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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 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, increasing fertiliser use to improve plant productivity may adversely affect the environment and generate greenhouse gas emissions.

6. There may be a role for organic soil carbon in carbon trading. Important issues include the economic potential of landholders to participate in carbon trading and the ability of soil carbon projects to meet certain technical requirements.

7. More work is required to develop consistent methods for measurement and to understand the risks from climate variability and climate change on organic soil carbon as well as the effects of different farming systems and land-use practices on stores 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.brs.gov.au/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.

Organic soil carbon is the organic form of carbon found in soil organic matter. It is more manageable than inorganic soil carbon, especially as a carbon store.

Soil organic matter comprises leaf litter, plant roots, branches, soil organisms and manure. Its chemical, physical and biological properties influence soil quality and function. Soil organic matter decays at varying rates, depending on

Figure 1. A simple diagram of the 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

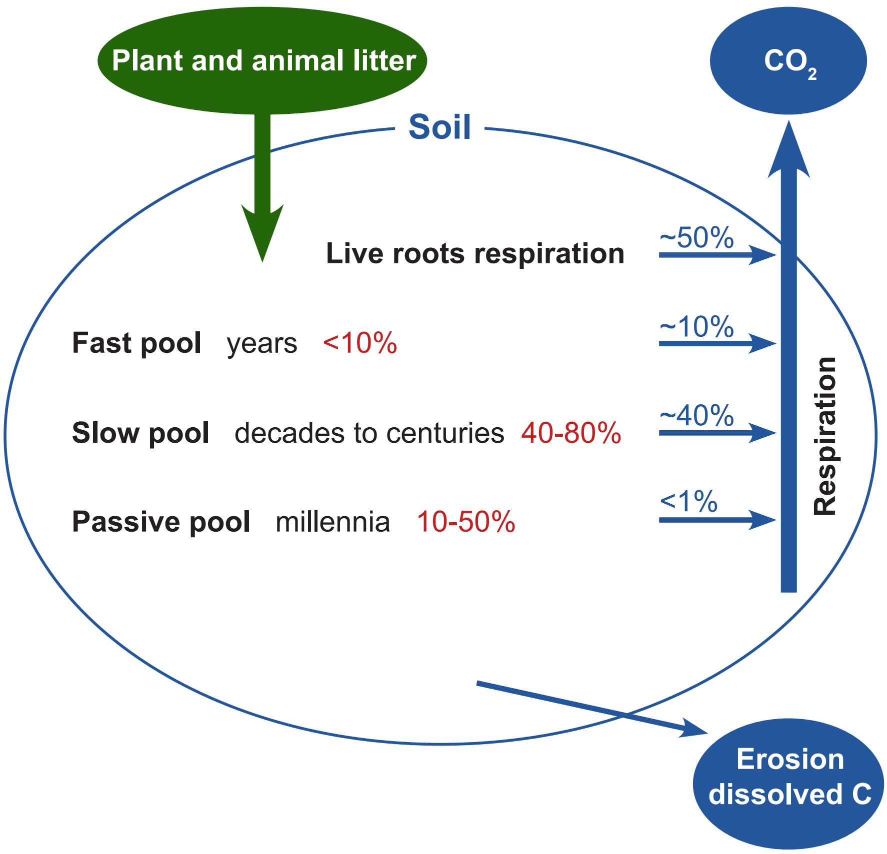
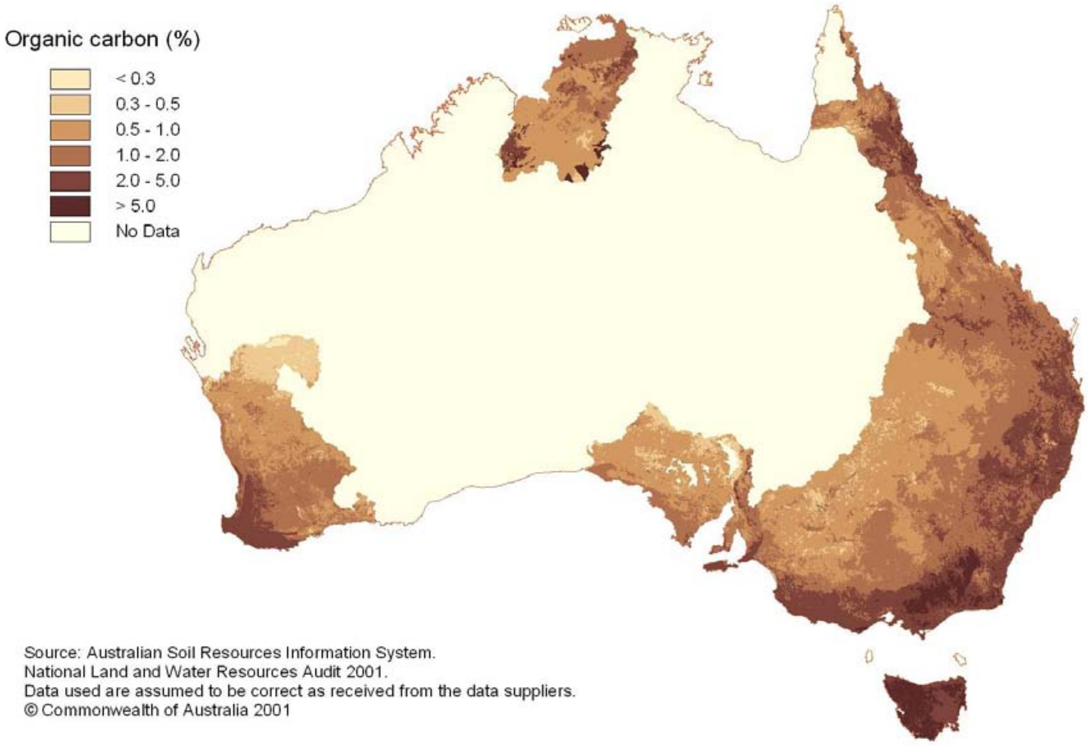


