MANAGING SOIL ORGANIC MATTER

A PRACTICAL GUIDE

GRDC Grains Research & Development Corporation
Your GRDC working with you

Title: Managing Soil Organic Matter: A Practical Guide

GRDC Project Code: KDI00023

In submitting this report, the researchers have agreed to the GRDC publishing this material in its edited form.

Report author: Dr Frances Hoyle, Department of Agriculture and Food Western Australia
Content editor: Janet Paterson, Sci-Scribe
Compilation and report contributions: Dr Meredith Fairbanks
Thanks also to Professor Daniel Murphy and Dr Ram Dalal for their valuable feedback.

Department of Agriculture and Food
GOVERNMENT OF WESTERN AUSTRALIA

ISBN 978-1-921779-56-5
Published July 2013

GRDC Grains Research & Development Corporation
Your GRDC working with you

For free copies please contact: Ground Cover Direct
Free phone: 1800 11 00 44
Email: ground-cover-direct@canprint.com.au
OR
Ms Maureen Cribb
Publishing Manager
GRDC
PO Box 5367
KINGSTON ACT 2604
Phone: (02) 6166 4500
Email: maureen.cribb@grdc.com.au
Web: http://www.grdc.com.au
Note: A postage and handling charge applies

FOREWORD

The one constant in agriculture is uncertainty and Australian grain growers are known globally for being ahead of the curve when it comes to adopting new farming practices to meet every challenge.

Climate change is already having a significant effect on how we farm today and how we adapt to future challenges will define what it means to farm sustainably this century. One of the biggest influences on farm productivity and its resilience to climate variations is soil health.

Soil organic matter contributes to a range of biological, chemical and physical properties of soil and is essential for soil health. This publication is a practical guide to understanding what soil organic matter is, why it's important as well as how you can manage it on-farm to increase soil functionality and enhance production benefits.

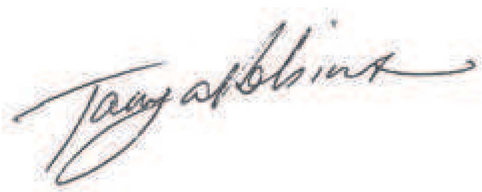
When selecting farming practices to maximise the benefits of soil organic matter it is important to consider the most important functions that soil organic matter provides to your crop and how that will bring benefits to your soil health and future crops.

Under the federal government's commitment to the Kyoto protocol, farmers can potentially earn credits by storing carbon in their soil, or in trees by reducing greenhouse gas emissions on-farm. This allows the grains industry to play a vital role in contributing to positive change in Australia's environmental performance.

I would like to make special mention and thank Dr Frances Hoyle, senior research scientist with the Department of Agriculture and Food Western Australia, for authorship of the content for this publication.

The Grains Research and Development Corporation promotes high quality science and research that raises awareness of current industry priorities and emerging issues.

Access to this information will allow growers to adapt to a changing agricultural economy and adopt new farming practices to improve on-farm efficiencies, profitability and sustainability. I hope you find this guide practical and informative.



Tanya Robinson
Project Manager Natural Resources
Grains Research and Development Corporation

CONTENTS

TABLES, FIGURES AND PLATES

INTRODUCTION

Increasing soil organic matter is widely regarded as beneficial to soil function and fertility and in agricultural production systems is integral to sustainable farming. Storing the carbon component of organic matter in agricultural, rangeland and forest soils is also seen as one way to decrease atmospheric carbon dioxide levels and mitigate the impact of climate change. Consequently, there is great interest in quantifying the capacity of various soil types and land management practices to support increases in soil organic matter and understanding how these changes impact soil health, ecosystem services and carbon sequestration in the medium and long-term.

ORGANIC MATTER STATUS OF AUSTRALIAN SOILS

Australian soils are ancient. They have inherently poor structure, fertility and low levels of organic matter in their surface layers – a condition made worse by historical land clearing and subsequent land management practices. Physical and chemical soil constraints such as salinity, acidity, disease, compaction and sodicity impact large areas of Australian soils. These factors limit their productivity and act as major constraints to increasing soil organic matter.

Australian soils are low in soil organic matter content by global standards, with the exception of soils that support high net primary productivity such as well-managed pastures and irrigated systems unconstrained by water availability. Recent estimates from the 2011 State of the Environment report suggest climate variability and the historic clearing of native vegetation for agriculture has resulted in a 30-70 per cent decline in soil organic matter content. However, while soil organic matter has declined in many systems over the past 100-

200 years, recent assessments suggest there is a high to moderate potential to increase the carbon content of soils across extensive areas of Australia (see Figure 1.1).

Recent measures of soil organic matter (0-30 cm) in Australian soils suggest they can contain between three tonnes of carbon per hectare (0.3 per cent carbon for desert loams) and 231 tonnes of carbon per hectare (14 per cent carbon for intensive dairy soils; see http://www.daff.gov.au/climatechange/australias-farming-future/climate-change-and-productivity-research/soil_carbon for the report). For Australian dryland agricultural soils the organic carbon content is more typically between 20-150 tonnes carbon per hectare (or about 0.7-4.0 per cent depending on soil bulk density).

