HOW TO MEASURE AND INTERPRET RESULTS IN RELATION TO SOIL ORGANIC CARBON

AT A GLANCE

- Local trial responses provide the strongest evidence for product performance.
- Adopt a trial and evaluate your approach to soil amendments.
- Sampling soil to a minimum of 30 cm in increments of 10 cm will provide valuable information on soil resource condition and constraints to production.
- Develop a soil sampling strategy to be undertaken over time that will better inform your management.
- It is a requirement for carbon markets and national accounting that soil organic carbon be reported on a tonnes per hectare basis.

Soil organic matter and soil organic carbon are often confused and mistakenly used interchangeably. However, while soil organic carbon is a component of organic matter it is not the same as organic matter, which also includes other elements such as hydrogen, oxygen and nitrogen. Soil organic carbon makes up about 58 per cent of the mass of organic matter and is usually reported in a soil analysis report as the concentration (i.e. per cent) of organic carbon in soil (see Chapter 1 for more detail).

It is important to understand how organic carbon is measured and reported as i) different analytical techniques are used in measuring organic carbon in soils which generate slightly different answers and ii) different reporting units may be used. In addition, it is desirable to keep records on paddock history, soil type, agronomic management, previous soil test results, rainfall (and if available temperature), grain and pasture yields to determine what factors are most influencing changes in measured soil organic carbon levels.

1.5% soil organic carbon = 1.5g carbon per 100g soil = 15g carbon per kg soil

HOW DO I ESTIMATE SOIL ORGANIC CARBON STOCKS?

It is often difficult to measure changes in soil organic carbon on an annual basis because changes in carbon content generally occur very slowly against a relatively large background of soil carbon.

For example, most Australian soils would be expected to contain between about 20-160 tonnes carbon per hectare to a depth of 30 cm (0.5-4.0 per cent organic carbon in soil assuming a bulk density of 1.3 g/cm^3). A typical Australian grain production system, yielding two tonnes wheat per hectare, is likely to retain between 0.1-0.5 tonnes of organic matter per hectare in the soil each year depending on microbial efficiency (see Chapter 1). This equates to a change in soil organic carbon in many instances of less than one per cent of the total stock. Additional inputs of organic carbon based on increasing grain yield by one tonne per hectare per year would result in less than 0.3 tonnes carbon being retained annually.

A larger change in total organic carbon stock, which may take several years or longer to occur, is required before a significant change could be measured with any degree of confidence. Given annual inputs of organic residues are likely to be less than the 0.2 tonnes carbon per hectare in typical Australian cropping systems, the time required to detect a significant change in soil organic carbon is generally more than 10 years.

Accurate measurement of changes in organic carbon requires:

- A soil sampling strategy that captures the natural variation in soil carbon across space and time and determines actual changes in soil carbon for a particular circumstance.
- A measure of soil organic carbon concentration.
- An estimate of bulk density of the soil to adjust for changes in soil mass at specified depth intervals.

Measuring bulk density is particularly important if attempting to capture changes in soil organic carbon through time (Don et al. 2007) because it accounts for changes associated with soil density and sampling depth. To be accurate, the percentage of organic carbon in a particular soil layer (for example, 0-10 cm; 0-30 cm) needs to be adjusted for bulk density and reported as a mass of carbon per unit area (tonnes organic carbon per hectare). Subsequent sampling should then consider reporting on the basis of the amount of carbon for an equivalent soil mass taking into account any changes in bulk density through time or space.

I) SAMPLING FOR SOIL ORGANIC CARBON

Sample depth

In Australian agricultural soils, a large percentage of the organic carbon is in the 0-10 cm layer due to a concentration of crop residues and roots in this layer, and this has traditionally been the focus of any soil sampling. Increasingly, it is becoming more important to consider purpose, sampling depth and potential redistribution of organic carbon and nutrients when attempting to capture changes in soil organic carbon over time.

For example, the national carbon accounts currently require an estimate of soil carbon stocks to 30 cm. Continuing changes in soil management and seeding technology have also resulted in significant changes to the degree of soil mixing previously experienced under more conventional systems. In older, conventional cultivation systems the distribution of nutrients and carbon was relatively even to about 20-30 cm due to soil mixing. However, the widespread adoption of minimum tillage systems has resulted in the concentration of inputs (and therefore carbon and nutrients) on the soil surface and a dilution of soil carbon at depth. Because of this situation it is important to sample for soil carbon to a minimum depth of 30 cm, so a true reflection of carbon stocks within the entire rooting zone can be captured. In addition, these samples can also provide valuable information on soil nutrient status and sub-soil constraints such as low soil pH or boron toxicity.

It is often difficult to measure changes in soil organic carbon on an annual basis because changes in carbon content generally occur very slowly against a relatively large background of soil carbon.

In Western Australia, about 60 per cent of the organic carbon to a depth of 30 cm is found in the top 10 cm of soil (Griffin et al. 2013). Therefore it is preferable to split soil samples into at least two sampling depths (0-10 cm and 10-30 cm) because it is more likely that any measureable changes will be in the surface layer. If sampling for other soil attributes such as pH, samples are best taken in 10 cm increments to more accurately identify soil constraints. A notable exception for depth of sampling are soils which have been re-engineered using a mouldboard plough or undergone spading for example, where the soil has experienced significant disturbance. In these situations it is advisable to sample to a depth at least 10 cm below the affected depth of soil and at least to a minimum of 30 cm.

Sampling strategy

Sampling in a paddock

Sampling strategies for soil carbon will depend on paddock size and the number of different soil types within the paddock. Typically, a minimum of 20 cores within a defined sampling area are bulked to capture the variability in soil organic carbon across an area (Don et al. 2007). Paddocks can either be sampled as a whole or zoned into several sampling areas based on soil type or properties, management history or yield potential. Position in the landscape, soil survey and farmer knowledge, land use and management history, yield maps, imagery and visual interpretation can all help determine where there is a need to soil sample.

Avoid sampling in atypical areas such as header trails, windrows, corners of paddocks, close to fences or tracked areas as these are likely to have different soil organic carbon levels to the remainder of the paddock due to overruns, double application of inputs or compaction.

An equal or proportional number of samples should be taken on and off rows to determine a paddock average for soil organic carbon. Similarly, in pasture systems a representative number of samples should be taken from areas where there is poor plant establishment as where pasture growth is high.

If traffic areas represent a significant proportion of the paddock, the sampling strategy should include samples taken on a proportional basis (i.e. if 40 per cent of the paddock is affected then 40 per cent of samples should be taken from these areas).

It is important to collect samples representative of the average soil condition. A reasonable approach is to take samples from areas that deliver average crop or pasture yields (i.e. avoid very low or very high yielding areas of a paddock). This is not an appropriate strategy if sampling to determine why these areas perform differently, or where you need a measure of how variable organic carbon stocks are within a paddock.

Fresh organic material such as crop residues, roots and manure are not technically part of soil organic carbon because most of the carbon they contain is readily lost as carbon dioxide during decomposition. Because of this situation these materials are generally either avoided at sampling or removed by sieving soil samples to 2 mm.

It is also important not to compress the soil when pushing in a soil core, or sampling at variable depths with an auger because this will contribute to errors in estimating soil carbon levels.

Site sampling (temporal)

Sampling for changes in soil organic carbon over time must be done at the same location and same time each sampling year. In the past, this has been done by taking 10 random cores from a 5 m intersecting grid across a 25m^2 area and bulking them for each of the following depth intervals: 0-10 cm, 10-20 cm and 20-30 cm at each benchmark site. At 10 per cent of sites the 10 individual samples are left un-bulked to gain an estimate of variability in carbon stocks. This does not provide a good estimate of average soil organic carbon across a large paddock,

but it is accurate for a specific location and useful for determining long-term trends.

On-farm, changes in soil organic carbon through time on a paddock basis could be determined by taking a similar or modified approach to that described above for paddock sampling.

Grid sampling

Grid sampling involves sampling and analysing soil samples taken at regular intervals throughout a paddock, or paddocks on either a 100 m^2 sized grid or 10,000 m^2 (one hectare) grid, or other nominated scale. This approach can be up-scaled to a regional, state and national delivery.

Time of sampling

Soil carbon stocks can vary seasonally, so it is important to take soil samples at the same time each year. Sampling during the non-growing phase (i.e. over summer in winter cropping areas) helps to minimise the influence of plant type and growth stage on soil organic carbon, particularly in soil carbon fractions that turn over rapidly.

Sampling for bulk density

Bulk density samples should be taken at the same time as soil carbon samples. The most common method used to assess bulk density involves driving small steel cylinders of known volume into each depth of soil sampled. The cylinders are then removed and the dry weight of the contained soil expressed per unit volume (g soil/cm^3). If being done manually, a minimum of three cores for each sampling depth should be taken. If bulk density is highly variable, the core number should be increased to five on surface (0-10 cm) soils.

Increasingly, technologies such as the neutron density meter are being assessed for their ability to accurately determine bulk density in soils (see Plate 8.1; Holmes et al. 2011).

II) ANALYTICAL TECHNIQUES FOR MEASURING SOIL ORGANIC CARBON

Soil organic carbon can be analysed using several methods, with each differing slightly in their approach and outputs.

In Australia, two methods (dry combustion and wet oxidation) are commonly used to determine soil organic carbon concentration, but neither method provides information on how stable the measured soil carbon is. A third method (mid-infrared spectroscopy), which at the time of writing was not yet available commercially, has the potential to provide a rapid, cheap and effective method of determining both soil organic carbon concentration and carbon fractions (stability).

1. Dry combustion methods use a Leco or Elementar to oxidise soil organic carbon at very high temperatures. The organic matter is ‘burnt-off’ and measured as carbon dioxide. This method can overestimate organic carbon because it includes inorganic carbon sources such as the carbonate in lime in its analysis. To avoid this scenario soils with carbonates are identified and must be acid treated before analysis.
2. The Walkley-Black wet oxidation method (Walkley and Black 1934) is the most common soil test for carbon. However, because it only oxidises readily decomposable carbon the Walkley-Black method underestimates total soil organic carbon

and on average detects only about 80 per cent of soil organic carbon. With heating this measure can be improved (Heanes 1984).

3. Mid-Infrared (MIR) spectroscopy identifies specific wavelengths and measures the light reflectance of soils, which can then be used to obtain a measure of soil organic carbon content (Janik et al 2007; Zimmerman 2007). The method is reliant on the development of robust and comprehensive calibration curves for a range of soils and environments. It is predominantly a research tool, but its potential for commercial application is being considered.

Most commercial soil tests report soil organic carbon results as a percentage, which translates directly as the weight of soil organic carbon (in grams) per 100 grams of oven-dried soil (g C/100g soil).

To compare soil carbon results obtained using the Walkley-Black and dry combustion methods it is necessary to use a correction factor. Walkley and Black used a correction factor of 1.3 for Australian soils though more recent work reports an average correction factor of 1.21 (Sanderman et al. 2010).

Calculating soil organic carbon

Soil sample depth (0–10 cm); 1.3 g/cm³ bulk density; 1.2% organic carbon

10,000 m² in one hectare x 0.1m soil depth x 1.3 g/cm³ bulk density x (1.2/100)

= 15.6 tonnes carbon hectare

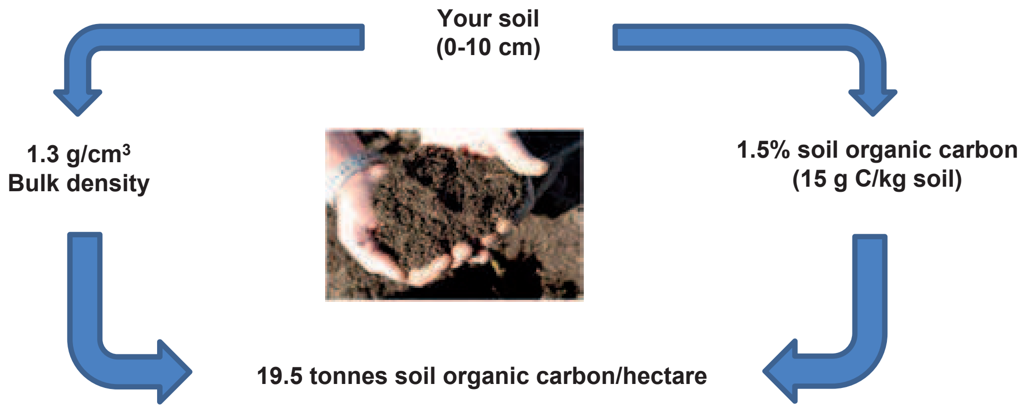
III) USING SOIL CARBON VALUES ADJUSTED FOR BULK DENSITY TO MEASURE TEMPORAL CHANGES IN SOIL ORGANIC CARBON OVER TIME

Bulk density is the weight of soil in a known volume. Different soils and soil depths have different bulk densities (see Chapter 2 for more detail about how to calculate bulk density). Soils of the same type with lower bulk density are often more porous and less compacted.

