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# SCIENCE *for* DECISION MAKERS

## Soil Carbon Management and Carbon Trading

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Its purpose is to make rural science more accessible to those needing to understand the benefits and implications of the most recent research as a basis for decision-making.

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### Key Points

**1** Soils play an important role in the global carbon cycle, both as sources and sinks of carbon. In soils, carbon exists in two forms—organic and inorganic. It is the organic form (referred 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.

**2** There is potential to increase stores of organic soil carbon. Relatively small increases in the proportion of organic soil carbon could make a significant contribution to reducing atmospheric carbon. In addition, increasing organic soil carbon can improve productivity and provide other beneficial ecosystem services such as erosion control.

**3** The ability of any soil to absorb additional carbon depends on many factors, including existing levels of carbon, soil type, temperature, rainfall, and how the land is managed.

**4** Accurately measuring changes in organic soil carbon for the purposes of carbon trading can be difficult and expensive.

**5** There are risks of potential leakage of organic carbon from the soil pool and some undesirable environmental consequences associated with methods for increasing organic soil carbon. For example, an increase in fertiliser use to increase plant productivity may increase greenhouse gas emissions.

**6** Inclusion of organic soil carbon in a carbon trading scheme will require more work: to understand the risks from climate variability and climate change on organic soil carbon; to develop consistent methods for measurement; and to understand the effects of different farming systems and land-use practices on the permanence of organic soil carbon.



## Introduction

Soil is both a source of greenhouse gases and a sink for carbon. In total, soils contain about 3 times more carbon than the atmosphere and 4.5 times more carbon than all living things. Hence, relatively small increases in the proportion of soil carbon could make a significant contribution to reducing atmospheric carbon. Agriculture occupies about 60 per cent of Australia's land surface and, if there is a role for soil carbon in reducing carbon in the atmosphere, much will depend upon agricultural managers.

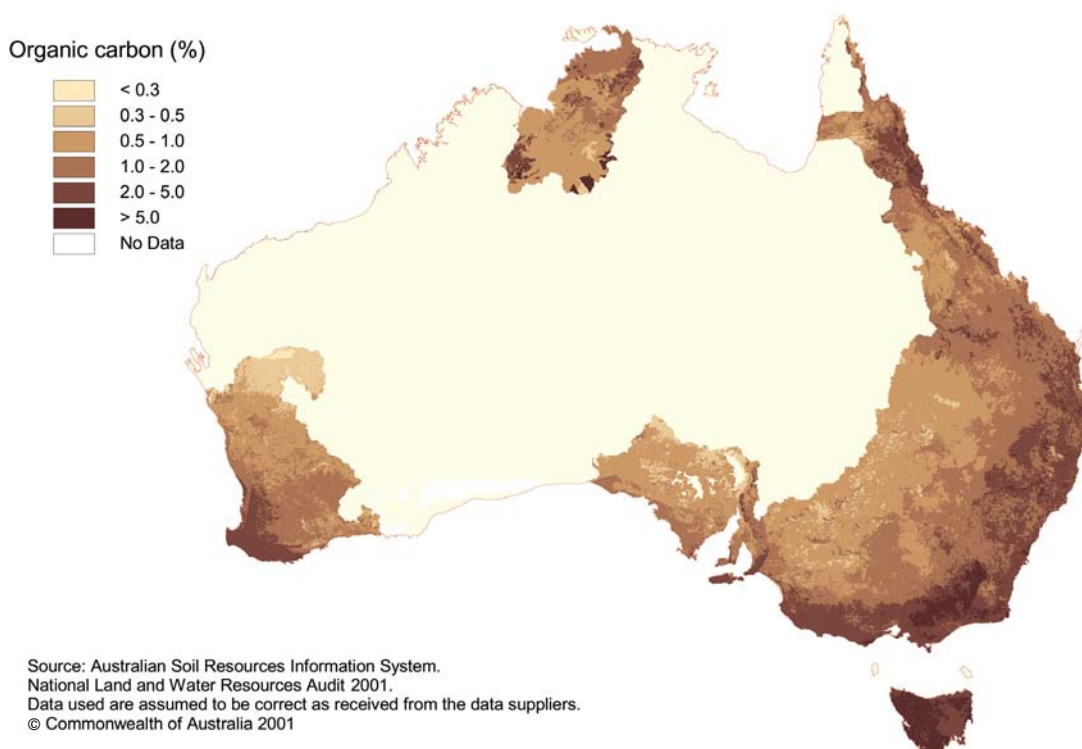
The purpose of this science for decision makers brief is to investigate the role of soil in capturing and storing (or sequestering) carbon emissions. A more comprehensive review of the science

surrounding carbon in Australian soils is available in *Soil carbon for carbon sequestration and trading: a review of issues for agriculture and forestry* ([www.daff.gov.au/brs/publications](http://www.daff.gov.au/brs/publications)).