Quantifying existing soil organic carbon stocks in key soil types under important farm management regimes within some of Australia's agricultural regions was a key output of the Soil Carbon Research Program (SCaRP), and has provided valuable information to baseline soil organic matter stocks across different environments (see Figure 1.2).

Management and site factors interact to influence the actual amount of soil organic matter in relation to the attainable amount of soil organic matter (as defined by climate and soil type). While there is a strong relationship between rainfall and the amount of soil organic carbon, regional data indicates that even within a rainfall zone soil organic carbon can vary widely and the highest variability occurs in areas of high rainfall, which support increasing biomass production (Griffin et al. 2013). Such variability is likely due to a range of factors influencing net primary productivity, including agronomic and soil management as well as variations in soil type and moisture – the influences of which are discussed in this publication.

Australian soils are low in soil organic matter content by global standards, with the exception of soils that support high net primary productivity such as well-managed pastures and irrigated systems unconstrained by water availability.

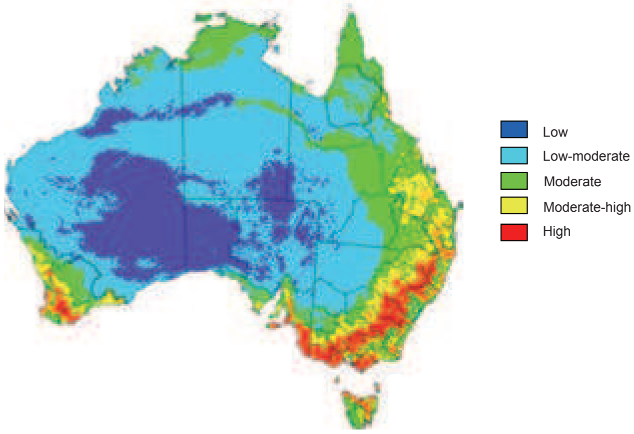


Figure 1.1 Potential for soil organic matter gain resulting from a combination of effective rain (considering amount and availability) and residue pressure, which reflects plant and livestock removals of organic matter (Baldock et al. 2009).

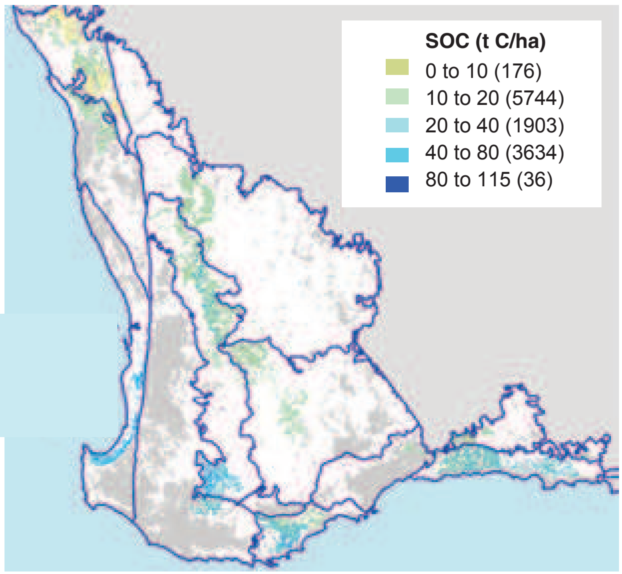


Figure 1.2 Soil organic carbon (tonnes per hectare) stocks in surface layers (0-10 cm) for south west Western Australia. Areas of low confidence (e.g. subsystems that only have one site) are masked out in white. Lines constitute agricultural soil zones: grey is remnant vegetation (Griffin et al. 2013).

SOIL ORGANIC MATTER

AT A GLANCE

- For all soils, organic matter is critical for biological processes and soil nutrient supply.
- In coarse textured sandy soils, organic matter largely determines cation exchange capacity and can influence water holding capacity to a degree.
- In finer textured clay soils, soil organic matter is critical in maintaining soil structure and stability.
- Information on the amount and quality of organic matter returned to soil can and should be used to help inform fertiliser management strategies.
- Soil organic matter content is determined by soil type, climate and on-farm management in that order and is slow to build-up, particularly in more stable fractions.
- Measuring soil organic matter over time helps inform growers of future changes in soil function.

WHAT IS SOIL ORGANIC MATTER?

Soil organic matter makes up only 2-10 per cent of the soil mass, but is vital to its physical, chemical and biological function (see Plate 1.1).

All soil organic matter has its origin in plants. It can be divided into both 'living' and 'dead' components in various stages of decomposition (see Figure 1.3) and ranges in age from very recent inputs (fresh residues) to those that are thousands of years old (resistant organic matter). Soil organic matter is composed of carbon and other organic particles such as hydrogen, oxygen and small amounts of nitrogen, phosphorous, sulphur, potassium, calcium and magnesium.