Bulk density is necessary to adjust soil carbon to an equivalent soil mass to: i) determine changes in soil carbon stocks for accounting purposes ii) measure changes in soil organic carbon under different management strategies and iii) determine any temporal trends in status. This is because over a number of years changes in bulk density and the distribution of elements can occur due to the adoption of a new management practice such as zero tillage, or through natural processes such as compaction or erosion.

Soil tests for organic carbon normally report a percentage total of soil organic carbon (% organic carbon). This is used with bulk density to calculate the amount of carbon per hectare at a given depth of soil (see Figure 8.1).

In a simple example, natural compaction of a coarse textured sandy soil often occurs over a number of years. If soil carbon were measured prior to and after compaction had occurred, the mass of soil taken after compaction would be greater as a result of the compaction ‘squashing’ the same weight of soil into a smaller volume. An estimate



i.e. 10,000 m² in one hectare x 0.1 m soil depth x 1.3 g/cm³ bulk density = 1,300 t/ha soil
15 x 1,300,000 = 19,500,000 g C/ha
= 19.5 tonnes carbon per hectare

Figure 8.1 Conversion of soil analysis values for soil organic carbon stock in a paddock to 10 cm depth.

of the change in bulk density is therefore used to adjust these values to an equivalent soil mass.

A simple web-based tool for adjusting soil carbon and nutrient concentration results for either bulk density or gravel/stone content is available at: **http://soilquality.org.au/calculators/gravel_bulk_density**

Laboratory measures of soil organic carbon are generally done on sieved soil samples, which in many cases exclude any materials larger than 2 mm in size. Consequently, if a soil has a significant amount of gravel or stone material, this fraction is removed before analysis with the final soil carbon or nutrient assessment being only representative of the mineral component of the remaining soil. To correct this, laboratory results need to be adjusted to reflect the original composition of the soil sample. For example, if the laboratory result is 1.4 per cent organic carbon, but 10 per cent of the original sample volume was gravel or stone, then the actual soil organic carbon content of that soil is 1.26 per cent organic carbon (i.e. 90 per cent of 1.4%). Such adjustments are sometimes overlooked and can lead to reports of rapid or unusually large changes in total soil organic carbon in Australian farming systems.

MEASURING SOIL ORGANIC CARBON FRACTIONS

Total soil organic carbon provides a measure of the amount of organic carbon present in a soil, but provides no information on its characteristics, function or stability. It is composed of four different fractions, which vary in their properties and decomposition rate (see Chapter 1). Understanding how each of these fractions change within the soil provides information on sequestration potential, nutrient turnover, biological function and soil properties such as water holding capacity. The following methods differ in their development, relative difficulty and expense, with the most promising commercial application associated with successful calibration of the mid-infrared technology for soil organic carbon.

Size fractionation

The size of soil mineral particles is often used to attribute the organic carbon contained within them to particulate, humus or resistant organic carbon fractions (see Chapter 1) that differ in their properties and decomposition rates. However, this is a time and labour intensive method for quantifying organic carbon fractions. Skjemstad et

Treated Rep 1	Untreated Rep 1	Untreated Rep 2	Treated Rep 2	Treated Rep 3	Untreated Rep 3

Figure 8.2 Possible trial design comparing two treatments with three replicates within a paddock.

al. (2004) and Sanderman et al. (2011) describe using size fractionation and 13C solid-state nuclear magnetic resonance spectroscopy to determine the particulate, humus and resistant components of organic carbon in a range of soils to calibrate against other methods such as mid-infrared spectroscopy.

Density fractionation

Density separation of soil carbon fractions uses water to isolate less decomposed organic materials (the ‘light fraction’), with a density less than 1 g/cm^3, and increasingly dense liquids such as sodium iodide to separate aggregates or particles (the ‘heavy fraction’) linked to biological processes and soil functions such as nutrient cycling and cation exchange capacity. This method is time consuming and is used primarily by researchers to link organic carbon fractions to soil function.

Mid-Infrared (MIR) spectroscopy

MIR spectroscopy is being assessed as a quick, cheap and effective tool for measuring soil attributes, including soil organic carbon content and carbon fractions (Janik et al. 2007; Zimmerman 2007). In Australian soils, initial calibrations for total, particulate, humus and resistant organic carbon fractions have been developed and are currently being validated nationally (Baldock unpublished). Analysis of soil organic matter fractions would provide landholders and industry with better information on carbon stability and potential changes in soil function.

Permanganate labile carbon

The carbon fraction measured using the permanganate oxidation method (Blair et al. 1995) has been linked to biological function, but can arguably be less sensitive to differences in soil organic carbon based on changes in management or land use. The method could be incorporated relatively easily into most commercial soil testing labs.

HOW DO I CONDUCT MY OWN FIELD TRIAL?

Organic and biological products often become commercially available with little or no scientific data on their field performance. On-farm trials and demonstrations can help quantify the impact of such products in different farming systems and climates. Designing such a trial requires a few basic steps:

1. Ensure a ‘control’ or untreated area is included within the same paddock or area the products are being tested, so the results can be meaningfully compared.
2. Ensure the ‘product’ is the only factor altered within the trial. If other factors such as fertiliser rate are changed it will be unclear whether measured responses are due to the product or the change in fertiliser application.
3. Measure something. The simplest thing to measure is often grain yield or in the case of organic matter a soil analysis with a measure of total organic carbon. This may mean hand harvesting a small area (1m x 1m) within each treatment to estimate average yields across treatments.
4. Where possible repeat each treatment at least three times (see Figure 8.2). This will provide an average response with an associated error term and can be used to exclude any differences due to changes in soil type and condition. Mark the treated areas with pegs to make them clear.
5. Keep records, including a map of the trial, paddock history, soil type, rainfall and management results.
6. Analyse your results using at least an average treatment result with a variability measure.

In many instances, it is advisable to critically assess what are the most limiting constraints in a soil prior to putting down a trial because these factors may limit any potential response. For example, in hostile subsoil, which limits root growth such as subsoil acidity, you are less likely to see a response to a product which works best when applied to a pH neutral soil.

Questions you may want to ask about the trial and in regards to specific product applications to check their usefulness include:

1. What is wrong with my soil and to what extent is it impacting on production?
2. Ask where the evidence for current claims comes from? Is there any local evidence available for reported responses?
   Where there is no local evidence consider the changes in response you might expect when applied in a different environment (e.g. warmer, drier).
3. If I apply this product what are the factors that will stop it from working?
   For example, biological agents are more likely to survive when soils are moist and there is sufficient organic matter and nothing that can eat them.
4. Is the product registered for its purpose?
   This generally ensures the product has been tested widely, is safe to use and provides response data on which you may base your decision.
5. What does the product contain and at what concentration?
   In some instances it is possible that your soil already does this job or has this characteristic.
6. Does the label provide sufficient information in regards to storage, safety and application?
7. How long will the product persist and how often do I have to apply it?
8. If part of a management package how do I know which components are contributing to the response?
9. How do I tell whether this product is working?

As a minimum undertake on-farm strip tests, including areas which are not treated. Follow the outline above for a field trial and measure things—don't just rely on visual assessments.

INDICATORS OF SOIL ORGANIC MATTER

– WHAT DO I SEE, FEEL AND SMELL IN THE PADDOCK?

AT A GLANCE

- While sensory and observational indicators are useful, a quantitative measure of changes in soil organic carbon is required.
- Measuring changes in soil condition will help determine what is driving changes in soil organic carbon and on-farm production.

Sensory indicators (sight, smell and touch) and some basic soil properties can provide a valuable and cheap way of identifying areas in which changes in soil organic matter may have occurred (see Table 9.1). This should not be considered a replacement for strategic soil sampling and analyses, but may help prioritise future sampling to validate what is a relatively subjective way of assessing changes in soil organic matter.

SOIL COLOUR

Soil colour is influenced by the mineral soil derived from the parent material, the amount and condition of organic matter, the presence of iron oxide and soil aeration. Soils with high organic matter content are often darker in colour and when dry leave hands dirty and dusty.

Soil colour can be characterised by using a Munsell colour chart to match the colour of moist, freshly broken soil (see Plate 9.1). Soil colour changes with depth due to differences in biological activity, water movement and weathering.

GROUND COVER

Soils with a high level of ground cover generally have a greater potential to generate soil organic matter because the cover promotes biological activity and helps protect the soil from wind, rain and temperature extremes (see Plate 9.2). Soil organic matter increases with the length of time that a soil has actively growing plants in it and the risk of losses due to erosion decrease. Stubble levels greater than 80 per cent are generally required, with bare soils less able to buffer changes in temperature and more prone to erosion (see Plate 9.3).

COVER CROPS, GREEN MANURES AND PASTURES

Cover crops provide soil cover and prevent soil erosion, while promoting the production of soil organic matter. When a cover crop is grown to decrease the risk of nutrient leaching or to retain nutrients that would otherwise move deeper into the soil profile, it is referred to as a 'catch-crop'. A green manure is grown primarily to manage weed populations and improve soil fertility, but may also be an option for a crop that has failed. Plant growth is stopped shortly after flowering and the residues either incorporated (green manure, Plate 9.4 a), surface mulched (see Plate 9.4 b), or desiccated (brown manure).

Pastures and perennial crop phases can potentially generate more soil organic matter than annual cropping sequences (where not limited by subsoil constraints and where summer rainfall supports continued growth). This is often associated with more below-ground biomass production deeper in the soil profile.

Crop rotations that include cover crops, perennial grasses and legumes are an important factor in soil organic matter management and can be adapted to any cropping system. Increasing the diversity of residues and quantity of soil organic matter using legume and cereal cover crops in low disturbance systems has the potential to increase the biomass and diversity of soil biota. Crop rotations that maximise soil carbon inputs and maintain a high proportion of labile carbon are important in maintaining a sustainable cropping system. For more on cover crops and cultivation see Chapter 10.

ROOT ARCHITECTURE AND ROOT EXUDATES

Roots are influenced by the physical structure of a soil and commonly follow cracks or bio-pores (see Plate 9.5) resulting in concentrated areas of below-ground carbon. Root architecture and biomass varies between plant species, genotype and even cultivars within the same species. These differences can alter the amount and spatial distribution of below-ground organic matter vertically and horizontally.

Increasing root biomass influences soil organic matter: i) directly by increasing organic inputs to soil and ii) indirectly by influencing the location of roots and production of root exudates that may stimulate mineralisation. Root exudates and other by-products are also more readily absorbed and protected by soil aggregates and where concentrated are more likely to persist in the particulate organic matter and humus fractions than shoot-derived soil organic carbon (Clapperton et al. 2003). This capacity to generate roots, in part explains why perennials and pasture phases are sometimes associated with increasing soil organic matter compared to annual crops.

PLANT RESIDUES

Plant type, species and rotational sequence influence the population size and diversity of decomposer organisms due to differences in their chemical composition and lignin content, which in turn affects the rate at which soil organic matter is decomposed.

Soils with a high level of ground cover generally have a greater potential to generate soil organic matter because the cover promotes biological activity and helps protect the soil from wind, rain and temperature extremes.

PRESENCE OF EARTHWORMS AND OTHER SOIL ORGANISMS

Earthworms modify the physical, chemical and biological properties of soil and contribute to nutrient cycling, soil aeration and water infiltration (Clapperton et al. 2003). The presence of earthworms is an indicator of soil health (see Plate 9.6). In high rainfall zones of eastern Australia, more than 10 earthworms per spadeful (20 cm x 20 cm x 10 cm deep) is indicative of an active biological system. However, earthworms are rarely found in sandy soils, which are low in calcium and often have low pH (less than 4.5) not suited to their survival.

Termites, ants, beetles and collembolan (commonly called ‘springtails’) help aerate and mix soils and are considered important indicators of soil organic matter. However, as soil biota is seasonally active its absence does not always indicate an unhealthy soil. For more information on earthworms and microorganisms see Chapter 4.

Table 9.1 Sensory and soil indicators of organic matter in the paddock.

What will you observe?	What will that indicate?
Presence of earthworms and microorganisms	Indicates a plentiful food supply of organic matter. Worm casts and biological secretions increase soil organic matter.
Soil depth	Determines rooting depth and net primary productivity. The deeper the rooting depth the greater the potential to produce organic matter and store it.
Soil colour	In soil, the presence of organic matter can be associated with a darkening or staining of the soil surface, or top layer of a soil profile.
Soil fertility	Increasing levels of organic matter are linked to greater nutrient availability due to enhanced biological activity.
Soil smell	An earthy smell is a good indicator of soil organic matter because this suggests active and healthy actinomycetes (beneficial soil bacteria).
Soil softness	Soils high in organic matter are often more ‘spongy’.
Ground cover	A high proportion of ground cover (e.g. stubble, leaf litter, pasture) minimises loss of organic carbon. A higher frequency of pasture phases can increase soil organic matter.
Greater below-ground biomass (e.g. roots)	More organic matter is likely to be present at greater depth and where root materials are concentrated.
High-quality crop residues	Carbon to nutrient balance supports higher microbial activity than poor quality residues such as wheat straw.
Neutral soil pH_{Ca}	The preferred range for most micro-organisms is pH 6-7.

