Soil Carbon Sequestration under Pasture in Australian Dairy Regions – 2018 Update

Prepared for Dairy Australia

Dr Beverley Henry (2018)

Dr David McKenzie (2010)

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Dr David McKenzie is a soil science consultant with over 30 years' experience in providing advice on soil management and amelioration to the Australian agriculture sector. Examples include provision of over 100 soil assessment and management reports for the winegrape, citrus, tree crop, cotton, wheat and dairy industries; carbon sequestration studies under 'Oldman saltbush' for Deutsche Bank; and over 60 soil management courses for farmers and advisors.

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Contents

Foreword

This document is an update of the report of the same name commissioned by Dairy Australia in 2010 and prepared by Dr David McKenzie. The 2010 review of technical literature and associated information about carbon sequestration relevant to dairy farms in southern Australia presented the state of knowledge at that time. This report summarises the advances that have been made over the past 8 years in the science of soil and agricultural management and in areas of climate change policy for carbon offsets. The considerable progress reflects global interest and investment, and Australia has been at the forefront of research and development of methods for quantifying soil carbon sequestration with funding support provided by the Australian government, state governments, academic institutions and industry organisations, including Dairy Australia.

The report focusses on providing a balanced analysis of the potential for soil carbon sequestration for climate change mitigation in the context of productive and profitable agricultural businesses, particularly targeting dairy farming in southern Australia. The science and policy settings are complex but the objective is to provide a resource for farmers and their advisers that presents a clear overview of current knowledge (in 2018), and the areas where there is still debate and lack of consensus. The report also discusses the risks and possible opportunities for farmers considering engaging in carbon markets to obtain income from soil carbon credits.

The following issues are addressed:

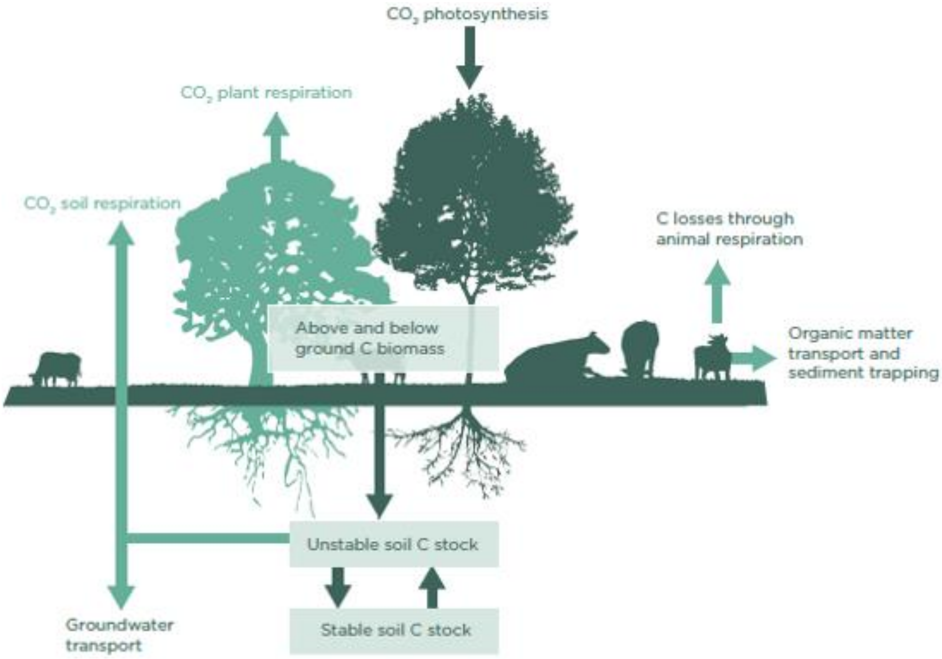
- The basic facts about soil carbon and its relation to soil health and pasture productivity;
- The role of soil carbon in the global carbon cycle and in climate change mitigation;
- Debate on the potential size of soil carbon offsets globally and at farm-scale;
- Recent scientific research to understand processes and quantification of soil carbon for productivity in agriculture and for climate change mitigation;
- Current understanding of how climate change will affect soil carbon stocks and sequestration potential;
- The challenges relating to permanency and measurement;
- Relationship between soil carbon, soil nitrogen and nitrous oxide emissions;
- Policy and Program settings for soil carbon sequestration, internationally and in Australia;
- Methods for crediting and reporting soil carbon in Australia and some economic considerations for soil carbon credit projects;
- Useful resources and links for credible information; and
- Specific issues relevant to soil carbon sequestration and soil carbon projects in dairy pasture.

Plain English Overview

- Soils are a large store of carbon, globally having about three times as much carbon as all the world's vegetation. Soils vary in how much carbon they contain and in their potential to store additional carbon.
- As plants grow they take carbon dioxide out of the atmosphere and store carbon in their biomass aboveground (shoots and leaves) and belowground (roots) – see illustration below. Much of this carbon cycles back to the atmosphere as carbon dioxide within a short time as plants respire or as parts of the plant die and decompose.
- When organic matter enters the soil (e.g. from roots, litter or organisms living in the soil), most carbon is re-released in a short period (weeks or months) due to microbial action. It is this labile carbon that helps to drive nutrient cycling, improve soil structure and water holding capacity, and gives better crop and pasture production on agricultural land.
- Only when carbon in soils is converted into stable forms and is protected from decomposition by microbes is there an increase in long-term carbon storage, known as soil carbon sequestration.
- The balance between additions of carbon in biomass and losses through decomposition and microbial breakdown determines whether there is a net increase or decrease in soil carbon storage. Climate, vegetation, soil and microbial factors influence this balance and determine the steady state level of soil carbon in undisturbed soils. In agricultural soils, this level is modified by management factors.
- Nutrients are essential for plant growth and a management practice common on dairy farms is adding nitrogen to improve growth of pastures. Addition may be through chemical fertilisers (e.g. urea), organic amendments (e.g. manure and compost) or via bacterial fixation of atmospheric nitrogen associated with the roots of legumes such as clover. The higher productivity can increase biomass inputs to the soil and tip the soil carbon balance towards net carbon storage. However, when the amount of nitrogen in soils exceeds the amount growing plants can take up, some is lost again through leaching or in gaseous forms, including nitrous oxide, a greenhouse gas with almost 300 times the global warming potential of carbon dioxide.
- The climate change benefit of soil carbon sequestration is equal to the net effect of the carbon dioxide removed from the atmosphere less the carbon dioxide-equivalent amount of any greenhouse gas emissions that are associated with the sequestration. If the amount of 'global warming' calculated for nitrous oxide emissions in a fertiliser project outweighs the effect of extra stored soil carbon, there is no net climate change mitigation and no soil carbon credits.
- Well-managed dairy pastures often have relatively high soil carbon levels. If the soil is close to the steady-state carbon content possible for the soil type and climate, the capacity to store more carbon will be small and the potential for the dairy farmer to gain carbon credits is limited.
- Soils rich in organic carbon generally have better texture, water retention and ultimately higher crop or pasture productivity. Soil carbon sequestration can, therefore, improve soil health, contribute to combating the risk of erosion and build resilience to the impacts of climate variability, climate change and extreme events such as drought and floods. On a dairy farm, these environmental and

economic benefits of carbon sequestration add to (and may exceed) possible income from carbon offsets.

- Accounting for the greenhouse gas mitigation from soil carbon sequestration at a farm scale is often constrained by natural biophysical factors and may be limited according to rules designed to ensure that offsets are 'genuine':
  - Time limitation: Under changed land management, soils move over time to a new steady state where inputs and outputs of carbon return to balance as determined by climate, soil and vegetation factors.
  - Spatial integrity: Where adding organic matter such as compost or biochar to pastures (e.g. to a dairy paddock or farm) involves removing organic matter from another area where it would otherwise have naturally decomposed and entered soil stores, the direct benefit from the carbon added to that area does not equate to overall climate change mitigation – it simply shifts it. There may, however, also be indirect soil carbon gains due to higher growth from structural or chemical improvements which can be credited. Accounting for these net benefits should avoid 'leakage' i.e. a gain in one location matched by 'loss' elsewhere.
  - Permanency: Gains in stored soil carbon are reversible and can be lost through natural or management factors that change the balance between inputs and loss. In general, loss of soil organic carbon occurs more rapidly than sequestration. For carbon market schemes such as Australia's Emissions Reduction Fund, legislated methods for carbon sequestration include a permanency requirement. This is currently 100 years or 25 years (at a discounted price to recognize the risk of reversal of the sequestered carbon).
  - Risks due to climate variability and climate change: Research shows the increased variability and more extreme climate events that are already being experienced in many regions, including southern Australia, will further constrain the capacity of soils to sequester carbon. Warmer temperatures and conditions less consistently favourable for plant growth appear to be pushing the net soil carbon balance to a lower level.
- The big picture:
  - Taking into account the natural, economic and practical constraints on the amount of soil carbon that can be sequestered in pastures and grasslands, the effectiveness of soil carbon sequestration to offset current ruminant livestock emissions is low, globally in the order of 20 to 60%. This is particularly the case in systems such as well-managed dairy farms, where a high soil carbon starting point and naturally high methane and nitrous oxide greenhouse gases from digestion and manure management limit the additional offsets that are practically achievable.
  - Soil carbon sequestration in pastures and other grasslands plays an important role in combating land degradation, promoting food security and managing the threat of climate change. In dairy pastures, maintaining optimal carbon levels for soil health supports a broad range of production and environmental goals such as improved water quality and biodiversity, and may provide a new income stream from carbon offset credits. However, it is important that farmers and other land managers obtain reliable advice on the risks and opportunities so that decisions align with farm business objectives.



Simplified illustration of key carbon cycling in a grazed land system. (From Garnett et al. 2017, Figure 6)

Some definitions and key terms

Biochar a carbon-rich material (a form of charcoal) that is produced by heating organic matter at high temperatures in oxygen-limited conditions (pyrolysis). Feedstock for biochar may include animal manure, plant residue and woody waste suitability for undergoing a pyrolysis process. Pyrolysis of material such as tyres, and human effluent are excluded in the context of soil organic carbon amendment.

Carbon dioxide equivalents (CO2-e)
expresses the warming effect of different greenhouse gases as an equivalent amount of carbon dioxide. It is the amount of carbon dioxide that would give the same warming effect as each greenhouse gas that is emitted or stored by an activity.

Soil carbon concentration
the amount of soil organic matter in soils is reported in g C per 100 g oven dry soil. Gravel (soil particles > 2 mm) and plant biomass (e.g. roots) are excluded from the analysis).

Soil carbon sequestration
the process of transferring carbon dioxide from the atmosphere into the soil of a land unit through plant residues and other organic materials which are stored or retained in the unit as part of the soil organic carbon with a long mean residence time so that it is not re-emitted back into the atmosphere.

Soil carbon stock
the mass of soil carbon per ha, which is calculated from the concentration and the soil bulk density and reported as tonnes/ha or kg/m^2 to a specified depth, most often 30 cm to comply with reporting requirements under international rules for national greenhouse gas inventories.

Soil health the capacity of a soil to function as a vital living system to sustain biological productivity, maintain quality of air and water, and promote plant, animal and human health. Soil quality is often used synonymously with soil health.

Soil organic matter (SOM)
based on the assumption that soil organic matter averages 58% carbon by mass, SOM is often estimated by multiplying the measured soil organic carbon value by 1.72, but the conversion factor actually varies depending on the nature of the carbon and may be up to 2.0 (Explanation given in the text).

Soil inorganic carbon
Predominately carbonates and bicarbonates of calcium and magnesium in soil.

Soil organic carbon (SOC)
A measure of carbon contained within soil organic matter, defined as the organic fraction of the soil ground to <2 mm and excluding >2 mm plant and/or animal residues.

Soil organic carbon fractions
An amount of measured organic carbon in a specified fraction, often specified as particulate organic carbon, humus organic carbon and resistant organic carbon.

Particulate organic carbon
Organic carbon measured in the <2 mm >0.5 mm soil fraction but excludes poly-aryl carbon.

Humus organic carbon
Organic carbon measured in the <0.5 mm soil fraction but excludes poly-aryl carbon.

Resistant organic carbon

Poly-aryl carbon (13C NMR region spanning 110 – 160 ppm) in the <2 mm fractions, apparently dominated by charcoal-like carbon or black carbon**.**

Soil organic carbon pool

An amount of carbon contained in a conceptual organic carbon pool (used for modelling purposes), for example, active, slow, and passive pools.

Active soil organic carbon
A pool of soil organic carbon with turnover period of weeks to a decade. It is also referred to as fast soil organic carbon.

Labile soil organic carbon
A pool or fraction of soil organic carbon that readily or continually undergoes chemical, physical, or biological change or decomposition. It has a turnover time of hours to months.

Slow soil organic carbon
A pool of soil organic carbon with a turnover period in the range of decades to hundreds of years. It is also referred to as humus or intermediate soil organic carbon.

Passive soil organic carbon
A pool of soil organic carbon with a turnover period of hundreds to thousands of years. It is also referred to as recalcitrant organic carbon.

Soil quality the fitness of a specific kind of soil to function within its capacity and within ecosystem boundaries (natural or managed) to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation (Singh et al. 2018). Soil quality is often used synonymously with soil health.

Soil natural capital

Soil's stock of natural assets yielding a flow of either natural resources or ecosystem services. Value can be assigned to the soil natural capital by quantifying the ecosystem services it provides.

Soil security The maintenance and improvement of the world's soil resources so they can continue to provide food, fibre and fresh water, make major contributions to energy and climate sustainability, and help maintain biodiversity and the overall protection of ecosystem goods and services.

1. Soil Carbon

1.1 Introduction

Soil provides ecosystem services, filters water and is vital to production of the food and fibre essential for human health through supplying nutrients and physical support for plants. Soil health is increasingly recognised as a key concept that treats soil as a living biological system[1]. The availability of macro- and micronutrients in soils is a major determinant of plant growth and is vital to the health of animals, humans, and ecosystems. Soil health is, consequently, a major determinant of global food and nutritional security and is vital to the resilience of natural ecosystems, agricultural production and human settlements to climate change.

A critical determinant of soil quality, functionality and health is soil organic carbon (SOC) which primarily consists of decomposed plant material and microbes. Carbon rich materials, such as the roots, stems and leaves of crops or pasture, cycle into the soil as part of the global carbon cycle. Some of this organic matter is rapidly broken down and respired into the atmosphere as carbon dioxide, but some remains and adds to the store of SOC. Soil carbon sequestration is the process of increasing the stable forms of carbon stored in soils – a process that starts with absorption of carbon dioxide (CO_2) in plant photosynthesis and incorporation of the carbon atoms into plant material. Different soil types vary in their capacity to both cycle and store carbon.

Australian soils are generally old and highly weathered. As a result, they have poor structure, low fertility and are low in organic matter and carbon. Since European settlement, historical land clearing and management practices not suited to Australian conditions, have built on natural physical and chemical soil constraints such as salinity, acidity, sodicity and compaction, leading to a decline in productivity across large areas. Along with high climate variability (especially severe droughts), unsuitable management has meant that plant biomass inputs have declined below natural levels, and the level of soil organic matter (SOM) has decreased, with losses estimated to be as high as 20 – 70%[2,3]. In well-managed pastures, however, SOM is generally higher, particularly where growth is not constrained by water availability. There is a strong relationship between reliable water supply (either from rainfall or irrigation) and SOM but variations occur even within high rainfall regions[4] suggesting that other factors that determine net primary productivity, also influence SOM inputs. Influences may include soil type and agronomic practices.

In this report, we review the current state of knowledge on carbon sequestration in soils with a strong focus on the potential for dairy pastures, providing an update to the report prepared by Dr David McKenzie for Dairy Australia (2010).

1.2 Soil carbon in the context of climate change mitigation

[1] Lal (2016)
[2] Luo et al. (2010)
[3] Sanderman et al. (2010)
[4] DAFWA (2013)

The past two decades have seen a marked increase in interest from scientists, governments and land managers in the role that soils can play in limiting the rise in atmospheric CO_2 and hence in managing the threat of dangerous climate change. The Intergovernmental Panel on Climate Change (IPCC) has developed specific guidance on calculating soil carbon stocks and both loss and sequestration potential under different biomes and management regimes directed towards national scale reporting[5]. Agricultural soils are the most actively managed and, therefore, the most accessible for promoting sequestration of atmospheric CO_2. They are also the soils most likely to have depleted levels of soil carbon due to management for production. Cultivation or other disturbance accelerates soil carbon oxidation and loss as CO_2, and crop harvesting and domestic livestock grazing remove plant biomass that could otherwise have been incorporated into soils. Globally, land clearing and land use for agriculture has been estimated to have resulted in the loss of 133 petagrams of carbon from soil[6]. Where SOC stocks have declined there is a generally a capacity to re-build them to their natural levels (Figure 1).

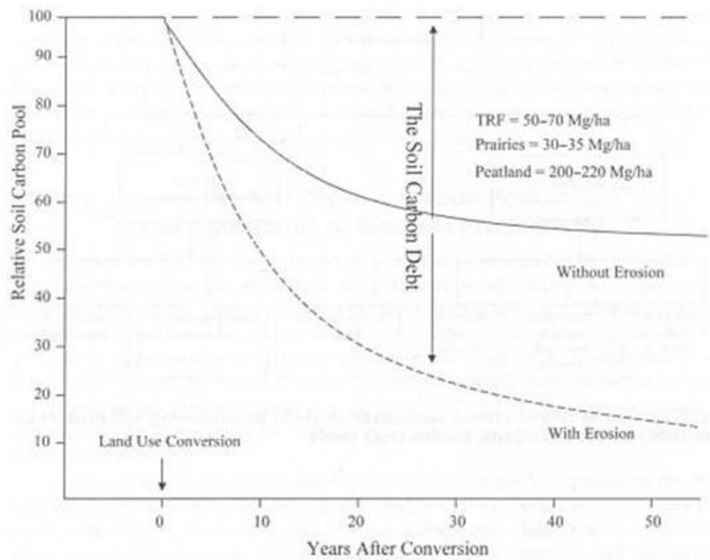


Figure 1. The soil carbon deficit, with and without erosion, following replacement of natural vegetation with farming. Typical pre-development amounts (1 metre depth) of soil carbon are listed for tropical rainforest (TRF), prairies and peatland (each is equivalent to a value of 100 on the graph)[7].

The IPCC estimates that globally, agricultural soils could sequester 1400–2900 Teragrams of CO_2 equivalents (1 Teragram = 10^{12}grams) annually for 50–100 years. There has been considerable research supporting the IPCC estimates of sequestration, which as a result has had considerable influence on climate policy. For example, the abandonment of cropping and establishment of grassland or forest has been proposed as a key to sequestering significant atmospheric CO_2. Early estimates put the potential for reduction or elimination of tillage and application of organic wastes to sequester SOC at rates in the order of 300–500 kg C ha^{-1} yr^{-1}, at least under some conditions[8] but more recent research is challenging these optimistic forecasts[9].

Due to the high spatial variability in soils and in the range of past management, average or global estimates

[5] IPCC (2006)
[6] Sanderman et al. (2017); 1 petagram = 10^{15} grams i.e. a billion tonnes of carbon
[7] Lal and Follettt (2009)
[8] Lal et al. (2007)
[9] Poulton et al. (2018)

will not apply uniformly. It is strongly recommended that regional or local data are used at farm or project scale. Where long-term measurements are available[10,11], actual soil carbon stock change for a specific land type and farm management practice has been shown to vary widely from some modelled estimates of the carbon sequestration potential. Therefore, published statements on the potential for soil carbon sequestration to mitigate climate change should be treated with caution where not backed up by credible science. Recent research that takes into account the key controlling factors in soil carbon stability and dynamics has revealed serious methodological problems in earlier assumptions and in some of the estimates cited in support of very high levels of SOC offsets.

More recently, there has been an increased focus on the benefits of soil carbon sequestration for improved soil health, which is critical for food security and climate adaptation[12]. Increasing the resilience of soils to the impacts of a future climate that is more variable and more extreme has emerged as a key concern. Specific benefits of SOM related to soil health include:

- Stabilisation of soil aggregates to reduce the risk of waterlogging under moist conditions and lessen compaction of dry soil;
- Food for beneficial organisms;
- Slow-release source of nutrients;
- Increased water holding capacity, particularly in sandy soil;
- Increase in nutrient holding capacity by improving cation exchange capacity;
- Binding of toxic cations (for example, extractable aluminium) in a form that is unavailable for plants.

1.3 The carbon cycle

Carbon cycles naturally between the soil, biosphere (plants and animals) and the atmosphere. In doing so, transformations in the form of carbon occur continuously (Figure 2). Soil, the largest of the carbon reservoirs, is able to both store and release carbon within the global cycle. Most soils contain carbon in organic and inorganic forms. The soil inorganic carbon (SIC) pool includes primary silicate materials that can contribute to net sequestration. However, it is the organic carbon that is the most dynamic and important in determining change in soil carbon stocks. SOC continually cycles into and out of the soil with the result that, over time, there can be periods of net carbon accumulation and net loss. At any one time, the amount of organic carbon in soil represents the balance between inputs and losses.

