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Soil carbon for carbon sequestration and trading: a review of issues for agriculture and forestry

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Foreword

Climate change is a major issue facing society today with extensive studies being undertaken to find ways to mitigate its effects and impacts in the future. A key factor contributing to climate change is excessive levels of greenhouse gases in the atmosphere and global efforts are focussed on both reducing our emissions of greenhouse gases and increasing the storage (sequestration) of atmospheric carbon.

Soil, as an important part of the carbon cycle of the planet, has the potential to store carbon and contribute to mitigating greenhouse gases. In total, soils contain about 3 times more carbon than the atmosphere and 4.5 times more carbon than all living things. Hence a relatively small increase in the proportion of soil carbon could make a significant contribution to reducing atmospheric carbon. The amount of organic soil carbon that can be stored is influenced by a number of factors, including land use practices, soil type and climate. Increasing the amount of organic soil carbon may also improve soil health, providing added benefits to ecosystems and agricultural and forestry productivity.

This review looks at factors that may influence organic soil carbon and issues facing its inclusion in a carbon trading scheme in the future. In order for organic soil carbon to be included in an enterprise-level carbon trading scheme, it must be measurable in an efficient and inexpensive way and at scales small enough to be applicable at the farm level. The review highlights areas where further information is needed.

Karen Schneider
Executive Director
Bureau of Rural Sciences

Executive Summary

The aim of this report is to inform decision makers of the potential role for soil carbon in carbon sequestration and trading

This report aims to inform decision makers about soil carbon, its role in carbon cycling and the potential for increased sequestration of carbon in soil. This document identifies and examines the issues surrounding the inclusion of soil carbon in carbon trading schemes for agriculture and forestry.

Soil carbon exists in two forms—organic and inorganic; organic soil carbon is the form most amenable to carbon sequestration

In soils, carbon exists in two forms—organic and inorganic. It is the organic form (which we refer to as organic soil carbon) that is most likely to be included in carbon trading. Most of the organic soil carbon comes from the decay of organic matter such as plants, animals and microbes. The amount of organic soil carbon in a particular area of soil will vary depending on factors such as climate, soil type and land management practices that influence the addition and decay of organic matter. The inorganic form of carbon in soils is unlikely to be used as part of a carbon trading scheme because it is not a net sink for greenhouse gases nor easily affected by land management.

Increasing organic soil carbon delivers a win–win situation

Increasing the amount of organic soil carbon may not only mitigate greenhouse gases but also benefit agricultural and forestry productivity (a ‘win–win’ situation) through improvements in soil health and ecosystem services such as erosion control and habitat for biodiversity.

Organic soil carbon breaks down at different rates; it is especially desirable to increase the amount of carbon that breaks down slowly

Organic soil carbon can be divided into at least three ‘pools’ according to how fast it breaks down and is replaced. The pools are commonly divided into: fast (e.g. annual), slow (e.g. decadal) and passive (e.g. millennial). For carbon sequestration (long-term storage) and carbon trading purposes, it is especially desirable to increase the total amount of carbon in the pools that break down slowly (e.g. the slow and passive pools).

Some land management practices can increase the amount of organic soil carbon

The amount of organic soil carbon in the slow and passive pools can be increased by adding plant material above and below the soil surface and by altering the rates at which this material decomposes. Factors likely to affect the efficiency of carbon sequestration include soil type, initial content of organic soil carbon, depth in the soil profile, climatic conditions and effects of climate change on mineralisation.

External inputs of carbon, such as biochar or manure, may increase organic soil carbon

The amount of organic soil carbon may be increased beyond levels attainable by on-site capture of carbon using land management practices through the application of external sources of carbon such as biochar (a form of charcoal converted from organic material), manure or other waste organic material. Life-cycle analyses are required to determine if there is a net gain in carbon sequestration with these proposed measures.

Measuring organic soil carbon directly is currently difficult and expensive for individual enterprises in carbon trading schemes

Traditional methods of directly measuring organic soil carbon are generally slow and expensive. To quantify organic soil carbon in units suitable for carbon trading, new techniques would be required to determine the amount of carbon and how it changes across a landscape. This could involve a combination of direct measurement and modelling approaches. Some new methods of direct measurement and modelling frameworks are being developed and calibrated. However, they will require extensive testing before they could be recommended for use in carbon trading schemes, especially to operate at fine spatial scales and small units (e.g. farms) and to capture small percentage increases in organic soil carbon.

To sequester carbon, soils need to withdraw carbon from the atmosphere for long terms

To mitigate greenhouse gases, sequestration of carbon must achieve long-term substantial withdrawal of carbon from the atmosphere, with a low risk of rapid or large-scale leakage. For long-term sequestration to be counted, consistent methods and transparent processes would need to be designed and funded. Methods may be required to efficiently allocate organic soil carbon into the different pools.

Carbon sequestration in soils needs further analysis to address significant uncertainties and risks

The net benefits of carbon sequestration in soils may not be as large as first expected (e.g. due to decomposition) and some processes that increase carbon sequestration may have adverse environmental effects, particularly on biodiversity and ecosystems. Uncertainties in measurement also mean that it is difficult to bundle organic soil carbon into tradeable units. Changes in land-use or management practices may also release stored organic soil carbon and would need to be considered.

To improve the likelihood of including soil carbon in carbon trading schemes more information is required

Potential participants in soil carbon trading are likely to require more information on the likely increases in organic soil carbon including the impacts of climate variability and climate change, the effects on associated greenhouse gases and the likely responses of land managers to incentives. Individual land managers will require information and user-friendly tools to help them trade small amounts of carbon over short periods. Further research is warranted into the effects of farming systems on storage and distribution of organic soil carbon and the effects of salinity and acidity on net sequestration of carbon in soils.

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Introduction

Greenhouse gases play a major role in climate change. The greenhouse effects can be mitigated by reducing the concentrations of these gases in the atmosphere by reducing their emission and increasing the sequestration (storage) of carbon. Soil contains approximately three times more carbon than the atmosphere and four and half times more carbon than all living things (Lal, 2007).

Sequestering carbon by increasing the amount of organic matter in soil is both a source of greenhouse gases and a sink for carbon. It could reduce levels of greenhouse gases in the atmosphere while improving the soil's contribution to agriculture and forestry productivity, creating 'win–win' scenarios.

The Australian Government is establishing a national emissions trading scheme—the Carbon Pollution Reduction Scheme—as part of a framework to reduce greenhouse gas emissions.

Recently, the potential for organic soil carbon to be part of an emission trading scheme has been investigated. There is uncertainty regarding the inclusion of carbon sequestration in soils in an Australian carbon trading scheme in part because such a scheme would require land managers to account for organic soil carbon in tradable units for defined times and terms. This can be difficult due to the many factors that complicate soil carbon accounting, such as:

- low soil concentrations of organic carbon in soils, which affects the accuracy of measuring changes
- large variation in carbon levels across a landscape, which presents a challenge for sampling methods
- presence of different forms of organic soil carbon, with different stability and longevity
- differing effects of land management practices on emissions of other greenhouse gases e.g. methane or nitrous oxide.

Despite these constraints, considerable progress in carbon accounting has been made worldwide in the past 10 years, in that:

- better simulation models are available for predicting likely changes in organic soil carbon over time and management
- the processes that influence changes in organic soil carbon are better understood
- carbon markets are becoming more sophisticated
- techniques for measurement and for sampling organic soil carbon are improving.

However, improvements are required to make organic soil carbon a viable component of carbon trading schemes especially at enterprise scales. In particular, a greater understanding of carbon cycle dynamics and improvements in measurement capabilities would be necessary (Dilling *et al.,* 2003). In Australia the National Carbon Accounting System (NCAS) and National Carbon Accounting Toolbox (NCAT) have made progress in developing suitable methods.

This report aims to inform decision makers about soil carbon, the role of organic soil carbon in carbon cycling and sequestration, current measurement techniques and its potential for inclusion in carbon trading schemes for agriculture and forestry. It was a desk-top review covering the recent Australian and international literature. From a carbon trading perspective, the report covers:

- a definition of soil carbon
- how organic soil carbon changes
- how organic soil carbon can be increased
- how much organic soil carbon can be stored

- the services provided by organic soil carbon
- the methods of measuring, sampling and modelling organic soil carbon for accounting purposes
- some of the practical issues of sequestration, monitoring and economics of including organic soil carbon.

Soil and soil carbon

Soil is a thin mantle (usually up to 2 metres thick) that covers most of the Earth's solid surface. It is a system of organic material, inorganic material and living organisms. Soil is formed by the weathering of rocks and minerals, transport of components in wind and water and through biological activity. As well as storing water, soil provides nutrients and is the physical support for the root of a plant. Soils are home to a wide range of organisms and are a repository for soil carbon (McKenzie *et al.,* 2004).

This section defines soil carbon and its various forms, how organic soil carbon changes, the processes that can increase organic soil carbon, the amount of organic soil carbon that can be stored, and the benefits provided by soil carbon.

What is soil carbon?

'Soil carbon' refers to the total carbon in soil and it includes both inorganic and organic forms, which are discussed below. In a carbon trading framework, the emphasis would be on the organic forms of carbon in the soil because the inorganic form is relatively stable and is not strongly influenced by land management.

Inorganic soil carbon

Inorganic soil carbon is the result of both weathering of rocks and of carbonic acid (carbon dioxide dissolved in water) in the soil precipitating as carbonate minerals such as calcite and dolomite (Lal, 2007) or as calcrete. According to world-wide estimates from soils to a depth of one metre, soils contain about half as much inorganic as organic soil carbon in total (Batjes, 1996). The timescale for inorganic forms of carbon to change and interact with atmospheric carbon is thousands of years. Therefore, inorganic forms are usually ignored when discussing agricultural production and carbon sequestration (Trumbore & Torn, 2003). However, the contribution from applications of agricultural lime can be significant at field scales, and the dissolution and precipitation of carbonate minerals may actually emit as much or more carbon than is stored (dependent on the source of the carbon in the carbonic acid, the soil pH and the amount of calcium in the soil (Schlesinger 2000)).

Organic soil carbon

Organic soil carbon is a measure of soil organic matter and comes from the leaf litter, plant roots, branches, soil organisms and manure. Organic soil carbon can make up more than 15 per cent of the total soil mass, but in agricultural soils is usually less than 5 per cent and diminishes with soil depth. Organic soil carbon (as a total measure over soil depths) is estimated to range from less than 10 tonnes of carbon per hectare (t C/ha) to more than 160 t C/ha in the top 30 cm of undisturbed soil (Valzano *et al*., 2003; Wynn *et al.,* 2006; Roxburgh *et al.,* 2006; Carter *et al.,* 2004) and even up to 250 t C/ha in some favourable undisturbed locations (Webb 2002).