Plate 9.1 Assessing soil colour at a field site using a Munsell colour chart.
Source: Frances Hoyle, DAFWA

Plate 9.2 Pasture growth under retained stubble provides complete ground cover.
Source: Frances Hoyle, DAFWA

Plate 9.3 Long-term experimental site with burnt stubble (on left of image) and retained stubble (on right of image) demonstrating significant differences in ground cover.
Source: Frances Hoyle, DAFWA

Plate 9.4 a) Crop residues being green manured and **b)** crop residues being mulched in a continuous cropping system.
Source: Frances Hoyle, DAFWA

Plate 9.5 Plant roots growing through soil. Note the proliferation of roots in previously formed channels and cracks.

Source: Steve Davies, DAFWA

Plate 9.6 Soil showing earthworms present in an arable system in Australia.

Source: Kondinin Group

ON-FARM MANAGEMENT OF SOIL ORGANIC MATTER

AT A GLANCE

- Soil organic matter content in soils is a result of inputs minus losses.
- Maximising crop and pasture biomass by managing soil constraints and optimising agronomic management should result in higher amounts of plant residues being retained and slowly increase soil organic matter.
- Increasing the proportion of the year under planted systems should support incremental gains in soil organic matter content.
- Soil amendments should be considered carefully in the context of their agronomic benefit, role in soil function, practicality and cost.
- Soil management often results in a change in distribution of soil organic matter (carbon) within the soil profile. Any measured changes in total soil organic matter should be considered over the depth of soil likely to be influenced by a particular practice.

Most Australian agricultural soils have lost soil carbon over time through land clearing and agricultural practices and therefore have the potential to restore some of this lost carbon (see Table 10.1).

MANAGING SOIL ORGANIC MATTER FOR AGRONOMIC BENEFITS

To increase soil organic matter, the rate at which organic matter is added to the soil must exceed the rate at which it is lost via microbial decomposition, erosion or leaching.

Cropping and pasture management practices that generate adequate amounts of high-quality residues are critical to rebuilding and sustaining soil organic matter (see Figure 10.1). Practices that enhance soil structure, support larger and more diverse microbial populations, which in turn improve soil fertility (see Table 10.1).

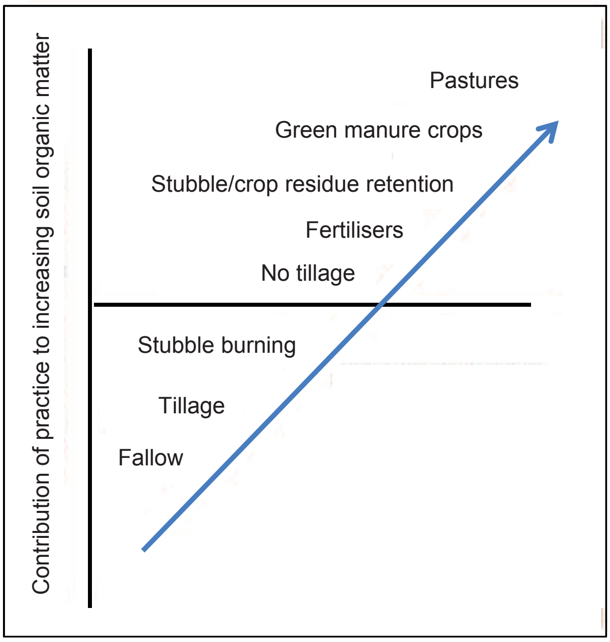


Figure 10.1 Summary of the relative effect of different management practices on soil carbon levels (Cotching 2009).

While soil organic matter can be increased in Australia (see Table 10.1) it is important to consider the economic cost of doing so. For example, soil organic matter can be increased substantially by adding high rates of organic amendments such as manure and compost, but this is likely to involve significant transport costs. Increasing soil organic matter will be more economic in farming systems and climates that support high production and generate on-farm supplies of organic soil amendments. In Great Britain, the continuous application of farmyard manure over 100 years almost tripled soil organic carbon content in long-term trials and resulted in higher yields (Johnston et al. 2009). Improvements in Australian soils, which by comparison are water and resource poor, are likely to be more limited.

MANAGING SOIL ORGANIC MATTER FOR CARBON SEQUESTRATION

One way to offset greenhouse gas emissions generated on-farm is to increase the amount of biomass carbon that is stored in soil. Any practice that increases the production of biomass carbon (via photosynthesis) and slows the return of this carbon back into the atmosphere as carbon dioxide (via respiration, fire or erosion) will increase soil carbon reserves (Smith et al. 2007). In this way the soil becomes a carbon 'sink' — removing atmospheric carbon dioxide from circulation and locking it away in organic carbon structures within the soil.

Each soil has a finite capacity to store carbon, with heavier soils generally able to store more than lighter sandy soils. Collectively, Australian soils have an enormous capacity to store carbon — the challenge is to ensure that once it is stored it remains in the soil for the long-term rather than just cycling through quickly and returning to the atmosphere as carbon dioxide. CSIRO analysis shows that if we could realise just 15 per cent of the capacity of Australian soils to store carbon we could offset about a quarter of Australia's current annual greenhouse emissions for the next 40 years (Wentworth Group of Concerned Scientists 2009).

Converting agricultural soils into carbon sinks requires the continued addition and maintenance of organic inputs (see Table 10.1), which for some Australian soils and climatic zones is a challenge (Hoyle 2011). In Australia, a one per cent increase in organic carbon in the top 30 cm of soil, with a bulk density of 1.3 g/cm^3 over 10 years, would require about 15-30 tonnes of additional organic matter each year depending on soil type. Given a typical two tonne wheat crop, with a harvest index of 0.4 and a root biomass half that of shoots, typically contributes about two tonnes of organic matter per hectare to soil if all post-harvest residues are kept in the paddock — this magnitude of increase is unlikely if not impossible. Probably less than 10 per cent of this is retained as carbon in soil.

HOW DO I INCREASE SOIL ORGANIC MATTER ON-FARM?

Potential strategies for increasing soil organic matter

Table 10.1 Management options for improving long-term soil organic matter levels in agricultural soils (from Sanderman et al

☺ = low potential for increase ☺☺moderate potential for increase ☺☺☺ = high potential for increase

Activity	Change in soil organic matter	Qualification	Influence on profit outcome
Increase biomass of crops and pastures	☺	Slow incremental increase in carbon (e.g. less than 0.2 tonne carbon/hectare for each tonne of extra yield). Higher fertiliser inputs may increase decomposition rate.	Where harvest index maintained, profit and organic matter should increase.
Retain crop and pasture residues on paddock	☺	Higher nutrient cycling capacity and biological fertility. Should increase organic inputs to soil and lower erosion risk.	Cost neutral long-term.
Burn crop and pasture residues	☹	Decrease in particulate organic matter and nutrient cycling capacity.	Can be positive or negative. Where high weed pressure exists it should increase yields. Burning leads to loss in soil fertility, which could decrease yields.
Increasing rotational diversity	☺	Higher amount and quality of organic residues supports a more functional microbial community.	Can be positive or negative. Lack of profitable break-crop options in low rainfall environments may decrease potential for profit.
Increase rotational frequency	☺☺		Positive provided no water deficit occurs in catch-crops
Add a pasture phase	☺☺☺	Mixed (grass and legume) provide best quality of organic inputs. Introducing perennial species with higher net primary productivity or carbon allocation to deeper roots can increase soil carbon (Smith et al. 2007). Much of this response is linked to perennial systems dominating higher rainfall areas.	Positive where good pasture establishment and weed and erosion risks are managed. Dependent on stock/meat/wool prices. Pasture cropping influence on soil organic matter dependent on soil moisture availability in subsequent crop.
Manage grazing intensity	☺	Lower grazing pressure should decrease erosion risk and increase the amount of organic matter returned to the soil. In theory, rotational grazing increases productivity and residues turn over more quickly, but field evidence for this is lacking.	Dependent on stock/meat/wool prices.
Cover crop, green manure, pasture cropping	☺☺	One-off cover crops likely to have little impact. Impact greater if able to support two or more crop/pasture phases in a year. Pasture cropping increases the proportion of the year during which organic matter is returned to soil.	Significant cash flow deficit in year of implementation for green manures. Viability dependent on opportunity costs, the cost of operation and subsequent seasonal conditions. Carefully consider the area of farm to be targeted.

. 2010; Hoyle et al. 2011).

Activity	Change in soil organic matter	Qualification	Influence on profit outcome
Apply off-paddock organic amendments such as manures, compost and biochar	☺	Carbon in manure and compost is often in a more stable form than that in biomass residues. While some farmers might be able to generate enough biomass residues to raise soil carbon, often only an external source of organic matter (manure, compost) will lift soil carbon levels. Amendments vary widely in their biological, physical and chemical properties and therefore in their effect on crops and soils.	Likely to be negative in the short-term with little evidence of long-term profit outcome. Economic outcomes likely to be constrained by rate of application and costs, including transport. Agronomic responses vary widely and can be negative. Seek local trial data. Consider any potential environmental risks.
Maintain low soil disturbance system	☺	Small, if any, benefit to soil organic matter levels. Long-term adoption can promote soil aggregation and slow decomposition rates of soil organic matter. Direct drilling decreases the risk of erosion and maintains soil structure, slowing soil organic matter decomposition. Organic residues remain on the soil surface and tend to decompose with only minor contributions to stable soil organic carbon fractions.	Effect on structured or aggregated soils greater than on coarse textured sand. Increased reliance on herbicides can contribute to negative profit base.
Increase bare fallow in the rotation	☹☹	Fallow contributes to soil carbon losses because no additional biomass is generated and erosion risk increases. Fallow during warm, moist periods will result in large losses of organic matter.	While short-term economic responses to fallow can be positive, medium to long-term profit outcomes are often negative.
Decrease erosion risk	☺☺☺		Low cost practices available. Likely to be positive though dependent on current losses and the intervention required.
Retirement of non-productive areas	☺	All annual carbon production (minus natural loss) is now returned to the soil, with replanting of native species on degraded land often resulting in large soil carbon gains.	There are direct and indirect costs in retiring agricultural land. Economic viability dependent on foregone opportunity costs, carbon price and market opportunities.
Revegetation and destocking of cleared areas	☺☺	Large potential for carbon storage through the establishment of forests, trees and other perennial vegetation.	Opportunity costs over the long-term should be considered. Economic viability dependent on carbon price and market opportunities.
Irrigation	☺☺	Higher biomass production. Increased frequency of crops and pastures supports higher soil organic carbon. Irrigating during warm periods can increase the rate of organic matter decomposition.	Large on-farm impact. Potential trade-off between additional amount of carbon being returned to soil and increased decomposition rates due to increased biological activity (dependent on temperature and change in soil moisture conditions).

Burning stubble results in the rapid loss of carbon, nitrogen (up to 80 per cent), phosphorous (about 25 per cent), sulphur (about 50 per cent) and potassium (20 per cent) from crop residues and contributes to the loss of surface soil via erosion.

in Australia are presented in Table 10.1. While the table provides commentary on the possible economic outcomes of the strategies, landholders should seek professional advice on how their farming circumstances could influence the viability of the suggested practices. To increase and maintain soil organic matter, practices must initially boost organic inputs above current levels and then sustain these on a frequent, if not continuous basis.

MANAGING FOR INCREASED NET PRIMARY PRODUCTIVITY (BIOMASS)

The primary drivers of plant biomass production are climate (rainfall, temperature and light), soil condition and agricultural inputs. Biomass can be readily estimated in plant production systems and expressed either in organic matter or carbon units (e.g. tonnes of carbon per hectare per year). Growing more above and below-ground biomass increases the amount of photosynthetic carbon gained over time by plants. This carbon can be allocated to the production of biomass in shoots and root material, weed and seed production, root exudation, symbiotic carbon transfer to microorganisms and the volatile organic carbon emissions that are lost from leaves to the atmosphere. A greater proportion of recalcitrant plant inputs become soil organic matter.

