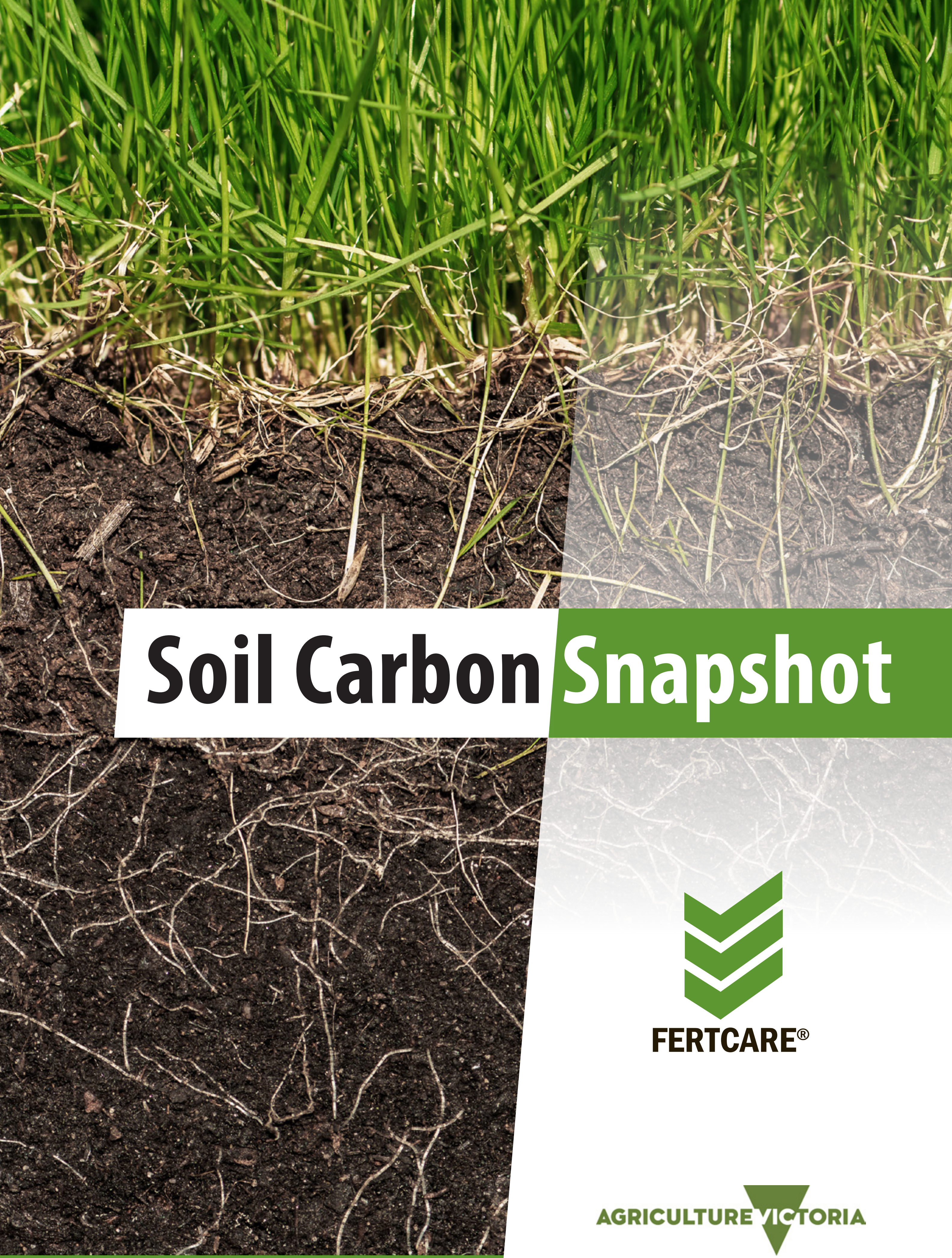

Soil Carbon Snapshot

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The abbreviations used in this document are:

C Carbon
CO_2 Carbon dioxide
GHG Greenhouse gas(es)
N_2O Nitrous oxide
SOC Soil organic carbon
SOM Soil Organic Matter

A soil carbon snapshot for advisors and farmers

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.

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Section 1 -
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 *GRDC Krull et al. (2006)* 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 more carbon than is found in the atmosphere and biomass combined, 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.

It is also important to consider that as global temperatures rise due to climate change, soil carbon stocks may also be at risk as soils warm and rainfall patterns change *Davidson et al. (2006)*; *Meyer et al. (2018)*, and *Roxburgh et al. (2020)*. 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 practices.

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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 and 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 to2.32% 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 (tCO_2/ha). Thus for every tonne of SOC increase, there will be 3.67 tonnes of CO_2 removed from the atmosphere, and vice versa, for every tonne of SOC lost there will be 3.67 tonnes of CO_2 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/cm^3).

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/cm^3).