The organic carbon accumulated in soils arises from conversion of atmospheric carbon dioxide in photosynthesis to form plant biomass (aboveground shoots and belowground roots). Higher primary productivity means higher organic inputs to the soil from root material and aboveground litter. Microorganisms break down these organic residues and contribute to loss of carbon dioxide back to the atmosphere and to accumulation of soil organic carbon through their own life cycle. Agricultural practices affect plant biomass production and can drive changes in microbial activity. In many agricultural soils, net

[10] Poulton et al. (2018)
[11] Lal (2018)
[12] Lal (2016)

emissions from the decomposition of organic matter have historically resulted in a decline in SOM and SOC, and contributed to human-induced rises in atmospheric carbon dioxide.

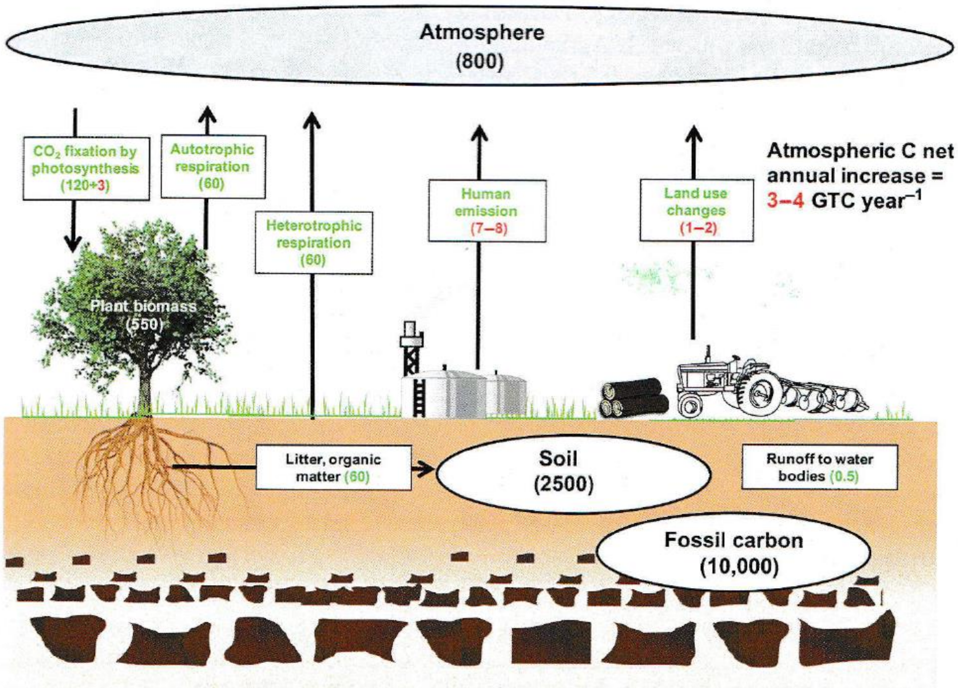


Figure 2. Simplified terrestrial carbon cycle. Values in brackets in each box represent the annual exchange of carbon between land and atmosphere in Gigatons (Gt C/year) - green numbers are natural fluxes; red numbers are fluxes due to anthropogenic activities. Numbers in brackets in ovals indicate the amount of C (Gt) in each reservoir[13]. (1 Petagram = 10^{15} grams)

1.4 Soil organic carbon balance

Soil organic carbon is in a constant state of flux, and moves towards a new steady state after a change occurs. For example, in systems where plant production is constrained, e.g. by drought or harvesting, organic matter inputs are lower and increasing depletion occurs as soil biota break down stored SOC for energy. This results in declining SOC content to a new lower balance. The new limiting level is determined in part by soil texture and the level of protection of SOM, and is influenced by decreasing biological activity, as microbes are essentially starved of decomposable carbon. Carbon turnover can also be limited by available nutrients and it is likely that more fertile soils will lose organic matter at a faster rate than lower nutrient content soils. The use of carbon to nitrogen ratio as an indicator of nutrient supply in carbon turnover is discussed below.

Current best estimates of exchanges between the major global reservoirs of carbon are shown in Figure 3, which was developed by an internationally-respected soil carbon expert, Rattan Lal[14], from data derived

[13] Reprinted from *Soil Carbon Storage*, Brajesh K Singh (Ed.), Figure 1.1, Page 3, Copyright 2018, with permission from Elsevier.
[14] Lal (2018)

from a range of reputable sources[15,16,17,18]. The balance between biomass carbon inputs to soil and soil respiration, both as 60 petagrams per year is affected by additional loss pathways through soil erosion and sediment transfer to oceans, together amounting to 1.65 petagrams per year.

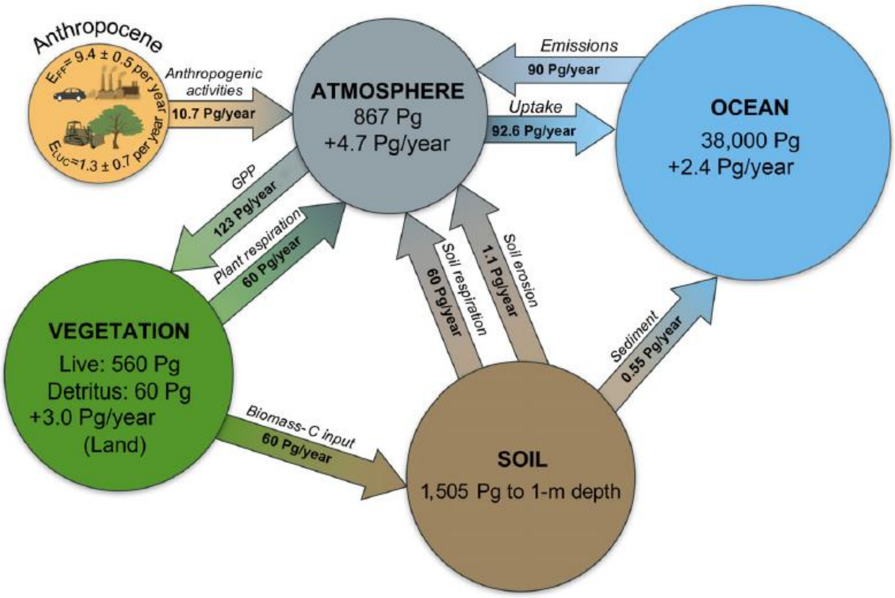


Figure 3. The contemporary global carbon cycle showing flows of carbon to and from global soils and for other reservoirs[19]. Data within arrows are fluxes (Pg C/year); values within circles are estimates of the carbon stock; values in circles with a + sign are annual rates of change in stocks. Within the circle labelled Anthropocene, E_{ff} is emissions by fossil fuel and E_{LUC} is the emissions by land use conversion. Atmospheric stock was computed on the basis of 406.29 ppmv of CO_2 on 26 November 2017[20].

When SOM is used as food by microorganisms, carbon dioxide is the main product, but mineral nutrients are also released and made available for uptake as plant nutrition. The majority of available soil nitrogen derived from SOM comes from the humus fraction (www.csiro.au/resources/soil-carbon). It tends to be immobilised in plant residues.

Apart from loss as carbon dioxide via microbial decomposition, soil organic carbon decline can occur through several other processes:

a. Soil erosion by water and/or wind can result in the carbon associated with eroded soil particles being locked up in lakebeds and seabeds, rather than being converted directly into carbon dioxide (Figure 3). Nutrients associated with these particles become inaccessible for plant uptake and, therefore, erosion decreases farm productivity.
b. Sediment losses and deep drainage of soluble organic acids.
c. Photodegradation (the breakdown of complex materials into simpler materials by light) is a form of oxidation that can supplement enzymatic oxidation and increase decomposition rates

[15] Batjes (1996)
[16] Batjes (2016)
[17] Lal (2004)
[18] Le Querre et al. (2017)
[19] Lal (2018), Figure 2
[20] An atmospheric CO_2 of 406.29 ppmv is 0.040629% by volume. This is equivalent to 0.06122% by mass of atmosphere, which is 5.148 x 10^{21}g containing 3.177 Pg CO_2 or 867 Pg C.

of aboveground vegetation components. As a result, organic matter decomposition in arid ecosystems is not restricted to periods of high moisture availability as is plant production[21]. Photochemical oxidation can be a risk in grazing systems unless livestock trample plant material and encourage soil contact and/or incorporation and decomposition[22].

Managing Dairy Pastures

The risks of cultivation in dairy pastures

Cultivation accelerates organic matter decomposition by exposing sites within soil aggregates that previously were protected. Most dairy farmers are aware that there is a risk that cultivation will negatively affects soil health. However, at times of water scarcity in the Murray Darling Basin, an area relevant to one-third of the Australian dairy industry, annuals may be preferred to perennials for maintaining production in the short-term, despite annuals usually requiring soil disturbance for establishment. During the drought of the early 2000s when there was limited availability of irrigation water in northern Victoria, a study at Kyabram (Greenwood et al. 2008) indicated that winter-growing annual pastures such as oats offered the potential to grow 70-80% of the feed produced by perennial forages (perennial ryegrass/white clover, tall fescue/white clover and lucerne), but using just 40-55% of the irrigation water. Practices to recover soil organic carbon in the longer-term may be needed.

1.5 Forms and stability of soil organic carbon

Living microbes may comprise 1% or more of the total amount of SOM present in soil. These microbes that digest up to 90 per cent of the organic matter added to soil, respiring carbon back into the atmosphere as CO_2, are made up of a number of different types of organisms (Table 1).

Table 1. Approximate numbers and biomass of organisms in a typical UK agricultural surface soil in a depth of 15 cm[23].

Organism	Numbers per gram dry soil	Mass, kg/ha
Bacteria	100 million	1600
Actinomycetes	2 million	1600
Fungi, eg. Mycorrhiza	0.2 million	2000
Algae	25,000	320
Protozoa	30,000	380
Nematodes	1.5	120
Earthworms	1 per kg	800

Mycorrhizal fungi are an important group of soil microbes that can connect directly with plant roots and utilise the dissolved carbohydrate exudate produced via photosynthesis. They assist plants by helping to

[21] Gallo et al. (2009)
[22] Schuman et al. (2009)
[23] Batey (1988)

scavenge for essential nutrients such as phosphorus. Mycorrhiza produce soil glomalin, an organic compound that is important for soil aggregation and relatively resistant to decomposition.

Microbes continually break down organic residues eventually converting a small proportion to humus, which gives the topsoil its dark colour. The amount of organic residues converted to humus depends on soil and climate factors, and while the theoretical level is as high as 30%, in Australian agricultural soils it is often much lower. Management practices also have a significant influence on whether actual SOC reaches the theoretically level attainable for the given soil and climate conditions. Continuous inputs of external organic carbon sources that are required to reach this level may be not practical or uneconomic. Raising inputs at one location, e.g. by resting from grazing, may also risk the depletion of organic carbon in another location, so that there is no real gain in stored SOC.

Management practices will only be effective in sequestering carbon into soils if the carbon is stored in stable forms that persist over a long period, nominally 100 years according to permanency requirements under carbon accounting methods. However, we currently have limited understanding of carbon dynamics in soil and transfers between different carbon pools. Transfers proceed from labile carbon that is turned over rapidly to provide nutrient cycling for plant growth through to resistant carbon that is stored for long periods improving soil structure, water holding capacity, and also giving carbon sequestration benefits. The models such as Century and RothC that are most commonly used to simulate soil carbon cycling, assume three pools of SOC. These pools are conveniently defined as a labile or active pool (turnover time of days to years), an intermediate–slow pool (turnover time years to decades), and a passive–inert pool (turnover time up to 1000 or more years)[24,25]. These carbon pools are used by modellers to simulate SOM turnover, and crop residues on the soil surface are assumed to progress through the pools after incorporation (Table 2).

Table 2. Composition of soil organic carbon as conceptual pools representing different stages of decomposition (Adapted from Baldock 2008).

Soil organic matter pool	Characteristics
Crop residues on the soil surface	Extent of decomposition increases
Buried crop residues (>2 mm)	Rate of decomposition decreases
Particulate organic matter (2mm – 0.05 mm)	C:N and C:P ratio decreases (i.e. become nutrient rich)
Humus (<0.05 mm)	
Resistant organic matter	Dominated by charcoal with variable properties

As microbial decomposition progresses to create humus, the ratio of C to N in SOM decreases and becomes lower and much less variable (Figure 4). The concentration of SOC in soils tends to be higher in the surface layers where more carbon is in particulate forms that are less stable and more susceptible to loss via erosion, particularly in poorly managed soils with low groundcover. In practice, the conceptual pools are difficult to measure and various approximations are made to quantify pool sizes[25]. The labile pool is currently

[24] Skjemstad *et al*. (1998)
[25] von Lützow *et al*. (2007)

quantified using measures of particulate organic carbon (POC) minus any charcoal present. The inert pool, referred to as resistant organic carbon (ROC), is quantified from measures of pyrogenic or black carbon using ^{13}C nuclear magnetic resonance (NMR) techniques, while the slow pool, referred to as humus organic carbon (HOC), is usually taken to be the difference between total organic carbon (TOC) and any POC+ROC present[26]. Other measurement techniques such as MIR indicate that ROC, which is primarily made up of char, is likely to be a poor measure of the inert carbon pool, and its value in soil carbon models is, therefore, in doubt[27]. In fact, the accessibility, availability, solubility and reactions of various components of SOC are determined not only by their molecular characteristics, but also depend strongly on their position within the soil matrix, which characterizes physical and chemical protection.

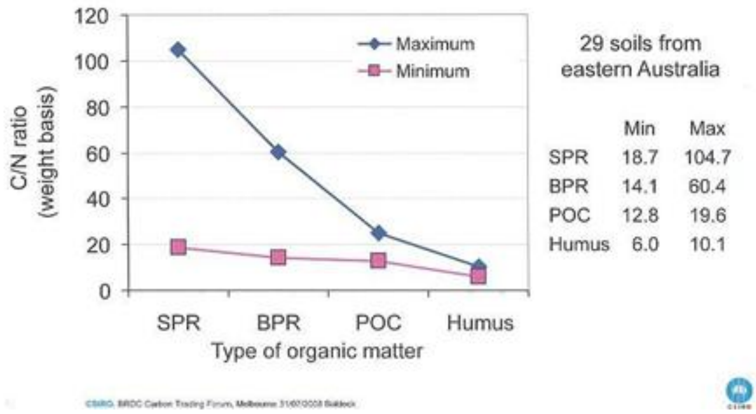


Figure 4. Carbon to Nitrogen (C:N) ratios for the carbon fractions shown in Table 2 (Baldock 2008). SPR, BPS are the surface and belowground plant residues, respectively; POC is the particulate organic carbon.

Soil organic carbon distribution as a function of depth at selected sites across southern Australia is shown in Figure 5. For three of the four profiles illustrated, most of the organic carbon was concentrated in the upper 15 cm of soil. The Chernic Tenosol is derived from young volcanic ash and subsoil constraints such as sodicity and pH imbalance are not present.

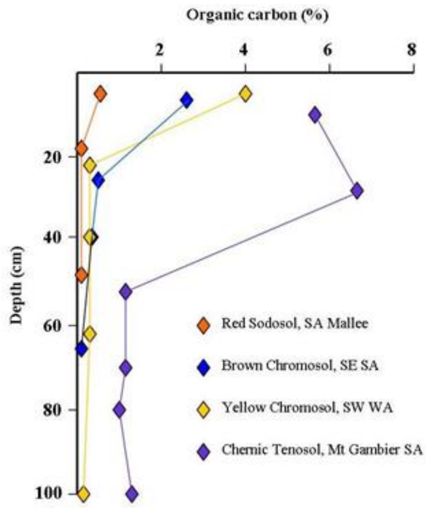


Figure 5. Soil organic carbon content as a function of depth for four soil profiles recorded for areas with pasture production[28]. Points on the graph indicate mid-points of soil horizons.

[26] Baldock et al. (2012).
[27] Page et al. (2013)
[28] McKenzie *et al.* (2004)

Recent research is emphasising that, while the pools in Table 2 are a convenient way of conceptualising SOC turnover and the influence of changes to agricultural management on storage of carbon, there is in reality a continuum of forms of carbon in soils as organic matter decomposes over time[29]. A “consolidated view” of SOM turnover[30] has been proposed according to which SOM is controlled by parallel biotic and abiotic processes, including continuous decomposition of plant and animal debris and oxidation that enables solubilisation or stabilization through chemical linkage to minerals, depending on the characteristics of the soil ecosystem[31]. The persistence of SOM cannot be solely attributed to chemical recalcitrance[32,33,34] and is likely due, in part, to the capacity of the soil to stabilise carbon through the availability of charged mineral surfaces[35]. Nevertheless, management practices that increase carbon in active pools, but have little impact on the more slowly cycling pools, will likely provide carbon gains that are vulnerable to loss if there is a subsequent change in management, climate or some other factor that affects the input of SOM. For this reason, the conceptual pools are still considered useful and continue to be applied in modelling.

2. Soil carbon sequestration

2.1 A note to units

The definition of soil carbon sequestration generally used, and adopted in this report[36], refers to the process of transferring carbon dioxide from the atmosphere into the soil and storing it as carbon. To be precise, therefore, carbon sequestration should be expressed in terms of carbon since soils do not store the greenhouse gas, carbon dioxide. However, to quantify the climate change effect and to compare with other greenhouse gases, particularly those emitted from agricultural systems (methane and nitrous oxide), soil carbon sequestration is usually expressed as carbon dioxide equivalents.

It is important not to confuse these units. Carbon has a unit mass of 12 and carbon dioxide has a unit mass of 44, so 1 gram of carbon is equivalent to 44/12 or 3.667 grams of carbon dioxide.

2.2 Global interest in carbon sequestration

Based on concern driven by the consensus view of the world’s most respected climate scientists, international governments agreed in Paris in December 2015 to take action to stabilise global temperatures

[29] Singh (2013)
[30] Lehmann and Kleber (2015)
[31] FAO (2018)
[32] Marschner et al. 2008
[33] Schmidt et al. 2011
[34] Dungait et al. 2012
[35] Yu et al., 2017
[36] Olson et al. (2014)

by limiting net emissions of greenhouse gases to the atmosphere. The goal of the Paris Agreement to limit temperature rise to 2°C above pre-industrial levels, and ideally to no more than 1.5°C higher, will require strategies to both reduce emissions and remove carbon dioxide from the atmosphere[37]. To promote greenhouse gas mitigation, at least 21 GHG emission cap-and-trade systems are now in operation across the world. States that maintain carbon trading schemes cover more than 50% of global GDP and encompass nearly one-third of the world's population.

As shown in Figures 2 and 3, the world's soils contain twice as much carbon (as organic carbon) as the atmosphere and three times as much as the terrestrial biotic pool[38]. Therefore, even a modest percentage change in SOC has the potential to significantly influence atmospheric CO_2 and drive change in atmospheric greenhouse gas concentrations, so it is not surprising that increasing storage of carbon in soils has been proposed as an important contribution to meeting national climate change mitigation targets. The Australian government has made clear statements on the importance of 'land sector sinks' (removal of carbon dioxide from the atmosphere and storing it in vegetation and soils) to achieving the country's 'Paris target' of reducing growth in emissions to no more than 26% above 2005 levels by 2020. Actions by land managers to increase storage of carbon in soils are supported by two soil carbon sequestration methods for credits under the Emissions Reduction Fund, which is part of Australia's Direct Action climate change policy (See Section 6.2).

Soil carbon sequestration depends on being able to establish a positive soil carbon budget by creating a shift in balance so that the input of biomass carbon exceeds SOC losses. In managed soils carbon losses occur mainly by mineralization and erosion. Maintaining the abundance and activity of soil organisms to prevent decline in soil function and biodiversity, nutrient cycling, and hence agricultural productivity while, at the same time, increasing carbon storage[39] is a major challenge in agricultural management, especially in a changing climate.

2.3 Carbon cycling in pasture soil

Soil carbon cycling may involve inorganic and organic forms of soil carbon. Sequestration of SIC is a minor pathway, but may occur through incorporation of carbon dioxide in soil air into carbonic acid and its subsequent re-precipitation as carbonates of calcium and magnesium or via leaching of bicarbonates into the deep subsoil. SIC stocks are not strongly influenced by land management, with the exception of lime applications[40], and SIC transfers are usually ignored when considering soil carbon sequestration in agricultural systems.

The main contribution to changes in total soil carbon is through SOC. Characteristics of pastures that influence SOC transfers in a way that is likely to increase chances of a positive carbon balance include:

- Dominance of perennial pasture species that provide growth throughout the year;
- Minimal disturbance (relative to cropping) so that SOC is protected within the soil structure; and

[37] Peters (2016)
[38] Gosling et al. (2017)
[39] Wagg et al. (2014)
[40] Bruce et al. (2009)

- Low erosion risk where groundcover is maintained.

An important determinant of SOC sequestration potential is the antecedent soil carbon levels. Dairy pastures are often well-managed with good water and nutrient supplies. This means that SOC may be close to the natural soil capacity determined by soil type and climate factors so that there is little opportunity for further sequestration.