Carbon losses occur in agricultural systems from organic matter decomposition, fire, erosion and the removal of biomass through harvesting. So, while a significant amount of carbon dioxide is fixed during plant photosynthesis, a large proportion (50-90 per cent) of the carbon is converted back to carbon dioxide and respired to the atmosphere as a result of microbial decomposition. This is why changes in soil organic matter are generally decadal since only a small amount of fixed carbon remains in the soil and accumulates in soil organic matter fractions as a result of short and long-term stabilisation processes (see Chapter 1).

Optimising agronomic management practices and water use efficiency to increase grain yield should result in higher plant biomass (as long as harvest index is maintained). The adoption of management practices such as low soil disturbance seeding (e.g. conservation tillage), stubble retention and increasing the frequency of crops and pastures (e.g. use of cover crops) can also contribute to higher soil organic matter through greater capture of carbon from the atmosphere to the soil and mitigation of losses from the soil.

Plant growth in agricultural systems is determined by the most limiting factor. For example, the application of nitrogen to soil with low phosphorous availability is unlikely to increase biomass and grain yields unless the limiting nutrient (in this case phosphorous) is also applied. Similarly, if root growth is constrained by subsoil acidity plants are not able to use the soil resources below this chemical barrier. Ameliorating production constraints such as acidic, sodic or compacted soils and nutrient toxicities and deficiencies should result in increased biomass production and support a more profitable farming base (see Plate 10.1).

Where soils and crops are managed optimally, irrigated systems are capable of reaching their attainable soil carbon potential (see Chapter 1) because water becomes a non-limiting factor to production. At a farm scale, the effect of irrigation on net primary productivity and stores of carbon, nitrogen and phosphorus are often large, but on a national scale have relatively little impact.

CROP AND PASTURE STUBBLE RETENTION

Leaving stubble standing will slow the decomposition rate, promote water conservation and decrease soil erosion (about 60 per cent of organic matter in the top 30 cm of cropped soils is stored in the top 10 cm and this can take years to replace). Frequent burning of crop residues decreases the amount of organic matter entering different soil fractions in Australian agricultural soils. The most significant effect of burning is a change in the composition of the residue and a resulting decrease in particulate organic matter in the topsoil (0-10 cm) and a lower potential for soil nitrogen supply (Gupta et al. 1994; Hoyle and Murphy 2006). This loss of particulate organic matter is reflected in a decrease in biological activity, microbial biomass and the biodiversity of soil organisms across a range of different agri-ecological zones in Australia (Hoyle and Murphy 2006). Burning of stubble and crop residues also contributes to a higher risk of surface crusting and hard-setting associated with the loss of organic matter content in soils.

Burning stubble results in the rapid loss of carbon, nitrogen (up to 80 per cent), phosphorous (about 25 per cent), sulphur (about 50 per cent) and potassium (20 per cent) from crop residues and contributes to the loss of surface soil via erosion. Nutrients that remain in the ash are also at risk of loss from wind or water erosion events. However, some studies have demonstrated no difference in soil organic carbon levels between systems where stubble is retained versus those where crop residues have been burnt (Hoyle and Murphy 2006; Rumpel 2008). This may be because both systems lose a similar amount carbon over the long-term through biological decomposition, with only the more stable carbon retained. A minimum of two tonnes of residue is recommended to retain cover and avoid erosion.

PASTURE MANAGEMENT

Maintaining a minimum 40 per cent pasture cover under grazing, introducing legumes into grass pastures and applying phosphorus fertiliser to maintain pasture production will increase soil organic matter in pasture systems. Managing the duration and intensity of grazing is also required to avoid overgrazing and minimise erosion (see Plate 10.2), which can dramatically decrease soil organic carbon levels by removing topsoil and associated organic matter. In mixed cropping systems the ability of pastures to rebuild soil organic matter after cropping depends on the productivity of the pastures.

Both short-term (up to 5 years) and long-term perennial pasture systems can have a positive effect on the quantity and quality of soil organic matter in Australian agricultural systems. This is because:

i) They have a higher root to shoot biomass compared to annual crops (meaning they produce more biomass underground where it is less susceptible to loss).
ii) Perennials grow for a longer proportion of the year.
iii) They are subject to less soil disturbance than cropping.
iv) They have a slower rate of decomposition associated with less available soil moisture.

The productivity of unimproved or native pastures is often limited by nutrients resulting in lower biomass yields and therefore lower organic matter inputs into the soil. Pastures managed for biomass production are associated with increased nitrogen fertility and soil structural stability. The higher organic matter inputs and less soil disturbance of managed pasture systems often results in higher earthworm populations and greater species diversity (Clapperton et al. 2003). Improved management of pastures in Australia can result in an increase in soil organic carbon of between 0.1-0.3 tonnes per hectare (Sanderman et al. 2010).

While recent studies in Western Australia measured more soil organic matter under perennial pasture systems than annual pasture, mixed cropping or continuous cropping systems, this was driven primarily by suitability of land use in relation to rainfall (i.e. it was 'fit for purpose'). In this study, pasture systems dominated the higher rainfall areas resulting in a greater potential for net primary productivity whereas cropping systems were largely excluded from these areas due to the risk of waterlogging (Hoyle et al. in printing).

Pasture cropping involves the sowing of a winter grain crop into a summer dominant perennial pasture and has some potential for increasing both the frequency and amount of crop and pasture residues entering the soil. Limitations exist in low rainfall, winter dominant environments where the soil water used by the perennial pasture may limit the successful establishment and yield of subsequent grain crops. Other influences such as providing a 'green bridge' for the survival of pathogens or the control of weeds must also be considered in the context of a profitable and viable farming system.

GRAZING

Overgrazing reduces ground cover and pasture species composition, increases erosion and nutrient loss, causing a subsequent loss in animal performance and a longer recovery period for pastures. Cell or rotational grazing allows pasture soil to be rested. This can help regenerate soil structure and improve permeability on self-mulching soils through clay swelling and shrinkage (limited to specific clay soils) and soil biological activity. Most importantly it prevents pastures from being overgrazed and soils from becoming compacted. Removing or reducing stocking rates (particularly cattle) when the soil is wet will help decrease the risk of compaction as will maintaining high stocking rates for shorter duration.

CATCH-CROPS

Catch-crops and pastures are used strategically and at times opportunistically to take up nutrients in the soil that would otherwise leach, provide ground cover, use excess soil moisture, control weeds and supply nitrogen to subsequent crops.

Cover crops

Cover crops established through summer help anchor soil and lessen the impact of raindrops, minimising wind and water erosion. They are also grown to take-up excess nutrients in the soil and prevent leaching between catch-crops, or fix nitrogen in the soil for future use (e.g. leguminous species). In addition, they can be used in a similar way to a break crop to control pests such as plant parasitic nematodes (Widmer et al. 2002). Since cover crops and pastures are being grown at a time where the soil would otherwise be bare (and often when hottest) they help moderate soil temperature and provide additional organic matter to soils providing a habitat for beneficial insects and other organisms.

While a range of crops and pastures can be used as vegetative cover, it is important to consider the benefits of each when planning a rotation scheme. Initially, easily established cover crops that cover the surface with a large amount of slow-to-decompose residues such as grasses and cereals are most appropriate because their intensive root systems can help improve soil structure. Plant residues with high levels of lignin and phenolic acids have a higher resistance to decomposition and result in soil protection for a longer period (Bot and Benites 2005). In subsequent years, legumes can be incorporated into the rotation to enrich soil nitrogen and stimulate the decomposition of residues. Once soil condition has improved, it may be possible to include cover crops with an economic function such as livestock fodder.

The use of cover crops in rotation is an effective way to increase soil organic matter and, depending on the plant species, deliver other beneficial functions to farming systems. Combined with low soil disturbance systems, increasing the diversity of residues and quantity of soil organic matter using legume and cereal cover crops has the potential to increase the population and diversity of soil biota. However, in very dry climates growing a cover crop is not always beneficial because there is not enough soil moisture to support the following catch crop.

Green manures

A green manure is a crop or pasture (see Table 10.2 for examples) that is grown and returned to the soil in situ to increase organic matter inputs, nitrogen supply or control weeds and manage erosion. The term green manure reflects the stage of plant growth (flowering) at which the crop is manured.

The different modes of operation include:

i) Green manuring incorporates a green crop or pasture into the soil using discs, plough or other mechanical means. It is generally sprayed with a non-selective herbicide before incorporation (see Plate 10.3).
ii) Desiccation with a non-selective herbicide and allowing the residues to be incorporated naturally over time. Also termed brown manuring.
iii) Using a slasher or mower to cut residues which are left in a layer on the soil surface. Also termed mulching. Spraying with a non-selective herbicide before slashing will decrease the risk of regrowth.

Table 10.2 Crop and pasture type suitable for using as a green manure phase.

Crop or pasture	Characteristics and management
Annual ryegrass	Large fibrous root system that contributes organic matter to the soil. The crop needs to be sprayed before incorporation to prevent re-growth.
Other annual or phase pastures	Serradella and other leguminous annual pastures add nitrogen. The last year of a pasture phase can be used to maximise benefits and decrease management costs. Maintain grazing to maintain a sufficient biomass.
Oats, rye or triticale	Vigorous crops that grow rapidly and produce large biomass. Should be sprayed before seed set. They can be mixed with vetch to add legume content. Higher carbon to nitrogen ratio means residues should reside in soil longer contributing to soil organic matter.
Grain legumes (field peas, vetch, lupins, faba beans etc.)	The seed may need inoculation to maximise nitrogen input. Can contribute up to 200 kilograms of nitrogen per hectare to the soil. Maximum nitrogen benefit gained when the crop reaches flowering. Not great for weedy paddocks due to low early vigour and will contribute less stable organic matter than higher carbon to nitrogen crops. Lupin residues on sandy soils have been associated with a higher risk of non-wetting due to waxes.
Canola and mustard	Select varieties high in glucosinolates to maximise any potential bio-fumigation effect.
Summer crops and pastures	Where summer rainfall allows can be used between catch-crops. Need to be sprayed out a minimum of six weeks before the next cropping phase.
Salvage crop	Often the best economic outcome from green manures stem from salvaging a crop that has failed to yield well through frost, disease, drought, etc.

While growing, green manures act as a catch crop absorbing and holding nutrients such as nitrogen that might otherwise leach away. The nutrients are later released when the plant decomposes. During decomposition, green manures increase the biomass and diversity of soil organisms by providing them a readily accessible food supply.

Carbon losses occur in agricultural systems from organic matter decomposition, fire, erosion and the removal of biomass through harvesting.

Management of green manures can range from none to normal management of a crop or pasture. Green manuring can be done in the last year of a pasture phase before cropping to minimise costs and maximise potential benefits. As costs increase, the requirement for a benefit to be realised in subsequent years increases, which may be constrained by rainfall. This presents a risk because the magnitude of the eventual benefits will depend on seasonal conditions. For maximum benefit in weedy paddocks green manuring should precede weed-seed set.

Green manure phases should be assessed against alternative management strategies and any unrealised benefits from foregone crops. Financial planning is critical to ensure a sufficient cash flow across the farm business and as a strategy should only be considered across a percentage (less than 20 per cent) of the property as a whole.

Soil type influences the choice of green manure crop, while the farming system may constrain how and when the green manure phase is implemented. Careful cultivation is recommended to minimise damage to soil structure. Lighter soils at risk of erosion should be treated with care, with mulching or brown manuring the safer options on these soils.

ORGANIC AMENDMENTS

Many organic soil amendments, which reportedly offer agronomic benefits, are now available to Australian farmers (see Table 10.3). Until recently, organic amendments have largely been used in intensive horticultural industries and organic farming systems. Increasingly, however, these products are being targeted at broadacre farming systems to supply plant nutrients, control pests and diseases and improve soil health. However, many products come with little independent or local evidence of their actual benefits.

Despite manufacturers claims of their benefits, large application rates (and cost) and in some cases the associated transport costs required to produce an agronomic benefit mean organic amendments can be uneconomic (Edmeades 2002). In addition, the variable results and lack of independent research limit the usefulness and adoption of products on-farm (Quilty and Cattle 2011). On-farm trials can improve knowledge at a local scale of potential responses (see Chapter 8).

HOW DOES TILLAGE INFLUENCE SOIL ORGANIC MATTER CONTENT?

Cultivation of agricultural soils causes an immediate and rapid loss of soil organic matter, followed by a slower rate of loss lasting several decades, which can deplete original levels by as much as 70 per cent regardless of climate, soil type or vegetation (McLauchlan 2006). While losses can be mitigated in soils to some extent when organic matter is associated with clay minerals, the destruction of soil aggregates through tillage exposes previously protected and stable soil organic matter to decomposition and a lack of plant cover compounds organic matter losses arising from tillage due to water and wind erosion. Tillage also decreases the number and diversity of soil fauna such as earthworms, beetles, nematodes, mites and collembolan (Wardle 1995).

