts of climate change (Paustian *et al.* 2016).

The amount of OC in soil is the balance between the rates of input (plant residue, composts or manures) and output (CO_2 release as a result of microbial decomposition, leaching and soil erosion). There are a number of factors that individually or in combination affect the total amount and distribution of OC in the profile, including soil type, climate, topography and soil biota (Krull *et al.* 2004).

Ingram and Fernandes (2001) grouped factors influencing soil carbon storage into potential, attainable and actual. Potential storage is determined by the soil type factors, including: clay content (potential is greater for clay than sandy soils); mineralogy (high cation exchange capacity and presence of multivalent cations such as calcium, aluminium and iron enhances C sequestration); soil depth (OC decreases with depth); and bulk density. Attainable storage is determined by environmental factors (climate and solar radiation) that affect plant production. Actual storage is determined by management practices that increase inputs or decrease losses. Optimising management practices will allow OC storage to increase up to but not beyond the attainable storage because of limitations affecting plant productivity. Thus, the only way to further increase OC is to permanently change the soil type, alter plant productivity through efficient use of resources such as water and/or regularly add an external source of carbon. However, for long-term storage, any OC added to the soil must be stabilised, as OC added beyond the protective capacity of the soil's clay component will be more susceptible to decomposition (Krull *et al.* 2001).

Stabilisation of soil OC can be defined as any process that slows the decomposition process (Sanderman *et al.* 2010). The processes can be divided into two categories (Six *et al.* 2002, Lützow *et al.* 2006):

1. spatial inaccessibility of OC to microbes and enzymes through: protection via soil aggregation (Six *et al.* 1999, Six *et al.* 2002, Tisdall and Oades 1982); storage in pores too small for most bacteria and fungal hyphae (Van Veen and Kuikman 1990); sparse and variable distribution of microbes and enzymes in the soil (Young *et al.* 2008, Ekschmitt *et al.* 2008); and hydrophobicity of OC as a result of partial degradation (Dal Ferro *et al.* 2012, Bachmann *et al.* 2008).
2. restricting access of microbes and enzymes by interaction of OC with minerals, metal ions and other organic substances involving sorptive reactions with mineral, complexation and precipitation with polyvalent metals (Denef *et al.* 2001a, 2001b, Fernández-Ugalde *et al.* 2011, Lutzow *et al.* 2006, Rakhsh *et al.* 2017, Saidy *et al.* 2012, Six *et al.* 2004, Sanderman *et al.* 2010).

Stabilisation mechanisms of OC differ in longevity according to: 1) soil biochemical recalcitrance (a few years to decades); 2) physical inaccessibility (decades to centuries); and 3) organo-mineral and organo-metal interactions (centuries to millennia) (Kögel-Knabner *et al.*, 2008). However, any change of land use (e.g. cropping to pasture) alters the OC balance and attaining a new equilibrium can take 25 (Alvarez, 2005) to more than 50 years (Baldock and Skjemstad 1999).

5.2.1 AUSTRALIAN CLIMATE AND ENVIRONMENTAL CONDITIONS

In Australia, soil OC stock varies greatly across the continent (Minansy *et al.* 2017), ranging in the surface 30 cm from less than 10 t ha^{-1} in arid regions to 250 t ha^{-1} in cooler and wetter regions in natural ecosystems (Luo *et al.* 2010). Water availability has a major influence on OC stock in Australia, where both the total amount and distribution of annual rainfall is important (Hobley and Wilson 2016). Average annual rainfall varies between 100 mm to 3000 mm (Figure 1), but over 80% of Australia has rainfall below 600 mm with 50% below 300 mm (ABS 2012). Seasonal rainfall results in different rates of relative OC input and loss in wetter and drier months (Hobley and Wilson 2016). Higher OC stocks are often associated with higher spring and summer rainfall (Orgill *et al.* 2017). Where water availability is limiting, biomass production is reduced, affecting OC input into soil. In contrast, where water is not limiting, radiation, temperature (Wynn *et al.* 2006) and land use (Bui *et al.* 2009) regulate biomass production. Biomass decomposition is controlled by temperature and water availability and largest changes occurred where total annual rainfall is between 400 to 600 mm (Luo *et al.* 2010). OC decreases with soil depth and different factors affect OC in the surface and subsoil (Hobley and Wilson 2016). Environmental and management factors strongly influence OC in the surface 10 cm with soil type and water availability more influential below 20 cm (Badgery *et al.* 2013, Hobley *et al.* 2015). Soils with no limitation to water availability had higher OC below 10 cm than areas with seasonal rainfall or those from warmer, drier climates (Hobley and Wilson 2016). The dominating effects of climate and soil type may make modest changes in OC stock due to management factors difficult to detect (Orgill *et al.* 2017).

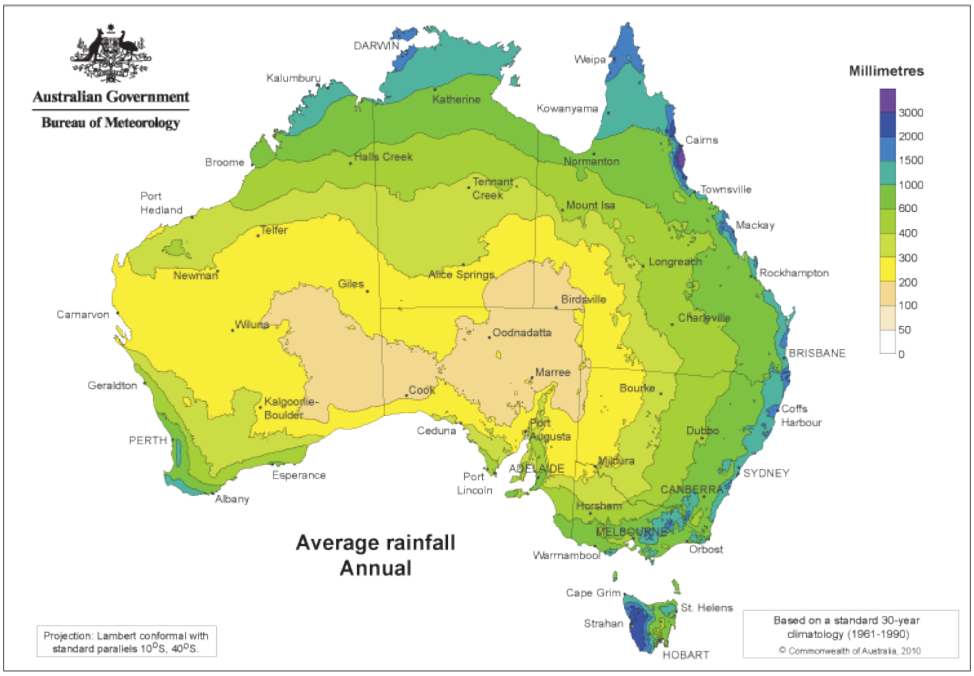

Figure 14. Average annual rainfall (mm) for Australia based on climatology 1961-1990. Bureau of Meteorology.

Early studies on soil OC under Australian cropping conditions identified the importance of conservation tillage (e.g. no-till with stubble retention) versus conventional tillage (Valanzo *et al.* 2005). However, no differences in OC were found in areas with rainfall below 500 mm because of limitations to biomass production (Chan *et al.* 2003). Under grazing, pasture improvements including fertilisation, liming, irrigation and sowing of more productive grass varieties, generally resulted in sequestration rates of 0.1 – 0.3 Mg C ha^{-1} yr^{-1} with larger gains of 0.3 – 0.6 Mg C ha^{-1} yr^{-1} after conversion of cultivated land to permanent pasture (Sanderman *et al.* 2010).

The Soil Carbon Research Program coordinated research across Australia to define realistic and scientifically robust carbon sequestration options for agricultural soil (Baldock *et al.* 2013). In south-eastern Australia the opportunities to store additional OC in the soil is less than the opportunities for loss where low winter-dominated rainfall and high temperatures make biomass production unpredictable (Davy and Koen, 2013). In sandy Western Australian soil, limited capacity for OC storage was identified where rainfall was below 551 mm and air temperature above 17.2˚C (Hoyle *et al.* 2016).

Where water availability was limiting, there was no to little difference in OC between management practices and it was concluded that conservation tillage (minimum tillage and stubble retention) may at best slow the rate of OC loss (Cotching *et al.* 2013, Davy and Koen, 2013, McLeod *et al.* 2013), but in doing so can still have a positive contribution to reducing greenhouse gas emissions (McLeod *et al.* 2013). However, the long-term use of multiple practices such as stubble retention, zero tillage, legume rotations and elimination of fallow may lead to increases in OC (Robertson et al 2015) and are likely to be adopted as long as they maintain or increase plant productivity and are economically sustainable (Cotching *et al.* 2013).

Increasing OC input through management practices is essential for increased OC but long-term storage is only possible with transformation to more stable OC fractions. Transformation of particulate OC (POC) into more stable forms of humus OC (HOC) and resistant OC (ROC) is essential for long term OC storage as the less stable forms are more quickly lost from the soil following disturbance (McLeod *et al.* 2013). HOC increased with depth and was influenced by soil texture, whereas POC decreased with soil depth and was influenced by management and climate factors (Davy and Koen 2013, Hoyle *et al.* 2016). In South Australian red brown earths, HOC was higher under cropping than mixed crop and livestock systems which may be explained by the higher fertiliser inputs required in a cropping system enabling transformation from POC to HOC (Macdonald *et al.* 2013).

With a changing climate, identification of management practices that minimise or reverse the decline in soil OC remains a major challenge for sustainable agricultural productivity (Macdonald *et al.* 2013).

5.3 Addition of clay to sandy soil

The potential of a soil to store more OC depends on OC inputs exceeding outputs; conversion of inputs to more stable forms of OC; and the capacity of the soil to store the new OC (Davy and Koen 2013). The amount of stored OC varies among soil types (Hoyle *et al.* 2013) and is strongly influenced by clay concentration (Rakhsh *et al.* 2017). In natural soils, there is a positive correlation between clay and OC concentration (Baldock and Skjemstad 1999, Dalal and Mayer 1986), largely due to the soils' capacity for plant productivity and protection from microbial breakdown.

The low nutrient and water holding capacity of sandy soil make it difficult to increase OC content (Hall *et al.* 2010). The addition of clay to sandy soil (clay modification) can increase OC storage through binding to clay surfaces (Baldock, 2007, Skjemstad *et al.* 1993) and by occlusion in micro-aggregates formed by clay (Tisdall and Oades, 1982). OC concentration of subsoil is generally lower than that of a similar textured topsoil due to lower OC input (Rumpel and Kögel-Knabner 2011) and therefore likely to have higher potential for stabilisation of OC as saturation of the mineral particles is unlikely to have occurred (Lutzow *et al.* 2006). Stabilisation of OC will depend on clay mineralogy, sesquioxide concentration, carbonate concentration and formation of stable micro-aggregates, (Denef *et al.* 2001a, 2001b, Fernández-Ugalde *et al.* 2011, Lutzow *et al.* 2006, Rakhsh *et al.* 2017, Saidy *et al.* 2012, Six *et al.* 2004).