For example, a scenario where 10cm soil sample SOC 1.2%, with a known soil bulk density of 1.5 g/cm^3:

→ 10,000 m^2 in one hectare
→ x 0.1m soil depth (10cm)
→ x 1.5 g/cm^3 bulk density
→ 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/cm^3 = 16tC/ha
- 2% SOC with soil bulk density 1.6 g/cm^3 = 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 soil 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 the DPI NSW Publication *'A farmer's guide to increasing soil organic carbon under pastures'*; and the GRDC Publication *'Managing Soil Organic Matter - a Practical Guide'.*

Soil carbon measurement procedures required for carbon accounting in carbon farming projects can be found in the Australian Government Clean Energy Regulator's methodology for soil sampling guidelines: *'Estimating soil organic carbon sequestration using measurement and models method'*.

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 *(Aust. Govt. Clean Energy Regulator 2021)*, 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 collected 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 is calcareous and has mineral carbonates, an acid pre-treatment is needed 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 correction to make it comparable to results from the dry combustion method described above.
- Mid-Infrared (MIR) spectroscopy is used by researchers but not yet readily available to farmers. 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 air-dried soil (g C/100g soil). Data on soil bulk density for the 0-30cm depth is used to convert these results to tC/ha.

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

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.

GRDC, Van Rees et al (2014) and *GRDC, Farrell et al (2021)* provide the following simple explanation of the key soil carbon fractions:

1. **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 CO_2 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).
3. **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.

Table 1: Functions of Soil Carbon Fractions

Soil Function	Particulate Organic Carbon (POC)	Humus Organic Carbon (HOC)	Resistant Organic Carbon (ROC)
Physical Properties			
Increased infiltration (better soil structure)	√√√ for sands and loams √ for clays	√ for all soil types	√
Tilth (improved structure, friability)	√√√ for sands and loams X for clays	√√ for sands and loams √ for clays	√
Lowering bulk density	√√ for sands and loams √ for clays	√ for all soil types	√
Increasing Plant Available Water	X	√ for all soil types	√
Chemical properties			
Improved Cation Exchange Capacity	X	√√√ for sands and loams X for clays	√ for sands and loams
Buffer against acidification (binds to Fe and Al)	X	√√√ for sands and loams X for clays	√
Biological properties			
Food source for micro-organisms	√√√ for all soil types	√√√ for all soil types	√ f or all soil types
Release of nitrate and ammonium	√ for all soil types	√√√ for all soil types	√ for all soil types

Functions of Particulate (POC), Humus (HOC) and Resistant (ROC) organic carbon where:
√√√ =very important, √√ =moderately important, √ =minor importance, X = not important.

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

1.10 Soil organic matter and implications for soil fertility

Soil organic matter 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 organic matter 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 *'Managing Soil Organic Matter - a Practical Guide' (2013)* suggests that as a general rule, for every tonne of carbon in soil organic matter about 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 matter 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 ratio (> 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 lower 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

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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.

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 2013).

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. The GRDC publication ***'Managing Soil Organic Matter – a practical guide' (GRDC 2013)*** is a useful resource for further information.

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) 'Stable soil organic matter: A comparison of C:N:P:S ratios in Australia' 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. ***Kirkby 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.

The GRDC Updates ***Grace et al 'Where does nitrogen fertiliser finish up?' (2015)*** and ***Farrell et al 'Addressing the Rundown of Nitrogen and Soil Organic Carbon' (2021)*** also provide insights into the relationship between crop nitrogen requirements and the role played by soil organic carbon.

The processes which affect soil carbon stores have several key drivers. The next section explains how much soil carbon can exist, and provides insights into the types of practices which can affect soil carbon reserves.

Section 2 -
Changing Soil Carbon

2.1 How much carbon is in Australian soils?

The CSIRO's ***Australian Soil Carbon Mapping Project (Rossel et al 2014)*** 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 ***Rossell et al (2014)***. 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 et al (2016)***.

The ***Australian Government State of the Environment Report (Metcalf et al 2016)*** also provides an overview of the national soil carbon stock, trends and key reference sources on land management drivers that can influence soil carbon.

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

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.

The ***SCaRP soil carbon dataset*** and the ***information on the soil carbon testing method*** that was applied in the collection of SCaRP data is publicly available, enabling advisors to explore the carbon levels (& carbon fractions) for soils across Australian agricultural regions.

In 2015 the Australian Government then funded the ***Filling the Research Gap - National Soil Carbon Program (QDSITI 2015)*** which further investigated soil carbon relationships relating to aspects such as changed land management and soil amendments. Summary report and case studies from this research are available at the ***Queensland Government publications portal***.

These investigations include measurements from longer term research sites where management history is known, thus changes to soil carbon are discussed.

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 (CO_2) 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 CO_2. Capture can occur at the point of emission (e.g. fossil fuel combustion) or through natural processes (such as photosynthesis), which remove CO_2 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.