CONSERVATION AGRICULTURE

Conservation tillage is often promoted as a way to increase or maintain soil organic matter with one study showing no-tillage increased soil carbon sequestration rates by about 0.4 tonnes per hectare annually compared to conventional tillage (Franzluebbers 2005). However, recent evidence suggests that in Australia conservation tillage results in, at best, only a slow increase in soil organic matter (Chan et al. 2011), and that perceived differences in soil organic matter stocks often did not exist when considered over soil depths greater than 30 cm (Luo et al. 2010).

Nutrients and organic inputs can become concentrated on the soil surface in no-tillage systems where they are less available to soil organisms. This concentration of organic matter, together with inadequate or spatially inaccessible fertiliser inputs can limit the availability of nitrogen, phosphorous and sulphur required to build up stable soil organic matter (Kirkby et al. 2011). Its placement on the surface also makes any newly acquired carbon vulnerable to losses. Retaining crop residues, conservation tillage and adequate inorganic fertiliser can lead to increased soil organic matter levels (Moran et al. 2005), but any measureable build up will be the result of a much slower process taking up to 15-20 years particularly in drier regions (less than 500 mm) of Australia (Chan et al. 2003).

BARE FALLOW

The longer a soil is left as bare fallow the less soil organic matter it will contain (Cotching 2009). Soils devoid of plants have no input of organic matter and soil microbes continue to metabolise remaining soil organic matter into carbon dioxide. Bare fallows also increase the chance of soil erosion and in a dry summer large amounts of top soil can be lost — dramatically decreasing soil organic carbon levels (see Plate 10.4).

EROSION

Soil forms at a very slow rate, typically about one millimetre (or 14 t/ha) every 100 years. Only a small amount of erosion is required to exceed this rate of soil formation and in Australian agriculture typical losses can be up to 50 t/ha of soil per year from bare fallow, 8 t/ha per year under a crop and 0.24 t/ha under pasture (www.soilhealthknowledge.com.au). Organic matter that is concentrated towards the soil surface would also be lost.

Organic residues that form mulch on the soil surface protect the soil from raindrop impact, minimise the risk of wind and water erosion, reduce evaporation and buffer the soil from extreme temperatures. Mulch also promotes root growth in the topsoil where nutrients tend to be concentrated and protect seedlings from wind damage. Under grazing, an initial ground cover of 70 per cent is desirable. A decreased risk of erosion in cropping systems requires a minimum 50 per cent of ground covered by standing stubble (minimum 10 cm height). Most significant erosion events occur on land before the opening rains where soils are bare, dry and loose due to cultivation or grazing.

Incorporate pasture phases, increasing cropping intensity to grow more plant biomass, increasing plant production and retaining stubble will decrease the risk of crusting and hard-setting soils, which increase the risk of erosion. On gypsum responsive soils (i.e. sodic soils) gypsum may also be required in combination with reduced tillage to manage the effects of high levels of sodium on soil structure and stability (see Plate 10.5).

Organic residues that form mulch on the soil surface protect the soil from raindrop impact, minimise the risk of wind and water erosion, reduce evaporation and buffer the soil from extreme temperatures.

RETIREMENT OF NON-PRODUCTIVE AREAS

Return of marginal agricultural land to native vegetation can have significant soil organic matter benefits because nearly all plant production is returned to the soil (Liddicoat et al 2010). Retirement of marginal agricultural land has been extensively undertaken in the United States through their conservation reserve program (CRP) in response to severe soil erosion and this land is now seen as a potential carbon sink with sequestration rates ranging from nil to 1.1 tonnes carbon per hectare annually. In Texas, the planting of agricultural land to permanent vegetation resulted in a carbon sequestration rate of 0.45 tonnes carbon per hectare annually to 60 cm over a 60-year period in clay soils (Sanderman et al. 2010).

Retiring agricultural land incurs direct and indirect costs. The American CRP program has been successful because the government pays the landowner in 10-year contracts. The recent acceptance of soil organic carbon credits in an emissions trading environment (see Chapter 7) provides some incentive for destocking of rangelands and reforestation of cleared farmland. In Western Australia it was estimated that while varying with carbon yield and project costs, this could be economically viable to landowners at a carbon price of AU$15 per tonne of carbon dioxide equivalent (Harper et al. 2007). Large amounts of marginally productive land could thus potentially be available for retirement given sufficient price incentives. At the time of writing carbon credits were trading at around AU$4.67 per metric tonne of carbon dioxide equivalents (CO_2-e).

Table 10.3 Type and application benefit of organic amendments in Australia (Quilty and Cattle 2011).

Type	What is it?	Response and application rates
Composted organic matter	Relatively uniform, stable organic material. Commonly made from crop residues, organic matter sourced from municipal waste materials and manures from intensive animal production systems (e.g. beef and chicken industries). Uniformity of compost varies with feedstock and composting method.	In contrast to fresh plant residues or animal manure, composted organic materials decompose slowly when added to soil because they have already undergone a significant amount of decomposition during the composting process. Source of plant nutrients, humified organic matter and microbial biomass. Can improve structural condition. Application rates between 2-30 t/ha on the surface of the soil often followed by incorporation into the topsoil. Potential risks associated with the application of composts, include contamination by weed seeds, heavy metals, salts, pathogens and compositional inconsistencies.
Compost tea/ extract	Compost tea usually derived from steeping compost in water. Other substances such as seaweed extracts, fish hydrolysates, or molasses are often added to the mixture.	Source of plant nutrients. Vector for beneficial microorganisms to control pests and disease. Applied as foliar spray or soil drench at rates ranging from 50-1000 L/ha.
Vermicasts	Worm castings (vermicasts) are produced as earthworms digest and excrete organic matter.	Moderate source of plant nutrients and humified organic matter. The manufacturers suggest application rates of 10-100 L/ha for liquid amendments and 2-50 t/ha for solid amendments.
Humic substances	Material extracted from composted and vermi-composted organic matter, coal and peat. Liquid or solid form.	Liquid forms mixed with water and applied to soil or plant foliage at application rates between 1-30 L/ha for liquid sprays or soil drenches. Granular products either: i) spread and mixed into soil or ii) combined with synthetic inputs before application at rates of 25-400 kg/ha.
Meat, blood, and bone meal	By product of meat processing industries.	Effective source of nitrogen. Used for remediation of contaminated soil. Application rates of 0.1-1 t/ha for solid material and about 30 L/ha for liquid products.
Fish hydrolysates	Hydrolytic or enzymatic breakdown of by-products from fish processing industries (e.g. tuna or mackerel).	Source of plant nutrients, enhanced disease resistance in plants, improved germination and seedling performance. Typical rates 10-30 L/ha for foliar spray and 20-60 L/ha when applied as a soil drench.
Seaweed extracts	Liquid seaweed extract usually produced via extraction methods designed to increase the level of enzymes and hormones contained in product.	Contain plant growth hormones cytokinins, which are responsible for enhanced crop performance. Application rates range from 0.5-5 L/ha for foliar application and from 5-20 L/ha when used as a soil drench.
Un-composted wastes	Municipal, industrial and agronomic waste products (e.g. olive and paper mill waste, treated sewage sludge and bio-solids and un-composted animal manures).	Improve soil condition and crop performance depending on degradability of material. Manure derived from feedlots can contain high levels of sodium which may promote subsoil constraints. A significant fraction of manure can be incorporated into more stable soil organic matter pools (Blair et al. 2006).
Bio-inoculants	Products that contain living microbial species such as arbuscular mycorrhizal fungi, Azospirillum and Pseudomonas sp. in a liquid suspension.	Improved nutrient uptake by plants, sequestration of atmospheric nitrogen, or via control, inhibition, or competition with plant pathogens and pests. Stubble digestion to increase the decomposition rate of crop residues. Bio-inoculants are usually applied through soil injection or sprayed over stubble. Soil injection rates are generally 20-30 L/ha, while the suggested application rates for stubble digesters are 15-25 L/ha.
Biochar	Solid, fine, granular, black charcoal produced by pyrolysis of organic biomass.	Potential to improve soil cation exchange capacity, enhance the efficiency of synthetic inputs and increase the organic carbon content of the soil. Can result in less plant available nitrogen and decrease herbicide activity. Biochar application rates used in research have ranged from 1-140 t/ha.

Plate 10.1 Proliferation of roots in a rip line on a compacted sand in Western Australia.
Source: Stephen Davies, DAFWA

Plate 10.2 Loss of organic matter and soil condition associated with grazing damage (right) compared to un-grazed pastures (left).
Source: Tanya Robinson

Plate 10.3 Green manuring by discing increases organic matter in soils.
Source: Kondinin Group

Plate 10.4 Bare fallow risks losing soil and associated organic matter from wind or water erosion.
Source: Stephen Davies, DAFWA

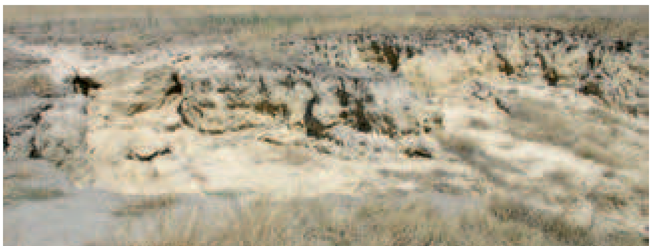


Plate 10.5 Soil collapse and erosion resulting from dispersion on a sodic soil.
Source: Tim Overheu, DAFWA

HOW FUTURE VARIABILITY IN CLIMATE MIGHT INFLUENCE SOIL ORGANIC MATTER IN AUSTRALIA

AT A GLANCE

- Significant or catastrophic weather events are likely to have a large influence on soil organic matter losses.
- The rate of soil organic matter decomposition will increase in regions, which experience warming conditions, where adequate soil moisture is available for biological activity.
- Elevated atmospheric carbon dioxide levels could increase plant biomass (organic inputs). However, the complexity of soil and plant responses to elevated carbon dioxide makes it difficult to determine long-term changes in soil organic matter.

The amount of organic matter a soil contains is a result of the interaction between several ecosystem processes – primarily photosynthesis, decomposition and respiration, which in turn are influenced by temperature and rainfall.

Soil organic matter is an indicator of a soil's potential resilience against climatic and management stressors. Such resilience will become increasingly important with the predicted increase in the frequency and intensity of extreme weather events such as droughts and heatwaves.

Interest in the impact of rising temperatures is high because of the critical role soil carbon plays in the global carbon cycle (Davidson and Janssens 2006). The potential impact of elevated atmospheric carbon dioxide levels (global warming) and increased air temperatures on soil organisms and soil carbon stores is as yet unknown. However, there are concerns that global warming could accelerate soil carbon decomposition and contribute further to greenhouse gas emissions.

ELEVATED ATMOSPHERIC CARBON DIOXIDE AND TEMPERATURE INFLUENCES

Significant changes in global climate and in particular temperature have been linked to an increased concentration of carbon dioxide in the atmosphere brought about by human-generated greenhouse gas emissions.

Experimentally, elevated carbon dioxide concentrations have been shown to increase the photosynthetic capacity of plants and thus plant shoot and root biomass (Drake et al. 1997; Luo et al. 2006). While higher organic inputs can potentially increase soil organic carbon, the enhanced respiration brought about by increased root biomass (Hungate et al. 1997) and accelerated microbial decomposition of organic matter (Zak et al. 2000) could cause carbon to be lost from farming systems. This could potentially offset any carbon gains brought about by enhanced photosynthesis under global warming.

In environments not limited by water, increased temperatures resulting from elevated atmospheric carbon dioxide could also result in increased plant productivity (Maracchi et al. 2005), higher rates of organic matter decomposition (Hoyle et al. 2006) and increased carbon dioxide emissions from soil (Pataki et al. 2003). In contrast, higher temperatures in drier environments are likely to result in decreased photosynthetic capacity and therefore fewer organic inputs.

The extent to which temperature can influence organic matter decomposition is not clear. In theory, decomposition of easily degraded soil organic compounds such as carbohydrates in leaf litter would be expected to increase with rising temperatures. In contrast, more biochemically resistant carbon structures such as lignin in woody tissues and lipids in leaf cuticles would be expected to remain stable over decades, possibly even centuries, despite a temperature increase. However, Fang et al. (2005) showed the degradation rate of resistant organic matter such as lignin and lipids also increased in response to rising temperatures and they concluded that both labile and resistant organic matter pools would respond similarly to global warming.

Soil carbon stocks will only increase when the amount of carbon entering the soil exceeds the rate at which soil organic matter is decomposed. Given the complexity of interacting factors that influence organic matter turnover, it is likely that any impact of carbon dioxide levels on soil carbon stocks will be site-specific and dependent on limitations to primary productivity, and controls on decomposition including soil temperature, nutrient, and moisture levels.