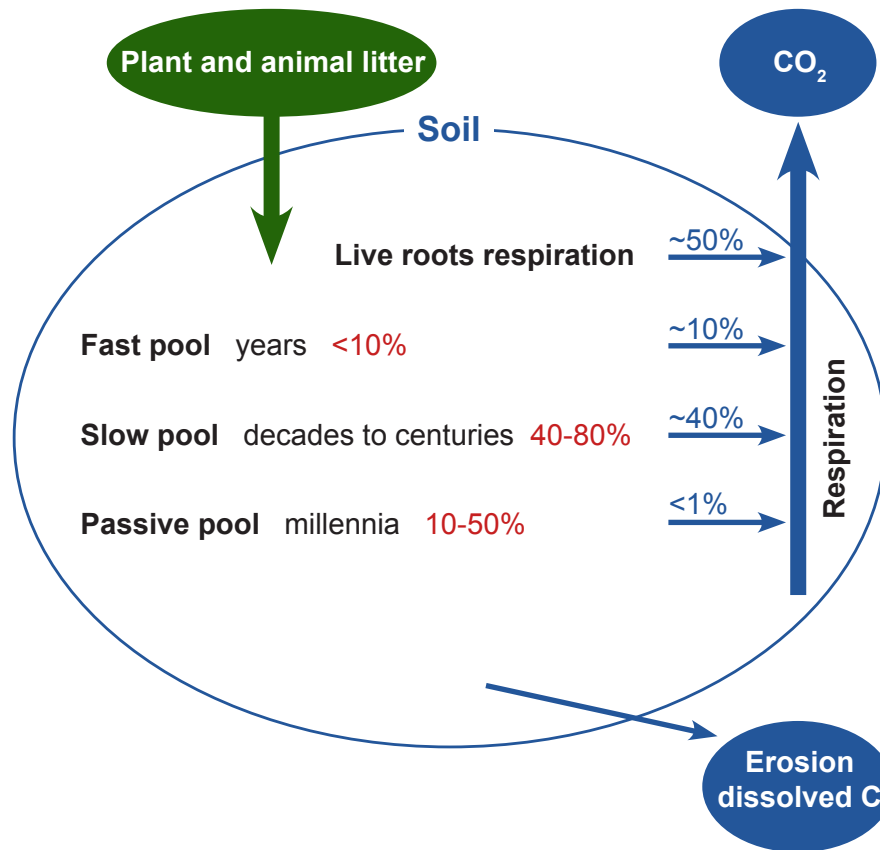
## What is soil carbon?

Soil carbon exists in various forms with differing longevity. Inorganic carbon, such as calcite and dolomite, makes up to a third of total soil carbon but is relatively stable and, except for lime applications, is not strongly influenced by land management. Therefore it is usually ignored when considering the effects of soil carbon on agricultural production and carbon sequestration.

**Figure 1. The concentration of soil organic carbon (%) in topsoils (between 10 and 60 cm deep).**



**Figure 2.** A simple diagram of soil carbon cycle, after Amundson (2001). The proportion of organic 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.



The organic form of carbon is more manageable, especially as a carbon store. Organic soil carbon is a component of soil organic matter and accounts for around half the mass of soil organic matter. Soil organic matter comes from the decay of leaf litter, plant roots, branches, soil organisms and manure. Soil organic matter is the component of interest for managers of soil quality and production, but it is the actual organic soil carbon content that is relevant to carbon sequestration. Soil organic matter is usually less than 5 per cent of soil mass and diminishes with depth (see Figure 1 for concentration of organic carbon in topsoils). The store of organic carbon in the top 30 centimetres of Australian soils commonly ranges from 5 to 250 tonnes carbon per hectare.

Soil organic matter goes through several stages of decay—each component has different properties that influence soil function and carbon sequestration.

‘Living organic matter’—plants, animals and microbes—is rarely included in measures of organic soil carbon sequestration because of its changeable nature. After death, it decays into various components of ‘non-living organic matter’ such as particulate organic matter, dissolved organic matter, humus and inert organic matter. Some components are more difficult to breakdown than others depending on their chemical composition; for example lignin, which is a complex chemical in wood, is broken down slowly by fungi and bacteria.