Soil carbon sequestration potential: A review for Australian agriculture by Sanderman et al. (2010) is a useful 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. ***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.

A Review of Carbon Sequestration in Vegetation and Soils: options, opportunities and barriers by Hamilton (2014) also offers useful insights into the evidence base for carbon sequestration for a range of land management practices.

2.4 What influences soil carbon increases or losses?

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.

The ***National Soil Carbon Program (QDSITI 2015)*** research suggests 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 led 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.


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Further important insights into soil carbon gains and losses were identified in a sixteen year study by ***Badgery et al. (2020)*** which showed unexpected increases in soil carbon in the first twelve years then fell and were reduced back to starting SOC levels in the following three years, demonstrating that monitoring temporal changes in SOC over twelve years did not indicate long-term sequestration.

The technical review by ***CSIRO, Roxburg et al. (2020)*** detailed a range of physical risks to carbon sequestration in Australia. The dominant risks to sequestration for the management of agricultural soil activity, for both risks to accumulation and maintenance, were associated with climate change impacts on the rates of organic matter input to soil, and the rates of loss through changes to soil respiration and the microbial biota.

Across the Australian 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 CO_2. Changes in soil management that reduce input rates or increase loss rates may mean that the carbon soil store changes ***Badgery et al. (2020)***, ***Roxburgh et al. (2020)***, ***Meyer et al. (2018)***.

Processes that accelerate decomposition or erosion will, in turn, accelerate the rate of soil carbon loss ***Sanderman et al. (2010)***. 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 waste)
- 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) and the *National Soil Carbon Program (QDSITI 2015)* 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 *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. (2008)*; *Sanderman et al. (2010)*; *Meyer et al (2015)*, most of these studies have also noted that management strategies aimed at increasing soil carbon may also lead to some 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 *Sanderman et al. (2010)*.

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 also taken into account *Meyer et al (2016)*.

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

Various Australian studies have noted that climate and soil type are the dominant drivers of soil carbon and land management practices often play a minor role *Sanderman et al. (2010)*.

A summary of the key research into changes to land management and effects on soil sequestration are in tables 3, 4 and 5. The implications of land management practices and soil carbon are then discussed in the sections that follow.

2.9 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 the task of maintaining or improving soil carbon levels even more challenging over coming decades.


JOHN DEERE

Section 3 - Management changes and effect on soil carbon

3.1 Key findings of recent soil carbon review in Australia

Sanderman et al. (2010) produced a review for Australian agriculture on soil carbon sequestration potential. Key findings of the review:

- Climate and physiochemical characteristics of a particular soil exert such overriding controls on overall SOC dynamics
- There was no strong or consistent evidence indicating that management practices, including no-till, 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.

Reports of the Soil carbon research programs are available at *The Soil Carbon Research Program (SCaRP)* and *Robertson et al. (2016)*. A review of carbon sequestration was also undertaken by *Hamilton (2014)* and CSIRO *Sanderson et al. (2010)*.

The importance of long term research trials was further detailed by *Badgery et al. (2020)* in 'Unexpected increases in soil carbon eventually fell in low rainfall farming systems' where a 16 year study investigated temporal changes in total SOC, total nitrogen (N), and carbon (C) fractions for four farming systems in a low rainfall region at Condobolin, NSW. The farming systems were conventional tillage mixed farming; reduced tillage mixed farming; continuous cropping; and perennial pasture. There was an increase in SOC for all farming systems over the first 12 years (total organic C to 10 cm increased from 1.3% to 1.8%), which was predominately in the particulate fraction. However, between 2012 and 2015, there was a decrease in SOC back to starting levels (total organic C to 10 cm decreased to 1.2%) in all systems. The perennial pasture system had higher SOC stocks to 30 cm depth at the final measurement in 2015 (perennial pasture had 30.4 t C ha compared to cropping systems 23.71 t C ha). There was a decrease in total nitrogen over time in all farming systems except perennial pastures. The average C:N ratio increased from 14.1 in 1999 to 19.7 in 2012, after which time the SOC levels decreased and the C:N ratio dropped back to 15.8. *Badgery et al. (2020)* then concluded that monitoring temporal changes in SOC over 12 years did not indicate long-term sequestration, such as that required to assure "permanence" in carbon trading schemes (25–100 years) due to the susceptibility of particulate organic carbon to degradation.