The transfers that occur in SOC sequestration are illustrated in Figure 6 [41]. These can be described in simplified terms as a sequence of processes starting with removal of carbon dioxide from the atmosphere in plant photosynthesis and progressing to storage in stable forms in the soil[42]:

The process of photosynthesis converts two chemicals, carbon dioxide and water, into simple carbohydrates, using sunlight as the energy source. The process takes place within the leaf and other green surfaces of plants. However, only part of the radiant energy from the sun is used in this way. At best, a plant can convert only about 6% of the total incoming solar radiation into 'stored energy'.

Water enters the plant mainly through the roots and brings with it essential nutrients. Carbon dioxide enters as a gas, mainly through holes (stomata) on plant leaves. Stomata open in response to light, but close in the dark and in response to adverse conditions such as lack of water or high temperature. When a crop is growing vigorously and without constraints, a daily inflow, via the stomata, of over 150 kg/ha carbon dioxide is needed, the amount contained in the air above the crop to a height of over 20 metres. Water is lost from plants while the stomata are open, sometimes over 100 t/ha each day.

In temperate climates, many crops increase their dry weight by about 200 kg/ha each day. Up to 15% of all the carbohydrate fixed by the plant leaks from roots into the soil and is utilised by soil microorganisms within the rhizosphere.

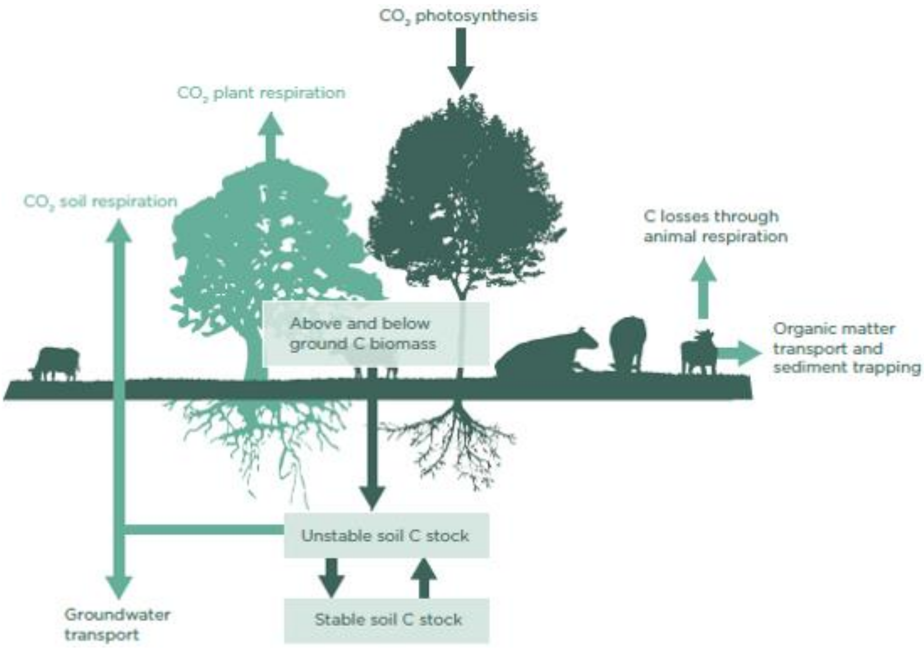


Figure 6. A simplified conceptual diagram of the role plant communities (such as a dairy pasture) can contribute to carbon sequestration in soils and loss pathways[41]).

[41] Garnett et al. (2017).
[42] Batey (1988)

An important factor in determining SOC levels is the composition of the plant community, which usually consists of a variety of species. In the case of a dairy pasture, the community may consist of mixed grass species and legumes. The plant community also influences the rate of decomposition of plant residues in soils since the characteristics of the biomass, including the ratio of carbon to nitrogen (C:N) and chemical properties such as the lignin, suberin and cellulose content, influence turnover. Autotrophic respiration, the biochemical process which breaks down products of photosynthesis such as sugars to provide energy, returns carbon to the atmosphere as carbon dioxide relatively rapidly. Organic carbon from plant material in the soil may be incorporated into microbial biomass or particulate SOC. Through further decomposition, particulate organic carbon may then be transformed to more stable forms such as humus which are retained for longer periods in the soil (Table 2).

Functional traits of plants also influence carbon cycling and SOC storage. Plant productivity (the rate of photosynthetic carbon assimilation) and biomass partitioning between above- and below-ground structures (root to shoot ratio) help determine inputs to the soil via litter, root exudates and mycorrhiza[43]. Because most of the SOC in grazed pastures derives from root material[45], factors affecting partitioning of biomass to roots are important determinants of SOC on dairy farms. For grazed annual and perennial pastures (without lime application) near Wagga Wagga in New South Wales, root to shoot ratios of 0.57 and 0.76, respectively were measured[44]. Within a pasture type, partitioning to roots is also influenced by management practices such as the frequency of grazing and fertilization. Average root to shoot ratios of 5.9 ± 1.9 for unfertilised soils and 2.4 ± 1.5 for fertilised soils have been reported for temperate grasslands[45].

Other important non-soil influences include climate and atmospheric factors (Figure 7). Climate, particularly rainfall (amount and distribution) and temperature influence plant growth and rate of decomposition[46]. Atmospheric concentration of CO_2[47] affects biochemical composition and may affect plant structure[48].

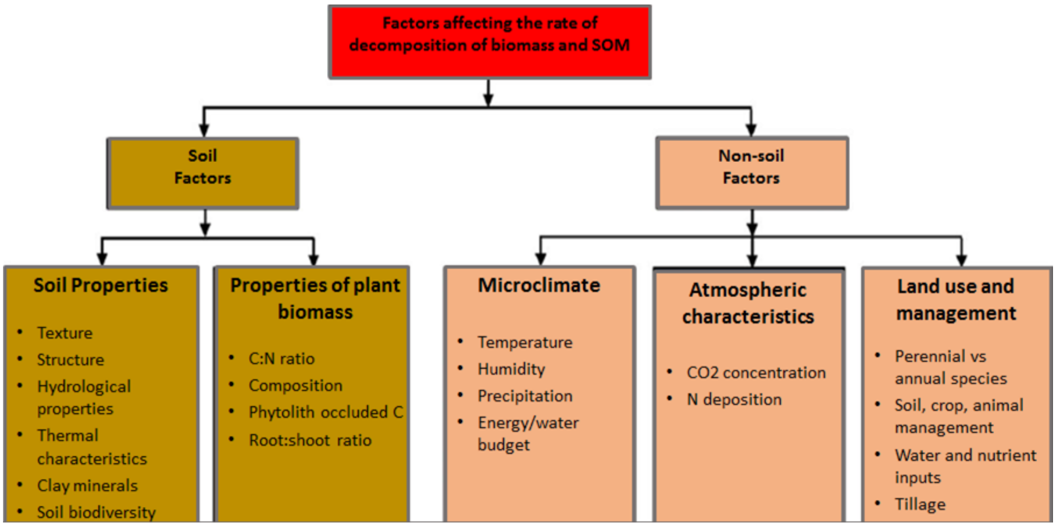


Figure 7. Factors affecting the rate of decomposition of plant residues in soils (Adapted from Lal 2018[48]).

[43] De Deyn et al. (2008)
[44] Li Liu et al. (2011)
[45] Poeplau (2016)
[46] Saiz et al. (2012)
[47] Torbert et al. (2000)
[48] Lal (2018)

The rapid turnover of labile organic matter is vital for healthy soils and productive plant growth, but contributes only indirectly to SOC sequestration. Long-term storage of SOC requires the carbon to be protected from decomposition by soil microbial populations and retained in stable forms (Figure 8). As discussed above, the amount of carbon entering stable pools is influenced by soil, climate, atmospheric and management factors.

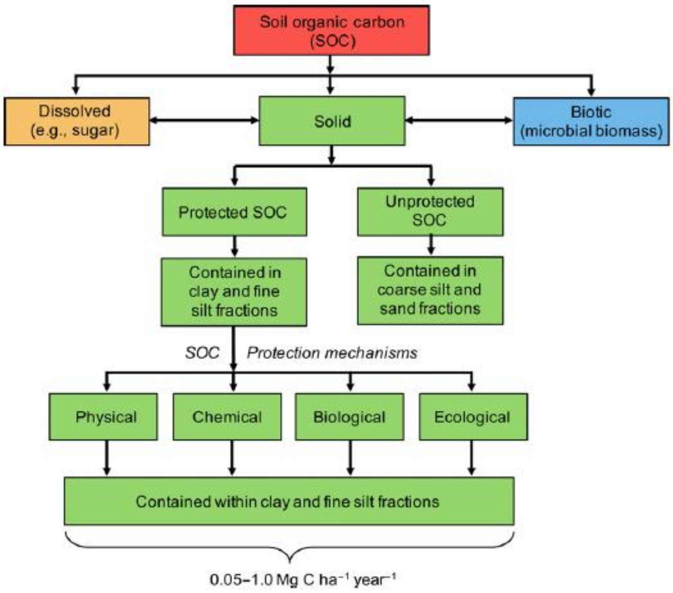


Figure 8. Components of SOC stocks showing factors affecting its retention. The SOC sequestration rate of 0.05 to 1.0 Mg per hectare per year reflects the range expected with adoption of site-specific good land management practices[49].

2.4 How much carbon can be stored in soil?

The amount of organic carbon that can potentially be sequestered into the world's soils through changes in management has been estimated to be possibly as high as 0.9 to 1.3 Gt C per year[50,51,52,53]. Up to three-quarters of this amount is projected for cropping lands, which are the most depleted by past management. However, this theoretical potential is very unlikely to be achievable in practice, and a more realistic estimate of what is economically possible for global soil organic carbon sequestration based on reasonable carbon prices is likely to be only half that estimate, 0.4 – 0.7 Gt C per year[51,54].

The rate of carbon sequestration in soils following adoption of an improved management regime not only varies greatly between situations, but for a given site and management it is not constant over time (Figure 9). Sequestration is more rapid initially, especially when the starting soil carbon levels are low as a result of past management practices, and will slow to be closer to zero as a new steady state is reached. Achieving

[49] Lal (2018)
[50] Lal (2004)
[51] Smith et al. (2008)
[52] Paustian et al. (2016)
[53] Minasny et al. (2017)
[54] Smith (2016)

this 'equilibrium' may take 20 to 100 years depending on such factors as soil type and climate. In addition, carbon sequestered in soil is vulnerable to loss due to natural factors such as drought and to human factors such as reversal of sustainable management practices. In some regions, particularly in less developed countries, there may also be institutional, educational and social barriers to maintaining conditions that promote soil carbon[55].

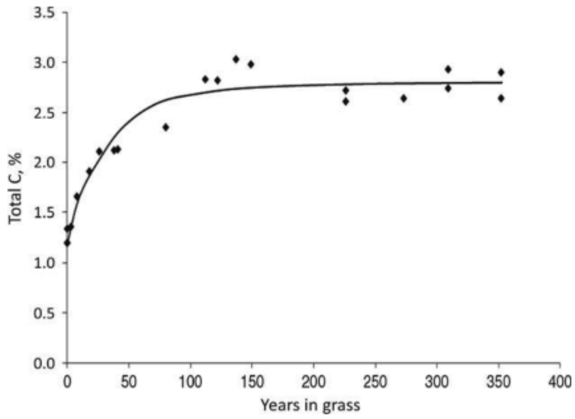


Figure 9. The changing rate of soil carbon sequestration over time as a new steady state is approached. This graph from Smith (2014)[56] shows the increase in % organic carbon to a depth of 23 cm, calculated for silty clay loam soils converted from cropping to grass at Rothamsted, UK.

Synthesis of published findings gives an estimated historic depletion of SOC in world soils of 115–154 Pg C (average of 135 Pg C)[57]. Assuming SOC sequestration is feasible across 4,900 Mha of agricultural land including 332 Mha equipped for irrigation, 400 Mha of urban lands and approximately 2,000 Mha of degraded lands, the estimated potential to store carbon in different land types was used to calculate the equivalent global technical potential of SOC sequestration as 1.45–3.44 Pg C/year (average of 2.45 Pg C/year)[55] (Table 3).

Table 3. Estimated technical potential to store carbon in soils globally (based on data in Lal 2018).

Land type	***Potential Sequestration (Mg C/ha/year)***
Croplands	0.25-1.0
Pastures	0.10-0.175
Permanent crops & urban lands	0.5-1.0
Salt-affected & chemically degraded soils	0.3-0.7
Physically degraded & prone to water erosion	0.2-0.5
Susceptible to wind erosion	0.05-0.2

[55] Lal (2016)
[56] Smith (2014)
[57] Lal (2018)

In summary, the capacity of soils to sequester carbon depends on many factors including depth, clay content and mineralogy, plant available water holding capacity, nutrient reserves, landscape position, and the antecedent SOC stock. Limitations on soil carbon sequestration as a greenhouse gas offset centre around issues of constraints due to soil and climate factors that lead to 'sink saturation' and to susceptibility of gains to reversal because of climate and management influences. However, even if the potential sequestration is limited, the co-benefits of management actions to build SOM go beyond climate change mitigation, frequently including better infiltration of water, higher moisture- and nutrient-holding capacity and greater resilience to climate extremes such as drought.

2.5 Factors affecting sequestration in Australian soils

Agricultural production in Australia has resulted in a decline in SOM in many regions, estimated to be as much as 30-70 per cent of the original content in grasslands and forest lands converted to cultivation. As organic matter and associated nutrient content has declined, crop yields having dropped markedly in many low input systems. Practices such as revegetation and destocking of land, increasing frequency and diversity of crops and pastures, amelioration of soil constraints, and soil conservation methods can contribute to preserving SOM levels and restoring soil fertility.

A review of research in Australia on the relationship between soil carbon stocks, land use and management demonstrated that in semi-arid and sub-humid zones, inclusion of pasture in cropping systems, crop residue retention, zero tillage, and phosphorus fertiliser application in pastures, have most potential to improve soil carbon stocks or slow down the rate of carbon loss[58]. Data from 1482 sites across the major agricultural regions of eastern Australia (Figure 10) surveyed as part of the Soil Carbon Research Program (SCaRP, Section 5.1) were analysed to determine the relative importance of land use vs. other drivers of SOC[58]. Sites included dairy pastures and other crop and grazing lands in southern Australia. The main regulators of SOC stocks under different land uses were found to be aridity and soil texture. Differences in land use and management explained only 1.4% of the total variation. The analysis suggested the greatest potential for increasing SOC stocks in eastern Australian agricultural regions lies in conversion from cropping to pasture on heavy textured soils in the humid regions.

[58] Rabbi et al. (2015)

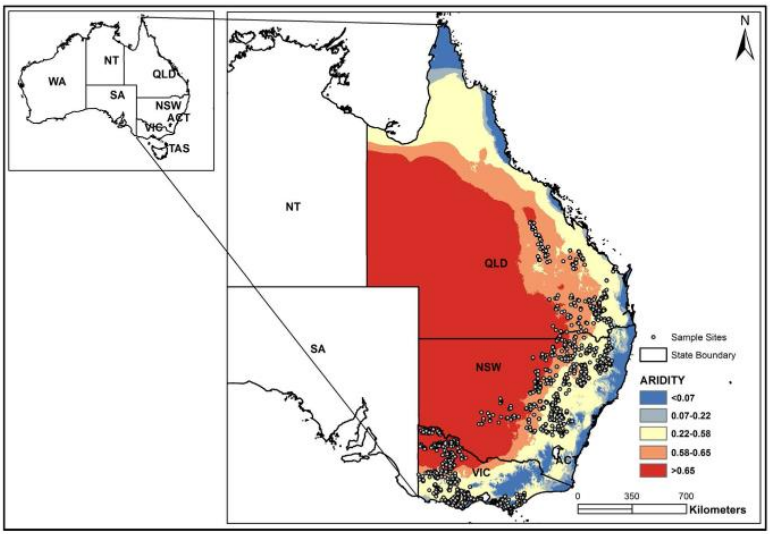


Figure 10. Sample sites across eastern Australia used in the analysis of factors affecting changes in SOC storage in agricultural soils showing one of the main drivers of change, aridity. Sample sites in southern Australia included dairy farms. (From Rabbi et al. 2015).

Some Australian soils have seen measured improvements in the SOM content following introduction of soil conservation practices but many areas cleared for agriculture continue to lose SOC. Only management practices that increase the proportion of stable carbon will lead to long-term changes in soil organic carbon. Potential SOC benefits of management practices relevant to pasture systems are shown in Table 4[59].

Table 4. Summary of the likely impacts of major management changes on carbon sequestration in Australian pasture soils based on a review of research findings to 2010[59].

Management	SOC benefit[a]	Confidence[b]	Justification
Shifts within an existing pastoral system			
Increased productivity irrigation fertilisation	0/+	L	Potential trade-off between increased C return to soil and increased decomposition rates
Rotational grazing	+	L	Increased productivity, increased root turnover and incorporation of residues by trampling but lack of field evidence[c]
Shift to perennial species	++	M	Plants can utilise water throughout the year; increased belowground allocation but few studies to date.
Shift to different system			
Cropping to pasture system	+/++	M	Generally greater C return to soil in pasture system; will likely depend greatly upon the specifics of the switch

[a] Qualitative assessment of the SOC sequestration potential of a given management practice. 0=nil, + = low, ++= moderate, +++=high

[b] Qualitative assessment of the confidence in the estimate of sequestration potential based on both theoretical and evidentiary lines. L=low, M=medium, H=high

[c] Recent research (Mitchell et al. 2016, 2019) indicates that trampling to increase contact of plant litter with soil surface may accelerate decomposition so that sequestration benefits are likely to be small.

[59] Sanderman et al. (2010)

Implementing irrigation and fertilization to increase productivity or adopting rotational grazing practices were assessed as providing only minor potential carbon sequestration although likely increasing biomass inputs to soil. There was low confidence in the estimate of sequestration potential. More positively, there was medium confidence that shifting from annual to perennial pasture species is able to provide moderate SOC increase through more efficient water and nutrient use throughout the year. Of the studies with suitable data for improved pastures relevant to dairy farms in southern Australia, carbon stocks were found to increase at a rate of 0.29 ± 0.17 Mg C ha^{-1} yr^{-1} (mean ± s.d., n = 15) with fertiliser use and by 0.11 Mg C ha^{-1} yr^{-1} (n = 4) with other improvements, including irrigation and sowing of legumes[59]. The absolute rate of increase following conversion from cropping to permanent pasture is very dependent on starting SOC levels.

For dairy farms, a constraint on potential SOC sequestration is that soils under pastures are generally relatively high in carbon and often close to the equilibrium level for the soil type and climate. This constrains the additional carbon that can potentially be stored while the farm continues to operate as a productive and profitable business. However, the same good management practices that promote SOC have value for soil health and productivity. Maintenance of SOM levels underpins sustainable agricultural production. Understanding the quantity and quality of SOC in pasture soils and how it is linked to soil biological processes and function can assist land managers in ensuring profitability and improve resilience to environmental stressors. For example, turnover in carbon pools can mobilise nutrients and improve soil condition and plant growth. Recognising these benefits is important in assessing the value of managing to optimize SOC levels and learning how organic matter cycles through the soil and what drives its accumulation and loss supports decisions for maintaining SOC at optimal levels within an agricultural system[60] (Table 5).

Table 5. Rate limiting factors in the accumulation of SOM and soil carbon (Adapted from GRDC 2013)[60].

Factor	Nature of the influence
Soil type	• Clay in soil binds to organic matter, which helps to protect it from being broken down or limits access to it by microbes and other organisms. • In coarse textured sandy soils, organic matter is not protected from microbial attack and is rapidly decomposed.
Climate	• Water is often the limiting factor for plant growth and higher rainfall generally supports more growth and more organic matter inputs to soil. In comparable farm systems with similar soil type and management, soil organic matter usually increases with rainfall. • Under moist conditions, each 10°C increase in temperature give a doubling in the rate of organic matter decomposition (Hoyle et al. 2006). Moist, warm conditions will often result in the most rapid decomposition of organic inputs.
Land and soil management	• Maximising crop and pasture biomass via improved water-use efficiency and agronomic management will increase organic matter inputs to soil. • The top 10 cm of soils hold a large proportion of organic matter so protecting the soil surface from erosion (e.g. with permanent pasture cover) avoids loss of soil organic matter. • Not tilling structured soils retains soil organic matter stocks and avoids exposing previously protected organic matter to microbial decomposition. • Adding off-farm organic residues such as manures, straw and char can increase soil organic matter depending on the quality of the added residues, but note that simply moving organic matter from one site to another does not give a net sequestration credit. • Soil constraints can influence humus formation by constraining plant growth and decomposition rates, potentially limiting movement of organic matter into more stable fractions. For example, microbial activity is lower in strongly acidic or alkaline soils and soil acidity affects availability of nutrients and hence available organic matter for growth of soil biota.

[60] GRDC (2013)

Emerging markets for carbon credits through private schemes and the Australian government's Emissions Reduction Fund (Section 6.2) are now functioning but the opportunities for income for Australian farmers is challenging. While they have the potential to provide incentives to implement practices to build SOC, the complexity of project development, costs associated with measurement, requirements for permanency, and potential trade-offs with farm business objectives can be difficult to negotiate for family farms and individual land managers. For many practice changes, several published economic analyses indicated the price is on carbon is currently (2018) too low to be attractive[61,62].