Between 5-10 per cent of below-ground soil organic matter containing roots, fauna and microorganisms is living (see Figure 1.3). The microbial component of this living pool is referred to as the microbial biomass and is considered essential for organic matter decomposition, nutrient cycling, degradation of chemicals and soil stabilisation. The remaining components include non-living organic matter such as dead and decaying plant and animal residues. Depending on soil type and farming system, the actual allocation of organic matter moving into different pools can vary widely.

Soil organic matter is a continuum of different forms, with turnover times ranging from minutes through to hundreds and even thousands of years. It exists as four distinct fractions, with each varying in properties and decomposition rates (see Table 1.1).

Dissolved organic matter can originate from the humus fraction (leaching of humic substances) as a soluble by-product from decomposition of the particulate organic matter fraction, or from root exudates. In agricultural systems, fresh residues and the living component of organic matter contribute to the particulate organic matter fraction (see Figure 1.3). This pool is readily decomposable and cycles rapidly (i.e. reproduces, dies and decomposes within years). In contrast, the stable humus fraction is nutrient rich and accumulates in the soil making up more than half of the soil organic matter in many soils (see Figure 1.3) and taking decades to turn over. The resistant organic matter fraction is relatively inert and can take thousands of years to turn over. The relative contribution of each organic matter fraction (as depicted in Figure 1.3) to the total organic matter pool varies widely depending on soil type and farming system.

Soil organic matter cycles continuously between its living, actively decomposing and stable fractions (see Figure 1.4). When conditions result in less organic matter (e.g. animals/plants) entering the soil organic pool, the particulate organic fraction declines. If this pattern continues, the total amount of soil organic matter will decline over time.

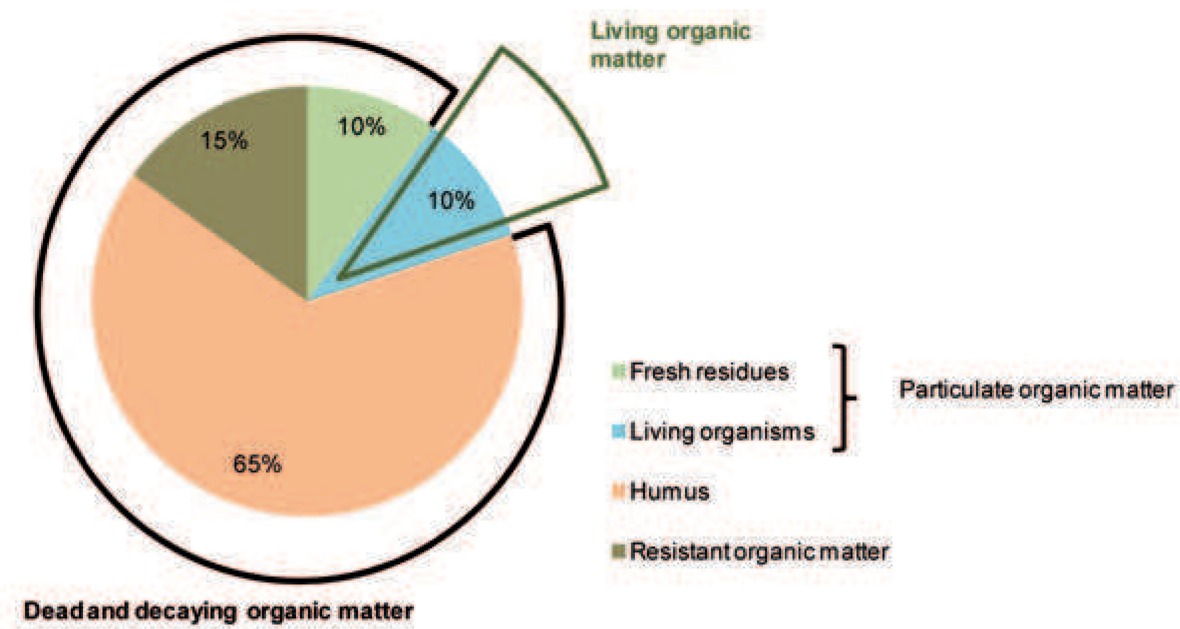


Figure 1.3 Proportional make-up of organic matter in an agricultural soil.

Fraction	Size	Turnover time	Composition
Dissolved organic matter	< 45 µm (in solution)	Dissolved organic matter generally turns over very rapidly (minutes to days)	Made up of soluble root exudates, simple sugars and decomposition by-products. It generally constitutes less than one per cent of total soil organic matter.
Particulate organic matter	53 µm – 2 mm	From months to decades	Composed of fresh and decomposing plant and animal matter with an identifiable cell structure. Makes up between 2-25 per cent of total soil organic matter.
Humus	< 53 µm	Decadal (from tens of years up to hundreds of years)	Made up of older, decayed organic compounds that have resisted decomposition. Includes both structural (e.g. proteins, cellulose) and non-structural (e.g. humin, fulvic acid) organic molecules. Often makes up more than 50 per cent of total soil organic matter.
Resistant organic matter	< 53 µm and in some soils < 2 mm	Ranges from hundreds to thousands of years	Resistant organic matter is relatively inert material made up primarily of chemically resistant materials or remnant organic materials such as charcoal (burnt organic material). This pool can constitute up to 30 per cent of soil organic matter.