Addition of clay from the subsoil to sandy topsoil first occurred in the 1970's in the south-east of South Australia (Cann 2000) to overcome water repellence in sands (Harper *et al.* 2000, Ma'shum *et al.* 1989, McKissock *et al.* 2000, Ward and Oades 1993). Co-benefits include yield increases between 20-130% (Davenport *et al.* 2011, Hall *et al.* 2010), increased nutrient availability (Bailey and Hughes 2012, Hall *et al.* 2010), increased root growth (Bailey *et al.* 2010, Hall *et al.* 1994), increased water retention (Betti *et al.* 2015), decreased saturated hydraulic conductivity (Betti *et al.* 2016) and a reduction in frost damage (Rebbeck *et al.* 2007). Improved yields have also been reported in Thailand with the addition of bentonite to sandy soil for forage sorghum (Noble *et al.* 2001) and Turkey with the addition of pumice to increase water holding capacity (Ozhan *et al.* 2008).

Subsoil clay addition to the surface of sandy soil is a practice used in South Australia, Victoria and Western Australia to overcome water repellence, improve water retention, fertility and plant productivity but little is known as to how it affects OC storage. Subsoil clay addition to sandy soil may increase OC input from improved plant growth resulting from increased nutrient and water retention.

Incubation experiments assessing the effect of clay addition to sand have shown higher OC concentration associated with finely ground clay (< 2 mm) mixed with sand than in sand alone 184 days after ground plant residue addition (Rakhsh *et al.* 2017). In clay-amended sand, Tahir and Marschner (2016) found no clear difference between OC concentration in 1 mm compared to 3 mm clods 45 days after residue addition. They concluded the lack of difference between clods may be because size and thus surface area were not sufficiently different. Cumulative respiration was reported to be lower after crop residue addition in finely ground (< 2mm) clay (Roychand and Marschner, 2013, Shi and Marschner, 2012) and in 3 mm clods when compared to 1 mm clods (Tahir and Marschner, 2016), indicating decreased accessibility of OC to microbial decomposition due to binding to clay surfaces.

In field studies OC was compared after subsoil clay addition to an untreated sandy soil. Hall *et al.* (2010) reported a 0.2% OC increase in the top 10 cm, eight years after clay addition. Churchman *et al.* (2014) reported increases in OC in the surface 30 cm ranging between 0.1 to 0.65% resulting in increased stock of about 12 t ha^{-1}, 29 years after addition of fine-textured bauxite processing waste. Bailey and Hughes (2012) found a 0.4% increase in OC in the bleached A2 horizon up to 7 years after addition of subsoil clay. Schapel *et al.* (2017) reported OC increases of 0.1 to 0.5% in the surface 30 cm equating to an increase between 1 to 22 t ha^{-1} (average 10 t ha^{-1}) in OC stock 3 to 9 years after addition of subsoil clay. The carbon sequestration rates of these studies varied between 0.1 to 7.5 t ha^{-1} yr^{-1} compared to the sequestration rates of 0.2 to 0.3 t ha^{-1} yr^{-1} reported by Sanderman *et al.* (2010) for different management regimes.

These studies indicate the potential for increasing OC by adding subsoil clay to sandy soils.

5.3.1 AREA OF SANDY SOILS SUITABLE FOR CLAY ADDITION

Sandy soils cover 900 million hectares (M ha) of the world's surface (FAO/UNESCO, 1995) and are used for agriculture in many regions (Usowicz and Lipiec, 2017). Sandy soils are often excluded from global agricultural soil sequestration models due to their low capacity to sequester C due to low clay content (Zomer *et al.* 2017). There is large potential to increase C sequestration if the OC storage capacity of sandy soils can be increased through clay addition.

Sandy soil includes sand to loamy sand textures (clay content < 15%) with or without the presence of a clay B horizon. Such profiles fall within the orders Chromosol, Sodosol, Kurosol, Tenosol, Calcarosols, Ferrosol and Kandosol (Isbell 2002). Chan *et al.* (2003) found light-textured soils covered the major soil types used for cropping corresponding to 86% of the area used for cereal cropping (Chromosols, Sodosols and Kandosols), a third of which are texture contrast soils.

In Australia, there are approximately 5 M ha of sandy soils used for agriculture (Harper, 2012) with clay-rich subsoil within 0.8 m of the surface suitable for clay addition; approximately 2.6 M ha in South Australia (J Hall 2011 pers. comm.). It is estimated that 0.16 M ha have already been clay-modified in Southern and Western Australia (Churchman *et al.* 2014).

5.3.2 CLAY ADDITION METHODS

In South Australia, the most common methods of subsoil clay addition are to the surface of the sand (spreading) or elevation of subsoil clay (delving, spading) throughout the soil profile (Figure 15).

Selection of the appropriate modification method is determined by the depth to clay-rich subsoil (Davenport *et al.* 2011) and the machinery available. Clay spreading is the only available option for deep sands where clay-rich subsoil is at more than 60 cm depth. Clay-rich subsoil is excavated from a nearby pit, spread on the sand surface and then incorporated. Delving is used where clay-rich subsoil is within 30-60 cm of the soil surface (Desbiolles *et al.* 1997) and purposely designed tynes elevate the clay-rich subsoil into the sand above. After delving, elevated clay clods on the ground surface are spread using bars, dragging clay from the delve line into the area between delve lines (0.7-2 m depending on machine design) and then incorporated using offset discs, spader etc. The area between delve lines is modified to the depth of incorporation but below this depth, the sand remains undisturbed. Spading can be used as a clay modification method where clay-rich subsoil is within 30-40 cm of the soil surface. Subsoil clay is elevated and incorporated in one pass using specially designed 'spades' spaced 0.35 m apart on a rotary axle. While delving creates distinct areas of modification, delve lines and area between delve lines, clay spreading and spading result in a more uniform distribution of subsoil clay clods to the depth of incorporation. All clay modification methods result in a mix of clay clods ranging in size from a few mm to greater than 200 mm (Schapel 2017 pers. obs.) in a sandy matrix.

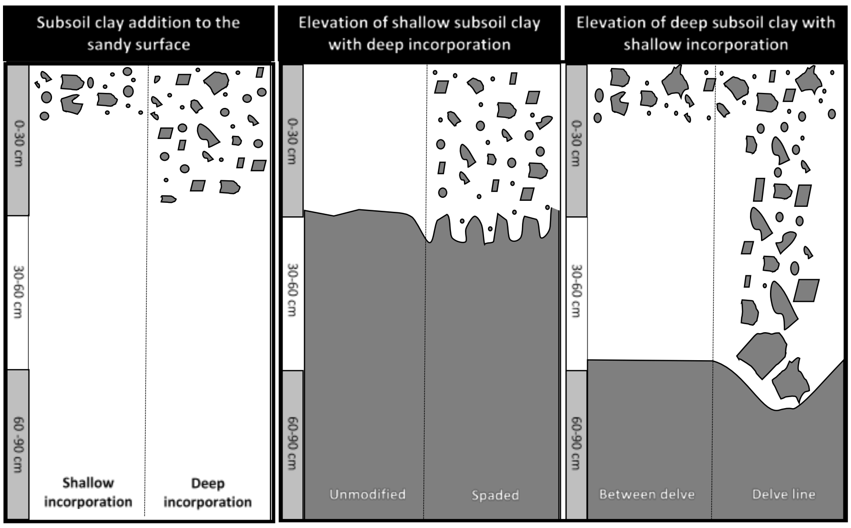

Figure 15. Schematic diagram (not to scale) of distribution of clay clods in the soil profile with clay addition to the surface or elevation from subsoil.

Clay spreading was first used in the 1970's (Cann 2000, Carter and Hetherington 1994), delving in the 1990's (Desbiolles *et al.* 1997) and deep incorporation by spading since the late 2000's in South Australia and Western Australia. Inversion ploughing is used in Western Australia to overcome water repellent sands but does not necessarily involve clay incorporation and due to its limited use in South Australia, is not discussed here.

Figure 16. . Clay modification methods: clay spreading using Clay Mate (1), clay spreading using carry grader (2) clay pit for clay spreading (3), delving (4), deep incorporation with spading (5) and close up of spades on rotating axle of spader (6).
Photo credit: David Davenport, Brett Masters and Amanda Schapel Rural Solutions SA.

5.3.3 ADDITIONAL FACTORS INFLUENCING CARBON STORAGE IN CLAY-MODIFIED SOILS – SYNTHESISED FINDING FROM THE LITERATURE

The factors discussed in Section 5.3 affect carbon storage in clay-modified soils. However, as a new soil profile is created, with subsoil clods distributed throughout sandy horizons, additional influencing factors need to be considered. The main variables hypothesised to affect OC storage are type and amount of subsoil clay applied, size and chemical properties of the clods and spatial distribution of clods. Very little is known about how these factors affect soil OC and what stabilisation processes occur in the newly generated profile.

Subsoil clay addition

Subsoil clay should have high potential for OC stabilisation as saturation of the mineral particles is unlikely to have occurred (Lützow *et al.* 2006). OC input into subsoils occurs via: plant roots and root exudates, leaching of dissolved organic matter and bioturbation (Rumpel and Kögel-Knabner 2011); and is influenced by clay parent material (Kögel-Knabner *et al.* 2008). However, the amount of OC in the subsoil is lower than in the topsoil (Hobley and Wilson 2016) suggesting there is capacity to stabilise additional OC with the incorporation of the subsoil clay into sandy horizons.

Stabilisation of OC will vary depending on the sesquioxide and carbonate concentration in the clods (Fernandez-Ugalde *et al.* 2011, Saidy *et al.* 2012) and, perhaps most importantly for long-term stabilisation, the formation of protective micro-aggregates (Denef *et al.* 2001, Denef *et al.* 2001, Six *et al.* 2004).

Clay mineralogy is important for protection of soil OC. In a laboratory experiment, cumulative respiration compared to sand alone was lower in sand where finely ground smectitic clay soil was added however addition of finely ground kaolinitic clay soil had no effect (Nguyen and Marschner, 2014). This was hypothesised to be due to the low surface area and cation exchange capacity of the kaolinitic compared to smectitic clay. However, kaolinitic and illitic clays are more effective than smectitic or vermiculitic clays in alleviating water repellence (Ma'shum *et al.* 1989) as the kaolinite is spread more readily over the sand grains and remain evenly distributed after drying (Ward and Oades 1993). Naturally occurring dispersible illites and kaolinites underlie large areas of water repellent siliceous sands in South Australia (Ma'shum *et al.* 1989). Kaolinite was identified as the dominant clay mineral in subsoil from the South-East and Eyre Peninsula regions in South Australia (Schapel *et al.* 2017, Schapel *et al.* 2018 in press) where clay modification had occurred. Although kaolinitic clay may have lower capacity for OC protection than other clay minerals due to its low CEC and surface area, addition of this subsoil clay to siliceous sand could result in higher OC stabilisation capacity than unamended sand.