Table 3: Land Management practice options and evidence

Practice option	Research Evidence & Confidence	Benefits for carbon sequestration	Negative impacts / risk
Stubble retention (compared with stubble burning or removal)	Most studies show limited to no effect on Soil C but good evidence in a few situations	Greater C return to the soil is likely to reduce C losses and may increase SOC stocks. Reducing C losses can result by reducing exposure to erosion	Any increases are small and emerge over long-term (10+ years). Many situations where C increase measured in top 5-10 cm, but this can be negated by a decrease in C at greater depth
Elimination or reduction of the length of time of bare fallow phases in crop rotations (can include using cover crops).	Reducing fallows - Very strong evidence for reducing carbon loss. Cover crops mitigate losses in some situations.	Added potential to reduce C losses through reduced erosion. Carbon losses continue during fallow without any new carbon inputs, and cover crops can mitigate this	None documented
Minimum tillage and direct drilling (compared with multiple-pass conventional cultivation)	Most studies show limited effect though some evidence in a few situations.	Reduces erosion and destruction of soil structure thus slowing decomposition rates of C. Can maintain or prevent decline of soil C	Reduced tillage has shown little SOC benefit. Any increases are small and emerge over long-term (10+ years). Surface residues decompose with only minor contribution to SOC pool. Some situations where C increase measured in top 5-10 cm, but this can be negated by a decrease in deeper soil.
Increasing productivity through fertiliser application (compared with zero fertiliser or other nutrient applications)	Good evidence in some situations but not in others. Key is to have balanced inputs (due to stoichiometry)	Good evidence where starting soil nutrient levels are deficient. Evidence re: N and P, but likely to hold for other nutrients too	Adding more N fertiliser leads to increased root growth leading to more SOC, however potential trade-off between increased soil C and increased decomposition rates. However, excess N inputs would lead to more N_2O emissions. Evidence that applying fertiliser, in excess of plant requirements, has either no effect or a negative effect on soil C. Likely to depend on original nutrient status. Increasing N use needs to be balanced against GHG emissions associated with manufacture and use of fertilizer
Increasing productivity through irrigation	Yield and efficiency increases do not necessarily translate to increased C return to soil. Good evidence in some situations but not in others.	Increased biomass production can increase C inputs but this is often balanced against increased C decomposition.	Potential trade-off between increased C return to soil and increased decomposition rates.
Grazing management	Strong evidence that over-grazing reduces soil C via erosion losses. Evidence for other grazing practices (stocking intensity, duration, rotational / set stocking etc.) is equivocal or non- existent.	Strong evidence that over-grazing reduces soil C via erosion losses.	Long term non-replicated trials at Hamilton (VIC), show no change in SOC for two plus decades under a range of grazing management systems. Any soil C change as a result of change in grazing pressure takes many years to be detectable.
Conventional to organic farming system	Insufficient data available	Further research required.	Variable outcomes depending on the specific organic system (ie.manuring, composts, cover crops). Increased cultivation can reduce soil C. Compost use may only be C transfer and not actual C sequestration.
Restoration of degraded land	Good evidence	Greater plant and groundcover will increase C return to soil.	Low soil C starting conditions can be improved over time but can also be undermined if degrading processes return (eg livestock removal replaced by increased feral grazing etc)

For further information and additional useful References, refer to Bibliography (4, 9-12, 14-19, 21, 22, 28, 30, 33, 35, 37, 39- 41, 46, 49-52, 56-59, 63-65, 67, 70, 64, 65, 67, 69, 72)

3.2 Land Management practice options and evidence (Table 3)

Management practices such as stubble retention, minimum cultivation, perennial pasture species, rotational grazing and fertiliser inputs were not significantly related to SOC stock *Robertson et al. (2016)*. In the Victorian Northern Wimmera region, SCaRP Project No. 12, longer term field trial results showed that management practices such as cultivation, stubble retention, and rotations in cropping systems had small or no effects on soil organic carbon stocks.

Studies in Victoria indicate that there is limited or no effect of grazing management (grazing management, pasture improvement, pasture, cropping, grazed woodlands) on total soil carbon *Robertson et al. (2016)*.

Badgery et al. (2013) reports four land uses were contracted in a NSW pilot: (1) reduced tillage cropping; (2) reduced tillage cropping with organic amendments (e.g. biosolids or compost); (3) conversion from cropping land to permanent pasture; and (4) conversion from cropping land to permanent pasture with organic amendments.

Sixty percent of sites show a significant increase, pasture had a higher rate of SOC sequestration than reduced tillage cropping (1.2 vs 0.28 Mg C ha^{-1} year^{-1}, 0–0.3 m); and organic amendments had higher rates of SOC sequestration than without (1.14 vs 0.78 Mg C ha^{-1} year^{-1}, 0–0.3 m).

The results of the pilot demonstrated increases in SOC, using quantification methods consistent with the current Measurement Method of the Australian Government's Emissions Reduction Fund policy used to generate Australian Carbon Credit Units.

The results require careful interpretation as rates of sequestration are likely to be lower in the longer term than initial rates of change seen in this pilot (five years), and the pilot intentionally selected sites with initially low SOC, which ensured a greater opportunity to sequester SOC.

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.

