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The abbreviations used in this document are:

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| (. · | L a i | bon |
| | | |

CFI Carbon Farming Initiative

CO₂ Carbon dioxide
GHG Greenhouse gas(es)
N₂O Nitrous oxide
SOC Soil organic carbon

A soil carbon snapshot for Fertcare advisors

There has been a renewed focus to better understand the role and function of soil carbon in Australian agricultural situations. This summary provides a snapshot of current knowledge and signposts the key messages and reports coming from recent research and investigations across Australia. It includes:

- An introduction to soil carbon and its role
- An overview of recent research and implications for land management practices
- Useful links to key information sources.



Introduction to Soil Carbon

1.1 Why is soil carbon important?

There is growing appreciation for the critical role played by the existing store of carbon in our agricultural soils. There has been considerable discussion around the possibility of increasing soil carbon levels for potential farmer income via future carbon credit markets. However, of greater importance is the story around the valuable role played by existing soil carbon stores that offer great benefit to both agricultural productivity and the wider environment.

Soil carbon and organic matter play a number of beneficial roles and biological functions in agricultural soils and supports productivity via:

- Providing a slow release supply of nutrients
- Improving cation exchange capacity and nutrient holding ability
- Assisting soil structure and aggregate stability
- Reducing erosion risk
- · Assisting soil water holding capacity
- Buffering against soil acidity
- Increasing soil biota diversity & abundance.

Maintaining or building reserves of soil carbon offers many benefits. As a result, farmer interest in practices and approaches that enhance the fertility, productivity and resilience of their soil assets is growing. There are also some positive signs that improvements to our understanding of the functions and measurement of soil carbon will prove useful for fertiliser decision making in future.

1.2 Climate change and the role of soil carbon as a sink

Soil is the largest reservoir of carbon in the terrestrial biosphere and a slight variation in this pool could lead to substantial changes in the atmospheric carbon dioxide concentration, thus impacting significantly on the global climate (Chan et al. 2008; Luo et al. 2010). With global soils containing three times as much carbon as found in the atmosphere, soil carbon stocks are a significant carbon sink. Over the coming decades there is likely to be an increasing focus on maintaining global soil carbon stocks and exploring pathways for enhancing soil carbon stores.

As a first principle, a core focus will be to ensure the existing asset of current soil carbon stocks are well understood and managed sustainably. As a general rule, many of Australia's agricultural soils have lost a significant portion of the original soil carbon that existed in their natural state. Luo *et al.* (2010) suggest that, for Australian agro-ecosystems, cultivation has led to declines with total carbon loss of approximately 51% in the surface 0.1 m of soil. While maintaining or increasing soil carbon levels is a popular objective for many Australian farmers, we should also be mindful that in many situations this task will not be easy or without some fundamental shifts in understanding and land management.

1.3 Soil carbon versus soil organic matter - what are we talking about?

Soil carbon is represented as Soil Organic Carbon (SOC) or Total Organic Carbon (TOC). While there is also inorganic carbon (minerals) found in some soils, it's the organic forms which are usually the largest proportion and the key driver of soil biology and function.

Soil organic carbon is a key component of the broader Soil Organic Matter (SOM) pool, which includes all of the organic components of the soil such as plant & animal tissue in various states of decomposition. Leaf litter and undecomposed materials on the soil surface are not considered to be soil organic matter until they start to decompose.

Soil organic matter contains important elements such as carbon, hydrogen, oxygen, calcium, nitrogen, phosphorus, sulphur and other elements found in living organisms. There is often some confusion between SOM and SOC. It is important to understand that on average soil organic carbon is only 58% of the soil organic matter component.

As a quick rule of thumb:

- Soil carbon (SOC) is on average 58% of soil organic matter (SOM).
- This is the same as saying SOM = SOC multiplied by 1.72.

For example:

- 2% SOC is the equivalent to 3.44% SOM (2% multiplied by 1.72)
- 4% SOM is the equivalent to 2.32% SOC (4% divided by 1.72)

1.4 Soil carbon metrics

There are a number of metrics used in the soil carbon space and it is important to know the differences when comparing different sites or reported changes over time.

Soil Organic Carbon (SOC) or Total Organic Carbon (TOC) refer to the same thing, and can be reported in a number of units either as:

- a percentage (%),
- grams of carbon per kilogram of soil (gC/kg soil), or
- tonnes of Carbon per hectare (tC/ha)

Note: SOC (gC/kg soil) can be quickly converted directly to SOC (%) by dividing by 10, for example: $15 \ gC/kg$ soil = 15/10 = 1.5%

For carbon accounting and sequestration projects the key measure is tonnes of carbon dioxide per hectare (tCO₂/ha). Thus for every tonne of SOC increase, there will be 3.67 tonnes of CO₂ removed from the atmosphere, and vice versa, for every tonne of SOC lost there will be 3.67 tonnes of CO₂ released into the atmosphere.

Note: 1 tonne of carbon is the equivalent of 3.67 tonnes of carbon dioxide.

To evaluate the actual mass of carbon stored or emitted from the soil it is necessary to convert carbon percent values into tonnes of carbon per volume of soil as t C/ha, and thus knowing the bulk density of the soil is critical. Compacted soils are denser and have a higher bulk density. Soils of the same type with lower bulk density are more porous and less compacted. Bulk density is basically a measure of the weight of dry soil per unit of soil volume i.e. (g/cm³).

To convert SOC (% or gC/kg) to SOC (t/ha) depends on soil bulk density and the depth of soil of interest: SOC (t/ha) = SOC (%) x depth (cm) x bulk density (g/cm³).

For example, a scenario where 10cm soil sample SOC 1.2%, with a known soil bulk density of 1.5 g/cm³:

- → 10.000 m² in one hectare
- → x 0.1m soil depth (10cm)
- \rightarrow x 1.5 g/cm³ bulk density
- \rightarrow x SOC 1.2 % (1.2/100)
- = 18.0 tC/ha.

The importance of knowing the soil bulk density is critical as shown here:

- 2% SOC with soil bulk density 0.8 g/cm³ = 16tC/ha
- 2% SOC with soil bulk density 1.6 g/cm³ = 32tC/ha

1.5 Soil carbon measurement

Accurate sampling methods are critical to assessing soil carbon levels and any changes over time. For example, when samples are being collected in the field it is important to remove any fresh organic materials (stubble, manure, plant leaves) from soils samples as these show up as additional organic carbon measurements and can be another potential source of error. There are also potential risks or errors associated with the gravel component within samples, so it's critical to follow accurate sampling protocols.

Some useful explanations of sampling techniques can be found at:

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

and the GRDC Publication 'Managing Soil Organic Matter - a Practical Guide':

www.grdc.com.au/Resources/ Publications/2013/07/Managing-Soil-Organic-Matter

The soil carbon measurement procedures required for carbon accounting in carbon farming projects can be found in the Australian government's methodology for soil sampling guidelines:

www.climatechange.gov.au/sites/climatechange/files/files/reducing-carbon/cfi/methodologies/determinations/cfi-soil-sampling-and-analysis-method-and-guidelines.pdf

1.6 Getting the sample depth right

The soil measurement depth is very important as carbon levels are much higher at the soil surface, thus for any soil carbon comparisons the depth of sample collections must be the same. For carbon accounting purposes the required depth is 30cm, which is deeper than most agronomic soil tests (usually only 10cm). As a rule, if soil testing samples have a depth bias then soil carbon values will also be biased. For example, if sampling in hard dry soils and actual sample depth achieved is only 8cm (instead of 10cm), then the bias will be towards a higher soil carbon reading as more soil carbon is located in the upper surface of the profile. If samples collect are from 12cm (instead of 10cm) then it's likely to bias results towards a lower soil carbon reading as soil carbon levels usually decline with depth.

1.7 Growing soil carbon or just squashing it? (bulk density)

Measuring bulk density is very important if seeking to understand changes in soil organic carbon over time. For soil carbon changes to be accurately measured, the percentage of soil organic carbon in a particular soil layer (0-10cm or 0-30 cm) also needs to be adjusted for bulk density changes that may have occurred over that same period of time.

For example, if a soil becomes more compacted over time (without any true change to soil carbon), when retested it will have a higher bulk density which could falsely indicate an increase in carbon sequestration: when in fact all that has happened in this instance is that the existing carbon stores have been squashed into less volume of soil.