Table 1.1 Size, composition, turnover rate and decomposition stage of the four soil organic matter fractions.

1. **Additions:** When plants and animals die they become part of the soil organic matter.
2. **Transformations:** When soil organisms break-up and consume organic residues to grow and reproduce, the organic residues are transformed from one form into another. For example, fresh residues are broken down into smaller pieces (< 2 mm) and become part of the particulate organic matter fraction. As the material is further decomposed (< 53 um) a smaller proportion of more biologically stable material enters the humus pool.
3. **Nutrient release:** Nutrients and other compounds not required by microbes are released as a result of this transformation and can then be used by plants.
4. **Stabilising organic matter:** As the organic residues decompose, a proportion becomes chemically stabilised enabling it to resist further change. Protection can also be afforded through occlusion within aggregates and through the formation of organo-mineral complexes. These materials contribute to the resistant organic fraction.

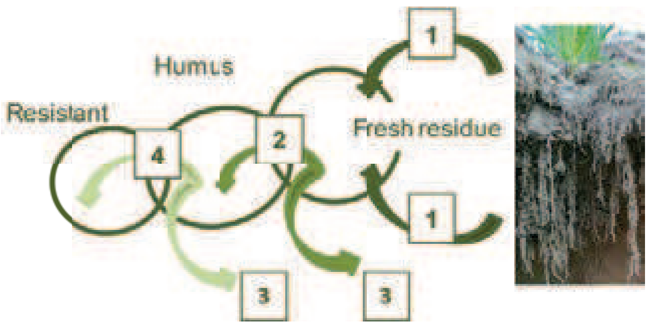


Figure 1.4 Pattern of organic matter transformation in soils (figure adapted from University of Minnesota extension publication WW-07402).

CALCULATING SOIL ORGANIC MATTER

Organic matter is different to organic carbon in that it includes all the elements that are components of organic compounds. Soil organic matter is difficult to measure directly, so laboratories tend to measure soil organic carbon and use a conversion factor to estimate how much organic matter is held within a soil.

Soil organic carbon is a component of soil organic matter, with about 58 per cent of the mass of organic matter existing as carbon. Therefore, if we determine the amount of soil organic carbon in a sample and multiply it by 100/58 (or 1.72) we can estimate the proportion of organic matter in the soil sample:

Organic matter (%) = total organic carbon (%) × 1.72

While the ratio of soil organic matter to soil organic carbon can vary with the type of organic matter, soil type and depth, using a conversion factor of 1.72 generally provides a reasonable estimate of soil organic matter suitable for most purposes.

Calculating soil organic matter content in soil

The amount of soil organic matter in your soil can be calculated as follows for a soil with 1.2 per cent soil organic carbon:
(Total organic carbon per cent x 1.72) x soil mass (tonnes per hectare)
= [(1.2 x 1.72)/100] x 1200 (for a soil with a bulk density of 1.2 to 10 cm depth)
= 24.8 tonnes organic matter per hectare

SOIL ORGANIC MATTER FUNCTION

Organic matter renders soils more resilient to environmental change and also influences characteristics such as colour and workability. It is central to the functioning of many physical, chemical and biological processes in the soil. These include nutrient turnover and exchange capacity, soil structural stability and aeration, moisture retention and availability, degradation of pollutants, greenhouse gas emissions and soil buffering (see Table 1.2).

An optimal level of soil organic matter is difficult to quantify because the quality and quantity of different organic matter fractions needed to support various functions varies with soil type, climate and management. However, it is generally considered that soils with an organic carbon content of less than one per cent are functionally impaired.

Soil function is influenced by the size, quality and relative stability of the four soil organic matter fractions (see Figure 1.5). In this figure, the width of the patterned or shaded areas within the shape indicates the relative importance of the soil organic matter fractions to a particular function or process. For example, on the left the decreasing width of the striped area indicates the importance of the humus fraction declines as the clay content of a soil increases. This is because the clay particles provide a large surface area for cation exchange, which renders soil organic matter increasingly less important as clay content increases. By comparison,

Table 1.2 Functional role of soil organic matter.		
Physical functions	Chemical functions	Biological functions
Improves soil structural stability	Increases capacity to hold nutrients (i.e. cation exchange capacity)	Energy (food source) for biological processes such as: Microbial decomposition; Nutrient transformation; Degradation of pollutants Binding soil particles and organic matter in stable aggregates
Influences water retention	Buffers pH	Major store of plant nutrients (N, P, S)
Buffers changes in temperature	Immobilises heavy metals and pesticides	Improves soil resilience

humus can be seen to be equally important for the provision of nutrients across all soil types and in particular it is critical to the supply of potentially mineralisable nitrogen (see Figure 1.5).