2.6 Pasture soils and soil carbon sequestration

The magnitude and rate of SOM decomposition and carbon sequestration in pasture soils depends on a range of soil, environmental and management factors (See Figure 7). The following farm management practices may contribute to changing soil factors in favour of increased SOM inputs and decreased loss of carbon as carbon dioxide to achieve net sequestration.

Actions that slow the rate of SOM decomposition

a. Clay soil tends to protect organic matter more effectively from decomposition than does sandy soil. On most farms, however, increasing clay content through techniques such as clay spreading is prohibitively expensive. In addition quantifying net greenhouse gas benefits would require accounting for both onsite and offsite effects and accounting for emissions due to fuel use and other sources. Activities of clay spreading, delving and/or spading with the objective of increasing SOC are currently not eligible under the soil carbon method for Australia's Emissions Reduction Fund.

b. Deep soil profiles with fertile subsoil allow deep root penetration into subsoil that is much cooler, and likely to have lower decomposition, than the topsoil in summer. The presence of restrictive layers such as unweathered bedrock and/or hostile subsoil conditions (eg. salinity, severe acidity) often prevents deep root penetration. Subsoil modification can overcome these constraints, but the cost is often high and only the net benefits could be counted towards carbon offsets where eligible under carbon credit methods.

c. Anaerobic (waterlogged) soil has lower rates of organic matter decomposition than well-aerated soil because of lower soil organism activity. However, this apparently beneficial process (peat creation) may be outweighed by release of the potent greenhouse gas methane under the waterlogged conditions. Productivity, and therefore SOM input, is also generally lower in waterlogged soils.

d. Organic amendments such as biochar, produced from heating organic materials to high temperature in low oxygen, and composted manure have chemical structures that may reduce

[61] Lam et al. (2013)
[62] White and Davidson (2016)

the rate of organic carbon decomposition in soil. Their use may be positive where financial returns are expected to exceed the costs of purchase, transport and application. However, according to Australian methods, accounting for climate change benefits does not count the carbon added in the amendment as sequestration (see later discussion and description of carbon credit methods), and only SOC increases via increased plant productivity or protection from microbial decomposition are eligible credits.

Actions that increase the rate of addition of organic materials

e. Soil amelioration can increase pasture production by overcoming physical and chemical constraints. For example, soil with favourable structure has higher infiltration and retention of water so that irrigation and rainfall are more effective for plant growth than compacted or dispersive soil. This extra water provides potential for higher pasture production. The intensive production that characterises dairy farming means that it is generally economically viable to correct soil problems such as sodicity that constrain pasture growth. Well-targeted applications of ameliorants such as gypsum for sodicity or lime to correct soil acidity that boost pasture productivity can also increase organic matter inputs to soil and raise SOC stocks.

f. Essential elements (eg. N, P, S, K, Ca) that are required for soil organic carbon and/or soil inorganic carbon transformations may be applied to optimise productivity. Fertilisation can increase SOM inputs and SOC stocks in soils but sequestration benefits may be partially or fully offset by increased greenhouse gas emissions, particularly nitrous oxide with a global warming potential of almost 300 times that of carbon dioxide.

g. Livestock management interacts strongly with soil management. For example, the reduction of pasture consumption by livestock allows litter to build up. In turn, incorporation and decomposition of this biomass creates extra SOC. However, recent research[63] has shown that increased litter can give a 'priming effect' and accelerate breakdown by soil microbes so that the net carbon increase in soils can be small (See Section 5.2.6).

Interaction of non-soil factors with soil properties

h. SOC sequestration rate is generally higher in regions with cool and humid climates than in those where conditions are warmer and more arid for equivalent starting levels and management regimes. Where there is adequate moisture, the rate of decomposition of organic matter by soil microorganisms tends to increase with soil temperature. The optimum for decomposition in temperate climates is 25-30°C. Little decomposition takes place below 10 °C[64].

i. Climate factors may affect total soil carbon through effects on storage of inorganic forms of carbon:
   - The rate of formation of secondary carbonates is generally higher in soils of arid and semi-arid regions than soils in sub-humid and humid conditions.
   - Soils in hot dry climates often tend to have minimal deep drainage, which can lead to precipitation of dissolved carbonates within the root zone. In an irrigated pasture

[63] Mitchell et al. (2016)
[64] Batey (1988)

paddock with negligible deep drainage, carbonate salts carried by irrigation water will likely precipitate in the root zone. This cannot be counted as sequestered atmospheric carbon because it is simply changing the transfer of river water carbonate that otherwise would have flowed out to sea.

In Australia, net primary productivity of agro-ecosystems is controlled mainly by climate and soil nutrient availability[65]. Figure 11a shows estimates of net primary productivity in Australia with current agriculture and climate; Figure 11b shows the ratio between current net primary productivity and that predicted without agriculture (ie. no irrigation, fertiliser addition or off-takes). While in many areas agriculture has increased productivity, in some cases almost two-fold, the combination of removal of vegetation and land cultivation has generally depleted SOM. Reduced biomass inputs and loss through increased disturbance and vulnerability of top soils to erosion have negatively affected SOC levels.

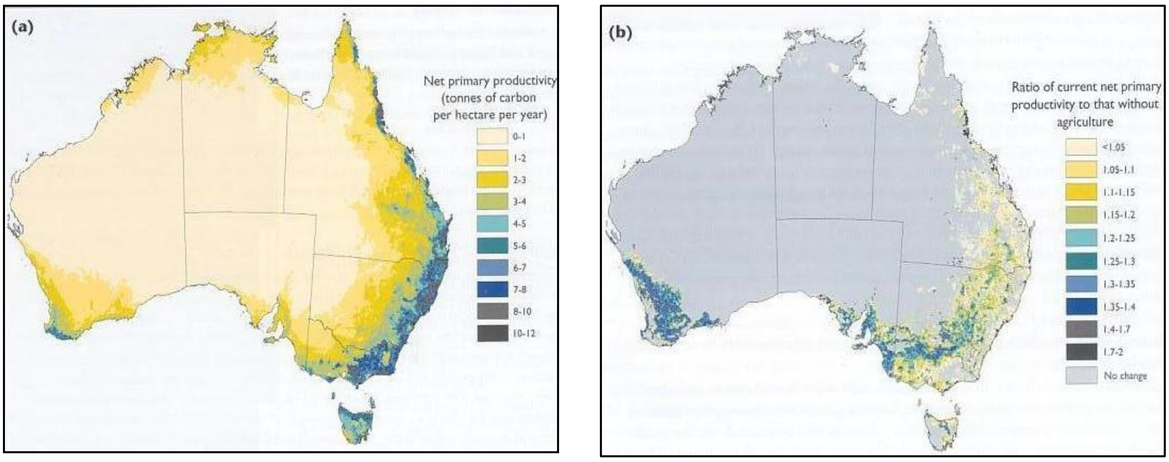


Figure 11. (a) Predicted mean annual net primary productivity of Australian ecosystems under the current climate and agricultural systems, and (b) ratio of current mean net primary productivity to that without agriculture (high-ratio areas are due to additions of fertilizers)[66] (Raupach *et al.* 2001; cited by McKenzie *et al.* 2004).

In Australian dairy regions, a long-term view is essential to soil management for continued pasture productivity[67]:

> *It is a great irony that in Australian agriculture, where the shortage of both water and nutrients greatly restricts yield, it is the loss of both precious water and nutrient beneath crops and pastures that is the fundamental cause of problems such as salinity and acidification. We can turn what is wasted into wealth.*

Agricultural and resource management experts generally recognize the challenges of managing soils in Australia where climate variability is amongst the highest in the world. Extended droughts and severe flood events mean that the proportion of years when productivity and soil properties can be managed in a way that enables optimal SOM inputs and decomposition is low.

In addition to biogeophysical factors, economic considerations also influence how much carbon is sequestered in agricultural soils. Estimates of the cost of using carbon sequestration to mitigate climate

[65] McKenzie et al. (2004)
[66] Raupach *et al.* (2001); cited by McKenzie *et al.* (2004)
[67] Williams and McKenzie (2008)

change are sensitive to assumptions about the dynamics of carbon price, the opportunity cost incurred by adopting the 'sequestering' practice, the dynamics of sequestration, and the use or non-use of discounting to compare benefits and costs that occur at different points in time[68]. The complexity of analysing economic influences on the feasibility of climate change mitigation through SOC sequestration adds to the biophysical-based challenges of actually achieving climate change mitigation. Some analyses have been conducted for southern Australia for either cropping land[69] or changing from cropping and grazing land[70] and these indicate that even optimistic carbon pricing would be insufficient to drive adoption of practices for SOC storage. For example, taking into account the cost of nitrogen fertiliser needed to stabilise SOC to help meet 'permanency' requirements of carbon markets, the minimum price needed for a net profit from SOC sequestration in Australian cropping lands is likely to be $36 per tonne CO_2-e[71]. Increased profitability from higher productivity associated with better soil health seems more likely to give a favourable cost-benefit ratio. A price on carbon may then provide additional income but full analysis of all project costs associated with participating in the carbon market is recommended for each proponent. The box below provides illustrative estimates for a soil carbon sequestration project in dairy pastures.

2.7 Illustrative calculations for dairy farmers

The calculations in the boxes in this section are intended to illustrate some challenges in quantifying SOC sequestration and assessing the risks and opportunities of 'soil carbon practices' on dairy farms in southern Australia. The values should not be interpreted as a real reflection of possible costs or gains and it is highly recommended that farmers and land managers make analyses using farm-specific data and seek up-to-date information from a trusted expert before committing to a soil carbon sequestration project. Scientific understanding, government policy, carbon prices and market opportunities are progressing rapidly. Some sources of credible information are provided in Section 5.3 of this report.

Handy factors for carbon calculations (FAO 2018)

One tonne carbon = 3.67 t carbon dioxide (CO_2) equivalent

Tonnes carbon per ha = % soil organic carbon x soil bulk density x sampling depth (cm)

% Soil organic matter = 1.72 x % soil organic carbon

Global warming potential (GWP) nitrous oxide (N_2O) = equivalent to 298 CO_2 equivalents (CO_2-e)

Global warming potential (GWP) methane (CH_4) = equivalent to 28 CO_2 equivalents (CO_2-e)

GWP is a relative measure of how much heat a greenhouse gas traps in the atmosphere. The value can change over time with changes in the composition of the atmosphere and calculation methods. These values are from the IPCC Fourth Assessment Report (AR4) as used for accounting in national inventories for the Kyoto Protocol.

[68] Thamo et al. (2016)
[69] Grace et al. (2010)
[70] White and Davidson (2015)
[71] Lam et al. (2013)

Biomass needed to increase SOC from 3% to 5% in top 10cm pasture soil (Baldock and Broos 2008)

To increase SOC from 3% to 5% in the upper 10 cm of soil in a dairy pasture, 24 t C/ha would have to be added to the soil. Since plant residues contain approximately 45% C, this would equate roughly to 50 t/ha dry matter (DM). If this increase was to occur over 5 years, then an additional net amount of 10 t DM/ha above current levels would be required annually. Since at least 50% of the added plant residues will decompose, annual minimum additions above current inputs of approximately 20 t DM/ha per year on average would be required to increase SOC content from 3% to 5% over 5 years.

Figure 12 shows that to achieve this aim from above-ground parts of pasture plants at Ellinbank, a high fertility dairy region in West Gippsland Victoria, pasture production would have to be *tripled* without increasing stocking rate. This appears to be an impossible challenge, particularly in drought years.

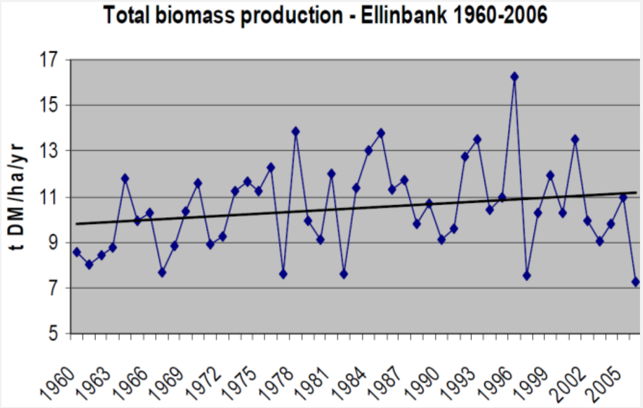


Figure 12. Total biomass production under grazed dairy pasture between 1960 and 2005 at Ellinbank Vic. (Warren Mason, pers. comm.).

Could income from carbon credits make actions to increase SOC viable?

The price under the Australian Government's Emissions Reduction Fund reverse auction purchase of carbon credits has been around $11 to $13 per tonne CO2e. The hypothetical estimate of the price necessary to offset all costs of implementing changes in management of dairy pastures given here does not take into account the productivity and efficiency benefit. It is intended to illustrate some of the costs relevant to entering into a formal contract for sale of offsets based on 2009 data and should not be taken as an actual situation under present cost-benefit analysis.

The values in Table 6 suggest that for carbon trading to be economically attractive for a dairy farmer, the carbon price would have to be at least $200 per tonne CO2e.

Table 6. Value of several options for the utilisation of one tonne of pasture.

Uses for one extra tonne (dry weight) of high quality pasture	Approximate gross value of one tonne of pasture
a. Produce hay bales	$150
b. Feed to cows and convert into milk (750 litres)	$260
c. Allowed to decompose on the soil surface to produce soil carbon (traded on a one-off basis at $25 per tonne CO2e)*	$21 (1 x 0.45 x 0.5 x 3.67 x 25)
d. Allowed to decompose on the soil surface to produce soil carbon (traded on a one-off basis at $250 per tonne CO_2e)*	$206 (1 x 0.45 x 0.5 x 3.67 x 250)

* Assuming that the one tonne pasture, when dry, contains 45% C; and ends up with 50% decomposition to create 0.23 tonne soil carbon (a mix of particulate organic matter and humus). 1 tonne C = 3.67 t carbon dioxide equivalent (CO_2-e). It is assumed here that the four options would have the same amount of root material associated with the extra tonne of pasture DM production.

It is important to note that the cost of the fertiliser used to produce the extra tonne of pasture has to be taken into account when calculating the costs and benefits of the scenarios outlined in Table 6. This calculation uses late 2009 fertiliser prices (Dairy Australia 2009),[**] and composition of urea (46% N = $500/tonne), single superphosphate (9% P = $320/tonne), gypsum (14% S = $100/tonne) to estimate respective N, P and S costs as $83, $50 and $14.

1 tonne C as humus requires sequestration of 83 kg N, 14 kg S and 20 kg P. Using above fertiliser prices, this gives a nutrient input cost of about $150 per tonne of humus-C. If the soil organic carbon is dominated by particulate organic matter, the ratios shown in Figure 4 suggests that a nutrient value of $80 per tonne of soil carbon is appropriate for the examples (options c and d) shown in Table 6. Therefore, the four options in Table 6 would have a nutrient cost of about $20 associated with the one tonne of pasture that converts to 0.23 tonne soil carbon for options c and d.

In the case of options c and d, the carbon (and associated nutrients) are required to be maintained in the stable SOC pool (e.g. in humus) for 25 or 100 years to meet the 'permanency' requirements of the Emissions Reduction Fund soil carbon sequestration methods and to count towards Australia's greenhouse gas reduction international obligations.

[**] Dairy Australia (2009): With late-2009 fertiliser prices (urea, 46% N = $500 / tonne; single superphosphate, 9% P = $320 / tonne; gypsum, 14% S = $100 / tonne), the respective N, P and S costs are $83, $50 and $14.

3. Soil carbon sequestration accounting challenges

3.1 Measurement

3.1.1 Introduction to measurement methods and sources of error

The internationally accepted operational definition of SOC is the organic carbon present in the fraction of the soil that passes through the 2 mm sieve[72], known as the fine earth fraction. This definition is used in conjunction with a standard sampling depth of 30 cm for greenhouse gas inventories used in national reporting to the United Nations Framework Convention on Climate Change (UNFCCC) against international climate change targets and for most carbon credit trading regimes.

Soil sampling protocols and conventional laboratory analyses can be used to directly measure organic carbon stocks. The protocols typically involve designing a sampling strategy, sampling the 0–30 cm soil layer and measuring the organic carbon concentration, bulk density and gravel content to derive the organic carbon stock of the soil in this layer[73]. The methods are complex, time-consuming, expensive and involve much sample handling and preparation. In combination, all of the procedures involved are susceptible to analytical inaccuracies. The challenges associated with conventional techniques are compounded if monitoring is needed for SOC in deeper soil layers. Because these conventional methods for measuring changes in SOC stocks are impractical, efforts have been made to develop rapid, practical, accurate and cheaper methods. Proximal soil sensing provides a range of tools that are now being explored to more efficiently measure the organic C stock of soil profiles[74]. The accuracy of these methods is improving and the capacity to take more samples in a limited time enables the uncertainty to be reduced to a level comparable with conventional direct measurements. Proximal techniques are now accepted in some carbon credit accounting methods such as those developed for Australia's Carbon Farming Initiative (See Section 3.1.3).

Sampling and analysis protocols for SOC stocks should take into account the heterogeneity due to grazing activities and natural spatial variability. This is critical to maximise the capacity to detect soil carbon stock changes, and the design of sampling protocols is critical if uncertainty in results of SOC stock change is to be minimised[75]. Table 7 summarises significant sources of error in SOC stock change measurements[76].

[72] Whitehead et al. (2012)
[73] FAO (2018)
[74] Viscarra Rossel et al. (2016), (2017)
[75] Hobley and Willgoose (2010)
[76] Vanguelova et al. 2016

Table 7. Sources of error in SOC evaluation at sample, plot and landscape scales. The sources likely to produce high errors are **in bold**. (Table from Vanguelova et al. 2016)

Sample	Soil composite samples are not homogenised
	Different analytical procedures for C applied
	Bulk density is not assessed correctly
	Coarse fragments volume not assessed
	Separation of soil horizons and layers not done accurately
	Inappropriate soil sampling time
Profile	Sampling by horizon versus soil depth depending on research aims
	Sampling at not full soil depth to account for vertical variability
Plot	**Micro-spatial variability not accounted for (not appropriate sampling strategy)**
	Statistical sampling error due to different sampling schemes
	Different inventory teams are not harmonised
	Lacking quality of the geo-referenced (or the reported values)
	Not adequate numbers of sampling points
	Bulk density and coarse fraction content not analysed
	Analytical (measurement) errors including sample preparation
	Missing values, recording and truncation errors
	Model errors (e.g. from the selection of inadequate pedotransfer rules or functions, inadequate model constants and conversion factors, etc. not site/soil specific calibrated)
Landscape /National	Lack of local and regional representativeness of sampling plots
	Important strata are underrepresented (e.g. wet mineral soils or peat soils)
	Lack of tree species/forest cover maps
	Lack of accurate soil/hydrology maps
	Landscape insufficient resolution of climatic data

Practical guidance on sources of errors when sampling and analysing soil content

The location of sampling points in a landscape must take into account spatial variability. Apart from knowing where to sample, deciding when to sample is also a challenge. Temporal variability associated with seasons of the year and cycles of drought and heavy rain needs to be taken into account when developing carbon assessment programs for entire farms and districts. Errors in the assessment of soil carbon credits will not be accepted for the Government Emissions Reduction Fund and will affect the confidence (and therefore the price) for offsets in secondary markets.

Soil sampling should always be conducted by operators who are properly trained and independent to avoid incorrect calculations of soil carbon levels or change in a pasture soil, and this is a requirement under the Government Emissions Reduction Fund measurement-based method. Other reasons for measurement inaccuracies (associated with bias or a lack of precision) include:

a. Surface vegetation/litter included with the sample, instead of being separated from the soil sample, according to Australian Greenhouse Office (AGO) protocols (McKenzie et al. 2000);
b. Large roots (>50 mm) not separated; root material (alive or dead) <50 mm diameter within soil samples should be treated as part of the soil organic matter;
c. Biased sampling, eg. directly beneath a grass tussock only, rather than both 'beneath tussock' and 'between tussocks';
d. Failure to take into account the gravel content of a soil profile;
e. Mistakes in bulk density assessment, eg. accidental compression of the soil when sampling with unsuitable equipment and/or techniques or unrepresentative sampling sites;
f. Calcium carbonate nodules accidentally counted as organic carbon when using the Leco method. Where soil organic carbon monitoring occurs in gilgaied landscapes, the inclusion of lime nodules in soil samples can greatly boost soil carbon readings and give the false impression that the organic carbon content of a soil has suddenly improved;
g. Use of the Walkley-Black analytical procedure (without appropriate corrections) for organic carbon analysis rather than the recommended Leco method.
h. Selection of a sub-set of the results that suits a pre-conceived idea of the result;
i. Reporting data without clearly specifying the sampling depth or comparing results that include subsoil carbon with analyses restricted to 0-30 cm.

