PIRSA
Discussion Paper

Soil carbon and climate change

Prepared by Rural Solutions SA

For the Sustainable Systems Group,
Agriculture, Food and Wine,
Primary Industries and Resources SA

June 2010

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Acknowledgements

This paper has built on previous literature review and scoping work (Schapel 2008) funded by DWLBC. Comments on key policy implications arising from their work in the field of soil carbon were also gratefully received from Richard Eckard (University of Melbourne), Jeff Baldock and Jonathan Sanderman (CSIRO Land and Water), and Tim Herrmann (DWLBC). Further information and review was also provided by Brian Hughes (Rural Solutions SA).

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30 June 2010

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EXECUTIVE SUMMARY

Agriculture is a carbon-based activity, utilising largely natural processes to capture the sun's energy in the form of carbon stores in plants, animals and soils. Carbon stores are also in a state of continuous change and renewal as carbon moves between different parts of the global carbon cycle. Within this context it is now widely recognised that human activities (including agricultural activities) have altered the carbon and energy balance of the atmosphere, due to excessive emissions of greenhouse gases (GHG). With the threat of dangerous climate change, there is a growing imperative for governments across the world to support the transition to low emissions agriculture.

With a general move by society to control carbon (and other GHG) emissions there will be indirect or direct pressures on farmers to also reduce the carbon emissions associated with food and fibre production. Even if agriculture is not included within early policy efforts to cap and reduce carbon emissions (such as Australia's proposed Carbon Pollution Reduction Scheme), it will need to contribute to ambitious mid to long term national commitments. Soil carbon sequestration may play a role in this, nicely dovetailing the need for climate change adaptation and mitigation. In regard to adaptation, soil carbon has recognised benefits in improving soil structure, water retention and fertility, enabling improved productivity, profitability and greater resilience to a warming, drying climate. Therefore, building soil carbon is considered a worthwhile activity regardless of whether sequestered carbon can be sold. On the mitigation side, additional incentives for farmers to build soil carbon would contribute to the global challenge of reining in our GHG emissions. However, simple messages that 'soil carbon holds great potential for mitigating climate change' are not universally true.

The ability of a farmer to (i) increase soil organic carbon levels and (ii) permanently retain that increase, depends on complex interacting environmental, economic and land management factors. Soil organic carbon (SOC) exists in various forms (with varying degrees of permanence) and is essentially in a constant state of flux, responding to changes in rates of accumulation and loss. High rates of production (associated with higher rainfall, fertility and high water use efficiency) with maximum return of plant residue to the soil are desirable to feed the soil carbon pool. Sufficient soil capacity is needed to store and protect the SOC from microbial attack (usually the higher the clay %, the greater level of protection). Microbial decomposition causes organic carbon to be mineralized and lost to the atmosphere as CO_2. Soil microbes are diverse ecological communities requiring the right environmental ranges (temperature, moisture, pH, etc) to thrive as well as a complex web of carbon-based food sources (including each other). Mixing plant residues with surface soil (e.g. tillage) delivers more food encouraging microbial decomposition. When environmental conditions are right and food is available, microbes will continue feeding. During seasons or months when plants aren't growing (e.g. out-of season in annual cropping situations, or fallowed paddocks) microbes can continue feeding and depleting stored SOC (except when microbial growth is limited by environmental conditions such as soil moisture deficiency). Erosion can also accelerate SOC losses. It should also be noted that SOC changes to a new equilibrium level may take decades to centuries, particularly if more resistant SOC pools are present. In some cases, SOC in agricultural soils may still be declining in response to the initial clearance of native vegetation. Climate change (warming and drying) may also reduce the potential of many areas of the State to build or maintain SOC, largely resulting from greater rainfall limitation to plant production.

Soil type and climate provide over-riding limitations to SOC potential. Any imported organic carbon which is surplus to the protective capacity of the soil type remains susceptible to microbial attack. The speed of breakdown will depend on the form of organic material applied, soil factors (e.g. clay percentage) and climate factors. Climatic factors also limit carbon inputs from farm production. However, farm management and land use can influence SOC storage within these boundaries. Resilient and well managed pastures will generally retain greater levels of SOC than cropping systems due to less soil disturbance. Changes from traditional tillage to conservation tillage and full stubble retention may halt SOC decline and potentially build SOC from levels depleted by tillage. However, conservation cropping technologies will generally not attain the levels of soil carbon found in perennial pasture or natural systems.

With much of South Australia dominated by low rainfall the statewide potential to build SOC through changes to agricultural practice appears limited. Questions over the ability of cropping areas below 500mm annual rainfall to build SOC requires long-term research to be conducted. Research is required using the latest developments in zero-till, precision agriculture with full stubble retention to determine if best practice conservation tillage is capable of building SOC in these lower rainfall areas, or whether it just halts SOC decline. Limitations to dry matter production also need to be addressed (for large areas of South Australia annual crop water use efficiency is estimated at between 50-70%). When trying to maintain or improve SOC, care is needed with the application of fertilisers. Over-application of readily plant-available N can stimulate microbial attack and the consequent breakdown of SOC, while also being associated with emissions of the damaging GHG nitrous oxide, not to mention wastage of inputs and embodied energy. There are opportunities to improve N use efficiency, for example through: better soil N testing, greater uptake of precision farming methods, slow-release coatings on urea, nitrification inhibitors and multiple smaller liquid N applications in response to favourable seasonal conditions (compared to a single large application). Synthetic N fertilisers have also been implicated more generally in the degradation of SOC quality (causing decline in more permanent SOC fractions) in some situations. It is suggested that labile synthetic N can stimulate rapid microbial attack on stored SOC including the organic binding agents which hold soil micro-aggregates together. Consequently any breakdown in soil micro-aggregate structure will adversely affect the protection and permanence of SOC.

Other options to increase SOC levels through changes to farming systems include: greater incorporation of pastures (including perennials) into cropping situations, and small management changes across large areas of degraded rangelands may offer significant potential. Some biological (/organic) farming methods have also been reported to offer SOC benefits and reduced emissions over conventional farming systems. The application of new technologies also offers some significant potential to increase SOC levels. Soil modification through clay spreading, delving and spading appears to increase the capacity of SOC storage and is applicable across large areas. Soil organic amendments (e.g. manure, biochar, compost, biosolids, etc) imported from off-site may also increase SOC but their application may be limited by availability and cost-effectiveness.

For any activities designed to sequester carbon, life cycle analyses are required to determine whether there has been a net sequestration of CO_2 (including CO_2-equivalence impacts of other GHG emissions such as nitrous oxide and methane), accounting for associated production methods, transport, embodied emissions in farm inputs and any carbon removed from external sites. While requiring the development of greater levels of scientific understanding, ultimately this type of holistic analysis will benefit moves towards low GHG emissions agriculture, which should be more sustainable in the long-term.

It is most likely that the value of soil carbon for carbon trading markets will be discounted due to uncertainty in relation to measurement of stocks, uncertainty about its permanence in our variable climate, and due to lower values associated with voluntary carbon markets. A low carbon price provides neither an incentive for changing management or just reward for farmer's efforts. If soil carbon stocks were accepted into formal (mandatory) carbon markets this may provide a higher carbon price and potentially allow offsets to count against our international obligations – but with the downside of exposure to natural SOC declines and associated liability under our highly variable climate. It should be noted that because of climatic differences, long-term sequestration of soil carbon is much more problematic in Australia (even more so in South Australia) compared to North America or Europe.

Soil carbon trading may be a viable option for some farmers, however this is likely to be restricted to particular situations, for example: currently degraded soils (with low initial SOC levels); higher rainfall areas (with greater production potential); heavier soil types (as clay particles help to protect SOC); systems with higher proportions of productive grass / legume pastures; adoption of biological farming methods (e.g. replacing synthetic N with organic fertilizer, reducing overall energy use and/or encouraging co-benefits of symbiotic mycorrhizal fungal associations best hosted by perennial pastures) and sustainable use of recycled organic wastes. Also retirement of marginal agricultural land back to native vegetation is thought to have significant SOC benefit, as nearly all plant production can be returned to the soil.

According to CSIRO estimates, Australia's current Kyoto Protocol commitments (which don't include soil carbon) already open the door to nearly 80% of the carbon sequestration potential of the continent, mainly in the form of forestry. CSIRO also estimates soil carbon to offer around 2.5% of the national sequestration potential, and this would be unevenly distributed towards favourable climates and soil types. Given our predominantly low rainfall and sandy soils, South Australia is not expected to be a large player in the area of soil carbon sequestration or trading. However, this view does not take into account the potential offered through soil modification. This highlights that an audit of existing capacity, and potential to improve capacity in South Australian soils is a key piece of work needed to build our understanding and support involvement of landholders in any carbon trading scheme.

If considered viable, any soil carbon trading scheme should consider learnings from a prominent existing scheme – the Chicago Climate Exchange – which utilises management bodies (called 'aggregators') to pool and verify farmers' soil carbon stocks, and regionally calibrated models to monitor SOC behaviour. We would require our own protocols for SOC verification based on a rigorous scientific understanding and locally relevant models describing the behaviour and permanence of soil carbon fractions in different combinations of soil type, climate, land use and management. Currently this rigorous understanding is lacking. While research is being undertaken by CSIRO, and supported by State agencies, funding is limited and additional support is needed. In this report options are also discussed which may reduce the risks to farmers from soil carbon trading, for those situations where it might be deemed a worthwhile exercise.

Related agricultural/soil management greenhouse emissions mitigation activities are possible through reduced emissions from fossil fuels, nitrous oxide (N_2O) and methane (CH_4). Some of these may be "win-win scenarios" (e.g. improved profitability through more efficient N fertiliser use, while reducing N_2O emissions). Arguably such activities would not satisfy carbon offset eligibility criteria (as they are arguably not 'additional' to business as usual), but if such activity was considered eligible for carbon offset trading, this would provide further incentive for adoption. This type of emissions reduction activity is of particular interest and has advantages over soil carbon sequestration in that (i) they are ongoing, not a 'once off' improvement, (ii) as a foregone emission they do not have the permanence requirements and risks of decline, and (iii) they do not represent an ongoing encumbrance on land title.

The following are recommended priority areas for further policy discussion:

Building SOC

- Building SOC in agricultural soils should be promoted – due to numerous co-benefits for productivity, profitability and resilience to climate change, regardless of the issue of selling carbon credits. The future viability of soil carbon trading (with possible retrospective payments) can be determined by farmers at a later date – following the development of cost-effective monitoring methods, regionally calibrated SOC models and collection of actual time-series trends in SOC stocks. (This is consistent with the message from key commentators that farmers should build SOC for farming benefits now and worry about possible carbon trading later.)
- An audit of existing capacity, and potential to improve capacity (e.g. through modification of sandy soils), to store increased SOC in South Australian soils be undertaken.
- Support existing industry bodies in the promotion of best practice farming methods that are consistent with SOC improvement goals
- Extend the latest science / developments in farm GHG abatement technologies to farmers as they become available to help inform management decisions (maximising opportunities and minimising threats)
- Support research efforts investigating cost-effective SOC improvements at the State scale, e.g. clay spreading / delving on sandy soils.
- Assess the SOC benefits and profitability of a 'carbon farming' approach – across a range of soil types, rainfall zones and enterprises (e.g. livestock focus, cropping focus, mixed livestock and cropping, organic farming methods, incorporating more perennials), with consideration to whole of farm economic modelling.
- Integrating developing knowledge of SOC improvement and reduced GHG emissions (CO_2, N_2O and CH_4) practices into climate risk management delivery programs.

Investigating climate change mitigation / carbon trading opportunities

- Seek clarification at the national level of key eligibility criteria affecting soil carbon trading opportunities in agriculture. These include "additionality" criteria (where "win-win" practices may be considered 'business as usual'), "permanence" requirements, and the potential for different treatment of management-induced versus naturally-induced SOC changes.
- If soil carbon trading is to become a viable opportunity in South Australia, this will require the development of a practical legal framework, allowing soil carbon property ownership rights.
- Investigate policy or education frameworks to encourage GHG abatement via incentives, improved efficiencies or optimising marketability of products, e.g. through:
  - reduced fuel use
  - reduced nitrous oxide and methane emissions
  - more efficient use of N fertilisers
  - greater use of N-fixing legumes / alternative fertilisers
  - product labelling to reflect climate change awareness and GHG abatement associated with overall farming practices and/or the farm product value-adding chain

1 INTRODUCTION

1.1 AIM

In expectation of growing impacts of climate change on our landscapes, natural resources and rural productivity, and in light of current research, novel concepts and recent experience on carbon in soil, this discussion paper presents a summary on:

- what is the status of information and potential best approaches in South Australia for managing soils for carbon sequestration with benefits for productivity, natural resources management and climate change mitigation?
- what are other climate change mitigation (carbon offset) tools that might be pursued in the area of soil management?
- and how might progress in this area best be facilitated by PIRSA?

This work will:

- build on PIRSA's climate change understanding, and inform policy development
- discuss potential economic and environmental opportunities and risks in the management of soil carbon as it relates to climate change mitigation
- identify and qualitatively evaluate a range of related opportunities – for example in farm productivity and efficiency, carbon trading, soil health, sustainable development, etc
- explore a potential framework for understanding, integrating and applying new knowledge and concepts on soil carbon and climate change

Soil carbon sequestration

...is the removal of atmospheric CO_2 through photosynthesis to form organic matter, which is ultimately stored in the soil as long-lived, stable forms of carbon.

For sequestered soil carbon to become a tradeable entity, it must satisfy a number of criteria, e.g. be measurable, additional to 'business as usual' investment, permanent, transparent, independently audited, and registered. (source: *National Carbon Offset Standard*)

While this paper has a focus on South Australian issues, we acknowledge there is a considerable body of expertise and ongoing knowledge gathering in these areas at the national level (e.g. Eady *et al* 2009[1], Sanderman *et al* 2010[2], Walcott *et al* 2009[3], The Climate Institute 2009[4], CSIRO 2009[5]).

1.2 PROJECTED CLIMATE CHANGE AND IMPLICATIONS FOR SA FARMERS

This paper is consistent with the PIRSA position[6] and the overwhelming scientific consensus (including climate scientists from BoM and CSIRO) that human-induced climate change is occurring as a result of emissions that are increasing atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHG).

Climate change projections for the agricultural regions of SA indicate that annual average temperatures will increase by 0.4°C to 1.8°C by the year 2030, and between 0.8°C and 5.5°C by 2070. Average annual rainfall may decrease by as much as 15% by 2030 and by 45% by 2070 (Suppiah *et al* 2006)[7].

Throughout the agricultural regions of South Australia the impact of a warming, drying climate is likely to be primarily negative, and exacerbated on the drier fringe (e.g. in already marginal / low return cropping land). Impacts are likely to include, but are not limited to (Suppiah *et al* 2006, McInnes *et al* 2003[8], CSIRO & BoM 2007[9], CSIRO 2008a[10], PIRSA 2009a[11], Stokes and Howden 2010[12], Ludwig & Asseng 2006[13], Hennessy *et al* 2008[14]):

- Rainfall declines mostly in winter and spring
- Increased frequency of low rainfall years
- Increased evaporative water loss combined with reduced water availability
- Longer dry spells between rainfall events
- Higher frequency and severity of droughts

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[1] Eady S, Grundy M, Battaglia M and Keating B (Eds) 2009, *An analysis of greenhouse gas mitigation and carbon biosequestration opportunities from rural land use*, CSIRO, St Lucia, QLD

[2] Sanderman J, Farquharson R and Baldock J, 2010, *Soil carbon sequestration potential: A review for Australian agriculture*, CSIRO Land and Water, prepared for the Department of Climate Change and Energy Efficiency, http://www.csiro.au/resources/Soil-Carbon-Sequestration-Potential-Report.html

[3] Walcott J, Bruce S and Sims J, 2009, *Soil carbon for carbon sequestration and trading: A review of issues for agriculture and forestry*, Bureau of Rural Sciences, Department of Agriculture, Fisheries & Forestry, Australian Government, Canberra, http://adl.brs.gov.au/brsShop/data/soil_carbon_report_final_mar_2009.pdf

[4] The Climate Institute 2009, *Towards climate-friendly farming: Policies, issues and strategies for low emissions agriculture and rural land use*, Discussion paper Oct 2009

[5] CSIRO 2009, *The Soil Carbon Research Program: assessing soil carbon across Australia* (website), http://www.csiro.au/science/Soil-Carbon-Research-Program.html

[6] PIRSA (Climate Working Group) Unpublished, *Climate Change, the Carbon Economy and the Primary Industries and Resources Sectors in South Australia, a policy discussion paper*, draft working document, viewed Jan 2010

[7] Suppiah R, Preston B, Whetton PH, McInnes KL, Jones RN, Macadam I, Bathols J & Kirono D, 2006, *Climate change under enhanced greenhouse conditions in South Australia—an updated report on assessment of climate change, impacts and risk management strategies relevant to South Australia*, CSIRO Marine and Atmospheric Research, Aspendale Victoria

[8] McInnes KL, Suppiah R, Whetton PH, Hennessy KJ and Jones RN, 2003, *Climate change in South Australia: Assessment of climate change, impacts and possible adaptation strategies relevant to South Australia*, CSIRO Atmospheric Research, Aspendale Victorian, viewed 1 March 2008, http://www.climatechange.sa.gov.au/uploads/pdf/CSIRO_Final_Report2.pdf

[9] CSIRO & BoM, 2007, *Climate change in Australia – Technical report*, viewed 8 Jan 2010, http://www.climatechangeinaustralia.gov.au/

[10] CSIRO 2008a, *An overview of climate change adaptation in the Australian agricultural sector – Impacts, options & priorities*, http://www.csiro.au/resources/AgricultureAdaptationReport2008.html

[11] PIRSA 2009a, *The changing climate – impacts and adaptation options for South Australian primary producers*, Primary Industries and Resources South Australia, October 2009

[12] Stokes C and Howden M, 2010, *Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future*, CSIRO Publishing

[13] Ludwig F and Asseng S, 2006, 'Climate change impacts on wheat production in a Mediterranean environment in Western Australia', *Agricultural Systems*, 90, 159-179

[14] Hennessy K, Fawcett R, Kirono D, Mpelasoka F, Jones D, Bathols J, Whetton P, Stafford Smith M, Howden M, Mitchell C and Plummer N, 2008, *An assessment of the impact of climate change on the nature and frequency of exceptional climatic events*, Bureau of Meteorology and CSIRO

- Increase in bush fire risk (20-30% increase by 2050)
- Accelerated crop growth due to warmer temperatures and expected declines in spring rainfall (likely to lead to different crop variety selections)
- Reduced viability for crops sensitive to dry conditions (e.g. canola and some pulses)
- Restricted options and times for crop rotation
- Reduced crop and pasture yields in warmer, low rainfall areas (where reductions in rainfall are expected to outweigh any benefits from increased CO_2 concentrations).
- Possible yield increases where rainfall or soil constraints are not limiting. This may also occur with faster crop development (with warmer temperatures) shifting the grain filling period into a wetter part of the season.
- Production may increase in cooler or wetter areas due to (i) warmer winter temperatures and (ii) reduced waterlogging and reduced nutrient leaching.
- Reduced grain and pasture protein quality resulting from increased nitrogen use efficiency under higher CO_2 levels
- Reduced dry down time prior to harvest (under hotter and drier conditions) which may affect grain quality, e.g. grain cracking or small grains
- Farms dominated by fine textured (more clayey) soils are likely to see much stronger negative effects of declining rainfall than farms dominated by more sandy soils
- Possible higher vulnerability of sandy soil types to reduced crop yields under high temperatures (although in low rainfall settings, moisture stress in heavy soils is likely to be a bigger problem)
- Increased rainfall intensity, which may increase opportunities for water harvesting, but also lead to higher incidences of flooding, erosion and storm damage
- More intense and frequent heatwaves (however for cropping the risk of heat stress will tend to be offset by faster crop development with flowering and grain fill during cooler periods)
- Increased heat stress in livestock due to heatwaves
- Reduced availability and quality of water for livestock
- Migration and changes in the competitiveness of pest plants, animals and diseases
- Problems with reaching chilling requirements in some established perennial horticulture crops due to rising minimum temperatures
- Problems with climatic indicators and potential mis-matches between plant development stages and synergistic species which assist with pollination, pest control, etc.
- Reduced ground cover protection for erosion control
- Salinity increases in soils and groundwater resulting from warmer, drier conditions and less flushing from rainfall
- Reduced recharge to groundwater / aquifers

Areas that might be advantaged by a warming, drying and increasing CO_2 will be predominantly currently cool and mid to high rainfall zones. Whereas already warm and low rainfall areas (ie. much of South Australia) are expected to be adversely affected.

Management will play a significant role in overcoming any future challenges and existing climate risk management strategies currently used successfully in low rainfall, less reliable country, will provide a valuable foundation for short and long term climate change adaptation across the State (e.g. Doudle *et al* 2008[15], PIRSA 2009a).

As outlined in later parts of this paper, steps taken to increase organic matter (and carbon) in soils will help to make agricultural land more resilient to a warming and drying climate. However, to some extent the task of accumulating soil organic carbon is made more difficult under such a climate trend.

1.3 WHY BUILD UP CARBON IN SOILS?

1.3.1 Productivity and sustainability

There are many important production and environmental benefits associated with increasing carbon (ie. organic matter) in soils including:

- Improved soil structure
- Increased soil fertility
- Increased water holding capacity (PAWC or 'bucket size')
- Increased infiltration capacity
- Increased water use efficiency – due to reduced moisture loss from runoff, evaporation[16] or deep drainage below the root zone
- Increased soil biological health resulting in higher nutrient cycling and availability

These factors result in:

- Increased crop yields and pasture growth
- Increased reliability of production
- Increased resilience to dry periods
- Increased economic value of the land
- Potential to reduce fertiliser (N, P) use over the longer term
- Reduced erosion risk (associated with higher levels of soil cover and reduced soil disturbance / erodibility)

Soils have a natural equilibrium of soil carbon determined by the rate of organic input versus the rate of breakdown. This can vary greatly according to factors such as climate conditions, soil type, land use and management but typically soils are below optimal levels under cropping systems and highly grazed pastures. Generally speaking, farmers' actions to improve soil carbon to achieve these types of benefits are worthwhile in their own right. There are also strong links between soil carbon levels and the long-term sustainability of farming enterprises and the natural resource (soils). Stewart 2006[17] argues that maintenance of soil carbon levels is critical for the sustainability of dryland agricultural systems. Cropping of lands is viewed as unsustainable where insufficient and highly variable precipitation has resulted in rapid declines of soil carbon. In addition to maintaining the economic productivity of landscapes, the diverse roles performed by healthy, well-structured soils are also critically important in the preservation of natural biodiversity and the functioning of ecosystems (Krull *et al* 2004)[18].

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[15] Doudle S, Hayman P, Wilhelm N, Alexander B, Bates A, Hunt E, Heddle B, Polkinghorne A, Lynch B, Stanley M, Frischke A, Scholz N and Mudge B. 2008, *Exploring adaptive responses in dryland cropping systems to increase robustness to climate change*. SARDI, Department of Climate Change comprehensive project report

[16] As soil carbon enhancement requires maintenance of good cover on soils.

[17] Stewart BA, 2006, 'Dryland agriculture challenges and opportunities', in Sommers L, Wilding L, Sparks D, Peterson G and Peterson L (Eds) *Frontiers of soil science – 18th World congress of soil science July 9-15th, Philadelphia, Pennsylvania*

[18] Krull ES, Skjemstad JO and Baldock JA, 2004, *Functions of soil organic matter and the effect on soil properties*, GRDC Project No CSO 00029, CSIRO Land and Water and CRC for Greenhouse Accounting

1.3.2 Climate change mitigation and potential market incentives

While there has been much focus on reducing future CO_2 emissions as a mitigation approach, the 'legacy load' of CO_2 already in the atmosphere means that we are locked into some degree of human-induced climate change. Sequestering carbon (e.g. by drawing and trapping atmospheric carbon into soils and plants) is seen as a primary means to rapidly reduce current CO_2 levels – thereby helping to avoid potentially devastating high-end climate change scenarios.

Soils are the largest sink of the global terrestrial carbon cycle holding 1,500 Gigatonnes (Gt), three times the amount of carbon in vegetation (~560 Gt) and twice as much as the carbon in the atmosphere (~770 Gt). Approximately half of all soil carbon in managed ecosystems has been lost to the atmosphere during the last two centuries due to cultivation. This now represents an opportunity for carbon storage (McCarl *et al* 2007)[19].

In anticipation of the introduction of a 'carbon economy' in Australia there may be economic incentives (e.g. carbon credits, product labelling, etc) for producers to take action to increase soil carbon levels. Article 3.4 of the Kyoto Protocol includes the sequestration of carbon in soil and (although not officially adopted by the Australian Government) has paved the way for carbon trading markets and potential monetary payments for fixing carbon in soils.

As discussed through this paper there are a range of economic and environmental factors which will determine a farmer's ability to build carbon in their soils. Whether South Australian farmers can justify changing management to sequester soil carbon, in pursuit of economic benefits via the 'carbon economy' (e.g. selling soil carbon credits) will be decided on a case by case basis – however some guiding principles are presented. At current price estimates, farmers should not expect large returns from carbon credits, making it difficult to justify changing management solely for this purpose (GRDC 2009)[20]. This situation may change into the future.

1.4 GOVERNMENT RATIONALE FOR SUPPORTING A LOW-CARBON AGRICULTURAL SECTOR –AND SUMMARY COMMENTS ON THE ROLE OF SOIL CARBON

Australia's agricultural industries are amongst those globally that stand to lose the most from unmitigated climate change. Long-term adaptation efforts are expected to fail if we fail to rein in global emissions, making national food security a real concern in a future, hotter world (The Climate Institute 2009). A national commitment to GHG abatement (including in agriculture) will help to strengthen international agreements and connections to low-carbon export markets, while placing additional pressure on non-complying nations.

There is a strong sense that the Australian Government and the national economy will ultimately be bound by international standards and targets for economy-wide GHG abatement – or face likely (i) international sanctions, (ii) export market backlash and/or (iii) commercial disadvantage due to a lack of technical knowledge, skills and capacity in emerging low carbon industries including in agriculture. Early action to support both mitigation and adaptation is seen as prudent risk management and advantageous to avoid greater costs and challenges of delaying action, and to provide certainty to investors, and potential commercial opportunities from research and technological innovation (The Climate Institute 2009).

Australia has two reporting commitments to account for its GHG emissions: (i) against international commitments under the Kyoto Protocol, and (ii) under the precursor agreement – the United Nations Framework Convention on Climate Change (UNFCCC)[21]. In terms of getting "bang for buck", the efficiency

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[19] McCarl BA, Blaine Metting F and Rice C, 2007, 'Soil carbon sequestration', *Climatic Change*, 80, 1-3

[20] GRDC 2009 *Carbon farming* (fact sheet), Grains Research and Development Corporation, http://www.grdc.com.au/uploads/documents/GRDC_CarbonFarming_4pp.pdf

[21] UNFCCC was a precursor to Kyoto; a non-binding treaty arising from the United Nations Conference on Environment and Development (UNCED), informally known as the 'Earth Summit' (Rio de Janeiro, 3-14 Jun 1992), with the objective of stabilising greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, http://unfccc.int/essential_background/items/2877.php

of policy tools to tackle GHG emissions is likely to be assessed on the ability to get timely results on either of these 'report cards'.

Formal or mandatory carbon markets (such as the proposed Carbon Pollution Reduction Scheme, CPRS) are seen by the Australian Government as the least cost way to achieve the required trajectory of GHG abatement targets. While agriculture is not expected to be included in mandatory carbon trading markets in the short term, this sector will eventually need to contribute to meet ambitious mid to long-term national GHG abatement targets. Consultation with the farming sector has begun along these lines (DCC 2009a)[22]. Arguably future climate change mitigation efforts will need to include (direct or indirect) incentives for reducing emissions from agricultural land if there is any hope of stabilising human impact on the global climate system.