There is a continuum of forms of organic carbon in most soils. For convenience, organic soil carbon may be grouped into three conceptual pools—fast, slow and passive—with different times to break down (known as residence or turnover times). The slow and passive pools are the most stable pools. The proportion of organic soil carbon in these pools varies, but some ranges are provided in Figure 2.



## What benefits are provided by organic soil carbon?

Increasing organic soil carbon enhances the level of services provided by soils to humans, including (see Box 1 for more detail):

- carbon storage
- food and habitat for biodiversity
- nutrient storage and supply
- erosion control
- buffering capacity (to moderate changes in pH and perhaps adsorb pesticides)
- soil moisture.

Increases in organic soil carbon could be a 'win-win' situation, helping to reduce greenhouse gas levels in the atmosphere and improving soil quality with flow-on ecosystem service benefits for agricultural and forestry industries.

The impacts of increasing organic soil carbon should be considered on a case-by-case basis, noting that some strategies adopted by land managers might have adverse impacts. For example, increasing fertiliser and pesticide use to increase plant productivity may increase nitrous oxide emissions (another greenhouse gas) or adversely affect the local environment.

## How does organic soil carbon change?

At any one time, the organic carbon content of a soil is a balance between the carbon inputs (for example from roots or crop residues) and carbon losses as a result of decomposition processes.

**A soil pit dug to show changes in soil properties along a transect between trees.**



The major inputs are dead plants, animals and microbes, which decay through different processes and at different rates depending on their composition. About half of the losses of carbon dioxide from soils come from respiration by plant roots (shown in blue in Figure 2). The key loss of organic soil carbon is its conversion to carbon dioxide through mineralisation, primarily by microbial activity in the upper layers of the soil. The loss of organic soil carbon in any one year occurs most rapidly in the fast carbon pool, less in the slow carbon pool and is usually negligible in the passive pool.

Organic soil carbon is influenced by soil type, position in the landscape, climate, management and soil biota. Organic soil carbon content varies with depth and with soil type. Typically, organic soil carbon content is greater at the surface and diminishes with depth. However, in some soils, high concentrations of organic soil carbon can be found at depths greater than 50 centimetres. The variability of organic soil carbon across fields can be substantial and can show different patterns at different depths in the profile.

Climate can influence the amount of organic carbon in soil because biological processes such as decay are affected by soil temperature, oxygen levels and soil moisture. As long as soil moisture is sufficient, higher temperatures lead to a faster rate of decomposition and respiration. Soils in humid regions generally have higher organic soil carbon contents because of increased plant growth and biomass production. However, wetter soils lead to faster rates of decomposition provided there is sufficient oxygen.

The amount and quality of organic carbon inputs into the soil are a function of the vegetation present. Increasing plant biomass production would be likely to increase organic soil carbon (see **How can the organic carbon in soils be increased?**). Animals such as earthworms, ants and termites may also influence the amount of stable organic soil carbon at lower depths in some soils. There is limited information on how vegetation and organisms affect the organic carbon levels in the stable organic carbon pools at different levels down a soil profile. However, decomposition of organic soil carbon is normally slower with increasing depth in a soil.

## BOX 1

### SERVICES PROVIDED BY ORGANIC SOIL CARBON

- *Carbon storage*—Increasing the amount of organic carbon in the soil may decrease atmospheric carbon.
- *Food and habitat for biodiversity*—Soils are home to many organisms that, together with plant roots, form the living organic matter, and often use the organic matter as food. They include earthworms, insects (for example, dung beetles, ants and termites, cicadas, locusts, millipedes and centipedes), spiders, mites, snails, nematodes and even some mammals (for example, mice, rabbits, platypus and wombats). In addition, there are many microorganisms—bacteria, fungi, algae and protozoa—that actively contribute to carbon cycling in soils.
- *Nutrient storage and supply*—Soil organic matter can form up to half of the sites for nutrient storage and exchange in some soils.
- *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 and may adsorb many pesticides.
- *Soil moisture*—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.