Schapel *et al.* (2019) identified that subsoil clod size, clay concentration, sesquioxide content and soil depth influenced OC concentration. Clay modification method and depth of incorporation influenced clod size, number and vertical distribution. Clod number per unit of soil mass had stronger influence on OC stock than OC concentration. These factors along with climate (rainfall and temperature) affect OC storage in clay-modified soil (Schapel *et al.* 2017).

The amount of subsoil clay added to the sandy profile will determine the clay concentration and hence stabilisation capacity of the engineered soil. Subsoil clay is not mixed homogenously with the sand but distributed as clods ranging in size from a few mm up to greater than 200 mm (Schapel 2019) in a sandy matrix (Figure 16). Size, chemical properties and distribution of subsoil clods are likely to influence soil OC although little is known about this effect.

Other processes that may influence OC content

Modelling has shown that sandy topsoils are often close to saturated with OC and new management practices or land use options that enable soil OC to be stored deeper in the soil profile are needed to increase OC storage (Hoyle *et al.* 2013). The mechanical tillage required for adding subsoil clay to sand (delving, incorporation etc.) can increase the capacity of the clay-amended soil to store OC at depth. Tillage of sand can also overcome physical limitations such as high bulk density and soil strength that reduce root growth and productivity (Usowicz and Lipiec, 2017). The incorporation of organic residues to depth during the clay modification process may offset the loss of OC resulting from soil disturbance. Olchin *et al.* 2008 observed that when residues were incorporated to 15 cm, tillage-induced aggregate disruption had greater influence on OC stabilisation than residue incorporation into the profile. However, when residues were incorporated to 30 cm, the negative disruption through tillage appeared to be offset by slower decomposition of residues deeper in the profile. Incorporation of organic matter during the clay amendment process may lead to improved soil function and OC storage due to the critical role OC plays in the soil. Schapel *et al.* 2017 reported that spading with added organic matter (10 t ha^{-1} of lucerne hay) gave the highest OC stock increase (22 t ha^{-1}) compared to the unmodified sand.

Increasing water storage in sandy soils can improve plant productivity where low and seasonal rainfall limits growth (Hobley and Wilson 2016, Usowicz and Lipiec, 2017). Betti *et al.* (2016) found that the addition of as little as 10% clay-rich subsoil to sand significantly decreased saturated hydraulic conductivity but plant available water only increased when more than 20% clay rich subsoil (5-10% actual clay concentration) was added and tended to be higher for mixtures with clod size less than 6 mm. Furthermore, they found that when clods less than 6 mm in size were added to sand an intimate mixture of smaller pores was created which retained more water whereas when clods greater than 6 mm were added a bimodal mixture was created where clods existed as discrete entities in a sand matrix, creating larger pores and lower water contents.

Hoyle *et al.* (2016) suggest that in sandy soils more efficient use of soil resources including water and nutrients to increase net primary productivity, can buffer against losses imposed by climate restrictions. However, the potential for OC storage in sandy soils is limited by inherently low soil fertility as nitrogen, phosphorus, and sulphur requirements for transformation of POC into HOC and ROC may not be met (Kirkby *et al.* 2011). The addition of subsoil clay to sand has been shown to increase the nutritional capacity (Bailey and Hughes 2012, Hall *et al.* 2010) and along with increased water retention (Betti *et al.* 2016), should improve OC storage in clay-modified soil.

Sampling procedures and laboratory analysis

The spatial distribution of clods is likely to influence not only soil OC but also the sampling methodology required to collect soil samples. Soil sampling procedures have significant impact on the validity and usefulness of the collected data. Clay-amended soils have variable distribution of clods horizontally and vertically, especially delved soils that have the greatest spatial heterogeneity (Betti *et al.* 2015) and may require adapted sampling procedures.

There are many sampling procedures described for Australian soils that are designed for specific purposes (McKenzie 2008). The national Soil Carbon and Research Program examined variations in OC content and composition under different agricultural practices and soil types across Australia and collected 10 samples within a 25 x 25 m area (Sanderman *et al.* 2011). Wilson *et al.* (2010) evaluated the effect of sampling procedure on total OC, bulk density, pH and total nitrogen and found that sampling intensity to achieve defined levels of precision and confidence differed among land uses and soil properties in northern New South Wales. They concluded that 10 samples across a sampling area of 25 x 25 m yielded adequate precision and confidence for OC. In clay-modified soils, 10 samples in a 25 x 25 m area is also sufficient to meet defined OC precision and accuracy standards (Schapel *et al.* 2017). They recommend sample locations be randomly allocated for clay spread and spaded treatments but stratified in delved treatments with sample allocation based on the proportion of area represented by delve lines and that between delve lines.

For accurate OC assessment, the method of laboratory analysis is also important. The use of catalysed, high temperature combustion is a requirement to measure soil carbon under the Carbon Farming Initiative (Australian Government 2018). This analytical method measures inorganic carbonates that are often found in South Australian soil. High concentrations of inorganic carbon can make small changes in OC difficult to detect. Chemically removing carbonates increases the accuracy of the OC measurement but is time consuming, costly and not commercially available. Wet oxidation is commonly used in Australia, with the Walkley and Black technique the most widely used. However, this test only provides an approximate measure due to incomplete oxidisation of the organic matter. The Heanes wet oxidation method that measures the total amount of organic carbon, TOC, is more accurate but it uses chemicals that are toxic and are difficult to dispose of in Australia so is not as extensively used (Conyers *et al.* 2011). Infrared reflectance spectroscopy (NIR and MIR) have been used with success but require a large dataset of soil types for calibration. Mid-Infrared (MIR) spectroscopy in combination with chemometric statistical methods, such as partial least squares (PLS) regression, is increasingly being recognised as a quick and effective tool for measuring numerous soil attributes including soil carbon pools (Sanderman *et al.* 2010). Physical or chemical fractionation of OC into particulate, humus and resistant fractions provides greater detail of the carbon pools in each of the size ranges and the fluctuations that can be sensitive to land use, soil type and climatic variables (Rayment and Lyons 2011). However, it is a time-consuming and expensive analytical test. The majority of reviewed studies on clay addition to sand used the Walkley and Black wet oxidation technique, possibly due to the high variable presence of inorganic carbonates in the added subsoil clay (Nguyen and Marschner, 2014, Schapel *et al.* 2017, Schapel *et al.* 2018 in press).

5.4 Summary

Agricultural soils are important not only for their contribution to the balance of greenhouse gas emissions but also their critical role securing global food supplies in a resource limited world (Hoyle *et al.* 2016). Globally, most agricultural systems have lost 40 to 70% of their natural soil carbon (Lal, 2004) so it is crucial to identify and implement practices suitable for the soil type and climate that minimise or reverse the decline in soil carbon (Macdonald *et al.* 2013) whilst balancing economic sustainability and global food needs.

Sandy soils are important agricultural soils globally and cover a large proportion of Australia's agricultural region. However, the often low nutrient and water retention in these soils is reflected by low plant productivity that makes it difficult to increase OC content. The addition of clay to sandy soils has the potential to increase soil OC storage through increased plant growth (above and below ground) and increased capacity to store and stabilise the new OC by binding to clay clods. It is unknown how clay addition to sandy soil affects the transformation of OC inputs into more stable forms of OC.

Subsoil clay addition to the surface of sandy soil is a practice used in South Australia, Victoria and Western Australia to overcome water repellence, improve water retention, fertility and plant productivity. However, little is known about the potential of clay-amended soils to increase OC content and whether clay addition methods can be optimised to increase OC storage capacity.

This literature review has identified the potential for increased OC storage in clay-modified soil compared to unmodified sandy soil. Variations in OC stock of both clay-modified and unmodified soil has identified factors that influence OC storage in clay-modified soil. It is recognised that the number of studies included in this review is low however the gathered information can be used as a guide to identify practices warranting further investigation. Key findings were:

- clay concentration (amount of clay added) of a modified soil positively correlated to OC content.
    - Schapel *et al.* (2018 in press) demonstrated a relationship between OC stock and clay stock (slope of 0.017 and R^2 of 0.47). The collation of sites in this report demonstrated a relationship between OC stock and average clay concentration of the surface 30 cm for the 400-500 mm rainfall zone (slope of 1.118 and R^2 of 0.41). A poor relationship (R^2 of 0.17) for all rainfall zones (350 to 600 mm) indicated that other factors influenced OC stock in clay-modified soil.
- subsoil clay iron content positively influenced OC concentration.
- subsoil clod size inversely influenced OC concentration and number positively influenced OC stock.
- clod distribution influenced OC concentration and stock, where higher OC stock occurred with deeper vertical distribution in the profile.
- greatest potential for increased OC storage in clay-modified soil was in the 10-30 cm depth.
- clay modification method influenced the size and distribution of clods in the soil profile, but this difference could be adjusted through the incorporation process.
- clay addition to sand increased water retention and decreased saturated hydraulic conductivity.
- depth to undisturbed subsoil influenced OC stock, with greater opportunity for increased OC stock where subsoil clay was deeper than 40 cm.
- rainfall and temperature influenced the biomass grown at a site.

6 Road map for future research

A greater understanding of the range of carbon stock for a given soil, of a known clay concentration within a particular rainfall zone will enable the development and provision of guidelines for clay-modification techniques for soil carbon sequestration in South Australia. To reach this point, there is a need to:

1. measure key parameters that have been identified as missing or inadequate in models (FullCAM, APSIM, HYDRUS and PHREEQC);
2. utilise models to gain a greater understanding of the mechanisms to improve carbon sequestration;
3. verify outputs of models with targeted field sampling and laboratory experiments;
4. overcome barriers to landholders entering into ERF soil carbon projects; and
5. identify rainfall zones and practices where clay modification has the greatest potential to increase OC stock.

This can be achieved through further investigation and research into the following areas:

- Greater understanding of subsoil clay addition to sandy soil and the effect on productivity, water and nutrient use efficiency.
- Identification of optimal clay addition rate, clod size and clod distribution for different rainfall and depth to undisturbed subsoil (soil type) scenarios to optimise OC storage in clay-modified soil.
- Identification and adaptation of machinery design to deliver the optimal outcomes.
- Focus on methods that increase OC input deeper than 10 cm in clay-amended soil. Trials of different crop and pasture varieties and rotations assessing root growth distribution and deposition at this depth; or the application of external OC sources such as composts or manures are recommended.
- OC stock needs to be monitored over time, ideally every 5 years. All field studies in the review have been a comparison of treatments at sites rather than monitoring over time. For an accurate assessment of OC storage potential for a given treatment such monitoring has to occur This information will help determine the rate of change in OC stock, the time to reach equilibrium, stability of bound OC and establish if clay-modified soils reach OC saturation.
- Through field and laboratory experiments, understand the effect of incorporation of additional and different sources of organic matter on OC storage, productivity and microbial activity. The impact of subsoil clods of various sizes on soil temperature, moisture, nutrient, biological activity and rate of turn-over of OC will provide better information to parameterise soil models.
- Understand the effect of clay-modified soil on OC fractions and decomposition rate to evaluate how stable the gains are and whether they are likely to persist following management changes compared to unmodified sandy soil. This data will strengthen the modelled outputs using the national carbon accounting model - FullCAM.
- Investigate the use of other models such as HYDRUS and PHREEQC to estimate OC storage to better account for changes in soil moisture availability on C inputs through plant growth.
- Use information from field and laboratory studies and explore the outputs of different models to determine the extent of OC offsets, time to C equilibrium and saturation points. This can lead to a greater understanding of the factors that influence OC storage in clay-amended soil.
- Measure OC in clay-amended soil to enable cost efficient monitoring of OC, evaluation of the accuracy and applicability of proximal sensors (e.g. portable MIR or NIR devices) . Data collected using commercially available proximal sensors needs to be compared to that analysed by laboratory methods. The processing requirements for analysing soil will need to be determined e.g. if soil needs to be dried, ground and mixed or can be assessed as sand and clod mix in the paddock.
- A life cycle assessment to develop an understanding the OC footprint of clay modification i.