1.8 Soil carbon analysis

Soil organic carbon can be analysed using several methods, with each differing slightly in their approach and outputs:

- The dry or furnace combustion method (eg Leco) uses high temperatures to 'burn-off' the carbon which then gets measured as carbon dioxide. This method actually measures total carbon, so if the soil sample contains inorganic carbon, an acid pre-treatment and correction is required so that soil organic carbon is not overestimated.
- The wet oxidation method (Walkley-Black) is an approach which oxidises the easily decomposable carbon, but it can underestimate the total soil organic carbon in the sample and thus requires calibration if comparing to the dry combustion method described above.
- Mid-Infrared (MIR) spectroscopy is used by researchers but not yet commercially available. This technique is also used to determine soil carbon fractions (see below).

Most commercial soil tests report soil organic carbon results as a percentage, which translates directly as the weight of soil organic carbon per 100 grams of oven-dried soil (g C/100g soil).

In future, the MIR spectroscopy technique has the potential to provide a cost effective and quick approach to identifying soil carbon including the more active soil carbon fractions which influence aspects of fertility and nitrogen mineralisation, which would be of benefit to advisors and farmers.



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1.9 What types of soil carbon are there? Do they behave differently?

Several types of organic carbon (fractions) can be identified in soils, each with different biological, physical and chemical properties which have different roles in soil function, health, fertility and productivity.

CSIRO (Baldock, 2011a) provides the following simple explanation of the key soil carbon fractions:

- Particulate Organic Carbon (POC) is the least stable and shortest lived, usually lasting only weeks or months before the carbon is decomposed further and either released as CO₂ or becomes part of the humus fraction. (Particle size is 0.05 to 2mm). Often referred to as the 'labile carbon' fraction.
- 2. **Humus Organic Carbon (HOC)** relatively stable and lasts for years or decades. Usually decomposed material found as large organic molecules attached to soil particles (size <0.05mm).
- Resistant Organic Carbon (ROC) very stable and may last for hundreds of years. Contains inert material, mostly charcoal, and levels change very little over time.

These fractions provide differing functions in the soil. These are summarised in Table 1.

1.10 Soil carbon and implications for soil fertility

Soil organic carbon is an important store of nutrients and can influence fertility by:

- Acting as a nutrient reserve in the soil (organic matter is made up of a range of nutrients and trace elements that are released at various rates as it decomposes)
- Encouraging microorganisms that are critical for converting organic matter and nutrients into forms that can more readily be taken up by plants
- Positively influencing the cation exchange capacity (CEC) and thus allowing the soil to better hold and transfer plant nutrients (humus organic carbon thought to have important influence here).

The most significant benefit of soil carbon for crop yields comes via increases in mineralised nitrogen. Soil organic matter contains a sink of bound up nutrients which are released into the soil as microorganisms mineralise or break down the organic matter for their own metabolism.

GRDC (2013a) suggests that as a general rule, for every tonne of carbon in soil organic matter about

Table 1: Functions of Soil Carbon Fractions

| Soil Function | Particulate Organic Carbon (POC) | Humus Organic Carbon (HOC) | Resistant Organic Carbon (ROC) | | |
|---|---|---|--------------------------------------|--|--|
| | | | | | |
| Increased infiltration (better soil structure) | $\sqrt{\sqrt{\sqrt{1}}}$ for sands and loams $\sqrt{1}$ for clays | √ for all soil types | √ | | |
| Tilth (improved structure, friability) | bility) X for clays √ for clays | | √ | | |
| Lowering bulk density | $\sqrt{}$ for sands and loams $$ for clays | √ for all soil types | √ | | |
| Increasing Plant Available Water | Х | √ for all soil types | √ | | |
| Chemical properties | | | | | |
| Improved Cation Exchange Capacity | x | $\sqrt{\sqrt{\sqrt{1}}}$ for sands and loams X for clays | √ for sands and loams | | |
| Buffer against acidification (binds to Fe and AI) | x | $\sqrt{1/2}$ for sands and loams X for clays | √ | | |
| Biological properties | | | | | |
| Food source for micro- organisms | $\sqrt{4}\sqrt{4}$ for all soil types | $\sqrt{\sqrt{\sqrt{1}}}$ for all soil types | √ for all soil types | | |
| Release of nitrate and ammonium | √ for all soil types | $\sqrt{\sqrt{1}}$ for all soil types | √ for all soil types | | |

Functions of Particulate (POC), Humus (HOC) and Resistant (ROC) organic carbon where: $\sqrt{\sqrt{}}$ =very important, $\sqrt{}$ =moderately important, $\sqrt{}$ =minor importance, \mathbf{X} = not important.

Source GRDC: Soil organic matter: What does it mean for you?

Website: http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2014/02/Soil-organic-matter)

100 kg of nitrogen, 15 kg of phosphorus and 15 kg of sulphur becomes available to plants as the organic matter is broken down.

While soil organic carbon can function as a significant source of nutrients for farm production, it is important to also consider the reverse of this process, as increasing or building stores of soil carbon will also require nutrients to be locked away and bound up along with the sequestered carbon.

1.11 Nitrogen wins & losses – the role of the carbon:nitrogen ratio

The nutrient types and amounts provided by the breaking down of organic matter will depend on the type of matter which is mineralised and its ratio of carbon and other nutrients, especially nitrogen. While nutrients are released in this process, much of the carbon in organic matter is converted by microbes back into carbon dioxide.

The various pools of soil carbon have differing rates of breakdown and thus nutrient release. The particulate organic carbon breaks down the fastest. The humus organic carbon takes years to decades to break down and is usually a larger but slower source of nutrients for plants.

The proportion of carbon relative to nitrogen is known as the Carbon; Nitrogen or C:N ratio. Plant residues can have substantial variations in the proportion of carbon to nitrogen. Microbes require sufficient nitrogen relative to carbon to decompose organic matter and release nutrients, thus the C:N ratio of the soil organic matter, plus it's overall quantity, can provide indications of soil fertility and quality.

Organic matter with a low C:N ratio (< 20:1) is generally considered high quality as its breaking down results in a higher level of nutrient available for plants. Conversely, organic matter with a high C:N ration (> 30:1) is generally considered lower quality as it can be slower to breakdown thus results in lower levels of nutrients freed up for plants.

When the C:N ratio is higher (>30:1 poorer quality), a key risk of nitrogen immobilisation or nitrogen 'lock-up' will exist. Basically, the microbial communities need their own nitrogen to build into their tissues, which can make it unavailable for plants for a period of time until these microbes die and break down. Nitrogen immobilisation occurs where there is sufficient carbon but insufficient nitrogen for both the microbial and plant populations. Microbes are usually much better at competing for available nitrogen than the plants, with significant implications for crop production.

Higher quality organic matter (eg <20:1 C:N) provides sufficient quantities of both carbon and nitrogen for the microbes, and has spare nitrogen which is then available for plants and crops. The C:N ratios for various organic residues are show in Table 2 below.

Put simply, nitrogen mineralisation occurs when there is more nitrogen available than what the microbes need. There are a range of factors that change through the season that can affect the dynamics of organic matter breakdown, microbes, mineralisation and crop needs hence there is much interest in improving the nitrogen mineralisation and fertility management understanding for Australian situations. The particulate organic carbon fraction (POC) is the most active pool for supplying organic nutrients over the short term, and over coming years the ability to cheaply test for this POC fraction could be useful for better understanding potential mineralisation estimations. A new GRDC publication 'Managing Soil Organic Matter – a practical guide' (GRDC 2013a) is a useful resource for further information, and can be found at:

http://www.grdc.com.au/Resources/ Publications/2013/07/Managing-Soil-Organic-Matter

Table 2. Carbon to Nitrogen ratios of various organic residues

| Poultry manure | 5:1 |
|-----------------|-----------|
| Humus | 10:1 |
| Cow manure | 17:1 |
| Legume hay | 17:1 |
| Green compost | 17.1 |
| Lucerne | 18:1 |
| Field pea | 19:1 |
| Lupins | 22:1 |
| Grass clippings | 15-25:1 |
| Medic | 30:1 |
| Oat hay | 30:1 |
| Faba bean | 40:1 |
| Canola | 51:1 |
| Wheat stubble | 80-120:1 |
| Newspaper | 170-800:1 |
| Sawdust | 200-700:1 |

From: Managing Soil Organic Matter – a practical guide, (GRDC 2013a)

Web link: http://www.grdc.com.au/Resources/ Publications/2013/07/Managing-Soil-Organic-Matter

1.12 Catch 22 – soil carbon sequestration requires nutrients

Building soil carbon stores is not easily achieved. As mentioned in the C:N discussion, soil microbes need organic matter as their food source, and when conditions are suitable for microbial activity (eg. warm & moist soils) much of the labile or particulate organic carbon is decomposed and released as carbon dioxide.