The components of soil organic matter (Figure 1) are defined by their origin and stage of decay. Their chemical, physical and biological properties influence soil functions and the potential of each to contribute to carbon sequestration. Plants, animals and microbes are known as 'living organic matter' which is rarely included in measures of soil carbon sequestration because of its changeable nature. After death, this matter goes through several stages of decay, to form components collectively referred to as 'non-living organic matter'. The components of non-living organic matter are measured as:

- *particulate organic matter*—an early stage of decay, composed of organic fragments that retain a recognisable structure including the litter fraction (organic matter at the soil surface), the macro-organic matter fraction (fragments >0.053 mm in diameter) and the light fraction (organic material that floats when soil is wetted)

- *dissolved organic matter*—made up of materials in solution, and a very small proportion at any one time
- *humus*—a dark-coloured organic material without a recognisable shape produced by the decomposition of vegetable or animal matter and essential to the fertility of the earth; its chemical structure provides a large area for chemical reactions and water holding
- *inert organic matter*—usually charcoal or charred material that comes from burning; it is also called *recalcitrant carbon* because it is resistant to chemical and biological reactions.

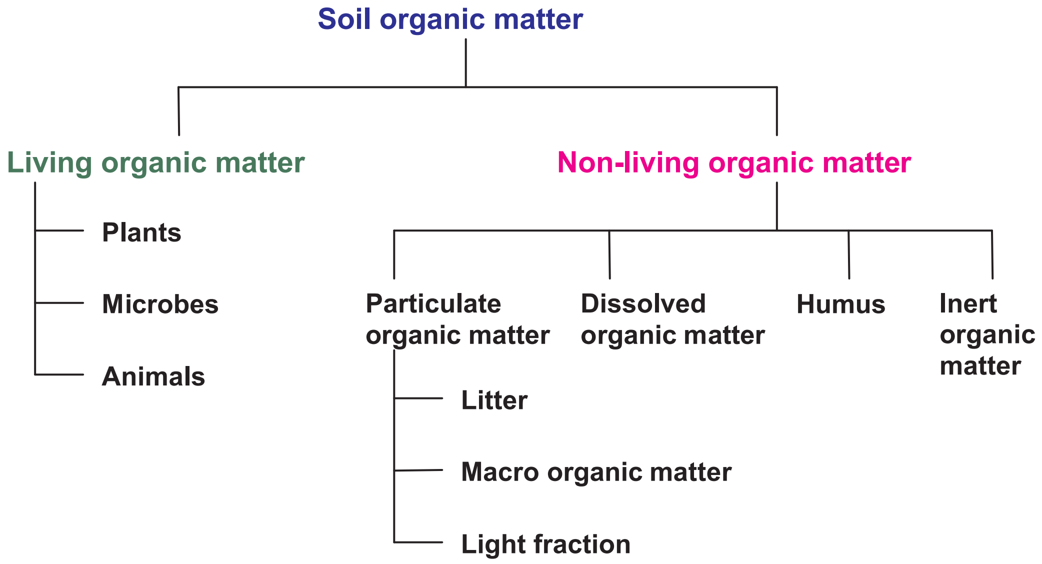


Figure 1 - Components of soil organic matter (modified from Baldock and Skjemstad 1999) with permission from CSIRO, Land and Water.

How does organic soil carbon change?

At any one time, the organic soil carbon content of soil is a balance between the rate of carbon deposition and the rate of carbon loss (Figure 2). To properly manage soil as a reservoir for organic carbon it is important to understand the processes that influence the change of organic carbon in the soil profile, and why organic soil carbon may become stable.

The major inputs are dead plants, animals and microbes, which decay through different processes and at different rates depending on their composition. They usually require several stages to break down because some components are difficult to digest biochemically, e.g. lignin, a complex chemical in wood that is slowly broken down by fungi and bacteria. Other components, such as carbohydrates and proteins, break down rapidly. Microbial activity is probably responsible for much of the change to the form of organic soil carbon in the upper layers of the soil.

Although most soils contain a continuum of components of organic soil carbon, for convenience the organic soil carbon is usually grouped into multiple 'pools', according to how fast it is broken down and replaced. The three pools commonly used are:

- *fast*—this pool has a short turnover time, with fast decomposition (e.g. daily to annual); also referred to as the *labile* or *active* pool
- *slow*—this pool has a longer turnover time, with slower decomposition (e.g. annual to decadal); also referred to as the *stable* or *humus* pool

- *passive*—this pool has a much longer turnover time (e.g. decadal to centennial/millennial); also referred to as the *refractory* or *recalcitrant* pool.

The percentage of total soil carbon in each pool varies, but some ranges are shown in Figure 2. For carbon sequestration and carbon trading purposes it would be desirable to increase the amount of organic soil carbon in the slow and passive pools due to their relative stability. While building the content of the fast pool is important for carbon sequestration it is also more vulnerable to loss if conditions change.

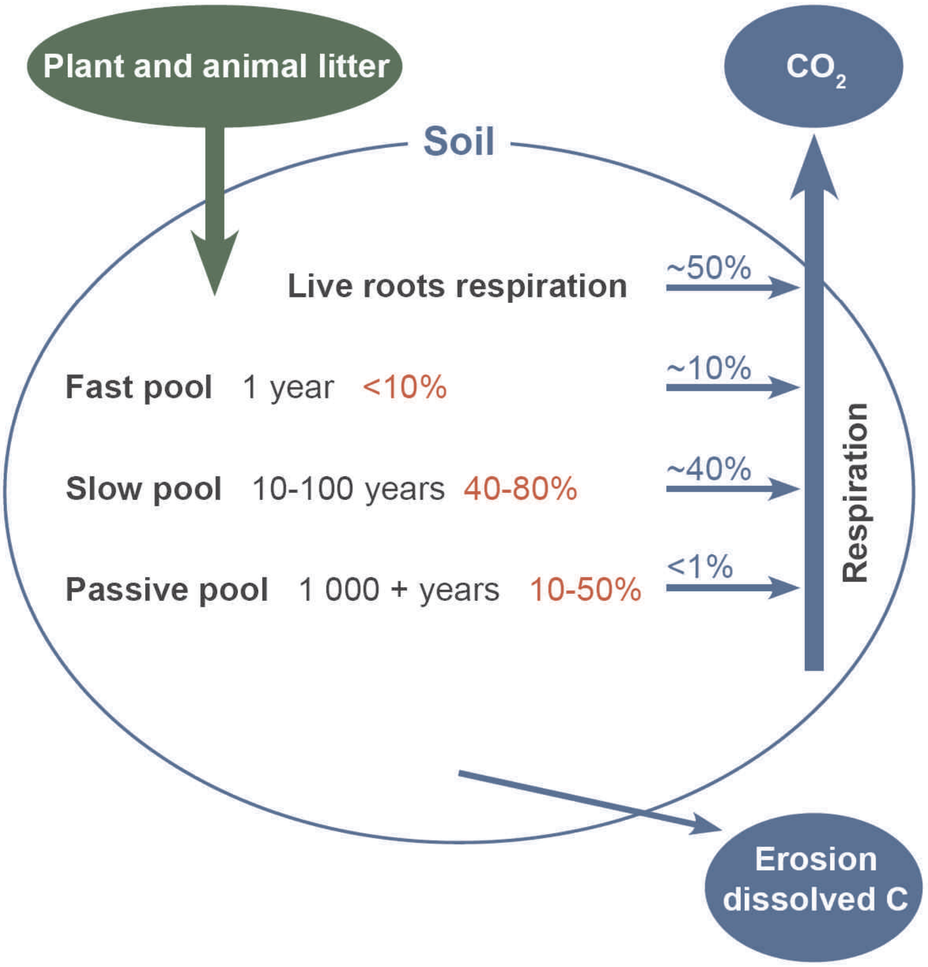


Figure 2 - A simple diagram of the soil carbon cycle, after Amundson (2001). The proportion of soil carbon in each of the pools is shown in red, and the contribution to respiration from each of the pools is shown in blue. With permission from Annual Reviews.

Carbon is lost from the soil through leaching of dissolved carbon, erosion, and conversion of carbon to carbon dioxide through mineralisation (Baldock, 2007) and respiration by plant roots. Because of its highly transient nature, respiration from plant roots is not calculated in losses of organic soil carbon for carbon sequestration, even though it contributes about half the carbon dioxide emissions from soil. As shown in Figure 2, about 40 per cent of losses of carbon dioxide come from the slow pool, whereas the fast and passive pools contribute about 10 per cent and less than 1 per cent, respectively, but this will vary with the relative sizes of the different pools under different conditions.

Biologically stable organic soil carbon can exist as a result of biochemical recalcitrance (the content of organic fractions that are difficult to decompose), and physical protection (where organic material is chemically bonded to soil minerals or is located in spaces too small for microbial access) (Krull *et al.,* 2003; Jastrow *et al.,* 2007). Biochemical recalcitrance depends on the vegetation type, because this affects the amount and type of lignin going into the slow pool. It also depends on burning, because this affects the amount of charcoal going into the passive pool and may therefore affect the amount of organic soil carbon in the different carbon pools. Physical protection is related to the clay content because clay increases the reactive surface area of a soil, meaning that reaction with minerals is more likely, it also reduces the spaces in soil aggregates to sizes inaccessible by degrading microbes.

Organic soil carbon is influenced by management, climate, soil mineral composition, soil biota, and position in the landscape (Lal, 2007; Baldock & Skjemstad, 1999). Due to the interactions that occur between these factors it is difficult to determine the absolute importance of any single factor on organic soil carbon. However, management is arguably the most important, followed by climate (Baldock & Skjemstad, 1999). The rest of this section considers the effects of such characteristics.

Influence of soil characteristics

Organic soil carbon content varies with depth and with soil type. Figure 3 shows how four soil types from different locations in Australia vary in the amount of organic soil carbon they contain. Typically organic soil carbon content is greater at the surface and diminishes exponentially with depth. However, in some soils, high concentrations of organic soil carbon can be found at depths greater than 50 cm (e.g. some vertosols where the shrink-swell nature of the soils encourages downward movement of organic matter) (Baldock & Skjemstad, 1999).

Soil mineral composition can affect mechanisms that stabilise organic soil carbon against biological oxidation (as described above). Dalal and Chan (2001) found that decomposition of humus in the slow pool is slower in clays and silts than in coarse soil and the presence of iron, aluminium and calcium ions in clays can help protect soil humus from further decay (Krull *et al.,* 2001).