For a greater understanding of what is required for land holders to engage in a soil carbon project a number of topics need to be addressed:

- Cost of implementing the soil carbon project including administration and verifying the OC stock (soil sampling).
- Clarity of 100 year permanence requirements to maintain the OC including legal liability and paddock encumbrances .
- Clear, consistent government policy.
- Uncertainty regarding the price of carbon.
- Uncertainty of implementation of future farming adaptations that are required for famer's survival during the 100 year permanence period that may contradict soil carbon accounting rules.
- From the research above, dissemination of information on
  - Best practice implementation of eligible activities.
  - Eligible activities and their effect on soil OC and productivity.
  - Emissions created by implementing an eligible activity.
  - Location of best return on farm and surety on investment.

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Appendix A - Parameters for data analysis

Parameter	No. Sites
Landholder	
GPS location	58
Sampling area m^2	
No. samples collected	
Modification machinery	
Delving - tyne width (m)	9 U*
Delving tine depth (m)	
Residue or ameliorants	49 M*
Incorporation machinery	
Management system	
Tillage	
Stubble retention	
Average Yield	
Total yield	
No Years cropped	
Region	
C-Rainfall (location specific rainfall)	
No years of rainfall	
Average rainfall (closest BOM station)	
Soil type	98
Depth subsoil clay (cm)	
Modification	
Rate Clay (tha^{-1})	49 U*
Depth Incorporation (cm)	
Year modified	49 M*
Yrs since modification	

Parameter	No. Sites
OC stock fixed depth gcm^{-3}	
OC Stock ESM 45 gcm^{-2} (5 percentile)	
OC Stock ESM 50 gcm^{-2} (95 percentile)	
For soil depth; 10, 20, 30, 50 cm	
OC (%)	
BD gcm^{-3}	98
OC Stock tha^{-1}	
pH $CaCl_2$	49 U*
EC 1:5 dSm^{-1}	
Clay concentration %	49 M*
Clay + Silt %	
Cation exchange capacity	
Colwell P mg/kg	30
Colwell K mg/kg	
Boron mg/kg	5 U*
Sulfur KCL mg/kg	
Mineral N mg/kg	25 M*
Mineral N stock kg/ha	
DTPA Fe mg/kg	25
Exch Ca meq/100g	5 U* 20 M*
DGT P ugL^{-1}	31 (3 U* 28 M*)
Dissolved OC $mgkg^{-1}$	
Microbial Biomass C mg kg^{-1}	28
Potential Mineralisable N mg NH4-N kg^{-1}	3 U*
Water holding capacity %	25 M*

*U indicates unmodified and M indicates clay-modified soils

Appendix B - Change in OC Stock (tha^{-1}) for key parameters

Average, standard error of the mean (SEM), number of samples (Ct), minimum, maximum, coefficient of variation (CV) and change in OC stock$_{ESM}$ (0-30 cm) compared to unmodified soil for key parameters.

	Ave	SEM	Ct	Min	Max	CV (%)	**Δ Stock to Nil/No**
Rainfall							
350	16.58	1.2	20	7.1	29.1	33	
400	18.65	1.7	28	6.3	37.6	49	2.1
450	20.15	1.4	31	7.8	35.5	37	3.6
500	30.11	2.2	19	15.2	49.9	32	13.5
Modification							
No	18.45	1.4	49	7.1	49.9	52	
Yes	23.30	1.2	49	6.3	43.5	35	4.9
Clay source							
Nil	18.45	1.4	49	7.1	49.9	52	
CA	22.88	1.5	33	6.3	43.5	39	4.4
CB	24.18	1.7	16	16.0	37.6	28	5.7
Incorporation depth							
No	18.45	1.4	49	7.1	49.9	52	
Shallow	22.78	2.0	22	6.3	43.5	41	4.33
Deep	23.73	1.4	27	14.0	40.2	31	5.28
OM Addition							
No	18.45	1.4	49	7.1	49.9	52	
Mod - No	23.25	1.4	39	6.3	43.5	37	4.8
Mod - Yes	23.51	2.3	10	14.0	35.5	31	0.3
Years since Modification							
Nil	18.45	1.4	49	7.1	49.9	52	
10	23.18	1.2	38	9.7	40.2	33	4.73
25	23.18	1.2	38	9.7	40.2	44	5.98
45	16.72		1	16.7	16.7		-1.73
Farming system							
CC	18.49	4	6	6.3	35.0	55	
CPG	22.30	1.1	63	7.1	49.9	39	
PL	18.28	2	29	7.4	43.5	54	
Soil type							**Δ to DS**
DS	15.35	2	24	6.3	40.2	56	
DTC	19.95	2	14	13.2	37.6	42	4.6
TC	22.22	1	47	7.9	49.9	42	6.9
SHTC	27.24	2	13	14.2	35.5	21	11.9

Bolded values denote significant difference to the unmodified samples

Clay source: CA clay above (spreading), CB clay below (delving, spading); Farming system: CC – continuous cropping, CGP – crop/pasture rotation with grazing, PL – pasture low intensity; Soil type: DS – deep sand (subsoil clay > 70 cm), DTC – deep texture contrast (subsoil clay 50-70 cm), TC – texture contrast (subsoil clay 30-50 cm), SHTC – shallow texture contrast (subsoil clay < 30 cm)

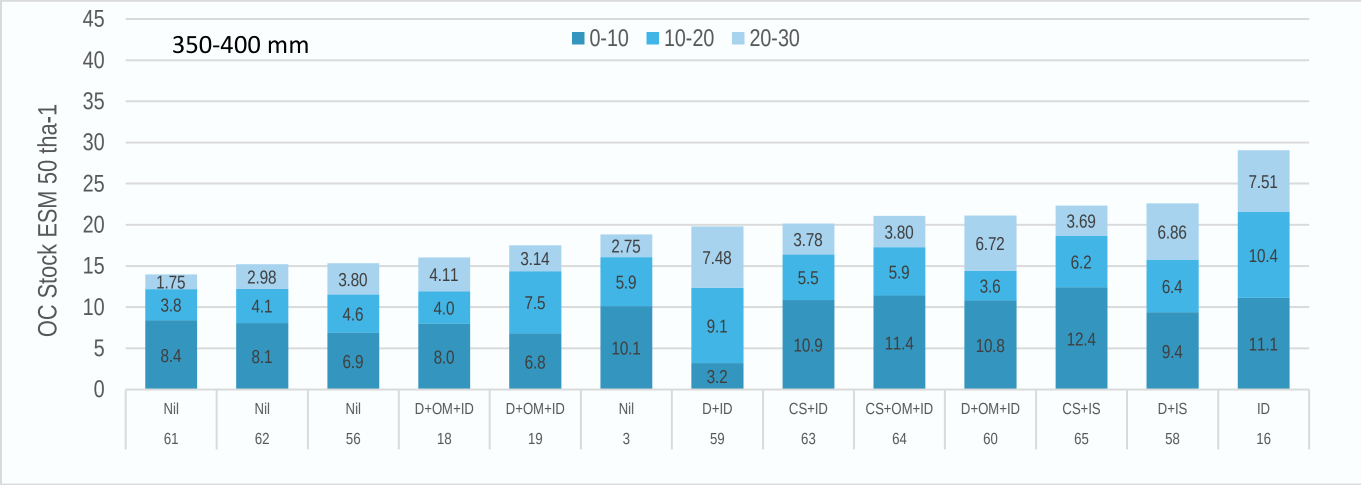
	Rainfall (mm)	Ave No	Ave Yes	SEM No	SEM Yes	Ct No	Ct Yes	Min No	Min Yes	Max No	Max Yes	CV No	CV Yes	Δ Stock (Y-N)
Modification														
	350	12.9	21.1	1.1	1.2	11	9	7.1	16.0	18.8	29.1	29	17	8.2
	400	16.0	21.0	2.2	2.4	14	14	7.9	6.3	30.6	37.6	52	43	*5.0*
	450	18.3	22.1	1.8	2.0	16	15	7.8	9.7	32.7	35.5	40	34	*3.8*
	500	30.7	29.7	4.2	2.5	8	11	15.2	16.7	49.9	43.5	39	28	-1.0
Soil type														
DS	350	10.10		1.4		5.0		7.1		14.4		30		
DTC														
TC		15.23	20.09	1.0	0.8	6.0	8.0	11.5	16.0	18.8	22.6	16	11	4.9
SHTC			29.07				1.0		29.1		29.1			
DS	400	10.70	6.31	1.1		4.0	1.0	8.5	6.3	13.0	6.3			-4.4
DTC		14.79	23.77		4.9	1.0	5.0	14.8	13.2	14.8	37.6	0		9.0
TC		15.20	21.11	3.0	2.4	7.0	8.0	7.9	16.6	29.8	37.4	52	32	5.9
SHTC		32.13		3.2		2.0		28.9		35.4		14		
DS	450	14.03	19.15	1.7		8.0	1.0	7.8	19.2	20.7	19.2	34		5.1
DTC		14.65	14.92		1.0	1.0	4.0	14.7	13.3	14.7	17.6			0.3
TC		21.57	22.07	3.1	3.8	2.0	5.0	18.4	9.7	24.7	32.8	21	38	0.5
SHTC		24.64	28.46	3.4	2.1	5.0	5.0	14.2	24.9	32.7	35.5		16	3.8
DS	500	26.07	28.42	7.2	6.8	2.0	3.0	18.8	16.7	33.3	40.2	39	41	2.4
DTC		19.78	31.70	4.6		2.0	1.0	15.2	31.7	24.4	31.7	33		11.9
TC		38.44	29.95	5.1	3.1	4.0	7.0	25.2	20.2	49.9	43.5	27		-8.5
SHTC														