Kirkby et al. (2011) explain that the more stable portion of soil organic material known as humus (HOC) has a constant C:N:P:S ratio, which means that the relative proportions of each of these elements can limit the formation of carbon sequestered in the humus fraction.

Thus, carbon sequestration can be limited by the supply of nutrients. Kirkby *et al.* (2011) estimated that each new tonne of soil carbon being created

in the stable humus fraction would require or lock up 80kg nitrogen, 20kg phosphorus and 14kg sulphur. Kirby et al. (2011) estimated that at 2011 fertiliser prices this equated to a nutrient cost of \$248 to build one new tonne of soil carbon in the humus portion. This has obvious ramifications for land managers when considering soil sequestration objectives, as the potential costs of any locked up nutrients could far outweigh potential income from carbon trading schemes. Irrespective of carbon trading aspirations, it is important to consider the implications for nutrients and crop production before embarking on soil carbon sequestration strategies.

This GRDC summary also provides an insight into the relationship between crop nitrogen requirements and the role played by soil organic carbon http://grdc.com.au/Research-and-Development/GRDC-Update-Papers/2015/02/Where-does-fertiliser-nitrogen-finish-up.



Changing Soil Carbon

2.1 How much carbon is in Australian soils?

The CSIRO's **Australian Soil Carbon Mapping** project provides national scale representation of soil organic carbon (SOC) stocks. The average amount of organic carbon in the top 30 cm of Australian soil was estimated to be 29.7 tonnes per hectare and the total stock for the continent at 25.0 gigatonnes (Gt= 1000 million tonnes) with a 95 per cent confidence of being within the range of 19.0 to 31.8 Gt. The total SOC stock in agricultural regions of Australia is 12.7 Gt with 95 per cent confidence of being within the range of 9.9 to 15.9 Gt.

The largest SOC stores per hectare occur in the cool, temperate zones, which have the highest average rainfall (CSIRO 2014a). The amount of organic carbon in Australian agricultural soils varies significantly, from peat soils under pasture where the organic carbon content can be greater than 10%, to heavily cultivated soils, where the levels are typically less than 1%, (Robertson, 2012). The local soil carbon data from the national Soil Carbon Research Program is publicly available as described in the next section.

2.2 Our largest ever soil carbon collaboration – Soil Carbon Research Program (SCaRP)

The Australian Government-funded Soil Carbon Research Program (SCaRP) was completed in June 2012. It represents the largest and most extensive soil carbon sampling and analysis effort to date. With 20,000 samples taken from more than 4000 locations, the data collected are a valuable resource for agriculture.

The multi-agency collaboration was led by CSIRO and involved state and federal agencies and university research teams working closely with many agriculture and farming groups. SCaRP collected information on soil carbon stocks, including studies around the potential of agricultural soils to store additional carbon, the rate at which soils can accumulate carbon, the permanence of this sink, and how best to monitor changes in SOC stocks. Information gained from these studies is aimed at underpinning Australia's greenhouse gas accounting, carbon farming and sustainable agriculture systems.

Table 3. SCaRP Reports and summaries available include:

| Project # | Report Title |
|-----------|---|
| 1 | Field and Laboratory Methodologies |
| 2 | Developing a Cost-effective Soil Carbon Analytical Capability |
| 3 | Rapid Measurement of Bulk Density |
| 4 | Quantification of carbon input to soils under important perennial pasture systems used in Australian agriculture |
| 5 | Quantification of carbon input to soils under important perennial pasture systems in Australian agriculture: pulse labelling field studies in Western Australia |
| 6 | Variations in SOC on two soil types and six land-uses in the Murray Catchment, NSW |
| 7 | The potential for agricultural management to increase soil carbon in NSW |
| 8 | Carbon sequestration in soil under no-till as affected by rainfall, soil type and cropping systems in Queensland |
| 9 | Pasture type and management affect soil carbon stocks in grazing lands of Northern Australia |
| 10 | South Australian dry-land cropping |
| 11 | Organic Carbon Balances in Tasmanian Agricultural Systems |
| 12 | Soil carbon in cropping and pasture systems of Victoria |
| 13 | Soil Carbon Storage in Western Australian Soils |

The full reports and summaries for each of the 13 research projects can be found at:

http://www.csiro.au/Organisation-Structure/Flagships/Sustainable-Agriculture-Flagship/Soil-Carbon-Research-Program.aspx

The SCaRP soil carbon dataset is publicly available enabling advisors to explore the carbon levels (& carbon fractions) for soils across Australian agricultural regions for the first time:

https://data.csiro.au/dap/landingpage?pid=csiro%3A5883

These investigations include measurements from longer term research sites where management history is known, thus changes to soil carbon are discussed. The summary reports provide important details for specific regions of Australia and provide a useful reference for farmers and advisors wanting to better understand the soil carbon research relevant to their area.

Fact sheets produced by CSIRO are another useful resource:

- The basics of soil carbon: http://www.csiro.au/Outcomes/Environment/ Australian-Landscapes/soil-carbon.aspx
- The factors that affect soil carbon: http://www.csiro.au/outcomes/climate/ adapting/soil-carbon-levels
- Why soil organic carbon matters: http://www.csiro.au/outcomes/food-and-agriculture/soil-organic-matter
- New technique for rapid measurement of soil carbon:
 - http://www.csiro.au/Outcomes/Climate/ Understanding/Measuring-Carbon-In-Soils.aspx

Sanderman *et al.* (2010) is a more in-depth report which provides an overview of soil carbon sequestration potential as well as a summary of management options for sequestering carbon in agricultural land:

http://www.csiro.au/Portals/Publications/ Research--Reports/Soil-Carbon-Sequestration-Potential-Report.aspx

2.3 Defining carbon loss mitigation and carbon sequestration

It is important to examine not only ways of *increasing, (sequestering)* carbon soil levels, but also ways of maintaining and preventing loss (mitigation) from existing stocks of stored carbon in soils.

Mitigation refers to avoiding emissions of greenhouse gases, (GHG) into the atmosphere. The decay or combustion of organic matter leads to carbon dioxide CO₂ release and, in most cases, debate about emissions reduction centres on reducing use of fossil fuels which are long term stores of organic carbon. However, as large quantities of carbon are stored in Australian soils and vegetation, mitigating any losses of carbon from these stores will be critical to ensure that these large quantities of currently stored carbon do not enter the atmosphere as GHG emissions.

Sequestration means 'stored for safekeeping'. 'Carbon sequestration' is used to describe the capture and long-term storage of CO₂. Capture can occur at the point of emission (e.g. fossil fuel combustion) or through natural processes (such as photosynthesis), which remove CO₂ from the earth's atmosphere and which can also be enhanced by appropriate land management practices.

Plant and soil carbon sequestration methods fall under three general categories:

- Changes in land use
- Maintenance or change in land management practices, and
- Addition of carbon to the land from external sources.

Carbon sequestration practices involve the enhancement of existing, or development of new, carbon stocks sequestered within either vegetation or soils or a combination of both.

Sanderman *et al.* (2010) found that at least for the more traditional agronomic systems, Australian soils will generally only be mitigating losses and not actually sequestering additional carbon from the atmosphere into agricultural soils.

2.4 What influences soil carbon increases or losses?

Baldock (2011b) explained how the amount of carbon in soil can be thought of as a 'leaking bucket that constantly needs topping up'. The size of the bucket represents the total amount of carbon the soil could potentially hold. Factors such as clay content, soil depth and soil density will affect the size of the bucket. For example, the size of the soil carbon bucket will be smaller for sand than it is for clay soil. Management practices can't influence the size of the bucket, (Baldock 2011b).

Soil carbon stocks are strongly related to annual rainfall and site primary productivity, highlighting the importance of water availability and plant production. Land management usually plays a less significant role. Prior to the introduction of agriculture in Australia, our SOC levels were more or less in a state of equilibrium. Land clearing and conversion to agriculture has lead to a decline in SOC across much of Australia and it is likely that many of these soils are still responding to the initial cultivation, and subsequently are still in a state of soil carbon decline (Chan *et al.* 2010; Sanderman *et al.* 2010).

The changes in soil carbon fractions being added or lost is also an important consideration. Sanderman *et al.* (2010) noted that in studies where soil carbon stocks were found to be in equilibrium or increasing, the majority of the new carbon was found to have

accumulated in the particulate organic carbon (POC) fraction, which has the shortest lifespan in soils and thus can be more easily lost.