THE GLOBAL SITUATION

In the cold, wet climate of the northern hemisphere soil organic matter tends to increase due to the region's high photosynthetic potential and slow decomposition rate of organic matter (Ontl and Schulte 2012). In the warm, moist conditions of the tropics increased primary production is offset by rapid decomposition of organic matter, which results in moderate soil organic matter levels (Ontl and Schulte 2012). In temperate systems where high primary productivity during the moist, warm spring and summer months is balanced by slow decomposition rates in the cooler winter and autumn months, incremental gains in soil organic matter are possible (Ontl and Schulte 2012). Mediterranean climates are characterised by mild, wet winters during which soil organic matter builds up and warm dry summers, with summer rainfall events during which much of this organic matter is mineralised. Finally, dry environments generate low levels of soil organic matter predominantly because of the low capacity for primary production in these areas.

THE AUSTRALIAN SITUATION

Mirroring global changes, average annual temperatures in Australia have increased since 1910 by about 0.8ºC (0.1ºC each decade, see Figure 11.1a). Over the same period, changes in annual rainfall have varied depending on location, with a pronounced drying trend experienced in the south-west of Western Australia, south-east Queensland and the southern regions of Victoria and South Australia (see Figure 11.1b), and an increase in rainfall recorded across northern Australia. In Western Australia the 5-30 mm decline in rainfall has been most apparent in late autumn and early winter.

The magnitude and direction of future changes in Australia's soil organic carbon stocks will depend on the temperature sensitivity of resistant soil carbon pools and changes in soil moisture. Across southern Australia a warmer, drier climate in winter could cause a decline in primary, particularly on clay soils in low rainfall areas. In areas with adequate soil moisture the rate of soil organic carbon decomposition could also increase because of warmer temperatures.

SIMULATING FUTURE CLIMATE CHANGE SCENARIOS FOR AUSTRALIA AND THE LINK TO SOIL ORGANIC MATTER

Grace et al. (2006) used the simulation model SOCRATES to assess the impact of predicted climate change on the cycling of soil organic carbon within terrestrial ecosystems across Australia. They found that the impact of future global climate change on soil organic carbon dynamics would depend primarily on the magnitude of the predicted temperature and regional rainfall changes.

Under a 'low' carbon dioxide emissions scenario (with a one degree increase in temperature and no change in the amount of average annual rainfall), Grace et al (2006) predict an increase in topsoil organic carbon (2.0–2.9 per cent) over the next century for northern parts of tropical Australia (i.e. Kimberley, Arnhem districts of Western Australia and Northern Territory and Cape York Peninsula). Over the same period, a small loss in soil organic carbon in south-eastern Australia was predicted due to increasing temperatures and a reduction in net primary production associated with changes in rainfall distribution.

Under a 'high' emissions scenario, Australia's average annual temperature is predicted to increase by 5.3°C along with changes in regional distribution of rainfall. According to the SOCRATES model this scenario will decrease topsoil organic carbon stocks by an average of 6.4 per cent across Australia. Under the same high emissions scenario areas of the tropics are expected to experience a decline in soil organic carbon of up to 10 per cent in response to a decline in primary productivity associated with lower average annual rainfall. By comparison, increases in net primary production in excess of 40 per cent were predicted for several regions of Australia, including Carnarvon, Western Australia, and the Riverina, NSW (Grace et al. 2006).

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Climate change projections made relative to the period 1980 to 1999 provide an estimate of the predicted climatic changes expected for 2050 under a moderate emissions scenario (IPCC Special Report on Emission Scenarios 2000, Scenario A1B).

Under this moderate emissions scenario a warmer, drier future is projected for the majority of Australia, with regional variations in seasonal responses (see Figure 11.2). Future temperature changes of between 1.5-2°C are predicted for the majority of Australian agricultural areas with mitigating coastal influences evident in the south and east.

The predicted change in rainfall will vary regionally and seasonally. The 5-20 per cent decline in winter and spring rainfall by 2050 projected for grain production areas under the moderate scenario (http://climatechangeinaustralia.com.au) has significant implications for primary production and associated organic matter inputs in many regions of Australia. A drying trend for autumn rainfall could potentially magnify these production losses through a decrease in stored soil moisture before sowing.

On a more positive note, in some areas where high rainfall has constrained crop production due to water-logging, a drying climate could in fact increase yield potential or stimulate land use change.

The possibility of increasing summer rainfall is predicted for New South Wales and north-eastern Australia. In northern Australia higher annual rainfall is predicted under climate change, but losses of soil water via increased transpiration are likely to counteract any potential yield increases.

The impact of a changing climate on soil organic matter is likely to be regionally variable and determined by its influence on the annual production of plant biomass and decomposition rates of soil organic matter. For example, declining winter rainfall

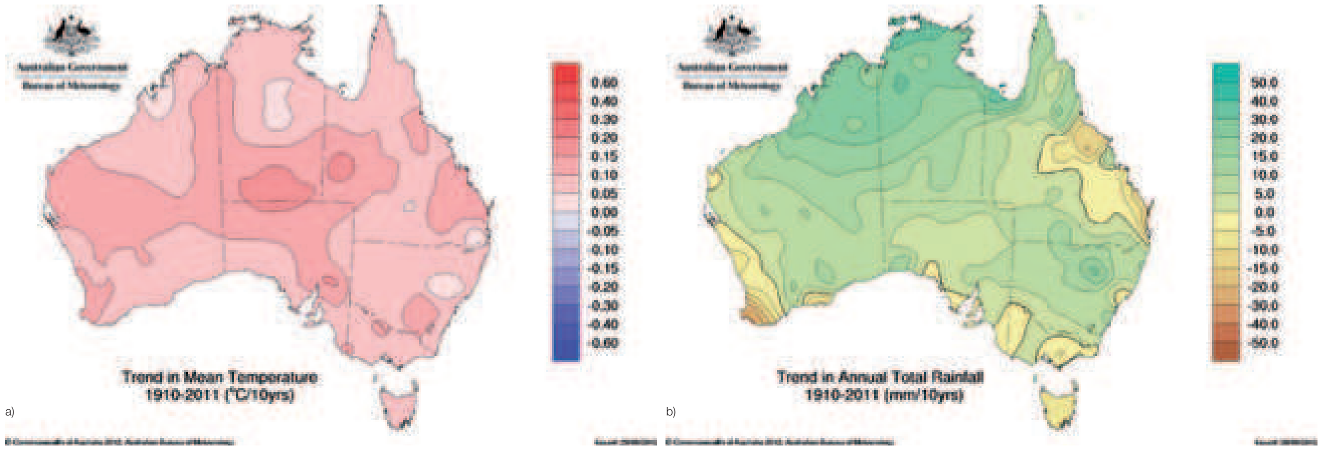
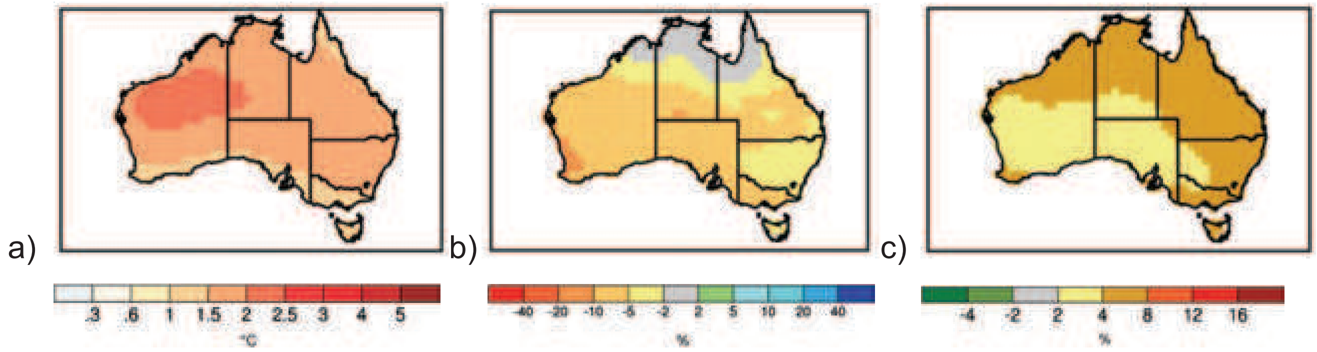


Figure 11.1 The trend in **a)** average temperature (°C) and **b)** annual total rainfall (mm) across Australia from 1910 to 2011 (Australian Bureau of Meteorology 2012).



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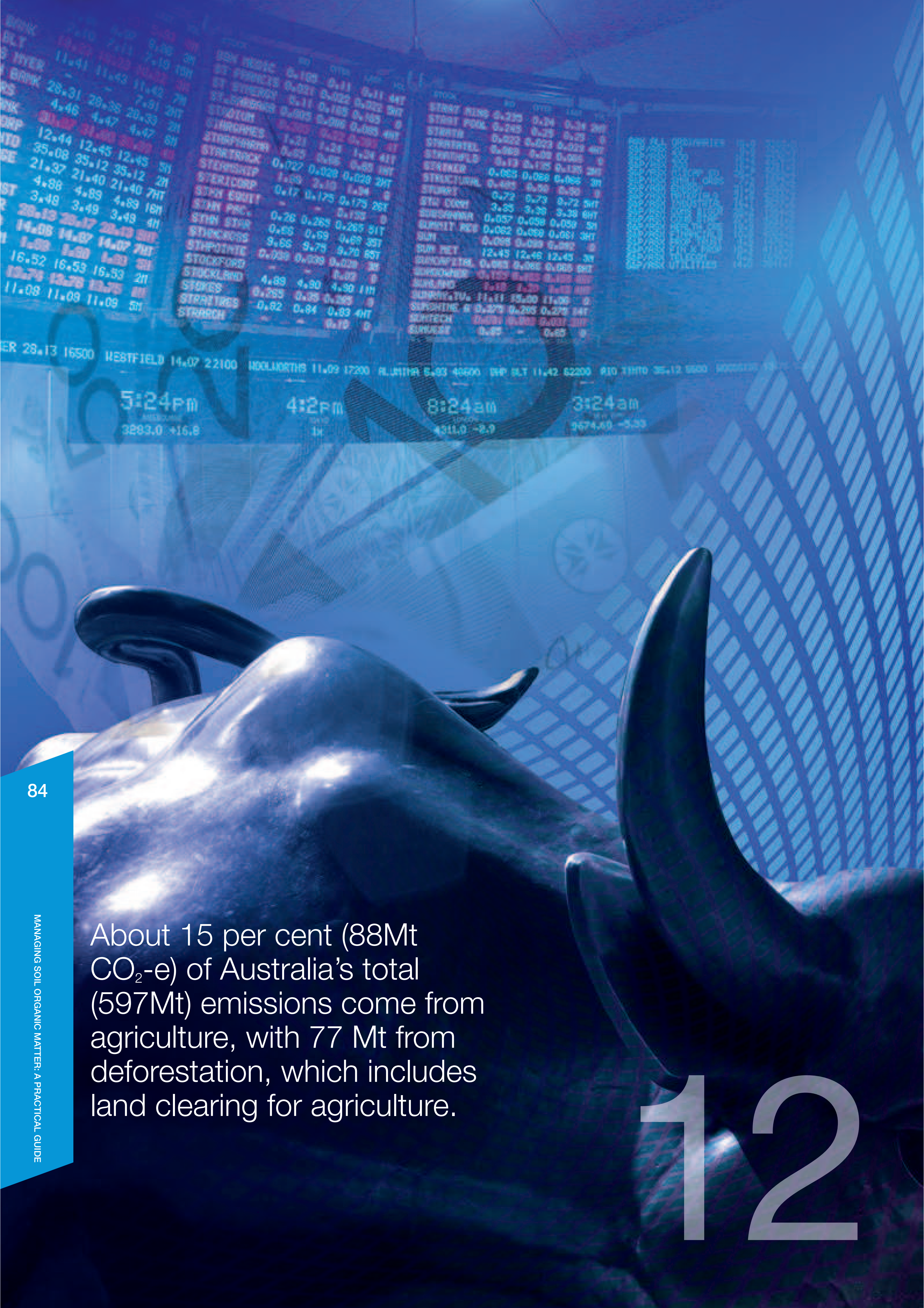

About 15 per cent (88Mt CO_2-e) of Australia's total (597Mt) emissions come from agriculture, with 77 Mt from deforestation, which includes land clearing for agriculture.

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ECONOMIC CONSIDERATIONS AND IMPLICATIONS IN A CARBON TRADING ENVIRONMENT

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Including agriculture in an emissions trading scheme presents some challenges due to:

i) The diffuse nature of emissions and sinks associated with farming system.
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In north-eastern Australia, the largest potential for greenhouse gas abatement is associated with carbon forestry, biodiversity plantings, commercial forest plantations and reduced clearing as well as managed regeneration of agricultural land in

Table 12.1 Change in the economic value of farm production in 2014-15; average per farm (from Whittle et al. 2011).