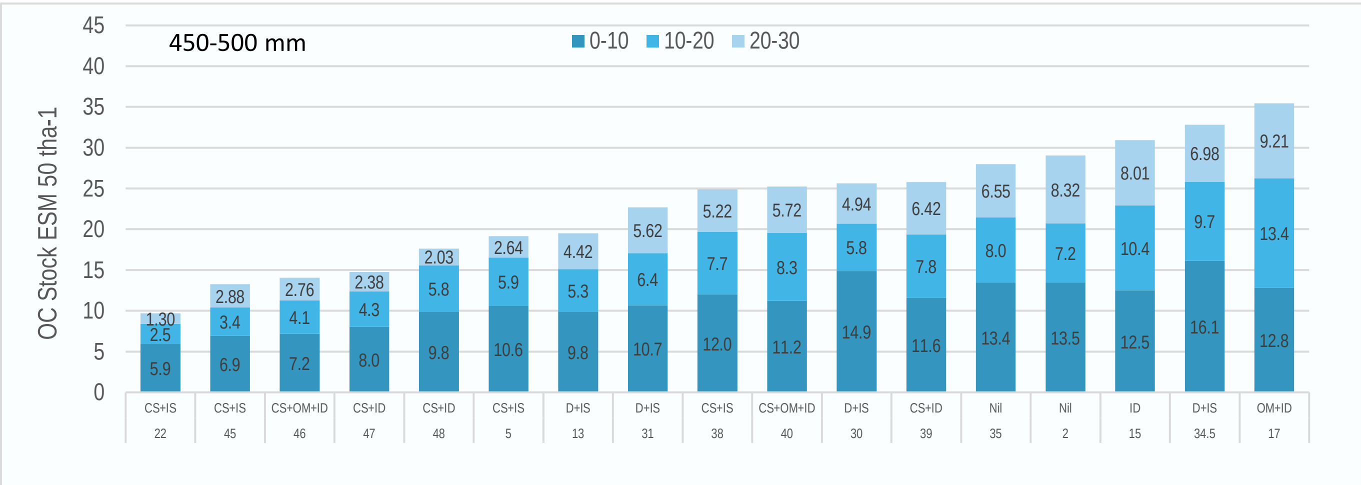
	Ave N	Ave SH	Ave D	SEM N	SEM SH	SEM D	Ct N	Ct SH	Ct D	Min N	Min SH	Min D	Max N	Max SH	Max D	CV N	CV SH	CV D	Δ Stock to No SH	Δ Stock to No D
Incorporation depth																				
350	12.90	22.47	20.69	1.1	0.1	1.6	11	2	7	7.1	22.4	16.0	18.8	22.6	29.1	29	1	20	9.6	7.8
400	15.96	20.86	21.20	2.2	3.9	2.6	14	8	6	7.9	6.3	16.6	30.6	37.6	33.4	52	53	30	4.9	5.2
450	18.33	21.16	22.92	1.8	3.0	2.7	16	7	8	7.8	9.7	14.0	32.7	32.8	35.5	40	37	34	2.8	4.6
500	30.68	28.24	30.91	4.2	4.7	2.8	8	5	6	15.2	16.7	21.8	49.9	43.5	40.2	39	37	22	-2.4	0.2

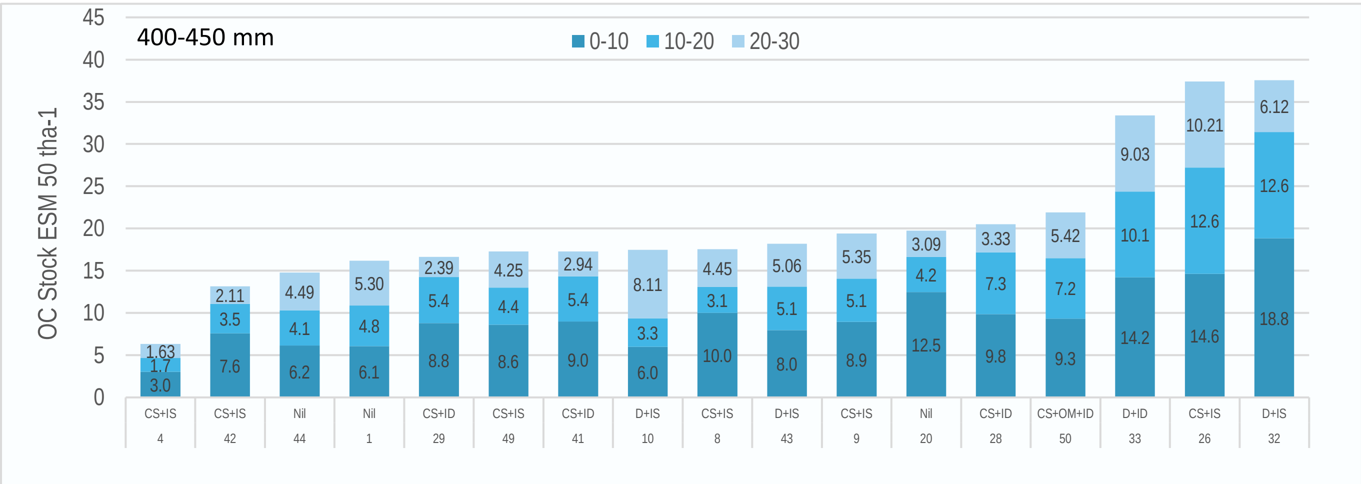
Bolded values denote significant difference to the unmodified samples

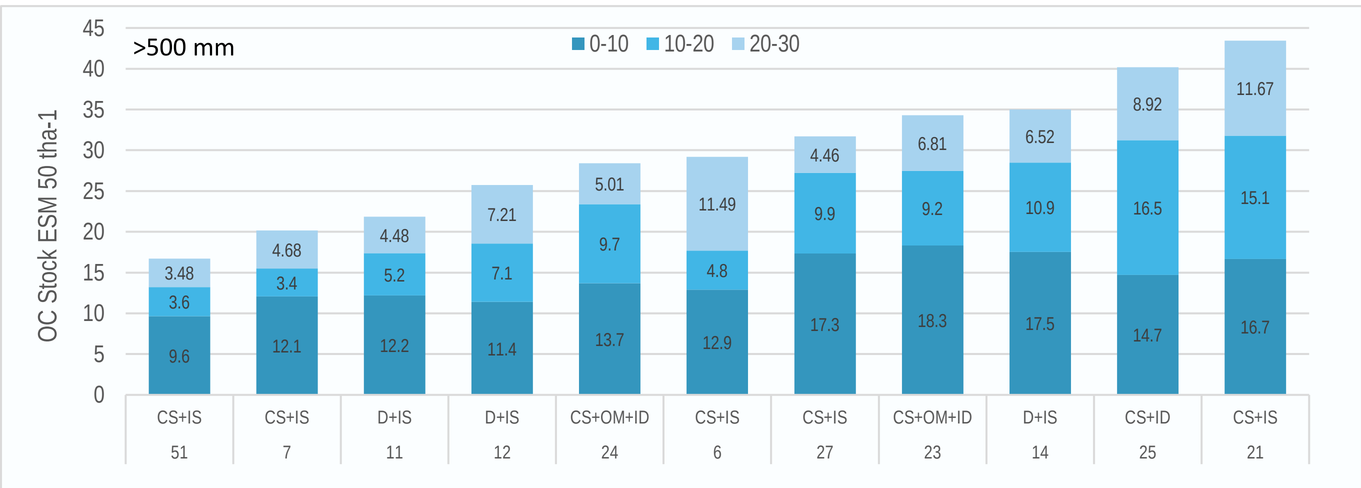
Soil type: DS – deep sand (subsoil clay > 70 cm), DTC – deep texture contrast (subsoil clay 50-70 cm), TC – texture contrast (subsoil clay 30-50 cm), SHTC – shallow texture contrast (subsoil clay < 30 cm); Incorporation depth: N (no incorporation unmodified soil), shallow (SH to 10 cm), deep (D to 30 cm).

Appendix C - Distribution of OC stock (per site) × rainfall









Appendix D - Identify and test existing soil carbon models

Michael Wurst, Rural Solutions SA, PIRSA

Executive Summary

The aim of this report was to identify and test soil carbon models for sensitivity and relevance (applicability) to clay modification for carbon sequestration.

- Clay modified soils may differ in the amount of carbon stored to unmodified soil, due to the uneven distribution of clay. Improved deep incorporation through spading will improve the distribution of clay.
- Century, APSIM, Roth C English and Australian versions were compared:
    - The Roth-C (Rothamsted soil carbon turnover) model was developed from long term rotation trials at Rothamsted, United Kingdom.
    - The Agricultural Production System sIMulator (APSIM) was developed in Australia as a crop production modelling shell and also has the capability to simulate soil carbon dynamics.
    - Century model was developed in the United States and simulates C, N, P, and S dynamics through an annual cycle over time scales of centuries and millennia.
- APSIM will be used to model crop production.
- The FullCAM model has been developed in Australia and extensively tested and verified for Australian conditions. The model has been widely used for simulating soil and biomass carbon dynamics at project level and nationally.
- FullCAM is required to be used for national soil C accounting and so is the model first assessed.
- Findings from FullCAM regarding clay-modified soils:
    - has indicated that it provides a realistic modelling of soil C levels;
    - limitations of the model are that clay content assumes even distribution within a soil;
    - soil C pools and the amount of biomass input are both sensitive to increasing carbon C stocks;
    - there is limited information regarding the level of carbon stored in the different soil C pools in South Australian sandy soils.
- Initial work with Hydrus SOM degradation model indicates the potential to model the impact of water movement in clay modified soils.
- Gaps in knowledge:
    - soil carbon pools in sandy and clay modified soils to provide realistic data for the model;
    - effect of uneven clay distribution in clay modified soils on C;
    - soil moisture in clay modified soils and effect of clay clod size and distribution.

2.1 Review of soil carbon models

As reported by Manzoni and Porporato (2009), a large number of models (> 250) exist for simulating soil organic matter (SOM) dynamics. They concluded that most new models are improvements over earlier ones, leading to many similar model structures and formulations and these mathematical features have changed slowly over time, generally produced more robust and effective models (as shown by model inter-comparisons and validation studies). Manzoni and Porporato (2009) found that the tendency for more recent models to have more sophisticated (and generally more mathematically complex) approaches is not always paralleled by improved model performance or ability to interpret observed patterns. Simple models based on physically and biologically based variables and parameterisations often provide equal or better insights in soil and litter dynamics than complex ones.

Many SOM models are so-called compartment models, which divide the heterogeneous nature of SOM into a number of homogeneous pools, and then simulate the fluxes between the pools. Some of these models have a rigid structure in the sense that the number of pools, abiotic factors that must be considered, their functional forms, and the extent of biotic-abiotic interactions, are fixed. It is therefore not always possible to perform a structured comparison between different types of model formulations (Jacques *et al.* 2017).