**Tree roots can add to soil carbon deeper in soil profiles**

Management practices such as levels of soil disturbance, rotations, and management history can influence the amount of organic soil carbon. Some practices, such as grain cropping with long bare fallow periods, may lose large amounts of organic soil carbon. Some practices such as minimum tillage and stubble retention may lose less organic soil carbon than bare ground, but do not maintain organic soil carbon at levels that could be achieved under pasture. Nevertheless, minimum tillage and no-till on cropping soils can sequester more carbon than bare ground cultivation. A 20 year study found an increase of 0.43 tonnes carbon per hectare on low rainfall sandy soils and 11.09 tonnes carbon per hectare on high rainfall soils using minimum tillage practices as compared to cultivation. Using the lower level as a conservative estimate, 8.6 megatonnes of carbon would be stored over 20 years if these practices were adopted uniformly

across the 20 million hectares of grain grown in Australia. This represents 1.48 megatonnes of carbon dioxide equivalents per year or about 8 to 10 per cent of the greenhouse emissions from cropping (15 and 18 megatonnes of carbon dioxide equivalents each year mostly as nitrous oxide from fertilisers). Therefore, organic soil carbon levels could be increased in cropping soils where conservation tillage techniques are not yet practiced or where there is a low frequency of pastures in crop rotation.

The likely responses of soils to management and environmental conditions can be estimated by land managers at field scales using simple organic soil carbon calculators<sup>1</sup>.

<sup>1</sup> <http://www.greenhouse.crc.org.au/tools/calculators/>;  
<http://www.isr.qut.edu.au/tools/index.jsp>;  
<http://lter.kbs.msu.edu/carboncalculator/>



## How can the organic carbon in soils be increased?

Changes in land management practices can increase the amount of organic soil carbon (see Box 2 for more detail), up to a limit. This limit—its potential level—is set by soil type. It is lower in coarser textured soils such as those with high sand content. No estimate of the potential levels of organic soil carbon has been published for Australia.

A more practical limit—an attainable level—is set by climatic factors through effects on plant growth and rates of mineralisation. Available estimates show that the level of organic carbon in many Australian soils is generally limited by rainfall, although it may be limited by temperature or nutrition in some areas and seasons.

There are two major strategies for managers to increase the amount of carbon presently sequestered in soils—reversing losses incurred from past management to achieve ‘attainable’ levels and taking sequestration to ‘potential’ levels (see Box 3).

The response of organic soil carbon to management changes depends greatly on the starting levels and environmental conditions. Starting levels can only be determined reliably by sampling and measurement. The biggest increases are most likely to be achievable in soils that are degraded because they are likely to have the largest difference between present and the attainable levels of organic soil carbon.

## How is organic soil carbon measured and predicted?

The density of organic soil carbon (mass of organic soil carbon per unit area) is used for calculating changes in the amount of organic soil carbon in the soil profile and would be important if organic soil carbon were included in a carbon trading scheme. Measurements of the density of organic soil carbon are determined from the concentration of organic soil carbon at various soil depths and bulk density (weight

per unit volume of soil). Organic soil carbon concentration can be directly measured through the use of wet or dry combustion techniques.

Traditional methods of sampling and measuring organic soil carbon are either slow or expensive. It is made difficult because of the combinations of large and fine roots and different forms of non-living organic matter that need to be removed. Some new methods for measuring organic soil carbon *in situ* appear promising and could speed up the process, reduce overall costs and minimise soil disturbance; but these methods would need improvement in terms of field-portability, accuracy and sensitivity to be of value in a conventional carbon trading scheme.

Perhaps most importantly, organic soil carbon is generally present at low concentration in soils (<5 per cent of soil mass) and changes of less than 10 per cent strain the limits of measurement. In addition, there can be large variations in the content of organic soil carbon across a landscape and down a soil profile. Taken together, these characteristics will continue to present major challenges to the reliable measurement of organic soil carbon over time.

Using models to predict changes in organic soil carbon under different scenarios can provide a clear idea of the effects of different land uses, crop yield expectations and management practices, such as stubble burning, grazing pressure and fertiliser use. Models are able to project likely changes in organic 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, and their accuracy depends on their calibration to real soils and Australian conditions. Predicting changes in organic soil carbon normally requires knowledge of the carbon contents of the different pools at appropriate soil depths along with an estimation of changes in soil bulk density.

## BOX 2

# LAND MANAGEMENT PRACTICES AND ORGANIC SOIL CARBON

Some land management practices may be likely to increase organic soil carbon compared with current practice.