There is also pressure from the business community for agriculture to accept a fairer share of the climate policy burden. The Business Council of Australia's position is to maximise the number of sectors included in emissions trading and to "introduce policies which ensure commensurate emissions reductions" if CPRS coverage of a sector is not practical (Business Council of Australia 2007)[23]. Garnaut 2008[24] states that pursuing new land management opportunities such as carbon sequestration, biomass energy production and low-emissions livestock production could significantly lower the economy-wide cost of an Australian emissions trading scheme.

At this stage, trading in sequestered soil carbon looks to be limited to voluntary markets. Farmer participation in this area can be seen as either:

(i) a transitionary step while building the knowledge and capacity to later participate in formal markets, which will actually contribute to Australia's international GHG reduction commitments, or

(ii) an opportunity to realise commercial benefits within a new operating environment with a price on carbon (which could otherwise just be seen as imposing costs on farming).

Aside from real technical and economic factors which limit the physical potential (and $ value) of soil carbon sequestration, while soil carbon is restricted to voluntary markets its monetary value as an offset will remain low (as compared to mandatory markets). As discussed later, there are additional reasons for discounting the value of soil carbon in carbon trading markets at present, including risks and uncertainty associated with measurement and permanence. But a low carbon price produces neither a strong enough stimulus for change or decent rewards for farmers. And a major dilemma with moving soil carbon to a formal (mandatory) carbon market – where eligible offsets would be more valuable and also contribute to our national abatement targets – is the high risk of exposure to natural decline in soil carbon stocks under Australia's variable climate. It is important to note that soil carbon stocks in Australia are much harder to manage than in North America or Europe. This is probably the reason that the Australian Government has not signed off on Article 3.4 of the Kyoto Protocol, which would open up higher value trading opportunities for soil carbon sequestration, but also expose the sector to the financial and carbon offset liabilities from natural losses. On the other hand, if cost-effective improvements in farm production, profitability and long-term sustainability can be demonstrated through SOC improvements then Government may not see itself playing a policy role in promoting soil carbon, aside from extension and delivery of agronomic advice.

It is also informative to note that the CSIRO suggests that **Australia's current Kyoto Protocol commitments already open the door to nearly 80% of the carbon sequestration potential of the continent, mainly in the form of forestry** (Eady *et al* 2009, The Climate Institute 2009). Meanwhile soil carbon is estimated to provide around 2.5% of the national sequestration potential (Eady *et al* 2009). While soil carbon is expected to play a part in future climate change mitigation at the global and national scales, South Australian farmers will need to be very selective in recognising where soil carbon trading may be a feasible option (driven

[22] DCC 2009a, *Terms of reference for a technical options development group to assess alternative greenhouse gas mitigation policies for Australian agriculture*, Australian Government Department of Climate Change, Canberra, (In The Climate Institute 2009)

[23] Business Council of Australia 2007, *Strategic framework for emissions reductions*, http://www.bca.com.au/Content/101042.aspx

[24] Garnaut R 2008, *The Garnaut Climate Change Review – Ch 22 Transforming rural land use*, http://www.garnautreview.org.au/

largely by soil type and existing condition, regional climate, potential for changed management and economic factors).

In summary, the growing imperative to cut global emissions is unavoidable, with the international trend towards stronger, broader action across all sectors. It is highly likely that governments regardless of political persuasion will eventually introduce policies to support low-carbon agriculture. The benefits of adopting early action and leadership include commercial innovation opportunities and the potential to inform new international rules for carbon management which may differentiate between natural and managed changes in landscape carbon (The Climate Institute 2009).

2 SOIL CARBON BASICS

2.1 WHAT IS 'SOIL CARBON'?

Soil organic carbon (SOC) is the carbon associated with organic matter in soils. This is distinct from soil inorganic carbon (SIC, see section 2.6) which is held in soil minerals such as carbonates (e.g. limestone) commonly found in calcareous or alkaline soils. With a focus on the organic component the term 'soil carbon' is used interchangeably with SOC in this paper.

Soil organic matter can be defined as all materials of biological origin found in soils irrespective of origin or state of decomposition (Baldock & Skjemstad 1999)[25]. Therefore it consists of plant residues in soils or on the surface, living roots, biological organisms, decomposing, decomposed and burnt material of varying sizes. SOC can be partitioned into different pools or fractions (Table 1), which vary in their size, ease of decomposition, level of permanence and key functions (such as nutrient release or retention). Other systems of nomenclature have been used but these are along similar lines (e.g. labile, slow and resistant).

Table 1. 'Pools' (or types) of soil organic carbon (Broos and Baldock 2008[26], GRDC 2009)

Organic carbon pool	Size	Stability	Turnover time	Key functions
(1) Crop residues Shoot and root residues on and in the soil	> 2mm	Labile (readily available)	Days	Provide energy and nutrients to biological processes; readily broken down providing soil conditions that favour soil biology
(2) Particulate organic matter (POM) Smaller plant debris	0.05-2mm	↕	↕	These are broken down relatively quickly in suitable conditions but more slowly than crop residues. Important for soil structure, provision of energy for biological processes and nutrients.
(3) Humus Decomposed material dominated by molecules stuck to soil minerals	< 0.05mm			This plays a role in all key soil functions, but is particularly important in the retention and provision of nutrients (e.g. the majority of available N is found in the humus fraction).
(4) Recalcitrant organic matter Biologically stable, dominated by pieces of charcoal	variable	Very stable / relatively inert	Hundreds of years	Decomposes very slowly and if present in large quantities can contribute to cation exchange capacity as well as controlling soil temperature.

Readily broken down (labile) SOC also includes the organisms living in soil, collectively called soil biota, although some of these may be difficult to sample. Soil biota (bacteria, fungi, protozoa, nematodes,

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[25] Baldock JA and Skjemstad JO, 1999, 'Soil organic carbon / soil organic matter', In Peverill KI, Sparrow LA and Reuter DJ (Eds) 1999, *Soil analysis: an interpretation manual*, pp 159-170, CSIRO Publishing, Collingwood

[26] Broos K and Baldock J 2008, 'Building soil carbon for productivity and implications for carbon accounting', in *2008 South Australian GRDC Grains Research Update*

collembola, mites, termites, ants, earthworms, etc.) are important in organic matter decomposition and carbon and nutrient cycling. Organic matter typically contains around 60% carbon, therefore a soil containing 1% SOC contains about 1.7% organic matter (Bell and Lawrence 2009)[27].

Most organic matter (apart from charcoal) decomposes over years or decades and needs to be replaced by fresh organic matter to maintain soil carbon levels. As SOC decomposes, particle size decreases, residues become more nutrient rich (ie. some C is lost while N and P are retained) and turn-over time increases from hours to days to decades and (under the right conditions) to hundreds of years (GRDC 2009).

2.2 THE ROLE OF SOIL CARBON

SOC contributes to a range of diverse and important soil biological, physical and chemical functions, with strong interactions between each (Figure 1). For example, soil organisms (biota) obtain energy from decomposing organic matter, which in turn cycles nutrients, contributes to improved soil structure and water-holding properties. SOC and associated soil biota support pedological development helping to stabilise soils from erosion and create pathways enabling greater water infiltration and utilisation (reducing runoff and shading from evaporation). Living plant root matter (also comprising soil carbon) is needed to make use of available water. Declining soil carbon can have a negative effect on soil structure and fertility, increasing run-off, decreasing water use efficiency and reducing yields. The different SOC pools contribute to soil characteristics to varying degrees (Figure 2). Soil structure and cation-exchange capacity (CEC) characteristics also vary with soil clay content.

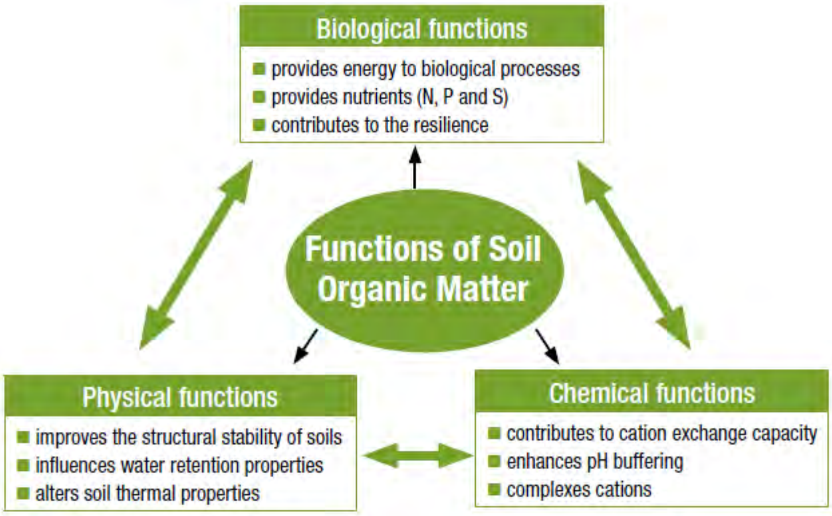

Figure 1. Diverse functions performed by organic matter in soils (GRDC 2009)

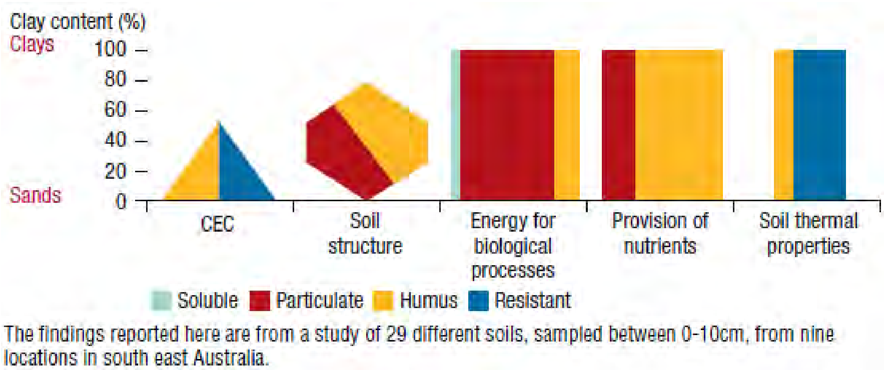

Figure 2. Contribution of SOC pools to soil characteristics, with varying soil clay content (GRDC 2009)

[27] Bell M and Lawrence D, 2009, *Soil carbon sequestration – myths and mysteries*, Queensland Department of Primary Industries and Fisheries

2.3 MEASURING SOIL CARBON

Commercially available techniques for measuring and monitoring SOC, particularly SOC pools, are currently limited (Bell and Lawrence 2009):

- Combustion methods do not discriminate inorganic from organic C
- The Walkley-Black wet oxidation technique (used in most routine soil test) only measures 70-90% of the total SOC, depending on soil type
- No current commercial technique can quantify the different SOC pools (Table 1) – this understanding is important to appreciate SOC quality and the period of residual value.

Soil carbon monitoring methodologies are also not yet well established. Changes in soil carbon content are slow and measurements over several decades may be needed to accurately define the effects of particular management treatments. As with any type of soil sampling, a cheap and rapid measurement method is needed to provide the replicate samples needed to account for the inherent spatial variability of soils.

Despite these issues there are some tools available. Locally calibrated models of soil carbon processes informed by baseline measurement (ie. long-term trials under different land use/ management, for different soil type and climate combinations) and expert knowledge can assist SOC measurement and monitoring (Chan *et al* 2008)[28].

Measurement of more labile pools can provide an indication of potential longer term change, provided improvements are sustained (GRDC 2009).

Developments in SOC measurement: Mid infra-red (MIR) spectroscopy

There is hope that recent developments in mid infra-red spectroscopy will allow a cheap and rapid assessment of SOC pools. MIR methods are current being developed through CSIRO's Soil Carbon Research Program. There is also interest in measuring soil biological activity (e.g. microbial biomass C, specific enzyme activities, and DNA to test for microbial diversity) however much work is still to be done before such techniques are available and useful for routine commercial SOC measurements.

Importance of measuring SOC pools

The amount of SOC that is stored in a soil can be calculated using the equation (Broos and Baldock 2008):
SOC (t/ha) = depth (cm) x bulk density (g/cm^3) x organic carbon content (%)

However the overall SOC content is a misleading indicator of soil behaviour. It is better to understand the relative proportions of the different pools – as this provides a better understanding of management effects and implications associated with soil physical, chemical and biological properties. The example shown below (see Figure 3) shows SOC measurements where a soil is examined twice in its management history.

Based on total SOC the soils appear very similar. In this example the amount of resistant/ char like material remains unchanged (due to a half life of centuries). Humus (taking decades to centuries to form) has been run down following initial native vegetation clearing[29] and over a period of continuous cropping. The level of humus continued to decline after the first measurement and is lower in the second test but is building up slowly under a land use change to permanent pasture. The particulate / labile (easily degraded) fraction has undergone a large increase in response to the pasture. The important points here are that, at the second measurement, (i) the long term/ long-lived soil nutrient stores (humus) have not recovered and (ii) SOC will decline much more rapidly if the land is returned to cropping (Bell and Lawrence 2009).

[28] Chan KY, Cowie A, Kelly G, Singh B and Slavich P, 2008, *Scoping paper: Soil organic carbon sequestration potential for agriculture in NSW*, New South Wales Department of Primary Industries

[29] It is worth noting that soils under native vegetation are also influenced by the factors discussed in this paper. Baseline SOC levels for some low rainfall, sandy soils under native vegetation in South Australia can be very low (B Hughes 2010, pers. comm.).

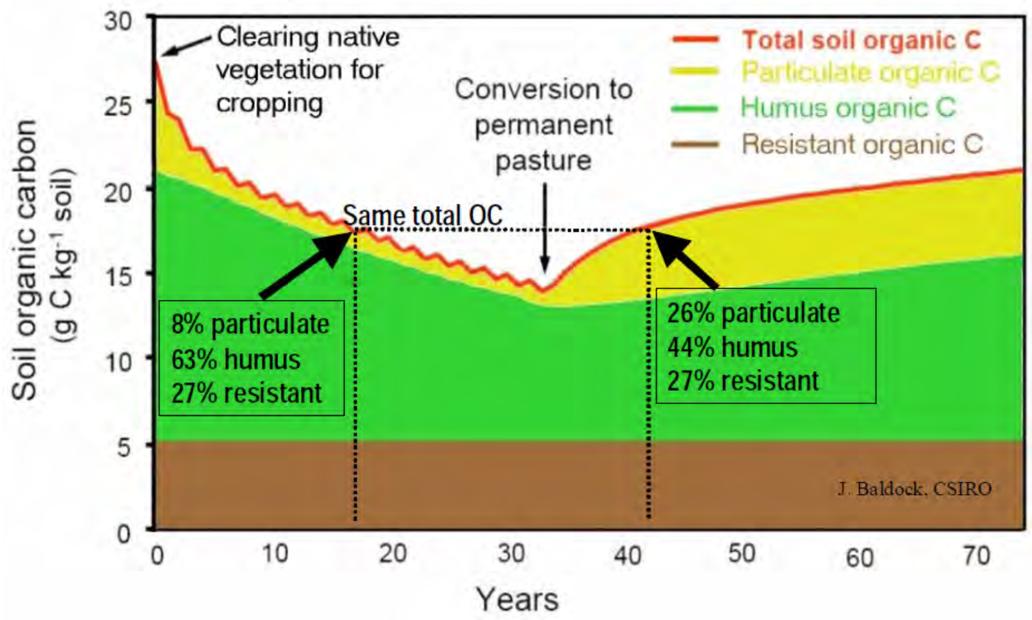

Figure 3. **Example SOC measurements under changing land use (Bell and Lawrence 2009). This shows the cumulative (stacked) contribution of SOC pools to total SOC. It is not representing a soil profile as SOC pools will be mixed up within the upper layer of soil. (Figure provided by J Baldock, CSIRO)**

Converting soil carbon to carbon dioxide

> **1** tonne of soil C = **3.67** tonnes of CO_2 (sequestered or emitted)

When SOC is sequestered from, or mineralised to, atmospheric CO_2, a conversion factor of 3.67 is used to determine the change in mass due to the loss or gain of oxygen molecules. This is based on the ratio of the molecular weights of carbon (12) and carbon dioxide (44), ie. 44/12 = 3.67.

2.4 Factors affecting soil carbon levels

Soil carbon occurs within a dynamic reservoir forming part of the global carbon cycle (Chan 2008)[30]. Carbon is continually entering and leaving the soil, reflecting opposing processes of accumulation and loss. SOC is not a uniform material, rather a complex mix of organic compounds, changing with different stages of decomposition – as the soil carbon cycle interacts with water and nutrient cycles as well as soil biota.

In general terms primary production (photosynthesis) converts atmospheric CO_2 into plant sugars which feed two food webs: through above-ground shoot growth and below-ground root growth. When plants are growing productively, roots and associated beneficial fungi and other micro-organisms grow and build up SOC. Carbon in root exudates provides a valuable food supply to elements of the soil biota. Decomposers (bacteria, fungi and larger biota) also grow and reproduce, consuming SOC and converting it into more stable forms, eventually into humus. Soil biota activity concentrates and recycles nutrients while some carbon is mineralised[31] to CO_2 and lost to the atmosphere. However, if plant production declines or stops, so do carbon inputs. To satisfy their energy requirements, soil biota increasingly consume stored soil carbon sources. If photosynthetic carbon inputs become totally absent, decomposers come to dominate and SOC levels decline.

SOC is effectively in a constant state of flux, slowly responding to environmental changes, and moving to reach a new equilibrium level whenever changes occur. Broos and Baldock 2008 make the following analogy for the cycling and storage of SOC – shown by a bucket (potential storage) with an input tap (plant residues) and losses tap (microbial decomposition and associated mineralisation).

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[30] Chan Y 2008, *Increasing soil organic carbon of agricultural land – PrimeFact 735*, NSW Department of Primary Industries (Jan 2008)

[31] In the context of SOC decomposition, 'mineralisation' refers to the conversion of organic carbon into inorganic CO_2.

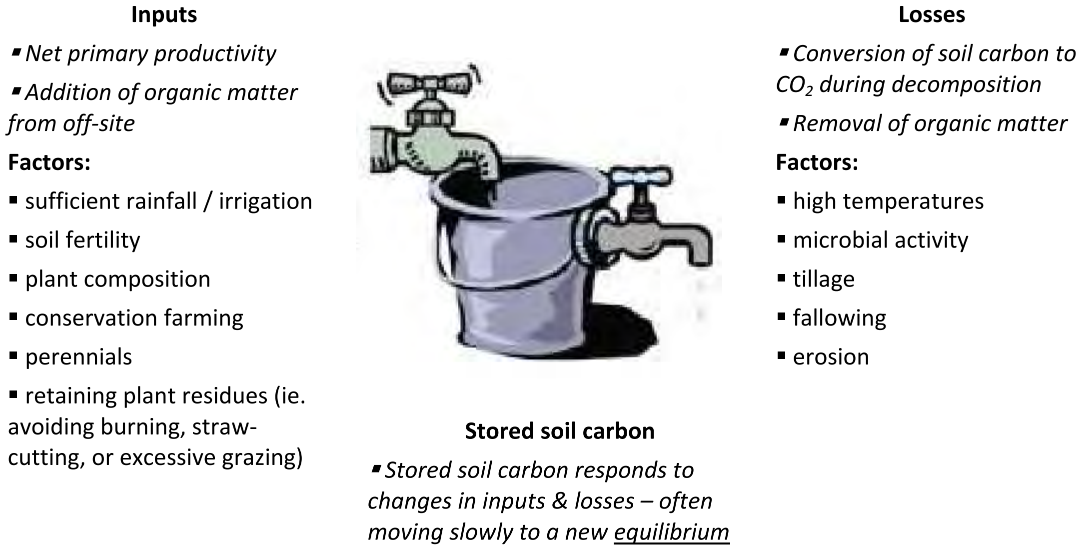

Figure 4. Soil carbon content is defined by potential storage, inputs and losses

2.4.1 "The bucket" (potential soil carbon storage)

The bucket is determined by soil properties (e.g. clay content [%], soil depth and bulk density) and is to a large extent beyond the influence of management (excepting for example management impacts on compaction / bulk density, or interventions such as claying of sandy soils). Each soil has a finite capacity, through a number of mechanisms, to protect SOC from biological attack.

Texture or % clay

The higher the clay % (heavier texture) the greater the ability of soils to retain carbon. Clay platelets coat organic matter to form stable aggregates, physically protecting organic matter from microbial decomposition. In comparison, rapid turnover of organic material occurs in soils with little or no clay content, explaining why increasing organic carbon in coarse textured sandy soil is difficult (Hoyle and Murphy 2008[32], Gupta *et al* 2008[33]). The bucket will always be smaller for a sand than a clay soil.

Mineralogy

The mineral composition of the clay can affect carbon storage. The presence of multivalent (having multiple sites available for bonding) cations such as calcium, aluminium or iron leads to accumulations of organic carbon in comparison to other soil types. Further details are provided in Krull *et al* 2001[34].

2.4.2 "Inputs tap" (building up soil carbon)

Inputs are controlled by the type and amount of plant residues added to the soil. Any practice that enhances productivity and the return of plant residues (shoots and roots) to the soil opens the input tap – building up SOC. The important qualifier here (as discussed in section 5.1.3) is that the analysis of net carbon sequestration also needs to consider energy requirements and CO_2 emissions from activities aimed at boosting SOC.

Input factors discussed below can also represent limitations, where not enough of a particular input will restrict plant productivity. There is also a temporal aspect as factors may change with time. Productivity improvements must be sustained in order to maintain improvements in SOC.

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[32] Hoyle F and Murphy D, 2008, 'Crop management and its impact on soil health and carbon', *2008 South Australian GRDC Grains Research Update*

[33] Gupta VVSR, Roget D, Davoren CW, Llewellyn R and Whitbread A, 2008, 'Farming system impacts on microbial activity and soil organic matter dynamics in southern Australian Mallee soils', *"Global issues, paddock action" Proceedings of the 14th ASA Conference, 21-25 September 2008, Adelaide, South Australia*, Australian Society of Agronomy

[34] Krull E, Baldock J and Skjemstad J 2001, 'Soil texture effects on decomposition and soil carbon storage', *NEE Workshop Proceedings*

Rainfall

In dryland farming the amount and seasonality of rainfall dictates what type of crops and pastures can be grown, the number of crops that can be grown in a year and the bulk of organic material produced. **In South Australia rainfall imposes one of the largest limiting factors to improving and sustaining SOC.**

Irrigation

Irrigation of crops can override the limiting rainfall factor but this will only work where water is readily available and it is practical to irrigate crops.

Importing organic matter

Organic material can be imported from off-site (e.g. manures, composts, plant debris, sewage biosolids, biochar / charcoal). Overall costs and emissions, and whether SOC is being lowered at the source, need to be factored in. Biochar is discussed in further detail in section 3.6.

Fertiliser

The use of fertilisers can maximise productivity ensuring the largest return of organic material to the soil. The old and degraded soils in many of our cropping areas generally require fertiliser to overcome low inherent fertility. Consequently there may be significant fertiliser costs involved with raising productivity for SOC improvement (excepting the addition of relatively inert material such as charcoal). In the more permanent humus fraction of the soil there are stable ratios of key nutrients: C:N= 10, C:P= 50 and C:S= 65. If SOC (as humus) is to be stored permanently as an offset then the N, P and S must also be stored permanently (Eckard 2010[35], CSIRO 2008b[36]). This also implies that if any key nutrients are limiting then other compounds may be formed, some of which may be easily leached or otherwise lost. Examples of nutrient requirements associated with SOC improvement (as humus) are shown below.

Table 2. Example nutrient requirements associated with building SOC (as humus)

Improvement	SOC (T/ha)	N (kg/ha)	P (kg/ha)	S (kg/ha)
1 tonne of humus / ha	0.6	60	12	9.2
1% to 2% SOC in the top 10cm (bulk density = 1.2g/cm^3)	12	1200	240	185

Aside from fertiliser application, nutrients may be provided by plant residues and N-fixing bacteria (free-living or associated with leguminous plants).

Paying for fertiliser just to build up SOC cannot be justified. For 1 tonne of humus, considering the costs of N fertiliser alone (based on urea at $650/tonne) would need a $38/t CO2-e (carbon dioxide equivalent) price just to pay for N (Eckard 2010). If significant losses occurred due to leaching, volatilisation and denitrification this would expand the cost. Fortunately N supplied from naturally occurring agents such as legume rhizobia and free-living N-fixing bacteria is of little cost.

> **Example calculation (if farmers pay for N):**
>
> 1 tonne of humus stores 600kgC and 60 kgN.
>
> Assuming urea (46% N) is $650/tonne,
> price of N = (650/0.46)x(60/1000) = $85/ t humus
>
> But 1 t humus = 0.6 t soilC, and
> 1 t soilC = 3.67 t CO2, therefore:
> price of N is equivalent to (85 / 0.6) x (1/3.67)
> = $38 / t CO2

While our understanding is growing (e.g. Gupta and Roget 2007[37]), there are still large knowledge gaps regarding the inherent capacity and techniques to better harness soil microbial communities across different climate and soil types, to:

- fix atmospheric N (using microbes which are free-living or associated with legumes)

[35] Eckard R, 2010, ‘Copenhagen, CRPS and beyond – What does carbon trading mean for growers?’, in *2010 South Australian GRDC Grains Research Update*, Grains Research and Development Corporation

[36] CSIRO 2008b, *The buried cost of soil carbon credits,* CSIRO web page, http://www.csiro.au/resources/ps4lu.html

[37] Gupta VVSR and Roget DK, 2007, ‘Overview - soil biology, nutrient cycling and disease supression - what can soil biota contribute?’, *GRDC Research Update for Growers (Northern Region) March 2005*, Grains Research and Development Corporation

- retain nutrients (N, P, S) from decomposing plant matter within the soil carbon bank (reducing losses to volatilisation, leaching and denitrification)
- cycle, or liberate, stored soil nutrients (e.g. P) that might have been unavailable to plants under conditions of low SOC and low microbial activity – note that the benefit provided by microbial activity to P and other nutrient uptake is largely due to symbiotic behaviour of mycorrhizal fungi rather than “liberation” from inorganic complexes.

Anecdotally, it has been observed that incorporation of organic matter doesn't necessarily lead to N or P deficiency as a general rule, but instead (after perhaps a short-term or one season yield reduction) productivity improvements are often observed (D Davenport 2010, pers. comm.) It is uncertain if these increases are driven by nutrient release, improved water holding capacity, increased biological activity or a combination of factors but does suggest that high rates of fertiliser application are not necessarily required to build up SOC.

The value of synthetic versus organic fertilisers for building SOC is also an area of current scientific debate. SOC benefits arising from increased C inputs under fertilisation may in some cases be partially reduced, or totally cancelled out in the longer-term, by increased decomposition rates due to the stimulation of microbial populations and/or impacts on residue quality and soil aggregates (Sanderman *et al* 2010, Khan *et al* 2007[38], Russell *et al* 2009[39], Philpott 2010[40]). It has been argued that use of labile synthetic N (e.g. urea) encourages the rapid build up of microbes that consume any form of organic matter, including stored SOC and even the organic binding agents (e.g. fungal hyphae, fine roots, etc) that hold soil micro-aggregates together (Fonte *et al* 2009)[41]. The resulting breakdown of micro-aggregates from bacterial attack can then diminish the permanence of C and N storage (Mulvaney *et al* 2009)[42]. Russell *et al* 2009 view selection of crops with high below-ground biomass production as a more effective approach to building SOC than increasing synthetic N fertiliser rates. Over-fertilisation (beyond crop requirements), aside from encouraging bacterial attack, also has the damaging effects of: contributing to nitrous oxide (N_2O) emissions, nitrate (NO_3^-) pollution of groundwater and surface water resources, and produces unnecessary GHG emissions from the manufacture and transport of wasted product. A shift from yield-based N management to soil N management (with regular soil N testing) is highly recommended (Khan *et al* 2007). Further opportunities to improve N use efficiency are discussed in section 4.