Figure 2. The concentration of soil organic carbon (%) in topsoils (between 10cm and 60cm deep)



chemical composition, into various components of 'non-living organic matter' such as particulate organic matter, dissolved organic matter, humus and inert organic matter. While these components are important for production, it is the actual organic carbon content of this non-living matter that is relevant to carbon sequestration.

'Living organic matter'—living plants, animals and microbes—typically accounts for a small and variable proportion of soil organic matter.

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 passive pool is the most stable, followed by the slow pool. The proportion of organic soil carbon in these pools varies, but some ranges are provided in Figure 1.

Typically, organic soil carbon accounts for less than 5 per cent of soil mass and diminishes with depth (see Figure 2 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.

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 retention.

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 improve plant productivity may increase nitrous oxide emissions (another greenhouse gas) or adversely affect the local environment.

Tree roots can add to soil carbon deeper in soil profiles

How does organic soil carbon change?

At any one time, the organic carbon content of soil is a balance between carbon inputs and losses. The major inputs are dead and decaying plants, animals and microbes (Figure 1). Organic carbon is lost from the soil through leaching, erosion, and conversion to carbon dioxide through mineralisation or respiration. A key loss is through mineralisation, primarily by microbial activity in the upper layers of the soil. Because of its highly transient nature, respiration from live plant roots is not calculated in losses of organic soil carbon for carbon sequestration purposes. Losses of organic soil carbon in any one year occur most rapidly in the fast carbon pool, less in the slow carbon pool and are usually negligible in the passive pool.

Organic soil carbon is influenced by soil type, position in the landscape, climate, management and soil biota. 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

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, thus increasing the infiltration rate (so that rainfall takes a shorter time to enter the soil) and water holding capacity of the soil.

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.

Management practices such as soil disturbance, rotations, and management history can influence organic soil carbon levels. Some practices, such as grain cropping with long bare fallow periods, may lose large amounts of organic soil carbon. This is because cultivation, followed by fallow periods, can disrupt the soil structure and create favourable conditions for wind and water erosion and decomposition of soil organic matter. Other practices such as minimum tillage, no-till 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.