	Average economic value[1] of farm production (2005/06 to 2009/10)	Percentage decrease in economic value of farm production resulting from a carbon price[2]			
Cost-price pass-through rate		**0%**	**20%**	**60%**	**100%**
Industry	$	%	%	%	%
All broadacre industries (except dairy)	64 322	-0.5	-0.9	-1.6	-2.3
Wheat and other crops	115 961	-0.4	-0.7	-1.2	-1.8
Mixed farming	56 266	-0.6	-0.9	-1.6	-2.4
Sheep	41 453	-0.6	-1.0	-1.7	-2.4
Beef	60 335	-0.5	-0.9	-1.7	-2.5
Sheep/beef	48 317	-0.7	-1.1	-2.0	-2.8
Dairy	97 292	-1.1	-1.8	-3.3	-4.7

1 The economic value of farm production is equal to net farm cash income (defined as total receipts minus total cash costs) plus the value of changes in stocks.
2 The net effects of a carbon price on the economic value of farm production are a combination of the projected change in input costs and receipts.

Queensland. These options have been relatively easy to implement and are estimated to mitigate about 105Mt CO_2-e per year (CSIRO 2009).

IMPACT OF A CARBON PRICE ON AGRICULTURE

Whittle et al. (2011) compared the estimated economic value of farm production in 2014/15 (under a carbon price), with historical averages, using a carbon price of $23 a tonne carbon dioxide equivalents (see Table 12.1). The impact of the carbon price varied considerably across farm types and the assumed rate at which the carbon price would flow through the agricultural value chain. The analysis found that dairy farms, which require a more intensive use of electricity than other farming systems, would be more affected by the carbon price than any other agricultural industry. By 2014/15 the economic value of dairy farm production was estimated to decrease by 4.7 per cent ($4580) and 1.1 per cent ($1090) under the 100 per cent and zero cost-price pass-through scenarios.

Secondary (indirect effects) reported in Australian government modelling show the agricultural sector will continue to grow under a carbon pricing scheme reflecting the ongoing productivity improvements and strong world demand for Australian agricultural goods. By 2019/20 agricultural growth is expected to increase by about 12 per cent of 2009/10 levels, based on a 2012/13 carbon price of $23 a tonne carbon dioxide equivalents and a 2.5 per cent annual growth in real terms (Whittle et al 2011). The modelling estimated that all agricultural industries were expected to grow, with growth rates ranging from one per cent in dairy to 10 per cent for sheep and cattle and 15 per cent for grain.

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CURRENT MARKET CONDITIONS

Despite initially high prices on carbon markets, in May 2013 international carbon credits were trading at just 3.5 Euros (AU$4.67 based on an exchange rate of 0.75 Euros per Australian dollar) per metric ton of carbon dioxide equivalents (CO_2-e) on London's ICE Futures Europe exchange. In 2013, Australia's carbon price was fixed at AU$23 and was expected to increase at five per cent per year until 2015 before shifting to a cap and trade scheme linked to the EU market. Future volatility in the carbon price generates some level of uncertainty for landholders in weighing up the economic benefits of engaging in a carbon market and could potentially limit the viability of future abatement schemes.

SOIL ORGANIC MATTER IN AUSTRALIAN FARMING SYSTEMS

Crop production has generally resulted in a worldwide decline in soil organic matter and soil fertility. Conversion of grasslands and forestlands to arable agriculture has resulted in the loss of 30-70 per cent of the organic matter originally present in these soils. In low input agricultural systems, yields have generally dropped rapidly as the nutrient and organic matter content of cropping soils has declined. However, restoration of soil fertility and organic matter is possible. Production systems that support revegetation and destocking of land, increasing frequency and diversity of crops and pastures, amelioration of soil constraints and soil conservation methods can be adapted regionally and will contribute to preserving soil organic matter levels.

Despite measured improvements in the organic matter content of some Australian agricultural soils, many continue to lose soil organic carbon as a result of initial land clearing. Sanderman et al. (2010) suggest that many management practices implemented to increase soil organic matter may in fact be primarily operating to mitigate these continued land clearing losses instead of sequestering new carbon into farming systems. Only management practices that increase the proportion of stable carbon entering the soil organic matter pool will lead to long-term 'permanent' changes in soil organic matter that are critical to participating in carbon trading schemes. Quantifying these changes through time is critical in developing our knowledge of the future impact of climate and developing strategies for improvement.

Emerging markets and opportunities that are readily accessible and promote the maintenance and build-up of stable soil organic carbon pools have to be viewed positively, as increasing awareness highlights the importance of soils and agriculture in a global context outside of the farming community. While global warming has raised awareness of the role for soil in mitigating climate change, realising these opportunities remains a challenge. Regardless, the maintenance of soil organic matter levels underpins sustainable agricultural production. Its location, quantity and quality is intimately linked to soil biological processes that support critical soil functions and build the resilience of soil to environmental stressors.

Improving or even maintaining organic matter requires that additions of soil organic matter exceed losses to decomposition, leaching and erosion. Understanding how organic matter cycles through the soil and what drives its accumulation and loss is therefore critical to maintaining it at optimal levels within agricultural systems.

GLOSSARY

Arbuscular mycorrhizal fungi (AMF)	Fungi that have a symbiotic association with the root of a living plant.
Biopores	Channels or pores formed by living organisms that improve the exchange of water and oxygen.
Bulk density	A measure of the mass of soil per unit volume (e.g. g/cm^3)
Carbon to nitrogen (C:N) ratio	The proportion of nitrogen (or other nutrients) relative to carbon in that material.
Cation	Positively charged ions, which can be exchanged, include calcium, magnesium, potassium, sodium, aluminium, manganese, iron, copper and zinc.
Cation exchange capacity	Capacity of a soil to hold and retain cations. Calcium, magnesium, potassium and sodium are generally the most dominant cations, although aluminium may also contribute.
Decomposition	Abiotic or biological process by which organic substances are broken down into simpler forms.
Greenhouse gas	A greenhouse gas (GHG) is an atmospheric gas that absorbs and emits radiation contributing to global warming. In agriculture the primary greenhouse gases are methane, nitrous oxide and carbon dioxide.
Hydrophobic	Water repellent.
Hyphae	Long, branching filamentous structure of a fungus (collectively known as mycelium).
Immobilisation	Uptake of plant available forms by microorganisms.
Inorganic carbon	Inorganic carbon is mineral based and is relatively stable.
Massive soil	Entire soil horizon appears cemented in one great mass.
Macro-organisms	Soil fauna larger than 2 mm in size.
Microbial biomass	Mass of microorganisms (fungi and bacteria).
Meso-organisms	Soil fauna between 0.2-2 mm in size.
Micro-organisms	Microbes less than 0.2 mm in size.
Mineralisation	Decomposition or oxidisation of the chemical compounds in organic matter into plant available forms.
Mobilisation	Move, make movable.
Nitrification	The biological conversion of ammonium to nitrite and then into nitrate.
Non-wetting	Water repellent.

Organic carbon	Organic carbon is the carbon component of decaying plant matter, soil organisms and microbes. Soil organic carbon is the fractions of soil that passes through a 2 mm sieve.
Organic matter	Organic matter includes all elements such as hydrogen, oxygen, phosphorous, sulphur and nitrogen that are associated with carbon in organic molecules.
Oxidation	Oxidation is the loss of electrons or an increase in an oxidation state by a molecule, atom, or ion.
Pathogen	Organisms that attack living plant tissue and cause plant disease.
Pore space	Space between soil aggregates or particles.
Resilience	The ability of a soil to recover after environmental stress.
Rhizosphere	Region of soil surrounding a plant root that is directly influenced by root secretions and associated soil microorganisms. Soil which is not part of the rhizosphere is known as bulk soil.
Saprophytic organisms	Any organism that lives on dead organic matter.
Sink (for carbon)	A soil reservoir able to store carbon within the global carbon cycle.
Sodic soil	A sodic soil has an exchangeable sodium percentage greater than 15 per cent. Present as sodium chloride (NaCl) in sodic saline soils and as excess sodium carbonate (Na_2CO_3) in sodic alkaline soil (pH_{Ca} above 9).
Soil organic matter	Non-living and living organisms (and by-products) derived from plants and animals, which is less than 2mm in size and no longer recognisable (exclusive of any matter that has not decayed). The total soil organic matter pool is made up of a number of different fractions: – Dissolved organic matter (soluble) – Particulate organic matter (fresh and decomposing residues 52 to 2000 µm in size) – Humus organic matter (older, decayed compounds less than 52 µm in size) – Resistant organic matter (inert char or chemically resistant organic matter)
Source (of carbon)	A soil reservoir able to release (emit) carbon within the global carbon cycle.
Symbiotic	Defined in the broadest terms as two or more organisms living together.
Transformation	A process that results in a change in form as a result of a chemical, physical or biological transition.
Turnover	Decomposition rate of organic matter.
Water repellent	Hydrophobic (repels water).

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The amount of organic matter a soil contains is a result of the interaction between several ecosystem processes – primarily photosynthesis, decomposition and respiration, which in turn are influenced by temperature and rainfall.

Soil organic matter is an indicator of a soil's potential resilience against climatic and management stressors. Such resilience will become increasingly important with the predicted increase in the frequency and intensity of extreme weather events such as droughts and heatwaves.

Interest in the impact of rising temperatures is high because of the critical role soil carbon plays in the global carbon cycle (Davidson and Janssens 2006). The potential impact of elevated atmospheric carbon dioxide levels (global warming) and increased air temperatures on soil organisms and soil carbon stores is as yet unknown. However, there are concerns that global warming could accelerate soil carbon decomposition and contribute further to greenhouse gas emissions.

ELEVATED ATMOSPHERIC CARBON DIOXIDE AND TEMPERATURE INFLUENCES

Significant changes in global climate and in particular temperature have been linked to an increased concentration of carbon dioxide in the atmosphere brought about by human-generated greenhouse gas emissions.

Experimentally, elevated carbon dioxide concentrations have been shown to increase the photosynthetic capacity of plants and thus plant shoot and root biomass (Drake et al. 1997; Luo et al. 2006). While higher organic inputs can potentially increase soil organic carbon, the enhanced respiration brought about by increased root biomass (Hungate et al. 1997) and accelerated microbial decomposition of organic matter (Zak et al. 2000) could cause carbon to be lost from farming systems. This could potentially offset any carbon gains brought about by enhanced photosynthesis under global warming.

In environments not limited by water, increased temperatures resulting from elevated atmospheric carbon dioxide could also result in increased plant productivity (Maracchi et al. 2005), higher rates of organic matter decomposition (Hoyle et al. 2006) and increased carbon dioxide emissions from soil (Pataki et al. 2003). In contrast, higher temperatures in drier environments are likely to result in decreased photosynthetic capacity and therefore fewer organic inputs.

The extent to which temperature can influence organic matter decomposition is not clear. In theory, decomposition of easily degraded soil organic compounds such as carbohydrates in leaf litter would be expected to increase with rising temperatures. In contrast, more biochemically resistant carbon structures such as lignin in woody tissues and lipids in leaf cuticles would be expected to remain stable over decades, possibly even centuries, despite a temperature increase. However, Fang et al. (2005) showed the degradation rate of resistant organic matter such as lignin and lipids also increased in response to rising temperatures and they concluded that both labile and resistant organic matter pools would respond similarly to global warming.

Soil carbon stocks will only increase when the amount of carbon entering the soil exceeds the rate at which soil organic matter is decomposed. Given the complexity of interacting factors that influence organic matter turnover, it is likely that any impact of carbon dioxide levels on soil carbon stocks will be site-specific and dependent on limitations to primary productivity, and controls on decomposition including soil temperature, nutrient, and moisture levels.

THE GLOBAL SITUATION

In the cold, wet climate of the northern hemisphere soil organic matter tends to increase due to the region's high photosynthetic potential and slow decomposition rate of organic matter (Ontl and Schulte 2012). In the warm, moist conditions of the tropics increased primary production is offset by rapid decomposition of organic matter, which results in moderate soil organic matter levels (Ontl and Schulte 2012). In temperate systems where high primary productivity during the moist, warm spring and summer months is balanced by slow decomposition rates in the cooler winter and autumn months, incremental gains in soil organic matter are possible (Ontl and Schulte 2012). Mediterranean climates are characterised by mild, wet winters during which soil organic matter builds up and warm dry summers, with summer rainfall events during which much of this organic matter is mineralised. Finally, dry environments generate low levels of soil organic matter predominantly because of the low capacity for primary production in these areas.