‘What was the pre-existing SOC condition?’ is probably an important question to ask in this debate. In high quality SOC situations (associated with historically fertile soils and/or long-term manuring), degradation in SOC quality might follow from a shift to labile synthetic N fertiliser. In the case of large areas of South Australia where infertile and low productivity soils dominate, synthetic N has probably increased productivity and SOC levels. “Historic practice involved 1 in 3 years of cropping, while 1 in 2 was seen as exploitative. The only reason continuous cropping has worked has been the use of synthetic N fertiliser to maintain N levels and not run down N and SOC reserves. Legume N in Australia does not seem to be high enough at the moment unless we reduce frequency of crop rotations” (B Hughes 2010, pers. comm.). Now if we don't maintain current rates of synthetic N application, production levels and total SOC are likely to fall.

The literature also provides examples of increasing SOC benefits with synthetic N fertiliser. Alvarez 2005[43] reviewed N fertiliser effects on conservation tillage trials finding generally positive benefits to SOC storage

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[38] Khan SA, Mulvaney RL, Ellsworth TR, Boast CW, 2007, ‘The myth of nitrogen fertilization for soil carbon sequestration’, *Journal of Environmental Quality*, 36, 1821-1832

[39] Russell AE, Cambardella CA, Laird DA, Jaynes DB, Meek DW, 2009, ‘Nitrogen fertilizer effects on soil carbon balances in Midwestern US agricultural systems’, *Ecological Applications*, 19, 1102-1113

[40] Philpott T, 2010, ‘New Research: synthetic nitrogen destroys soil carbon, undermines soil health’, *Energy Bulletin* (online journal), http://www.energybulletin.net/node/51697

[41] Fonte SJ, Yeboah E, Ofori P, Quansah GW, Vanlauwe B, Six J, 2009, ‘Fertiliser and residue quality effects on organic matter stabilisation in soil aggregates’, *Soil Science Society of America Journal*, 73, 961-966.

[42] Mulvaney RL, Khan SA and Ellsworth TR, 2009, ‘Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production’, *Journal of Environmental Quality*, 38, 2295-2314

[43] Alvarez R, 2005, ‘A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage’, *Soil Use and Management*, 21, 38-52

(compared to unfertilised controls), with SOC accumulation occurring in a S-shaped time dependant process which reached a steady state after 25-30 years. Hati *et al* 2006[44] found increasing SOC benefits with N fertiliser applied to match crop requirements. They also found that balanced (NPK) mineral fertilisers in combination with organic manure provided the best environment for improving SOC under intensive crop production.

Recent breakthroughs by researchers at Stanford University show promise in the future for increasing the nitrogen fixing efficiency in legumes, which has the potential to dramatically reduce the amount of synthetic N fertilisers used in agriculture (Bergeron 2010[45], Cramb 2010[46]). Another innovative technology that has reached the commercial phase is BioAgtive™ exhaust fertilisation (http://www.bioagtive.com/) which injects exhaust gases into the soil to help offset GHG emissions while stimulating soil biology (Cawood 2009)[47]. Trials of the system are being undertaken in the Mallee - Lower Murray Catchment Management Authority (CMA) region.

Plant type and composition

The type of plant grown affects the quantity of organic matter that can be returned to the soil. Selecting plants with greater root mass and/or slower decomposing roots will aid SOC sequestration. Deep-rooted perennial plants are generally required to improve SOC in deeper soil layers (below the surface ~10cm). Note that deep placement of organic material is likely to have longer sequestration than shallow placement due to reduced microbial activity. Carbon to nitrogen ratios (C:N) of particular plants can effect the length of storage of carbon in the soil. Organic matter with a high C:N (e.g. wheat) breaks down more slowly than residue with low C:N (e.g. legumes) and is more likely to contribute to increased soil carbon where inputs are sustained (Hoyle and Murphy 2008). Where possible, the presence of year-round green crop or pasture growth will provide the best supply of organic carbon to soils. Jones 2007a[48] states "the cheapest, most efficient and most beneficial form of organic carbon for soil is exudation from the actively growing roots of plants in the grass family, which includes many crop plants."

There is research into the selection of certain varieties of plants that generate higher than normal levels of phytoliths. Phytoliths (also called 'plantstones' or 'plant opal') allow carbon to be protected in a similar way that clay platelets protect organic matter. Long-term phytolith accumulation rates under grasslands are commonly 5-10 times greater than under forests. Phytoliths offer potential to boost carbon sequestration in agricultural soils, wetlands and degraded saline and acid sulphate affected areas. Further details are provided in Parr and Sullivan 2005a[49], 2005b[50].

Long-term breeding programs have been initiated offering promise for the future development of perennial grain crops. The aim of this research is to eventually provide the grain and oilseed that dominate modern human diets while providing the numerous soil, biomass, climate resilience, efficient nutrient use and natural resources management benefits of perennials (Cox *et al* 2006)[51].

Phytoliths

…are bio-mineralised silicates that can enclose and protect carbon structures of various plant parts. It is suggested they have potential to increase SOC sequestration by reducing long-term decomposition of some plant residues. (Source: Parr and Sullivan 2005)

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[44] Hati KM, Swarup A, Singh D, Misra AK and Ghosh PK, 2006, 'Long-term continuous cropping, fertilisation and manuring effects on physical properties and organic carbon content of a sandy loam soil', *Aust. J. Soil Res.*, 44, 487-495

[45] Bergeron L, 2010, 'Discovery in legumes could reduce fertiliser use, aid environment, say Stanford researchers', *Stanford University News,* http://news.stanford.edu/news/2010/february22/legumes-nitrogen-fertilizer-022610.html

[46] Cramb A 2010, 'New research has the potential to reduce the use of nitrogen fertilisers in agriculture', *The organic advantage*, e-newsletter from the Biological Farmers of Australia, http://www.bfa.com.au

[47] Cawood M 2009, 'How BioAgtive is cutting fertiliser costs', *The Land*, 10 Oct 2009, http://theland.farmonline.com.au/news/nationalrural/agribusiness-and-general/general/how-bioagtive-is-cutting-fertiliser-costs/1643237.aspx

[48] Jones C 2007a, 'Carbon, air and water – is that all we need?', Paper at *Managing the carbon cycle*, Katanning Workshop 21-22 March 2007

[49] Parr JF and Sullivan LA, 2005a, 'Soil carbon sequestration in phytoliths', *Soil biology and biochemistry*, 37, 117-124

[50] Parr JF and Sullivan LA, 2005b, 'Carbon sequestration in plantstones', *Proceedings of the 'managing the carbon cycle' forum*, Armidale 13-14 Sep 2005

[51] Cox TS, Glover JD, Van Tassel DL, Cox CM and DeHaan LR, 2006, 'Prospects for developing perennial grain crops', *Bioscience*, 56(8), 649-659

The beneficial role of mycorrhizal fungi

Symbiotic mycorrhizal fungi[52] can play an important role in building and maintaining SOC. According to grassland ecologist Christine Jones, this has been greatly underestimated in the current debate about soil carbon potential and permanence (Jones 2008a)[53]. Mycorrhizal fungi must form an association with living plants, siphoning their energy in the form of liquid carbon via root exudates from actively growing plants. Mycorrhizal fungal hyphae (thin, hair-like filaments) spread out in a fan-shaped structure exploring the soil matrix and provide absorptive capacity that is 10-100 times that of root systems alone (Jones 2009)[54]. In exchange for soluble carbon from their host they supply key plant nutrients and moisture from the soil. With the capacity to connect individual plants they can facilitate the transfer of carbon and nitrogen between species. In seasonally dry, variable or unpredictable environments they can play an extremely important role in plant-water dynamics, humification (humus formation) and soil building processes (Jones 2008a).

While boosting the productivity and resilience of host plants they also play a key role in building soil structure and storing carbon. Glomalin, a by-product of arbuscular mycorrhizal fungi has been identified as an important 'organic glue' for stabilising soils and building long term soil carbon stores (Wright 2002) [55]. Networks of mycorrhizal fungal hyphae also provide an important first step in the formation of humus (Jones 2009). Under appropriate conditions it is suggested that the major portion of soluble carbon siphoned into short-lived mycorrhizal hyphae can undergo humification, a process in which simple forms of carbon are resynthesised into highly complex polymers.

According to Jones 2008a, suitable biological conditions for humus formation are commonly found in association with year-round green farming practices such as pasture cropping or regenerative grazing (see section 3.2); enhanced in the presence of humic and fulvic acids, compost teas and microbial inoculants; and diminished in the presence of herbicides, fungicides, pesticides, and artificial N and P fertilisers.

(Source: Jones 2009)

Mycorrhizal hyphae (white) colonising the roots (yellow) of a pine seedling. Photo courtesy Aberdeen Mycorrhiza Research Group

Humification cannot proceed unless there is a continuous supply of 'fuel' for soil microbes, and if it does not occur then carbon inputs are relatively quickly oxidised and recycled back to the atmosphere (Jones 2007b)[56]. Jones argues further that both glomalin and humus are of significance to the current debate on soil carbon permanence as these long-lived SOC fractions cannot be lost under transient impacts of drought or fire.

Most perennial grasses are excellent hosts for mycorrhizal fungi (Jones 2007b). Mycorrhizal fungi have mechanisms to survive while host plants are dormant but cannot survive if host plants are removed.

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[52] A 'mycorrhiza' is a symbiotic association between a fungus and the roots of a vascular plant. In a mycorrhizal association the fungus colonizes the host plants' roots either intracellularly (penetrating the membrane of plant root cells) as in 'arbuscular mycorrhizal fungi', or extracellularly (surrounding the plant root cells) as in 'ectomycorrhizal fungi'. (Source: http://en.wikipedia.org/wiki/Mycorrhiza)

[53] Jones C, 2008a, 'Liquid carbon pathway unrecognised', *Australian Farm Journal*, July 2008, 15-17

[54] Jones C, 2009, 'Mycorrhizal fungi – powerhouse of the soil', *Evergreen Farming Newsletter Sept 2009*, http://www.amazingcarbon.com/

[55] Wright S, 2002, 'Glomalin: Hiding place for a third of the world's stored soil carbon', *Agricultural Research Magazine,* United States Department of Agriculture, http://www.ars.usda.gov/is/AR/archive/sep02/soil0902.pdf

[56] Jones C, 2007b, 'Building soil carbon with year long green farming', *Evergreen Farming Newsletter September 2007*

Factors negatively impacting on mychorrhizae and glomalin production include lack of continuous groundcover, intensive tillage, single species crops and pastures (monocultures) and application of artificial N and P fertiliser, herbicides, pesticides or fungicides, and the presence of plants from the Brassica family (this includes canola, cabbage, cauliflower) which do not form mycorrhizal associations (Jones 2007b, Wright 2002, Better Soils Technical Committee 1998[57]). These latter crops need to be rotated with other crops to avoid negative impacts on glomalin levels and hence SOC.

Lorenz and Lal 2005[58] also suggest that ectomycorrhizal fungi (that form a sheath around the root tips of particular plants) could be harnessed to build SOC as they help to reduce decomposition of roots.

Land use / land management

The land use or management system will affect the amount of plant residue grown and the amount of carbon returned to the soil (see table below). Practices that will generally increase SOC include:

- Maintaining soil cover all year round, preferably including living plant material.
- Conservation farming (see section 3.1) – which is rapidly gaining acceptance as best practice for soil and moisture conservation. Reducing tillage reduces carbon losses from both reduced cultivation and reduced fossil fuel use. Increasing stubble retention increases carbon inputs. Both of these lead to increasing SOC.
- Pasture leys – increasing the frequency and duration of pasture in crop rotations
- Grazing management that increases forage production and manure inputs.
- Perennial plantings – increasing the amount of perennial pasture and convert land which consistently yields low or negative returns to perennial vegetation.
- Returning more plant material to the soil – via reduced stocking rates, increased use of green manure crops, in addition to increasing crop residue retention.
- Optimising farm management inputs to maximise water use efficiency.
- Using more of the available annual rainfall – via improved rotations, double cropping, opportunity cropping, pasture cropping and landscaping to increase retention of rainfall.
- Reversing land degradation (e.g. saline, acidic and eroded land) will boost production and SOC. (The exception to this general rule is that some production-limited land where microbial activity is highly suppressed tend to have higher SOC levels, e.g. highly acidic soils as discussed in section 2.4.3.)

Annuals versus perennials?

Anecdotal reports suggest that highly productive annual crops may provide greater dry matter production than perennials in some low rainfall broad acre agricultural environments in SA (D Davenport 2010 pers. comm., M-A Young 2010, pers. comm.). The theory that SOC will be higher under perennials revolves around the fact that soil biota are digesting carbon to live. Whenever there is no fresh carbon going into the system then soil biota start mining the carbon already stored. Ultimately it's a question of inputs versus losses over time for each particular system.

[57] Better Soils Technical Committee 1998, 'Biological activity', In *Better soils mean better business*, An Agricultural Bureau project supported by PIRSA, GRDC, NHT, Soil Conservation Boards and the Australian Soil Science Society

[58] Lorenz K and Lal R, 2005, 'The depth distribution of organic soil carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons', *Advances in Agronomy*, 88, 35-66

Table 3. Example SOC sequestration rates under different land use/ management (Chan *et al* 2010[59], Sanderman *et al* 2010.

Agricultural activity	Management practice	Carbon sequestration rate (t C/ha/yr)	Average estimates by Sanderman *et al* 2010
Cropping	increase soil fertility improve rotations irrigate eliminate fallows use precision agriculture	0.05-0.15 0.10-0.30 0.05-0.15 0.10-0.30 not available	Up to 0.3 t C/ha/yr (with combination of enhanced rotation, adoption of no-till and improved stubble management)
Conservation tillage	retain stubble reduce tillage use no- till systems	} 0-0.40	
Grazing	use fertilisers manage grazing time irrigate introduce legumes	0.30 0.35 0.11 0.75	Up to 0.3 t C/ha/yr (with pasture improvements)
Addition of organic amendments	add animal manure add biosolids	0.1-0.6 1.0	Influenced by composition, amount & duration of inputs
Land conversion	convert degraded cropland to pasture	0.8-1.1	Up to 0.6 t C/ha/yr (to permanent pasture)

2.4.3 "Losses tap" (causes of soil carbon decline)

SOC losses occur from decomposition and conversion (/mineralisation) to CO_2. Factors which accelerate decomposition open up the "losses tap" further.

Temperature

In areas with higher temperatures, organic material will mineralise faster (where adequate moisture is also available). This is unavoidable and it will be more difficult to be able to store large amounts of SOC in locations with high temperatures. Decomposition under higher temperatures (e.g. in large parts of South Australia) may also occur year-round which is not the case in many other countries.

Microbial activity

Warm, moist environments can support high levels of microbial activity. If plant inputs stop, existing organic matter can be decomposed quickly. Conversely, under very low levels of soil microbial activity, organic carbon may slowly accumulate and build to relatively high levels, despite being in an environment of poor productivity. Examples of this can be found in problem soils which are highly acidic, highly alkaline, waterlogged or very clayey (B Hughes 2010, pers. comm.). This is because organic matter accumulates but does not break down. As discussed in section 2.4.2, fertiliser can sometimes promote microbial activity and SOC decomposition, particularly when used inefficiently / excessively.

Soil tillage / disturbance

Tillage practices can accelerate the rate of organic matter and residue decomposition, increasing the rate of mineralisation. This occurs primarily by making more of the organic matter available to soil microbes for breakdown. Ploughs that invert the soil are worst. Reviewing overseas data, the greatest loss of SOC comes from cropping due to cultivation, therefore changing to conservation tillage is seen as having the greatest potential to maintain and/or re-introduce carbon into soils (Schapel 2008)[60] which may build progressively

[59] Chan KY, Oates A, Liu DL, Li GD, Prangnell R, Polie G and Conyers MK, 2010, *A farmer's guide to increasing soil organic carbon under pastures*, Industry & Investment NSW, http://www.dpi.nsw.gov.au/agriculture/resources/soils/soil-carbon/increasing-soil-organic-carbon-farmers-guide

[60] Schapel A, 2008, *Climate change and land capability: Soil carbon sequestration scoping report*, unpublished report, prepared for the Department of Water, Land and Biodiversity Conservation

over time (Sá 2004)[61]. However rainfall (< 500mm) may be a limiting factor to building SOC in many cropping situations (Chan *et al* 2003[62], Valenzo *et al* 2005[63]). More research is needed on the SOC sequestration potential in lower rainfall situations of new and evolving conservation farming technologies.

Fallowing

Fallowing, under conventional farming methods, was maintained by repeated cultivation for weed control and 'preservation of water'. SOC rapidly declines under fallowing due to the increased decomposition of organic matter due to cultivation as well as higher microbial activity associated with higher soil moisture. Prolonged chemical fallowing, where weed control is achieved via herbicides rather than cultivation, also results in declining SOC because of the absence of plant production and microbial attack on stored SOC.

Erosion

SOC can be lost as a result of wind and water erosion due to removal of topsoil and exposure of the sub-surface to higher temperatures.

Summary – factors affecting SOC

Summary – What causes soil carbon decline?

Declining SOC represents a shift towards a new equilibrium position under lower carbon inputs (and/or higher losses) than that which has existed previously. Native vegetation and well managed perennial pastures maximise water use with increased biomass production feeding the soil carbon pool all year round. In contrast, annual crops (even under the best conservation farming practices), or highly grazed pastures, will not be able to utilise as much annual rainfall. For much of South Australia annual crop water use efficiency is between 50-70% (Payne and McCord)[64]. During seasons or parts of the year when annual plants aren't growing, microbes continue to consume SOC. Tillage, fallowing and erosion will accelerate SOC losses.

Summary – How can soil carbon be restored?

The most effective strategy to re-build SOC levels is to grow the greatest level of biomass possible, while maximising the return of plant residues to the soil. "100% ground cover 100% of the time is the carbon farmer's goal" (GRDC 2009).

Soil organic amendments might also be an option if they are available and cost-effective, however this may mean that carbon is being removed from their site of origin.

Reducing SOC losses presents a conundrum, as many functions of a healthy soil are provided by microbial activity during organic matter decomposition (Bell and Lawrence 2009). The goal is to control rates of decomposition (to match soil type and climate conditions) rather than trying to stop decomposition and CO_2 emissions altogether. This means (i) more inputs are needed to outweigh inevitable SOC losses, and (ii) not losing SOC too rapidly (e.g. burning or over-grazing).

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[61] Sá JCM, 2004, 'Adubação Fosfatada no Sistema de Plantio Direto', In: *Sympósio sobre Fósforo na Agricultura Brasileira*, Anais (ed.) T. Yamada, Silvia, R. S. Abdalla, p.201-222, Piracicaba, SP, POTAFÓS, 2004, 726p

[62] Chan KY, Heenan DP and So HB, 2003, 'Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: a review', in *Australian Journal of Experimental Agriculture*, 43, 325-334

[63] Valenzo F, Murphy B and Koen T, 2005, *The impact of tillage on changes in soil carbon with a special emphasis on Australian conditions*, National Carbon Accounting System Technical Report, No. 43, Australian Greenhouse Office

[64] Payne R and McCord A, 2004, *Report on the condition of agricultural land in South Australia*, Report No 1, December 2004, Department of Water, Land and Biodiversity Conservation, http://www.dwlbc.sa.gov.au/assets/files/ki_AgLandSA_Report04.pdf

2.5 HOW MUCH CARBON CAN BE STORED IN SOIL?

Broos and Baldock 2008 also provide the following conceptual diagram summarising the potential storage of SOC in soils. By virtue of the different levels of protection provide for SOC, particular soil properties will ultimately define the long term storage potential for even relatively inert forms of SOC. Any organic carbon added to the soil which is surplus to the protective capacity of the soil type will remain biologically active and be more susceptible to faster decomposition (Krull *et al* 2001). Factors related to the farm setting (e.g. climate) provide the over-riding limiting factors for SOC inputs from farm production. However, farm management can influence SOC storage within these boundaries and economic and climatic pressures will play an important role in the practicality and effectiveness of strategies to build up SOC.

Eady *et al* 2009 estimate the national potential for SOC sequestration at around 25 Mt CO_2-e/yr over a 40 year time horizon (2010-2050). Garnaut 2008 (Chapter 22) suggests a higher Australia-wide average potential for soil carbon sequestration in the order of 68 Mt CO_2-e/yr over 38 million ha (0.5 t C/ha/yr) on cropped land and 286 Mt CO_2-e/yr over 358 million ha (0.2 t C/ha/yr) on grazing land including low rainfall pastoral rangelands, over a period of 20-50 years. (Over the same period potential reductions in soil nitrous oxide emissions through improved fertiliser management were estimated at around 0.3 Mt CO_2-e/yr over all agricultural soils – refer to section 5.) The Wentworth Group 2009[65] suggest national SOC sequestration estimates that are higher again, around 900 Mt CO_2-e/yr (averaging 0.59 t/ha for the top 1m of soil). As discussed in the next section, these average figures appear well beyond the potential of South Australia's low rainfall climate. However this type of methodology, utilising a calibrated soil carbon model, and deriving SOC sequestration estimates for different soil types, is an approach that could be tailored to South Australian datasets.

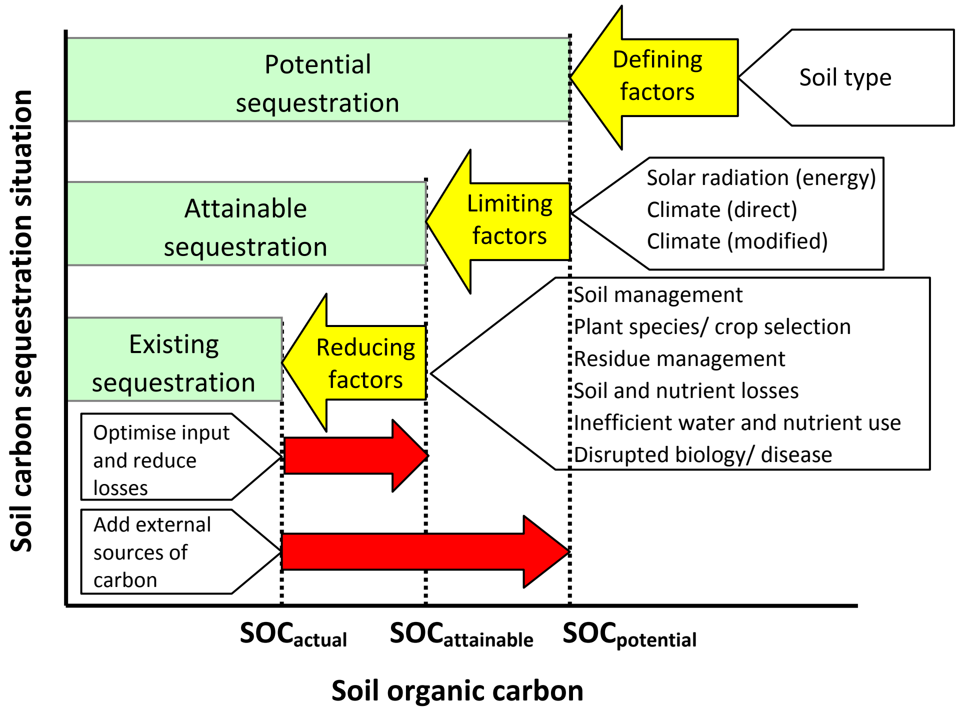

Figure 5. Factors influencing the levels of soil organic carbon for a particular soil (Broos and Baldock 2008)

SOC sequestration has a finite capacity. Soil carbon stock may increase only until the environmental equilibrium level is achieved. With concerted efforts to improve management practices this may occur possibly in 50 years (Chan *et al* 2008). Sanderman *et al* 2010 found that the largest SOC gains will generally occur within 5-10 years after a management change, with a reduced rate of change after that. Despite

[65] The Wentworth Group of Concerned Scientists 2009, *Optimising carbon in the Australian Landscape*, http://www.wentworthgroup.org/uploads/Optimising_Terrestial_Carbon.pdf

occurring over a number of years, payments for SOC sequestration could be regarded as a 'once off'. In contrast, the associated management implications to ensure permanency will be lasting.

2.5.1 Soil carbon measurements in SA soils

Analysis of existing ASRIS[66] soil data for South Australia provides generalised information on total soil carbon content for different soil types, land use and rainfall zones. Figure 6 and 7 show average SOC contents for different soil types, rainfall zones and landuse (cropping and pasture respectively). Note: some averages are based on very limited sample numbers. This database does not contain information on SOC pools.

Current work by DWLBC, CSIRO and Rural Solutions SA, through the nationally funded Soil Carbon Research Program is gathering field measurements of SOC pools for a range of soil types and climate zones across South Australia. This data is not yet available.

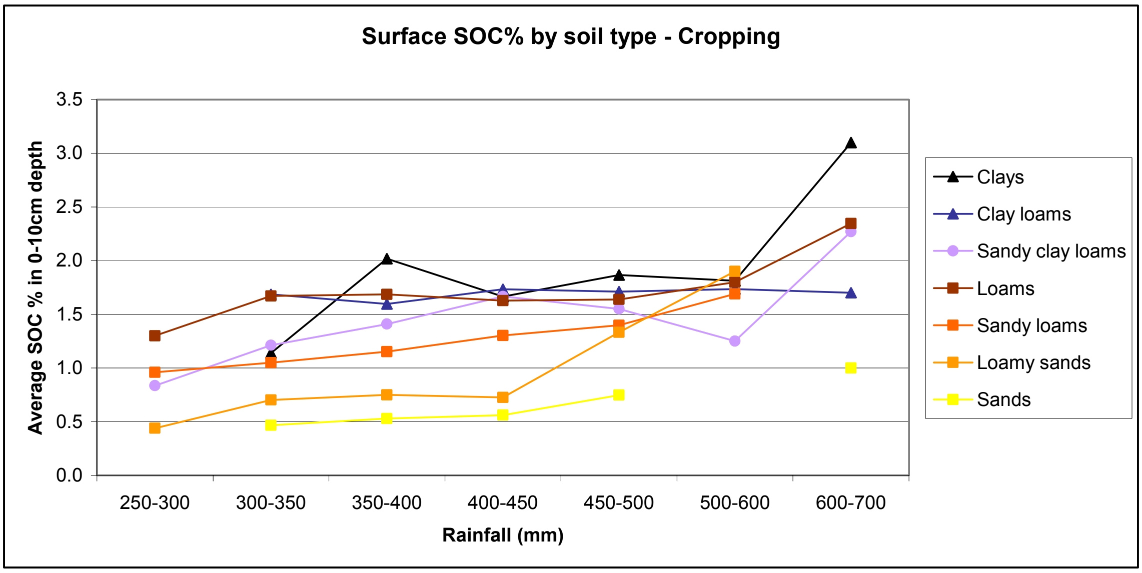

Figure 6. Average surface SOC % for cropping soils (derived from ASRIS database, May 2010)

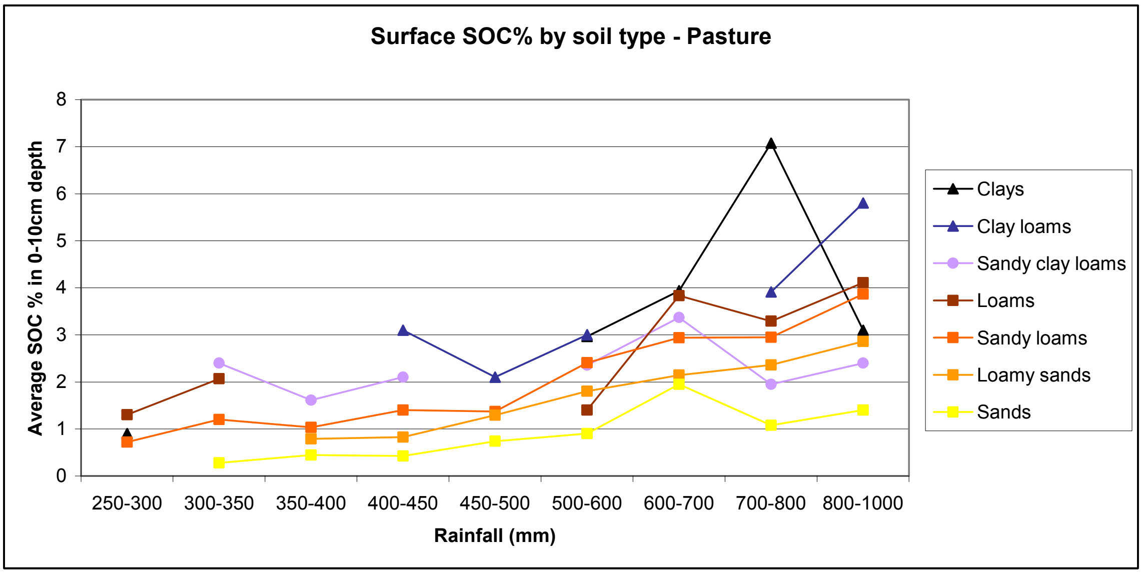

Figure 7. Average surface SOC % for pasture soils (derived from ASRIS database, May 2010)

[66] Australian Soil Resource Information System (ASRIS), http://www.asris.csiro.au – this is a detailed soil and landscape dataset managed in South Australia by DWLBC.