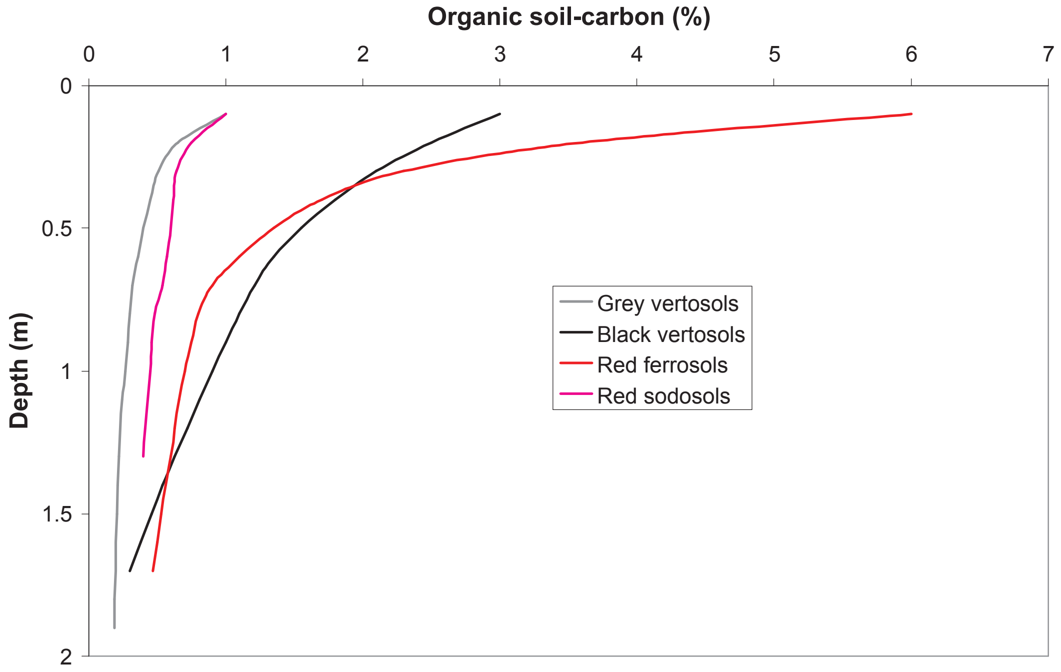


Figure 3 - Profiles of organic soil carbon in different soils. Grey vertosols (shrink and swell clays) are from arid to semi-arid grasslands, black vertosols are from subtropical grasslands, red ferrosols (uniform with high iron content) are from tropical rainforests and red sodosols (contrast texture with high sodium) from cultivated sites with 350–450 mm annual rainfall. Adapted from Spain *et al.* (1983) with permission from CSIRO Publishing on behalf of Australasian Soil and Plant Analysis Council.

Soil texture can also affect the amount of carbon in the different pools. In soils with a high level of fine particles (e.g. clays and silts), about 30 per cent of organic soil carbon tends to be found in the passive pool (in the form of charcoal and physically protected carbon), whereas in soils with a low level of fine particles the figure is about 4 per cent (Skjemstad *et al.,* 2001).

Influence of climate

Climate can influence the amount of carbon in soil. Biological processes such as the amount of organic matter input and the rate of decay of these residues are affected by soil temperature, oxygen and soil moisture levels (Baldock, 2007). Provided that sufficient water is available, higher temperatures lead to faster decomposition of soil organic matter, less storage of carbon in the slow and passive pools, and greater loss of carbon through respiration (Canadell *et al.,* 2007). Thus, in warm climates, soils generally contain less organic soil carbon than in cold climates (Lal, 2007).

The rates of decomposition of soil organic matter as influenced by temperatures are usually described by exponential functions (Baldock, 2007) that look similar to

Figure **4**, which allows the changes in organic soil carbon to be calculated. These functions provide a value averaged over the different components of organic soil carbon.

Rainfall also affects the amount of organic soil carbon, with soils in humid regions generally containing more organic soil carbon than soils in dry regions (Lal, 2007) because of higher plant growth. Soil properties such as pore space and pore size affect the availability of water and oxygen in the soil (Figure 5) that, in turn, affect the mineralisation of organic soil carbon (Baldock, 2007).

Microbial activity is limited in dry soils, so wetter soil leads to faster breakdown of organic matter, provided there is sufficient oxygen. In continually saturated soils decomposition rates are reduced and highly organic soils such as peats can develop.

Analysis of data on sandy soils from 48 regions around Australia by Wynn *et al*. (2006) indicated that, in water-limited environments, both production and decomposition of organic soil carbon increase as water availability increases. Overall, the analysis indicated that water (by increases in plant production) and temperature (by increases in organic-carbon decomposition) can explain most of the variability in organic soil carbon although it is also modified by soil texture in some regions.

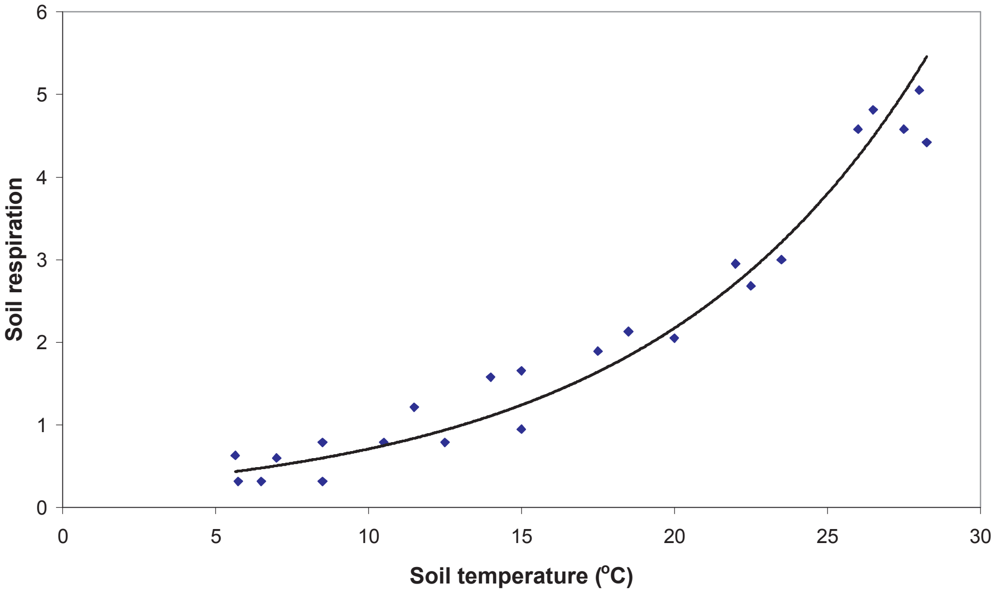


Figure 4 - An example of response of soil respiration (in mol m^{-2} s^{-1}) to soil temperature under a tall grass prairie as it fluctuated over a full year in Oklahoma, USA. Adapted from Luo *et al.* (2001) with permission from Macmillan Publishers Ltd**.**

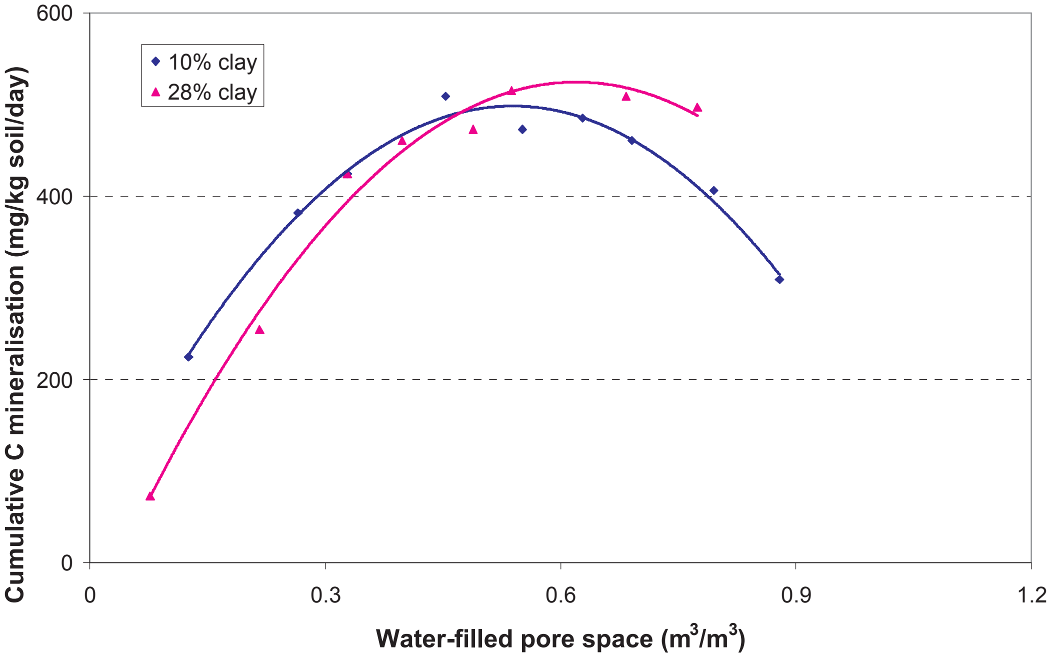


Figure 5 - Effect of water content and porosity on mineralisation of organic soil carbon - modified from Krull *et al.* (2001)

Influence of land management and biota

The amount and quality of organic carbon inputs into the soil are a function of the vegetation present (Baldock & Skjemstad, 1999). Increasing plant biomass production would likely increase organic soil carbon, while adding plant residues with higher carbon:nitrogen (C:N) and lower nitrogen:lignin ratios would reduce residue decomposition rates and potentially maintain or increase organic soil carbon. The activity and diversity of soil decomposers and fauna may also be important for organic soil carbon. Earthworms, ants and termites may increase the amount of stable organic carbon in some soils and in soils with high populations of soil organisms. Decomposition of plant residues and organic soil carbon may be enhanced (Baldock & Skjemstad, 1999).

There is limited information on how biota (vegetation and organisms) affects carbon levels in the stable carbon pools at different depths in a soil profile (Lorenz & Lal, 2005). Shrubs tend to have a higher proportion of their roots below 1 metre in the soil than trees or grasses, and as a result have higher organic soil carbon at depth (Lorenz & Lal, 2005). The spatial variability of pastures and woodlands can also influence soil carbon. For instance, the soil carbon level is usually higher around trees compared to around other plants in the vegetation community in more arid locations in Australia (Wynn *et al.,* 2006).

Management practices such as levels of soil disturbance, rotations and management history can influence the amount of organic soil carbon in the soil.

Soil disturbance with cultivation has a significant impact on organic soil carbon, and the amount lost will be influenced by the initial organic carbon content, the level and type of plant residue input and the intensity of cultivation employed (Baldock & Skjemstad, 1999). For example, some practices such as minimum-tillage and stubble retention lose less soil organic soil carbon than clean cultivation, but still do not maintain organic soil carbon at contents that could be achieved under pasture (Heenan *et al.,* 2004). Cultivation leads to movement of carbon from the soil to the atmosphere in the form of carbon dioxide. Emissions of organic carbon due to cultivation in the cereal belt may be considerable. For example, in 1997 such emissions from the cereal belt were calculated at 54 Mt CO_2-eq (total CO_2 equivalent greenhouse gases), by Dalal and Chan (2001), compared to the 94.2 Mt CO_2-eq from agriculture overall estimated by the National Greenhouse Gas Inventory (but this does not include changes in soil carbon due to management).