The effect of tillage management on soil carbon is not uniform across Australia. Studies indicate organic soil carbon levels can be higher on some Australian cropland when maintained under no-till practices compared to conventional tillage. Other studies—of crop regions with different soil types or climates—show little change in organic soil carbon under altered tillage practices. One study suggests that low rainfall, sandy soils in the Mallee maintained under no-till practices for 20 years would have around 1.4 tonnes carbon per hectare more than similar soils maintained under conventional tillage. Soils in the west of NSW had around 2 tonnes carbon per hectare more when maintained under no-till practices over 20 years, while soils in the South West Slopes region of NSW had around 3 tonnes carbon per hectare more. These differences reflect a reduced rate of soil carbon loss under no-till compared to conventional tillage. The figures indicate an average yearly reduction in soil carbon losses for these regions of between 0.07 to 0.15 tonnes carbon per hectare. In carbon dioxide equivalents (CO_2-e), this is around 0.25 to 0.55 tonnes CO_2-e per hectare per year.

Studies show that minimum tillage and no-till practices are already practiced on much of Australia's cropping land, although adoption varies from region to region. Figures indicate around one third, or about 9 million hectares, of Australia's cropland may be available for a change to no-till practices. Using the indicative rates shown above, adoption of no-till practices across 9 million hectares of cropland may offer up to 2 to 5 million tonnes of avoided CO_2-e emissions per year. The actual potential to reduce losses of organic soil carbon through increased adoption of no-till practices on Australia's cropland will depend on many factors, including the area of cropland where it is feasible to adopt and maintain no-till practices, climate, soil type and existing levels of soil carbon. It is important to note that any emissions reductions offered by these practices are likely to diminish over time, as organic soil carbon content reaches equilibrium.

How can the organic carbon in soils be increased?

There are two major strategies for managers to reduce soil carbon losses or potentially increase the amount of carbon sequestered in soils: changing land management practices (see Box 2) to achieve 'attainable' levels or enhancing sequestration to achieve 'potential' levels (see Box 3).

The 'attainable' level is determined by soil type and climatic factors, through effects on plant growth and rates of mineralisation. Available estimates show that the attainable 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.

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 attainable levels of organic soil carbon.

The 'potential' level is determined by soil type. Enhancing sequestration to achieve potential levels will require practices that overcome the limitations imposed by climate, perhaps by adding carbon to the soil from external sources. No comprehensive estimate of the 'potential' level has been published for Australia.

How is organic soil carbon measured and estimated?

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. The task 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.

There are major hurdles to using a measurement program to estimate field-scale changes in organic soil carbon. The substantial variability in soil carbon concentration across paddocks and down the soil profile poses difficulties for extrapolating in situ measurements to paddock-scale estimates. In addition, organic soil carbon is generally present at low concentration in soils (less than 5 per cent of soil mass) and changes of less than 10 per cent strain the limits of measurement.

Using models to predict changes in organic soil carbon under different scenarios can provide an idea of the effects of different land uses and management practices, such as stubble burning, grazing pressure and fertiliser use. Models are able to estimate likely changes in organic soil carbon under a range of conditions, across a range of spatial scales, 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. Estimating 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 reduce organic soil carbon losses or potentially increase organic soil carbon compared with current practice.

- For cropping systems, increasing the frequency of pasture leys in rotations, increasing fertiliser use, conservation tillage and retaining crop residue offer some promise, particularly in the wetter (greater than 500 millimetres rainfall) temperate parts of Australia.
- Selecting species that increase the amount of roots in the subsoil or have slower decomposing roots. In the future biotechnology could aid the development of such crops by plant breeders, or may offer genetically modified varieties with the desired characteristics.
- Selecting species that offer potential increases in productivity and plant biomass. Prospects for improved productivity include plant varieties with increased photosynthetic efficiency, improved water-use efficiency or resistance to insect pests and diseases.
- Incorporating a higher proportion of pasture legumes or shrub legumes (for example Leucaena or tagasaste, where appropriate) to increase biomass.
- 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 regrowth forest, crop to pasture or crop to plantation, although these land-use changes do not account for changes in non-soil carbon, such as plant biomass.