Across the Australia wheatbelt, it has been estimated that over 60% of SOC has been lost from the top 10 cm of soil (Chan *et al.* 2010). In simple terms, SOC can be maintained or increased by increasing organic carbon inputs or by reducing organic carbon losses.

Overall it is important to remember that it is the balance between the amount of plant biomass produced at a site, and the rate of decomposition that determines net changes to soil carbon. In many instances, increased organic matter production can be equally matched by increased rates of decomposition, thus while there is more carbon 'turnover', the net carbon store in the soil will not have changed.

2.5 How to lose soil carbon

Soil carbon is in a constant state of flux as microbes and other soil fauna decompose and convert carbon in plant residues and soil organic materials into CO₂. Changes in soil management that reduce input rates or increase loss rates may mean that the carbon pool size changes (CSIRO 2013b).

Processes that accelerate decomposition or erosion will, in turn, accelerate the rate of soil carbon loss. The rate that soil carbon is lost is influenced by the:

- Type and amount of organic matter, both plant and animal, entering the soil
- Management practices which reduce carbon inputs, increase erosion and/or increase the decomposition of soil organic matter including fallowing, cultivation, stubble burning or removal and overgrazing
- Climate conditions (rainfall, temperature, sunlight). For example, soil microbial activity can fluctuate depending on soil moisture and temperature, thus changes due to seasonal variability and climate change may be expected to also affect carbon levels in soil
- Soil properties (including the clay, silt or sand content).

2.6 What might increase or at least maintain soil carbon?

Improving SOC levels can be achieved by either increasing organic carbon inputs or decreasing organic carbon losses. The CSIRO (Sanderman *et al.* 2010) undertook a worldwide review of peer-reviewed studies of traditional management practices used to sequester soil carbon and concluded that:

Within an existing agricultural system, the greatest theoretical potential for [soil carbon] sequestration will likely come from:

- Large additions of organic materials (manure, green wastes)
- Maximising pasture phases in mixed cropping systems, and
- Shifting from annual to perennial species in permanent pastures.

Perhaps the greatest gains can be expected from more radical management shifts such as conversion from cropping to permanent pasture and retirement and restoration of degraded land' Sanderman *et al.* (2010).

Chan *et al.* (2010) identified ways of potentially improving (sequestration) SOC levels, including increasing crop yield, optimising rotations to increase carbon inputs per unit land area, stubble retention, increasing the amount of pasture grown or returning manure and other organic materials to soils.

SOC losses can potentially be reduced (mitigation) by reducing tillage, minimising stubble burning, minimising periods of fallow, reducing erosion and avoiding overgrazing.

Chan et al. (2010) give estimates of average SOC sequestration rates relating to a number of agricultural practices, and noted that sequestration rates vary both between, and within, management practices. Carbon sequestration rates were generally much less than 1 tonne of carbon/ha/yr averaging around 0-0.3 tonne of carbon/ha/yr.

2.7 The natural limits to soil carbon sequestration

While in theory it is possible to increase soil carbon, in practice there are often limitations or specific levels of soil organic matter that can be achieved for any farming system in a particular geographic region and soil type (Baldock 2011a; Powlson *et al.* 2011).

Lam et al. (2013) assessed the feasibility of increasing soil carbon stocks by improved management practices (conservation tillage, residue retention, use of pasture and nitrogen fertiliser application). Their results indicate that the potential of these improved practices to store carbon is limited to the surface 0–10 cm of soil and diminishes with time. They also noted that low sequestration levels means that emerging carbon markets may not be financially attractive to farmers in many situations.

Whilst most studies conclude that management options that increase SOC usually increase overall farm productivity and sustainability, (Chan *et al.*, 2009; Vic ENRC, 2010; Sanderman *et al.*, 2010), most of these

studies have also noted that management strategies aimed at increasing soil carbon may also lead to potentially negative impacts. Issues such as soil carbon and nitrogen cycling, plus the wider carbon emissions lifecycle impacts of changes to farming systems still require significant research (Barlow et al. 2011; Vic ENRC 2010; Sanderman et al. 2010; MacEwan, 2007).

For example, changing from annual crops to permanent pastures may increase soil carbon, but it may also lead to an overall increase in total emissions when the additional ruminant livestock production (methane emissions) is taken into account.

2.8 The effectiveness of land management practices and practice change on soil carbon

Various Australian studies have noted that there is a general lack of research in this area making it difficult to make definitive assessment of the sequestration potential of agricultural soils (Vic ENRC 2010; Sanderman et al. 2010).

A summary of the key research into changes to land management and effects on soil sequestration are in tables 4, 5 and 6. The implications of land management practices and soil carbon are then discussed in the sections that follow.

Ten key considerations for soil carbon changes

- 1. Accurate longer term measurement and monitoring is essential to determine changes to soil carbon levels. Factors such as soil carbon testing methods and accuracy, the age of trials (particularly if less than 5 years old), plus rainfall and seasonal variability are all factors which must be carefully considered before conclusions are made.
- 2. Increasing carbon input rates, or decreasing carbon loss rates can improve soil carbon levels and have other benefits including improved soil nutrient uptake, (where nutrients are available), water holding capacity and overall productivity.
- 3. While soil organic carbon can function as a source of nutrients for farm production, it is also important to consider the reverse of this process, as increasing soil carbon levels will require nutrients to be locked away and bound up with the sequestered carbon.
- 4. Soil carbon occurs in a number of different fractions, each having different properties, vulnerabilities and rates of decomposition. The Particulate Organic Carbon or labile fraction can be easily lost and decomposed in the soil and subsequently released back into the atmosphere as carbon dioxide.
- 5. The capacity for soils to sequester carbon is finite and there are specific maximum achievable equilibrium levels of soil organic matter for most farming systems due to climatic and primary productivity limits to plant dry matter production and decomposition rates.
- 6. For carbon accounting purposes, genuine carbon sequestration must result in an additional net transfer of carbon from the atmosphere to land, not just movement of a carbon source from one site to another.
- 7. Changes in land management which lead to increased carbon in soil must be continued indefinitely if farmers wish to maintain the increased stock of SOC. For many farmers, committing to long term land use may be undesirable if it reduces their ability to adjust land management to meet changing market or profitability drivers over the longer term.
- 8. Some management practices may only be reducing losses of soil carbon and not actually sequestering additional atmospheric carbon into the soil. Many soils are still responding to initial cultivation of the native soil and experiencing soil carbon decline.
- 9. Increasing soil carbon may potentially lead to perverse impacts as a consequence of the links between soil carbon, nitrous oxide and methane cycles. For example, changing from annual crops to permanent pastures may increase soil carbon, but may also lead to an overall increase in total net emissions via increased ruminant livestock production. Soil carbon needs to be considered in a wider systems context.
- 10. Climate change and changing patterns of seasonal variability will affect the ability of soils to maintain or sequester carbon. For some regions this may make to task of maintaining or improving soil carbon levels even more challenging over coming decades.

Land management changes and effect on soil carbon

3.1 Key findings of recent soil carbon research in Australia

The Australian Department of Agriculture produced a summary of the key findings of this research:

- 'There was no strong or consistent evidence indicating that management practices, including notill, increased soil carbon. The results were consistent across sites with a long prior history of soil carbon sampling (10 years) to those tested for the first time under the program (3 years).
- In most areas, soil type and rainfall were the strongest determinants of soil carbon levels with management practice having a minor influence.
- Perennial pastures often have higher soil carbon levels than annual crops'.

A summary can be found on the Department of Agriculture website which lists the soil carbon research programs both completed and those currently underway:

http://www.daff.gov.au/climatechange/ australias-farming-future/climate-change-andproductivity-research/soil carbon

Practice options and evidence for cropping systems (Table 4)

Field trial results from DEPI's 'Soil carbon in cropping and pasture systems of Victoria, funded under the Climate Change Research Program (CCRP), showed that management practices such as fertiliser application, cultivation, stubble retention, crop rotations and grazing management had relatively small or no effect on SOC stocks, (DAFF 2012).

Robertson & Nash (2013) studied eight regions that represent the climatic range of the Victorian cropping industry (annual rainfall 330-700 mm). They concluded that, 'With current technology, the potential for significant and verifiable soil carbon accumulation in Victoria's croplands is limited'. Furthermore, they found that even if all of Victoria's cropland were converted to a canola, wheat, triticale rotation with stubble retention, and if 50% of the modelled potential carbon change were achieved, this would be equivalent to 0.8-2.3 MtCO₃-e/year, or 0.7–1.9% of Victoria's greenhouse emissions (ibid). Furthermore, it would generally take 10-25 years for the soil carbon changes to become measurable using conventional soil sampling and analytical methods.