2.5.2 What is the potential for SOC improvement for SA soils?

Chan *et al* 2008 suggest that the highest potential for SOC improvements will occur in higher rainfall (>450 mm) permanent pastures, or ley pastures in cropping zones. Also they suggest that the SOC potential of agricultural systems may be able to exceed that of natural ecosystems (in some situations) because of the additional nutrients supplied by fertiliser.

It has been suggested that in the favourable areas of Australia, with clayey textured soils, perennial pasture and high annual rainfall (>650mm), that over a 20 year period up to 8 t C/ha might be sequestered (ie. 400 kg C/ha/yr) (Schapel 2008).

The majority of cropping areas of SA, with sandy topsoils and low annual rainfall may be able to sequester 100 kg C/ha/yr, or 2 t C/ha over 20 years (Schapel 2008). This is of the same order of SOC improvement suggested by GRDC 2009, reporting that reduced tillage trials have shown that gains of 0.1-0.2 t C/ha/yr may be possible. **Currently there are questions over the ability of cropping areas under 500mm annual rainfall to actually build SOC levels**, even under best practice conservation farming practices (see section 3.1). This is an important area for research, given the area of agricultural land in the State below this annual rainfall amount (Figure 8).

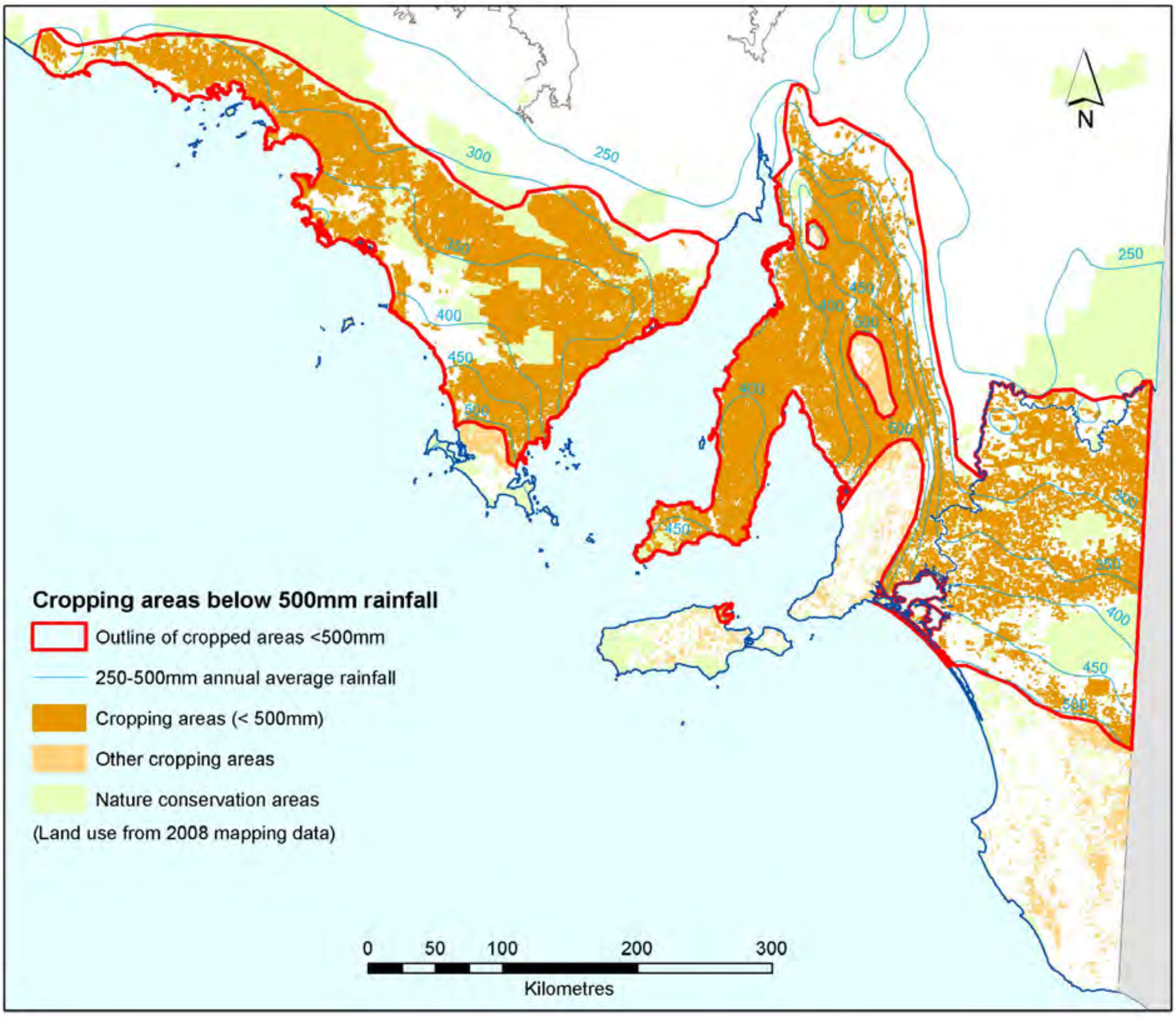

Figure 8. South Australian cropping areas below 500mm rainfall

There may also be significant SOC potential in the low rainfall rangelands. On currently degraded land, small rates of SOC sequestration per hectare could achieve large total SOC improvements (Chan *et al* 2008).

In terms of generating an estimate of the SOC sequestration of South Australian soils, this is an area that needs much better understanding. That is, what are potential SOC improvements under different land uses, soil types and climates, and what are the actual areas which might be suited to different levels of SOC gain?

An 'audit of SOC sequestration potential for SA' is proposed, which would identify the current capacity and potential to increase the capacity (see section below) of South Australian soils to store carbon. Such a carbon audit should also link into a capability assessment of farmers to adopt the necessary management changes to build SOC.

2.5.3 Increasing the surface clay content of sandy soils

The other major opportunity to increase SOC levels is to increase the inherent capacity of soil to hold carbon by increasing the clay content (clay platelets provide organic material greater protection from decomposing organisms). Clay spreading, delving and spading (a more recent technology) have been widely used across South Australia to increase the clay content of sandy soils. Initially this work was conducted to eliminate soil hydrophobic (non-wetting) characteristics on sandy soils caused by waxes left from decaying vegetation. Other benefits have since been recognised including; increased soil fertility, reduction in erosion potential and increased soil water holding capacity. The outcome has generally been increased levels of production (up to 350%) and less restriction on farming systems due to soil improvements.

At this stage there is limited data to confirm increases in SOC delivered through these technologies, however significant increases can be expected due to: (i) the role of clay in protecting carbon from decomposition and (ii) changes to water balance leading to higher water availability and increased vegetative growth.

The potential to increase soil carbon levels across South Australia can be demonstrated by a comparison of SOC of South Australian soils on the ASRIS data base. The difference in the mean SOC content of topsoil horizons between sand and sandy loam soils is 0.7%, approximately double. Preliminary investigations suggest that clay incorporation into sandy subsoils may be able to achieve increases of the same magnitude. There are approximately 3.16 million ha of sand and loamy sand textured soils under agricultural production in South Australia. Of these approximately 1 million ha have suitable clay available for spreading, delving and spading. A 100% increase in SOC to a depth of 30 cm over 1 million ha would potentially sequester 31.5 Mt of carbon (equivalent to 115.6 Mt of CO_2).

The advantages of promoting these technologies include:

- These technologies are applicable to all sandy soils in South Australia that have suitable clay at depth
- Equipment and operators are readily available
- Farmers are familiar with the technology
- Agricultural and NRM benefits are well documented
- Due to the productivity gains farmers are willing to invest in the technology
- Investment is a "one off" with the increase in clay content apparently a permanent feature

While it is probable that the higher SOC potentials achieved through clay spreading and delving would be a permanent feature of the modified soils, the actual increase in SOC and the time taken to achieve the long-term equilibrium levels may vary. Incorporation of organic material by spading may shorten this time frame and also may be useful on other soils apart from sands. However, more research is required to:

- Determine how much organic material can be incorporated into the soil profile
- Determine how much of this material remains in the profile in the long term
- Assess the most suitable sources of organic carbon
- Assess if this technology has application to other soils with bleached A2 horizons

This work should be a high priority as soil modification probably presents the most significant and most obtainable opportunity to increase soil carbon levels in at least the short term (D Davenport 2010, pers. comm.).

2.5.4 Potential climate change impacts

Broadly speaking, a warming, drying future climate across southern Australia is expected to cause declines in productivity and organic carbon inputs (due to rainfall decline and heat stress on crops) and increase rates of SOC decomposition (through increased temperatures). Although farmers will be continuously adapting farming systems and management to optimise production in accordance with the actual climate trends over the short and longer term, the range of traditional adaptation responses may be increasingly restricted as climate impacts accelerate. Canadell *et al* 2007[67] suggest that with global CO_2 and temperature increases, terrestrial sinks are likely to show a saturation response within the next 50 years, meaning that atmospheric CO_2 may accumulate at a faster rate than currently thought. The SOC environmental equilibrium is also likely to be lower than the current level under a warmer, drier climate future (Chan *et al* 2008). A drying trend (especially in low rainfall areas) is expected to have greater impact on heavier (clayey) soil types, increasing the frequency of years with poorer production and reduced plant residue C inputs.

A current DWLBC project (Liddicoat *et al*, in prep)[68], working with SARDI and Rural Solutions SA, is using APSIM wheat production simulations to investigate climate change effects on wheat crop production and erosion potential for different soil types and climate zones. This project is examining stubble biomass production and will provide useful quantitative information about potential impacts on crop residues.

2.6 WHAT ABOUT SOIL INORGANIC CARBON?

While not addressed in this paper, soil inorganic carbon (manifested in the form of calcareous soils) is an important component of South Australian agriculture. Of the area of the State with more than 350mm winter dominant rainfall (the area with the most productive agriculture), nearly half contains carbonate soils. A preliminary investigation by Fitzpatrick and Merry 2000[69] suggests that “increasing aridity could contribute to the preservation of carbonate in the profile, but could also lead to increased recirculation of calcareous dusts.” In some situations it is also suggested that processes of acidification and potentially rising watertables (due to inefficient landscape water use) may influence carbonate weathering and dissolution.

3 THE ROLE OF LAND USE, LAND MANAGEMENT AND TECHNOLOGY IN CARBON SEQUESTRATION

This section provides a more detailed look at land use, land management and technologies associated with SOC sequestration.

3.1 CROPPING

Soil fertility related to SOC in Australian soils has declined over decades of cropping and is still in decline in many cropping soils (GRDC 2009). Conventional tillage systems are estimated to lose SOC at rates of around 200-400 kg/ha/yr (Chan *et al* 2008).

The potential to build SOC in cropping systems depends on the capacity to produce large quantities of crop biomass that can be returned and retained as carbon in the soil. Management that eliminates residue burning or removal, soil erosion, fertility decline, over-grazing, compaction and low biomass crops will help

[67] Canadell JG, Pataki DE, Gifford R, Houghton RA, Luo Y, Raupach MR, Smith P and Steffen W, 2007, ‘Saturation of the terrestrial carbon sink’, in Canadell JG, Pataki D and Pitelka L (Eds) 2007 *Terrestrial ecosystems in a changing world*, The International Geosphere-Biosphere Programme (IGBP) Series, Springer-Verlag, Berlin Heidelberg

[68] Liddicoat et al 2010 (in preparation), *Impact and adaptation to climate change in low rainfall cropping zones of SA: Linking production and land management outcomes (NY pilot study)*, Department of Water, Land and Biodiversity Conservation

[69] Fitzpatrick RW and Merry RH, 2000, ‘Pedogenic carbonate pools and climate change in Australia’, In: Lal R, Kimble JM, Eswaran H and Stewart BA (Eds) 2000, *Global climate change and pedogenic carbonates*, CRC Press LLC

to maintain or build SOC levels. Of course the capacity of any farming system to build SOC depends on the factors previously discussed.

Umbers 2007[70] expresses caution regarding the capacity of Australian rainfed cropping soils to significantly increase SOC, given the age, degraded nature, and naturally low soil carbon levels. SOC levels in cropping soils are frequently < 1%, while SOC levels in remnant 'virgin' soils of the larger cropping areas are often around 1.5%. Altered practices required to maintain high organic matter inputs (to maintain SOC improvements) may also be uneconomic in some situations.

Tillage definitions

Generally speaking, no-till means "sowing a crop without prior cultivation and very little soil disturbance at seeding." The following are stricter definitions used by WANTFA and SANTFA:

- Conventional tillage – multiple tillage
- Reduced tillage – one pass prior to seeding with a full cut-out
- Direct drilling – one pass seeding using a tine fitted with a full or less than full cut device
- *No-till – one pass seeding with a narrow / knife point tine with less than full cut-out
- *Zero-till – one pass disc seeding

* No-till and zero-till are considered 'conservation tillage' and promoted by no-till farmer groups as having the least soil disturbance and best residue retention. Minimum tillage is a confusing term and should be avoided.

(Sources: http://www.wantfa.com.au; Butler 2008)

Conservation farming techniques (no-till or zero-till systems, combined with stubble retention) are readily accessible options to build up topsoil SOC in cropping situations. This is due to reduced soil disturbance and differences in soil biological activity under conventional tillage versus no-tillage situations. The break down of aggregates in conventionally tilled soils and mixing of the litter with the soil allows direct contact between decomposing bacteria and the substrate. In these soils, the physical protection of SOC provided by aggregates is lost and soil biota tends to be dominated by bacteria (Beare *et al* 1992)[71]. In contrast no-tillage systems tend to be dominated by fungal hyphae which are required to contact plant residues left on the surface. In the presence of fungal-dominated pathways, soil carbon cycling tends to lead to a build up of SOC in the form of relatively stable polymers (Stahl *et al* 1999, Bailey *et al* 2002), while fungal hyphae and roots are seen as key binding agents in stabilising soil aggregates for soils recovering from disturbance (Jastrow *et al* 1998[72]) (see figure below). Therefore, a reduction in tillage allows soil aggregation processes to re-establish with stable soil micro- and macro-aggregation providing the best protection for accumulating soil carbon in the mineral-associated fraction of macro-aggregates (Anderson 2009[73], Jastrow 1996[74]).

Additional information is provided by Jones (2003, 2008) claiming that fungi surviving in conventionally managed agricultural soils are mostly decomposers, obtaining energy from decaying crop residues. Generally decomposer fungi have relatively small hyphal networks, and while important for soil fertility and soil structure, they play only a minor role in carbon storage (Jones 2008). In contrast, it is claimed that symbiotic mycorrhizal fungi (see section 2.4.2) have much larger hyphal networks and are capable of providing greater long-term SOC storage. As such, Jones is an advocate of cropping into dormant perennial ground cover (or pasture cropping, see section 3.2) whereby farmers can better utilise the benefits of symbiotic fungi and other microbial activity that is best hosted by a perennial plant based system. In annual cropping systems Jones 2008a suggests that humus formation will only occur if long fallows are avoided, soil is kept covered at all times and biologically-friendly fertilisers/inputs are used, excluding inputs with anti-microbial effects.

[70] Umbers A 2007, *Carbon in Australian cropping soils,* A background paper prepared by Alan Umbers for the Grains Council of Australia, July 10th 2007, Kingston ACT

[71] Beare MH, Parmelee RW, Hendrix PF, Cheng W, Coleman DC and Crossley DA, 1992, 'Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems', *Ecological Monographs*, 62, 569-591

[72] Jastrow JD, Miller RM and Lussenhop J, 1998, 'Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie', in *Soil Biol Biochem*, 30, pp 905-916

[73] Anderson G 2009, *The impact of tillage practices and crop residue (stubble) retention in the cropping system of Western Australia*, Government of Western Australia Department of Agriculture and Food, Bulletin No 4786

[74] Jastrow JD 1996, 'Soil aggregate formation and the accrual of particulate and mineral-associated organic matter', *Soil biology and biochemistry*, 28, 656-76

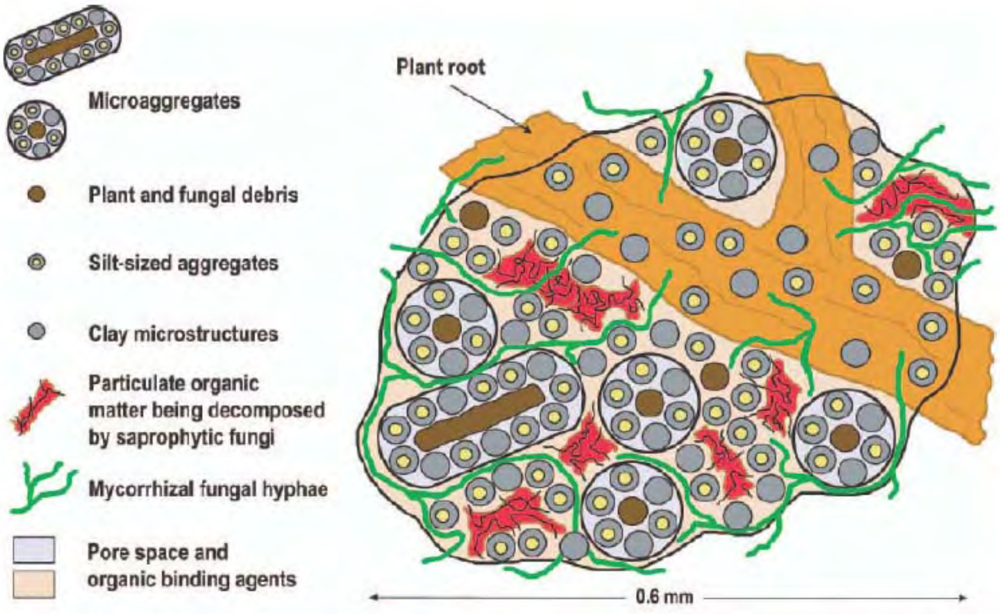

Figure 9. Illustration of micro-aggregate structures and the enveloping macro-aggregate under the binding influence of mycorrhizal fungal hyphae (Jastrow and Miller 1998)[75].

A number of productivity, soil carbon and GHG emissions reductions benefits are reported from adoption of conservation tillage practices and additional high accuracy precision agriculture / controlled traffic cropping systems (Table 4). Derpsch 2005[76] and Sá 2004 claim that a long term approach is required to reap the full benefits of conservation tillage systems (see figure 10 below). They suggest that optimum SOC levels will only be achieved in the consolidation phase (10 to 20 years) with full benefits to soil fertility and production coming after that. Best practice involving disc seeding (zero-till), full stubble retention, adequate crop rotations and inclusion of the occasional green manure cover crop are claimed to reduce the time taken to reach the optimum 'maintenance' phase (Rainbow 2008)[77]. No-till systems without full stubble retention (e.g. letting livestock graze paddocks, baling or burning residues) are not expected to reach beyond the 'initial' phase. The two major limitations of livestock in no-till systems are removal of residues and compaction – however these may be managed to some extent through rotational grazing and close monitoring of paddock condition. Systems sown with a tine (even with no-till and full stubble retention) are not expected to pass the 'transition' phase. The majority of Australian growers practicing conservation agriculture have done so for less than 15 years, with many continuing to let livestock graze stubbles for a number of years following. As such many of these growers are still in the consolidation phase (Rainbow 2008). Challenges for conservation tillage associated with different soil types and environments are being addressed through collaborative research and extension (Butler 2008).

[75] Jastrow JD and Miller RM, 1998, 'Soil aggregate stabilization and carbonate sequestration: feedbacks through organomineral associations', in Lal R, Kimble JM, Follett RF and Stewart BA (Eds) *Soil processes and the carbon cycle*, CRC, Boca Raton, Florida, pp 207-223

[76] Derpsch RW 2005, *Situational analysis of no-tillage systems in WA and recommendations for the way forward*. A report on a consultancy to WANTFA, GRDC and DAFF

[77] Rainbow R 2008, 'Moving beyond adoption', in Butler G (Ed) 2008, *Conservation agriculture: moving beyond adoption*, South Australian No-Till Farmers Association

Table 4. Potential benefits from conventional 'best practice' cropping systems (derived from WANTFA 2009[78], Anderson 2009, Butler 2008[79])

Potential productivity, soil carbon and GHG emissions reduction benefits	System		
	No-till	Zero-till	Zero-till / precision agriculture / controlled traffic
Productivity and soil carbon benefits:			
▪ Reduced land degradation	✓	✓	✓
▪ More flexible, timely, quicker seeding	✓	✓✓	✓✓
▪ Improved soil structure, organic matter and biological activity	✓	✓✓	✓✓
▪ Improved moisture retention / water use efficiency	✓	✓✓	✓✓
▪ Better weed control	✓	✓	✓✓
▪ Less compaction in controlled traffic situations, particularly under precision systems	✓	✓	✓✓
▪ Ability to handle and retain higher stubble loads (with zero-till, 'residue managers' – ie. specialised seeding equipment, and particularly with precision inter-row sowing)		✓	✓✓
Reduced GHG emissions due to:			
▪ Reduced requirement for labour, fuel and machinery	✓	✓	✓
▪ Increased sowing speed and reduced horsepower requirements (zero-till)		✓	✓
▪ Further reduced fuel use and reduced fertiliser use, through reduced overlap (precision systems)			✓
▪ Further N fertiliser efficiencies with variable rate precision ag systems			✓

✓ benefits; ✓✓ increased benefits

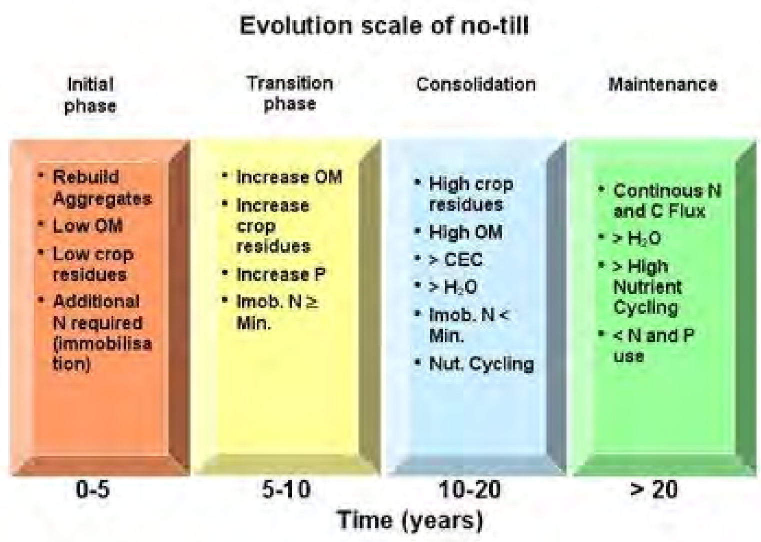

Figure 10. Progression of the no tillage system over time (derived from Sa 2004) (Source: http://www.wantfa.com.au)

[78] WANTFA 2009, No-till farming – Western Australia No-Till Farmers Association (WANTFA) website, http://www.wantfa.com.au

[79] Butler G (Ed) 2008, *Conservation agriculture: moving beyond adoption*, South Australian No-Till Farmers Association

What is the potential SOC sequestration under best practice cropping?

Current estimates of SOC increase possible under conventional best tillage practices in typical soils, and non-limiting rainfall, are in the order of 100-200 kg/ha of carbon per year (Schapel 2008, Umbers 2007).

Notwithstanding the promising potential of conservation tillage to improve SOC levels, there are doubts as to whether this is possible when rainfall is limiting (thought to be under 500-550mm). Cropping areas below 500mm cover a large area of the State (see figure 8). As such, more research is needed to determine whether new and evolving conservation farming techniques are able to achieve long-term SOC sequestration improvements (or perhaps just halt SOC losses). Existing Australian continuous cropping trial results have found that tillage practices have little or no effect on SOC levels where annual rainfall is less than 550mm (Schapel 2008, Valenzo *et al* 2005). However it should be noted that these results were obtained from experiments that were not established with monitoring organic carbon as the main purpose and in a number of cases very little data was provided on what the tillage practices were (Schapel 2008).

Heenan *et al* 2004 reported that after long term (20 year) trials in Wagga Wagga NSW (570mm annual rainfall), traditional cropping (multiple tillage and burning stubbles) was losing SOC at 400 kg/ha/yr, whereas conservation tillage (no-till and stubble retention) stopped SOC losses but did not lead to any detectable increases over the same period.

Only very recently in South Australia has there been significant uptake of zero-till practices that do not involve a single tillage operation. It is possible that a single tillage operation can be as significant as several in lower rainfall cropping (B Hughes 2010, pers. comm.), so the effects of shifting to zero-till will need to be investigated further. Levels of adoption of no-till for South Australia in 2008 have been estimated at around 76%, while maximum adoption levels are starting to plateau around 90% in many Australian grain growing districts (Llewellyn and D'Emden 2010)[80]. The proportion of SA farmers using the least impact disc seeding technology remains low (4% using disc openers only and 8% using a combination of disc openers and points).

Recently experiments have been designed specifically to investigate the effect of different tillage practices on soil carbon. Tillage and farming practices are continually evolving which may make it possible for lower rainfall areas to be able to increase soil carbon levels. While SOC improvements may be limited by climate conditions (and potential to incorporate 'out-of-season' pastures/crops), adoption of conservation farming is still seen as essential to avoid SOC loss in Australian cropping systems. As discussed earlier, an alternative view expressed by Jones 2003 is that a major rethink of cropping practices, incorporating perennial ground cover, is needed in order to build SOC. This is further discussed under 'pasture cropping' below.

After changing to conservation tillage practices a new soil carbon equilibrium is reached over a period of time in the order of decades (Schapel 2008). Once a new equilibrium is established other methods will need to be implemented to increase SOC further. For SOC sequestration below the surface 0-10cm this is likely to require more deep-rooted plants such as perennials.