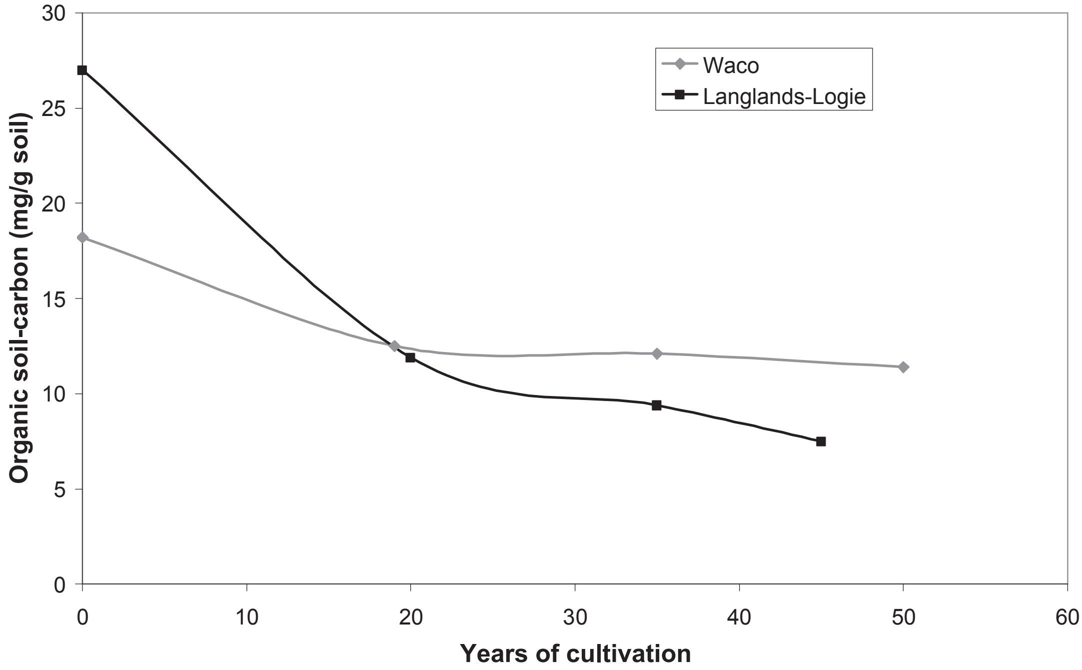
Altering land management practices may create a system where organic soil carbon levels become unstable; however, if management practices are maintained for an extended period then it is possible for the soil to attain an average equilibrium value indicative of a particular management practice (Baldock & Skjemstad, 1999). Long-term trials in different parts of Australia have shown that different management practices reduce organic soil carbon (Table 1): cropping generally tends to reduce the organic soil carbon content, especially with long fallow periods but less so with pasture phases in the rotations (Grace *et al.,* 1995). The effect is most pronounced in the top 10 cm of soil, but is also noticeable at 22.5 cm depth (Figure 6). Other research (Grace *et al.,* 1997) found that continuous cropping had reduced organic soil carbon in the top metre of soil from 1117 kg C/m^2 in 1880 to 932 kg C/m^2 in 1990, and was likely to reduce it further to 837 kg C/m^2 by 2100. By contrast, converting from cropping to pasture would achieve levels of 1154 and 1121 kg C/m^2 if undertaken in 1990 and in 2100 respectively.

Table 1 - Effect of agricultural management systems over the long term on organic soil carbon (shown as SOC) in the top 10 cm of soil

	Waite, SA	**Longeranong, Vic**	**Rutherglen, Vic**	**WaggaWagga, NSW**
Soil type	Red-brown earth (a chromosol)	Self-mulching grey clay (a vertosol)	Silt loams (a rudosol)	Red earth (a ferrosol)
Original SOC %	2.75	1.00	0.76	1.3
Years of treatment	68	32	36	21
% change in SOC under constant management treatment				
Wheat/fallow	-63	-26	-32	
Wheat/pasture/fallow	-60	-14		
Wheat continuous	-45			-41
Pasture/wheat				-8
Pasture	-11			
Source:	Grace *et al.* (1995)	Grace *et al.* (1995)	Grace *et al.* (1995)	Heenan *et al.* (2004)

Gower (2003) observed that the effect of management and disturbance on soil carbon in forests is poorly understood and often difficult to detect. Gower concluded that the likelihood of forests being able to sequester large amounts of carbon in the soil is low, and preferred the option of storing the carbon in the trees. Net carbon accumulations in soil 40 years after establishing a forest where one did not previously exist (i.e. afforestation) were generally minimal.

Some long-term forestry studies looked at the effects of different one-off forestry management practices (sawlog, clear felling and whole-tree removal) at different locations in the eastern United States. The studies found that although there were short-term differences in soil carbon under the different practices, these differences had largely disappeared after 15 years of regrowth (Johnson *et al.,* 2002). Some of the effects were thought to be due to the large amounts of carbon in the decomposing roots, large pieces of woody debris and differences between areas. The total amount of organic soil carbon within the top 30 cm varied, depending on the location, from 37 Mg C/ha to 115 Mg C/ha. The authors concluded that the once-off residues from logging contribute little over the longer term to organic soil carbon.



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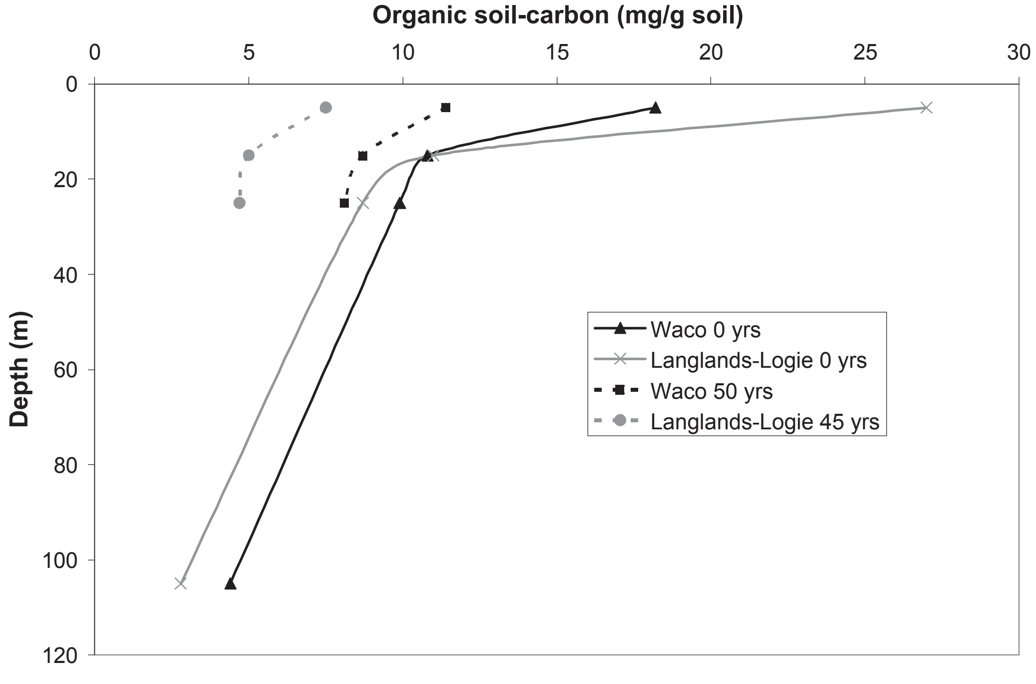

b)

Figure 6 - Changes in organic soil carbon with cultivation, a) in the top 10 cm over time and b) with depth after more than 40 years cultivation. Both soils are vertosols but the Waco soil, originally under Queensland blue grass (*Dicanthium sericeum*), has higher clay content (69-80%) than the Langlands-Logie soil (50-53%), originally under brigalow (*Acacia harpophylla*). Data from Skjemstad *et al.* (2001).

Table 2 - Effects of management on soil carbon

Land management change	Percent change in total soil carbon	Range of percent change in total soil carbon
Pasture to plantation	–10	–15 to –5
Native forest to plantation	–13	–21 to –5
Native forest to crop	–42	–49 to –34
Pasture to crop	–59	–63 to –54
Native forest to pasture	+8	+5 to +12
Crop to pasture	+19	+14 to +24
Crop to plantation	+18	+10 to +27
Crop to secondary forest	+53	+37 to +62

A worldwide meta-analysis of the effects of management on soil carbon indicated the changes in the total amount of soil carbon varied with the type of land-use change (Guo & Gifford, 2002) (see Table 2). The results shown in Table 2 are from experiments that are not directly comparable (e.g. they use different techniques, sample different depths of soil and over different times) but do indicate the scale of possible effects of changing land use. In addition, some studies suggest that conversion from native forest or pasture to pine plantations reduce total soil carbon by 12–15 per cent, whereas conversion to broad-leaf tree plantations has no effect on total soil carbon. This finding is supported by recent data from southeast Australia, which show that conversion of native, broadleaf forest to pine plantation reduced soil carbon content by 30 per cent after 37 years (Kasel & Bennett, 2007).

What processes can be used to increase organic soil carbon?

There are two major strategies for increasing the amount of carbon presently sequestered in soils (Figure 7). The first involves reaching 'attainable carbon'—that level of carbon achievable with present climate. The second involves taking sequestered carbon to a higher level referred to as 'potential carbon'—that limited by soil characteristics. The second strategy is likely to require external inputs of carbon.

An example of the first strategy, is to alter factors that affect carbon sequestration such as crop selection, soil management, fertilisation, animal grazing pressure (stock numbers), and pest and disease control. Of note is that in most of Australia's dryland agriculture and forestry, rainfall limits the amount of organic carbon that can be added, although sometimes it is plant nutrition that sets the limit.

A number of approaches have been proposed to increase the amount of attainable organic soil carbon particularly that stored below a depth of one metre where it is likely to be kept for longer in stable forms. These include:

- for cropping systems, increasing the frequency of pasture leys in rotations, increasing fertiliser applied and retaining crop residue offer some promise, particularly in the wetter (>500 mm rainfall) temperate parts of Australia (Dalal & Chan, 2001), which includes about a quarter of the area cropped in Australia
- selecting plant species that would provide a greater amount of roots in the subsoil, to increase the amount of organic soil carbon likely to dissolve and move down (Lorenz and Lal, 2005)

- selecting plant species with slower decomposing roots, more resistant chemical composition and more use of ectomycorrhiza (fungi that form a sheath around the root tip of a plant) (Lorenz & Lal, 2005). For instance, Parr and Sullivan (2005) suggest that phytoliths—that is, mineralised silicates that can enclose and protect the carbon structures of various plant parts for long times—have some potential to increase sequestration of carbon in soil by reducing the decomposition of some plant residues
- increasing the activity of soil fauna and soil microorganisms (e.g. developing access channels deep in the soil with 'primer plants') (Lorenz & Lal, 2005)
- changing land uses to have a greater proportion of shrublands (Lorenz & Lal, 2005), of pasture legumes or of shrub legumes (e.g. *Leucaena* or tagasaste) may increase biomass that can then flow on to organic soil carbon over time
- reversal of existing degradation (saline, acidic and eroded land) by planting of perennial species may increase organic soil carbon over time
- incorporating grazing management that increases forage production and manure inputs may increase organic soil carbon content (Conant *et al.,* 2001).