In South Australia, the SCaRP Dryland Cropping Project No. 10 research concluded that management approaches which maximise plant productivity may have the greatest potential in increasing soil organic carbon.

In Tasmania, SCaRP Project No. 11 researchers concluded, 'Results collected suggested the following hierarchy of influence of variables on soil organic carbon: Soil order > mean annual rainfall > land use > cropping frequency > tillage type'. They also concluded that, aside from changing land use from cropping to pasture, increasing pasture phases and shifting to minimum and no-tillage cropping are likely to be key mechanisms farmers can use to increase soil carbon.

In Victoria, SCaRP Project No. 12, longer term field trial results showed that management practices such as cultivation, stubble retention, and rotations in cropping systems in the Northern Wimmera region had small or no effects on soil organic carbon stocks.

Reducing bare fallow phases in crop rotations/ **cover crops** - Periods of fallow between crops leave soils exposed to wind and water erosion which can lead to soil carbon losses. Losses continue during fallow without any new carbon inputs from vegetation such as cover crops which help mitigate this. There is strong theoretical evidence, backed by cropping trial results that soil carbon losses are reduced through either the elimination, or at least reduction in the length of time of bare fallow periods in the cropping cycle.

Stubble retention - Stubble retention can potentially reduce the extent of carbon losses by reducing the physical loss of top soil from erosion, and may reduce SOC stock losses. However, Powlson (2011) noted that most of the organic carbon added in straw will decompose and be returned to the atmosphere as CO₂, with only a fraction retained in soil. Under temperate climate conditions, typically about one-third of plant material added to soil is retained at the end of one year, with about twothirds being emitted to the atmosphere.

There are a number of situations where carbon increase has been measured in the top 5-10 cm of soils, but this is negated by a decrease in carbon at greater depth. However, any increase in SOC from stubble retention tends to be small and emerge over the long-term (10+ years). Most trials indicate that retention of stubble, (as an alternative to stubble burning or other forms of removal), generally leads to little, if any, long term increase in SOC (Sanderman et al. 2010).

Table 4: Practice options and evidence for cropping systems

| Practice option | Research evidence | Relevant CFI methodology | Benefits for carbon sequestration | Negative impacts / risk |
|--|---|--|--|---|
| Elimination or reduction of the length of time of bare fallow phases in crop rotations by using cover crops. | Very strong evidence for reducing carbon loss, near universal finding. ^A | None currently approved | Losses continue during fallow without any new C inputs – cover crops mitigate this. ^C Added potential to reduce C losses through reduced erosion. | None documented |
| Stubble retention (cf. stubble burning /removal) | Most studies show no effect. but good evidence in a few situations. ^A | None currently approved | Greater C return to the soil is likely to reduce C losses and may increase SOC stocks. ^c | Any increases are small and emerge over long-term (10+ years). ^ Many situations where C increase measured in top 5-10 cm, but this is negated by a decrease in C at greater depth. ^ $^{\rm A}$ |
| Minimum tillage and direct drilling (cf. multiple-pass conventional cultivation) | Most studies show no effect though some good evidence in a few situations. ^A | None currently approved | Direct drilling reduces erosion and destruction of soil structure thus slowing decomposition rates. ^c | Reduced tillage has shown little SOC benefit C. Any increases are small and emerge over long-term (10+ years). A Surface residues decompose with only minor contribution to SOC pool. Many situations where C increase measured in top 5-10 cm, but this is negated by a decrease in deeper soil. A |
| Inclusion of leguminous pastures in rotation with crops (cf. continuous cropping with nonlegumes). | Strong evidence in many situations, but not in others. A | None currently approved | Particularly effective where N is limiting. ^A Pastures generally return more C to the soil than crops. ^C | Potential of increased CH $_4$ and N $_2$ O from livestock production systems need to be accounted for from conversion of cropping to grazing land. $^{\rm DE}$ |
| Inclusion of non-leguminous pastures in rotation with crops (cf. continuous cropping with non-legumes). | Evidence in some situations but not in others. ^A | None currently approved | Depends on dry matter inputs from the pasture. ^A Pastures generally return more C to the soil than crops. ^C | Potential of increased CH $_4$ and N $_2$ O from livestock production systems need to be accounted for from conversion of cropping to grazing land. $^{\mathrm{DE}}$ Lack of legumes likely to increase need for N fertiliser resulting in additional N $_2$ O emissions. |
| Inclusion of leguminous crops (pulses) in rotation with non- leguminous crops (cereals & oilseeds) (cf. continuous cropping with non-legumes). | Good evidence but only in very few situations | None currently approved | Potentially effective where N is deficient. $^{\text{A}}$ | Most studies show no effect. ^ SOC effects likely to be influenced more by how the crop was established rather that the crop itself. ⁸ |
| Increasing productivity through increasing irrigation | Yield and efficiency increases do not necessarily translate to increased C return to soil. | None currently approved | | Potential trade-off between increased C return to soil and increased decomposition rates. $^{\rm c}$ |
| Increasing productivity through fertiliser application (cf. zero fertiliser or other nutrient applications) | Good evidence in some situations but not in others. ^A | CFI methodology being developed. However, initially focused just on cotton. ⁸ | Good evidence where soil nutrient levels are deficient. Evidence re: N and P, but likely to hold for other nutrients too. ^A | Potential trade-off between increased C return to soil and increased decomposition rates. ^c Adding more N fertiliser leads to increased root growth leading to more SOC. However, high N inputs would lead to more N_2O emissions. ^a Evidence that applying fertiliser, in excess of plant requirements, has no effect or negative effect on soil C. ^A |

A: Dr. Fiona Robertson – DEDJTR Victoria, (2014); B: Prof. Richard Eckard – University of Melbourne, (2014); C: Sourced from Table in: Sanderman et al. (2010); D: Cowie (2010); E: Chan et al. (2008)

Stubble retention, (cont.) - Results from the SCaRP Project No. 8, investigating SOC in specific Queensland crops, indicate that there is 'no evidence that the use of no-till and/or stubble retention is capable of increasing soil organic carbon stocks in Queensland grain cropping systems'. Results of measurements conducted over time would also suggest that organic carbon is lost from crop-fallow grain rotation systems regardless of tillage or stubble management practices'.

Minimum tillage and direct drilling - In general, increases in SOC from reduced tillage may also be much smaller than previously claimed, at least in temperate regions (Sanderman et al. 2010; Powlson et al. 2011). Minimum tillage and direct drilling, in comparison to multiple-pass conventional cultivation, has generally shown to result in little SOC benefit (Sanderman et al. 2010; Dalal et al. 2011). Surface residues decompose with only minor contribution to the SOC pool and any increases in SOC tending to be small and only becoming evident over the long-term (10+ years). Furthermore, although there are many situations where SOC increase has been measured in top 5-10 cm, this is usually negated by a decrease in deeper soil (Sanderman et al. 2010).

However, a potential may exist to increase carbon sequestration in soil under no-till in higher rainfall areas >550 mm in southern Australia and >700 mm in subtropical Queensland (CSIRO 2009a).

Results from the SCaRP Project No. 8 investigating SOC in specific Queensland crops indicate that 'no-till systems are not capable of increasing soil organic carbon in either Queensland grain or sugarcane systems. However, no-till may be capable of slowing carbon loss following a period of carbon input from, for example, a pasture ley'.

As with all potential management changes which affect soil carbon levels, the net story for greenhouse gases needs to be understood as in some situations increased N₂O emissions may negate any increase in stored carbon (Powlson et al. 2011).

Inclusion of various pasture phase systems in rotation with crops - In theory, maximizing pasture phases in mixed cropping systems, are likely to build up soil carbon levels, since pastures generally return more carbon to the soil than crops (Sanderman et al. 2010). Under pastures, soils tend to have higher SOC levels than soils under crops because they have higher root to shoot ratio than many crops, which are relatively undisturbed and decompose at lower rates. This trend is usually even more so as rainfall increases (Chan et al. 2010).

SCaRP Project No. 7, which investigated soil carbon levels in cropping and pasture systems of central

and northern NSW, concluded that increasing the proportion of pasture may be a viable option for sequestering carbon in mixed farming systems.

In mixed cropping/pasture systems, SOC levels generally decline under cropping phases and increase during the pasture phases (Chan et al. 2010).