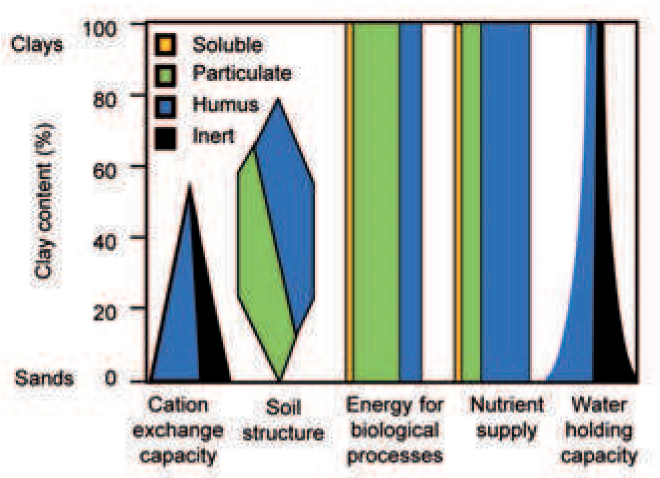


Figure 1.5 A conceptual representation of the role of soluble, particulate, humus and resistant (inert) organic matter fractions for a range of soil functions (from Hoyle et al. 2011).

While not all of the relationships depicted in Figure 1.5 have been quantified for Australian soils, the contribution of the soil organic carbon fraction to the ability of a soil to hold nutrients has been demonstrated at Young River, Western Australia (see Figure 1.6). This study suggests a stronger relationship between soil organic carbon and nutrient exchange in soils, with less than 10 per cent clay and organic carbon explaining nearly 40 per cent of the variation in cation exchange. In soils with greater than 10 per cent clay, a one per cent increase in organic carbon increased nutrient exchange by about 3 meq/100 g soil, but explained just six per cent of the variation in higher clay soils. It is not known how this relationship would differ when considering clay applied to soils for the treatment of non-wetting.

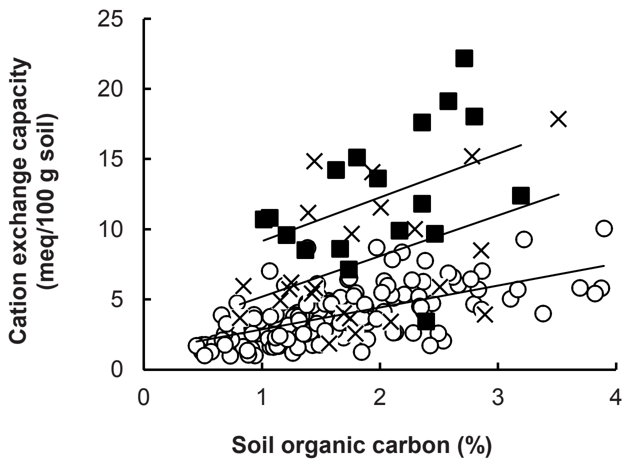


Figure 1.6 The influence of soil organic carbon on cation exchange capacity for Young River, Western Australia in soils with clay content between 0-10% (o), 10-20% (x) and 20-30% (■). Sourced from www.soilquality.org.au.

While the relative importance of any given fraction of organic matter will vary from one soil to another and depend on factors such as climate and cropping history, we do know that organic matter influences plant growth primarily through its effect on the physical, chemical and biological properties of the soil.

For example, fresh crop residues which are readily broken down provide energy for key soil biological processes such as nutrient cycling. The particulate organic matter fraction decomposes at a slower rate than crop residues and is important for soil structure, energy for biological processes and provision of nutrients. Humus generally dominates

Table 1.3 Indicative carbon to nitrogen (C:N) ratio of various organic residues.

Organic material	Units of carbon per unit of nitrogen (C:N ratio)
Poultry manure	5:1
Humus	10:1
Cow manure	17:1
Legume hay	17:1
Green compost	17:1
Lucerne	18:1
Field pea	19:1
Lupins	22:1
Grass clippings	15 – 25:1
Medic	30:1
Oat hay	30:1
Faba bean	40:1
Canola	51:1
Wheat stubble	80 – 120:1
Newspaper	170 – 800:1
Sawdust	200 – 700:1

soil organic matter and is particularly important in the provision of nutrients, cation exchange, soil structure, water-holding capacity and in supporting biological processes. Indirectly, the humus pool also influences micronutrient uptake and the performance of herbicides and other agricultural chemicals. The resistant organic matter fraction is dominated by old recalcitrant residues and char — a product of burning carbon-rich materials (e.g. grasslands). This fraction decomposes over millennia and although biologically inert contributes to cation exchange capacity, water holding capacity and the stability (persistence) of organic carbon in soils.

CARBON TO NITROGEN (C:N) RATIO AND SOIL ORGANIC MATTER

Plant material contains about 45 per cent carbon and depending on residue type between 0.5-10 per cent nitrogen. The ratio of organic carbon to total

While plant residues and other organic inputs vary widely in their C:N ratios, the C:N ratio of soil organic matter is generally constant for a given environment (ranging from 10:1 to 15:1).

nitrogen is referred to as the carbon to nitrogen (C:N) ratio. This ratio indicates the proportion of nitrogen and other nutrients relative to carbon in that material. Organic matter varies widely in its C:N ratio (see Table 1.3) and reflects how readily organic matter decomposes, providing an indication of both the amount and rate of nitrogen release that might be expected to result from decomposition.