The energy and carbon costs associated with achieving attainable organic soil carbon levels need to be counted in any carbon budget (Schlesinger, 2000). Factors to be considered include the energy and carbon costs of preparing and transporting fertilisers, pumping irrigation water, and any release of nitrous oxide or methane.

For the second strategy—taking sequestration to 'potential carbon' levels—it has been proposed to sequester carbon in soils using external sources of carbon, such as manure or other organic wastes. Because this is likely to be relatively inefficient (see Figure 8), more resistant material such as biochar (a form of charcoal), charcoal, or fly ash have been suggested (Lehmann, 2007). Biochar is the residue from low-temperature pyrolysis of organic materials—an approach most recently used for bioenergy production due to the energy products released during the process (Lehman, 2007). Using the low-temperature pyrolysis method, up to half of the organic carbon in plant material can be returned to the soil as biochar (Lehmann *et al.,* 2006). The process is estimated to cost about US$4 per gigajoule for heating and machinery, but this does not include any costs of returning the biochar to the soil. Biochars are more recalcitrant than uncharred organic matter due to the structure being dominated by aromatic carbon (Baldock & Smernik, 2002), and hence may have potential for soil improvement and carbon sequestration (Lehmann *et al.,* 2006).

Fly ash, one of the residues generated in the combustion of coal, and charcoal may boost the adsorptive capacity of soils that have low cation exchange capacities and poor structure (Jastrow *et al.,* 2007). Farmyard manure, which contains a high proportion of slowly decomposing lignin, may boost organic soil carbon but not necessarily total carbon sequestration (Schlesinger, 2000).

For all these techniques, a full life-cycle analysis is required to determine whether there is a net gain in carbon sequestration (or just a relocation of carbon to satisfy requirements for carbon trading). The life-cycle analysis should also include impacts on soil biology.

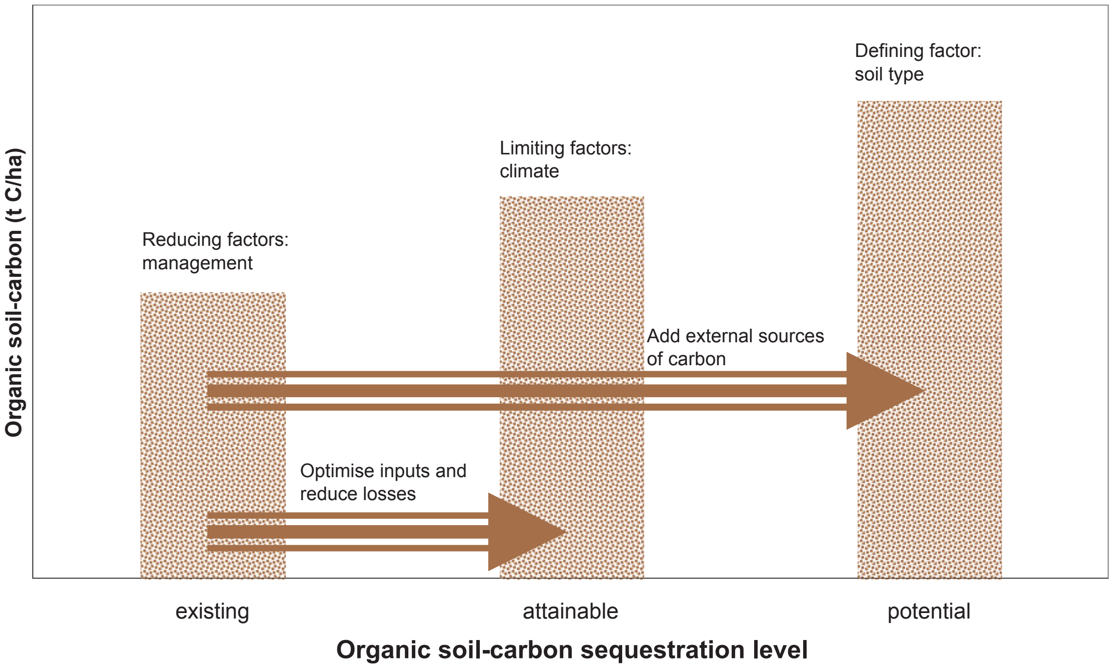

Figure 7 - Diagram of strategies for increasing the sequestration of organic soil carbon. Modified from Baldock *et al.* (2007).

How much organic soil carbon can the soil store?

The limit to carbon sequestration—the point at which the levels of organic soil carbon can no longer increase, regardless of management options, production or external inputs—is referred to as carbon saturation or maximum capacity. This limit appears to depend on two elements of soil texture, mineralogy and particle size distribution (Krull *et al.,* 2003; West & Six, 2007). A recent review of agricultural experiments indicated that adding increasing levels of organic soil carbon to the soil may lead to organic soil carbon saturation (Figure 8).

West and Six (2007) estimate that the saturating level increases with clay content because it provides increased capacity to adsorb and protect organic carbon in soils. The authors suggest that knowing the saturation level is important in determining how much carbon the soil can sequester, how fast it can be sequestered, and for how long sequestration will occur. Using Figure 8 as an example, it is obvious that increasing the amount of soil carbon sequestered by one unit requires more carbon input when moving from level C_2 to C_3 (i.e. the difference between inputs I_3 and I_2) than when moving from C_1 to C_2 (i.e. the difference between inputs I_2 and I_1). This indicates that the greatest gains in terms of carbon sequestration are likely from the initial carbon inputs, with the effect of the input diminishing as the amount of soil organic-carbon sequestered approaches the saturation level.

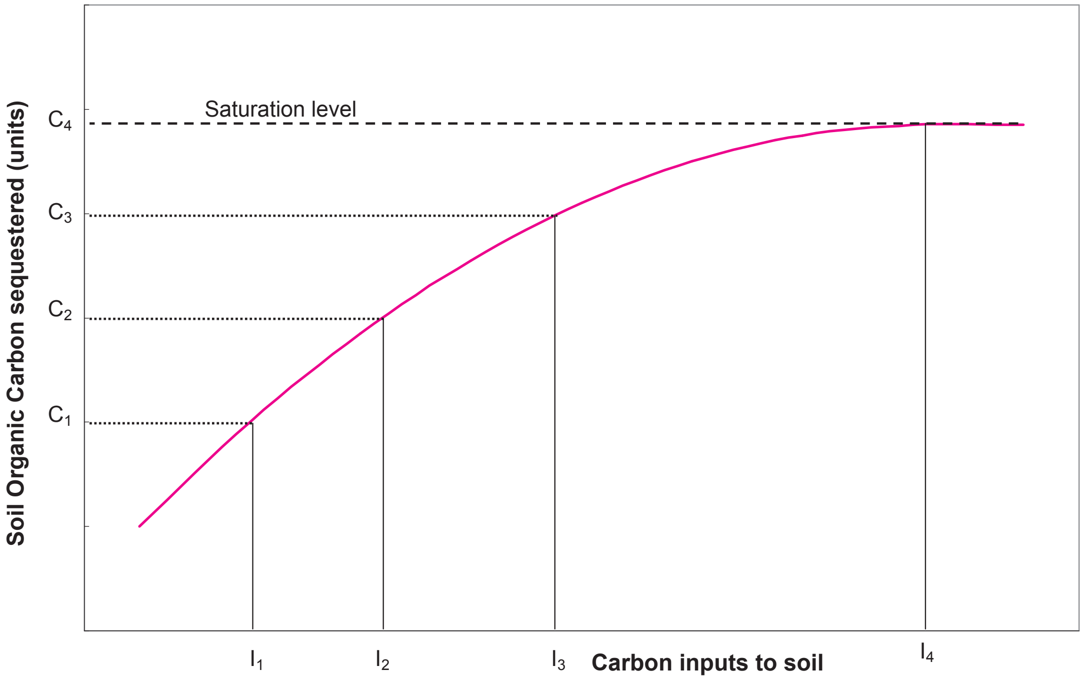

Figure 8 - Organic soil carbon responses to steady state inputs of organic carbon. From West and Six (2007) with permission from Springer Science and Business Media.

What benefits are provided by organic soil carbon?

Soils effectively function as ecosystems when they form soil organic matter from living organisms and undertake the many reactions to convert organic matter into plant-available inorganic elements plus carbon dioxide (Baldock & Skjemstad, 1999).

The soil ecosystem also provides benefits, or services, to humans, which are enhanced by increasing soil organic matter, including:

- *carbon storage*—as discussed
- *food and habitat for biodiversity*—Soils are home to many organisms that often use the organic matter as food. These organisms, together with plant roots, live within the soil environment (Figure 1). The largest total weight generally comes from earthworms, but other groups include insects (e.g. dung beetles, ants and termites, cicadas, locusts, millipedes and centipedes), spiders, mites, snails, nematodes and even some mammals (e.g. mice, rabbits, platypus and wombats). In addition, there are many microorganisms—bacteria, fungi, algae and protozoa—that actively contribute to carbon cycling in soils (McKenzie *et al.,* 2004)
- *nutrient storage and supply*—Soil organic matter can form up to half of the sites for nutrient storage and exchange (referred to as 'cation exchange capacity', CEC) (McKenzie *et al.,* 2004). The mineralisation of N (making this element available to plants) occurs particularly in the active pool (Haynes, 2005); however, the role of soil organic matter in providing plant-available phosphorus in soils is not well understood (Dalal & Chan, 2001)
- *erosion control*—Soil organic matter stabilises other parts of the soil, binding soil particles into aggregates that are more resistant to erosion
- *buffering capacity*—Soil organic matter increases the soil's ability to buffer against changes in pH (Dalal & Chan, 2001). It also adsorbs many pesticides, although there is little research on this aspect in Australia

- *soil water*—Soil organic matter helps to increase soil aeration, allowing water and air to move more easily through the soil and thus increasing the infiltration rate (so that rainfall takes a shorter time to enter the soil) and water holding capacity of the soil (Dalal & Chan, 2001)
- *plant Growth*—The effect of increased soil organic matter in improving plant growth is frequently demonstrated in 'islands of fertility' in arid and semiarid ecosystems (Ehrenfeld *et al*., 2005). The benefit of additional soil organic matter on plant growth appears to diminish as it approaches some equilibrium level of organic soil carbon in undisturbed systems and in some disturbed systems may be less than expected from similar undisturbed systems.