In general, research into the inclusion of leguminous pastures in rotation with crops, as compared to continuous cropping with non-legumes, or pasture phases incorporating non-leguminous pastures, appear to be an effective way of increasing SOC in many situations, particularly where nitrogen levels are limiting soil fertility. There may also be a reduction in total GHG emissions from replacement of added nitrogen fertiliser via potential savings from manufacture, transport and emissions release from urea hydrolysis (CSIRO 2009a).

Inclusion of *non-leguminous pastures* in rotation with crops, compared to continuous cropping with non-legumes has shown to be an effective way of increasing soil carbon in *some* situations but has shown to be ineffective in others. In terms of GHG emissions reduction, inclusion of non-leguminous pasture phases in cropland may potentially increase the need for nitrogen fertiliser resulting in additional N₂O emissions and increased CH₄ emissions during the livestock production phase which would need to be accounted for if GHG emissions reduction is a driver for such land use change (Barlow et al. 201; Cowie 2010a).

Inclusion of leguminous crops (pulses) in rotation with non-leguminous crops - Research suggests that inclusion of leguminous crops (pulses) in rotation with non-leguminous crops (cereals & oilseeds) can lead to an increase in SOC (in comparison to continuous cropping with non-legumes), especially where nitrogen levels are limiting soil fertility. However, most studies show no effect.

Increasing productivity through increasing **irrigation -** There is limited evidence that increasing productivity through increasing irrigation will effectively increase SOC, as crop yield and production efficiency increases do not necessarily translate to increased carbon returned to soils (eg more carbon turnover rather than extra carbon sequestration). Furthermore, there is the potential trade-off between any increase in carbon returned to soil through increased vegetative growth and increased decomposition rates (Sanderman et al. 2010). There is evidence in some situations but not in others. Irrigation can stimulate microbial activity leading to increased decomposition rates, thus the soil carbon levels will depend on the overall balance between increased SOC inputs versus total decomposition.

Increasing productivity through fertiliser

application - There is good research evidence that increasing productivity through fertiliser application can increase SOC, especially where soil nutrient levels are deficient, (in comparison to using no fertiliser or other nutrient applications), (Robertson pers. comm. 2014). Evidence has been shown for nitrogen and phosphorous application and is likely to hold for other nutrients too, (ibid). However, there is also evidence that applying fertiliser, in excess of plant requirements, will have no effect or even a negative effect on soil carbon (Eckard pers.comm. 2014) and potential for increased N₂O emissions.

Further, as with increased irrigation, there is a likely trade-off between increased soil carbon and increased decomposition rates (Sanderman et al. 2010). Adding more nitrogen fertiliser can lead to increased plant growth, but can only result in increased SOC if there is no subsequent increase to SOC decomposition. Also, high nitrogen inputs could lead to more N₂O emissions, thus again this area requires more research and a thorough understanding of the wider life-cycle effects.

3.3 Practice options and evidence for mixed systems (Table 5)

Conversion of cropping to permanent pasture - There is very strong evidence that conversion of cropping to permanent pasture will increase SOC in most situations. Pastures generally return more carbon to soils than crops (Sanderman et al. 2010; Cotching 2009). Current research suggests that where there is low SOC, with high potential, then the net effect of the conversion on GHG emissions may be positive initially, but after about 20 years it would switch the other way (Eckard pers. comm. 2014). The beneficial effect on SOC appears to be greater where cropping has been undertaken over the long-term.

Powlson et al. (2011) state that 'Because arable soils usually have a much smaller SOC content than the equivalent soil under forest or grass, this type of change in land use will almost always lead to an accumulation of SOC'. They provide examples of considerable SOC accumulation after land-use change, from arable to woodland, at two temperate region sites in the United Kingdom.

Although conversion of cropping land to permanent pasture is widely considered to lead to an increase in soil carbon stocks, conversion to pasture for food production in Australia almost exclusively involves ruminant livestock resulting in potential for increased methane and nitrous oxide emissions. Consequently, a thorough understanding of greenhouse gas lifecycles is required to ascertain the overall implications of changed land use for climate change mitigation.

Shifting from Annual to Perennial Pasture

Systems - The research evidence for the SOC benefits of shifting from annual to perennial pasture species is weak as there is insufficient conclusive data available. Theoretically, perennial pasture plants can utilise water throughout the year which is likely to lead to an increased below ground allocation of biomass and potentially carbon, but there are few studies to validate this (Sanderman et al. 2010). For example perennial pastures, such as phalaris have long-lived deep root systems which can utilise water at depth. Furthermore, annual pastures die off returning their above and below ground biomass to soils every year whereas the carbon stored in perennial pasture root systems is less readily decomposed than carbon in soils close to the surface (Chan et al. 2010).

Current research suggests that where there is low SOC, with high potential for gains, then the net effect of converting to perennial pastures may be positive initially, but may only last for a number of decades (Eckard, pers. comm. 2014).

Recent results from SCaRP Project No.4 concluded that 'Kikuyu-based pasture systems in the Southern Agricultural District of Western Australia, Kangaroo Island and the Fleurieu Peninsula of South Australia had greater SOC stocks relative to annual based pastures. The SOC difference between the kikuyu and annual pasture increased linearly with the age of the perennial pasture'. However, the researchers also emphasised that the soil type of the pasture may play a major role in the long-term stability of the newly sequestered carbon.

Where annual pasture systems are exposed to soil erosion, shifting to perennial pastures may offer carbon benefits by reducing carbon losses through erosion. Overall, the evidence for SOC benefits of shifting from annual to perennial pasture species is weak and more research is required.

Shifting from conventional to organic farming

- The evidence as to the benefit of shifting from conventional to organic farming system is inconclusive due to a lack of available data. Results of studies give variable outcomes depending on the specifics of the organic system such as rates and types of manuring and cover crops etc. (Sanderman et al. 2010). Further research is required to better describe the GHG emissions lifecycles for specific farming systems, whether they be conventional or organic farming.

Increasing productivity through fertilization -

Historically agriculture has been able to achieve an increase in crop yields, which has led many to believe that the increased plant production should automatically flow on to an increase in the SOC store. However, whilst this may be the case for

Table 5: Practice options and evidence for mixed systems or system conversion

| Stabilised C in Biochar which is added to soil for potential long term C sequestration benefits and productivity gains. | Conventional to organic farming system | Shift from annual to perennial pasture species. | Conversion of cropping to permanent pasture | Sub-soil manuring | Top soil application of imported organic material (compost, manure etc) | Practice option |
|--|--|--|--|--|---|-----------------------------------|
| Work being undertaken via the National Biochar Initiative. | Insufficient data available. ^A | Evidence equivocal, little data available. ^{A.} | Very strong evidence in most situations. ^{A.} | Current DAFF funded project is investigating carbon sequestration through subsoil manuring.1 | Strong evidence in many situations for wide variety of organic materials. A. High confidence in improving C sequestration rates based on both theoretical and evidentiary lines. ^c | Research evidence |
| Biochar is on the CFI Positive list of activities, however there are no current approved methodologies though two biochar methodologies are currently being developed for a single feedstock | Currently, no CFI methodology approved | A new Carbon Farming Initiative (CFI) methodology has recently been approved, 'Sequestering carbon in soils in grazing systems,' which applies to land managed using a range of activities to build soil carbon including, but not limited to, converting cropland to permanent pasture, rejuvenating pastures or changing grazing patterns. | New CFI methodology: Website here Sequestering carbon in soils in grazing systems; applies to land that is either under permanent pasture, or that is converting to permanent pasture. | Currently, no CFI methodology approved | Currently, no CFI methodology approved | Relevant CFI methodology |
| C in plant material, converted to a highly stable form of C as biochar, can be regarded as genuine C sequestration. Biochar may also reduce N ₂ O and CH ₄ losses. DEFG | | Plants can utilise water throughout the year, increased below ground allocation but few studies to date. ^c Current research suggests that where there is low SOC, with high potential, then the net effect may be positive initially, but after about 20 years it would switch the other way. ^B | Pastures generally return more C to soils than crops. ^{C,J} Current research suggests that where there is low SOC, with high potential, then the net effect of the conversion on GHG emissions may be positive initially, but after about 20 years it would switch the other way ^{B,H} Effect is greater where cropping was long-term. ^A | Likely that the practice has the potential to increase soil carbon at depth ¹ | Depends on amount and type of material applied. A Direct input of C, often in a more stable form, into soil may stimulate plant productivity. C | Benefits for carbon sequestration |
| Validation of GHG mitigation benefits of biochar, requires a full life-cycle assessment across the whole system — i.e. biomass source and procurement, biochar production system, and its application DLEFIG. Evidence for reduced N2 O is mainly because the biochar changes the soil C:N ratio and thus immobilises soil N. However, more N may need to be added to the system to become productive again. B Point of 'sequestration' is at the biochar pyrolyser. Land application is technically carbon transfer and not actual sequestration. B | Variable outcomes depending on the specifics of the organic system (i.e. manuring, cover crops etc) $^{\rm c}$ | | The added CH ₄ and N ₂ O from ruminants may more than neutralise the increased soil carbon benefit. 8,D Benefit will likely depend greatly upon the specifics of the switch. ^C Shifting from cropping to pasture, without any decrease in market demand for crops, will lead to other land being put into cropping, merely transferring SOC losses to another farm, | The increased soil C may not constitute C sequestration (only C transfer), depending upon the alternative fate of the organic material. $^{\rm G}$ | The increased soil C may not constitute genuine C sequestration (only C transfer), depending upon the alternative fate of the organic material. $^{\rm G}$ | Negative impacts / risks |

some systems, in many a subsequent increase in SOC, decomposition negates any soil carbon gains (Sanderman et al. 2010).