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

BOX 3

SEQUESTERING CARBON

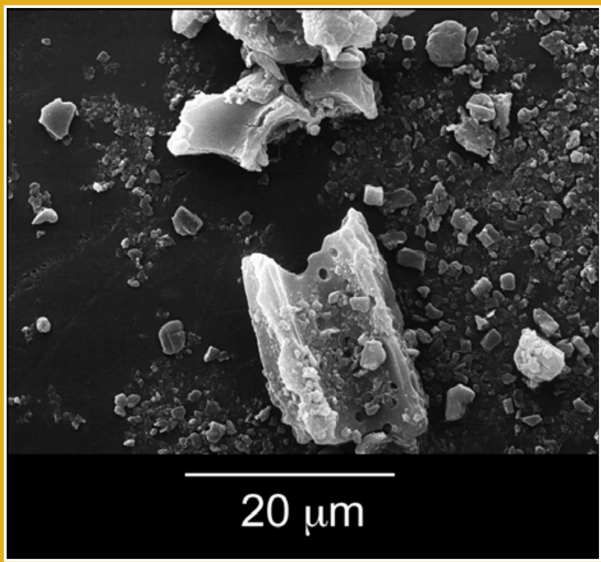
The first of the two broad strategies to sequester more organic soil carbon—changing land management practices to achieve **'attainable'** carbon levels—involves altering those factors that affect carbon sequestration. They include crop selection, soil management, fertilisation, animal grazing pressure (stock numbers), and pest and disease control. In much of Australia's dryland agriculture and forestry, our ability 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 nitrous oxide 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.

A magnified image of charred organic carbon fragments



What will be the impact of a changing climate?

The effect of a changing climate on organic soil carbon is likely to be mixed and change with time. Increased atmospheric carbon dioxide may 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 (such as plant biomass) to the soil, 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 adversely impact 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?

There may be a role for organic soil carbon in a voluntary carbon market or carbon trading scheme. Important issues include the economic potential for landholders and the ability of soil carbon projects to meet the technical requirements for carbon trading.

Farmers are likely to be interested in sequestering carbon in their soils if the price per tonne of carbon received is greater than the opportunity cost of capturing and storing the carbon. The opportunity cost of carbon sequestering practices includes any loss in revenue from changed agricultural production, increased fixed costs because of new machinery and additional transaction costs.

Other factors that affect the adoption of land management practices and the potential to store carbon in soil include the variable nature of agricultural production, uncertainty associated with the use of new practices and varied bio-physical and socio-economic conditions. Variations in socio-economic conditions include changes in agricultural prices, production technology, and differences in farmers' decision making abilities and knowledge.

Projects aiming to increase soil carbon in exchange for a payment may need to satisfy certain technical requirements:

- removing measureable amounts of carbon dioxide from the atmosphere and having a low risk of rapid or large-scale leakage
- achieving abatement that is additional to current practice, permanent and verifiable by a third party
- monitoring sinks once they are established to ensure their continued existence
- determining if there is 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).

Meeting these requirements could involve significant transaction costs. 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, modelling could be used to estimate the rate of carbon sequestration achieved in a soil carbon offset project, where particular management practices are adopted over a set period.

BOX 4

KYOTO AND SOIL CARBON

The Kyoto Protocol is an international treaty created under the United Nations Framework Convention on Climate Change. The Kyoto Protocol sets binding targets for the reduction of greenhouse gas emissions by developed countries and countries in transition to be met within the first commitment period of 2008 to 2012 compared to emissions during the baseline year of 1990.

The Kyoto Protocol treats soil carbon in different ways according to land-use type and history. Changes in stocks of soil carbon on 'deforested land' (only land cleared since 1990) are currently included in Article 3.3 of the Kyoto Protocol and are counted in Australia's Kyoto National Account. Changes in stocks of soil carbon in most crop and grazing lands (cleared prior to 1990) are currently included in Article 3.4 of the Kyoto Protocol, but are not counted in Australia's national account. Australia chose not to include Article 3.4 activities due to the potential impacts of natural disturbance and inter-annual climate variability on carbon stocks during the commitment period. For example, major fires or droughts can lead to emission spikes and may lead to a liability in Australia's accounts.

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

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.

Inclusion of organic soil carbon in a carbon trading scheme or voluntary offset market will require improved methods for measuring and monitoring and a better understanding of soil carbon in the Australian context, such as:

- 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
- practices that increase the level of stable carbon pools deeper down a soil profile.

In assessing the benefits of land management practices that increase organic soil carbon, consideration should be given to all greenhouse gas emissions associated with these practices.

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Further reading

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