If soil organic matter is increased through the use of carbon trading, increases in these ecosystem services will be of benefit to agricultural and forest industries. Thus, carbon sequestration in soil could be a 'win–win' situation, helping to reduce greenhouse gas levels in the atmosphere and improving soil quality for agricultural and forestry industries. However, Dilling *et al.* (2003) note that some processes to increase carbon sequestration may lead to undesirable consequences for biodiversity and ecosystems. Examples of such consequences could be:

- an increase in pesticide use in some methods of increasing plant productivity
- increased emissions of nitrous oxides (which are greenhouse gases with Global Warming Potentials up to 300 times that of CO_2) from applying fertilisers
- reduced surface albedo (i.e. the reflectivity of the soil surface) as increased soil organic matter darkens some soils, which increases heat absorption during the day
- loss of biodiversity, if areas with low biomass but high biodiversity are converted to areas with high biomass but low-diversity (e.g. if an area of native forest is replaced with sown pastures or plantations).

Main points

- **Carbon exists in soil in two forms—organic and inorganic. The inorganic form is relatively stable and is not strongly influenced by land management and is therefore unlikely to be part of a carbon trading scheme. The organic form, which comes from the decay of organic matter, is less stable and will vary depending on factors that influence this decay, such as climate, soil type and land management practices.**
- **Increasing the amount of organic soil carbon in the soil may not only mitigate greenhouse gases but also benefit agricultural and forestry productivity (a 'win–win' situation). However, the benefits may not be as large as expected (e.g. due to decomposition); and processes that increase carbon sequestration may have adverse environmental effects.**
- **Organic soil carbon can be divided into three 'pools' according to how fast it breaks down and is replaced. These pools are: fast (e.g. annual), slow (e.g. decadal) and passive (e.g. millennial). For carbon sequestration and carbon trading purposes, it is desirable to increase the total amount of carbon especially in the slow and passive pools (referred to as the 'stable' pools).**
- **The amount of organic soil carbon in the stable pools can be increased by adding plant material above and below the soil surface, and by altering the rates at which this material decomposes.**
- **The amount of organic soil carbon may be increased through some land management changes or through the application of external sources of carbon, such as biochar (a form of charcoal converted from organic material) or manure, to the soil. Life-cycle analyses are required to determine if there is a net gain in carbon sequestration with these proposed measures.**

Measuring soil carbon

Most analytical methods used routinely for measuring the amount of soil organic matter actually determine the concentration of organic soil carbon (on a mass basis as g C/g soil). Direct measurements of soil organic matter are difficult due to variations in the contents of its component elements (carbon, hydrogen, oxygen, nitrogen, phosphorous, sulphur) (Baldock & Skjemstad, 1999). The values for organic soil carbon content are then converted using other soil characteristics to a measure of organic soil carbon density (mass of organic soil carbon per unit area) for use in carbon accounting and trading.

This section describes the standard methods for determining the density of organic soil carbon. It includes soil sampling requirements and analytical methods for measuring organic soil carbon concentration, the use of indirect methods for measuring organic soil carbon and the use of models for predicting soil carbon under different management scenarios.

How do you measure the density of organic carbon in soils?

Measurements of the density of organic soil carbon are determined from the concentration of organic soil carbon at various soil depth intervals along with the soil bulk density (weight per unit volume of soil) (Swift, 2001), and it may be determined for the various carbon pools. This is difficult because of the costs and labour-intensive nature of the soil sampling and analytical methods, and the approximate nature of attributing organic soil carbon to the various pools.

Soil sampling and the use of indirect methods

Organic soil carbon concentration may vary considerably across a paddock due to localised variation in soil characteristics, topography and past management. Increasing the number of soil samples will provide a more accurate description of the organic soil carbon status. However, the intensity of the sampling will need to be balanced against the level of accuracy required and the time and costs associated with the sampling process, sample preparation and analysis.

A major hurdle is the need to develop soil sampling schemes that are repeatable and representative, both in spatial directions (i.e. from one part of a landscape to another) and vertical directions (i.e. from one depth of soil to another). Such schemes are necessary to accommodate the long time spans needed to detect changes in soil carbon stores for carbon accounting purposes, and to cover the variability of soils across landscapes.

The variability of soils in fields can be substantial. For example, Knowles & Singh (2003) studied variation in soil properties across a 128 ha field that had been cropped to cotton and wheat for over 20 years on a commercial farm in northern New South Wales. A summary, derived from samples in 120 locations and given in Table 3, indicates that the surface 30 cm contained more organic soil carbon (5 t C/ha more) than the next 30 cm (i.e. at a depth of 30–60 cm), and that about 62 per cent of total carbon was in the form of organic soil carbon. The spatial variation in organic soil carbon concentration across the field at the two uppermost depths (Figure 9) illustrates the difficulty in obtaining representative samples for the whole field.

New techniques for taking samples to provide a representative specimen are being developed (Wynn *et al.,* 2006; Mooney *et al.,* 2007). These techniques include stratification, spatial autocorrelation, weighting for the distribution of vegetation types and bulking of samples into specimens for measurement. They can reduce the number, and hence cost, of actual measurements of organic soil carbon concentration, its components and soil physical attributes, but may mean that the collection of samples is the most expensive part of the process.

Estimates of the components of organic soil carbon are often derived from other measures, for example, they may be derived by relating above-ground vegetation biomass to below-ground biomass, using remote sensing (Gehl & Rice, 2007). Another approach is to use a typical profile for soil, climate and vegetation combinations and apply average organic soil carbon across the designated area (Swift, 2001).

Table 3 - Total carbon and organic soil carbon for four depths in a vertosol field. Values are means ± standard deviation (Knowles & Singh, 2003)

Depth (m)	Total carbon (t/ha)	Organic soil carbon (t/ha) (% of total carbon)
0-0.15	15.7 ± 3.2	9.8 ± 3.0 (62%)
0.15-0.30	15.9 ± 4.7	9.2 ± 4.1 (58%)
0.30-0.60	26.1 ± 8.3	15.8 ± 5.3 (60%)
0.60-0.90	20.6 ± 7.8	13.8 ± 6.1 (67%)
0-0.90	**78.3 ± 19.5**	**48.6 ± 13.3 (62%)**

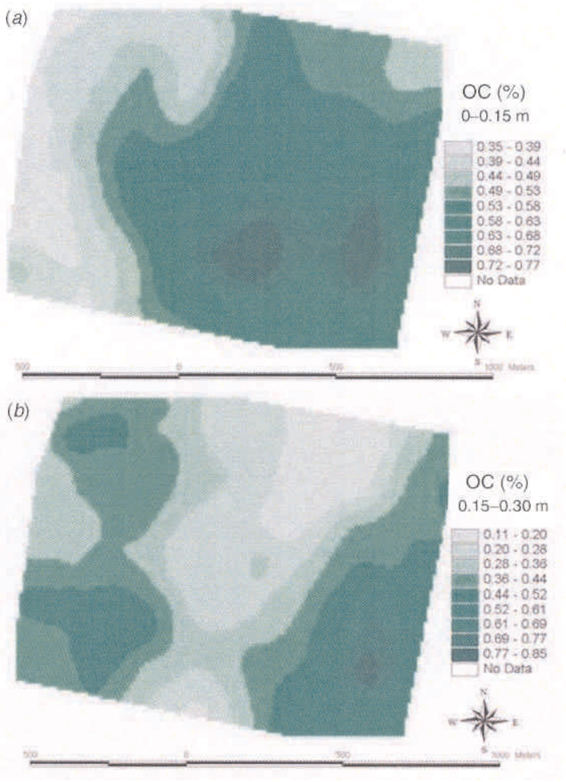

Figure 9 - Spatial variability of organic soil carbon content (%) at 2 depths across a 128 ha cotton field in northern NSW. From Knowles & Singh (2003) with permission from CSIRO Publishing.

Soil carbon concentration

Standard analytical methods (Rayment & Higginson, 1992) for measuring the organic soil carbon concentration (weight of carbon per unit weight of soil) in soils include:

- the wet oxidation method, developed in 1935 by Walkley and Black, modified with external heat by Heanes; this uses inexpensive equipment but is laborious with inconsistent results
- the dry oxidation method where soil samples are heated in a stream of oxygen and all carbon inorganic and organic is converted to CO_2; the results must be corrected for carbonates and it requires more expensive equipment but is faster and more convenient than wet combustion and provides reproducible results.

Measuring organic soil carbon in the individual carbon pools

Organic soil carbon consists of a continuum of decomposing materials, so the attribution to individual pools is approximate (Table 4).

Table 4 - Approximate relationship between different pools in FullCAM model, measured fractions and physical components of organic soil carbon

FullCAM model pools	Measured fraction	Components
Fast	Plant residues >2 mm size	Decomposable plant material, microorganisms
Slow	Particulate organic carbon <2 mm – >0.053 mm	Resistant plant material
Passive	Calculated by subtracting particulate organic carbon and charcoal carbon from the total organic soil carbon	Moderate to highly resistant humus stuck to soil minerals
Recalcitrant	Charcoal carbon	Highly protected pieces of carbon

To measure the organic soil carbon concentration of the various fractions, physical sorting of a soil specimen into different components is usually carried out prior to analysis. One approach is to use sieves of different size to isolate free pieces of organic matter (inter-aggregate organic soil carbon), pieces of organic residue between soil particles (intra-aggregate organic soil carbon) and strongly bound organic matter (mineral-associated organic soil carbon). Another method is by flotation, using liquids of different density to separate the soil into free particulate organic matter (<1.6 g cm^{-3}), light occluded particulate organic matter (<1.6 g cm^{-3}), dense occluded particulate organic matter (1.6–2.0 g cm^{-3}) and mineral-associated organic matter (>2.0 g cm^{-3}).

Some of the methods commonly used for measuring the organic soil carbon content of particular fractions include the following:

- *particulate organic soil carbon*—the Cambardella and Elliot method uses wet sieving (200 and 53 μm sieve holes) of sample material before dry combustion
- *charcoal carbon*—the Skjemstad method uses the pass-through liquid (i.e. less than 53 μm), which is photo-oxidised and the carbon remaining measured using the Heanes wet oxidation technique. The samples are then analysed by nuclear magnetic resonance (NMR) spectroscopy to estimate the amount of charcoal carbon present (Skjemstad *et al.,* 2004). This method is time consuming and expensive

- *subtraction*—as shown in the table above, the humus fraction is determined by subtracting the amount of particulate organic soil carbon and charcoal carbon from the total organic soil carbon
- *MIR spectroscopy*—when used with partial least square analysis (PLS), mid-infrared spectroscopy is a low-cost and relatively simple method for estimating total, particulate, charcoal and humus organic carbon (Janik *et al.,* 2007)
- *carbon isotope techniques*—these have been developed to determine turnover and residence times of carbon in soils (Trumbore & Torn, 2003)
- *long term incubations*—these are used to indicate the relative amount of biologically available carbon. The method is time consuming (at least 30-100 days) but indicates the availability of carbon to microbiological decomposers (Paul *et al.,* 2006).

Given its potential use in the field and the range of fractions that can be measured the MIR spectroscopy technique is especially promising. This technique requires further development to build its calibration database for confident prediction of the allocation of soil carbon to the various component fractions.