Emissions reductions and net emissions

Umbers 2007 claims that the shift to reduced and no-till systems has reduced on-farm fuel use by about half. As discussed later there is future potential for emissions reductions associated with reduced and/or more efficient N use. Precision agriculture techniques offer scope for reducing costs and emissions of wasted inputs associated with overlap during various crop management phases.

Modelling of GHG emissions from typical cropping operations (with estimates ranging from 0.3 – 1.5 t C/ha/yr) indicates that the grains industry is a net emitter of GHG (Umbers 2007). Taking a rough estimate of emissions of 0.5 t C/ha/yr, and potential sequestration of the order of 0.1 t C/ha /yr, means that annual C sequestration will be outweighed by emissions by around 0.4 t C/ha /yr. Even higher total on-farm

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[80] Llewellyn RS and D'Emden FH, 2010, *Adoption of no-till cropping practices in Australian grain growing regions*, Grains Research and Development Corporation, GRDC Project Code: SAN00013

emissions were estimated by Robinson 2005[81], at 1.5 – 7.8 t C/ha/yr (5.7-28.6 t CO_2-e/ha /yr) for a range of cropping treatments.

Whether farmers might be liable for these emissions if agriculture is included in a future emissions trading scheme will depend whether the scheme considers (i) net sequestration rate/ emissions or (ii) improvements to the 'business-as-usual' scenario. Total emissions accounting is discussed further in section 5.1.3.

3.2 Pastures, crop and pasture rotations, inter-cropping, pasture cropping

Pastures are an option to improve or maintain SOC levels. Soils under pasture tend to have a higher SOC than cropped soils (refer to figure 11) because they have a higher root to shoot ratio than many crops, are typically less disturbed and have lower rates of SOC decomposition (Chan *et al* 2010). However, the amount of carbon returned to the soil will depend on:

- the form of pasture – perennials will generally return more organic material to the soil than annual systems, the depth of root material is also an important difference.
- the species grown – clover/medic pastures could be expected to return less than grass pastures due to more complete and rapid breakdown of organic material due to higher N levels. A grass-legume pasture can build soil carbon levels by more than 1 t/ha per year (0.05% C per year) (GRDC 2009). Whitbread *et al* 2000[82] found lucerne more effective at building SOC than chickpea or medic.
- the density and levels of dry matter production of the pasture – which will be influenced by pasture establishment and grazing management. Adaptively managed rotational (or cell) grazing with ample periods of rest is considered the best approach to building pasture density, biodiversity and hence resilience.

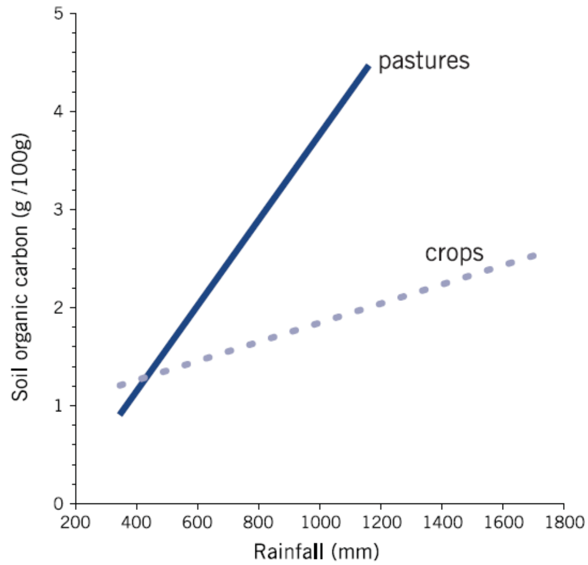

Figure 11. SOC levels in pasture soils compared with cropping soils (0-10cm) as a function of rainfall in NSW (Chan *et al* 2010)

- the length of pasture phase – pasture phases undertaken in rotation with cropping can help to maintain or build SOC (Chan *et al* 2008) however the amount of carbon retained will vary depending on the respective lengths of each phase.
- Post pasture management – excessive tillage should be avoided at the end of the pasture phase or much of the organic matter will be rapidly depleted (GRDC 2009).

Legume and grass pasture phases in a rotation with grain growing are reported to offer reduced carbon emissions primarily through their nitrogen replacing qualities (The Land 2010)[83]. Dr Ram Dalal (Qld DERM)

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[81] Robinson M, 2005, 'Three prong strategy key to soil carbon', *Australian Farm Journal*, June 2005, 44-46

[82] Whitbread AM, Blair GJ and Lefroy RDB, 2000, 'Managing legume leys, residues and fertilisers to enhance the sustainability of wheat cropping systems in Australia: 2. Soil physical fertility and carbon', *Soil & Tilllage Research*, 54, 77-89

[83] The Land 2010, 'Combat carbon emissions with legumes', *The Land* (online news) 10 Mar 2010 , http://theland.farmonline.com.au/news/nationalrural/grains-and-cropping/general/combat-carbon-emissions-with-legumes/1772660.aspx

advocates the inclusion of legumes in farming systems to reduce energy use and carbon emissions related to the manufacture and transport of N fertiliser, which is primarily derived from natural gas. Dr Dalal says energy use for cereal production exceeds energy stored in soil carbon sinks in cereal cropping farming systems, and "a major shift in land use is required to balance energy input and energy output".

A useful guide to developing SOC in pastures is *"A Farmer's Guide to Increasing Soil Organic Carbon Under Pastures"* (Chan *et al* 2010). The guide is based on findings from a three year project investigating soil carbon levels in pastures under different management systems in south east NSW. A free PDF version of the guide can be downloaded from the website:

www.dpi.nsw.gov.au/agriculture/resources/soils/soil-carbon/increasing-soil-organic-carbon-farmers-guide

Aside from rotations, other options to incorporate pastures to build up SOC include: inter-cropping with perennial pastures (crop and pasture plants are sown in different rows using precision agriculture techniques and have different periods of activity/growth), or pasture cropping (expanded on below, where winter active crops are sown into existing predominantly summer active perennial pasture).

Pasture cropping

Pasture cropping (Jones 2003[84], 2008b,[85] Bruce *et al* 2009[86], Cluff and Seis 1997[87]) is reported to offer particular benefits for building SOC. Jones claims that year-round carbon additions from the perennial grass evolve into highly stable forms of SOC (humus), facilitated by mycorrhizal fungi (see section 2.4.2), while high sugar exudates from annual cereal crops roots stimulate beneficial microbial activity. Through the combined activity of the perennial pasture and annual crop, photosynthesis and plant production is occurring for a much greater portion of the year. Moisture competition in lower rainfall areas may be a limiting factor, however proponents of this approach claim a number of benefits associated with the presence of mycorrhizal fungi and dormant host perennial pasture. These include: improved soil structure and water-holding capacity (through higher SOC); micro-climate benefits (due to perennial cover); weed control; and nutrition and water-balance advantages (with the mycorrhizal fungal hyphae able to lift moisture and nutrients from deeper in the profile and re-distribute it in the crop root zone) (Jones 2008a, 2008b). Maintaining the perennial pasture base (which is dormant during the cropping season) maintains soil cover to protect from erosion and excess soil water evaporation. Modern no-till cropping machinery equipped to handle high stubble loads has been used to successfully establish crops into established dormant perennial pastures (Jones 2008b). This system relies on the action of soil microbial communities and as such only microbial-friendly inputs are recommended. Establishing what might be the best (or most appropriate) mutualistic combinations of annual crops and perennial pastures for varying soils and climatic conditions is expected to take time. The quantity and timing of year-round rainfall on particular soil types will ultimately determine if it is viable to grow both a winter-active annual crop and a summer-active perennial. The winter dominant, relatively low rainfall of much of South Australia may restrict the use of this system.

Pasture cropping trials in 2007-2008 at Peterborough and Morchard, in the Northern & Yorke region, attempted to demonstrate the potential of this flexible farming system to provide additional feed value (in poorer years) and successful grain crops in better years (M Wurst 2010, pers. comm.). The composition of the native pasture mix was seen as a critical factor for the success of the system. To minimise moisture competition with winter-growing annual crops, established stands of summer-active (winter-dormant) native grass pastures are needed. If cereals are sown into pastures for mostly grazing purposes, then a proportion of winter-active native grasses in the mix provides better overall feed value. There is ongoing interest to examine the potential of pasture cropping systems in traditionally low return, unreliable cropping situations. Using summer-active C4 perennial grasses to gain increased grazing / production from

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[84] Jones C, 2003, *Recognise, relate, innovate*, NHT Funded Project BD0444.98 Ecological and technical support for Landcare on rangelands, NSW Department of Land and Water Conservation

[85] Jones C, 2008b, *Our soils, our future*, http://www.amazingcarbon.com/

[86] Bruce S, Seis C, Graham S, Howden M and Ash J, 2009, 'Pasture cropping: effect on biomass, soil cover, soil water and nitrogen', *Proceedings of the 'managing the carbon cycle' forum*, Armidale 13-14 Sep 2005

[87] Cluff D and Seis C, 1997, 'Should farmers and graziers be garmers and fraziers?', p22-23 in *Landcare Best Practice* released at the *Landcare Changing Australia National Conference*, Adelaide September 1997

summer rainfall (which would otherwise be mostly wasted through evaporation or summer weeds) is seen as an important opportunity in low rainfall areas. The 2007-2008 trials were beset by drought years, poor establishment, pest grazing and in one case an unforgiving clayey soil type. Future work is needed in establishing appropriate summer-active native grass pasture stands which will be well suited to winter-active annual crops.

Carbon focussed grazing practices

Terms such as 'carbon grazing', 'regenerative grazing', 'regenerative grassland management' and 'holistic management' have emerged which describe similar principles of intensive herding style management with intermittent, short, intense ('pulsed') grazing events, frequent stock movements and long rest periods. This enables palatable plants to recover and re-establish healthy root mass between grazing episodes, while the increased SOC and landscape vegetation allows the soils and landscape to absorb and hold more water.

'Carbon grazing' principles are described by Queensland grazier Alan Lauder in his book *"Carbon grazing: The missing link"* (Lauder 2009)[88] and on the website: www.carbongrazing.com.au . His ideas have received support from some high profile scientists, including members of the Wentworth Group of Concerned Scientists. The similar concept of 'regenerative grassland management', advocated by Lovell and Ward 2008[89] (from Soil Carbon Australia, www.soilcarbon.com.au/) was among the top ten ideas in the *Manchester Report*[90], judged by an independent panel of UK science and policy experts as offering the world's most promising solutions to climate change. Case studies showing the benefits of this approach in arid and seasonally dry areas are shown on their website. Many of these principles have general merit for any climate and to some extent are already captured within best practice adaptive rotational (cell) grazing systems used in South Australia. Grassland ecologist Christine Jones (http://www.amazingcarbon.com/) advocates the application of similar principles (in both grazing and cropping situations) while emphasising the importance of plant dynamics and associated soil microbial communities (Jones 2003). The important role of microbial communities and links to plant diversity, management and soil carbon are also becoming more widely recognised (Cawood 2008[91]).

Through collective management of multiple properties some farmer groups are integrating this large herding style rotational grazing with long rest periods into holistic management plans for large areas of landscape, with the goal of bringing ecological, economic and social resilience (Brunckhorst and Coop 2003)[92].

Some of the general principles of carbon-focussed grazing include (Lauder 2009, Lovell and Ward 2008, Jones 2003):

- Maximise all forms of landscape carbon, including getting plant cover on degraded parts of the landscape
- Maximise water for plant transpiration, by maximising soil water-holding capacity (related to SOC), minimising water lost through evaporation and deep drainage past the root-zone. In other words maximise water use efficiency.
- Focus on plant and landscape resilience, not just growing more feed
- Maintain significant living plant material and surface residues to make the most of rainfall when it falls. Jones 2003 suggests that no more than 60% of available forage be consumed (allowing approximately 20% to be trampled for surface litter and 20% left standing).

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[88] Lauder A 2009, *Carbon grazing: The missing link*, www.carbongrazing.com.au

[89] Lovell T and Ward B, 2008, *Soil carbon case studies*, Soil Carbon Australia, http://www.soilcarbon.com.au/case_studies/index.html

[90] Anon, 2009, *The Manchester Report: A search for the world's most promising solutions to climate change*, Commissioned by the Guardian and Manchester International Festival

[91] Cawood M, 2008, 'Microbes: the next livestock boom?', *The Land – Farm online news*, 8-07-2008

[92] Brunckhorst DJ and Coop P, 2003, 'Tilbuster Commons: Synergies of theory and action in new agricultural commons on private land', *Ecological Management and Restoration*, 4(1), 13-22

- Intermittent intense grazing events cause root pruning (Richards 1993)[93]. Pruned roots provide valuable organic matter to the soil and stimulate microbial activity.
- Long recovery periods ensure palatable plants are healthy and persist in the pasture mix. According to holistic management ideas (Savory and Butterfield 1999[94], http://www.holisticmanagement.org/) grasslands should not be re-grazed until monitoring indicates that the most heavily grazed plants are fully recovered. Depending on environmental factors this may take from 3-12 months (Jones 2003).
- Another theory of 'carbon grazing' is that pastures should be rested for 4-6 weeks after rains – on the basis that the bulk of carbon enters the landscape during the short period immediately following rain
- During recovery periods deep roots are re-established, recycling leached nutrients and building SOC in association with mycorrhizal fungal networks.
- Pastures should not be left so long that they go tall and rank, with declining quality
- Some degree of soil disturbance is desirable and mimics the natural ecological interactions of herbivores, plants and soil (Jones 2003).
- During the transition phase (while soils are still dysfunctional) high density stocking to mulch the soil (trampling more biomass than is grazed), intermittent root pruning and biological preparations to stimulate soil microbial activity are recommended.

In addition to SOC sequestration, a range of co-benefits are suggested to arise from these approaches:

- Greater landscape water retention due to higher SOC levels
- Greater resilience to drought
- Increased profitability, higher productivity and stocking rates
- Increased pasture digestibility
- Reduced methane emissions per kg of production from ruminants
- Improved water quality, native habitats and biodiversity

Some of the principles outlined above may sound, to a degree, difficult to reconcile with conventional thinking (e.g. partial grazing while avoiding rank pastures, beneficial levels of soil disturbance, etc.) but advocates suggest that net benefits appear with time following adoption of the total grazing management package. Like any other farming innovation, farmers usually want to see successful local demonstrations before they would be confident to take up alternative management ideas.

Rangelands

Inherent productivity and SOC levels are low in the rangelands, largely due to hotter temperatures and low, unreliable rainfall. However because of the large area involved, small increases in soil carbon under change management practices could result in significant sequestered SOC. Currently degraded land would offer the greatest potential for SOC increases. Pulsed/ herding-style/ carbon-focused grazing management practices (as discussed above) are also thought to benefit SOC stocks in these low rainfall rangelands (Lovell and Ward 2008). This grazing management approach is likely to be assisted by the use of temporary electric fencing and mobile water points. Well managed grazing is suggested to offer the best option for rehabilitation of degraded rangelands due to the cost-effective delivery of nutrients by grazing animals and use of animal hooves to help plant seeds deeper in the soil where than can reach more reliable water. Avoiding overgrazing in good rainfall years by stock, locusts, feral herbivores, excess numbers of kangaroos, or loss of plant residues by uncontrolled bushfire, is seen as important for building SOC levels. Further

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[93] Richards JH, 1993, 'Physiology of plants recovering from defoliation', *Proceedings of the XVII International Grasslands Congress*, Palmerston North, New Zealand, 85-94

[94] Savory A and Butterfield J, 1999, *Holistic management: A new framework for decision making*, Island Press, USA

issues and knowledge gaps in this area are discussed in Gifford and McIvor 2009[95]. In the arid and semi-arid rangelands, cyanobacterial crusts are being investigated which offer potential to increase soil C and N levels (Queensland Country Life 2009)[96].

3.3 PERENNIAL PLANTINGS

Forestry

Chan *et al* 2008 provides some considerations for SOC under forestry, of which previous land use and SOC condition are very important. During the phase of plantation establishment SOC levels are likely to decline, due to the impact of initial clearance. As plantations grow soil carbon can be replenished from litter fall and root turnover. Conversion of cropland to forest is expected to increase soil carbon stock, with average increases of 18-20% reported (Guo and Gifford)[97]. However conversion of pasture to forest can increase SOC in some cases and decrease it in others (Chan *et al* 2008). Factors such as the plant species, soil type, climate, changing soil biota, time to harvesting, etc. can also determine the new long-term equilibrium SOC level. Hobbs 2009[98] presents production and economic modelling for biomass plantations across different regions of South Australia.

Saltbush

It has been suggested that saltbush plantations warrant further attention and research to assess their SOC and vegetative carbon sequestration potential, and to test their compliance against current Kyoto rules for 'forestry' (Benjamin 2009)[99]. This is of particular interest in South Australia given their suitability to low rainfall zones and mixed livestock-cropping farming systems. Theoretically saltbush could fit the Kyoto rules for forestry, with potential to exceed 2 m in height and they can be planted at a density to achieve at least 20% crown cover. They are also likely to fit the revegetation scheme criteria if planted on degraded land (e.g. land affected by dryland salinity).

Assessments of above and below ground carbon stocks in a five-year-old Old Man Saltbush (*Atriplex nummularia*) stand exceeded that of an adjacent pasture. Considering only below ground carbon, the saltbush recorded 5.7 t CO_2e/ha below ground biomass (compared to 2.9 t CO_2e/ha for the pasture) and 237.6 t CO_2e/ha SOC to 1m depth under the saltbush (compared to 221.5 t CO_2e/ha to 1 m under the pasture) (K Montagu and K Duttmer unpublished data, in Benjamin 2009).

Forage shrubs including saltbush are already being successfully adopted within South Australian dryland farming systems to boost profitability and resilience to climate fluctuations. This is backed up by whole-farm economic modelling suggesting that forage shrubs have the potential to increase farm profitability by an average of 24% for an optimal 10% of farm area (Monjardino *et al* 2010)[100].

Biodiversity plantings

Retirement of marginal agricultural land, and planting to perennial native vegetation, is thought to offer significant potential for carbon sequestration in soils as well as in vegetation (Sanderman *et al* 2010). SOC will be maximised as nearly all the net primary production of the vegetation would be returning to the soil. It should be noted that climate and soil type limitations still apply and in some South Australian settings (e.g. with low rainfall, sandy and infertile soils) the equilibrium SOC potential would be expected to be relatively low. Potential growth rates of biodiversity/ habitat plantings have been modelled across different

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[95] Gifford R and McIvor J 2009, 'Chapter 5 – Rehabilitate overgrazed rangelands, restoring soil and vegetation carbon-balance', In Eady S, Grundy M, Battaglia M and Keating B (Eds) 2009, *An analysis of greenhouse gas mitigation and carbon biosequestration opportunities from rural land use*, CSIRO, St Lucia, QLD

[96] Queensland Country Life 2009, 'Cyanobug unlocks soil carbon potential', *Farm Online* (website), 2/11/2009

[97] Guo LB and Gifford RM, 2002, 'Soil carbon stocks and land use change: a meta analysis', *Global Change Biology*, 8, 345-360

[98] Hobbs TJ [ed], 2009, Regional industry potential for woody biomass crops in lower rainfall southern Australia. FloraSearch 3c, Report to the Joint Venture Agroforestry Program (JVAP) and Future Farm Industries CRC. Publication No. 09/045, Rural Industry Research and Development Corporation, Canberra

[99] Benjamin C 2009, 'Saltbush plantations awaiting recognition for sinking carbon in low-rainfall zones', *Australian Farm Journal*, April 2009, 42-45

[100] Monjardino M, Revell D and Pannell DJ, 2010, 'The potential contribution of forage shrubs to economic returns and environmental management in Australian dryland agricultural systems', *Agricultural Systems*, 103, 187-197

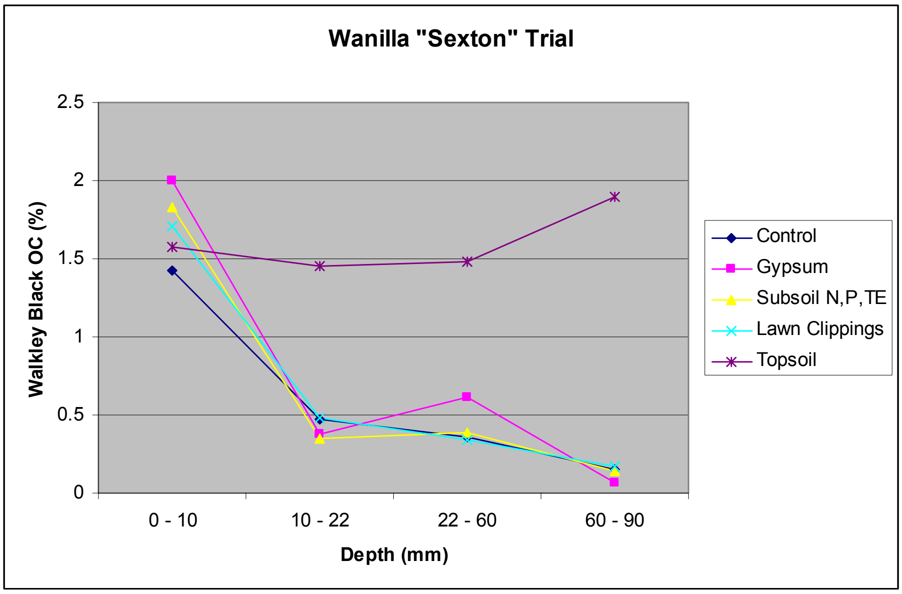
regions of South Australia, by the former Department of Water, Land and Biodiversity Conservation (now the Department of Environment and Natural Resources) (T Hobbs 2009, pers. comm.).

3.4 AMELIORATING SOIL LIMITATIONS / SOIL MODIFICATION

Addressing soil limitations and thereby improving productivity is likely to have a significant impact on SOC potential, for example:

- Liming acid soils
- Spreading gypsum to improve structure on sodic (dispersive and hard-setting) soils
- Clay spreading on non-wetting sands

The age and relatively low SOC levels of South Australian soils compared to many other parts of the world is widely recognised. Soil constraints such as poorly structured subsoils, salinity, non-wetting nature, etc. are a major factor impeding development of SOC. This is particularly evident in the low levels of SOC found in many subsoils. Analysis of a site at Wanilla on Eyre Peninsula demonstrates that long term increases in SOC are possible where these issues are addressed (refer figure 12). Although on this site it is unclear if this is due to the presence of residual SOC or if SOC has been increased. Soil modification of sandy soils via clay spreading and delving is clearly a major opportunity to increase SOC and deliver higher levels of agricultural production. This delivers a long term change allowing greater SOC storage potential. There are other soils that may provide a significant opportunity. Soils with a bleached A2 horizon (usually located at between 10-40 cm) may also provide an opportunity to increase carbon levels.



The "Sexton" sites were developed by Robin Graham in the late 1980's at a number of sites in South Australia. They comprised a series of plots excavated by a backhoe and then backfilled with a number of treatments. The Wanilla site was re-sampled by David Davenport and Geoff Braun in 2003. The "Topsoil" treatment (backfilled with topsoil from the adjacent scrub) showed significantly higher levels of SOC in the subsoil. Crop growth was also significantly greater.

Figure 12. SOC measurements at the Wanilla "Sexton" soil modification trial site

3.5 ORGANIC / BIOLOGICAL / BIODYNAMIC FARMING METHODS

Organic farming methods are reported to mostly offer reduced emissions benefits, SOC sequestration benefits, and/or lower energy consumption over conventional farming methods (Pimentel *et al* 2005[101], Robertson *et al* 2000[102], Stolze *et al* 2000[103], Wells *et al* 2000[104], Azeez 2009[105], Marriot and Wander

[101] Pimental D, Hepperly P, Hanson J, Douds D and Seidel R, 2005, 'Environmental, energetic and economic comparisons of organic and conventional farming systems', *Bioscience*, 55(7), 573-582

[102] Robertson GP, Paul EA and Harwood RR, 2000, 'Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere', *Science*, 289 (No 5486), 1922-1925

[103] Stolze M, Piorr A, Haring A and Dabbert S, 2000, 'The environmental impacts of organic farming in Europe', In *Organic farming in Europe: Economics and Policy (Vol 6)*, Department of Farm Economics, University of Hohenheim, Germany, Stuttgart-Hohenheim

[104] Wells AT, Chan KY and Cornish PS, 2000, 'Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales', *Agriculture Ecosystems and Environment*, 80, 47-60

2006[106]) while offering increased resilience to climatic extremes (Lotter *et al* 2003[107]). A 23-year ongoing research project by the Rodale Institute in the United States has found that two organic systems (one legume based and one manure based) have shown SOC increases of 15-28%, while an adjacent conventional system has shown no statistically significant increase (Sayre 2003)[108]. Organic farming achieves high carbon inputs through the use of animal and green manures, greater crop rotations and cover crops, and the use of composting techniques. CO_2-e emissions are reported to be around 40-60% lower in organic farming systems than conventional systems, largely because they don't use synthetic nitrogen fertilisers which require large amounts of energy in their production and are associated with emissions of the powerful GHG nitrous oxide (Sayre 2003, BFA 2007[109],). Organic farming is also considered a local production system, with crop nutrition, animal health and pest control carried out largely by natural processes on the farm. In this respect "food miles" (and associated road transport GHG emissions) are reduced, compared to transport requirements for fertiliser, animal feed, pesticides and veterinary drugs associated with conventional farming practices (Smithson ?[110]). Azeez 2009 reports an average of 20% higher SOC sequestration rates for organic farming (and 25% higher for biodynamic farming) compared to non-organic farming, for all countries studied including Australasia.

While some organic farming methods rely on multiple tillage operations for weed control and incorporating manure and cover crop residues, the SOC losses associated with tillage may be counteracted by the use of organic matter inputs (e.g. manure) that provide a more stable form of organic carbon. It is also argued (in both conventional and organic systems) that tillage operations which incorporate organic inputs at depth can offer lasting SOC benefits due to lower decomposition rates deeper in the soil profile. Lower production levels (ie. less removal of product through the farm gate) in organic farming systems may also be a factor contributing to higher SOC levels (B Hughes 2010, pers. comm.). Azeez 2009 comments that organic matter inputs that have already undergone some microbial digestion (e.g. farmyard manure or compost) will retain a higher % of carbon when converted to soil carbon. Estimates are provided of the proportion of carbon retained in different organic inputs – straw 5-7%, legumes 17%, manure 23%, compost 50% (Azeez 2009). As discussed earlier (in section 2.4.2) labile synthetic N fertiliser (not used by organic farmers) has also been connected with reducing SOC quality (through the degradation of soil micro-aggregate binding agents, thus diminishing the permanence of N and C storage) in some situations. SOC storage is aided by mychorrizal fungi and the potent glue-like substance called glomalin, as these help to bind soil micro-aggregates together. Research has shown that mycorrhizal fungi are more prevalent and diverse in organic farming systems and suppressed in conventional, chemical-based agriculture (Douds and Miller 1999[111], LaSalle and Hepperly 2008[112], Jones 2008).

Other SOC enhancing soil management practices include adoption of no till cropping, and innovative living bed systems where crops are planted and re-planted in the same permanent living mulch (BFA 2007, Sullivan 2003[113]). Organic methods also encourage synergies with beneficial fauna (including macro-invertebrates) which can benefit soil fertility and production levels (e.g. Miller 2009)[114]. Pimentel *et al* 2005 suggest that conventional agriculture can be made more sustainable and ecologically sound by adopting some traditional organic farming technologies.