Long term trials of 12-, 28-, and 94 year old treatments at sites in the Wimmera and Mallee regions were compared by *Robertson et al. (2015)* for changes to SOC stocks (30cm) under various tillage, residue management and rotation treatments. They found that: 'zero tillage and stubble retention increased SOC in some circumstances (by up to 8%) but not in others; inclusion of bare fallow in rotations reduced SOC (by 8–12%) compared with continuous cropping; including a pulse crop (field pea, where the grain was harvested) in rotations also increased SOC in some instances (by 29–35%) but not in others; leguminous pasture (medic or lucerne) phases in rotations either increased SOC (by 21%) or had no significant effect compared with continuous wheat; and inclusion of a vetch green manure or unfertilised oat pasture in the rotation did not significantly increase SOC compared with continuous wheat.'

Robertson et al. (2015) concluded that 'the management practices examined in the present study may not reliably increase SOC on their own, but that significant increases in SOC are possible under some circumstances through the long-term use of multiple practices, such as stubble retention plus zero tillage plus legume N input plus elimination of fallow. The circumstances under which increases in SOC can be achieved require further investigation.'

Stubble retention (compared with stubble burning or removal)

Stubble retention can potentially reduce the extent of carbon losses by reducing the physical loss of topsoil 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 CO_2, 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 two-thirds 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)*.

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'

Elimination or reduction of the length of time of bare fallow phases in crop rotations (can include using 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.

Minimum tillage and direct drilling (compared with multiple pass conventional cultivation)

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 (2009)*.

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 N_2O emissions may negate any increase in stored carbon *Powlson et al. (2011)*.

Increasing productivity through fertiliser application (compared with zero fertiliser or other nutrient applications)

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). *Chan et al. (2010)* showed increased phosphorus application improved SOC, similarly nitrogen application and is likely to hold for other nutrients too.

A study comparing 5 management practices included: native v. introduced perennial, perennial v. annual, continuous v. rotational grazing, pasture cropping v. control, and improved v. unimproved pastures was undertaken by *Chan et al. (2010)*.

Results indicated a wide range of soil organic carbon (SOC) stocks over 0–0.30 m (22.4–66.3 t C/ha), with little difference when calculated based on either constant soil depth or constant soil mass. Significantly higher SOC stocks were found only as a result of pasture improvement using P application compared with unimproved pastures. Lack of significant differences in SOC stocks for the other pastures and pasture management practice comparisons.

Finn et al. (2015) investigated decomposition of three plant species in four varying pasture soils. The respiration of organic carbon in response to nitrogen addition was monitored. Nitrogen addition increased the loss of carbon from some soils but not others.The soil carbon to nitrogen ratio determined how decomposition responds to nitrogen.

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 and potential for increased N_2O emissions. 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)*; *Cowie (2010)*.

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 N_2O emissions, thus again this area requires more research and a thorough understanding of the wider life-cycle effects.

Increasing productivity through 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.

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 (2009)*.

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.

Conventional to organic farming system

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 life- cycles for specific farming systems, whether they be conventional or organic farming. A recent *meta analysis* suggested that organic farming does not increase soil organic carbon compared to conventional farming if there is no carbon transfer from other agroecosystems.

Restoration of degraded land

Consider de-stocking low productive land for revegetation to reduce impacts of soil erosion, improve biodiversity and potential opportunity for SOC sequestration.

3.3 Crop and pasture based practice options and evidence (Table 4)

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 starting SOC, with high potential, then the net effect of the conversion on GHG emissions may be positive initially, but after a few decades would likely reach a new equilibrium. 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.

An analysis by *Rabbi et al. (2015)* looked at data from 1482 sites surveyed across agricultural regions of Eastern Australia to determine the relative importance of land use versus other drivers of SOC. They found that variation in land use explained only 1.4% of the total variation in SOC, with climate and soil texture the main regulators. Their results suggested 'the greatest potential for increasing SOC stocks was via converting land use from cropping to pasture on heavy textured soils in the humid regions'.

Badgery et al. (2013) surveyed 354 sites across NSW to determine soil organic carbon stocks. The influences of climate, soil physical and chemical properties, landscape position, and 10 years of land management information were assessed. They observed that environmental variables described most of the regional variation compared with land management. The strongest influence on SOC stock at 0–10 cm was from climatic variables, particularly 30-year average annual rainfall. Of the difference in SOC stock explained by land use, permanent pasture and pasture in rotation had higher soil carbon levels than cropping land use.

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 (CH_4) and nitrous oxide (N_2O) emissions. Consequently, a thorough understanding of greenhouse gas lifecycles is required to ascertain the overall implications of changed land use for climate change mitigation. *Meyer et al. (2016)* assessed the influence of soil carbon on net greenhouse gas emissions from sheep grazed pasture systems and found 'Because of greater pasture productivity, and consequent higher sheep stocking rates, high-rainfall sites were associated with greater GHG emissions that could not be offset by C sequestration.' However, they also found that on low-rainfall sites, C sequestration in low-C soils could more than offset livestock GHG emissions, whereas if the starting SOC contained high-C soils then C sequestration would only offset 75–86% of the CH_4 and N_2O emissions related to livestock.