Reactive transport models, on the other hand, provide a flexible structure that enables the introduction of different SOM degradation networks within the same simulation framework. In addition, existing compartment models sometimes strongly simplify flow and transport processes and /or the geochemistry involved, such as simplifying or ignoring pH and buffering effects on degradation or CO_2 geochemistry. Jacques et al (2017) concluded that for predictions to be more accurate and also within the framework of climate predictions, SOM models should consider temporarily and spatially variable abiotic factors such as temperature and moisture, nutrient dynamics, microbial activity, solid-water interactions, and transport processes of solid and dissolved organic matter and/or inorganic carbon (e.g., Schmidt *et al.* (2011), Tang and Riley (2015)). Reactive transport models should account for these factors and effects, such as illustrated in recent studies by Tang *et al.* (2013) and Riley *et al.* (2014).

In Australia, soil organic matter (SOC) models such as Century soil organic model (Parton *et al.*, 1987), Roth-C (Jenkinson, 1990) and APSIM (Probert *et al.*, 1998) are widely used in research. The Roth-C (Rothamsted soil carbon turnover) model was developed from long term rotation trials at Rothamsted, United Kingdom. The Agricultural Production System sIMulator (APSIM) (Probert *et al*, 1998) was developed in Australia as a crop production modelling shell and also has the capability to simulate soil carbon dynamics. Century model was developed in the United States and simulates C, N, P, and S dynamics through an annual cycle over time scales of centuries and millennia. It was developed to deal with a wide range of cropping system rotations and tillage practices for system analysis of the effects of management and global change on productivity and sustainability of agroecosystems. Ranatunga *et al.*, (2001) compared the three models against measured soil carbon data for six sites in Southern Queensland.

Ranatunga *et al.*, (2001) compared the three models and described that they differ in time step (how often data is calculated) and also in how the crop-soil system is represented (Table 1). In APSIM, the cropping system sub-model operates on a daily time step and includes a water balance, N and P transformations, soil pH, erosion and a full range of management controls. The Century model has soil organic matter, water budget, grassland/crop, forest production sub-models and management and event scheduling operating on a monthly time step. Roth-C models the turnover of organic carbon in non-waterlogged soils, taking into account clay content, air temperature and soil moisture content and operates on a monthly time step. Roth-C does not have a crop growth model. Ranatunga *et al.*, (2001) used APSIM's crop model outputs to provide plant residues, yield and root data for Roth-C.

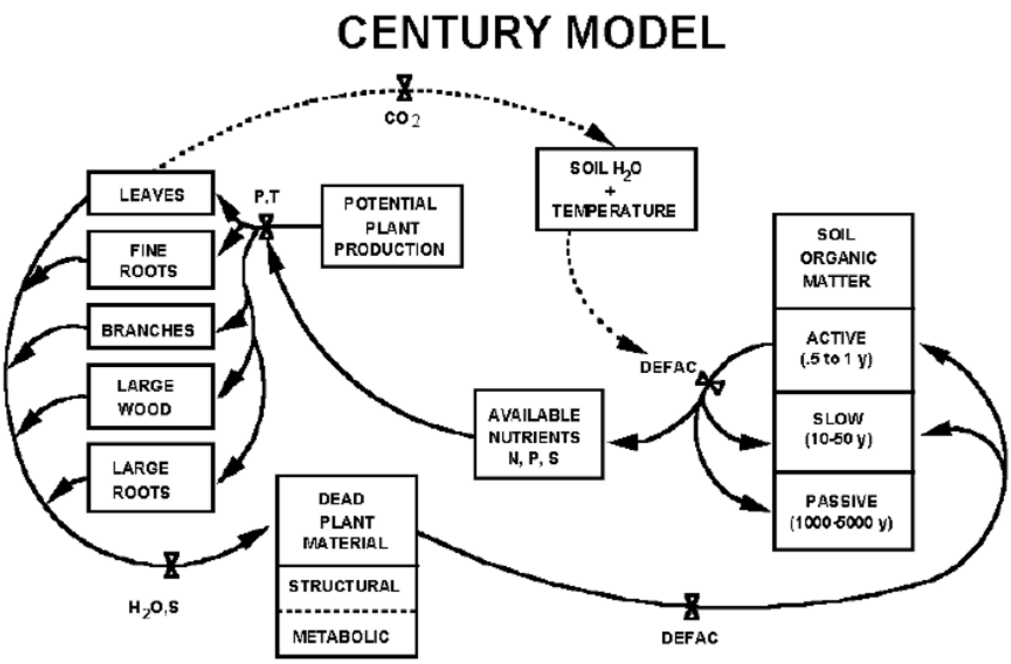


Figure 1: Flow diagram for Century model

Table 1. Suggested table for comparison

Model	Model origin	Time step	Model modules/sub models	Missing model	Model parameters
APSIM	Australia	Daily	Modules include a diverse range of crops, pastures and trees, soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls. Crop growth Water budget Nitrogen budget Soil organic matter budget	Clay content	Drained Upper and lower soil limit – depend on bulk density and clay concentration Soil organic carbon content SOIL N is the module that simulates the mineralisation of nitrogen and thus the N supply available to a crop from the soil and residues/ roots from previous crops. Soil nitrogen content – impact on C Temperature, evaporation and rainfall
Century	United States	Monthly	Soil organic matter N, P & S dynamics Water budget Grassland/crop Forest production		Generalised plant-soil ecosystem model that simulates plant production, soil carbon dynamics, soil nutrient dynamics, and soil water and temperature. Soil nutrient cycling and soil organic matter dynamics are represented in great detail, while plant growth is represented using relatively simple sub-models. The major input variables include: 1) monthly precipitation, 2) monthly average maximum and minimum air temperature, 3) soil texture, 4) lignin, N, S, and P content of plant material and 5) soil and atmospheric N inputs.
Roth-C	United Kingdom	Monthly	Turnover of organic carbon Clay content Temperature Moisture content	Crop growth	Clay content – has little impact on C stocks Biomass production – increases with increasing clay content, which has a large impact on C stocks
FullCAM	Australia	Monthly	CAMFor – C mass and transfer in forests CAMAg – impact of management on C accumulation and pools Roth-C. – calibrated for Australian conditions	Crop growth and yields	
HPx	Belgium/USA	Daily	HYDRUS 2D/3D– flow transport PHREEQC-3 - biogeochemistry		Rainfall, temperature and evaporation Nitrogen Microbial activity Organic carbon The Flow equation incorporates a sink term to account for water uptake by plant roots. Inputs - unsaturated soil hydraulic properties comprising the water retention curve (or soil moisture characteristic) and the hydraulic conductivity function The Heat transport equation considers conduction as well as convection with flowing water. The Solute transport equations consider advective-dispersive transport in the liquid phase, and diffusion in the gaseous phase. The transport equations also include provisions for nonlinear and/or nonequilibrium reactions between the solid and liquid phases, Inputs - dispersivities, diffusion coefficients in the liquid and gaseous phases) and reaction (sorption and degradation) parameters

Ranatunga *et al.*, 2001 found that all three models provided a satisfactory representation of the pattern of soil carbon decline under continuous cultivation. The total error between measured and modelled values was moderately low (5 < Root Mean Square Error > 20) for all models. The values of modelling efficiencies and coefficients of determination were shown to be in a similar range for all sites. Roth-C was found to have less bias than the other two models. All models show a positive correlation between measured and modelled data, although there are some statistical differences in soil C outputs. Ranatunga *et al.*, (2001) concluded that all three models could be used to effectively and accurately model soil carbon dynamics at the test sites.

The level of site-specific information required as part of the modelling exercise was a concern raised by Ranatunga *et al.*, (2001), concluding that as Roth-C requires less site specific information, basic inputs and is less complex, it is well suited to simulations where information is limited or for special arrays. However, independent systems are needed for the estimation of plant residue inputs.

The CSIRO has developed a model for Australian soils and systems based on the Roth-C model, which has been incorporated into FullCAM. The Roth-C Soil Carbon Model is able to predict changes in soil carbon caused by shifts in agricultural practice and has been used to provide estimates for the National Carbon Accounting System (NCAS).

Roth-C Soil Carbon Model

The Roth-C soil carbon model is able to predict changes in soil carbon content as a result of agricultural practices. To confidently use this model, it is good practice to understand the sensitivity of the model to changes in input variables over a range of conditions.

Janik et. al. (2002) conducted a sensitivity analysis of the variables for the Roth-C Soil Carbon Model with much of the data for the study obtained from a Brigalow site in Queensland and from the Waite Institute in South Australia. The findings from this report are summarised below.

Impact of decomposition rates and plant input data

Variables related to plant material inputs: there is a high sensitivity to the ratio of AGDM (above-ground dry matter) : grain yield (Table 1). AGDM data can be obtained from site data or can be modelled, therefore the uncertainty of the variable can be reduced. The high sensitivity of the model to the ratio of root:AGDM, makes this data more important. However, root data are difficult to obtain, especially under field conditions, and may be subject to bias, as most studies refer to sandy soil rather than clay. For example, root:AGDM can be expected to vary from 1 for pasture and 0.4 for wheat to less than 0.2 for sugar cane in some soils.

Because of the limited availability of data on root biomass, its incorporation into soil organic matter and the high sensitivity to plant residue inputs, Janik *et. al*. (2002) identify the root:AGDM as a variable that is potentially highly sensitive.

Table 1 Summary of model response to changes in rate constants and plant input data

Variable	Response	Expected variability	Uncertainty	Contribution to uncertainty	20 year change (t C/ha)
Decomposition rate of BIO pool	Very low	High	Moderate	Very small	< 0.1
Decomposition rate of DPM pool	Very low	High	Moderate	Very small	< 0.1
Decomposition rate of RPM pool	Moderate	High	Moderate	Significant	1.1
Decomposition rate of HUM pool	Moderate	High	Moderate-high	Moderate	0.4
Ratio AGDM:Grain yield	Moderate	High	Moderate	Significant	1.4
Ratio Root:AGDM	Low	High	High	Significant	0.8
Ratio OC:TDM	High	Low	Low	Small	1.2

BIO - biomass; DPM – degradable plant material; RPM – resistant plant material; HUM – humic acid; AGDM – above-ground dry matter; TDM – total dry matter (grain, stubbles and root mass); OC – Organic carbon

Soil Variable

The response of the model to changes in the soil variables, including the values of the soil carbon within the individual pools is summarised in Table 2. The prediction of soil carbon was fairly insensitive to the amount of clay in the soil. The final estimate was affected by less than 0.1 t C ha^{-1} when the clay content varied between 5 to 70%, but was increasingly sensitive with very low clay content (<5%).

The model showed a moderate response to all carbon pool values, with soil carbon changes of approximately 0.3 t ha^{-1} for a 10% change in carbon pool over 30 cm depth. Estimates of these soil variables may be highly uncertain, so these components have a potentially large impact on the overall uncertainty. Rank correlations, between soil carbon and the RPM pool variable in the @Risk™ analysis was highly significant and appeared among the top three variables. The inert organic matter (IOM) pool, which consists mainly of charcoal was ranked much lower throughout the test period.