- For cropping systems, increasing the frequency of pasture leys in rotations, increasing fertiliser use and retaining crop residue offer some promise, particularly in the wetter (>500 mm rainfall) temperate parts of Australia.
- Selecting species that increase the amount of roots in the subsoil or have slower decomposing roots.
- Incorporating a higher proportion of pasture legumes or shrub legumes (for example *Leucaena* or tagasaste).
- Incorporating grazing management that increases forage production and manure inputs.
- Reversal of existing degradation (saline, acidic and eroded land) by planting of perennial species.
- Converting crop to secondary forest, crop to pasture, crop to plantation and native forest to pasture.

**From the air an irrigated landscape shows many different land management practices**





## BOX 3

# SEQUESTERING CARBON

The first of the two broad strategies to sequester more organic soil carbon—reversing losses incurred with past agricultural land uses to achieve ‘attainable carbon’ levels—involves altering those factors that affect carbon sequestration. They include 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 the amount of carbon sequestration required to reverse past losses is limited by rainfall, and sometimes by plant nutrition. Additionally, the greenhouse gas emissions associated with these interventions need to be counted in any carbon budget of the benefits of sequestration, such as the energy and carbon costs of producing and transporting fertilisers, pumping irrigation water, and any release of ammonia or methane.

For the second strategy—taking sequestration to ‘potential carbon’ levels—it has been proposed to add external sources of carbon such as biochar (a form of charcoal), charcoal, fly-ash or manure. Biochar is the residue from low-temperature pyrolysis of organic materials—an approach most recently used for bioenergy production because of the energy products released during the process. Using the low-temperature pyrolysis method, up to half of the organic carbon in plant material can be returned to the soil as biochar. Biochars are more recalcitrant than uncharred organic matter because the structure is dominated by aromatic carbon, and hence may have potential for soil improvement and carbon sequestration.

Fly-ash, one of the residues generated in the combustion of coal, and charcoal may boost the adsorptive capacity (collection of chemicals on the surface of soil particles) of poor soils. Farmyard manure, which contains a high proportion of slowly decomposing lignin, may boost organic soil carbon locally, but not necessarily total carbon sequestration because the organic soil carbon has been relocated from one area to another.

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.

### Sampling soils for later chemical analysis



## What will be the impact of a changing climate?

The effect of a changing climate on organic soil carbon is likely to be mixed. Increased atmospheric carbon dioxide is likely to increase inputs of carbon to soil (through greater inputs of plant biomass). However, increased soil temperature is likely to hasten the breakdown of organic matter and the emission of carbon dioxide from the soil.

Changes in rainfall, nitrogen availability and fire regimes are also likely to influence the level of organic soil carbon. A reduction in rainfall is likely to decrease inputs of carbon to the soil (through a reduction in inputs of plant biomass), and decrease rates of organic soil carbon breakdown as a result of limited water availability. An increase in rainfall may lead to an increase in the breakdown of organic soil carbon, provided there is sufficient oxygen and soil nitrogen. Burning can reduce organic soil carbon levels and may also be a significant emitter of greenhouse gases.

## Is there a role for organic soil carbon in carbon trading?

In order for organic soil carbon to be included in a carbon trading scheme it would need to satisfy certain conditions:

- the soils would need to remove measureable amounts of carbon dioxide from the atmosphere and to have a low risk of rapid or large-scale leakage
- carbon credits would need to be measurable, permanent, and verifiable by a third party
- it would be necessary to monitor sinks once they are established to ensure their continued existence. This could entail considerable expense
- life-cycle analyses would be required to determine if there were a net gain in carbon sequestration with measures used to increase organic soil carbon (for example fertilisers used to encourage biomass growth may increase nitrous oxide production).

Market rules are also likely to play a part in determining if there is a role for organic soil carbon in a carbon trading scheme. These would include:

- size of tradeable units
- agreements on which land and crop management changes should be included
- ownership of the carbon, for example whether located on freehold or leasehold properties.

Small potential changes in organic soil carbon at the paddock scale and the costs of compliance could outweigh the benefits for individual producers of participating in a carbon trading scheme (see Box 4). Alternative approaches could involve pooling arrangements whereby industries, regions or smaller groups of farmers 'bundled' their carbon sequestration activities.

An alternative to on-farm measurement and monitoring of soil carbon could be to adopt a modelling approach, although this would involve varying degrees of accuracy and confidence. For example, schemes could adopt standard rates of carbon dioxide abatement for the adoption of particular management activities for a length of time. Here, the confidence of investors in the contracts is likely to be based on information about management activities rather than actual sequestration rates. However, there is a need to ensure that any scheme achieves the objective of sequestering carbon.