Soil carbon density

The soil carbon density can be calculated using the following equation:

Soil carbon density (t C/ha) = weight carbon per unit weight of soil (g C/kg) × bulk density (g/cm^3) × depth of the soil layer (cm) × 0.1 (conversion factor)

Some methods for measuring organic soil carbon density *in situ* appear promising, and could speed up the process, reduce overall costs and minimise soil disturbance (Gehl & Rice, 2007). The most promising are laser-induced breakdown spectroscopy (LIBS), inelastic neutron scattering (INS) and infrared reflectance spectroscopy (NIR and MIR). However, these methods still have disadvantages, and need to be improved in terms of:

- applicability to the field—field-portable equipment needs to be developed
- greater accuracy—less errors and better calibrations are needed, documented against the dry combustion method
- greater sensitivity—lower detection limits are needed.

Can models be used to predict changes in organic soil carbon?

Several models have been developed to predict how organic soil carbon and the different pools of soil organic-carbon will change in response to the effects of different land uses, and the effects of management practices, such as stubble burning, grazing pressure and fertiliser use (Skjemstad & Spouncer, 2003). Such models may play an important role in monitoring carbon for a carbon market. Models are able to project likely changes in soil carbon under a range of conditions, and for much longer times than can be accommodated in experiments. Their usefulness depends on how well they represent the different processes in soils, the scale of application, and their accuracy.

All the models assign organic soil carbon into several pools, depending on their rates of turnover. Some models that have been commonly used in Australia are (Kirschbaum *et al.,* 2001):

- RothC—this model uses five pools:
  - easily decomposable plant material
  - resistant plant material
  - microbial biomass
  - humified organic matter
  - inert organic matter.

- CENTURY—this model is largely empirical and needs many parameters, and early versions were limited to 30 cm deep layers of soil using 11 pools (the last 3 of which equate to the fast, slow and passive pools shown in Figure 2):
  - aboveground live carbon
  - belowground live carbon
  - standing dead carbon
  - surface structural carbon
  - surface metabolic carbon
  - belowground structural carbon
  - belowground metabolic carbon
  - surface microbe carbon
  - active organic soil carbon
  - slow organic soil carbon
  - passive organic soil carbon.
- SOCRATES—this model was developed as simpler versions of RothC and CENTURY and includes five pools:
  - decomposable plant material
  - resistant plant material
  - unprotected microbial biomass
  - stable organic matter
  - protected microbial biomass.

The FullCAM integrated accounting tool of Australia's National Carbon Accounting System is based on the RothC model and is used to predict changes in soil carbon in response to land use changes (Kirschbaum *et al.,* 2001; Richards 2001). RothC appears to work well in Australian conditions (Skjemstad *et al.,* 2004). The other models, SOCRATES and CENTURY, appear to predict results with similar reliability (Grace *et al.,* 2006; Kelly *et al.,* 1997; Smith *et al.,* 1997). Despite this more work is required before these models can provide good spatial resolution and an acceptable level of uncertainty at enterprise level.

Because organic soil carbon consists of a continuum of decomposing materials measurements of the individual pools will not fit exactly into categories defined within organic soil carbon models (Skjemstad *et al.,* 2001; Krull *et al.,* 2003). Consequently, models need to be calibrated with many field sites where the contributing factors are well known. There have been many attempts to relate the measurable fractions of organic soil carbon to the different pools of soil carbon used in simulation models (Baldock, 2007). Skjemstad *et al.,* (2004) successfully calibrated the RothC component of the FullCAM model to use measurable fractions of soil carbon as follows:

- particulate (>53 µm) organic soil carbon replaced the resistant plant material in the model
- charcoal (<53 µm photo-oxidised and NMR analysed) carbon replaced the inert material in the model
- the humus pool calculated as the difference between total organic soil carbon and the sum of particulate organic soil carbon and charcoal C replaced the humus in the model.

Main points

- **Standard methods of measuring organic soil carbon and attributing organic soil carbon to the individual pools are generally slow and expensive. To quantify carbon in units suitable for carbon trading, combinations of methods would be required to determine the amount of carbon and how it changes spatially, vertically and under different management regimes.**
- **There are some new methods for measuring organic soil carbon that show promise for *in situ* field use but require more testing.**
- **In Australia, several models are used to estimate changes in organic soil carbon with reasonable accuracy. These will require more work, however, before they can provide good spatial resolution and an acceptable estimate of uncertainty at enterprise level. Direct measurement techniques will still be required to calibrate and verify these models.**

A potential role for soil carbon in carbon trading

While there is considerable potential for soils to contribute to mitigating climate change through net sequestration of carbon dioxide, there are practical matters to be resolved before soil carbon could be included in carbon trading schemes. Challenges include the ability to monitor, report and verify soil carbon emissions at meaningful scales in the context of carbon trading. In addition to the problems mentioned above—for measuring carbon, sampling soil and assigning carbon to different fractions within models—there are other issues that need to be resolved, such as:

- the effects of climate change on sequestration and decomposition rates
- agreements and protocols for carbon sequestration contracts
- agreements on which management changes should be included.

This section outlines the issues of estimating soil carbon for carbon trading, how to monitor organic soil carbon for carbon trading and then some of the economic considerations of including organic soil carbon in a carbon trading scheme.

What are the issues of estimating soil carbon for carbon trading?

To develop policies for carbon sequestration and carbon trading, we need to know how much carbon is stored, by what means and for how long. A range of issues including measurability, separating human management change from climate change, the initial organic soil carbon levels, the ability to measure at enterprise scales, and the depth of soil to be included are outlined below.

Any carbon market will require that carbon credits are technically credible, measurable and able to be verified by a third party. Ideally, processes should account for changes in the different forms of organic soil carbon (Canadell *et al.,* 2007). At present, measuring changes of less than 10 per cent in soil inventory are not feasible because of errors in sampling, small-scale variability and uncertainties with measures and analysis (Trumbore & Torn, 2003).

Carbon trading schemes require the contributions from *human management* to be distinguished from those due to *changes in climate and carbon dioxide concentration*. The differentiation between human and other contributions is important for equity. Storage of soil carbon may increase or decrease under future climates—a situation that would create winners and losers— without effort on the part of managers. Increases in temperature at any particular location will affect both the gain in organic matter from plant biomass and the loss of soil carbon through decomposition of soil organic matter (Dalal & Chan, 2001) and both of these effects will be complicated by uncertain changes in rainfall, fire regimes and nitrogen availability. Thus, both the gain and the loss need to be considered when attempting to determine the net effect of future climates.

The response of soil carbon to management changes depends greatly on the *starting soil carbon levels* and environmental conditions. Starting levels of soil carbon can only be reliably determined by sampling and measurement. Land managers can then estimate the approximate responses of soil carbon to management and environmental conditions at field scales to aid their decisions using simple soil carbon calculators.[1]

If individual producers are to participate in carbon trading schemes, then the carbon needs be countable in tradeable lots that can accommodate the relatively *small scales* at which soils and management vary within a landscape. For instance, it is important for carbon trading to include erosion losses of organic soil carbon at landscape scale, where the soil may be lost from the management area. At catchment or national scales, where a significant proportion of the translocated organic soil carbon is retained within their boundaries, erosion losses are less

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[1] www.greenhouse.crc.org.au/tools/calculators.

www.isr.qut.edu.au/tools/index.jsp.

http://lter.kbs.msu.edu/carboncalculator/.

important as a source of greenhouse gas emissions (Robertson & Grace, 2004), but the fate of the carbon still needs to be determined for purposes of carbon accounting and to determine ecological impacts.

An important consideration will be the *depth of soil* to be included in estimating carbon stores in the soil. The Intergovernmental Panel on Climate Change (IPCC) guidelines use a default depth of 0–30 cm for its Tier 1 [2] calculations of organic soil carbon, but allow for country-defined depths (e.g. 100 cm) for more detailed Tier 2 and Tier 3 calculations. The depth chosen for determining soil carbon credits to be traded in carbon markets will need to bear some of these international standards in mind.

How do you monitor organic soil carbon for carbon trading?

If carbon is to be accounted as permanently sequestered, long-term monitoring methods will need to be designed and funded, data will need to be adequately archived, and methods will need to be consistent and processes transparent (Dilling *et al.,* 2003).

Possible methods to determine changes in soil carbon must accommodate variations in climate, long-term changes in climate and carbon dioxide, and the types and age of vegetation. Suggestions by Canadell *et al.* (2007) include the use of:

- longer measuring periods (e.g. 10 years) between base period (when the level of emissions was first established) and interim targets (set under an emissions reduction initiative, such as the Kyoto protocol), so as to accommodate climate variability between years
- specific sites to monitor management, and use of carbon response curves to extrapolate changes to similar sites within a region
- baseline scenarios or benchmarks, which may be adjustable later
- time-averaged carbon stocks for different land-use systems under typical management to reduce the annual variations due to fluctuations in climate and management
- a combination of process and empirical models, to account for management and land use changes at regional and local scales (such models may still not be able to adequately separate human from environmental changes).

An expert panel recommended[3] to the National Committee on Soil and Terrain for the National Land and Water Resources Audit that a system of permanent monitoring sites for soil quality, including soil carbon is required. The strategies could also apply to monitoring organic soil carbon for carbon trading, and they include:

- long-term research sites (up to 10) to investigate processes and refine soil carbon models
- permanent monitoring sites with detailed profiles, samples to be archived and management practices recorded
- surveillance sites, with minimum variables for only the top soil layer, measured with inexpensive methods, though a strategy with limited utility
- modelling with a simple calculator to achieve possible targets.

This system should be allied with any other ‘sentinel farm’ projects, so that land practices and their impact on economic performance can be followed strategically.

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[2] The ‘tiers’ are the different levels of method used to estimate greenhouse gas emissions, in terms of accuracy and precision. In Tier 1, consumption is used to calculate emissions; in Tier 2, emission factors are used; and in Tier 3, mass-balance approaches are used. The national significance of a source of emissions determines which tier is used for the estimation.

[3] McTainsh, G. H.; Leys, J.; Carter, D.; Butler, H. J.; McCord, A.; Wain, A.; Dixon, J.; McKenzie, N. (2006) Monitoring soil condition across Australia: recommendations from the expert panels. Technical Report. National Committee on Soil and Terrain for the National Land and Water Resources Audit, Canberra, Australia. http://eprints.usq.edu.au/2889/.

What are the economic considerations of including organic soil carbon in carbon trading?

In 1997, Izaurralde *et al.* calculated that soil analysis would cost between C$10 and C$30 per sample in Canada. If applied to a 100 ha field to measure a change of 1.5 t C/ha, this would require prices of C$7–$21 per tonne of carbon. Therefore, better and cheaper methods of analysis would be required otherwise the unit cost of sequestered carbon would be higher than buyers would be willing to pay. No agricultural industries (but 12 forestry industries) have registered on the Canadian Greenhouse Gas Challenge Registry to date (February, 2009), despite the development of general Canadian standards for monitoring and reporting on greenhouse gas emission reductions (CSA ISO 14064-2). Further work is required to:

- develop scientifically defensible auditing methods that are cost-effective as a transaction cost
- establish the extent of soil–climate–management combinations suitable for carbon sequestration, and establish the willingness of farmers to cooperate
- establish agreements and protocols to ensure that government recognises processes
- develop necessary protocols and contracts with farmers and other partners.