3.1.2 The question of sampling depth

It is widely accepted that agriculture has a large impact on SOC storage and the global carbon cycle (See Section 2). However, studies on the effects of agriculture on SOC cycling have frequently focused on carbon dynamics in topsoils only[77,78] and data are frequently available only for the surface 30cm of soil as required in most international and Australian measurement protocols. The 0 to 30cm depth has been estimated to hold about 55% of the total SOC stock to 1 m, 62% to 1.5 m, 67% to 2 m and 77% of all SOC stored to a depth of 3 m[79].

[77] Poeplau et al., (2011)
[78] Rabbi et al., (2015)
[79] Lal (2018)

The extent to which measurements based solely on surface soils correctly represent the influence of agricultural practices on total SOC storage is still debated. The drivers of SOC storage vary with depth[80,81,82] and while there is some older evidence of actively cycling subsoil carbon associated with deep root activity[83] subsoils have generally been seen as a repository of slow-cycling organic carbon. A recent study[82] has challenged this acceptance of subsoils as a store of stable organic carbon, showing analysis of SOC cycling down to 1 m under native vegetation and agriculture (cropping and grazed pastures) in eastern Australia. Examination of different SOC fractions and isotopes led the study authors to conclude that large losses of young carbon can occur down the entire soil profile within decades. Further, organic carbon storage in soils appeared input driven down the whole profile.

On dairy farms, it has been suggested that more efficient use of water that is often lost via deep drainage in high rainfall years, may be achieved through planting deep rooted perennial shrubs (eg. tagasaste on light-textured soil). These species sequester organic carbon deeply, and may provide forage, but they may also lead to higher rates of nitrogen mineralization in topsoils through recycling of nitrogen from the deep subsoil to the surface layers[84]. Perennial shrubs are now common in rangeland grazing systems, but there has not been a comprehensive evaluation of suitable options for the deep placement of organic carbon via root systems for a broad range of pasture species. To be considered as a practical management option, the evaluation must also show that it can be done in a way that does not decrease dairy farm profitability.

Ongoing research will improve understanding of SOC dynamics and clarify whether sampling of SOC to a depth of 30cm is adequate to indicate the impacts of management on SOC stocks in agricultural soils. Future changes may then be introduced to measurements and modelling of soil carbon offsets in carbon pricing schemes as well as in national greenhouse gas inventories. It is strongly recommended that farmers or land managers seek up-to-date information on measurement protocols for soil carbon offsets, including on the depth of sampling.

3.1.3 Existing measurement protocols

Recent advances in measurement

Sampling and analysing of soil to determine soil properties that affect productivity is vital for decision-making by farmers and is also required to understand carbon sequestration potential and inform decisions on possible participation in carbon credit markets. The cost and time for measurement relative to possible financial returns can be a strong deterrent for participation in these market. Measurement and reporting protocols specified under the Emissions Reduction Fund are designed to be rigorous in order to ensure integrity of the carbon credits. They are based on credible scientific research for both modelling and measurement approaches.

Projects under the National Soil Carbon Program built on earlier work by the University of Sydney[85,86] as well as legacy datasets for Australian soils are used in Australian models to reduce the monitoring costs of soil

[80] Jobbagy & Jackson, (2000)
[81] Hobley et al. (2017)
[82] Hobley & Wilson, (2016)
[83] Trumbore et al., (1995)
[84] Angus et al. (2006)
[85] McBratney and Minasny (2008)
[86] McBratney et al. (2009)

carbon for landholders. The ability to rapidly assess various organic amendments using mid infra-red (MIR) and near infra-red (NIR) spectroscopy provides data to improve modelling across scales in the national greenhouse gas inventory Full Carbon Accounting Model (FullCAM), and industry models such as DairyMod. These data and methods have been used in a soil carbon crediting method (See below). *In situ* near infra-red (NIR) field estimation of SOC stocks in grazing lands (including rangelands and forestry) is also providing ways reduce the cost of monitoring. Research on proximal models using NIR and MIR continues to improve confidence in the measurements and modelling[87] and these advances will continue to be incorporated in method development.

Australian Emissions Reduction Fund Methods

Two soil carbon methods have been developed for use in Australia's Emissions Reduction Fund[88]:

- a model-based method, the *Carbon Credits (Carbon Farming Initiative—Estimating Sequestration of Carbon in Soil Using Default Values) Methodology Determination 2015;* and
- a measurement method, the *Carbon Credits (Carbon Farming Initiative) Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018* which improves on a 2014 measurement method for grazing systems.

The method, *Estimating sequestration of carbon in soil using default values,* is based on the use of default rates for soil carbon stock change over time, in response to changes in specified management practices for cropping systems. These default values were predicted using simulation results obtained by applying the FullCAM tool developed for, and used in, the Australian National Greenhouse Gas Inventory. The values are conservative as required under the scheme Offsets Integrity Standards.

The measurement method is more complex than that using default values. It includes detailed requirements for developing and implementing a sampling strategy, analytical/measurement methods and managing uncertainty for both baseline (without project) and over time after the project starts. The protocols aim to minimise the sources of error and uncertainty in results of changes in SOC stocks resulting from a change in management practice and the Explanatory Statement that was developed[88] in conjunction with the method is a valuable source of information for a land manager considering entering into a soil carbon project.

FAO Livestock Environmental Assessment and Performance (LEAP) Partnership Guidelines

A Technical Working Group engaged by the FAO LEAP Partnership has drafted guidelines for estimating soil carbon in livestock production systems to support consistent reporting of environmental impacts, *Measuring and modelling soil carbon stocks and stock changes in livestock production systems – Guidelines for assessment*[89]*.* This document contains detailed guidance on methods for quantifying soil organic carbon and changes due to management practices. The recommended protocols for measurement are broadly consistent with the Australian Emissions Reduction Fund methods.

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[87] Viscarra Rossel et al. (2016), (2017)

[88] http://www.environment.gov.au/climate-change/government/emissions-reduction-fund/methods

[89] http://www.fao.org/partnerships/leap/publications/

3.2 Accounting for nitrous oxide emissions

Nitrogen is essential to plant and animal growth and maintenance. Nitrogen is abundant in the atmosphere in a highly stable gaseous form, N_2 (di-nitrogen), but for plants to use it, it needs to be available in the soil in reactive forms. Under certain conditions, nitrogen in the soil readily converts into other forms, one of which is nitrous oxide (N_2O), a strong greenhouse gas (298 times as strong as CO_2).

Soil carbon sequestration derives ultimately from plant growth, which depends on access to nitrogen in the plant cells. Hence, the carbon and nitrogen cycles are closely bound in the terrestrial ecosystem and actions to increase soil carbon sequestration require the presence of nitrogen (Figure 13). It follows that since reactive forms of nitrogen in soils readily convert to N_2O, there is always a risk that adding N to soils (e.g. as urease) to promote growth and foster soil carbon sequestration will lead to N_2O emissions. Nitrogen can also increase soil carbon release into the atmosphere by accelerating microbial decomposition. The net greenhouse effect of carbon sequestration and N_2O emissions can sometimes be an increase in the global warming effect.

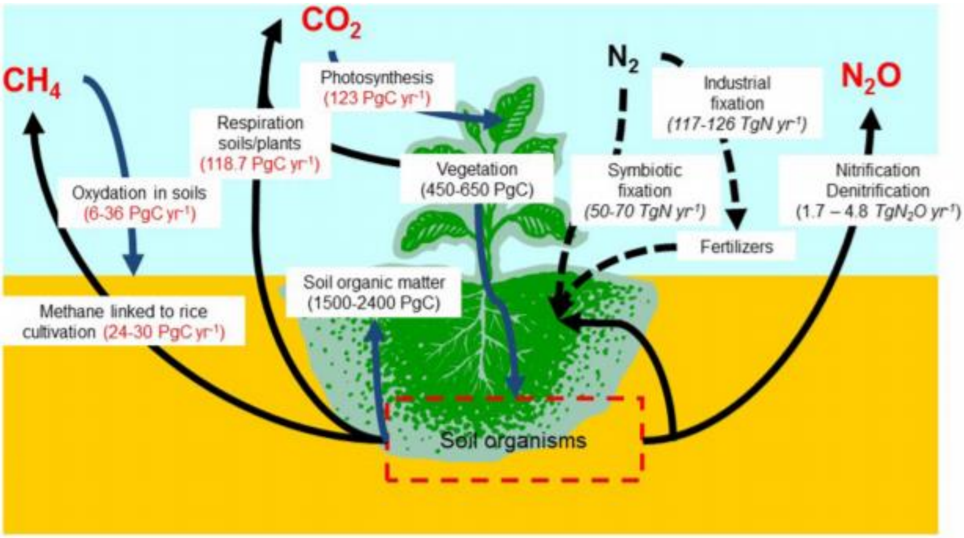

Figure 13. Soil greenhouse gas fluxes illustrating the close link between carbon and nitrogen cycling (From Ciais et al. 2013)[90].

A major investment by the Australian Department of Agriculture supported the National Agricultural Nitrous Oxide Research Program (NANORP), which ran in parallel with the National Soil Carbon Program from 2012 to 2016[91]. In addition to undertaking projects to measure N_2O emissions and providing new data for improved inventory and emissions factors for a range of agricultural systems, the NANORP and NSCP cooperated on understanding the interactions between SOC and nitrogen in agricultural soils, including in dairy pastures (Figure 14).

[90] Ciais et al. (2013)
[91] DAWR (2016)

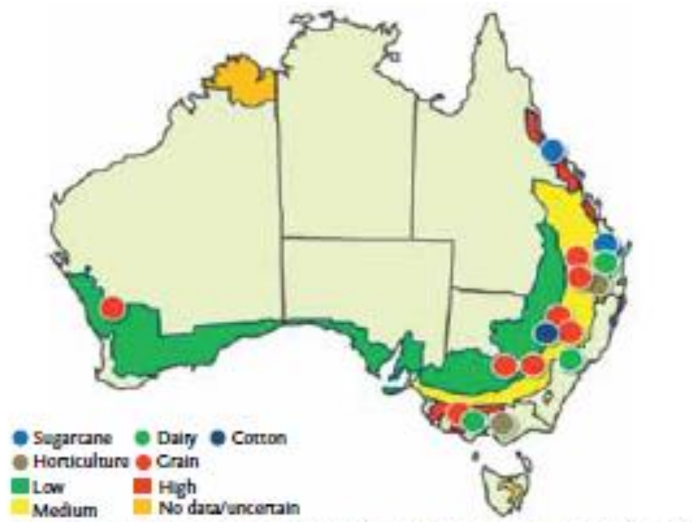

Figure 14. Map of the anticipated relative scale of N_2O emissions (Green – low, Yellow – Medium, Red – high). Dots show the sites for research projects measuring nitrous oxide emissions, which include 3 sites in dairy pastures (green dots). (From DAWR 2016) [91]

4. The debate on soil carbon sequestration

4.1 Background

Soil carbon is naturally highly variable across the landscape and over time due to factors such as soil and vegetation characteristics and climate factors. While variability in SOC content is largely explained by climate and soil properties, human activity also plays a role. In Australia this is most obvious in the general loss of soil carbon from agricultural soils since the 1800s following conversion from natural land cover. The carbon balance of agricultural soils is expected to continue to change as farming practices evolve and as factors such as elevated atmospheric CO_2, global warming and altered rainfall amounts and distribution take effect. In some regions, observations are showing that the climate is already changing from what was considered 'normal' seasons over the past hundred or more years of records.

With this degree of complexity in the natural system and limited data records to understand the unprecedented nature of human interventions and climate changes, it is hardly surprising that there are a range of views on what the impacts mean. An area of ongoing debate is how SOC will respond to various management and environmental factors, and how much changes in the carbon content of soils can add to, or offset, greenhouse gas emissions now and in the decades ahead. Some differences in opinion undoubtedly arise through inaccurate reporting which is inevitable in a new and complex area of 'public interest science'. Misinterpretation of units used to quantify SOC stocks or greenhouse gas emissions and unbalanced accounting (sometimes comparing net emissions and gross emissions) have caused confusion (See Section 3.1). For example, counting SOC sequestration resulting from increased plant growth after application of nitrogen fertiliser to pastures but not counting any associated nitrous oxide emissions will overestimate the climate change mitigation of this management practice. Ensuring use of credible scientific or industry sources helps manage the risks of misleading information, but it is also important to stay up-to-date in areas where the science is not yet resolved and there is such a large amount of active research.

This section provides a summary of recent contributions to the ongoing debate on the significance of SOC stock changes and potential climate change mitigation achievable through soil carbon sequestration on scales from individual farm to global. All aspects of the debate cannot be fully covered or resolved in this report (and it will be immediately out-of-date). However, from the farmer perspective, it is worth noting that regardless of whether 'permanent' SOC sequestration is limited or represents a substantial offset for anthropogenic greenhouse gas emissions, there is widespread consensus that activities promoting increase or decreasing loss of SOC are very likely to provide value through productivity and sustainability benefits.

4.2 Views and emerging science in the sequestration debate

Johnston et al. (2017) and Poulton et al. (2018)

Some of the longest-running experiments on soils have been conducted at Rothamsted in southeast England. These trial sites provide the data underpinning one of the most widely used soil carbon models, Roth C, which also underpins modeling of soils in FullCAM for Australia's national greenhouse gas reporting. Measurements over 7 to 157 years in 16 long-term experiments with trials on three soil types, compared SOC in 114 treatments that included organic amendments, nitrogen fertilizers, introducing pasture leys into continuous cropping systems, and converting arable land to woodland. In only 65% of cases with good practice applied, SOC in the 0–23 cm depth increased at a rate of more than 0.7% per year. The largest increases in SOC occurred in treatments where high levels of manure were added (35 tonnes fresh weight per hectare per year, equivalent to about 3.2 t organic C /ha/year). However, results showed that when only inorganic nitrogen fertiliser was added a decline in SOC occurred, and that manure was only effective in increasing SOC if applications exceeded 10 t/ha/yr. The best results for SOC sequestration were wilderness succession to woodland, or conversion to permanent pasture. It could be argued that the practices showing substantial SOC sequestration do not represent common or practical farm management. The authors concluded from this analysis of long-term research trials that:

- For practical farm businesses, there are "severe limitations" to achieving ongoing significant increases in soils; and
- Even small increases in SOC can have substantial positive effects on soil health and production.

He et al. (2016)

A study published in 2016 using radiocarbon dating of soils provided evidence that the average age of soil carbon is more than six times older than previously thought. When combined with previous models of carbon uptake, this research indicates that:

- The assumed potential for carbon sequestration has been overestimated by as much as 40%, which, in turn, means that it would take hundreds or possibly thousands of years for soils to soak up the large amounts of the extra CO_2 pumped into the atmosphere by human activity.

Garnett et al. (2017)

The Food Climate Research Network (FCRN), based in Britain at the University of Oxford, conducts and communicates research on food systems and sustainability. FCRN undertook an assessment of the claims that carbon sequestration in lands used for grazing livestock provided a major greenhouse gas offset. While this synthesis report focussed on grass-fed systems generally, including extensive beef cattle and small ruminants as well as dairy cattle, there is no evidence that the conclusions would not apply to intensive dairy farming in Australia. The report concluded that:

- "Better management of grass-fed livestock, while worthwhile in and of itself, does not offer a significant solution to climate change as only under very specific conditions can they help sequester carbon"; and
- "sequestering of carbon is small, time-limited [and] reversible".

Savory (2015)

The Savory Institute[92] has developed a holistic grazing method based on high intensity, intermittent grazing on rotating areas of land. Their methods and data have not been peer reviewed but cattle and sheep producers in several countries subscribe to the Savory methods and testify to production and landscape health benefits. The claims of soil carbon sequestration are much higher than in published research studies in scientific journals. The Savory Institute[93] estimates that:

- Application of the Savory holistic grazing method across the world's grasslands can produce rates of carbon sequestration of sufficient magnitude to not only offset all greenhouse gas emissions from ruminant livestock but potentially from all human activities.

Norborg et al. (2016)

This study is one of several that have undertaken critical review and analyses of global data [94,95] and failed to find evidence for the very high rates of soil carbon sequestration claimed by Allan Savory[93]. The study did not dismiss the value of good management of the grazing resource but concluded that the potential sequestration was overstated:

- Improved grazing management on all grasslands could store on average around 0.35 tonnes C per ha per year, a rate seven times lower than the rate used by the Savory Institute.

Gosling et al. (2017)

A comprehensive review of published studies examined the basis of the assumption that agricultural soils can sequester significant atmospheric CO_2. The authors sought to determine the potential for conversion of arable cropland to grassland in the UK to sequester carbon in the short to medium term and assess potential limiting factors. Across 14 sites in the UK, there were no differences in SOC stocks in the top 30 cm between grassland up to 17 years old and arable cropland. However, distribution patterns differed between the two land use types, with SOC concentrated in the top 10 cm under grassland. There were also significant differences in microbial communities between arable and grassland soils. Grassland soils had higher microbial biomass and lower bacterial dominance. Experimental land use conversions indicated that these changes occurred within one year of land use change. One of the study's conclusions indicates that the practice of adding nitrogen fertilizer to dairy pastures may overcome a significant limitation on SOC sequestration:

- The failure of grassland soils to accumulate SOC shown in several studies can be attributed to

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[92] https://www.savory.global/
[93] https://www.ted.com/talks/allan_savory_how_to_green_the_world_s_deserts_and_reverse_climate_change
[94] Garnett et al. (2017)
[95] Nordbborg et al. (2016)

low productivity resulting from reduced available soil nitrogen.

Luo et al. (2010)

Many of the contentious issues on the potential climate change mitigation of SOC sequestration relate to conversion of land between cropping and improved pasture. Results of a review of global and Australian data were that evidence is highly variable and, even for the same management practice, SOC outcomes differed with different climate and soil combinations. No consistent correlation was found between increase in SOC and duration of application of a particular management practice, raising doubt on the value for climate mitigation of long-term adoption of good management practices.

Overall, this review indicated that cultivation for 40 years in Australian agricultural systems resulted in a SOC loss of approximately 51% in the surface 10 cm of soil. Adoption of conservation agricultural practices generally increased SOC, with the greatest potential for increase (only 18%), attributed to introduction of perennial plants into rotations for cropping sites. Conclusions on how to improve understanding of the relationship between management and SOC sequestration in Australia included:

- Data on SOC change and dynamics for soil layers below the top 30 cm is a gap in knowledge for understanding the contribution of change in root growth with various agricultural practices;
- Elevated atmospheric CO2 concentration, global warming and rainfall change could all alter the carbon balance of agricultural soils into the future and should be investigated; and
- Because of the complexity of soil C response to management and environmental factors, a systems modelling approach supported by sound experimental data would provide the most effective means for analysing the impact of different management practices and future climate change on soil C dynamics.

Lam et al. (2013)

A meta-analysis of published data from field studies across Australia on SOC response to improved agricultural practices in cropping land, specifically conservation tillage, residue retention, conversion to pasture, and fertiliser N application, indicated the greatest change in SOC with improved practices occurred in the surface 10 cm. Changes were attributed to enhanced biomass production (above- and below-ground), higher return of residues from litterfall to the soil, and improved soil aggregation that protects SOM from rapid decomposition. The analysis did not detect evidence for consistent changes in deeper layers. The data synthesis suggested a range of factors challenging confidence in published results on SOC sequestration in agricultural land:

- The relative SOC gain appeared to decrease with time, regardless of which agricultural good practice was introduced into Australian cropping systems;
- After three to four decades, the use of pasture in a farm system out-performed the use of any of the cropping good practices evaluated in this analysis;
- Detected increases in SOC with management change were small (7 to 13%) relative to the range of sources of variation, including sampling errors, spatial variability and measurement and analysis uncertainties;
- Management-induced increases in SOC in the top 10 cm soil layer are vulnerable to environmental and management pressures and may be readily lost again;
- Serious gaps in scientific knowledge exist regarding the capacity of Australian soils to store carbon under future climates, such as warmer and drier conditions and higher atmospheric CO_2 levels.

Robertson et al. (2016)

Data from measurements of SOC stocks at 615 sites in pasture and cropping systems across Victoria covering a range of soil types and management regimes, which included dairy pastures, was used to assess the relationships between the SOC stocks and environmental, soil and management factors. SOC varied from 2 to 239 t C/ha in the top 30 cm, with almost 80% of this variation explained by climate factors (annual rainfall or humidity (vapour pressure deficit)). An additional small amount of difference in SOC could be accounted for by texture-related soil properties and only a minor (often non-significant) amount of the remaining variation was attributable to management. Modelling approaches in other studies for Victorian farms[96] also found large variations in the response of SOC stocks to management practices. The relationships between SOC and environment, soil and management factors found by Robertson et al. were scale-dependent and, within individual regions, the apparent influence of climate and soil properties on SOC stock varied. In some regions, the data could not explain much of the variation in SOC stocks. However, overall the results across Victoria suggest that:

- There is a hierarchy in influence on SOC stock decreasing from climate to soil properties to management class to management practices; and
- Management practices, such as stubble retention, minimum cultivation, perennial pasture species, rotational grazing and fertiliser inputs, were not significantly related to SOC stock in the agricultural soils sampled across Victoria.