There is evidence for increased SOC in some situations where fertilizer has been used, but not in others, as there is a potential trade-off between increased carbon return to soil and increased decomposition rates. Increasing nitrogen use also needs to be balanced against the GHG emissions associated with manufacture and use of fertilizer (IPCC 2014; Powlson et al. 2011; Barlow 2011; Cowie pers. comm.).

Topsoil addition of organic matter (eg compost, manure) - There is considerable evidence, both theoretical and evidentiary, in many situations that SOC can be increased through the addition of a wide variety of organic materials (Sanderman et al. 2010). The extent to which adding organic matter benefits SOC depends on the type, composition and amount of organic material applied. Direct input of carbon often in a more stable form, into soil may also have the benefit of stimulating plant productivity. Carbon derived from organic inputs that are high in lignin, may reside in soil longer than the labile carbon in crop residue.

However, in regards to genuinely reducing carbon sequestration (resulting in GHG emissions reduction), Powlson et al. (2011) concluded that 'Adding organic materials such as crop residues or animal manure to soil, whilst increasing SOC, generally does not constitute an additional transfer of carbon from the atmosphere to land, depending on the alternative fate of the residue'. It is also important to understand the implications of nitrous oxide and methane GHG emissions before conclusions on the mitigation effects of organic matter additions can be made.

Results from SCaRP Project No. 7, which investigated the soil carbon levels in cropping and pasture systems of central and northern NSW, indicated that alternative management practices (reduced/no tillage practice, organic amendments) appears to have had little impact on soil carbon stocks. The researchers also note though that 'further research, through longitudinal studies, is required to generate data that definitively assess the potential for change in land management to increase soil carbon'.

Subsoil manuring - Generally, subsoils contain smaller concentrations of carbon than the adjacent topsoil, with the implication that subsoils may contain unused capacity for carbon storage. If this capacity could be used it could, in principle, increase the potential for genuine additional carbon sequestration in soils. In addition, there are some indications that organic carbon in subsoil is more strongly stabilized than carbon in topsoil (Powlson et al. 2011).

CSIRO SCaRP Project No 13 examined SOC in Western Australian soils and concluded that maximum storage of SOC in WA soils is rarely achieved, due to sub-optimal climatic conditions. Although the WA modelling suggests that the 0-0.1 m layer is largely saturated (full) in terms of carbon storage, the researchers also found that soils below 0.1 m are currently at less than half their storage capacity. They therefore concluded that, 'to increase carbon storage in soil, it is important that management practices remove any constraints to plant growth, where it is cost effective to do so. Strategies that deliver organic matter below the surface 0.1 m soil layer are more likely to build soil organic carbon'.

Sub-soil manuring is an emerging practice under investigation in Victoria, where trials applying large volumes of nutrient-rich organic matter are deposited into the upper layers of clay subsoils, (GRDC 2013b). This may offer potential to increase soil carbon at depth by encouraging deeper root development and biomass (Peries pers.comm. 2014), however this has not been proven and is the focus of current research. Recent Victorian DEDJTR trials have indicated substantial increases in crop yield (lasting at least 5 years) in test sites and across seasons in high rainfall zones. Further investigations are required to understand the overall implications for soil carbon levels and the effects on other GHG lifecycles associated with novel practices such as this, as well as the longer term fate of subsoil carbon stores.

Biochar additions to soil - Biochar is a stable form of charcoal produced from heating natural organic materials under high temperature and low oxygen in a process known as pyrolysis. Biochar can enrich soils, acting as a stable carbon sink for anywhere from hundreds to thousands of years (CSIRO 2013a). There has been recent interest in the potential use of biochar to build soil carbon stocks. Sources of information include the CSIRO. DPI NSW, the International Biochar Initiative, (IBI) and the Australia New Zealand Australian Biochar Researchers Network (ANZBRN). http://www. anzbiochar.org/index.html

It is generally accepted that biochar is a highly stable form of carbon and as such has the potential to form an effective carbon sink (Sohi et al. 2009). More broadly, the potential SOC and GHG reduction benefits of biochar, as identified by CSIRO (2009a 2013) include:

- Stabilisation of biomass carbon via delayed decomposition
- Stabilisation of native soil carbon
- More efficient retention of nutrients and avoided leaching from the soil profile
- Reduced nitrous oxide emissions from soil
- Avoided emissions from waste management from urban, agricultural and forestry
- Displacing fossil fuel use through bioenergy production.

A recent NSW DPI trial indicated that some of the biochars tested were effective in reducing emissions of N₂O from soil (ANZBRN website). However, evidence for reduced N₂O may be mainly because the biochar changes the soil Carbon: Nitrogen ratio and thus immobilises soil nitrogen. However, more nitrogen may need to be added to the system to become productive again (Eckard pers. comm).

In Australia, NSW DPI, in conjunction with CSIRO, is leading the research into biochar and currently claims to be running the world's largest demonstration of biochar, with over 150 field plots under management. The NSW DPI website

outlines a number of studies that they are undertaking to help quantify any possible carbon sequestration benefits of biochar.

Biochar effectively removes carbon from the active carbon-cycle due to its nature of locking up carbon for long periods. Biochars produced at higher temperature are more stable than those pyrolysed at low temperature. The CSIRO State that "biochar is chemically and biologically in a more stable form than the original carbon form it comes from, making it more difficult to break down. This means that in some cases it can remain stable in soil for hundreds to thousands of years", (CSIRO 2013a). However, there are few studies quantifying the net GHG impacts of actual biochar systems. To calculate the mitigation benefits of biochar, a life-cycle approach needs to be undertaken, taking into consideration all aspects of the biochar system, including - the type of biomass, it's procurement, the type of production system and technology, (pyrolyser) used, and its application. To determine the true carbon sequestration benefits, each stage needs to be assessed as to the net GHG impacts across the entire system (CSIRO 2009a). For example, producing biochar in a poorly designed pyrolyser can lead to the production of toxic and/or powerful GHG's, such as methane which may negate biochar's carbon sequestration benefits.

In a recent review of biochar research, the authors state that 'there are not enough data to draw conclusions about how biochar production and application affect whole-system GHG budgets. Wide-ranging estimates of a key variable, biochar stability in situ, likely result from diverse environmental conditions, feed-stocks, and study designs. There are even fewer data about the extent to which biochar stimulates the decomposition of soil organic matter or affects non-CO₂ GHG emissions' (Gurwick et al. 2013).

Regarding carbon credits for biochar, it is important to remember that any credit will be applied at the point of manufacture (pyrolysis plant). That means farmers spreading biochar on their soils would not constitute sequestration unless there were additional responses to soil carbon reserves beyond that of the added biochar.