More recently, an analysis for the central United States cropping region (Antle *et al.,* 2007) used modelled carbon changes in the soil and set carbon contracts. The aim was to increase the stock of carbon in the soil by a set amount and maintain it for a specified time. The analysis recognised that farmers in different locations face different opportunity costs, but will participate when the opportunity cost is below a certain threshold. Carbon sequestration rates varied substantially over the study region, and transaction costs were an important consideration, particularly at lower carbon prices. Overall, a carbon price of about US$50 per tonne C achieved about half the feasible total of carbon storage from changes in cropping systems. In other parts of the world, e.g. in southern Australia, much less than half the feasible carbon may be achieved for this price (Grace *et al.,* 2005, pers. comm.). In comparison, trading in carbon credits in the European Carbon Market and the Kyoto Carbon Market has ranged between US$5 and US$40 per tonne CO_2-eq (approx US$16 to US$130 per t C).

An analysis for the United States suggested that this approach would be more efficient than using a per-area (practice based) basis, despite the extra costs in accounting for spatial heterogeneity (Antle *et al.,* 2003). However, if the North American experience is relevant to Australia, then trades in carbon will be in parcels of 273 t C or 1000t CO_2-eq (Mooney *et al.* 2004). Achieving parcels of this size would entail substantial proportions of most Australian farms. For example, using the results from Table 3, a 10 per cent gain in organic soil carbon will generate approximately an additional 1 t C/ha. Therefore, the minimum area needed for a carbon trade would be at least 275 ha. The average farm size across Australia is now about 3300 ha, but varies from less than 500 ha in Victoria and Tasmania to more than 150,000 ha in the Northern Territory. However, the tradeable parcel could be made up of smaller parcels, perhaps put together by an intermediary (Mooney *et al.,* 2004).

The costs of sampling and measuring organic soil carbon per credit are likely to vary, depending on the region and the unit price of carbon credits (Mooney *et al.,* 2004). Areas with greater spatial variability will require more samples and hence cost more per unit carbon credit.

Sequestered soil carbon can be lost with changes in management, meaning that some adjustments to carbon crediting are required. The accounting needs to cover leakage beyond project boundaries—in particular, actions to sequester carbon in one area may cause off-setting responses elsewhere if not also credited (Murray *et al.,* 2007). For example, crop land converted to pasture or plantation for inclusion in soil carbon trading may lead to pasture land elsewhere being converted to cropping which may not then be included in carbon trading. For overall efficiency, it is desirable that credit is given only for the amount of carbon stored in addition to that which would occur in the absence of carbon trading (referred to as the ‘additionality’ feature). One response is to set a baseline level and estimate projected changes under a business-as-usual scenario. Even so, there are likely to be opportunities for managers to ‘game’ the systems, for instance, by changing their management the year before entering the contract, or by only entering part of a holding and compensating for it in other parts. Several methods for accommodating these risks have been proposed (Murray *et al.,* 2007):

- a comprehensive, or ‘pay as you go’ system for a time-averaged storage based on changes in stock
- an *ex ante* system that reduces the amount of credit on the basis of risk of loss
- a ‘leasing’ system that provides debits and credits for finite periods.

In the first round of Australia’s proposed Carbon Pollution Reduction Scheme voluntary offsets may be available to forestry[4] provided they are for domestic emission sources and sinks that are counted in Australia’s Kyoto Protocol national account. At this stage it does not account for soil carbon from forest management, cropland management, grazing land management or revegetation. It recognises that to maximise the credibility of offsets, internationally recognised standards would need to apply. These would ensure that offsets could only be issued for abatement that is:

- measurable
- has actually occurred
- additional to business-as-usual
- permanent (i.e. is not subsequently reversed).

Main points

- **As carbon trading expands and becomes more sophisticated, reliable methods will be required to measure changes in the different pools of stored carbon that can be verified by a third party. At present, it is difficult and expensive to directly measure changes in the soil inventory of less than 10 per cent, because of small-scale variability in soils and uncertainties with measures and analysis.**
- **For individual managers to participate in carbon trading, carbon needs to be countable in relatively small units and scales, to cater for a range of soil types and land uses. A combination of different methods could be required to determine the amount of carbon and how it changes. Some new methods in development will require extensive testing before they could be recommended for use in carbon trading schemes.**
- **There are still significant uncertainties and risks in using soil carbon sequestration in a carbon trading market. In addition, any protocols developed will need to take into account possible leakages of greenhouse gases and reduce opportunities for managers and traders to abuse the system.**
- **More information is required on the potential gains from trading in organic soil carbon, the risks from climate variability and climate change, the effects on associated greenhouse gases and the likely responses of land managers to incentives. Individual managers will require information and user-friendly tools to trade small amounts of carbon over short periods.**

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[4] Carbon Pollution Reduction Scheme White Paper Vol 1, December 2008. plvii, p6-46, pC-9 http://www.climatechange.gov.au/whitepaper/report/index.html

Discussion

Soils are often proposed as major sinks to sequester carbon, and this review of the literature explores some of the practicalities involved. Organic soil carbon is the most important form of soil carbon for carbon sequestration and trading. Agriculture and the environment could benefit from increasing organic carbon content of soils through carbon sequestration, creating a ‘win–win’ scenario.

Use of soil to sequester carbon will require changes in management, either through reducing carbon emissions associated with decomposition or by adding extra organic material (e.g. plant residues or external sources derived from organic wastes) above that already being added. However, there is a limit to the amount of carbon that a soil can sequester. Key factors in the efficient sequestration of more carbon in the soil are likely to be the starting content of organic soil carbon, the soil type (particularly clay content and mineralogy) and the impacts of climate change on the balance between the addition of plant residues and the mineralisation of organic soil carbon.

The biggest gains are most likely to be achievable in soils that are presently degraded, because they are likely to have the largest deficit between present and the attainable levels of organic soil carbon. However lifting crop production to enhance soil carbon storage could be more costly in degraded than non-degraded soils, e.g. because of higher fertiliser needs with impoverished soils. Carbon levels could also be increased in some cropping soils that do not yet practice conservation tillage techniques and under pastures with improved pasture management.

A large proportion of Australia has arid and semiarid rainfall patterns that will limit the potential amount of plant material that can be grown and therefore the amount of carbon that can be added to the soil each year. Land management and land use will need to change over a large area if significant amounts of carbon are to be sequestered. Land managers may not wish to have their management options curtailed for the extended periods likely to be involved for contributions to carbon sequestration.

Certain characteristics of soil carbon make it difficult to incorporate into carbon trading at this time:

- carbon is generally present at low concentration in soils (<5 per cent of soil mass), and small changes over time strain the limits of measurement within the relatively short timeframes desirable for carbon trading
- the large variations in the content of soil carbon across a landscape and down a soil profile challenge the reliability of sampling methods
- organic soil carbon converts (or decomposes) into different forms with varying stability or longevity. Depending on the lifespan of the carbon trade, only a proportion of soil carbon is sufficiently stable to be considered in carbon trading, and increasing the amount of carbon in this stable fraction is generally a long-term process (Swift, 2001).

Consequently, it is possible, but difficult for soil carbon to be bundled into units tradeable by land managers for the defined terms and times necessary for trading in carbon.

Any carbon market will require that carbon credits are technically credible, measurable and able to be verified by a third party. In particular:

- despite expense and slowness of current methods for measuring organic soil carbon, techniques for sampling and measuring are improving, and should lead to the development of methods that can be used for rapid, *in situ* determination of carbon on farms that are sufficiently accurate for trading in carbon
- it is now possible to model the general processes of the carbon cycle in soils, although interactions between some components require more work before it will be possible to provide good spatial resolution and estimate uncertainty to acceptable levels for verification and compliance

- to achieve credibility it will be necessary to monitor sinks, once they are established, to ensure their continued existence. Hence, there is a need for scientifically defensible auditing methods and for conditions or incentives under which farmers would be willing to participate in carbon sequestration.

There are risks in participating in carbon trading due to uncertainties in accounting for soil carbon storage, which may lead to discounts in the price of carbon credits and less than optimum amounts or duration of carbon sequestered. These risks could affect:

- the confidence of producers to achieve targets set out in carbon contracts
- the degree to which changes in soil carbon due to climate variability can be accommodated
- the correspondence between carbon contracts and true sequestration
- the observance of the protocols and regulation of any carbon market.

The protocols will need to cover probable leakages of carbon in other forms and reduce the opportunities for gaming by managers and traders.

Information needs

Information needed to decide on whether agriculture and forestry may use soil carbon to participate in carbon trading in Australia includes:

- spatial and temporal estimates of the potential gains in storing organic soil carbon (as done for south-east Australia by Grace *et al.,* 2005 pers. comm.) in stable pools. These will need to describe the existing and attainable total organic soil carbon
- full life-cycle analysis of associated greenhouse gas emissions that could result from agricultural practices to sequester carbon
- economic and social analyses of the likely adoption patterns and responses by farmers to different incentives to sequester soil carbon in Australia
- reliable methods to account for relatively small amounts of carbon to be stored on individual farms in relatively short times, and to incorporate the effect of high levels of climate variability into estimates of soil carbon change.

Information needed for individual managers to participate in such a scheme includes:

- cost-effective methods to measure and assess the changes in organic soil carbon under different management options
- tools to help them decide on the processes, benefits, costs, risks and responsibilities of trade in soil carbon.

Background information needed to increase confidence in carbon trading could include:

- the effect of salinisation and acidification on the ability of soils to store organic soil carbon
- loss and buildup of soil carbon in the range of soil types and management practices in Australia
- a continent-wide spatial status report of soil carbon in the soil as a baseline for monitoring possible responses to changing climates and to carbon sequestration
- relatively cheap and simple methods for directly measuring the stable pool of organic soil carbon and its residence times at different depths in soils.

Establishing some long-term monitoring sites that can evaluate changes in climate, management, vegetation and soil carbon over extended times will help in checking the validity of the various methods of carbon accounting. Such sites will have many other benefits for sustainable development.

Conclusions

There is a potential to increase organic soil carbon, with benefits for productivity in agriculture and forestry, as well as mitigate greenhouse gas emissions through carbon sequestration. However, there are still significant uncertainties and risks in using soil carbon in a carbon trading market.

It is likely to be difficult to bundle soil carbon into tradeable units by land managers under the defined times and terms necessary for trading in carbon. The transaction costs in monitoring and verifying these units could be expensive.

Key factors in the economic and efficient sequestration of carbon are likely to be the soil type, the initial starting content of soil organic matter (the more degraded the soil, the greater the potential gains) and the impacts of climate change on mineralisation of organic soil carbon.

Decisions on how to manage carbon are likely to continue to have some uncertainty. However, with more improvements in methods, soil carbon could become a viable component of carbon trading schemes.

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