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[105] Azeez G, 2009, *Soil carbon and organic farming: A review of the evidence on the relationship between agriculture and soil carbon sequestration, and how organic farming can contribute to climate change mitigation and adaptation*, Soil Association (UK), http://www.soilassociation.org/Whyorganic/Climatefriendlyfoodandfarming/Soilcarbon/tabid/574/Default.aspx

[106] Marriot EE and Wander MM, 2006, 'Total and labile soil organic matter in organic and conventional farming systems', *Soil Science Society of America Journal*, 70, 950-959

[107] Lotter DW, Seidel R and Liebhardt W, 2003, 'The performance of organic and conventional cropping systems in an extreme climate year', *American Journal of Alternative Agriculture*, 18(3), 146-154

[108] Sayre L 2003, *Organic farming combats global warming – big time*, Web article, Rodale Institute, http://www.rodaleinstitute.org/ob_31

[109] BFA 2007, *Soil makes the carbon cut – BFA Press Release 13th December 2007*, Biological Farmers of Australia, http://www.bfa.com.au/

[110] Smithson A, ?, *Organic farming, tackling global warming*, Biological Farmers of Australia, http://www.bfa.com.au/

[111] Douds DD (Jr) and Miller PD, 1999, 'Biodiversity of arbuscular mycorrhizal fungi in agroecosystems', *Agriculture, Ecosystems and Environment*, 74, 77-93

[112] LaSalle TJ and Hepperly P, 2008, *Regenerative 21st century farming: A solution to global warming*, The Rodale Institute

[113] Sullivan P, 2003, *Overview of cover crops and green manures*, US National Center for Appropriate Technologies, http://attra.ncat.org/

[114] Miller C, 2009, 'Beetlemania rejuvenates SA pastures', *Stock Journal* August 27 2009, Farm online 29/08/2009

Utilising biomass waste products / recycled organics / wastewater

SOC benefits are likely from the use of organic matter inputs such as waste or recycled organic matter, sewage biosolids and wastewater. Benefits (e.g. to SOC, productivity, profitability, etc) and/or adverse impacts (e.g. salinity, nutrient leaching, off-site odours, etc) will depend on properties of the particular waste product, soil type, application / incorporation rates and techniques, and relevant buffer zones (e.g. to receiving water bodies or odour receptors). Recycled organic wastes (e.g. manures) are often an integral component of successful biological farming systems. Wastewater and solids from intensive animal operations (such as dairies and feedlots) are also recognised in conventional farming systems as a valuable source of nutrients and organic matter when applied at sustainable rates (Clark 2003)[115].

Using recycled organic material helps to address some critical sustainability issues looming for modern farming and food production, in particular the removal of mineral nutrients and trace elements from rural soils and transfer to urban waste streams. Another issue is that conventional fertiliser supplies of synthetic N and phosphorous (P) are tied to depleting finite resources (Parliament of South Australia 2008[116], Cordell *et al* 2009[117]). Whereas potential advantages of returning organic materials to soil include improving the structure, water-holding capacity, nutrient, trace element and SOC status, and productive capacity of soils. Composting methods are able to kill pathogens and weed seeds, while balancing plant and animal wastes (including human biosolids) offers real advantages as these streams have complimentary nutrient profiles (Scott-Orr 2005[118], Gillespie 2005[119], Paulin and O'Malley 2008[120]). Information resources and recycled organics industry links are available through the website: http://www.compostforsoils.com.au/ .

Opportunities and issues relating to sequestration involving waste and recycled organic matter are also discussed in Gibson *et al* 2002[121] and Eady *et al* 2009. Life cycle analysis of carbon sequestration (see section 5.1.3) is designed to account for SOC improvements which benefit because of carbon declines in other systems. Organic matter feedstocks used for building SOC should only comprise of organic matter waste streams that have already left the farm. This includes feedstocks for biochar (see below).

3.6 BIOCHAR

Biochar is a fine-grained charcoal high in organic C that will sequester carbon when applied to soil. Most types of biochar take hundreds of years (GRDC 2009) and in some cases thousands of years (Krull 2009a)[122]to degrade and release carbon.

Biochar is created by the pyrolysis (heating in the absence of oxygen) of organic wastes such as crop residues, wood chips, sewage biosolids or manures, to convert them into relatively inert C compounds.

As opposed to charcoal, biochars need to be produced under carefully controlled oxygen-reduced conditions with greater carbon capture (GRDC 2009). The process also produces biofuel that can be used for energy generation (e.g. to fuel the pyrolysis process) and/or stored for later use. As feedstocks and processing conditions (e.g. temperature and time) can vary, biochar properties can also vary significantly. Hence benefits and costs vary with the biochar properties, soil types and ultimate purpose (Eckard 2010). For example, biochar made from manure will have a higher nutrient content and be less stable than biochar made from wood cuttings. Biochar produced at higher temperatures will have greater adsorptive capacity which may be useful for adsorption of toxic substances and rehabilitating contaminated soils (Krull 2009a).

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[115] Clark T 2003, *A manual for spreading nutrient-rich wastes on agricultural land*, (CD manual) prepared by Rural Solutions SA for Primary Industries and Resources SA and the Environment Protection Authority

[116] Parliament of South Australia 2008, *Report of the select committee on the impact of peak oil on South Australia*, 25 November 2008

[117] Cordell D, Drangert JO and White S, 2009, 'The story of phosphorus: Global food security and food for thought', *Global Environmental Change*, 19, 292-305

[118] Scott-Orr H, 2005, 'Organic recycling and sustainable food production', In *CSIRO Sustainability Network Update – No 54E*, 1 Nov 2005

[119] Gillespie G, 2005, 'From the farm to the city – from "City to Soil"', *Proceedings of the 'managing the carbon cycle' forum*, Armidale 13-14 Sep 2005

[120] Paulin B and O'Malley P, 2008, *Compost production and use in horticulture*, Western Australia Department of Agriculture and Food, Bulletin 4746

[121] Gibson TS, Chan KY, Sharma G and Shearman R, 2002, *Soil carbon sequestration utilising recycled organics: A review of the scientific literature*, prepared for Resource NSW by the Organic Waste Recycling Unit, NSW Agriculture

[122] Krull E 2009a, *Biochar* (fact sheet), CSIRO Land and Water, http://www.csiro.au/resources/Biochar-Factsheet.html

When added to the soil biochar contributes to the resistant / recalcitrant SOC pool which is important for C sequestration. Some studies (Krull 2009a, ANZBRN 2008[123]) have shown that biochar can offer benefits including:

- Improved nutrient use efficiency (soil fertility)
- increased nutrient retention and release (by proving increased storage for nutrients)
- increased water holding capacity
- improved soil structure
- increased microbial activity
- greater soil cation-exchange capacity
- improved soil thermal properties
- decreased release of non-carbon dioxide GHG such as methane and nitrous oxide
- greater soil buffering capacity decreasing rate of soil acidification
- decreased uptake of soil toxins

Some soil types are reported to be very receptive to biochar application and have shown increases in fertility and structural benefits, while other soil types have shown no benefits. “Studies that have reported positive effects with regard to crop production often involved highly degraded and nutrient-poor soils, whereas application of biochar to fertile and healthy soils does not always yield a positive change.” “In fact, some biochars may have adverse effects on plant growth.” (Krull 2009) As biochars vary in their properties, testing is required to determine the suitability of different biochars to particular soil types.

Bell and Lawrence 2009 express caution with the use of biochars. The long residence times and relatively inert nature of chars to microbial decomposition (although good for sequestering C in soils) may come at a cost. “All that biological nutrient cycling, building of soil structure and disease suppression that are characteristic of a healthy soil could be compromised by converting what are already scarce resources (organic matter inputs) into more expensive and relatively inert organic matter inputs.” Baldock 2010[124] comments that “we shouldn’t cut out the microbial loop – biochar feedstocks should mainly comprise waste streams of carbon that have already left the farm.” While other benefits of biochars (e.g. immobilising toxic Aluminium) are claimed, these are likely to apply to specific combinations of soil types and climate and shouldn’t be extrapolated across all agricultural soil (Bell and Lawrence 2009).

Biochar production is seen as beneficial due to the carbon-negative process, associated bioenergy production and site-specific benefits (e.g. crop yields, contaminated site remediation) (Krull 2009). However, in broad terms the economic viability and carbon offset value of using biochars remain to be tested. This will depend on the cost (and CO_2 emissions) of feedstock, processing and transport. It will also depend on whether it is included in an emission trading scheme where biochar producers or users may receive credit for stabilising organic C. Eckard 2010 suggests that the carbon credit for converting organic material into a more permanent form of C may well be attributed to the factory where pyrolysis occurred, providing the farmer with little incentive unless this is specifically negotiated.

Eckard 2010 suggests biochar should be seen as a complimentary measure (playing a role in carbon storage) but not the cure-all. GRDC 2009 state that more research is needed to investigate claimed benefits to determine whether biochar offers any real benefits under Australian conditions.

The Australian and New Zealand Biochar Researchers Network (ANZBRN) has been established to help improve the coordination of biochar research and provide information about biochar and its benefits via its website: http://www.anzbiochar.org/index.html . Further information is available from the CSIRO fact

[123] ANZBRN 2008, Biochar basics, Australia and New Zealand Biochar Researchers Network, http://www.anzbiochar.org/biocharbasics.html

[124] Baldock J 2010, pers. comm., Stream Leader - Soil Carbon and Nitrogen Balance in Agricultural Lands, CSIRO Land and Water

sheet (Krull 2009a), Krull 2009b[125], Sohi *et al* 2009[126], McHenry 2009[127] and the Australian Parliamentary Library website[128].

3.7 OTHER SOIL ADDITIVES

A range of non-traditional soil amendments, including microbial inoculants, have been claimed to increase SOC sequestration in recent years. At the current time there is inadequate scientific evidence to fully assess their impact on SOC sequestration, outside of the yield gains shown in some field trials (Sanderman *et al* 2010). Some of these products work by accelerating the mineralisation of organic matter to increase availability of plant nutrients. In such cases there would need to be large increases in plant productivity and return to the soil to realise any SOC gains. Increased levels of free living N fixing bacteria are likely to result in reduced use of synthetic N fertiliser. This is another factor to be weighed up when determining the possible net benefits of such products.

3.8 MICRO-CLIMATES

The creation of micro-climates may offer the capacity to modify local climatic conditions. For example the use of wind breaks[129] on a broad-hectare scale (e.g. alley and paddock perimeter plantings) may reduce evaporative water loss and minimise the impacts of extreme wind events, allowing for improved plant production. Alignment of crop rows, to enhance shading of the soil and/or to counter prevailing wind directions have also been proposed as a means to improve crop water use efficiency. Mulch is widely used in intensive perennial horticulture. Shading of soils may also have beneficial impacts by reducing soil temperatures and hence SOC decomposition rates.

4 OTHER SOIL-RELATED GREENHOUSE GASES

Other key GHG of interest to agricultural systems management are methane (CH_4) and nitrous oxide (N_2O). In terms of global warming potential, methane and nitrous oxide are respectively 23 and 296 times more potent than CO_2, however due to overall atmospheric concentrations carbon dioxide is the more important GHG (Table 5).

Table 5. Other key greenhouse gases (Stern 2006, IPCC 2001[130])

Greenhouse gas	Lifetime in atmosphere	100 year Global Warming Potential (GWP) relative to CO_2	% of 2000 emissions in CO_2-e
Carbon dioxide (CO_2)	5-200 years	1	77%
Methane (CH_4)	10 years	23	14%
Nitrous oxide (N_2O)	115 years	296	8%

125 Krull E 2009b, 'Agricultural sequestration and mitigation options: What are the realistic options for soil sequestration?', *Agriculture, Greenhouse and Emissions Trading Conference Proceedings*, Maroochydore 6-7May, Australian Farm Institute

126 Sohi S, Loez-Capel E, Krull E and Bol R, 2009, *Biochar's roles in soil and climate change: A review of research needs*, CSIRO Land and Water

127 McHenry MP, 2009, 'Agricultural bio-char production, renewable energy generation and farm sequestration in Western Australia: Certainty, uncertainty and risk', *Agriculture, Ecosystems and Environment*, 129, 1-7

128 http://www.aph.gov.au/library/pubs/bn/sci/biochar.htm

129 A case study on the potential benefits of wind breaks is contained in: Hosking R, 2007, *Climate change, carrying capacity of grazed pastures and potential benefits of windbreaks, a single-site case study*, Available from the Healthy Soils Australia website: http://www.healthysoils.com.au/docs/HSA_climate_chg.pdf

130 IPCC 2001, *Climate Change 2001: Working Group I: The Scientific Basis (Third Assessment Report)*, http://www.grida.no/publications/other/ipcc_tar/

Mitigation of other key GHG

Examples of changed farming practices which could reduce CH_4 and N_2O emissions include (Eady *et al* 2009, Eckard 2010):

- Reduction in N_2O emissions from reduced N fertiliser use or improved N use efficiency (through regular soil N testing, optimising application rates, balanced supply of key nutrients, timing of application, split applications with foliar liquid N application at critical growth stages with appropriate seasonal indicators of likely crop success, avoiding waterlogged areas, maintain equipment to ensure precise applications, use nitrification inhibitors, slow release products, use alternative N sources which minimise excess inorganic N, greater use of legumes, etc.)
- Reductions in CH_4 and N_2O emissions from changes in animal management practices, including dietary modifications in feed lotting situations, careful management of pasture feed quality, etc.
- Reductions in CH_4 and N_2O emissions through improved manure / effluent handling, e.g. anaerobic digestion prior to land application
- Management practices to avoid CH_4 emissions, e.g avoid waterlogging

Fossil fuel emissions associated with farm production, transport and storage of farm inputs and outputs, and embodied in farm inputs also come into consideration as there is increasing focus on the lifecycle emissions (see section 5.1.3) associated with consumer products.

5 OPPORTUNITIES AND RISKS

5.1 ECONOMIC OPPORTUNITIES FOR SOIL CARBON

5.1.1 Production and environmental benefits

It appears that management actions consistent (at least in part) with SOC improvement goals will be economically viable in some areas, without the need to sell carbon credits. This is often in line with current best practice management options addressing profitability and environmental issues (e.g. no-till / zero-till and residue retention, claying to improve sandy soils, improved grazing management, soil erosion protection, biodiversity plantings assisted by existing incentive schemes, etc).

Sometimes, changes to improved management will pay for itself. For example case studies on the economics of adopting precision agriculture (PA), in conjunction with conservation tillage technologies, have shown investments can provide a capital payback within 5 years (Robertson and McCallum 2008)[131]. Here, SOC benefits of conservation tillage and PA are boosted by increased fuel efficiency and reduced wastage of inputs. Incorporating perennials and better grazing management systems can offer (in addition to building or maintaining SOC): greater water use efficiency through better use of annual rainfall, out-of-season feed, reduction of early grazing pressure on winter growing pastures leading to better establishment, provide multiple benefits (livestock shelter, shade windbreaks, dryland salinity control, water quality and biodiversity values) and greater resilience to climate change.

However SOC improvement is not universally compatible with farm economics. GRDC 2009 notes that in many areas (particularly where rainfall is limiting), achieving higher SOC levels while maintaining an economically viable farm enterprise will challenge many farmers.

[131] Robertson M and McCallum M, 2007, 'PA investment pays its way in grains', *Precision Ag News (Spring Summer 2007)*, http://www.spaa.com.au

5.1.2 The carbon market

Late in 2009 the Australian Government announced its plan to exclude agricultural emissions from the proposed Carbon Pollution Reduction Scheme (CPRS) and work consultatively with the sector to explore ways to reduce GHG emissions. While not directly included in the CPRS, there is an expectation that the agricultural sector will contribute to help meet the 60% national emissions reduction target by 2050 given the sectors relatively high emissions profile (DCC 2009b[132] , Eckard 2010).

Opportunities for farmers to generate a new income stream associated with trading carbon offsets are thought possible in three areas (Eckard 2010):

1. *A voluntary market trading in reduced or avoided emissions of methane and nitrous oxide* – Subject to the development of robust methodologies, these activities may attract CPRS permits and be counted towards Australia's international emissions reduction targets.
2. *A voluntary market for non-Kyoto-compliant agricultural emissions offsets through the National Carbon Offset Scheme* – This is likely to provide opportunities for the development and sale of offset credits **involving agricultural soils (soil carbon, biochar etc)**, in a voluntary carbon market. However these credits are likely to trade at a significant discount to CPRS permits and abatement is not counted towards Australia's international commitments.
3. *Voluntary opt-in scheme under the CPRS* – This is relating to Kyoto-compliant reforestation, avoidance of deforestation and allowance for regrowth.

The Australian Government is currently working on a policy and legislative framework that meets internationally agreed principles, including the *National Carbon Offset Standard* (NCOS) (DCC 2009c)[133]. The NCOS will underpin a voluntary offset market for emissions outside the scope of the proposed CPRS and not counted towards Australia's international obligations – including agricultural soils (PIMC 2010)[134]. Voluntary carbon markets operate where businesses or individuals are not required by law to reduce their emissions, but choose to do so voluntarily. Accredited offset activities will be overseen by the Australian Climate Change Regulatory Authority (through the NCOS framework) and will be expected to satisfy agreed standards of permanence, measurability, transparency, independent auditing and registration and additionality (ie. be beyond activities that are normally required under existing laws or regulations, or that farmers would be undertaking anyway). The 'additionality' clause may have important implications, as it puts into question whether SOC sequestration activities, (that are also inherently profitable), can be traded in carbon markets (Pannell *et al* 2008)[135]. Currently under the NCOS, **'permanence' criteria for soil carbon "requires the generation of offsets to have actually occurred and the carbon stored or sequestered not to be released into the atmosphere in the future"** (DCC 2009c). Voluntary soil carbon trading is also expected to comply with relevant existing administrative and legislative frameworks such as the *Trade Practices Act* (ACCC 2008)[136].

As at 27 April 2010, the Prime Minister announced that the Australian Government would delay the implementation of the Carbon Pollution Reduction Scheme until after the end of the current Kyoto Protocol commitment period (which ends in 2012) (DCCEE 2010a)[137]. A lack of bipartisan political support for the CPRS legislation and slower than expected global policy action were cited as reasons for the delay.

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[132] DCC 2009b, *National inventory report 2007 – Volume i. The Australian Government submission to the UN Framework Convention on climate change May 2009*. Department of Climate Change, Canberra ACT, http://www.climatechange.gov.au
16% of 2007 national emissions are directly attributed to agriculture (largely livestock and nitrous oxide emissions from soils), with additional contributions to the 'transport' (diesel use) and 'stationary energy' (on-farm electricity use) sectors.

[133] DCC 2009c, *National Carbon Offset Standard* (Revised Dec 2009), Department of Climate Change, Canberra ACT, http://www.climatechange.gov.au

[134] Primary Industries Ministerial Council notes, April 2010, *Annex A – Amendments to the proposed Carbon Pollution Reduction Scheme*

[135] Pannell et al 2008, *Pannell Discussions - Sequestering carbon in agricultural soils*, http://cyllene.uwa.edu.au/~dpannell/pd/pd0127.htm

[136] ACCC 2008, *Carbon claims and the Trade Practices Act*, Australian Competition and Consumer Commission, http://www.accc.gov.au/content/index.phtml/itemId/833279/

[137] DCCEE 2010a, *CPRS latest updates*, Australian Government Department of Climate Change and Energy Efficiency, http://www.climatechange.gov.au/government/initiatives/cprs/latest-news.aspx

What are price estimates for sequestered carbon?

GRDC 2009 states a current estimated carbon price of \$10/ t CO_2-e. This figure is consistent with the transitional fixed carbon price planned at the start-up of Australian Government's proposed CPRS (DCCEE 2010b)[138] and the proposed payments to farmers for soil carbon sequestration under the Coalition's 'Direct Action Plan' policy (Coalition policy paper 2010)[139]. Soil carbon improvements are multiplied by 3.67 (conversion to CO_2), and then by the CO_2-e price to obtain the value of sequestration. For example, with low potential rates of SOC change around 0.1 t C/ha/yr at \$10/ t CO_2-e, non-discounted payments will be in the order of \$3.70/ha/yr. At \$20/ t CO_2-e, payments are around \$7.30/ha/yr. However price discounts are generally imposed on soil carbon to deal with uncertainties associated with measurement and permanence. Consequently likely carbon prices of \$2-3/ha/yr are reported by GRDC 2009. AFI 2010[140] suggests that carbon offsets in voluntary markets may be less valuable (one third value) than offsets in mandatory markets.

Likely farmer costs associated with carbon trading may include:

- Initial base line measurement of SOC levels
- ongoing costs from verification and auditing (e.g. in the form of commission payments to a management body).
- costs involved with (at least partial) supply of nutrients (N, P and S) to build soil carbon levels.
- opportunity costs associated with (i) maintaining higher organic matter inputs to the soil (thereby foregoing seasonal income from higher levels of grazing, straw baling, etc.), (ii) moisture competition and possible yield penalties for annual crops associated with supplementary biomass production (e.g. pasture cropping, inter cropping) and (iii) committing to long-term land use/ management decisions when other more profitable crops may arise in the future.

On this pricing scheme GRDC 2009 state that it will be hard to justify changing practices solely for the purpose of selling carbon credits. When combined with the low rainfall setting of much of South Australian dryland agriculture (ie. low potential rates of SOC accumulation), it would appear that there are significant obstacles to widespread change in farm management solely on the basis of selling carbon credits. Other examples of carbon pricing are discussed below.

The 'Australian Soil Carbon Accreditation Scheme (ASCAS)' is a pilot project funded by Rio Tinto Coal providing incentives for WA farmers in selected regions to build SOC (Jones 2007c[141], Porteous and Smith 2008[142]). Soil carbon credits are calculated at 1/100th the 100 year rate of \$25/ t CO_2-e and are paid annually and retrospectively based on validated SOC increases in 'defined sequestration areas'. Example annual payments for SOC improvements over a 3 year period are shown in the graphic below. This example shows much greater expected SOC sequestration rates than the earlier example (~ 20 t C/ha/yr compared to 0.1 t C/ha/yr) and soil carbon prices which aren't discounted.

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[138] DCCEE 2010b, *Trading eligible emissions units in the carbon market – Carbon prices and managing the price* risk, Australian Government Department of Climate Change and Energy Efficiency, http://www.climatechange.gov.au/government/initiatives/cprs/how-cprs-works/trading-eligible-emissions-units-in-the-carbon-market.aspx

[139] Coalition policy paper 2010, *Direct Action Plan on the Environment and Climate Change* (policy paper), The Liberal Party of Australia and the Nationals Coalition, http://www.liberal.org.au/Issues/Environment.aspx

[140] AFI 2010, *Soil carbon sequestration – lifeline or lead boots?*, Australian Farm Institute website, April 2010, http://farminstitute.org.au/newsletter/April_featurearticle.html

[141] Jones C 2007c, 'Australian Soil Carbon Accreditation Scheme', Paper at *Managing the carbon cycle*, Katanning Workshop 21-22 March 2007

[142] Porteous J and Smith F, 2008, 'Farming a climate change solution', *Ecos*, (Feb-Mar 2008), 141, 28-31

Table 1: Increase in total soil carbon stocks in tonnes per hectare (tC/ha), tonnes of carbon dioxide equivalent sequestered per hectare (tCO_2-e/ha) and value in dollars per hectare ($/ha) [at one hundredth the 100 year rate of $25/tonne CO_2-e], for estimated total soil carbon net increases of 0.15%pa, 0-110 cm, BD 1.4g/cm^3, over a three year period.

Year	Net % increase	tC/ha	tCO_2-e/ha	$/ha
1	0.15	23.1	84.78	21.19
2	0.30	46.2	169.55	42.39
3	0.45	69.3	254.33	63.58
TOTAL	**0.45**	**69.3**	**254.33**	**127.16**

(Jones 2007c)

In the NSW Greenhouse Gas Abatement Scheme carbon prices are effectively constrained by the penalty cost of non-compliance at around $12/t CO2-e (CORE 2010)[143] and in recent times are trading at around $5/t CO2-e (NGES 2010)[144]. On the European Climate Exchange carbon prices are around 14 Euros/ t CO_2-e ($AUD 20/ t CO_2-e) as at the end of April 2010[145].

The Chicago Climate Exchange (CCX) provides an interesting model for trading of soil carbon credits in particular (Massey 2009[146], Chicago Climate Exchange 2006[147], Miller 2009[148]). CCX soil offsets have traded in the range $US 1-5 /t CO_2-e ($AUD 1.10-5.40 /t CO_2-e) but have recently dropped in value as investors await news on the possible establishment of a formal US emissions trading scheme. Soil carbon credits (traded as 'exchange soil offsets' or XSOs) are awarded at variable rates to land owners committing to conservation tillage or continuous grass cover, with rates also varying with regional climate conditions. Contracts are usually for a minimum 5 year period. Management bodies called 'aggregators' are used to collectively pool soil carbon stocks of farmer groups to meet minimum trading requirements of 12,500 t CO_2-e / yr for this exchange. Both farmers and aggregators bear price and financial risk. Aggregators charge 8-10% commission and are responsible for verification expenses during the life of the contract. CCX protocols expect only a certain percentage of farm area to be verified. Farmers meet contract requirements by observing agreed input and management activities. Specific activities may be prohibited, e.g. burning, harvesting residue or the use of specific implements such as ploughs. Farmers are not required to individually prove through soil testing that actual SOC has been sequestered as this would be cost prohibitive. Soil carbon models are used to assume that specific farming practices will sequester different amounts of carbon in different regions (Massey 2009). Drage 2009[149] cites recent observations by US soil scientists that winter freezing (and associated halting of microbial decomposition) may be a factor contributing to good SOC building potential in the areas offering viable potential for CCX soil carbon offsets. Accordingly, any South Australian scheme would need to justify SOC building potential against totally different models of soil carbon behaviour.

Financial modelling (AFI 2010) was undertaken for a high rainfall, legume-based, improved pasture system on a small and large farm, achieving a soil carbon sequestration rate of 2.02 tCO2-e/ha/yr. With many underlying assumptions (including farmer payments for soil testing and regular fertiliser), under a mid-range pricing scenario, it took 10 years for farm cash margins to exceed business as usual margins. At the lower assumed price ($5/t CO2-e, reflecting possible prices in a voluntary market), costs exceed carbon offset payments and both the small and large farm would be better off not participating in the carbon

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[143] CORE 2010, *New South Wales Greenhouse Gas Reduction Scheme, Carbon Offset Research & Education*, Stockholm Environment Institute, http://www.co2offsetresearch.org/policy/NSWGGAS.html

[144] NGES 2010, 'Spot RECs and Spot NGACs', *Australian Carbon Market (Feb 2009 – Feb 2010 time trend for NSW Greenhouse Gas Abatement Certificate (NGAC) prices)*, Next Generation Energy Solutions, http://www.nges.com.au

[145] European Climate Exchange 2010, *ECX historical data (Certified Emission Reduction units daily futures)*, http://www.ecx.eu/ECX-Historical-Data

[146] Massey R 2009, *Soil carbon sequestration contracts*, University of Missouri Extension, http://extension.missouri.edu/publications/DisplayPub.aspx?P=G313

[147] Chicago Climate Exchange 2006, *CCX Agricultural Soil Carbon Offsets* http://www.chicagoclimatex.com/news/publications/pdf/CCX_Soil_Offsets.pdf

[148] Miller D 2009, 'The voluntary soil carbon marketing the USA: Is this a viable model for Australia?', *Agriculture, Greenhouse and Emissions Trading Conference Proceedings*, Maroochydore 6-7May, Australian Farm Institute

[149] Drage D 2009, *Carbon pollution reduction schemes – Threats and opportunities for broad acre agriculture*, Nuffield Australia Project No 0902

offset market. Less rigorous monitoring, reporting and verification systems (similar to that used by the CCX) may make the lower carbon price more attractive. The message from this is that the economic viability of carbon trading needs to be determined on a case by case basis, and underlying assumptions and whole farm impacts can greatly influence the potential profitability of carbon offset trading.