A carbon trading scheme is only one of a range of actions by governments that could be used to promote activities to increase organic soil carbon. Other potential actions include programs to inform farmers of the benefits of increasing organic soil carbon and how this can be achieved and programs to encourage farmers to change land use or land management practices. Some of these actions, already in place, may reinforce or counteract incentives for managers to sequester organic carbon in soils.



## BOX 4

# MANAGEMENT CONSIDERATIONS

Economic analyses indicate that transaction costs, such as soil analyses and bundling of organic soil carbon parcels, are important considerations for carbon trading, particularly at lower carbon prices. Trading in carbon credits in the European Carbon Market has ranged between €0.1 and €30 per tonne carbon dioxide equivalents (approximately AUS \$0.5 to AUS \$160 per tonne of carbon). The trades are in terms of contracts, where one contract represents 1000 tonnes of carbon dioxide EU Allowances.

Producing a tradeable parcel of this size would require a large proportion of an Australian farm because of the low concentration of carbon in soils. For example, if a 10 per cent gain in organic

soil carbon approximates an additional 1 tonne carbon per hectare the minimum area needed for a carbon trade would be at least 275 hectares. The average farm size across Australia is now about 3300 hectares, but varies from less than 500 hectares in Victoria and Tasmania to more than 150 000 hectares in the Northern Territory. However, the tradeable parcels could potentially be made up of smaller parcels, perhaps put together by an intermediary.





## Conclusion

Increasing organic soil carbon has the potential to reduce atmospheric carbon and offers benefits for farmers through improved ecosystem services, such as better soil condition and increased productivity.

There are elements of measuring and monitoring changes in organic soil carbon that need to be better understood if it is to have a role in a carbon trading scheme, including:

- the limits to storing carbon for long times in Australian soils under changing climates
- management practices that can demonstrably increase sequestration of organic carbon in soils
- effects these practices have on the delivery of other ecosystem services, including food production
- the life cycle impacts on greenhouse gas balances of these practices
- practices that increase the level of stable carbon pools deeper down a soil profile.

**An aerial view of the variation in soil properties across a cropping landscape in the Victorian Mallee. The light-coloured sandy dunes have lower organic soil carbon than the darker coloured swales in between.**

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Figure 2 used with permission from Annual Review of Earth and Planetary Science, Volume 29 © 2001 by Annual Reviews [www.annualreviews.org](http://www.annualreviews.org)



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## Further reading

Amundson, R. (2001). The carbon budget in soils. *Annual Review of Earth Planetary Sciences* 29: 535-62.

Baldock, J.A. (2007). Composition and cycling of organic carbon in soil. In Marschner, P. and Rengel, Z. (eds) *Nutrient Cycling in Terrestrial Ecosystems*. Springer-Verlag, Berlin Heidelberg <http://www.springerlink.com/content/u747745786g03618/>.

Grace, P.R., Post, W.M., Godwin, D.C., Bryceson, K.P., Truscott, M.A. and Hennessy, K.J. (1997). Soil carbon dynamics in relation to soil surface management and cropping systems in Australian agroecosystems. In Lal, R., Kimble, J.M., Follett, R.F. and Stewart, B.A. (eds) *Management of carbon sequestration in soil*. CRC Press, Boca Raton, Fla.: pp 175-193.

McKenzie, N.J., Jacquier, D., Isbell, R. and Brown, K. (2004). *Australian soils and landscapes: an illustrated compendium*. CSIRO Publishing: Collingwood, Vic. 416 pp.

NLWRA (2001). *Australian agriculture assessment 2001, volumes 1 and 2*. National Land and Water Resources Audit: Canberra. [http://audit.ea.gov.au/ANRA/agriculture/docs/national/Agriculture\\_Contents.html](http://audit.ea.gov.au/ANRA/agriculture/docs/national/Agriculture_Contents.html).

Skjemstad, J. and Spouncer, L. (2003). Integrated soils modelling for the National Carbon Accounting System. National Carbon Accounting System Technical Report No. 36. Australian Greenhouse Office, Canberra. 670 pp. <http://www.greenhouse.gov.au/ncas/reports/pubs/tr36final.pdf>.

Walcott, J., Bruce, S. and Sims, J. (2009). Soil carbon for carbon sequestration and trading: a review of issues for agriculture and forestry. Bureau of Rural Sciences, Department of Agriculture, Fisheries & Forestry, Canberra. <http://www.daff.gov.au/brs/publications>.

West, T.O. and Six, J. (2007). Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. *Climatic change* 80: 25-41.

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