Inclusion of pasture phases in rotation with crops (compared to continuous cropping with no pasture phases)

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)*.

Conyers et al. (2015) evaluated the ability of crop residues to contribute to SOC sequestration in southern NSW and state that 'Rates of change in SOC under agriculture were generally slow; crop residue retention did not contribute to increases in SOC; a warming drying climate will further limit the accumulation rate and stock of SOC.' They also noted that the retention of C in soil organic matter runs counter to its traditional use as a source of N after a pasture phase, and also that potential soil acidity and the need to apply limestone might dampen the environmental benefit of SOC accumulation in organic matter.

In mixed cropping/pasture systems, SOC levels generally decline under cropping phases and increase during the pasture phases.

To quantify the soil carbon stocks under different pastures and a range of pasture management practices, *Chan et al. (2010)* undertook a field survey of soil carbon stocks in central and southern NSW as

Table 4: Crop and pasture based practice options and evidence

Practice option	Research evidence	Benefits for carbon sequestration	Negative impacts / risk
Conversion of cropping to permanent pasture	Very strong evidence in most situations	Long lived Pasture systems generally return more C to soils than annual crops. Current research suggests that where there is low SOC (with high potential for SOC improvement), then the net effect of the conversion on GHG emissions may be positive initially, but after about 20 years it would reach equilibrium. Increased soil C gain is greater where cropping was long-term or starting levels are low.	The added emissions (CH_4 & N_2O) from ruminant livestock grazing pastures needs to be considered, and may neutralise or detract from any soil carbon benefit. Benefit will likely depend greatly upon the specifics of the switch. Switch from cropping to pasture, without any decrease in market demands for crops, will lead to other land being put into cropping, merely transferring SOC losses to another farm.
Inclusion of pasture phases in rotation with crops (compared to continuous cropping with no pasture phases)	Good evidence in many situations, but not in all. Depends on the system.	Pastures generally return more C to the soil than annual crops, but also depends on dry matter inputs from the pasture. Legume based pasture phase can be effective where N is limiting.	Potential of increased CH_4 and N_2O from livestock production systems need to be accounted for from conversion of cropping to grazing land. A non-legume pasture phase may increase need for N fertiliser which could result in additional emissions.
Inclusion of pulses (leguminous crops) with cereal & oilseed cropping rotations (compared with continuous cropping without leguminous crops).	Evidence but only in very few situations	Potentially effective where N is deficient.	Most studies show limited effect on SOC.
Shift from annual to perennial pasture species.	Evidence equivocal, little data available.	Perennial plants can utilise water throughout the whole year, with increased below ground allocation but few studies to date. Current research suggests that where there is low SOC (with high potential for SOC improvement), then the net effect may be positive initially, but after a few decades it would reach equilibrium.	Few studies to date.
Native grassland pasture systems versus introduced (sown) pastures	Insufficient data available.	Native pastures usually (but not always) have higher SOC than introduced pastures, simply because they remain relatively undisturbed. Improved pastures have may not have regained the original SOC prior to clearing and disturbance. It is possible that some introduced pasture sites can show improved SOC via improved nutrition.	The potential to increase SOC of undisturbed native pastures may be limited as it has likely reached equilibrium.

For further information and additional useful references, refer to Bibliography (2, 4, 9-12, 14-22, 28, 30, 34, 35 37, 40, 41, 46-48, 50-52, 57-59, 62-65, 67,68, 71.

well as north-eastern Victoria. Comparisons included: native versus introduced perennial; perennial versus annual; continuous versus rotational grazing; pasture cropping versus control; and improved versus unimproved pastures. Results indicated a wide range of soil organic carbon (SOC) stocks over 0–30cm (22–66 t C/ha. Significantly higher SOC stocks were found only as a result of pasture improvement using P (phosphorus) application compared with unimproved pastures. In this case, rates of sequestration were estimated to range between 0.26 and 0.72 t C/ha/year, with a mean rate of 0.41 t C/ha/year. *Chan et al. (2010)* also noted a lack of significant differences in SOC stocks for the other pastures and pasture management practice comparisons could be due to a range of issues and concluded 'there is a need for scientific long-term trials to quantify the SOC sequestration potential of these other pastures and pasture management practices.'

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'. Crop-pasture rotations with stubble retention generally accumulated carbon, whereas continuous cropping with stubble retention resulted in loss or accumulation, however in either case it would generally take 10–25 years for the soil carbon changes to become measurable using conventional soil sampling and analytical methods.

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 (2009)*.

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 N_2O emissions and increased CH_4 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 *Cowie (2010a)*; *Meyer et al. (2016)*.

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, as yet there is little scientific data available to support these claims *Chan et al. (2010)*.