Carbon to nitrogen (C:N) ratio of organic residues

The C:N ratio of organic inputs influence the amount of soil nitrogen made available to plants. Organic residues with a C:N ratio of between 25:1 and 30:1 have sufficient nitrogen available for microbes to decompose them without needing to use soil nitrogen stores. Residues with a lower C:N ratio (< 25:1) such as pulses and legume pastures will generally result in more rapid decomposition of organic residues and tend to release plant-available nitrogen. Residues with a higher ratio (> 30:1) such as cereal crops will decompose more slowly and result in less plant-available nitrogen being released.

To grow and reproduce soil microbes requires a balanced amount of carbon and nitrogen that reflects a relatively low C:N ratio (generally less than 15:1). In plant residues such as wheat stubble, which have a high C:N ratio (120:1) and contain relatively more carbon than nitrogen, soil microbes must find another source of nitrogen to fully digest wheat stubble and this often results in soil nutrient reserves being immobilised and soil becoming nitrogen deficient. Such nitrogen deficiency is often seen in the field where stubble has been incorporated during sowing operations and nitrogen availability

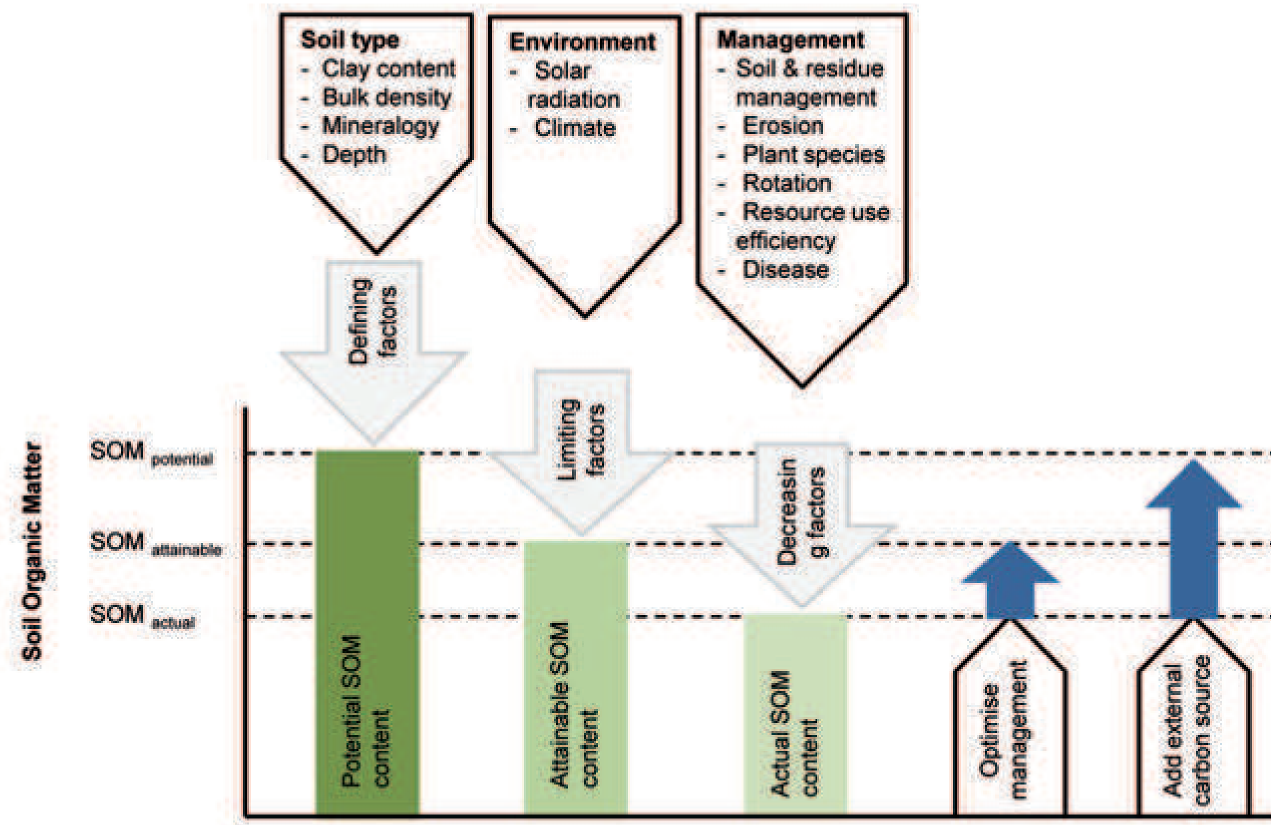


Figure 1.7 The influence of soil type, climate and management factors on potential soil organic matter content (Ingram and Fernandes 2001).

decreases in the soil because it becomes tied-up, or immobilised in the microbial biomass. Therefore, residues with a high C:N ratio are considered nutrient poor and can take years to decompose. In contrast, fresh legume residues with a low C:N ratio (less than 25:1) have proportionally less carbon per unit of nitrogen enabling them to decompose faster and release surplus nitrogen for plant use.