Carbon rights and carbon credits

Currently the status of soil carbon as a tradeable entity within South Australia is not defined. Recent amendments by the South Australian Parliament to the *Forest Property Act 2000*[150] have enabled separation of ownership of land, forest vegetation and carbon rights within forest vegetation (PIRSA 2009b)[151]. This legislation was designed to enable landholders to be able to sell their forests and/or carbon rights (including carbon in biodiversity plantings) to provide additional income without selling their land. The amended *Forest Property Act 2000* does not cover soil carbon, nor is there any other South Australian legislation which covers soil carbon. However this Act provides a guide to how potential future legislation might cover the soil carbon issue.

Carbon rights have been defined by legislation differently in each Australian State in recent years, causing problems with interpretation at a national level. Recently the Australian Property Institute (NSW and Queensland Divisions) noted that: "A carbon property right has not yet been clearly defined in Australia. A clear, coherent definition is essential to provide traders in carbon assets with certainty about the nature and worth of what is being traded."[152]

In general terms carbon rights are seen as a form of real property or rights over land and registrable on land title, whereas carbon credits are "a benefit" that can be used to offset or nullify GHG emissions and their associated liability (The Carbon Store 2008)[153]. Arguably, the carbon rights owner should be provided with the "the enforceable right to ensure that an agreed management plan for the vegetation and soil of the land is carried out, for the term of the carbon rights contract" and rights to both the benefits and (arguably a share of) liabilities associated with the storage of carbon on the land (The Carbon Store 2008).

In regard to potential liabilities (who is responsible) for any losses of soil carbon, under management-induced or natural causes, it is expected that this would need to be the subject of a 'carbon property rights agreement' made between the farmer and purchaser of carbon rights. Legal advice should be sought to protect the interests of parties considering entering into any such contracts. Management of risks associated with potential loss of SOC storage tied up with carbon credits is discussed further below.

5.1.3 Total system accounting

To assess the viability of any carbon sequestering activity, accounting will need to occur in (i) financial terms and (ii) changes in overall GHG emissions to determine net carbon sequestration. Note: the change in emissions from shifting to a new activity is likely to be important and should be distinguished from whether the new activity itself is a net source or sink of emissions. To illustrate this point, cereal cropping operations are typically net emitters of GHG (Umbers 2007). However changes in fertiliser use, shifting to precision agriculture, etc. will likely reduce GHG emissions, while adopting long-term conservation tillage and full stubble retention with incorporation of a legume pasture phase may build up SOC. The new farming system may still be a net emitter of GHG however there is an improvement from the 'business-as-usual' situation.

There are different ways to account for emissions:

- What is the net CO_2-e sequestration rate for a particular farming system?
- What is the change in net CO_2-e sequestration rate going from 'business as usual' to an improved farming system?

[150] South Australian Government 2007,*Forest Property Act 2000 (South Australia),* Amended version 1.7.2007

[151] PIRSA 2009b, 'Forestry Property Act', *PIRSA Forestry – Forest policy* (website), Primary Industries and Resources SA, http://www.pir.sa.gov.au/forestry/programs/forest_policy

[152] Australian Property Institute (NSW and Queensland Divisions) 2007, *Conceiving property rights in carbon: A policy paper*, Sydney NSW, 26 July

[153] The Carbon Store 2008, *Submission to the Carbon Pollution Reduction Scheme – Green Paper*, 10 September 2008

Grace 2007[154] and Lal 2002[155] list a range of components that should be accounted for in calculations of net carbon sequestration from a particular farming system, including the carbon-equivalence of other key GHG (N_2O and CH_4). This might be summarised in the hybrid equation:

$$\mathbf{(SOC)_n = (SOC)_g - (SOC)_{embodied\ emissions}}$$

Where: $(SOC)_n$ = net carbon sequestration

$(SOC)_g$ = *gross carbon sequestration

(*this is determined by changes in measured or modelled SOC over time)

= antecedent SOC + $(C_{residues} + C_{biosolids}) - (C_{mineralised} + C_{erosion} + C_{leached})$

$(SOC)_{embodied\ emissions}$ = embodied emissions of associated activities including:

- CO_2 from fuel use in cultivation, preparation, seeding, harvesting, spraying chemicals, etc
- N_2O emissions from inefficient N fertiliser use and other N losses
- Embodied emissions for synthetic N fertiliser production (estimated at 5 kg CO_2 per kg N) (Leach 1976)[156].
- Embodied emissions of other fertilisers, pesticides and other farm chemicals
- N_2O and CH_4 from burning (if applicable)
- Transport of farm inputs and products
- CH_4 from animals (ruminants belching and manure handling)
- Pumping of irrigation water
- Off-site SOC losses relating to imported organic waste inputs, and associated processing, transport and spreading
- Any product processing and storage (e.g. refrigeration) undertaken on the farm

The *National Carbon Offset Standard* (NCOS) (DCC 2009c, http://www.climatechange.gov.au) provides guidance on the calculation of an overall carbon footprint associated with a business or product, via a rigorous life cycle analysis in accordance with international standards.

These guidelines can help establish the scope and general approach for accounting of overall emissions, however the scientific measurement and monitoring methods for soil carbon (and wider agricultural GHG emissions) are generally not yet well established or commercially available. The NCOS states that at this stage only fuel use can be accurately estimated for GHG emissions.

The interactions between SOC sequestration and soil-based emissions of CO_2, N_2O and CH_4 can be complex and there is a need to better understand these, particularly under changes in land use and management (Chan *et al* 2008). Online tools (once supported by accurate and calibrated models) will be a useful way for farmers to assess the total carbon-equivalent emissions related to management changes (Institute for Sustainable Resources 2010[157], NSW DPI 2008[158]).

5.1.4 Other related potential economic benefits

Peripheral impacts associated with climate change and emerging demands from environmentally concerned consumers have the potential to impact on farm operations and marketing – with the potential for economic benefits.

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[154] Grace PR 2007, *Carbon farming – facts and fiction*, Presentation at Healthy Soils Symposium, 4 July 2007

[155] Lal R, 2002, 'Soil carbon dynamics in cropland and rangeland', *Environmental Pollution*, 116, 353-362

[156] Leach G 1976, *Energy and food production*, IPC Science and Technology Press, Guildfor, Surry UK

[157] Institute for Sustainable Resources 2010, *Farming enterprise greenhouse gas emissions calculator*, Online tool, Queensland University of Technology, http://www.isr.qut.edu.au/greenhouse/map.jsp

[158] NSW DPI 2008, *Carbon sequestration predictor*, Online tool, New South Wales Department of Primary Industries, http://www.dpi.nsw.gov.au/forests/info/csp

Product labelling

Marketing trends such as carbon footprint labelling may provide a means to improve marketability in association with changed management practices. Carbon labelling has matured from earlier concepts of "food miles" (describing the embodied fossil fuel associated with product transport) to a current push for the development of International Standards Organisation recognised rules (ISO 14067 "Carbon Footprint of Products") involving life cycle analysis including emissions associated with production methods (Drage 2009, Priess 2010[159]). This type of lifecycle carbon footprinting analysis is expected to be consistent with principles outlined in the NCOS.

Increasing community concern surrounding climate change and other sustainability issues (e.g. summarised by ecological footprint[160] concerns and resource depletion issues such as peak oil[161,162], etc) may also offer marketing incentives for producers to switch to more sustainable farming practices. The growing popularity of regional farmer's markets with low-carbon footprint localised value chains (e.g. ASFM 2010[163], WFM 2010[164], BFM 2010[165]) and other community-supported agriculture projects (e.g. Food Connect 2010)[166] provide examples whereby producers who are endeavouring to engage in more sustainable production can gain direct access to (and more worthwhile reward from) increasingly environmentally conscious consumers. While representing a growing sector, these are currently niche markets. However the nature of these markets may align well with the likely numbers of farmers progressively adopting such an approach.

Along these lines, capitalising on opportunities for greater value adding to farm produce, consistent with "consumer demand pull" (e.g. increasing demand for ethical or environmentally friendly products) is seen as an important component of future market development for South Australian primary producers (SA Food Centre 2010)[167].

Nitrous oxide and methane emissions reductions

Although some farming systems will be net emitters of GHG through the use of fossil fuels and fertiliser, there is arguably potential for the generation of tradeable offsets from management changes which reduce emissions of nitrous oxide and methane emissions compared to the business-as-usual situation. This is discussed in section 4.

5.2 RISKS AND RISK MANAGEMENT IN CARBON TRADING

There is a widely held and justifiable opinion among some leading farmers, scientists and industry groups that under current rules the risks of trading soil carbon as a new source of income probably outweigh the benefits (GRDC 2009, Eckard 2010, Drage 2009, AFI 2010, Crombie 2009[168]). Furthermore, recent fluctuations in farm input costs and commodity prices have heightened the awareness among farmers that they need to become better managers of risk. This has a bearing on routine farm management decisions, let alone new business ventures that farmers might consider. Awareness and aversion to risk is likely to make farmers especially wary of engaging in new, unproven ventures such as farming for carbon credits. Although it should be said there are divisions among farming groups on the merits and potential of carbon

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[159] Priess R 2010, 'International developments in product carbon footprinting and carbon labelling', *PCF World Forum News #2 March 2010*, http://www.pcf-world-forum.org/wp-content/uploads/2010/03/pcf-world-forum-news2_march-2010.pdf

[160] Global Footprint Network 2010, *Footprint for business* (web page), Global Footprint Network, http://www.footprintnetwork.org/en/index.php/GFN/page/footprint_for_business/

[161] Waters J 2010, 'Peak oil crunch', *Radio Australia News*, 27 Apr 2010, http://www.radioaustralianews.net.au/stories/201004/2883729.htm

[162] Parliament of South Australia 2008, *Report of the select committee on the impact of peak oil in South Australia*, 25 November 2008

[163] ASFM 2010, *Adelaide Showground Farmers Market* (Web page), http://www.asfm.org.au/home.html

[164] WFM 2010, *Willunga Farmers Market* (Web page), http://www.willungafarmersmarket.com/

[165] BFM 2010, *Barossa Farmers Market* (Web page), http://www.barossafarmersmarket.com/home/

[166] Food Connect 2010, *Food Connect* (Home web site), http://www.foodconnect.com.au/

[167] SA Food Centre 2010, *SA Grains Market Overview*, South Australian Food Centre (is a partnership between PIRSA, SARDI, DTED and TAFE SA), http://www.safoodcentre.com.au/

[168] Crombie D, 2009, 'Farmers priorities on climate change mitigation and adaptation ', *The Land- Farm online* (blog), NFF President, 14-12-09, http://theland.farmonline.com.au/blogs/farmonline-opinion/farmers-priorities-on-climate-change-mitigation-and-adaptation/1704630.aspx

trading[169]. That said, there are already soil carbon credit schemes operating in the Australian voluntary carbon trading market (Soil Carbon Information Service 2010)[170].

Risk management by farmers

If considering trading in soil carbon, the first step for landholders is to conduct their own risk assessment. Biophysical questions about sequestering SOC are outlined in this document. Climate change also represents a risk to SOC stocks if rainfall declines emerge as predicted. On top of this, there needs to be due consideration of (i) financial viability and (ii) associated management issues, which may include:

- What legal agreements need to be made?
- Who owns the carbon and what are the responsibilities and potential liabilities for land management and natural impacts on SOC stocks?
- How will the risk of climate-driven SOC variability be managed? Will this involve planning by the property owner or aggregator of SOC stocks?
- Are there any local government/ planning issues associated with land use change, changes to council rates or local fire plans?
- Can insurance be taken to cover any risks?
- Are there any tax implications from carbon trading income?
- What happens if the land is put up for sale?
- What happens if the sequestration agency goes out of business?
- Are there any potential escape clauses that can protect my business viability?
- Is the soil carbon aggregator / broker properly accredited and offering services compliant with the relevant legislation[171]?

Managing liabilities – through contract formulation and managing SOC stocks?

If rights to soil carbon are sold, the SOC is no longer owned by the farmer. In theory, SOC that is sold off must remain sequestered permanently and not be released into the atmosphere in the future. This can potentially create the situation where a farmer no longer owns the right to disturb the carbon content of their paddocks. Essentially, even ploughing the field can create a liability (from lost SOC) that the farmer may have to pay to the owner of the soil carbon. Likewise a liability may be created due to factors beyond the farmer's control, e.g. protracted drought, major erosion events, etc. (Note – it is unlikely that one off events such as bushfire would reduce sequestered SOC, however there is concern that such events may become more frequent under climate change.)

However the assignment of liability could be addressed within the legal area of contract formulation and the content of a 'carbon property rights agreement' which would be made between the farmer (land owner) and carbon rights owner. In the absence of a mandatory or strictly defined legislative framework for soil carbon trading contracts, agreements for the distribution of liabilities associated with SOC stocks under agreed management practices are at the whim of the parties involved. This currently means that soil carbon trading on the voluntary market may potentially involve sharing of liability for SOC losses (e.g. from natural causes) between a land owner and the carbon rights owner, in accordance with a 'carbon property rights agreement'.

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[169] Bardon J 2007, 'Farm group divisions over soil carbon trading', *ABC Rural news NSW* (web site), 12-07-2007, http://www.abc.net.au/rural/nsw/content/2006/s1977061.htm

[170] Soil Carbon Information Service 2010, *Carbon farming handbook: An introduction to soil carbon, land management and climate change,* http://carbonfarminghandbook.blogspot.com/

[171] ACCC 2010, *News release – ACCC institutes proceedings against Prime Carbon Pty Ltd*, Australian Competition and Consumer Commission, Release NR 001/10, 5 January 2010

"There are many examples of this type of risk management in existing agreements and these range from shared liability, carbon pooling schemes, including a discount of up to 30% in the rates to allow for variations. Perhaps the safest is the concept of carbon pooling between a number of farmers or catchments, with the actual carbon traded moving between properties over time depending on cultivation, rainfall or disturbance" (R Eckard 2010 pers. comm.).

Eckard also provides the cautionary opinion: "Policy makers shouldn't promote schemes which will create unmanageable risk / liabilities for landholders (or develop collective/pooled schemes in which the risks are socialised). Current markets tell us that this will not attract much of the price anyway. We are seeing more governments avoiding rather than embracing soil C. Rather they should develop schemes for reducing methane and nitrous oxide emissions as these do not have the same permanence requirement (an emission forgone, not sequestered in perpetuity)."

Managing liabilities – through insurance?

Private or government backed insurance schemes may be another option to cover farmer liabilities associated with natural SOC losses. This is of course another form of socialising or spreading the risk among the community, however taxpayers may support such a scheme if net SOC and climate change mitigation benefits can be demonstrated.

5.3 ENVIRONMENTAL TRADE OFFS

Building SOC relies on catching and using more water in the landscape where it falls. There is potential for environmental trade offs and disadvantages of SOC improvement practices in some situations.

A notable example will be catchment water yield. Reductions in farm dam yields have been widely recognised across the agricultural zone with the increased adoption of farming practices that retain and use more water (e.g. no-till, stubble retention, greater perennial plantings, more productive crops and pastures, etc). Reduced catchment water yield has the potential to impact on aquatic and riparian ecosystems, farm stock and domestic water supplies and downstream users.

The possibility of increased fire risk, with greater levels of retained pasture or crop residues may be another trade off that needs to be managed in high fire risk areas.

Integrated economic and environmental modelling systems, which incorporate spatial and temporal complexity, are proposed to help inform multi-criteria decision making – thereby optimising positive outcomes and minimising unintended outcomes associated with the introduction of future low-carbon policy measures. If developed, CSIRO's proposed Australian Integrated Carbon Assessment System (AICAS) will use this type of approach to examine and attempt to minimise negative environmental, economic and social trade-offs associated with carbon policy (Bryan 2010)[172].

5.4 FRAMEWORK FOR UNDERSTANDING THE VIABILITY OF SOIL CARBON SEQUESTRATION AND CARBON CREDITS

The flow chart below (Figure 13) attempts to summarise the various complex and often inter-related factors which will determine whether or not (i) soil carbon levels can be improved and sustained and (ii) soil-related carbon credits might become a viable new business enterprise for South Australian farmers. Failures or limitations in any particular aspect mentioned below might represent a major stumbling block.

[172] Bryan B 2010, *Seminar – The Australian Integrated Carbon Assessment System 26/05/2010*, Principal Research Scientist, CSIRO Sustainable Ecosystems, http://www.csiroalumni.org.au/events/event_details.asp?id=109508

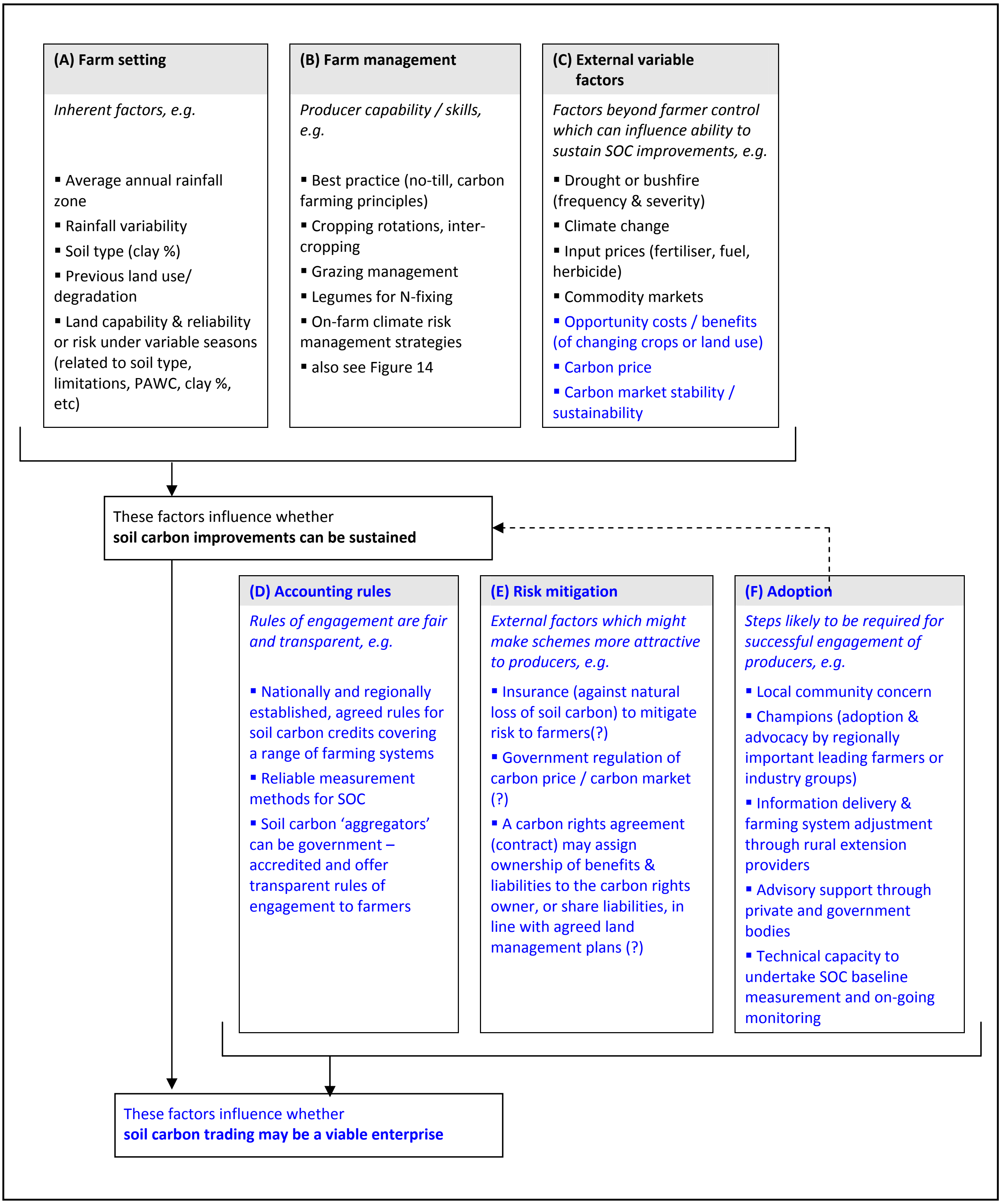

Figure 13. Proposed framework for assessing the regional viability of (i) soil carbon sequestration, and (ii) soil carbon trading

The following diagram (adapted from Lal 2002 and Krull *et al* 2004) provides a summary of technical options to sequester SOC and/or reduce associated farm GHG emissions.

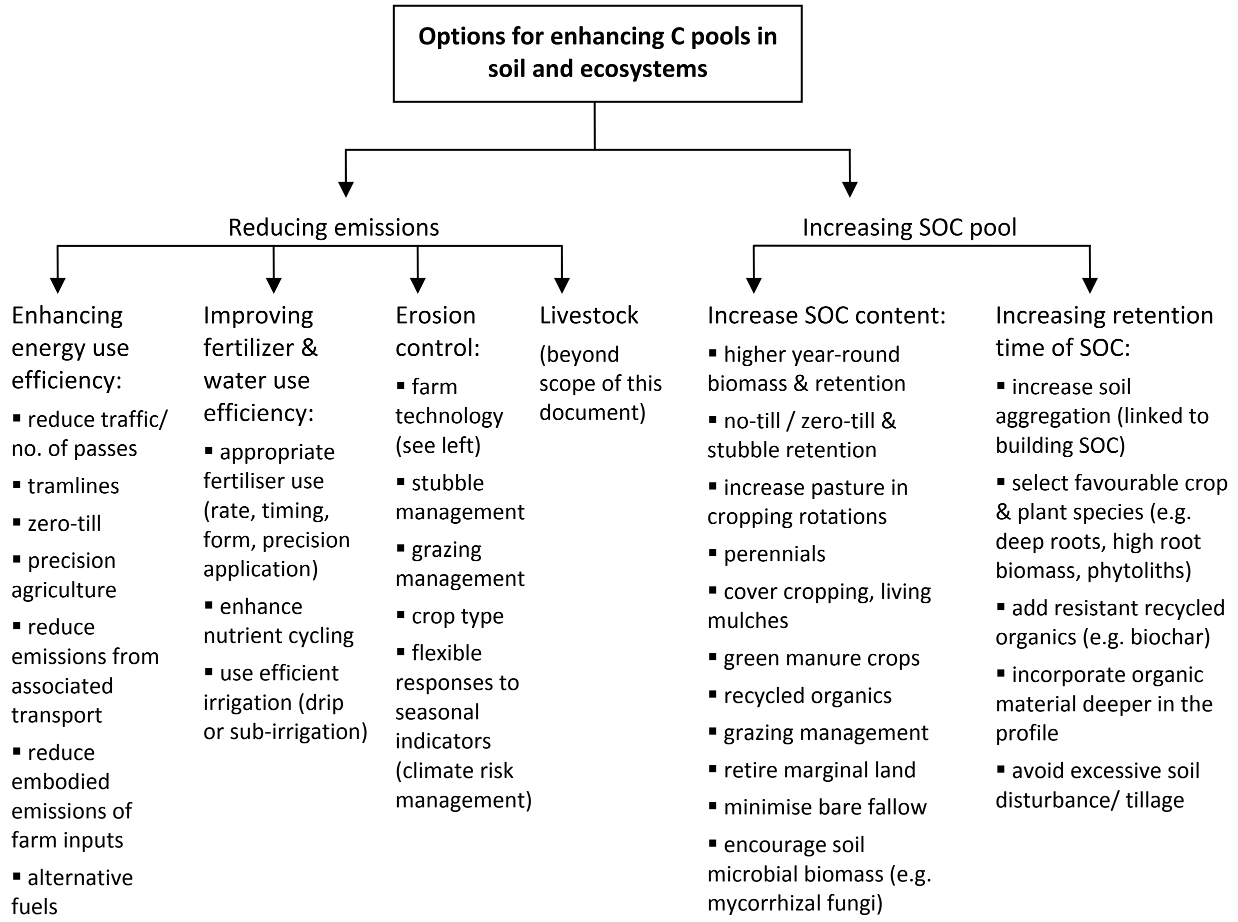

Figure 14. Technological options for enhancing C pool in soil and ecosystems (adapted from Lal 2002, Krull *et al* 2004)

6 KEY RESEARCH QUESTIONS FOR SOUTH AUSTRALIA

There are still large gaps in our knowledge on what effects SOC under Australian conditions. Schapel 2008 lists major Australian research projects directly related to SOC sequestration. The generally warmer, drier and variable climate of South Australia also presents relatively unique conditions which can impact SOC and limit sequestration potential. The following table summarises key knowledge gaps concerning SOC sequestration and measurement in South Australia. (This table provides a summary guide only and is not intended to provide a complete summary of all national, interstate or SA based research activities or organisations involved in this area.)

Table 6. Key research questions relating to soil carbon (and soil GHG emissions) in South Australia

Key research area		More detailed description	Current research organisations (*Proposed or potential research)
1	Measuring SOC pools	Commercial (cheap and reliable) measurement technique for measuring SOC pools. Mid-infrared (MIR) spectroscopy is being demonstrated for measurement of total SOC and fractions.	CSIRO
2	Monitoring SOC	Agreed monitoring protocols for SOC pools in agricultural soils	CSIRO, Australian Government
3	Knowledge of soil carbon resource	Assessing the SOC equilibrium potential of SA climate zones / soils (Mapping of SOC content/ potential could be overlaid with rainfall, soil texture, and land use / land management) Field measurements also feed into the knowledge base underpinning SOC models (below)	CSIRO, DWLBC, Rural Solutions SA
4	SOC models	Soil carbon (& related soil GHG) models will underpin cost-effective monitoring of sequestration activities under different climate, soil type, land use & management (e.g. National Carbon Accounting System / Toolbox). Ongoing field measurements and long-term trials will further refine these models. SOC models are expected to be available for testing in 2011-2012.	CSIRO
5	Improving sandy soils	Quantifying SOC and productivity improvements from increasing the clay content of sandy soils by clay spreading, delving, spading and/or deep ripping	*CSIRO, DWLBC & Rural Solutions SA
6	Addressing subsoil constraints that limit production	Large areas of South Australian soils have subsoil constraints that limit production. Successful amelioration of these constraints or the breeding of tolerant crop and pasture varieties will increase return of organic material to the soil	
7	Developments in conservation tillage	Assess the long-term SOC status / improvements under latest best practice zero till and precision agriculture technology, including residue managers to handle heavy stubble, in <500mm rainfall zones	SANTFA(?)
8	Role of perennials	▪ Assess the suitability of perennial pastures for cropping zones, e.g. inter-cropping, pasture cropping, rotational cropping with perennial pastures. (Including investigating the productivity and SOC sequestration potential of productive annual crops versus perennials.) ▪ Assess SOC under perennial grasses ▪ Assess differences between C3 and C4 plants (?) ▪ Assess SOC under drought hardy fodder shrubs.	CSIRO (sub-tropical C4) *Future Farm Industries CRC (Steve Hughes)
9	'Carbon farming' trials	Quantifying net SOC sequestration, and profitability, under management practices with a soil carbon focus for different soil types, climates and agricultural systems. This may involve the following activities: ▪ Better pasture and grazing management ▪ Integrating annual and perennial pastures with cropping	
10	Biochars & other recycled organics	Quantifying the potential SOC, productivity and net GHG emissions benefits / impacts (via life cycle analysis) of importing biochars and other recycled organic materials	CSIRO (biochar)
11	Total soil GHG emissions	Quantifying interactions of SOC sequestration with soil emissions of other GHG, namely nitrous oxide and methane.	(?)
12	Rangelands	Quantifying potential SOC improvements from management change in rangelands (semi-arid / arid grazing areas). Substantial benefits may accrue from small changes over large areas.	(?)
13	Role of microbial action	Quantifying the capacity of soil microbial activity (healthy soils), across different climate and soil types, to: (i) fix atmospheric N, (ii) retain nutrients (N, P, S) from decomposing plant matter within the soil carbon bank, and (iii) cycle (or liberate) stored soil nutrients (e.g. P) that might have been unavailable to plants under conditions of low SOC / low microbial activity.	(?)