Table 6: Practice options and evidence for grazing systems

| Practice option | Research evidence | Relevant CFI methodology | Benefits for carbon sequestration | Negative impacts / risks |
|--|--|--|--|--|
| Grazing management | Strong evidence that over-grazing reduces soil C eg. via erosion losses. A Evidence for other grazing practices (stocking intensity, duration, rotational / set stocking etc.) is equivocal or non-existent. AH | New CFI methodology: Website here Sequestering carbon in soils in grazing systems; applies to land that is either under permanent pasture, or that is converting to permanent pasture. | Strong evidence that over-grazing reduces soil C eg. via erosion losses. ^A | Long term trials at Hamilton, (Vic) show no change in SOC for two plus decades under a range of grazing management systems. B Any soil C change as a result of change in grazing pressure takes many years to be detectable. H |
| Increasing productivity through irrigation | Good evidence in some situations but not in others. A | None currently approved | | Potential trade-off between increased C return to soil and increased decomposition rates. ^C |
| Increasing productivity through fertilization | Good evidence in some situations but not in others. ^A | None currently approved | | Potential trade-off between increased C return to soil and increased decomposition rates. ^C Likely to depend on original nutrient status. ^A Increasing N use needs to be balanced against GHG emissions associated with manufacture and use of fertilizer. D.E.F.G |
| Native v. sown pastures | Insufficient data available. [^] | None currently approved | | Many native pastures have higher SOC than sown, simply because they remain relatively undisturbed. Many improved pastures have still not regained the original SOC prior to clearing and disturbance. ^B |

A: Dr. Fiona Robertson; B: Prof. Richard Eckard; C: Sanderman et al. (2010); D: Cowie (2010); E: IPCC (2014); F: Powlson et al. (2011); G: Barlow et al. (2011); H: CSIRO (2009a)

3.4 Practice options and evidence for grazing systems (Table 6)

Most studies indicate that there is limited or no effect of grazing management (grazing management, pasture improvement, pasture cropping, grazed woodlands) on total soil carbon (Robertson 2012; CSIRO 2009b).

In Victoria, long-term field trial results showed phosphorus fertiliser application and grazing management in sheep production systems in the Victorian Volcanic Plains region had little or no effect on soil organic carbon stocks. It should be noted, however, that investigations are continuing and results are still preliminary.

In temperate regions, the type of pasture grass grown may influence soil carbon levels, as investigated by the SCaRP Project No 8 which suggested SOC increasing under Kikuyu grass but not under Panic or Rhodes grass, although the authors felt that the soil type of the pasture is likely to be a key contributor in the long-term stability of the newly sequestered carbon.

Grazing management - Overgrazing has been a major cause of land degradation in Australia, particularly under traditional continuous grazing systems, as it often leads to erosion and subsequent loss of nutrients and carbon. It can also lead to soil compaction, reducing the productive capacity of pasture systems (Chan et al. 2010). Overgrazing

resulting in the replacement of productive species with weed species can also increase the likelihood of carbon loss through erosion. Chan *et al.* (2010) give the example of capeweed which is less-productive and rapidly dies off in late spring leaving bare areas that are prone to erosion.

Rotational grazing systems have the potential to increase biomass production over time, but there is no conclusive evidence that rotational grazing and other such practices, including reduction of stocking intensity, grazing duration and set stocking rates, increase SOC (CSIRO 2009b). However, it is likely that grazing management practices that reduce the size or frequency of bare patches and reduce the extent of compaction will reduce erosion and hence carbon losses.

SCaRP Project No. 7, which investigated the soil carbon levels in cropping and pasture systems of central and northern NSW, indicated limited or no effect of management (grazing management, pasture improvement, pasture cropping, grazed woodlands) on total soil carbon.

Exceptions to these general findings include recent research results from the SCaRP Project No. 9, which investigated pasture management systems and SOC in the northern Australian rangelands and savannas. The researchers concluded that 'significant differences in SOC stock relating to pasture utilisation rate at long-term trial site, and which relates to measures of total standing dry matter and remote sensing information (NDVI).' Pasture utilisation at 20% apparently provided the optimum SOC stock while at 80% pasture utilisation the SOC stocks were the lowest.

Pasture cropping - Pasture cropping involves direct drilling of winter cereal crops into predominantly summer-growing native perennial pastures, a technique first developed in central-west New

South Wales (Chan et al. 2010). Theoretically, this system has potential to restore or enhance SOC more than that of conventional ley/crop systems, particularly in degraded pastures. However, there is little scientific data available to support these claims (Chan et al. 2010).

A recent comparison of soil carbon under different land use (Badgery et al. 2014) was undertaken for mixed farming and pasture cropping systems in the slopes region of central west NSW. The influences of management actions and pasture composition were assessed across pasture and cropping land uses and the analyses indicated that cropping systems had lower SOC stocks in the soil than pasture systems in each region, but pasture cropping was not different from perennial pasture. Further research was recommended to better understand the causality behind the differences in soil carbon levels across these management systems.

Native versus sown pastures - There are insufficient data available to confirm whether native pastures are able to sequester higher levels of SOC than sown pastures. However, many native pastures inherently have higher SOC than sown pastures, simply because they remain relatively undisturbed. Many improved pastures have still not regained the original SOC prior to clearing and disturbance (Eckard pers. comm. 2014). Improved pastures generally have greater ability to sequester soil carbon than unimproved native pastures, (which usually have low P levels) due to their higher productivity. If fertiliser is used to increase productivity and carbon sequestration in native pastures, the carbon sequestration benefit will only be maintained as long as fertiliser inputs are maintained (Chan et al. 2010). However, if increased plant production is matched by an increase in organic matter decomposition, there will not be a net increase in soil carbon stocks.



3.5 Carbon Farming and soil carbon links

The potential role of carbon markets and schemes which offer incentives for farmers to be paid for building soil carbon sequestration stores has been an active area of policy and carbon market development in recent years. The latest information will be available at the following websites.

The Emissions Reduction Fund and Australia's **Carbon Farming Initiative**

The Australian Government's Emissions Reduction Fund (ERF) incorporates the Carbon Farming Initiative (CFI) and aims to purchase lowest cost emissions reductions from across the economy. The ERF provides opportunities for farmers and land managers to participate in emissions reduction projects

www.daff.gov.au/climatechange/cfi

www.environment.gov.au/climate-change/ emissions-reduction-fund/carbon-farminginitiative-project-transition

A new ERF method was approved in late 2014 by the federal government; 'Sequestering carbon in soils in grazing systems' which applies to land managed using a range of activities to build soil carbon including, but not limited to:

- Converting cropland to permanent pasture
- Rejuvenating pastures, or
- Changing grazing patterns.

Longer term accurate soil carbon measurements will be required for projects seeking to demonstrate soil carbon sequestration under this methodology. Further details can be found at:

www.climatechange.gov.au/reducing-carbon/ carbon-farming-initiative/methodologies/ sequestering-carbon-soils-grazing-systems

A summary is provided in a fact sheet on soil carbon methodology:

www.climatechange.gov.au/sites/climatechange/ files/files/reducing-carbon/cfi/methodologies/ determinations/factsheet-soil-carbon.pdf

Over the past decade there have been a number of carbon trading pilots which have provided income opportunities for a number of farmers, and which also offer some insights for landowners when considering longer term contracts or obligations specific for carbon sequestration projects on their properties.

Some things to consider include:

Understanding longer term obligations, and what happens if carbon stores are released or if farmers wish to terminate their involvement at a later date.

- Income from sequestration will not continue indefinitely (there is a natural limit to how much carbon can be stored per hectare), so it should not be considered an ongoing revenue stream into the long term future. This may have intergenerational implications.
- Appreciating the costs required to take carbon from the paddock to the marketplace, which will involve costs for measurement, auditing, accounting and brokerage.
- Economies of scale and making sure the quantity of carbon is sufficient to cover all project costs.
- Longer term implications regarding flexibility for farmers to alter or change land use as might be required due to changing circumstances (changing market conditions or new technology opportunities). Assessing the implications of longer term contracts and possible future obligations for other parties such as banks, lessees or potential property buyers.
- Implications of fluctuations and changes to carbon prices and policies over the longer term.

Carbon markets and rules are still developing, and participants are advised to always seek independent expert advice for their own personal situation.

As new developments arise (research, technologies, policies) in the emerging carbon farming area it is important to stay in touch via the websites listed.

Further information on the many climate and carbon research, development and extension projects underway across Australia can be found at the following Federal Department of Agriculture links:

www.daff.gov.au/climatechange/ carbonfarmingfutures

Filling the Research Gap - a number of soil carbon research projects are currently underway across Australia. Find them at:

www.daff.gov.au/climatechange/ carbonfarmingfutures/ftrg

Action on the Ground – there are also many soil carbon related projects currently underway in collaboration with farming groups across most industries.

www.daff.gov.au/climatechange/ carbonfarmingfutures/action-on-the-ground

Extension and Outreach program - these sites have useful information for extension providers

www.daff.gov.au/climatechange/ carbonfarmingfutures/extensionandoutreach

www.extensionprovidersportal.org.au/

www.mycfi.com.au/

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