A 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 than pasture systems in each region. They noted that pasture cropping was not different from perennial pasture, however further research was recommended to better understand the causality behind the differences in soil carbon levels across these management systems.

Inclusion of pulses (leguminous crops) with cereal & oilseed cropping rotations (compared with continuous cropping without 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. *Farrell et al. (2022)* explains the important role of nitrogen in supporting soil organic matter development and the potential benefits from nitrogen fixing crops to achieve this.

Robertson et al. (2015) analysis of long term trial sites for changes to SOC stocks (30cm) under various tillage, residue and rotation treatments found including a pulse crop in rotations had increased SOC in some instances (by 29–35%) but not in others, The study found that leguminous pasture (medic or lucerne) phases in rotations either increased SOC (by 21%) or had no significant effect compared with continuous wheat. They also found that the inclusion of a vetch green manure in the rotation did not significantly increase SOC compared with continuous wheat.

Further analyses by *Grace et al. (1995)* on a long term (commenced 1925) rotation trial at Waite in South Australia showed that for the 11 rotations, soil organic carbon (SOC) in the top 10 cm declined from 2.75% in 1925 to a mean value of 1.56% in 1993. One plot, which had reverted to permanent pasture in 1950, showed the smallest decline with an SOC content of 2.46% in 1993.

Shift from Annual to Perennial Pasture species

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 whole 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)*.

It is likely that where there is low SOC, with high potential for gains, then the net effect of converting to perennial pastures may be positive in some situations, however any increases may only last for a number of decades until a new equilibrium is reached.

Results from National Soil Carbon Research 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. *Thomas et al. (2012)* also assessed benefits of shifting an annual system to perennial kikuyu pastures in Western Australia and indicated improvements to soil carbon.

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.

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 mixed and more research is required.

Native grassland pasture systems versus introduced (sown) pastures

There are insufficient data available to confirm whether native pastures are able to sequester higher levels of SOC than introduced and sown pastures. However, many native pastures may inherently have higher SOC than sown pastures simply because they remain relatively undisturbed. It is possible in many situations that improved pastures may not have regained the original SOC prior to clearing and disturbance.

In comparisons between native versus introduced perennial and annual pasture systems, *Chan et al. (2010)* found that 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 the higher nutritional 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.

3.4 Soil amelioration practice options and evidence (Table 5)

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 additional SOC storage capacity is limited to the subsoil below 0.1m ***Hoyle et al. (2013)***. 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'.

Surface and sub-surface soil constraints reduce crop productivity across cropping regions of Australia. Long term trials throughout south eastern Australia indicate plant and animal based manures provide improved grain yields ***GRDC (2021b)***. Responses to amelioration is strongly influenced by water availability and the impact of organic materials appear to be soil type specific. This may offer potential to increase soil carbon at depth by encouraging deeper root development and biomass. Future analysis of current ***GRDC (2021c)*** project may provide a better, understanding of the overall implications for soil carbon levels and the effects on other GHG lifecycles associated with practices such as this, as well as the longer term fate of subsoil carbon stores.

Topsoil application of imported organic material (compost, manure etc)

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 regard 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'.

Farrell et al. (2017) assessed a range of parameters found across 60 soil amendments, testing 38 of these in field experiments conducted at eight sites across the country and offers useful insights and recommendations for farmers when considering use of soil amendments.

Stabilised C in 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. While biochar can enrich soils and act as a stable carbon sink for possibly hundreds of years, ***Sohi et al. (2009)*** reviewed the available published and peer-reviewed literature on biochar which looked at biochar types, safety, agronomic and greenhouse benefits and further research questions.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 Biochar Industry Group (ANZBIG)***.

Table 5: Soil amelioration practice options and evidence

Practice option	Research evidence	Benefits for carbon sequestration	Negative impacts / risks
Sub-soil amelioration of imported organic material (composts, manures etc)	Evidence in some situations.	Depends on amount and type of material applied. Likely that the practice has the potential to increase soil carbon at depth.	The increased soil C may not constitute actual C sequestration, but might only be C transfer, depending upon the alternative fate of the organic material being used or brought in. Requires C lifecycle analysis.
Top-soil application of imported organic material (compost, manure etc)	Evidence in some situations.	Depends on amount and type of material applied.	The increased soil C may not constitute actual C sequestration, but might only be C transfer, depending upon the alternative fate of the organic material being used or brought in. Requires C lifecycle analysis.
Stabilised C in Biochar application to soil	Evidence in some situations. Can vary depending on biochar source, characteristics and the C life cycle. Point of 'sequestration' is at the biochar pyrolysis plant.	C in plant material is converted to a highly stable form of C as biochar, however the point of 'sequestration' is at the biochar plant (pyrolysis). Benefits of adding biochar to soils will vary depending on biochar source, type and soil limiting factors	Validation of GHG mitigation benefits of biochar, requires a full life-cycle assessment across the whole system – ie. biomass source and procurement, biochar production system, and its application. Evidence for reduced N_2O 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. Point of 'sequestration' is at the biochar pyrolyser. Land application is technically carbon transfer and not actual sequestration.
Other soil intervention strategies (eg clay spreading, delving, ripping)	Insufficient data available.	While can improve site biomass and productivity, soil carbon benefits less clear.	Variable outcomes depending on the specifics of the intervention. In situations where site production is increased, it may only lead to increased soil C turnover.