Case Study – Portugal

The following information, from an article entitled '*Portugal gives green light to pasture carbon farming as a recognised offset*' (Watson 2010), is relevant to managers of degraded land in Australia where pasture production may be able to provide carbon credits for landholders.

"The Portugese government will pay an estimated 400 farmers for improving grassland in an area of up to 42,000 hectares with the aim of sequestering 0.91 million tonnes of carbon dioxide equivalents (CO_2e) from 2010 to 2012. To achieve this, the farmers used a technique known as 'sown biodiverse permanent pastures rich in legumes' (SBPPRL). Degraded soils are targeted. The system involves no-till seeding of rainfed pastures with a biodiverse mix of grasses and legumes that contains up to 20 different species and cultivars, followed by '*careful management with sustainable stocking rates'*. Trials of SBPPRL across 84 properties showed that SOM increased on average by 0.2% a year, which corresponded to 5 t/ha/year CO_2e." The method is described in Teixeira et al. (2011).

Sheep were the main grazing animals within the SBPPRL system. They return a large proportion of the material they harvest in the form of manure. In contrast, in dairy systems large amounts of carbon and nutrients leave grazing paddocks in the form of milk.

To reflect the limited permanence of this soil sequestration beyond the contract period, payments are about 2/3 of the price of CO_2e on the European Union Emissions Trading Scheme.

The developer of the SBPPRL system, Professor Domingos, noted that the system is particularly suited to soils with low soil organic matter and it appeared to have been relatively successful in these land types after implementation (Proenca et al. (2015). However, farmers who have already increased soil organic matter to levels close to the natural steady state would be unlikely to achieve significant carbon credits.

[96] Meyer et al. (2016)

4.2.1 Debate on soil carbon sequestration at global scale

The "4 per 1000 Initiative" launched at the COP21 meeting in Paris in 2015 (www.4p1000.org) promotes increasing soil carbon storage as a way of offsetting the annual increase of carbon dioxide in the atmosphere. The initiative proposes that even an annual increase of 0.4% in soil carbon, averaged over all soils, would help to limit the global temperature increase to 1.5–2°C, as agreed by over 100 countries. The initiative is discussed in Section 5.1.2.

While there is consensus on the value of SOC for improving soil health and agricultural production for global food security and ecosystem services, there is less agreement on whether a 0.4% increase across all soils is practicable. Soil carbon sequestration is described by some scientists[97] as the largest potential sink compatible with food production with the size of the potential mitigation possibly as high as 1.2 GtCO2e yr^{-1} in 2030 at US$20 per tonne CO_2e. Other researchers point out the need to consider that the effects of soil carbon are easily reversed with tillage or soil disturbance[98].

Views supporting achievement of the goals of *4 per 1000*

Supporters of '4 per 1000' argue that, calculated relative to global topsoil SOC stocks, 0.4% increase is consistent with published estimates of the technical potential for SOC sequestration[99]. While conceding that the achievable potential is likely to be substantially lower given socio-economic constraints[98], they present calculations showing that land-based removals from additional SOC sequestration could significantly contribute to reducing the anthropogenic CO_2 equivalent emission gap identified from voluntary targets agreed at the 2015 Paris talks.

Regardless of this assertion, to be realistic, the 4 per 1000 target should be implemented by taking into account differentiated SOC stock baselines and the value of reversing current rates of loss in some soils. To inform the potential effectiveness, the benefits of stewardship for both degraded and healthy soils along contrasting spatial scales (field, farm, landscape and country) and temporal (year to century) horizons have been discussed, along with implications for non-CO_2 GHGs emissions (such as nitrous oxide), water and nutrient cycling, and crop yields. Rates of adoption and the duration of improved soil management practices were seen as challenging issues but supporters concluded that SOC sequestration has the potential to support multiple environmental benefits and to achieve the proposed climate change mitigation.

Views challenging the feasibility of the *4 per 1000* initiative

There have been several analyses challenging whether a 0.4% increase in managed soils is really achievable. White and Davison (2016) argue that the whole concept is flawed because the requirement is for a slightly bigger increment in SOC each year as stocks increase to maintain 0.4% increase. Thus it is analogous to compounding bank interest on savings (Figure 15). They conclude that although actions to increase SOC levels are positive to improve soil fertility and agricultural productivity, sequestering carbon in agricultural soils is unlikely to provide a major offset for greenhouse gas emissions[100].

[97] Wollenburg et al. (2016)
[98] Williamson (2016)
[99] Soussana et al. (2017)
[100] White and Davison (2016)

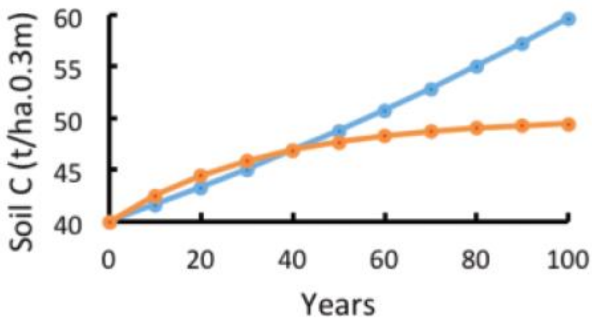

Figure 15. Illustration of the difference between observed pattern of SOC sequestration towards a steady state level where loss is approximately in balance with inputs (orange line) and the hypothetical compounding rate of increase required to achieve '4 per 1000' increase over a 100 year 'permanency' period (blue line). (Figure from White and Davison, 2016).

The '4 per 1000' initiative translates to a goal of sequestering 12000 Tg C per year (1 Tg = 10^{12}g). The feasibility has also been challenged on the basis of stoichiometry constraints. SOM contains nitrogen as well as carbon and the source of the nitrogen needed for global inputs of SOM for 0.4% increase in SOC is not clear. It would require an estimated 100 Tg N per year (assuming a C to N ratio of 12 in SOM), which is equivalent to an increase of about 75% in global N-fertiliser production or a doubling of symbiotic nitrogen fixation across all agricultural systems[101]. Even allowing for an increase in C:N as SOM decomposes in soils (see Table 2), supplying the N required remains a large challenge. Theoretically storage of surplus nitrogen in soils as part of SOC sequestration could reduce N pollution. However, actually achieving this co-benefit in practice is complicated by the fact that excess nitrogen is far from being evenly distributed in landscapes, especially comparing intensive high input agriculture vs low or no-input extensive rangeland grazing systems. In addition, the extent of nitrogen surpluses in intensive grazing and cropping lands is likely to decrease in future due to more efficient management and/or regulatory controls.

The difficulty with strategies such as *4 per 1000* that identify broad targets is that they ignore the great diversity in potential SOC sequestration across the world's agricultural soils. While the potential is high in degraded soils where SOC stocks have been reduced to a low level through past management practices, in soils such as most Australian dairy soils where baseline SOC levels are high, the potential is generally low. Greater climate change mitigation in these already well-managed systems would likely be achieved through targeting reduction in emissions of non-CO_2 greenhouse gases such as nitrous oxide from N-fertilisers or manure management.

5. Recent scientific research

5.1 Major Australian soil carbon research programs 2012-16

The Australian government invested in two major soil carbon research programs, the Soil Carbon Research Program 2009 – 2012 and the National Soil Carbon Program 2012 – 2015[102]. Both were supported by co-investment from agricultural industries, including Rural Research and Development Corporations, State governments, universities and CSIRO. The major findings of the two programs are summarised below.

[101] Van Groenigen et al. (2017)

[102] http://www.agriculture.gov.au/ag-farm-food/climatechange/australias-farming-future/climate-change-and-productivity-research

Together they represent a large body of high quality research and new data that has underpinned method development for soil carbon credits available for voluntary participation in carbon offset projects under the Emissions Reduction Fund or other market mechanisms, and improvements in Australia's national inventory reporting to the UNFCCC.

Soil Carbon Research Program (SCaRP) 2009-2012, led by Dr Jeff Baldock, CSIRO.

Key outcomes

- Developed a nationally consistent approach to assessing soil carbon stocks for some of the major land use and soil type combinations used for agricultural production.
- Developed rapid and cost-effective ways of assessing the total soil carbon, the amount of various forms of soil carbon and soil bulk density.
- Identified land-uses and management strategies with higher soil carbon stocks or potential for enhancing soil carbon at regional level.
- Quantified the inputs of carbon to soils under agricultural systems based on perennial vegetation.
- Provided data for FullCAM, Australia's national carbon accounting tool.

National Soil Carbon Program (NSCP) 2012-2016, led by Professor Ram Dalal, QLD Government.

Key outcomes

- Filling the Research Gaps (for increasing soil carbon)
    - Improved measurements and examination of temporal change in SOC based on use of *in situ* Visible – Near Infra-red and Near Infra-red – Mid Infra-red techniques
    - Crop and pasture management e.g. nitrogen applications, introducing perennial pastures, grazing management, carbon inputs
    - Vegetation management (regrowth, plantation forestry, reforestation)
    - Soil amendment additions to soil (compost, organics, biochar)
- Modelling (measurement and modelling methods linked to reduce costs of project implementation and verification)
- Linking to Carbon Farming Initiative method developments
- Linked Action on the Ground projects to demonstrate practical on-farm applications.

5.2 Key research areas of interest for dairy farmers

5.2.1 Dynamics of the different carbon pools under pasture

Improvement in SOC stocks in pasture systems is mainly via particulate organic carbon (POC)[103]. POC is labile and is broken down relatively quickly to provide energy for biological processes and nutrients for plant uptake. Concentrations of POC in soil are maintained only when there are continuous and relatively high inputs of residues. Soil content will rapidly decrease following significant reduction in SOM inputs and hence POC, even for only a few years (Figure 16). This can happen during extended drought periods.

[103] Baldock (2008)

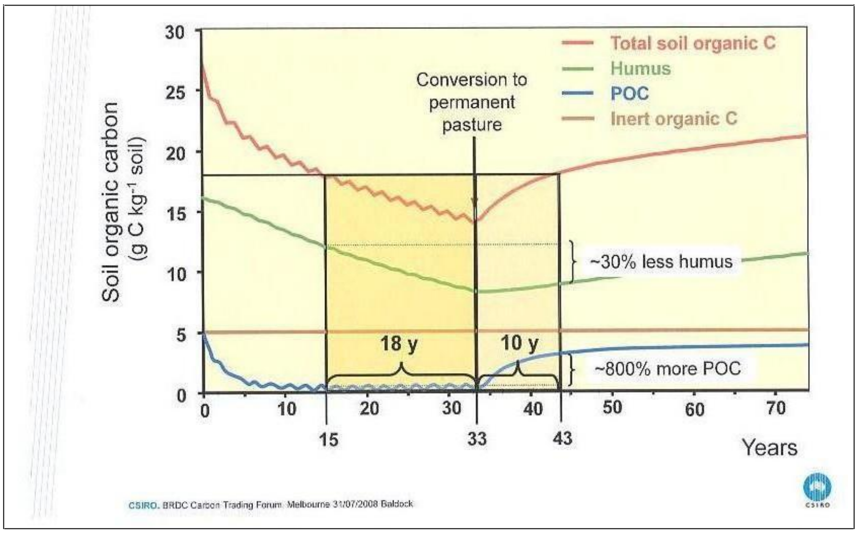

Figure 16 Changes in soil organic fractions following conversion of cropland to permanent pasture (Figure from Baldock 2008). Note the dominance of the particulate organic carbon (POC) increase, in relation to the much smaller humus increase, 10 years after conversion.

While POC is often the dominant fraction in the soil, as illustrated in Figure 17 the proportions of organic carbon fractions under pasture vary from site to site. Many Australian soils have high concentrations of charcoal from past burning events, possibly spanning millenia.

The organic carbon content of soils used for dairying are typically very high relative to most Australian soils, with SOC often in the range of 3 to 7% in the top 10 cm[104]. Some natural organic molecules, such as waxes, e.g. cutin and suberin, can resist microbial decomposition because of certain molecular properties and these forms may be referred to as having 'intrinsic recalcitrance'. Future availability of grass, legume and herb species that increase the recalcitrance of residues, they would be of value for dairy farmers in sequestering soil carbon, provided they do not compromise other soil factors and nutritive value for livestock that affect production and profitability.

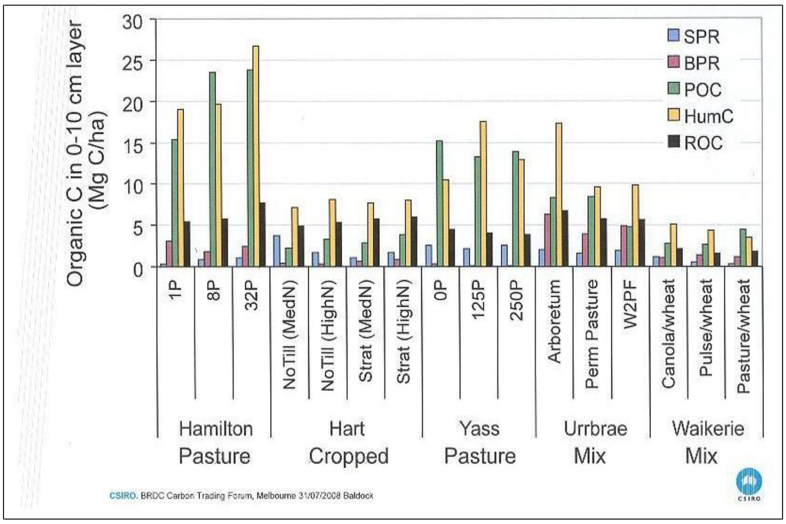

Figure 17. Variations in the amount of C associated with soil organic fractions for a range of sites in southern Australia[103] (Figure from Baldock 2008).

104 Dougherty (2007)

Soil aggregation is known to be an important factor in protecting soil carbon and decreasing rates of microbial turnover. A pasture site in northeastern NSW provided an opportunity to study the relationship between the rate at whichsoil carbon is lost and soil aggregation[105]. A change in vegetation cover from rainforest with a C_3 photosynthetic pathway to tropical grasses (*Paspalum dilatatum* and *Pennisetum clandestinum*) with the C_4 pathway was used to follow input rates and turnover of organic matter in a krasnozem (Red Ferrosol) over an 83 year period using isotopic analysis. Turnover times for organic matter from the three sampling depths (0.0-7.5, 7.5-15.0, 60.0-80.0 cm) were calculated as 60, 75 and 276 years respectively, compared with 75, 108 and 348 years for the organic matter protected within microaggregates from the same horizons. The indicates that the deeper the soil organic carbon is sequestered in soil, the longer the residence time. This was most evident where soil microaggregation is strongly developed and disruption of microaggregates through excessive tillage allows soil carbon previously protected from microbial action to decompose rapidly.

5.2.2 Permanency of soil organic carbon

To be counted under UNFCCC national greenhouse gas inventory accounting rules, and to be eligible for credits under most carbon pricing schemes, sequestered soil carbon has to be maintained for long periods i.e. 'permanently' (nominally 100 years). Some schemes, including Australia's Carbon Farming Initiative, allow for carbon stored in the soil for a shorter period (25 years) to gain credits but apply a discounted price to account for the risk that the sink is reversed. None of the carbon pools, with the possible exceptions of charcoal and biochar, are truly permanent when considered over a period of 100 years in conditions across a broad range of soil types and the range and variability of climatic conditions in Australia.

Greenhouse gas accounting for soil carbon in agricultural lands in Australia's national inventory report is calculated from a model of change in carbon stocks for a type of management, i.e. it represents the net result of inputs and losses. Therefore, in land where SOC stocks are declining due to past and present management, adopting a new practice (e.g. moving from annual to perennial pastures), which reduces the rate of loss of carbon, should be eligible for carbon credits. Requirements for net accounting and any other method rules under the carbon credit scheme would also have to be met.

5.2.3 Biochar and other organic soil amendment

Biochar is a stable form of organic carbon produced through the combustion of biomass in limited oxygen, a process called pyrolysis. Some supporters claim a wide range of benefits from adding biochar, including improvements in soil structure, enhanced crop performance, greater soil biodiversity, enhanced fertiliser use efficiency, greater stabilisation of other soil carbon, suppression of other greenhouse gas emissions (such as nitrous oxide) and a near permanent increase in soil carbon. Emerging trials, conducted using controlled scientific methods, are questioning some of the more extreme claims and challenging how great the increases in yield and carbon really are. Examination of the processes making biochar are also examining the risk that pyrolysis may lead to the production of polyaromatic hydrocarbons and other persistent organic pollutants (POPs), which may present a local health issue near the site of production. In some Australian States or Territories, the use of biochar as a soil amendment for agricultural use may require a licence or

[105] Skjemstad et al. (1990)

permit.

Experimental results as well as observations indicate that the stability of the biochar and the production and carbon outcomes from adding it to agricultural soils depend on several variables[106]. These include the starting organic material (feedstock), pyrolysis conditions, soil characteristics and management. Two examples of research results highlight the gaps in understanding:

- In a project funded under Australia's National Soil Carbon Program, Michael Bird and colleagues evaluated the effect of biochar, compost and co-composted biochar+compost (COMBI) on the soil properties, crop yield and greenhouse gas emissions from fruit crops in northern Australia[107]. All three amendments improved soil properties and soil carbon content. Counter to expectations, increases in soil nutrient content and improvements in physical properties did not translate to improved yield, with decreases up to 24% in the case of banana crop. Soil efflux of CO_2 was elevated by addition of compost and COMBI amendments, and this was likely due to an increase in labile carbon for microbial decomposition. At least in the short-term, it is clear that the benefits (increased soil nutrient content, increased SOC and reduced N_2O emissions) need to be carefully weighed against potentially negative effects on crop yield. Similar research is needed for Southern Australian soils to enable dairy farmers to make informed decisions on the use of biochar and other organic amendments on pastures.
- An incubation experiment[108] found that slow-pyrolysis wood-derived biochar had potential to provide annual emission reductions of 0.58–1.72 Mg CO_2-eq per hectare at an application rate of 25 tonnes biochar per hectare. However, results varied depending on management, with the greatest greenhouse gas mitigation potential from carbon sequestration and nitrous oxide reduction in soils with mineral nitrogen fertilisation. In unfertilised soils, there were minimal impacts on N_2O emissions, carbon dioxide emissions, and methane uptake.

For climate change benefits from biochar application, the emissions from energy used in pyrolysis, transporting starting material and transporting biochar must be counted. In addition it is important to understand that redistributing carbon from one site to another does not give a net carbon sequestration[109]. Therefore, applications to dairy pasture of biochar or other organic carbon-rich amendments (e.g. compost) brought in from outside the farm is essentially a redistribution of pre-existing carbon rather than sequestering new carbon from the atmosphere. If these products improve pasture production and lead to an incremental increase in organic matter input into the soil there can be a net increase in SOC but note that the results from northern Australia described above question whether this increase in yield will occur. Carbon crediting for biochar under Australia's Emissions Reduction Fund method for soil carbon in agricultural land involves counting only the additional indirect sequestration[110], and carbon added in as biochar is subtracted again from the measured SOC stock (a net zero gain) to calculate the net benefit.

5.2.4 Glomalin from mycorrhizal fungi

[106] McBeath et al. (2015)
[107] Bass et al. (2016)
[108] Ramlow and Catrufo (2017)
[109] Bruce et al. (2009)
[110] DoEE (2018)

Arbuscular mycorrhizal fungi (AMF) produce glomalin (a glycoprotein) within their hyphal walls[111]. As the hyphae senesce, glomalin is deposited within the soil where it accumulates until it represents as much as 5% of soil C. Standing stocks of AMF hyphae in soil are in the order of 0.05 to 0.90 t C/ha; glomalin constitutes a modest proportion (0.4-6%) of this biomass. Glomalin concentrations are positively related to net primary productivity. In Australia, while often associated with mycorrhizal fungi, phosphorus is a key driver of pasture productivity, regardless of AMF status (see Section 5.2.7).

Benefits of glomalin are believed to include stabilisation of soil aggregates and provision of a slow-release source of nutrients. However, its potential for long-term soil carbon sequestration appears limited. Carbon dating of glomalin in a forest soil study indicated turnover at unspectacular time scales of several years to decades[112]. In addition, glomalin may induce water repellence in soil and adversely affect water entry. Some plants, including some used in pastures, e.g. brassicas valued for production, do not have associations with AMF, and some enthusiastic support for the benefits of AMF have limited scientific evidence.

5.2.5 Plant stones

Phytoliths, also referred to as plant opal or plant stones, are silicified features that form as a result of biomineralisation within plants[113]. The silicification results in the occlusion of carbon and renders it highly resistant to decomposition in the soil environment. Species known to be prolific producers of phytoliths include barley, sugarcane and wheat. Limited measurement in northeastern NSW indicated that sugarcane is able to sequester carbon within phytoliths at a rate of 0.18 tonne C/ha/year.

The significance of this process under dairy pasture appears to be unknown. The fact that SOM improvement does not last for long after removal of a POC-dominated pasture phase (Figure 16) suggests that current pasture varieties in southern Australia do not contain large quantities of phytoliths. More research is needed to evaluate whether there is any potential for phytolith-enhanced sequestration in southern Australian dairy soils.