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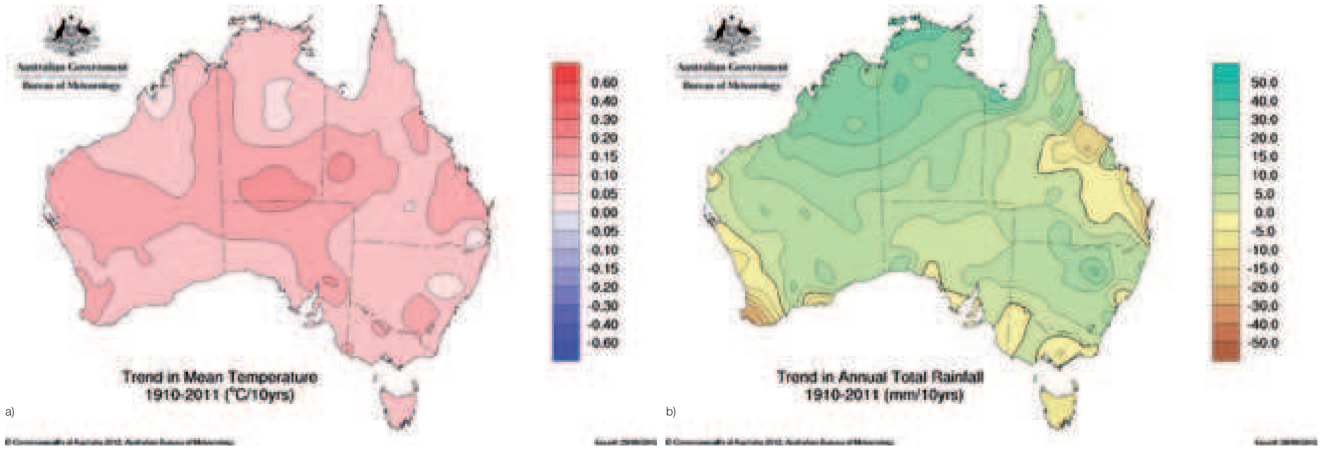

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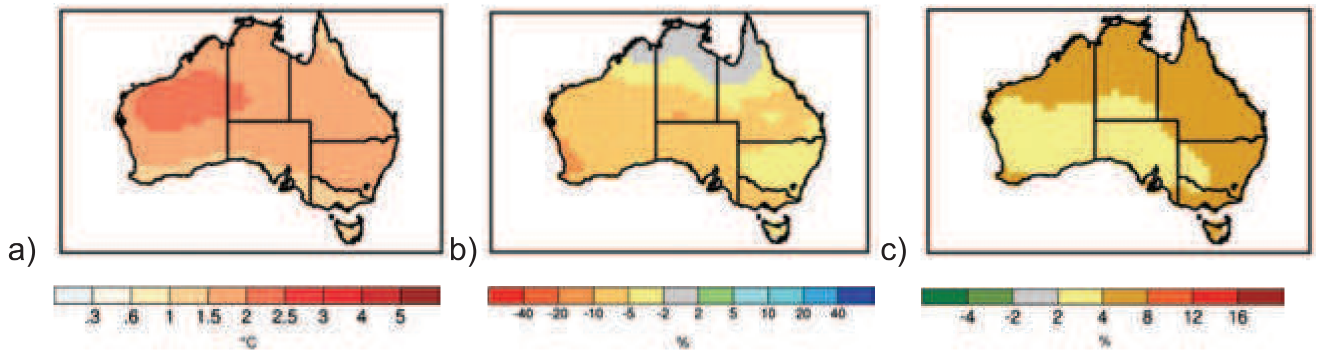

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In north-eastern Australia, the largest potential for greenhouse gas abatement is associated with carbon forestry, biodiversity plantings, commercial forest plantations and reduced clearing as well as managed regeneration of agricultural land in

Table 12.1 Change in the economic value of farm production in 2014-15; average per farm (from Whittle et al. 2011).

	Average economic value[1] of farm production (2005/06 to 2009/10)	Percentage decrease in economic value of farm production resulting from a carbon price[2]			
Cost-price pass-through rate		**0%**	**20%**	**60%**	**100%**
Industry	$	%	%	%	%
All broadacre industries (except dairy)	64 322	-0.5	-0.9	-1.6	-2.3
Wheat and other crops	115 961	-0.4	-0.7	-1.2	-1.8
Mixed farming	56 266	-0.6	-0.9	-1.6	-2.4
Sheep	41 453	-0.6	-1.0	-1.7	-2.4
Beef	60 335	-0.5	-0.9	-1.7	-2.5
Sheep/beef	48 317	-0.7	-1.1	-2.0	-2.8
Dairy	97 292	-1.1	-1.8	-3.3	-4.7

1 The economic value of farm production is equal to net farm cash income (defined as total receipts minus total cash costs) plus the value of changes in stocks.

2 The net effects of a carbon price on the economic value of farm production are a combination of the projected change in input costs and receipts.

Queensland. These options have been relatively easy to implement and are estimated to mitigate about 105Mt CO_2-e per year (CSIRO 2009).

IMPACT OF A CARBON PRICE ON AGRICULTURE

Whittle et al. (2011) compared the estimated economic value of farm production in 2014/15 (under a carbon price), with historical averages, using a carbon price of $23 a tonne carbon dioxide equivalents (see Table 12.1). The impact of the carbon price varied considerably across farm types and the assumed rate at which the carbon price would flow through the agricultural value chain. The analysis found that dairy farms, which require a more intensive use of electricity than other farming systems, would be more affected by the carbon price than any other agricultural industry. By 2014/15 the economic value of dairy farm production was estimated to decrease by 4.7 per cent ($4580) and 1.1 per cent ($1090) under the 100 per cent and zero cost-price pass-through scenarios.

Secondary (indirect effects) reported in Australian government modelling show the agricultural sector will continue to grow under a carbon pricing scheme reflecting the ongoing productivity improvements and strong world demand for Australian agricultural goods. By 2019/20 agricultural growth is expected to increase by about 12 per cent of 2009/10 levels, based on a 2012/13 carbon price of $23 a tonne carbon dioxide equivalents and a 2.5 per cent annual growth in real terms (Whittle et al 2011). The modelling estimated that all agricultural industries were expected to grow, with growth rates ranging from one per cent in dairy to 10 per cent for sheep and cattle and 15 per cent for grain.

Secondary (indirect effects) reported in Australian government modelling show the agricultural sector will continue to grow under a carbon pricing scheme reflecting the ongoing productivity improvements and strong world demand for Australian agricultural goods.

CURRENT MARKET CONDITIONS

Despite initially high prices on carbon markets, in May 2013 international carbon credits were trading at just 3.5 Euros (AU$4.67 based on an exchange rate of 0.75 Euros per Australian dollar) per metric ton of carbon dioxide equivalents (CO_2-e) on London's ICE Futures Europe exchange. In 2013, Australia's carbon price was fixed at AU$23 and was expected to increase at five per cent per year until 2015 before shifting to a cap and trade scheme linked to the EU market. Future volatility in the carbon price generates some level of uncertainty for landholders in weighing up the economic benefits of engaging in a carbon market and could potentially limit the viability of future abatement schemes.

SOIL ORGANIC MATTER IN AUSTRALIAN FARMING SYSTEMS

Crop production has generally resulted in a worldwide decline in soil organic matter and soil fertility. Conversion of grasslands and forestlands to arable agriculture has resulted in the loss of 30-70 per cent of the organic matter originally present in these soils. In low input agricultural systems, yields have generally dropped rapidly as the nutrient and organic matter content of cropping soils has declined. However, restoration of soil fertility and organic matter is possible. Production systems that support revegetation and destocking of land, increasing frequency and diversity of crops and pastures, amelioration of soil constraints and soil conservation methods can be adapted regionally and will contribute to preserving soil organic matter levels.

Despite measured improvements in the organic matter content of some Australian agricultural soils, many continue to lose soil organic carbon as a result of initial land clearing. Sanderman et al. (2010) suggest that many management practices implemented to increase soil organic matter may in fact be primarily operating to mitigate these continued land clearing losses instead of sequestering new carbon into farming systems. Only management practices that increase the proportion of stable carbon entering the soil organic matter pool will lead to long-term 'permanent' changes in soil organic matter that are critical to participating in carbon trading schemes. Quantifying these changes through time is critical in developing our knowledge of the future impact of climate and developing strategies for improvement.

Emerging markets and opportunities that are readily accessible and promote the maintenance and build-up of stable soil organic carbon pools have to be viewed positively, as increasing awareness highlights the importance of soils and agriculture in a global context outside of the farming community. While global warming has raised awareness of the role for soil in mitigating climate change, realising these opportunities remains a challenge. Regardless, the maintenance of soil organic matter levels underpins sustainable agricultural production. Its location, quantity and quality is intimately linked to soil biological processes that support critical soil functions and build the resilience of soil to environmental stressors.

Improving or even maintaining organic matter requires that additions of soil organic matter exceed losses to decomposition, leaching and erosion. Understanding how organic matter cycles through the soil and what drives its accumulation and loss is therefore critical to maintaining it at optimal levels within agricultural systems.

GLOSSARY

Arbuscular mycorrhizal fungi (AMF)	Fungi that have a symbiotic association with the root of a living plant.
Biopores	Channels or pores formed by living organisms that improve the exchange of water and oxygen.
Bulk density	A measure of the mass of soil per unit volume (e.g. g/cm^3)
Carbon to nitrogen (C:N) ratio	The proportion of nitrogen (or other nutrients) relative to carbon in that material.
Cation	Positively charged ions, which can be exchanged, include calcium, magnesium, potassium, sodium, aluminium, manganese, iron, copper and zinc.
Cation exchange capacity	Capacity of a soil to hold and retain cations. Calcium, magnesium, potassium and sodium are generally the most dominant cations, although aluminium may also contribute.
Decomposition	Abiotic or biological process by which organic substances are broken down into simpler forms.
Greenhouse gas	A greenhouse gas (GHG) is an atmospheric gas that absorbs and emits radiation contributing to global warming. In agriculture the primary greenhouse gases are methane, nitrous oxide and carbon dioxide.
Hydrophobic	Water repellent.
Hyphae	Long, branching filamentous structure of a fungus (collectively known as mycelium).
Immobilisation	Uptake of plant available forms by microorganisms.
Inorganic carbon	Inorganic carbon is mineral based and is relatively stable.
Massive soil	Entire soil horizon appears cemented in one great mass.
Macro-organisms	Soil fauna larger than 2 mm in size.
Microbial biomass	Mass of microorganisms (fungi and bacteria).
Meso-organisms	Soil fauna between 0.2-2 mm in size.
Micro-organisms	Microbes less than 0.2 mm in size.
Mineralisation	Decomposition or oxidisation of the chemical compounds in organic matter into plant available forms.
Mobilisation	Move, make movable.
Nitrification	The biological conversion of ammonium to nitrite and then into nitrate.
Non-wetting	Water repellent.

Organic carbon	Organic carbon is the carbon component of decaying plant matter, soil organisms and microbes. Soil organic carbon is the fractions of soil that passes through a 2 mm sieve.
Organic matter	Organic matter includes all elements such as hydrogen, oxygen, phosphorous, sulphur and nitrogen that are associated with carbon in organic molecules.
Oxidation	Oxidation is the loss of electrons or an increase in an oxidation state by a molecule, atom, or ion.
Pathogen	Organisms that attack living plant tissue and cause plant disease.
Pore space	Space between soil aggregates or particles.
Resilience	The ability of a soil to recover after environmental stress.
Rhizosphere	Region of soil surrounding a plant root that is directly influenced by root secretions and associated soil microorganisms. Soil which is not part of the rhizosphere is known as bulk soil.
Saprophytic organisms	Any organism that lives on dead organic matter.
Sink (for carbon)	A soil reservoir able to store carbon within the global carbon cycle.
Sodic soil	A sodic soil has an exchangeable sodium percentage greater than 15 per cent. Present as sodium chloride (NaCl) in sodic saline soils and as excess sodium carbonate (Na_2CO_3) in sodic alkaline soil (pH_{Ca} above 9).
Soil organic matter	Non-living and living organisms (and by-products) derived from plants and animals, which is less than 2mm in size and no longer recognisable (exclusive of any matter that has not decayed). The total soil organic matter pool is made up of a number of different fractions: – Dissolved organic matter (soluble) – Particulate organic matter (fresh and decomposing residues 52 to 2000 µm in size) – Humus organic matter (older, decayed compounds less than 52 µm in size) – Resistant organic matter (inert char or chemically resistant organic matter)
Source (of carbon)	A soil reservoir able to release (emit) carbon within the global carbon cycle.
Symbiotic	Defined in the broadest terms as two or more organisms living together.
Transformation	A process that results in a change in form as a result of a chemical, physical or biological transition.
Turnover	Decomposition rate of organic matter.
Water repellent	Hydrophobic (repels water).

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