For further information and additional useful references, refer to Bibliography (1, 4, 12, 13, 15, 16, 21, 22, 25, 30, 37, 42-46, 53, 58, 59, 67, 69)

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 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 NSW DPI trial indicated that some of the biochars tested were effective in reducing emissions of N_2O from soil *(ANZBIG website)*. However, evidence for reduced N_2O 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.

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. *Sohi et al. (2009)*. state that "It is generally accepted that biochar is a highly stable form of carbon and as such has the potential to form an effective C sink, therefore sequestering atmospheric carbon dioxide." 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 *Sohi et al. (2009)*. 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-CO_2 GHG emissions' ***Gurwick et al. (2013)***.

Regarding gaining carbon credits for biochar, it is important to remember that any credit will be applied at the point of manufacture at the pyrolysis plant. That means spreading biochar onto soils would not constitute additional carbon sequestration unless there were additional agronomic responses to soil carbon reserves beyond that of the added biochar. However, if farm businesses converted their own excess biomass or waste residues via pyrolysis on site, then the overall process of biochar creation (converting short term biomass carbon into a longer term biochar for carbon credits) could be captured on farm if it was economic to do so.

Other soil intervention strategies (clay spreading, delving, ripping etc)

Research has shown the value of applying clay-rich subsoil (claying) to ameliorate water repellent soils, improve nutrient retention and increase crop yields. There is some evidence of very small improvements in organic carbon as a longer term effect of claying ***Hall et al. (2010)*** in Western Australia.

Strategic deep tillage (ripping, spading, inversion ploughing) and profile amelioration approaches to overcome a range of soil constraints (with and without amendments) has shown variable outcomes in the southern region ***MacDonald et al. (2019)***. Further work is required to better understand the longer term implication for overall soil carbon levels.

3.5 Carbon Farming and soil carbon

As carbon markets emerge there are schemes which can offer to pay farmers for building new soil carbon sequestration stores on their farms. As the market expands it is first worth farmers considering their long-term goals for their property and which options will suit their situation best.

Farm businesses may have a variety of options with regards to how they may choose to utilize any carbon or emissions gains that occur on their farms, including:

- Using to balance against their own farm emissions
- Selling carbon to other entities via carbon markets
- Using towards certification programs for low emissions or carbon neutral produce (eg low emissions milk, meat or grain).

Farmer participation in carbon markets projects is voluntary. It is always best to seek advice, as carbon sequestration is a new type of product that in many ways is different to the traditional income sources farmers receive when selling food and fibre.

This section provides some links to programs and information on the emerging carbon market and policies in Australia.

The Emissions Reduction Fund

The ***Australian Government's Emissions Reduction Fund (ERF)*** is a scheme that aims to provide incentives for a range of organisations and individuals to adopt new practices and technologies to reduce their emissions.

The ERF provides opportunities for farmers and land managers to participate in emissions reduction projects via a range of "approved methodologies". Administered by the ***Australian Government's Clean Energy Regulator*** there are a number of methodologies for carbon project development for the ***land, agriculture and vegetation management*** sectors, including for soil carbon.

Over the past decade there have been a range 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.

Eckard et al. (2022) provides further insights into the practicalities of attempting to increase soil carbon along with some longer-term risks to be considered by farmers.

Some further useful *'Questions to ask before a farmer sells their carbon'* are outlined by Agriculture Victoria which suggests considering:

- Understanding longer term obligations, and what happens if carbon stores are released (drought or bushfires) 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 for the long-term. This may have intergenerational implications for farms
- 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 development and management 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 long-term contracts and the possible future obligations for other parties such as banks, lessees or potential future property buyers
- Implications of fluctuations and changes to carbon prices and policies over the longer term. 'Sequestration' means stored for safekeeping, so when a farm creates a new tonne of stored carbon, they may get paid but will then be required to maintain and keep it there for 25-100 years depending on the contract.

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 with the latest information.

The *Australian Government Department of Agriculture Water and the Environment (DAWE)* provides further information on the carbon and emissions initiatives that have been developed across Australia.

This includes the *National Soil Strategy* which sets out how Australia will value, manage and improve its soil for the next 20 years.

The *National Soil Strategy* prioritises soil health, empowers soil innovation and stewardship, and strengthens soil knowledge and capability. These priorities have been identified through research and practical examples, government policies and programs, and by consulting with governments, industry, researchers, farmers and other land managers across Australia.

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