5.2.6 Acceleration of humus breakdown by microbial priming

Labile carbon (C) input to soil can accelerate or slow the decomposition of SOM, a phenomenon called priming[114]. In experimental conditions, the action of substrates with readily available energy (eg. glucose and cellulose) added to the soil stimulates the decomposition of ‘old’ soil carbon. This suggests that a change in agricultural practice that increases the distribution of fresh carbon along the soil profile could stimulate the loss of older buried carbon[115]. However, priming is difficult to predict in the field, making its relationship with C input elusive.

There is a positive linear relationship between carbon input and priming in all soils – priming increases from negative or no priming at low carbon input to strong positive priming at high C input. However, priming is not strongly related to the size of the soil microbial biomass so that while priming generally increases with

[111] Treseder and Turner (2007)
[112] Rillig et al. (2001)
[113] Parr and Sullivan (2005)
[114] Mitchell et al. (2016)
[115] Fontaine et al. (2007)

the rate of labile C input, the magnitude of increase varies among soils[114]. Dairy cow urine can decrease SOM[116]. It contains easily degradable carbon, which may lead to acceleration of soil carbon cycling by priming.

5.2.7 Phosphorus nutrition

Several Australian studies[117,118] showed a fairly consistent gain in SOC in pastures fertilised with superphosphate. However, other studies[119] did not measure a response, indicating that results may depend on local soil, climate and management factors. In general, more consistent increase in SOC has been observed in nutrient-limited soils when phosphate fertiliser is applied and especially when accompanied by the introduction of legumes, such as clover.

In general, soil carbon gains from improved pasture nutrition may be difficult to prove during the early stages of sequestration. On an experimental site near Hamilton Victoria[120], pasture production was strongly increased by phosphorus application, which allowed a three-fold increase in sheep stocking rate and a doubling of wool production. Soil carbon sequestration was not significantly affected by either phosphate application rate or stocking rate, even after 25 years of treatment. However, increasing rates of P application produced a trend of slowly increasing SOC that would only be detectable by soil analysis if the higher application rates were continued for periods in excess of 30 years.

Early work compared soil biological communities on organic and conventional dairy farms in the Goulburn Valley, northern Victoria[121]. Pasture plants (perennial ryegrass and white clover) in the biodynamic soil had a slower growth rate and a higher level of colonisation by VAM fungi due to lower initial soil P and N concentrations, ie. the fungi were unable to compensate for no inorganic P addition. There was no indication that the biodynamic and conventional soils had developed substantially different processes to enhance plant nutrient uptake or that the indigenous VAM fungi differed in their tolerance to applications of soluble nutrients.

5.2.8 Lime application

Lime application is an important practice for managing soil acidity and productivity in many Australian farm systems. For example, on pure subterranean clover pastures in southern Australia lamb growth rates were 20-30% greater than on a conventional perennial ryegrass-subterranean clover mixture[122] but lime is often needed to manage soil acidification in these systems. Treatment with lime releases additional CO_2 to the atmosphere[123] (Page et al. 2009). Research in WA under the National Soil Carbon Program showed that

[116] Lambie et al. (2008)
[117] Chan et al. (2010)
[118] Sanderman et al. (2010)
[119] Wilson and Lonergan (2014)
[120] Graham et al. (2005)
[121] Ryan and Ash (1999)
[122] McCaskill (2008)
[123] Page et al. (2009)

adding lime did not lead to increased SOC levels even after relatively long time frames, i.e. there was no carbon sequestration benefit.

5.2.9 Risk of nitrogen deficiency in high organic matter soil

The Chernic Tenosol soil type shown in Figure 5 (Mount Gambier, SE SA) has unusual properties under dairy pasture[124]. Despite the high organic carbon content (humus dominated) and an apparently excellent mineralisation potential, the dairy pasture is responsive to nitrogen fertiliser. A likely contributing factor is the exceptionally good subsoil structure that would allow rapid loss of nitrogen via leaching from the root zone.

5.2.10 Interaction with other greenhouse gas emissions from pasture

Nitrous oxide

The interaction between carbon and nitrogen in soils and implications for accounting for soil carbon sequestration were discussed in Section 3.2. Here we expand on some specific questions for dairy pastures, particularly relating to managing nitrous oxide emissions.

Nitrification inhibitors (or stabilised fertiliser treatments) are chemicals which slow down or delay the biological conversion of applied nitrogen fertiliser compounds to nitrate. Delaying this conversion ensures that more nitrogen remains available to the crop for longer, without the risk of losses through leaching or denitrification. The National Agricultural Nitrous Oxide Program (NANORP) investigated the impacts of nitrogen inhibitors in dairy pastures[126]. If equivalent yield increases could be achieved as with conventional mineral fertilisers such as urea but with less nitrous oxide emissions, this would, in theory, give higher net SOC sequestration for the same (or better) productivity gains. The inhibitor DMPP reduced nitrous oxide emissions by up to 50% in intensive dairy production systems in southern Victoria. Fertiliser cost savings for intensive dairy production was estimated to be more than $150 per hectare per year. This indicates potential savings in nitrogen fertiliser for the dairy industry (500 farms with average pasture area of 60 hectares) of $4.5 million per year. DMPP had more variable impacts on ammonia loss from manures and urea in testing at different dairy pasture sites. Productivity benefits were only seen in a subtropical dairy pasture near Gympie, most likely due to the low background mineral nitrogen levels. Practices that reduce excessive nitrogen inputs in these systems will have significant economic as well as climate change and other environmental benefits.

Examples of other factors known to have an effect on nitrogen response and nitrous oxide emissions from dairy pastures include waterlogging and pH. Waterlogging, which is known to occur seasonally in southern Australian dairy pastures, can incease the risk of nitrous oxide emissions associated with nitrogen applications to promote growth and C-sequestration. In turn, higher SOC content may reduce the severity and duration of waterlogging due to the likely improved soil structure with higher organic matter content[125]. These changes must be considered in estimating SOC sequestration benefits.

Soil pH is a major influence on the ratio of N_2O to N_2 emissions from denitrifying soil. Where a pasture production system leads to acidification ofthe soil profile and this is not corrected by lime application the

[124] Howieson (2009)
[125] Li et al. (2005)

risk of nitrogen loss as nitrous oxide, when denitrification occurs, is likely to become greater. These nitrogen transformations and a description of research on the biochemistry of nitrogen transformations and factors affecting nitrous oxide emissions from Australian agricultural soils is available in the outputs of the National Agricultural Nitrous Oxide Research Program[126].

Methane

Methane (CH_4) is a greenhouse gas with warming potential 25 times stronger than carbon dioxide, according to the IPCC AR4 as used in Australia's inventory reporting for the Kyoto Protocol. Methane can be produced by methanogens in soils under anaerobic conditions and consumed through oxidation by methanotrophs under aerobic soil conditions. At low soil water contents, CH_4 consumption can be limited, as sufficient water is required to initiate methanotrophic activity. Methane is released from soil under anaerobic conditions, i.e. when soils are swampy and oxygen is not available. In these soils, as the severity of waterlogging in soil becomes greater, organic matter may decompose to produce CH_4. This scenario appears to be very unlikely under Australian dairy pasture and CH_4 release is minor from soils compared to the main dairy farm sources of enteric fermentation (digestion in the rumen of the cattle) and loss from urine and dung.

5.2.11 Observed national scale soil carbon losses

Soil carbon losses over entire regions have been reported in the United Kingdom[127] and New Zealand[128] for the approximate period 1980-2000. A similar trend is expected in Canada as conditions become warmer[129]. There are no definitive explanations for soil carbon losses in UK and NZ. However, a study in Wyoming, USA[130] where there were similar observations of SOC loss provided some insights. Data (Table 8) show that there was a loss of soil carbon from three prairie grazing treatments (exclosure, continuous light grazing and continuous heavy grazing) between 1993 and 2003. The losses were most evident after heavy grazing, where the shorter grass provided less shade and apparently led to higher soil temperatures and more rapid decomposition of soil organic carbon. The Wyoming study site experienced several years of moderate to severe drought during the period 1994 to 2003 so organic matter input would likely have been below average.

Table 8. Soil organic C mass under various grazing treatments (exclosure [EX], continuous light grazing [CL], continuous

Soil depth	1993			2003			Change from 1993 to 2003		
	EX	CL	CH	EX	CL	CH	EX	CL	CH
cm	Mg C ha^{-1}						%		
0–15	28.2b†	35.1a	35.9a	27.3a	32.0a	26.0a	−3	−9	−28‡
0–30	47.9b	58.0a	58.3a	47.3b	54.2a	42.5b	−1	−7	−27‡
0–60	88.2b	91.9ab	101.4a	80.5b	92.5a	70.5b	−9	+1	−30‡

† Different lower case letters indicate significant differences between grazing treatments (within a year and soil depth), $p \leq 0.10$.

‡ Significant difference in C mass between years, $p \leq 0.10$.

[126] DAWR (2016)
[127] Bellamy et al. (2005)
[128] Schipper et al. (2007)
[129] Bhatti and Tarnocai (2009)
[130] Schumann et al. (2009)

heavy grazing [CH]) on northern mixed-grass prairie in Wyoming[130] (Table from Schuman *et al.* 2009).

Further research is needed to understand the complex interactions between climate, soil and management factors and the scale and extent on which these are acting to cause widespread loss of SOC over decadal or longer time periods.

5.2.12 Climate Change impacts on soil carbon

Global warming will affect plant and microbial processes that drive the balance between soil carbon gains and losses to the atmosphere in several ways. The evidence that both sides of the equation – inputs and outputs – will respond to climate changes is outlined below.

Outputs
On the output side of the SOC equation, it has been hypothesised that global warming will accelerate loss of carbon from soils and consequently drive a feedback cycle of ever-increasing transfer of soil carbon to the atmosphere accelerating climate change. However, limited available evidence at this time means that soil science and climate experts have not reached consensus on the direction or magnitude of warming-induced changes in soil carbon.

A global database, which was compiled from published studies to help address conflicting results from individual experiments[131], provides greater confidence that generally warming enhances carbon fluxes to and from the soil. Data on warming-induced changes in soil carbon stocks estimated as the net result of changes in fluxes entering and leaving the soil were used in modelling exercises to project rising temperature effects on Earth system dynamics. An empirical relationship developed from model outputs suggested that global soil carbon stocks in the upper soil horizons will fall under one degree of warming, conservatively driving the loss of 55 ± 50 petagrams[132] of carbon from the upper soil horizons by 2050. In CO_2 equivalents this loss is equivalent to about 12–17 per cent of the expected anthropogenic emissions over the same period. Therefore, while the magnitude of the effect has a high uncertainty, there is increasing consensus on the direction of change raising concern that rising temperatures will stimulate the net loss of soil carbon to the atmosphere. This will drive a positive land carbon–climate feedback that could accelerate climate change.

Inputs
Considering inputs, climate change impacts on productivity and vegetation communities through a warmer, drier, more extreme climate will differ regionally. However, it is very likely that the amount and consistency of SOM entering the soil will change. Two factors important in determining inputs into soil are the amount and type of SOM and indicators of these in natural communities are, respectively, potential natural vegetation (PNV) types and net primary productivity (NPP). The impacts of climate changes on PNV and NPP in Australia was investigated using a model that could simulate these variables and widely accepted climate scenarios[133]. The first step in the modelling analysis was to assess whether the model could reasonably simulate known changes of the recent past. It reasonably modelled the substantial shift in areas of vegetation classes from the 1931–70 period to the 1971–2010 period due to the increased rainfall over large areas across Australia (Figure 18). This provided confidence in the approach and, when used with projected

[131] Crowther et al. (2016)
[132] 1 petagram = 10^{15} grams
[133] Liu et al. (2017)

future climate scenarios, it showed significant shifts in vegetation classes by 2050 (Figure 18). Of concern for dairying regions was a consistent loss in NPP in southern Australia by 2050. If there was a significant negative impact on NPP in dairy pastures, it could mean a decline in SOM inputs to the soil. This would drive net losses particularly if coupled with global warming-induced acceleration of decomposition losses (see above). There is insufficient evidence at this time to confidently predict outcomes, but there appears a consistent trend towards a lower balance in SOM which would indicate net loss of SOC due to climate change. On this basis, caution is recommended when considering soil carbon sequestration projects that are subject to permanency requirements.

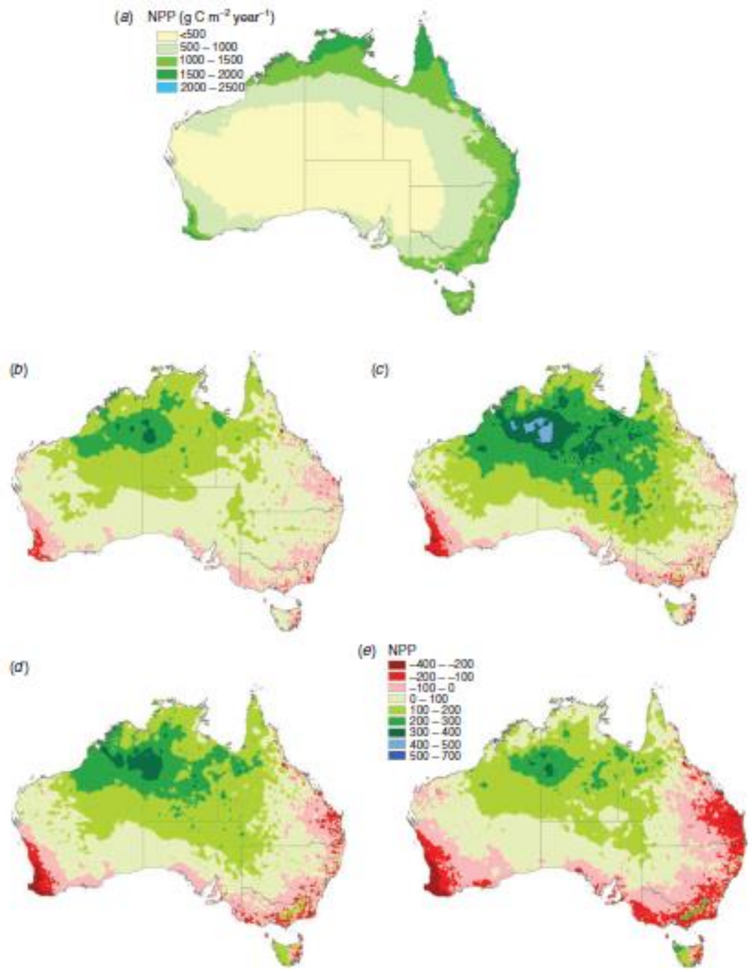

Figure 18. Simulated Net Primary Productivity (NPP) in Australia for the period 1931-1970 (a) and changes in NPP relative to 1931-1970 for: (b) the period 1971-2010; (c) 2050 under a cool-wet scenario; (d) 2050 under an average scenario; and (e) 2050 under a warm-dry scenario.[134] (Figure from Liu et al. 2017).

5. Institutional arrangements and Initiatives

5.1 *Global drivers for understanding soil organic carbon*

Previous sections of this report have concentrated on technical aspects of soil carbon sequestration. In this section the focus is broadened to look at institutional arrangements and policy settings. The drivers for research, development and extension to improve soil health and to understand the contribution of soil organic carbon was explained by Rattan Lal in 2016[134]:

> *Numerous soil functions and ecosystem services depend on SOC and its dynamics. Improvements in soil health, along with increase in availability of water and nutrients, increases soil's resilience against extreme climate events (e.g., drought, heat wave) and imparts disease-suppressive attributes. Enhancing and sustaining soil health is also pertinent to advancing Sustainable Development Goals of the U.N. such as alleviating poverty, reducing hunger, improving health, and promoting economic development.*

Australian scientists are active internationally in the development of processes for reliable mapping, monitoring and forecasting of soil carbon. Dr Neil McKenzie, Chief Research Scientist CSIRO, made the following observations in 2015[135]:

> *Unprecedented demands are being placed on the world's soil resources, and by 2050 they need to support a 70% increase in food production. However, arable land is finite and major crops are reaching yield plateaux. Better soil management is needed to conserve nutrients, improve water-use and reduce emissions. Climate change also compounds the situation.*
>
> *Some of Australia's soil management challenges are immediate and obvious, such as widespread soil acidification of cropping lands. Others are more subtle but just as important, such as erosion and nutrient imbalances.*
>
> *We need to improve soil management across the continent. This requires new diagnostic systems for determining when and where soil function is being compromised. Australia also needs more effective institutional arrangements for providing information on the condition of our soil resources.*
>
> *Research investment in these areas will generate large economic returns through increases in agricultural productivity and avoided costs in other soil-dependent industries. This is before we consider the equally large environmental benefits.*
>
> *At the global scale, improved soil management is needed in nearly all countries. Without these changes, food-price volatility is likely to increase and this will potentially send millions of people into poverty. This is avoidable but only if there is a concerted response by individuals, the private sector and governments.*

5.1.1 2015 International Year of Soils

The United Nations declared 2015 as the International Year of Soils and nominated the Food and Agriculture Organization (FAO) to implement the program. The International Year of Soils provided a focus for soil research and management and raised awareness of the importance of soil for food security and essential ecosystem functions. It also drew attention to the role of soil carbon in these functions and in climate

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[134] Lal (2016)

[135] https://blogs.csiro.au/ecos/science-can-drive-the-sustainability-of-our-precious-soils-water-and-oceans/

change mitigation, and promoted global cooperation in activities such as the development of a global soil map and information resources to promote actions for healthy soils (e.g. Figure 19).

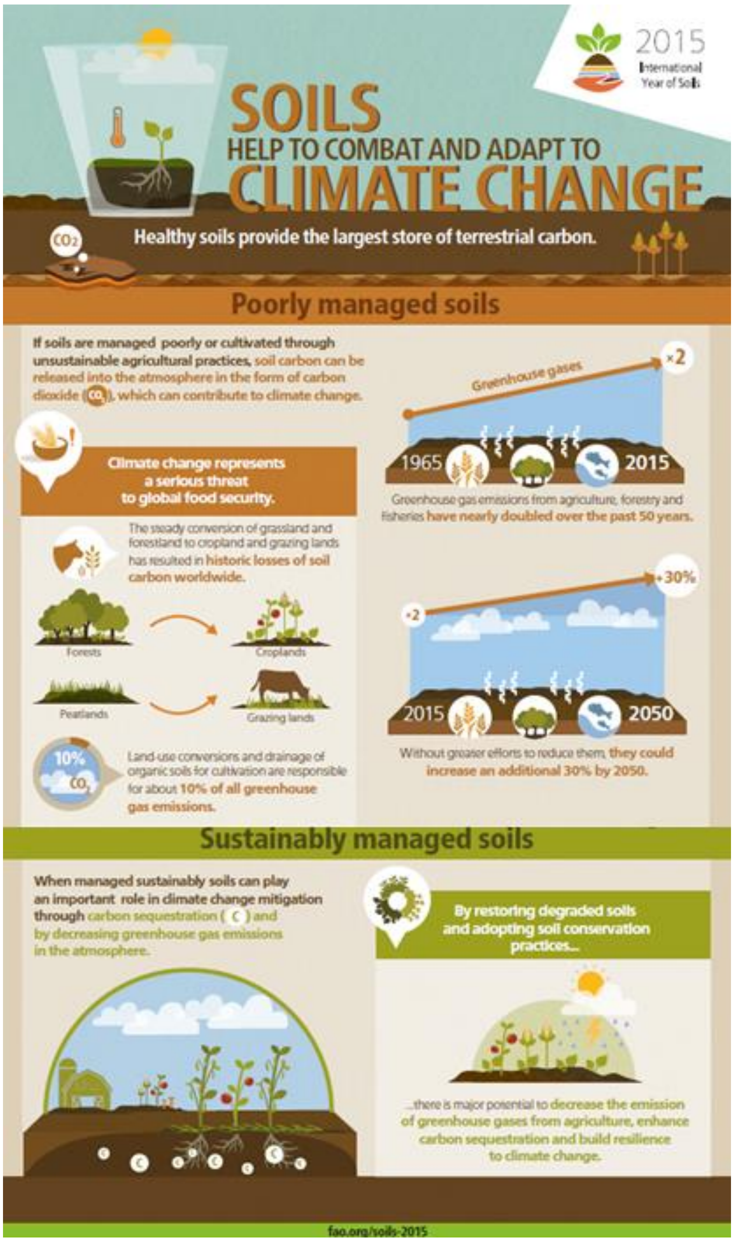

Figure 19. The role of carbon stored in healthy soils in climate change mitigation and adaptation. Extract from an FAO Infographic produced for the International Year of Soils 2015 (http://www.fao.org/soils-2015).

5.1.2 The 4 per 1000 (four per mil)

The 4 per 1000 initiative was launched in December 2015 at the Paris climate change talks that achieved a major international greenhouse gas mitigation agreement ('The Paris Agreement') signed by over a hundred countries. Each signatory committed to setting national targets to reduce net greenhouse gas emissions (total emissions minus sequestration) to contribute to restricting global warming to below 2°C and make efforts to constrain global temperature rise to 1.5°C, a level believed necessary to manage the risks of dangerous climate change impacts to the world's ecosystems and to human well-being.