While plant residues and other organic inputs vary widely in their C:N ratios, the C:N ratio of soil organic matter is generally constant for a given environment (ranging from 10:1 to 15:1). This results from the dominance of the humus and resistant organic matter fractions in soil and reflects the significant loss of carbon associated with organic matter decomposition. In Australia, agricultural soils generally store between 10-12 units of carbon for every unit of nitrogen (i.e. 10 tonnes carbon per hectare for every tonne of nitrogen). Therefore, increasing organic matter (and hence organic carbon) in soil requires a balance of carbon and nitrogen as well as other nutrients.

To maintain or increase a soil's stock of organic carbon long-term, increased amounts of organic matter must be continually added. Any decline in the amount of organic material being returned to soils will result in a decrease in the soil's organic carbon content.

When soil organisms digest organic residues part of the carbon originally in these residues is used for new growth and cell division, with the remainder being emitted as carbon dioxide. As a general rule, less than one-third of the applied carbon in fresh residues remains in the soil after the first few months of decomposition. As the material is decomposed the C:N ratio decreases and the remaining organic material becomes more resistant to further decay.

How do I calculate the impact of incorporating organic residues on my soil nitrogen supply?

Scenario
A grain grower retains three tonnes per hectare wheat stubble, with a C:N ratio of 120:1 and wants to estimate the likely impact of the stubble on soil nitrogen levels in the paddock.

Step I
The amount of carbon present in the plant residues added to the soil.
3000 kg of stubble x 0.45 carbon content = 1350 kg of carbon in plant residues

Step II
The amount of nitrogen present in the organic matter added to the soil. The stubble contains 1350 kg of carbon and has a C:N ratio of 120:1.
1350 kg carbon ÷ 120 = 11.25 kg nitrogen in organic matter

Step III
Allow for 30 per cent of the carbon being used by microbes to grow, with the remaining 70 per cent respired as carbon dioxide.
The amount of carbon used by microbes is 1350 kg carbon x 0.3 = 405 kg carbon
Given that microbes have a C:N ratio of 12:1 they therefore require 1 kg of nitrogen for every 12 kg of carbon to grow.
405 kg carbon ÷ 12 = 34 kg N

Step IV
Compare the two nitrogen values; the fresh organic matter contained 11 kg of nitrogen and the microbes require 34 kg of nitrogen to grow.
The nitrogen balance = 11 – 34
= - 23 kg N ha

A NEGATIVE balance indicates that nitrogen in the organic matter was LESS than the nitrogen required by the microbes. This nitrogen deficit will be sourced from the soil, making it unavailable for plants. In this case, a grower should consider fertiliser strategies which will ensure sufficient nitrogen is available to plants early in their growth.

If the nitrogen balance had been POSITIVE a surplus of nitrogen would then become available to plants because there would be MORE nitrogen than required for microbial use. If this was the case, growers may consider split applications of nitrogen to save input costs and minimise losses of nitrogen via leaching.

Knowing the contribution of organic matter to your soils nutrition can help inform more profitable fertiliser management strategies.

HOW MUCH ORGANIC CARBON REMAINS IN SOIL?

Microbes digest up to 90 per cent of organic carbon that enters a soil in organic residues. In doing so, they respire the carbon back into the atmosphere as carbon dioxide (CO_2). Microbes continually break down organic residues eventually converting a small proportion of them to humus, which gives the topsoil its dark colour. While up to 30 per cent of organic inputs can eventually be converted to humus depending on soil type and climate, in Australian agricultural soils this value is often significantly less.

> Soils naturally higher in clay content generally retain more organic matter than sandy soils.

Soil type, rainfall and temperature limit the amount of soil organic matter generated via plant biomass and subsequently stored as humus for the long-term. As a result, soils rarely reach their theoretical potential for organic matter storage (see Figure 1.7). Management practices also have a significant influence on whether actual soil organic matter (and carbon) reaches its attainable level as determined by climate (see Figure 1.7). Beyond this threshold, continuous inputs of external organic carbon sources are required, which can be logistically difficult and expensive, and risk the depletion of organic carbon in another location.

Examples of the influence of soil type, climate and management on the amount of soil organic matter (and carbon) accumulated in and lost from agricultural soils is presented in Table 1.4. To maintain or increase a soil's stock of organic carbon long-term, increased amounts of organic matter must be continually added. Any decline in the amount of organic material being returned to soils will result in a decrease in the soil's organic carbon content.

Plate 1.1 The organic horizon is often related to a darkening of soil colour and is particularly evident on the soil surface.

Source: Department of Primary Industries, Victoria

Table 1.4 Rate-limiting influences on the accumulation of soil organic matter.