Table 2: Summary of model response to changes in soil variables

Variable	Response	Expected variability	Uncertainty	Contribution to uncertainty	20 year change (t C/ha)
Percent clay	Small	Large	Moderate	Small	< 0.1
RPM pool (t C/ha)	Moderate-high	High	Moderate	Significant	1.5
IOM pool (t C/ha)	Moderate	High	Low-Moderate	Moderate	0.3

Crop Variables

Model response is expected to depend on the effect of the particular crop variable in modifying the amount of plant material entering the system. Of these variables, Janik *et al.*, (2002) found the time of sowing (crop start) and the number of months in crop (months cropped) had only a small contribution to the model uncertainty.

Janik *et al.*, (2002) found moderate sensitivity to crop grain yield but records are available for this value in most situations, or yield can be modelled. Variability in yield will, therefore, have only a moderate contribution to the overall uncertainty. The fraction of stubble retained has a low to moderate level of sensitivity and uncertainty. Therefore, fraction of stubble retained is rated as having only a relatively low contribution to the overall model uncertainty.

Climate Variables

The temperature variations had only low to moderate sensitivity. This, combined with low to moderate uncertainty in the temperature data, would mean that this variable contributes only a small degree to the overall uncertainty. Rainfall plays a pivotal part in the soil moisture rate modifying variables, in addition to its impact on the correlation with biomass production that may impact on soil carbon.

The predictions of soil carbon were, therefore, strongly affected by some (but not all) changes in rainfall. That, together with extrapolation uncertainties and the possibility of local variability in rainfall, makes rainfall a sensitive variable. It was not only average rainfall that was found to be important, but also its variability. The response for a 10% change in variation is very low. The variability within a year was not important at all sites – it had little effect on the soil carbon predictions when the model was used on the Waite, Tarlee and Wagga Wagga sites (due to less variability between seasons). Both rainfall data and the variability of rainfall data, therefore, appear to be sensitive variables. The effect of the among years variability at the Brigalow site highlights the dangers of using long-term means as inputs to the *Roth-C* model. This reinforces the need to generate monthly-interpolated deviate surfaces for model implementation.

Summary

Janik *et al.*, (2002) found the most sensitive variables are; resistant plant material (RPM) pool size and decomposition rate; and variables associated with plant inputs. Annual rainfall variability is also highly sensitive in some regions where occasional high rainfall events occur. Variables of moderate sensitivity are the humic acid (HUM) decomposition rate, the size of the inert organic matter (IOM) pool and a number of climate variables. Other variables have relatively low sensitivity.

Roth-C has been assessed for Australian conditions and the default figures have been adjusted accordingly, however the model itself has been largely incorporated into FullCAM.

FullCAM 4.1.6.19417 (2016)

The Full Carbon Accounting Model (FullCAM) is the model used to construct Australia's national greenhouse gas emissions account for the land sector and must be used to model carbon stock change and emissions for some CFI methodology determinations. FullCAM includes the Rothamsted Soil Carbon Model (Roth-C) described in Jenkinson *et al.*, (1987, 1991) and Jenkinson (1990) [13]. During the development of FullCAM, a research project was commissioned by the Australian Greenhouse Office (AGO) to calibrate the Rothamsted soil carbon turnover model (Roth-C version 26.3) for Australian conditions (Skjemstad and Spouncer, 2003; Skjemstad *et al.*, 2004). The model parameters derived from this calibration activity were incorporated into FullCAM.

FullCAM deals with both the biological and management processes which affect carbon pools and the transfers between them in forest and agricultural systems. FullCAM uses data processed from satellite imagery, in combination with input data on land management, climate, and soil, and applies ecosystem models to estimate the flow of carbon dioxide between the atmosphere and the different carbon pools of the land sector. The exchange of carbon loss and uptake between the terrestrial biological system and the atmosphere are accounted for in a closed cycle mass balance model which includes all biomass, litter, and soil pools.

The FullCAM framework and its development are described by Richards (2001) and Richards and Evans (2004).

FullCAM has been selected for the Tier 3 method[14] based on several criteria:

1. The model has been developed in Australia and extensively tested and verified for Australian conditions (National Inventory Report 2013, Vol. 2). In addition, the model has been widely used for simulating soil and biomass carbon dynamics at project level (Australian Government Carbon Farming Initiative and future Emission Reduction Fund) and nationally.
2. FullCAM is capable of simulating, cropland, grassland, and forest eco-systems and land-use transitions between these different land uses at the 25m pixel level. As most emissions and removals of greenhouse gases occur on transitions between forest and agricultural land use, integration of agricultural and forestry modelling was essential.

[13] FullCAM is a result of continuous work and contributions from a range of organisations, made up of both data providers and IT service providers. To view the FullCAM institutional arrangements relating to the collection and preparation of input data for FullCAM, refer Volume 1 of the 2013 National Inventory Report (Section 1.2). The development of FullCAM and its component models is described in Volume 2 of the 2013 National Inventory Report (Appendix 6B).

[14] The Intergovernmental Panel on Climate Change (IPCC) methods for estimating emissions and removals are divided into 'Tiers' encompassing different levels of activity and technology detail. Tier 1 methods are generally straightforward (activity multiplied by default emissions factor) and require less data and expertise than the most complicated Tier 3 methods. Tier 2 and 3 methods have higher levels of complexity and require more detailed country-specific information on things such as technology type or livestock characteristics. The concept of Tiers is also used to describe different levels of key source analysis, uncertainty analysis, and quality assurance and quality control activities.

3. The model is designed to simulate management practices that influence soil carbon dynamics including quantification of inter-annual variability.
4. FullCAM has components that deal with both the biological and management processes which affect carbon pools and the transfers between pools in forest, agricultural and transitional systems. The exchanges of carbon, loss and uptake between the terrestrial biological system and the atmosphere are accounted for in the full/ closed cycle (mass balance) model which includes all biomass, litter and soil pools (Appendix A).
5. The data required for FullCAM to simulate is available nationally at appropriate scales for the data in a spatially and temporally time series consistent format.

FullCAM Sub-Models

FullCAM has been developed as an integrated compendium model that provides the linkage between various sub-models.

The three sub-models integrated to form FullCAM as used in the National Inventory are:

1. CAMFor (Richards and Evans, 2000a), the carbon accounting model for forests.
    a. CAMFor is used to model carbon mass and transfers between the living tree and debris pools of forest lands.
    b. CAMFor has its origins in the 1990 CO_2 Fix model of Mohren and Goldewijk (1990);
2. CAMAg (Richards and Evans, 2000b), the carbon accounting model for cropping and grazing systems (Figure 1).
    a. The CAMAg model reflects the impacts of management on carbon accumulation and allocates masses to various plant, debris and soil pools. Yields need to be prescribed in the model;
3. Rothamsted Soil Carbon Model, Roth-C (Jenkinson, *et al.* 1987, Jenkinson *et al.* 1991).
    a. Roth-C models changes in soil carbon based on the inputs of organic matter from dead plant material and soil carbon decomposition rates. It is used in conjunction with both CAMFor and CAMAg.

Estimating Changes in Soil Carbon

Roth-C models the changes in soil carbon based on the inputs of organic matter from dead plant material and soil carbon decomposition rates. Plant residues are firstly split into decomposable and resistant plant material. Soil carbon is fractionated into various soil carbon pools, generally defined by classes of resistance to decomposition. Turnover rates for each soil fraction are determined by rainfall, temperature, groundcover and evaporation. Roth-C is used in conjunction with both CAMFor and CAMAg to model soil carbon stocks in the national account.

Soil inputs to the model are soil type (for fractionation), clay content and the initial topsoil moisture deficit. These affect the amount of carbon in each soil fraction (e.g. RPM, DPM) and the subsequent rates of loss or gain in soil.

Soil C Model Determination/Suitability

From the soil C model reviews, it was prioritised to evaluate FullCAM for modelling changes in carbon stocks in South Australian clay modified soils, primarily as it is used to model carbon stock change and emissions by the National Carbon Accounting System. APSIM was considered but the soil module is difficult to change and as no clay modified soil has been characterised, the model predictions are unlikely to be accurate.

FullCAM Evaluation in Clay Modified soils

To evaluate the FullCAM model for clay modified soils the “Configuration” of agricultural soil was chosen rather than agricultural system, to simplify the process. Real data from the New Horizon trial sites at

Karoonda and Brimpton Lake were used. Site information regarding average rainfall, pan evaporation and average air temperature were sourced from Bureau of Meteorology (http://www.bom.gov.au/climate/data/).

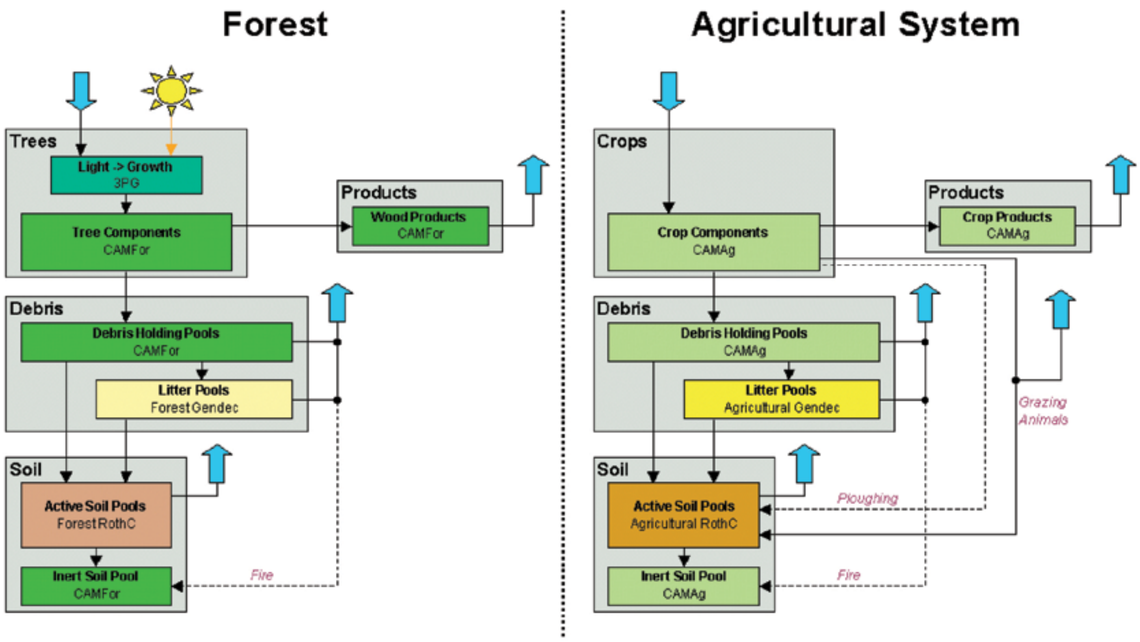


Figure 1 The FullCAM model pool structure

Agricultural soil inputs were determined from biomass cuts conducted at the New Horizon trial sites. Dry matter was assumed to contain 40% C with above ground (tops) dry matter measured (no below ground (roots) dry matter measurements were taken). A range of seasons were used for plant residue inputs – dry, average and wet, rather than just an average season. It was assumed that the majority of C inputs occurred in late spring, summer and autumn with low levels in winter and early spring.