French representatives proposed the initiative now referred to as 4 per 1000. The infographic in Figure 20 explains this global ambition to increase the carbon stored in soils by 0.4% (4 per 1000) per year. The 4 per 1000 initiative predicts that by following the land management practices it proposes, SOC could be increased by 0.4% to a depth of 40 cm for all soils globally. This would sequester around 8.9 Gt of carbon each year, roughly equal to annual global fossil fuel emissions, thus resulting in atmospheric carbon remaining at current levels.

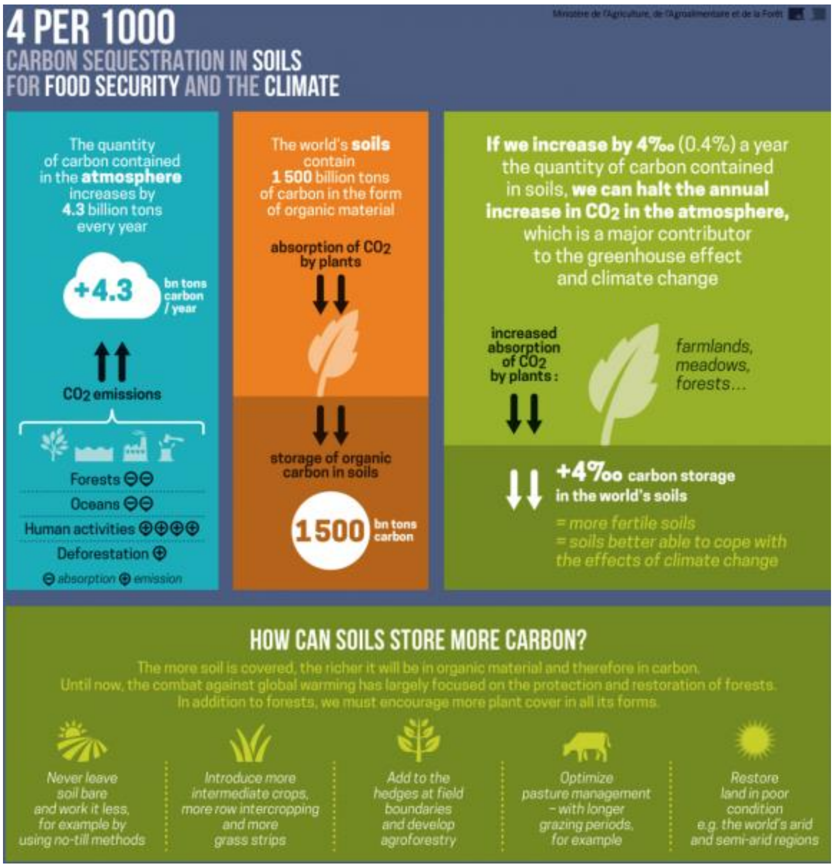

Figure 20. The 4 per 1000 Initiative concept of carbon sequestration for climate change mitigation and agricultural production for food security (www.4p1000.org).

While many consider the 4 per 1000 aspiration to be positive for the environment, research by several groups[136] note that there are practical constraints that mean it is unlikely to be achieved (Refer to Section 4.2). The 4 per 1000 initiative now recognises that SOC increases are only likely in actively managed agricultural land, and even there the increases might not be as high as the initiative had initially hoped. Constraints include:

- Some of the SOC-enhancing techniques promoted by 0.4% have already been widely adopted restricting the potential for new sequestration.
- Some of the methods are uneconomic for farmers, so adoption would require either regulation or subsidies.
- Lack of necessary resources for soil amendments and unrealistic, impractical application rates.
- Practices such as removal of land from agriculture that are proposed would have negative impacts for global food security.

[136] Poulton et al. (2018)

5.2 Australian policy and incentives in agriculture

5.2.1 Australia's Carbon Farming Initiative

The main climate change policy relevant to management of carbon sequestration in Australian land systems is the Direct Action policy and its Emissions Reduction Fund (ERF). The ERF is a voluntary scheme that aims to reduce Australia's greenhouse gas emissions by providing incentives for organisations and individuals to adopt new practices and technologies to implement new activities to reduce emissions.

ERF projects must use a legislated method. There are two approved methods for crediting soil carbon sequestration that could be applied on dairy farms:

(1) a model-based method that estimates the amount of soil carbon using default factors that have been developed for each region (local government areas); and
(2) a measurement-based method that requires periodic sampling and analysis of soil samples to provide a calculation of the change in soil carbon stocks over time.

Eligible projects can earn Australian carbon credit units (ACCUs) with one ACCU awarded for each tonne of carbon dioxide equivalent (t CO_2-e) stored by a project. ACCUs may be sold to generate additional income: either to the government through a Carbon Abatement Contract, or on the secondary market to industries wishing to offset emissions from their business activities.

Soil carbon and agricultural practices that influence soil carbon – summary

Soil carbon is primarily made up of decomposed plant material and microbes. Carbon rich materials, such as the roots, stems and leaves of crops or pasture, cycles into the soil, where part of it is broken down and respired into the atmosphere as carbon dioxide. Some remains to form soil carbon.

Soil carbon is highly variable across the landscape and through time. Research shows that this variability is largely explained by climatic factors and soil properties but that human activity also plays a role. This role can be observed in the general loss of carbon in agricultural soils since the 1800s due to changing land use.

In many cases, there are opportunities for land managers to improve soil carbon stocks by increasing the amount of carbon added to the soil and by slowing the rate of loss of carbon from the soil. These opportunities will be highly dependent on a number of site specific factors including the soil properties and selecting land management activities according to those factors. Furthermore, with climatic factors impacting soil carbon content, any attempt to increase soil carbon may also be affected by long term climate trends.

Soil carbon methods

Before 2018, there were two existing Emissions Reduction Fund soil carbon methods: the *Carbon Credits (Carbon Farming Initiative) (Sequestering Carbon in Soils in Grazing Systems) Methodology Determination 2014,* and the *Carbon Credits (Carbon Farming Initiative—Estimating Sequestration of Carbon in Soil Using Default Values) Methodology Determination 2015.*

The first method, *Sequestering carbon in soils in grazing systems,* is based on the direct measurement of changes in soil carbon stock over time, in response to changes in grazing systems management. Collection and analysis of soil samples over time generates the data to estimate soil carbon stock change.

The second method, *Estimating sequestration of carbon in soil using default values,* is based on the use of default rates for soil carbon stock change over time, in response to changes in specified management practices for cropping systems. These default values were predicted using results from the FullCAM tool developed for, and used in, the Australian National Greenhouse Gas Inventory. The values applied to several acceptable management activities implemented as new practices in a project are conservative to be consistent with the scheme 'Offset Integrity Standards'.

Soil Carbon Sequestration in Agricultural Systems Method

The 2015-16 method prioritisation process resulted in an agreement that a new soil carbon method should be developed building on the two existing soil carbon methodologies. There had been limited uptake of the existing soil carbon measurement method, attributed to the narrow range of farming systems that were able to participate and the high costs of direct measurement. The *Carbon Credits (Carbon Farming Initiative—Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018* introduced more flexibility in eligible farming activities and in sampling and measurement options:

- an improved soil sampling strategy to reduce uncertainty of soil carbon estimates, supporting the participation of a wider range of production systems;
- an increased range of eligible farming systems including cropping, grazing and horticultural production systems;
- allowing the use of soil amendments containing biochar and accounting for other additives that may contain carbon, including clay;
- an additional measurement option allowing for the ability to estimate carbon stocks using in-field or laboratory sensors and associated models as well as the combustion techniques.

Changes in the 2018 method including introduction of measures to help ensure that farmers received good advice on how a soil carbon project could be integrated into their farm business and that they are aware of potential risks and opportunities, e.g. vulnerability to climate impacts and permanency obligations, by requiring the development and regular review of a land management strategy. The land management strategy must be developed by an independent person, i.e. not a person who would benefit financially from the project such as a carbon broker.

6. Useful resources

This section lists a few key resources focusing on those produced by leading Australian soil scientists and government departments providing reputable links to information, guidance or reference material about soil carbon measurement and management in southern Australia, relevant to dairy pastures. It is not a comprehensive list but intended to provide an entry point to those looking for more detail.

1. **Department of Agriculture and Water Resources Climate Change Research Booklet**

The Australian Department of Agriculture and Water Resources produced a booklet summarizing the latest Australian government funded climate change research http://www.agriculture.gov.au/SiteCollectionDocuments/climate-change/carbon-farming/boosting-farm-productivity.pdf

2. Department of Environment and Energy – Emissions Reduction Fund

A description of the Emissions Reduction Fund can be accessed on the Australian Department of Environment and Energy (DoEE) website, as well as links to methods for carbon credit projects in agricultural lands using measurement and modelling http://www.environment.gov.au/climate-change/government/emissions-reduction-fund/

A Factsheet, *Increasing soil carbon under the Emissions Reduction Fund,* produced by the Australian Department of Environment and Energy explains the 2018 method, including advice on obtaining guidance and understanding risks and opportunities for SOC sequestration projects and a summary of some factors that influence the likelihood of practice change achieving an increase in SOC (Table 9). http://www.environment.gov.au/system/files/resources/24cf7e41-feeb-4fa8-a42a-1220d3b0d946/files/fs-increasing-soil-carbon-erf.pdf

Table 9. Examples of factors that influence the likelihood of soil organic carbon stock change in Australian agricultural soils[137].

137 http://www.environment.gov.au/system/files/resources/24cf7e41-feeb-4fa8-a42a-1220d3b0d946/files/fs-increasing-soil-carbon-erf.pdf

	Increase in soil organic carbon likely[1]	Increase in soil organic carbon unlikely[2]
Location factors		
Native soil type	High clay content High soil fertility High porosity	Low clay content Low soil fertility Low porosity
Annual average rainfall	High (> 600 mm)	Low (< 600 mm)
Seasonal climate and rainfall (throughout project)	Rainfall consistent with average conditions Moderate temperatures	Flood Drought Frost Extreme heat or cold
Initial conditions		
Pre-project SOC stocks	Low*	Medium to high*
Management history	Low inputs of biomass or large removal of biomass from system *(Eg. Low yields, stubble burning, poor grazing management, low ground cover)* Tillage history with high amount of soil disturbance *(Eg. Conventional tillage, disc ploughs)* Poor nutrient and soil chemical environment management *(acidity, salinity, sodicity).*	High amount of biomass input to the soil *(Eg. High yields, stubble retention, good grazing management, maintain high ground cover)* Minimal soil disturbance by tillage *(Eg. Direct drilling, minimal disturbance at sowing, perennial pastures)* Maintain or improve soil nutrient levels and address barriers to soil chemical health *(acidity, salinity, sodicity).*
Proposed new management		
Activities influencing organic matter inputs	Major increase in amount of biomass entering the soil Large increase in ground cover	Minimal change to amount of biomass entering the soil Minimal increase in ground cover

* relative to the expected long term equilibrium levels of SOC for the soil type, climate and proposed land management.

[1] when a specific site has all or most of the factors as classified in this column, chances of an increase in soil organic carbon are maximised. Note: no site is likely to fall into either column entirely.

[2] when a specific site has all or most of the factors as classified in this column, chances of an increase in soil organic carbon are minimised. Note: no site is likely to fall into either column entirely.

3. GRDC Guidance

An-easy-to-read paper with helpful overview of credible evidence and practical information on good management for soil carbon including some interpretation of relevant results from the SCaRP project is available on the GRDC website.

Managing Soil Organic Matter: A Practical Guide. (2013) Report author: Dr Frances Hoyle, Department of Agriculture and Food Western Australia www.grdc.com.au/GRDC-Guide-ManagingSoilOrganicMatter.

4. FAO Livestock Environmental Assessment and Performance (LEAP) Partnership

These Guidelines are a product of the Livestock Environmental Assessment and Performance (LEAP) Partnership of the United Nations Food and Agriculture Organisation (FAO). LEAP is a multi-stakeholder initiative whose goal is to improve the environmental sustainability of the livestock sector through better methods, metrics and data. The comprehensive guidance on measuring and modelling SOC aims to promote a harmonised, international approach for estimating SOC stocks and stock changes in livestock production systems. The document recommends a set of methods and approaches relevant to rangelands and grasslands for use by individual farmers or land managers, by those undertaking life cycle assessment of livestock products, policy makers, or regulators at local, regional or national scales.

Measuring and modelling soil carbon stocks and stock changes in livestock production systems – Guidelines for assessment (Draft for public review). http://www.fao.org/partnerships/leap/en/

5. Comprehensive book on issues affecting soil carbon storage

This book by one of Australia's most respected soil scientists provides more in-depth information. It is a useful reference for technical information and explanation of terms relevant to soil carbon.

Singh B.K. (Ed.) (2018). *Storage Soil Carbon Storage: Modulators, Mechanisms and Modeling*. Academic Press London.

7. Summary for dairy farmers

When considering SOC sequestration for climate change mitigation the following points are important:

- *Time limits on sequestration:* a new carbon steady state is often reached in soils within 20-30 years
- *Permanence and the reversibility*: While climate change and carbon offset accounting require sequestered SOC to be maintained for a nominal 100 years, soil carbon, especially in surface layers may be readily lost due to reversal of management actions or climate events such as drought.
- *Net climate change mitigation:* Management to promote SOC sequestration may result in emissions of other greenhouse gases, such as nitrous oxide from fertilizer application, and these may out-weigh the benefits so that the net mitigation in terms of CO_2 equivalents is low or a net increase in emissions.

On the other hand, SOC sequestration can provide co-benefits such as improved fertility and soil structure. About 22% of the carbon in crop residues added to soil is retained, the rest being released as carbon dioxide to the atmosphere but also providing productivity benefits. Adding crop residues, such as straw stubble to soil is now common practice in many pasture systems so there is little scope for additional benefit and applying more in one place at the expense of another soil will not provide a net climate change mitigation.

7.1 The benefits of soil organic matter

Understanding soil carbon is important for anyone interested in the sustainable production of healthy food and in caring for the environment. Apart from its capacity to offset carbon emissions associated with human activity, soil organic carbon has many other benefits for dairy farmers including:

a. Stabilisation of soil aggregates which reduces the risk of waterlogging under moist conditions and softens the soil when dry;
b. Source of energy (food) for beneficial soil organisms;
c. Slow-release source of nutrients;

d. Increased water holding capacity, particularly in sandy soil;
e. Increase in nutrient holding capacity by improving cation exchange capacity;
f. Binding of toxic cations such as aluminium in a form that is unavailable for plants.

Alternative approaches

The more severely degraded a block of land is, the greater the chances of success with carbon sequestration. In the event that severely degraded land was purchased for dairy farming, and then if the subsoil constraints were overcome and productive dairy pastures were established, there almost certainly would be a significant increase in soil carbon. For example, a strongly compacted soil with poor shrink-swell capacity that is shedding most the rainwater that falls could be ameliorated in a cost effective fashion with agrowplowing at an appropriate moisture content and a pasture established.

If carbon sequestration became a major driver of dairy farm profitability, then dairy farmers could encourage plant breeders and research scientists to accelerate progress with some of the following:

g. Develop deeper root systems for pasture plants which may access more soil water and nutrients, thereby increasing total carbon capture and perhaps deposit more of that carbon deeper in the soil where it is better protected from decomposition;
h. Evaluate the viability of alley farming systems with strips of deep rooted edible shrubs, which could provide the same function as deeper rooted pasture species;
i. Develop better water use efficiency for pasture plants so that despite declining water availability, total pasture production, and therefore soil carbon level, might be increased;
j. Explore the economics of converting pasture/shrubs/trees etc into biochar on-farm. (However, note only SOC gains above the carbon added directly as biochar count as carbon credits.)

7.2 Considerations for potential carbon credits in dairy pastures

There is a potential opportunity for farmers to get an income from the sale of carbon credits from soil carbon sequestration, which represents a removal of carbon dioxide from the atmosphere and storage of the carbon in their soil.

Two markets exist in Australia – the $2.55 billion Government Emissions Reduction Fund that purchases carbon credits through a reverse auction system, and a secondary market where credits can be sold privately. The price under auctions to mid 2018 has been in the order of $11 - $13. The prospects for higher prices in the future will depend on both domestic policy which has not enjoyed stability in the early 2000's and international commitments and arrangements (e.g. possible trade restrictions for countries or products with low abatement policy/procedures).

These constraints indicate the need for caution in committing to any carbon sequestration contractual arrangements, and for a comprehensive analysis on a case-by-case basis of the risks that a soil carbon project will end up being unachievable and/or economically unviable for dairy farmers. However the benefits of practices building SOC in pastures for soil health, associated environmental outcomes such as water quality, and milk production should also be considered.

7.2.1 Issues affecting carbon sequestration offsets in dairy pastures

Starting carbon content is high giving limited scope for additional storage

Dairy farmers generally have a relatively high concentration of organic matter in their soil following application of best-practice soil management such as fertilisation, land application of effluent and improved pasture cultivars and limited cultivation. In addition, dairy farms tend to be on the very best soil in a district, e.g., basaltic soil of west Gippsland and south-western Victoria. This means that further improvements in soil condition are difficult to achieve and small.

Southern Australia is becoming hotter and drier

Southern Australia has become warmer over the last 50 years and a range of credible agencies, including the Bureau of Meteorology and CSIRO predict this trend and changes to rainfall amount and patterns will continue. For example, a key finding of The Climate Council of Australia (2015) was that '*Average rainfall in southern Australia during the cool season is predicted to decline further, and the time spent in extreme drought conditions is projected to increase*.'[138]

In combination, these trends are likely to decrease SOM inputs to the soil through decreased pasture growth and temperature-induced accelerated decomposition. Studies in the UK and New Zealand have demonstrated country-wide declines in soil carbon content over the last 3 decades, with the greatest losses occurring in soil with the highest initial organic matter content. A possible driver is accelerated decomposition of soil carbon due to the now well-established increase in temperature due to climate change as discussed in Section 5.2. Projected continued global warming will likely negatively affect future soil carbon sequestration, exacerbating the problem for farmers. If cultivation is part of the pasture production system, or if increased cultivation is part of future dairy systems, the chances of accumulating soil carbon are reduced even further as disturbance exposes SOC and accelerates decomposition further.

Nutrient tie-up in humus is expensive to replace.

Even if cool wet seasons were to return, there is a challenge associated with the economics of 'carbon farming' because expensive nutrients are locked up in humus. The cost of fertiliser is likely to increase, at least over the next decade, due to supply constraints. Phosphorus application is a key driver of pasture productivity in southern Australia, but there is a major concern that world supplies of phosphorus are limited.

Carbon trading contracts

The signing of a carbon sequestration contract by a dairy farmer may provide additional income but brings obligations and risks. Soil carbon sequestration may be lower than expected and if there is a contract to deliver a certain number of carbon offset credits, there may be a liability to either repay moneys already received or buy credits from elsewhere possibly incurring a financial loss.

The following advice is provided by the Department of Environment and Energy in a Factsheet on soil carbon

[138] Climate Council of Australia (2015)

projects under the Emissions Reduction Fund[139]. While addressing farm land managers more broadly it has some important cautions for dairy farming.

> *Project proponents should seek as much expert advice as necessary on the management actions that will best suit their project area. They should consider other key drivers of soil carbon change such as climatic factors, geographical features and soil properties.*
> *[Table 9] shows examples of factors that influence the likelihood of soil organic carbon stock change. These factors should be considered and discussed with agronomic experts prior to engaging in a soil carbon project. Note: these examples are a small subset of the drivers that could influence soil carbon stock change.*

While there may be less risky strategies in schemes that reward the reduction in emissions of potent greenhouse gases such as nitrous oxide and methane, including through practices that are eligible under other Emissions Reduction Fund methods, these are beyond the scope of this review.

8. Overall conclusions

Soil carbon is an essential component of all healthy soils. Management practices that boost pasture production tend to increase soil carbon levels and vice versa. However, because dairy pastures tend to be high in soil carbon relative to other agricultural soils and relative to the 'natural, undisturbed' level for the region and climate, there is limited scope for further increases in soil carbon under dairy pastures in southern Australia, even if building soil organic carbon was a management focus. Uncertainty in the scope to build and maintain soil organic carbon is exacerbated by uncertainty in how much effect future climatic conditions, driven by human greenhouse gas emissions, will limit soil organic carbon net sequestration.

Research and evaluation of available data by leading soil scientists over the past decade indicates that the potential for soil carbon sequestration to have a significant impact on Australia's national greenhouse gas emissions is likely to be limited. Earlier predictions for soil carbon sequestration being able to make a substantial contribution to mitigation targets are now thought to be unachievable.

The greatest potential for carbon offsets is in soils that have been highly degraded. Nevertheless, for dairy farmers as with other agricultural land managers, understanding and monitoring soil carbon under crops or pastures has advantages even when opportunities for income from carbon credit markets is not substantial. Soil carbon is a key aspect of soil health that drives pasture growth and hence milk production and long-term sustainability of the land resource. Despite most dairy farms offering little practical opportunity for financial return from soil carbon credits, there is evidence that activities favouring soil carbon sequestration will be good for long-term farm business and profitability.

[139] DoEE (2018)

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