14 New technologies	Quantifying benefits of new technologies (e.g. exhaust gas fertilisation and reduced emissions using BioAgtive^{TM} technology)	

7 POLICY IMPLICATIONS

7.1 GENERAL CONCLUSIONS

Factors influencing soil carbon sequestration

- Climate (rainfall & temperature)
- Soil type
- Original soil condition
- Year-round plant dry matter production
- Soil disturbance (level & type of tillage)
- Plant matter retained (e.g. stubble management)
- In cropping rotations:
  - Length & type of pasture phase
  - Length & type of fallow

Organic matter inputs and SOC are keys to healthy functioning soils that are able to support productive and sustainable land uses – in either an agricultural or natural setting. It is generally believed that equilibrium SOC contents can be increased through combinations of land use and land management change. However the extent to which this will be possible depends on a number of limitations, in particular soil type, previous land use/ management, climatic and economic factors. Better knowledge of equilibrium SOC potential for different combinations of climate and soil type would greatly assist management decisions, providing a guide as to whether changes in land use / management practices are likely to improve SOC, and by how much. A number of other key knowledge gaps exist as outlined in the previous section.

The greatest SOC benefits to agricultural landscapes will come by growing higher yielding crops and pastures more often, and maximising return of plant residues to the soil. This will typically follow efforts to make the most efficient use of the scarce resources available to grow biomass.

Landholder understanding of the important role of SOC is increasing however (as expected), economic factors will remain an important driver for management change. Increased emphasis on SOC improvement across the farm may occur (i) with a sufficiently high carbon price, or (ii) it can be demonstrated that long-term profitability is improved (e.g. via more fertile soils, greater resilience to climate risk, etc).

Selling soil carbon credits represents a separate issue. Current unknowns associated with the carbon credit market (e.g. pricing, market regulation, accounting rules), along with potential ways to mitigate risks / liabilities for farmers will need to be well established before the issue of carbon credits is even 'on the radar' for many farmers. GRDC 2009 conclude that, "at this stage carbon credits should be considered as a secondary benefit that may be realised while attempting to enhance soil productivity by building soil carbon content". Avoided GHG emissions from changed farming practice may represent another area where incentives or education can be applied. These may offer a profit driver in themselves (e.g. reduced N use, reduced fuel use), do not go against land title, can occur on an ongoing basis, and do not have the permanency requirements of sequestration.

7.2 CURRENT KEY CONSTRAINTS FOR SOIL CARBON TRADING

A number of constraints to building SOC and implementing soil carbon credit schemes are recognised:

Building SOC:

- Statewide SOC sequestration potential is limited due to large areas of low rainfall and sandy soils.
- Costs of maximising production and returning plant matter to soils may be prohibitive for many farmers (e.g. fertiliser, changing management or machinery, opportunity costs, etc).
- Cropping operations under 500mm rainfall may not be able to build up SOC, even with conservation farming techniques. The latest technology/ management needs further testing.

- There are currently no commercially available testing methods for SOC pools (although mid infrared spectroscopy is being developed for this purpose).
- Monitoring protocols for SOC (and related soil GHG) are not well established. SOC changes may need to be monitored over periods of decades.
- There is insufficient understanding of current soil processes specific to South Australian soils to predict the amount of carbon that can be stored or the permanency of storage.
- South Australia's variable climate, with risks of drought and bushfire, will limit long-term equilibrium SOC.
- Climate change (warming, drying and more extreme events) will make it harder to build SOC.
- A disciplined 'carbon farming' approach may not fit well with the flexible 'climate risk management' approach that is being increasingly adopted by farmers (ie. variable management according to seasonal indicators, maximising profits in good years to remain viable when production is downscaled for bad years). This is particularly so in lower rainfall areas.
- Research and extension – there is limited knowledge of soil carbon and the processes to build carbon in specific South Australian soils. A reduction in research and extension capability has severely undermined the technical support available to farmers to support changes to farming systems that will realise more SOC.

Soil carbon trading:

- Permanency requirements of SOC sequestration sold as carbon credits may be difficult to satisfy.
- Current unknowns and perceived risks with a market for soil carbon (e.g. price, regulation, liabilities from natural SOC loss) are barriers to farmer interest. Risk management strategies (e.g. shared liability, insurance, regulated market) may make soil carbon trading more attractive in regions with SOC sequestration potential.
- Costs are likely to outweigh benefits at a low carbon price (e.g. \$10/t CO_2-e).
- Soil carbon offsets are likely to be traded at a discount because of concerns with measurement, permanence, and the lower value of offsets in a voluntary market compared to a mandatory market.
- Australia has not signed onto Article 3.4 of the Kyoto Protocol (which would mandate accounting of carbon stocks in soils) in part due to risks from natural SOC losses. This currently limits soil carbon offsets to less valuable non-Kyoto compliant voluntary markets and they can not be counted towards Australia's international commitments.
- Carbon sequestration payments (in soil and vegetation) can be described as a 'once off' payment – which stops when a new equilibrium level is reached. As such carbon offsets from sequestration do not offer a long-term ongoing income source. Emissions permits would need to be purchased in the event that sequestered carbon starts to decline.

7.3 POLICY CONSIDERATIONS AND OPTIONS

Arguably, agriculture needs to play a role in offsetting GHG emissions – improving from the 'business as usual' situation, even if it remains a net emitter. In this respect, in the presence of market failure, it can be argued that governments could play a role in supporting uptake of agricultural systems that: (i) reduce GHG emissions and (ii) sequester CO_2 into soil and vegetation.

It is apparent that governments and land managers must operate on totally different levels and timeframes of consideration and influence. Many farm management decisions are made on the basis of short to medium term economic viability, and there is no reason to believe that decisions involving soil carbon trading will be any different to this. In contrast, governments have a responsibility to consider potential climate change impacts to local and international communities, natural resources and biodiversity, and future generations. Together with the uncertainty of projected spatial and temporal impacts, it is very difficult to simply weigh up costs versus benefits in terms of a $ value (or any common indicator for that matter).

Nevertheless, governments at the State, National and international level have agreed that the potential adverse risks from climate change warrant urgent mitigation action. It would appear that political and international disagreements to-date in this area are mainly about the costs that ought to be borne, and what may constitute the most cost-effective action – not whether or not there is a need to do something. While inter-governmental policy makers work towards a mutually agreeable policy solution, government bodies at more local levels are also operating under political mandates to deliver workable climate change mitigation policies.

While some analysts (e.g. Pannell 2010)[173] suggest a restricted role for government spending in support of farmers adapting to climate change (arguing that they are good adapters anyway and will have time to make informed choices), this should be recognised as a completely different issue to the challenge of climate change mitigation. For effective mitigation, early coordinated action is essential to avoid high-end dangerous climate change scenarios, and reduces the growing challenge of curbing emissions at a later date (Garnaut 2008).

As alluded to, justification for policy intervention (incentives) should not be assessed purely in terms of short-term economics. Greater political (broad-based tax-payer) acceptance of economic costs associated with GHG mitigation policies may need to wait for increased public awareness of the triple-bottom-line costs of emerging climate change. But this is the policy challenge of mitigating climate change: "The time frames within which effects become evident are too long, and the time frames within which action must be effected are too short" (Garnaut 2008).

Policy goals for climate change mitigation in agriculture

- Provide efficient incentives for reducing GHG emissions from agriculture and expanding carbon sequestration from land management (in soil and vegetation)
- Avoid excessive risk to landholders
- Avoid excessive administration, monitoring and compliance costs
- Achieve net economic, social and environmental benefit

Incentives for sequestering soil carbon must also be weighed up against other potentially more efficient / effective forms of mitigation. At present, key limitations facing any soil carbon schemes are (i) the need to develop commercially available, cost-effective SOC measurement and monitoring tools and (ii) insufficient understanding of current soil processes specific to South Australian soils required to predict the potential amounts and permanence of soil carbon storage.

Areas of potential policy development in relation to building SOC and soil carbon trading are discussed further below.

Promoting multiple benefits of SOC

Improving or at least maintaining SOC is an important priority for the sustainability of agriculture on a statewide, national and global scale. The many benefits to production, natural resource management and farm profitability warrant increased policy efforts in this area (e.g. education/ extension). In the absence of specific financial incentives, presumably such SOC improvement activities would need to be profit-driven, through demonstrated production benefits and/or increased resilience to climate risk.

There are current management 'best practices' that should be supported (or expanded) due to their capacity to improve productivity, profitability, conserve the resource base and protect the environment, while also achieving SOC maintenance and/or improvements. These include: conservation farming / precision farming techniques, incorporating pastures into cropping systems, better grazing management, incorporating perennials to increase productivity in suitable landscapes, etc.

[173] Pannell, DJ 2010, *Policy for climate change adaptation in agriculture*, http://cyllene.uwa.edu.au/~dpannell/dp1003.htm

Research into other land use and management actions that improve SOC in a cost-effective manner should also be supported.

Better understand equilibrium SOC potentials and SOC processes

There is a need to better understand equilibrium SOC potential for different combinations of climate, soil type, land use and management in South Australia. Inter-agency work is already underway in this area (involving CSIRO, DWLBC and Rural Solutions SA) however greater funding support is required to improve the local knowledge base.

This work builds several areas of knowledge[174], consistent with current research priorities under the DAFF national soil carbon research program[175]: (i) regional SOC potential, (ii) long-term temporal SOC trends, (iii) potential for management to change SOC at a regional level, (iv) modelling of carbon pools and (v) development of mid infrared spectroscopy measurement techniques.

With greater confidence in modelling of soil carbon processes under various South Australian conditions this provides the opportunity for cost-effective compliance audits of soil carbon credit schemes. For example, compliance might be based on land management practice (and other easily measured parameters) rather than intensive on-farm measurements of actual SOC stock, similar to the approach adopted by the Chicago Climate Exchange.

Build the potential of South Australian soils to store carbon

Climate and soil type represent fundamental limits to the equilibrium SOC sequestration potential. However clay spreading / delving has the potential to increase equilibrium SOC potential on sandy soils. The mixing of soil horizons and the associated incorporation of organic material into subsoil horizons may see significant carbon storage and production benefits.

Use relevant existing programs, mechanisms and networks

This will reduce unnecessary new expenses and capitalise on the efficiencies that are available through existing research, policy, advisor, industry and farmer networks. Likewise if existing mechanisms can be employed this will reduce costs. For example farmer payment schemes to improve the drought-tolerance, sustainability or environmental benefits from farming systems might also be used (indirectly or directly) to improve SOC.

Assessing the profitability of a 'carbon farming' approach

In a range of conventional farming activities, there will often be trade offs between annual production (short-term economic) objectives and SOC enhancement objectives, and priorities will vary with annual rainfall zones. For example:

- Grazing stubbles, baling straw or burning – versus – stubble retention
- Fallowing and summer weed control for moisture conservation – versus – summer (cover) cropping, pasture cropping or letting weeds accumulate biomass until just prior to seed development
- Investing in new or modified machinery (no-till or zero-till, with residue managers) – versus – retaining older style machinery with greater soil tillage/ disturbance

Some of these short-term management decisions are likely to be made on an increasingly flexible basis as more producers adopt a climate risk management approach in their farming operations – in which they might explore a range of management activities – each year responding to different seasonal factors.

Long-term trials are likely to be required to assess the comparative profitability (both with and without selling carbon credits), across a range of annual rainfall zones, of practices which focus on building or maintaining SOC, compared to conventional practices which maximise short-term farm profitability.

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[174] Baldock J 2010, pers. comm., Stream Leader - Soil Carbon and Nitrogen Balance in Agricultural Lands, CSIRO Land and Water

[175] http://www.csiro.au/science/Soil-Carbon-Research-Program.html

Integrate SOC messages into farm 'climate risk management' programs

Further to the point made above, the importance of SOC to long-term farm production and sustainability needs to be integrated into delivery of farm climate risk management extension programs.

Investigate perennial systems, including within cropping systems

Perennial systems and year-round productive pasture mixes are better than annual cropping systems at sequestering carbon and net carbon cycling (Schapel 2008). Greater use of well managed perennial plants, and pasture phases in cropping rotations will help to build SOC. Altering grazing practices from set stocking to rotational grazing and careful attention to stock water delivery systems may improve plant matter production and maintenance.

Tradeoffs would need to be considered regarding opportunity costs and potential yield penalties from (i) fewer years under annual crops (e.g. wheat, barley, etc) and/or (ii) reduction in moisture available to annual crops.

Pasture cropping is extremely successful at sequestering SOC in higher rainfall, high plant available water-holding capacity (PAWC) (e.g. deep and/or clayey) soils. Pasture cropping / rotational cropping in lower rainfall areas using perennial based pastures needs to be investigated and assessed.

Develop 'win-win' options (profit driven GHG reductions)

Investigate emissions reductions / carbon offset programs associated with nitrous oxide and methane emissions (e.g. more efficient N fertiliser use, livestock management) and reduced fuel use. Win-win options can provide a profit driver for reducing emissions, without the need to sell carbon credits. Furthermore, emissions reductions (i) do not have the risks associated with requirements for permanence (as it is an emission forgone, not sequestered in perpetuity, (ii) provide ongoing rather than a once-off benefit, and (iii) do not have to go against land title.

If these emissions reductions can be measured and traded, they may be more valuable as carbon offsets than sequestered SOC (foregone emissions don't have the risks associated with permanence requirements). However, for any inherently profitable activity, 'additionality' criteria would need to be clarified, as this may pose a barrier to trading as a carbon offset.

"Demonstrating reduced emissions per unit food (or product) produced may also allow for product labelling / marketing opportunities (note this may not lead to a net reduction in emissions, if animal numbers increase, but it does allow productivity with efficiency gains)" (Eckard 2010 pers. comm.[176]).

Private companies are already assisting farmers and corporations in the promotion of 'carbon friendly' and 'carbon neutral' products and services which offer a marketing advantage for GHG mitigation activities. Assessment of potential schemes and carbon claims of this type are expected to be overseen by the *National Carbon Offset Standard* (NCOS) and associated administration. Extension or promotion of these types of activities to other farmers may lead to greater adoption of GHG mitigation practices.

Avoid risky schemes

Eckard 2010 (pers. comm.) comments "policy makers shouldn't promote schemes which will create unmanageable risk / liabilities for landholders (or develop collective/pooled schemes in which the risks are socialised). Current markets tell us that this will not attract much of the price anyway. We are seeing more governments avoiding rather than embracing soil C."A number of pitfalls associated with soil carbon trading are discussed under the previous sub-heading.

If promoting soil carbon trading, then consider ….

Subject to our developing knowledge-base, SOC sequestration may well remain a prospective climate change mitigation tool for policy makers – given the scale of the climate challenge and potential danger of high-end atmospheric GHG concentrations. The following are put forward for discussion if extension / promotion / incentives for soil carbon trading are being contemplated:

[176] Richard Eckard, Melbourne School of Land and Environment, University of Melbourne, 20-04-2010

- **Focus efforts** – arguably efforts should be biased towards areas likely to provide the greatest returns. Poor (e.g. shallow, inherently low fertility) soils in low rainfall areas show little promise for SOC sequestration. Clayey soils in higher rainfall areas will have the greatest potential. Previous condition is important as degraded soils will have potential for improvement. However areas such as rangelands should not be totally discounted. Degraded low rainfall rangelands with only small SOC improvement potential per ha, but large areas, may offer considerable sequestration potential.
- **Provide a practical legal framework** – this should set out the legal standing of soil carbon, soil carbon property rights agreements, and importantly clarify requirements such as measurement, compliance auditing, additionality and permanence.
- **Utilise carbon models and simplified verification process** – this would provide cost-effective compliance auditing, for example using the Chicago Climate Exchange style of system where 'aggregators' are responsible for monitoring (not individual farmers) and compliance is based on land management rather than rigorous soil testing.
- **Tiered pricing option** – the option for higher (less discounted) carbon pricing should be made available for operators who are willing to undertake more rigorous soil testing, which provides greater confidence in the value of the offset. Higher pricing should also apply to past measurement compared to forward selling
- **Supplementing carbon price** – State funded supplementation of the national carbon price may provide additional incentive to engage farmers in climate change mitigation action.
- **Maintenance payments** – After a new SOC equilibrium is reached payments for sequestration will cease. But maintaining elevated SOC in the ground is also valuable for climate change mitigation. Additional SOC maintenance payments might make an attractive ongoing incentive for farmers undertaking activity for climate change mitigation.
- **Risk management options** – consider risk management options such as (i) sharing liability for natural SOC losses (via a carbon property rights agreement), (ii) insurance schemes to protect against SOC losses due to natural factors beyond the farmer's control (e.g. drought, bushfire, erosion events, etc) and (iii) spreading / rotating SOC verification sites across large numbers of properties or allowing SOC to vary within acceptable limits as paddocks rotate through different management phases. In the absence of strict legislation, the terms of any carbon property rights agreement (with potential for sharing of liabilities under an agreed management plan) are at the whim of the parties involved. Other aspects of SOC offset accounting are necessarily overseen by NCOS.
- **Net benefits** – any incentive schemes will need to achieve net benefits for farmers and climate change mitigation.
- **Consult** – with farmers, industry groups and existing carbon market administrators to work through potential system pit falls, and learn from existing schemes (CORE 2010, Massey 2009).

Integrated solutions to meet complex objectives

Seek multi-purpose outcomes through a market based instrument (MBI) approach – to achieve property wide GHG emissions reductions, carbon sequestration in soils and vegetation, and improve biodiversity values, catchment water quality, erosion protection, etc.

SOC improvement objectives are aimed at addressing a range of related issues including productivity, farm profitability, natural resources management / environmental sustainability and importantly climate change mitigation. These are far-reaching and complex issues with triple bottom line (economic, social and environmental) impacts. Arguably, such important issues can not be judged against a single dimension such as (short-term) economics alone.

Individual SOC improvement practices may not be justified on a stand alone basis, in terms of economics or SOC sequestration ability. However cumulative effects from adopting a number of changed practices may be able to achieve net SOC sequestration, or at least provide improvement from business as usual. At the same time, actions may be able to satisfy multiple outcomes (as discussed above). In determining the cost-effectiveness of taking action, policy makers may need to consider a triple-bottom-line scorecard (not using economics alone). This is particularly relevant given the dangerous potential impacts and hence importance of addressing climate change.

'Re-valuing' our natural resources

Arguably SOC is undervalued, in the same way that biodiversity, water and other natural resources are largely undervalued by modern society. By undervaluing our natural resources we have overseen decades of biodiversity decline, unsustainable water management and declining SOC stocks (among other natural resources issues). Just as proponents of sustainable water resource management want to see the price of water rise, we may need to see a higher carbon price and greater incentives for (i) enhancement and (ii) preservation of terrestrial carbon stocks – before soil carbon is seen as a worthwhile means to encourage climate change mitigation action.

Manage environmental risks

Investigate and manage environmental trade offs associated with SOC-building- land management, for example:

- Catchment water yields – conservation of critical aquatic habitats or critical water supplies, particularly under a warming, drying climate, may require policy makers to identify catchment (or sub-catchment) areas where runoff requirements should take priority over measures to improve landscape water-use and SOC improvement.
- Bushfire risk – plant dry matter production (ie. fuel loads) will need to be monitored and managed, particularly in high fire risk areas and seasons.

Wait

There may be benefit in waiting for (i) soil carbon research outcomes and/or (ii) increases in carbon price and farmer interest in carbon trading. However waiting can also be dangerous, as indicated by Garnaut 2008: "The time frames within which effects become evident are too long, and the time frames within which action must be effected are too short."

Policy ideas put forward by The Climate Institute

A range of policy ideas for encouraging low carbon agriculture suggested by The Climate Institute 2009 are also worth further discussion and include:

- A 'decade of climate-friendly farming' funding program to drive innovation, investment and on-ground action
- 'Dove-tailing' mitigation and adaptation responses where possible (sequestering soil carbon is a good example of this as it also builds the resilience of production landscapes to climate change)
- Levies on emissions-intensive farm inputs and farm gate products – and investing proceeds into research, extension or incentives for improved practice
- Hybrid coverage of farm emissions, for example along the lines of the New Zealand emissions trading scheme which tries to limit administrative burdens on individual farmers (NZ MAF 2010)[177]
- Interim measures – such as low-interest loans for investing in best-practice / low-carbon farm equipment or infrastructure, competitive grants for implementing low-carbon demonstration practices or low-carbon practices with co-benefits (e.g. environmental / biodiversity outcomes)

[177] NZ MAF 2010, *A guide to agriculture in the emissions trading scheme*, New Zealand Ministry of Agriculture and Forestry, http://www.maf.govt.nz/climatechange/agriculture/agriculture-in-nzets-guide/index.htm

- Coordinating different levels of government to ensure that land use planning is equipped to cope with regionally appropriate carbon sequestration activities
- Careful exploration of the role of demand management strategies to reduce sectoral emissions and promote high value, climate friendly production

  This is based on UK findings that on-farm abatement measures alone will not produce the required emissions reductions and that changes in consumption patterns are also needed (MacMillan and Durrant 2009)[178]. While Australian policy development for demand management is relatively advanced in the electricity and transport sectors, we are well behind the United Kingdom and other European countries in gaining stakeholder involvement, gathering the evidence base and discussing such strategies in the food and fibre sector (The Climate Institute 2009). Reduced emissions from kangaroo meat production (which have a different digestive process to methane producing ruminant livestock) is a good example of this (Isaac 2008)[179].
- Consider using existing NRM organisations as aggregators to pool and administer carbon sequestration offsets.
- If necessary limit excess carbon sequestration offsets so that the CPRS is not flooded with offsets, driving down the price of carbon and diminishing drivers for important innovation and industry development elsewhere in the economy.
- Default regulation of emissions associated farming practices – if other policy options fail to achieve the required GHG abatement

7.4 Recommended priority actions

The following are recommended priority areas for further policy discussion. Some of these are recognised gaps that Government may assist with over the next 3-5 years, as part of the transition to low-carbon agriculture:

Building SOC:

1. Building SOC provides multiple benefits and where viable should be promoted, regardless of selling soil carbon.
2. Identify both the current capacity and potential to increase the capacity of South Australian soils to store carbon. It is fundamental for strategy development to understand the potential capacity of the resource. A carbon audit with a capability assessment should be conducted as a matter of urgency. An understanding of the potential to increase soil carbon levels and the production benefits to be gained is essential to support farmer decision making when investing in these technologies. It is difficult to see how any major carbon trading scheme can proceed without confirmation of the long term storage capacity of a specific soil.
3. Promote / support existing industry bodies and farmer networks which promote best practice consistent with SOC improvement goals, e.g. conservation farming (no-till or zero-till and plant residue retention), grazing management to enhance quality pasture production.
4. Extend the latest science / developments in farm GHG abatement technologies to farmers as they become available to help inform management decisions (maximising opportunities and minimising threats)

[178] MacMillan T and Durrant R 2009, *Livestock consumption and climate change. A framework for dialogue*. WWF (UK) and Food Ethics Council, http://www.foodethicscouncil.org/livestockconsumption

[179] Isaac J 2008, 'Is kangaroo really a more sustainable choice?', *ECOS Magazine*, Issue 145 (Oct-Nov 2008), CSIRO Publishing, 26-27

5. Support research efforts investigating cost-effective SOC improvements at the State scale, e.g. clay spreading / delving on sandy soils.
6. Establish long-term trial / demonstration sites (where they do not already exist) to investigate impacts on SOC levels, whole-of-farm profitability and environmental indicators, across different climate zones and soil types – for locally relevant SOC improvement practices, e.g.
    - Conservation tillage (e.g. zero-till), stubble retention with additional pasture / opportunity crops where applicable
    - Managing for resilient pastures, maintaining 100% ground cover 100% of the time through well managed grazing (perhaps incorporating innovative technologies such as temporary electric fencing, mobile water points, etc)
    - Annuals versus perennials, particularly in lower rainfall settings
    - Organic versus conventional farming methods
    - Creating micro-climates, e.g. wind breaks to reduce evaporation and water loss on a broad-hectare scale
7. Integrating developing knowledge of SOC improvement and reduced GHG emissions (CO_2, N_2O and CH_4) practices, into climate risk management delivery programs.

Investigating climate change mitigation / carbon trading opportunities:

8. Seek clarification at the national level of key eligibility criteria affecting voluntary and potential mandatory soil carbon/ carbon offset trading from agriculture. These include “additionality” criteria (e.g. for desirable “win-win” practices), “permanence” requirements, and the potential for different treatment of management-induced versus naturally-induced SOC changes.
9. If soil carbon trading is to become a viable opportunity in South Australia, this will require the development of a practical legal framework, allowing soil carbon property ownership rights.
10. Investigate policy or education frameworks to encourage GHG abatement via incentives, improved efficiencies or optimising marketability of products, e.g. through:
    - reduced fuel use
    - reduced nitrous oxide and methane emissions
    - more efficient use of N fertilisers
    - greater use of N-fixing legumes / alternative more cost-effective fertilisers
    - product labelling to reflect climate change awareness and GHG abatement associated with overall farming practices and/or farm product value-adding chain

8 GLOSSARY

ASRIS – Australian Soil Resource Information System

BoM – Bureau of Meteorology

Carbon dioxide equivalence (CO2-e) – A standard measure that takes account of the different global warming potentials of greenhouse gases and expresses the cumulative effect in a common unit.

Carbon footprint – A measure of the CO_2-e emissions attributable to an activity, commonly used at an individual, household, organisation or product level.

Carbon offset – Represents a reduction in GHG, or enhancement of GHG removal from the atmosphere by sinks, relative to the business-as-usual baseline. Carbon offsets are tradeable and often used to negate (or offset) all or part of another entity's emissions.

CCX – Chicago Climate Exchange

CPRS – Carbon Pollution Reduction Scheme (a form of ETS proposed by the Australian Government)

CSIRO — Commonwealth Scientific and Industrial Research Organisation

DAFF – Department of Agriculture, Fisheries and Forestry (Australian Government)

DCC – Department of Climate Change (Australian Government)

DCCEE– Department of Climate Change and Energy Efficiency (Australian Government)

DWLBC – Department of Water, Land and Biodiversity Conservation

ETS – Emissions Trading Scheme

FFI CRC – Future Farm Industries Cooperative Research Centre

GRDC – Grains Research and Development Corporation

Greenhouse gases (GHG) – Atmospheric gases responsible for causing global warming and climate change, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons (HFCs), per-fluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

N – Nitrogen

NCOS – National Carbon Offset Standard

NRM – Natural Resources Management (stewardship of the environment and its natural resources to maintain social, economic and environmental values)

P - Phosphorus

PAWC — Plant available water-holding capacity. In layman's terms this is the size of the bucket for holding soil-water that is able to be filled by rainfall and is available for plant uptake. This is surplus to the soil-water that is held tightly in a soil matrix (ie. lower limit or wilting point, WP) and is limited by gravitational drainage (field capacity, FC). The total PAWC represents the sum of (FC-WP) x depth for each layer down the soil profile until the impeding depth for plant root growth for that crop species is reached.

SANTFA – South Australian No-Till Farmers Association

Sequestration – The removal and long term storage of atmospheric CO_2 either through biological processes (e.g. photosynthesis in plants) or geological processes (e.g. capture and storage of CO_2 in underground reservoirs).

SOC – Soil organic carbon

UNFCCC – United Nations Framework Convention on Climate Change

WANTFA – Western Australia No-Till Farmers Association

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