Soil cover was estimated from biomass production at the sites, taking into account management and natural degradation. The "whole plot clay content" in the model was varied to determine the impact of claying from 3% for unmodified sand to 9% for clayed soils[15]. It is assumed that good incorporation of the clay to a depth of 30cm has been undertaken.

The "initial soil" conditions were assumed to contain 13t C ha^{-1}. (average C stock content of deep sand – unmodified soil). In lieu of measured data, carbon masses outlined for SOC pool values within FullCAM for Australian soils (Janik *et al.* 2007) were used —1%, 20%, 2%, 0.2%, 60%, 17% for DPM, RPM, BIOF (biomass fast), BIOS (biomass slow), HUM, and IOM, respectively. Janik *et al.* (2002) report that errors in estimates of the IOM, HUM, and RPM pools contribute to uncertainty in the modelled total soil carbon, with the RPM pool demonstrating most sensitivity in model outputs.

Water moisture deficit was estimated at 10mm/10cm soil for sand (3% clay) and 15mm/10cm soil for sandy loam (9% clay).

Initial testing of the model has indicated that it has potential to simulate changes in carbon stocks in South Australian modified soils (Figure 2).

[15] Soil clay contents of 5-9% have been measured in the 0-30 cm in productive systems after soil modification (Schapel pers comm).

For example at a low rainfall site (370 mm annual rainfall) the carbon stocks increased from the original 10.8t C/ha to 14.9 t C/ha for 3% clay, 20.2 t C/ha for 6% clay and 20.5t C/ha for 9% clay after 25 years (Figure 2). This gave an increase of 4.1 t C/ha at 3% clay, 9.4 t C/ha for 6% clay and 9.7 t C/ha for 9% clay over this period. The largest change in C is driven by the increase in biomass returned with only a relatively small difference between the 6% and 9% clay.

Increasing the clay content to 18% would increase carbon stocks to 22.7t C/ha, 11.9t C/ha above the original levels. However, clay rates this high have been shown to have a negative effect on production (and be uneconomical).

Rainfall had a minor impact on C stocks with the major impact being the changes in biomass produced as a result of the rainfall rather than the rainfall itself.

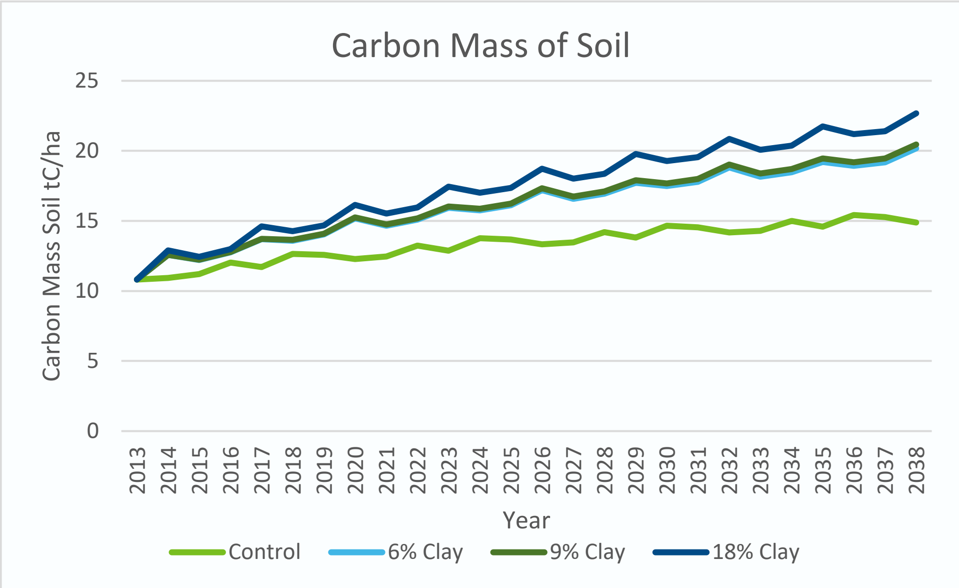


Figure 2 Modelled carbon mass of soil following modification by clay minimum (6% clay) and target (9% clay) at a low rainfall (370mm annual) site.

Carbon pools are relatively sensitivity to C changes in C stocks, therefore it is critical to ensure that the starting levels of the different pools are as accurate as possible. This appears to be the largest gap in our current knowledge with only limited information available about the different carbon pools for South Australian sandy soils. Currently we are using data from Western Australia (Janik *et al.* 2007). Segmentation of the different carbon pools on a range of South Australian soils is a high priority, however the cost of doing this is relatively high and there are currently insufficient funds available. CSIRO (Lyn McDonald) is keen to undertake this work, however they are looking for partners to help fund the analysis.

Additional analysis using FullCAM is required to further assess the impact of rainfall and biomass input from various sites throughout South Australia on C stocks.

Hydrus (HPx) Model

This is a reactive transport model with a flexible framework able to define reaction networks, including soil organic matter (SOM) degradation. It allows users to incorporate a range of user-defined conceptual models to tackle specific projects. The model is able to couple geochemistry with transport properties, colloid and colloid-affected transport, bioturbation and root solute uptake. Jacques *et al* (2017) used the model to implement a reaction network with three organic matter pools:

1) A fast decomposable SOM pool with concentration
2) A slow decomposable SOM pool with concentration

3) A biomass pool (Biomass) with concentration.

In addition, inorganic carbon is released in the aqueous and gaseous soil phases, during decomposition.

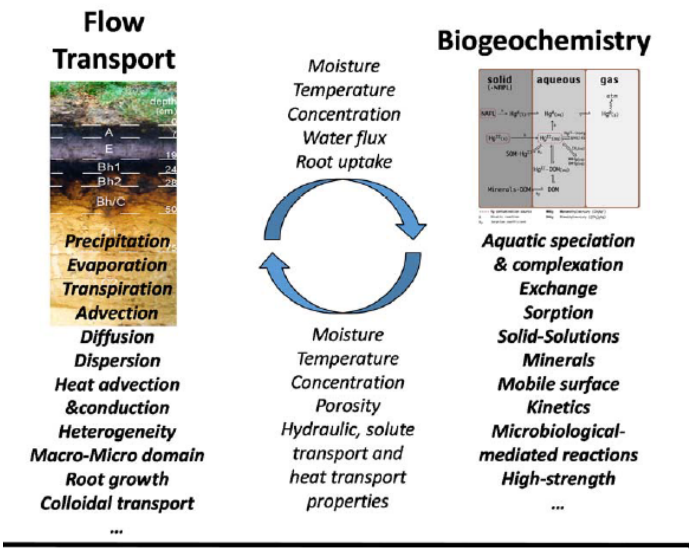


Figure 3: HPx is a reactive transport model coupling water flow and solute transport with biogeochemical processes.

The long term prediction of soil carbon cycling requires an explicit representation of the vertical distribution of soil organic matter, and hence a model able to represent processes leading to the vertical distribution of SOM such as the root litter distribution and the transport of soil organic matter (Braakhekke *et al.*, 2011). The biological transport of soil solid phases, often referred to as bioturbation, depends strongly on the behaviour of the biological community species, which necessitated the development of different modelling approaches (Meysman *et al.*, 2003a).

Jacques *et al* (2017) implemented a biodifussion model within HPx and applied it to the three organic matter pools above and found that a smooth profile of the three organic pools developed over the course of 3 years to about 15 cm below the initial layer with organic matter.

HPx is one of only a few SOM degradation models that can consider spatial-temporal variations in water contents, water fluxes and temperatures, as well as different conceptual models for SOM degradation networks, advection-dispersive transport of decomposable OM, carbon dioxide transport and bioturbation in one modelling framework.

Mallants, D (per. comms 2017) implemented a flow transport model within HPx using a sand and clay. The sand represents the top soil while the clay is used to represent clay clods that were added to the top soil layer to improve the soil water holding capacity. The hydraulic parameters were based on findings from a study from Betti *et al.* (2016) that focused on how the size of subsoil clods affect the soil-water availability in sand-clay mixtures. The saturated hydraulic conductivity was taken directly from Betti *et al.* (2016).

Mallants (2017) found that clay clods of 5cm diameter gave more even distribution of moisture between the clay and sand compared to clay clods with a 10 cm diameter This would indicate that the model has the potential to model how quickly boron and salt would be leached from clay clods. This initial work by Mallants (2017) using the HPx model indicates that it has potential to further model the impact of water movement, soil carbon mineralisation and sequestration in clay modified soils and that this should be further investigated.

Appendix D1

Plant partitioning by crop and pasture type

Species Name	Yield Allocation to Grains, Buds or Fruit (fraction)	Yield Allocation to Stalks (fraction)	Yield Allocation to Leaves (fraction)	Yield Allocation to Coarse Roots (fraction)	Yield Allocation to Fine Roots (fraction)
Annual & perennial	0	0	0.5	0	0.5
Annual grass	0	0	0.50	0	0.50
Annual legume	0	0	0.5	0	0.5
Annual legume irrigated	0	0	0.5	0	0.5
Annual weeds	0	0	0.5	0	0.5
Aristida-Bothriochloa	0	0	0.5	0	0.5
Barley	0	0.3	0.4	0	0.3
Black speargrass	0	0	0.5	0	0.5
Bluebush/Saltbush	0	0	0.5	0	0.5
Canola	0	0.27	0.51	0	0.22
Chickpeas	0	0.3	0.48	0	0.22
Faba beans	0	0.3	0.48	0	0.22
Field pea	0	0.3	0.48	0	0.22
Grazed cereal	0	0	0.6	0	0.4
Grazed cereal – irrigated	0	0.26	0.44	0	0.3
Grazed vetch	0	0.3	0.48	0	0.22
Lentils	0	0.3	0.48	0	0.22
Lucerne	0	0	0.5	0	0.5
Lucerne irrigated	0	0	0.5	0	0.5
Narrow-leaf lupin	0	0.23	0.55	0	0.22
Native annual	0	0	0.5	0	0.5
Native annual improved	0	0	0.5	0	0.5
Native perennial	0	0	0.5	0	0.5
Native perennial improved	0	0	0.5	0	0.5
Oats	0	0.26	0.43	0	0.31
Oil poppies	0	0.4	0.4	0	0.2
Perennial grass	0	0	0.5	0	0.5
Perennial grass irrigated	0	0	0.5	0	0.5
Perennial grass/clover	0	0	0.5	0	0.5
Perennial legume	0	0	0.5	0	0.5
Samphire	0	0	0.5	0	0.5
Spinifex	0	0	0.5	0	0.5
Triticale	0	0.26	0.43	0	0.31
Vetch	0	0.3	0.48	0	0.22
Weeds annual	0	0	0.5	0	0.5
Weeds perennial	0	0	0.5	0	0.5
Wheat	0	0.26	0.44	0	0.3

The Goyder Institute for Water Research is a partnership between the South Australian Government through the Department for Environment and Water, CSIRO, Flinders University, the University of Adelaide, the University of South Australia, and the International Centre of Excellence in Water Resource Management.