Influence	Cause
Soil type	Naturally occurring clay in soil binds to organic matter, which helps to protect it from being broken down or limits access to it by microbes and other organisms.
	In contrast, organic matter in coarse textured sandy soils is not protected from microbial attack and is rapidly decomposed.
Climate	In comparable farming systems with similar soil type and management, soil organic matter increases with rainfall. This is because increasing rainfall supports greater plant growth, which results in more organic matter accumulating in the soil.
	Organic matter decomposes more slowly as temperatures decline. Under moist conditions each 10°C increase in temperature doubles the rate of organic matter decomposition (Hoyle et al. 2006). This means moist, warm conditions will often result in the most rapid decomposition of organic inputs.
Land and soil management	Maximising crop and pasture biomass via improved water-use efficiency and agronomic management will increase organic matter inputs.
	As a large proportion of organic matter is present in the top 0-10 cm of soils, protecting the soil surface from erosion is central to retaining soil organic matter.
	Tillage of structured soils decreases soil organic matter stocks by exposing previously protected organic matter to microbial decomposition.
	Adding off-farm organic residues such as manures, straw and char can increase soil organic matter depending on the quality of the added residues.
	Landscape can influence water availability. Transfer of soil and organic matter down slope via erosion can increase the amount of soil organic matter in lower parts of the landscape.
	Soil constraints can influence humus formation by constraining plant growth and decomposition rates. This could slow both the amount and transformation rate of organic matter moving into more stable fractions.
	Microbes and particularly bacteria grow poorly in strongly acidic or alkaline soils and consequently organic matter breaks down slowly. Soil acidity also influences the availability of plant nutrients and in turn the amount of organic matter available for soil biota growth.

02

BIOLOGICAL TURNOVER OF ORGANIC MATTER

AT A GLANCE

- Soil biota is primarily responsible for decomposing organic matter and nutrient cycling in soil.
- Less than five per cent of soil biota is active at any one time, so estimates of the number of organisms as a meaningful indicator of soil quality without a measure of their specific activity or function are questionable.
- Soil microorganisms are active only when soil is moist and are often constrained by a lack of food.
- Greater diversity in soil biota is linked to the suppression of soil pathogens and maintaining soil function under variable conditions.
- Organic matter breakdown is influenced by its composition, physical location and climate.

A diverse range of organisms both beneficial and harmful to plants is active in soil. These organisms contribute significantly to the living component of soil organic matter (see Chapter 1) and can be classified according to their size or function in the soil:

- Microorganisms (e.g. bacteria, fungi, actinomycetes, viruses, protozoa and algae) less than 0.2 mm in size.
- Soil fauna (e.g. earthworms, ants, nematodes, beetles, mites, termites, centipedes and millipedes), includes both macro-sized organisms (larger than 2 mm) and meso-sized organisms (between 0.2 and 2 mm).

SOIL MICROORGANISMS

Microorganisms play a significant and critical role in nutrient and carbon cycling within soil. Soil microbes decompose fresh animal, crop and pasture residues, using the carbon and nutrients for food and growth. In the process they produce new compounds, which can be used by a large variety of organisms, or they incorporate some of the carbon and nutrients that were in the organic matter into their own microbial biomass. As a result, in many soils the microbial biomass is often directly proportional to the size of the actively decomposing organic matter fraction (Hoyle et al. 2011). While a large proportion of the organic matter that enters soil is available for mineralisation, nutrients can remain trapped in tiny (< 53 µm) particles of organic residue that are either chemically or physically protected from decomposition and remain unavailable to plants.

By breaking down carbon structures, soil microbes play a significant role in nutrient cycling processes. In addition, the microbial biomass itself is also a significant contributor to carbon and nutrient cycling because they reproduce and die quickly, contributing significantly to fluctuations in nutrients available for plant or microbial uptake. Free living nitrogen fixation can also occur in specialised bacteria and has been estimated at the rate of 0-15 kg of nitrogen each year (Peoples 2002). In low fertility soils, much of the carbon and other nutrients originally contained within the crop and pasture residues remain unavailable to plants due to its uptake (immobilisation) in the microbial mass. However, any nitrogen, phosphorous and sulphur that are in excess of microbial requirements is released into the soil and becomes available for plant use.

If photosynthetic carbon inputs such as crop residues or root exudates become totally absent, decomposers come to dominate and increasingly the soil biota consume stored carbon sources resulting in declining soil organic carbon levels. The use of herbicides, pesticides and fungicides that cause a temporary decline in beneficial microorganisms that build humus, suppress diseases and make nutrients available to plants can influence the turnover of carbon in soil.

Soil fungal to bacterial ratio

An estimate of the biomass (or a count) of fungi and bacteria is sometimes used to determine the ratio of fungi to bacteria, with a ratio between 0.5-1.5 reportedly associated with enhanced soil health, nutrient cycling and residue breakdown. However, there is little evidence or quantification to support this relationship in the context of Australian agricultural systems, which are often dominated by bacteria. In addition, the methods sometimes used to determine the fungi to bacteria ratio may only capture a small proportion of the total microbial biomass or are not specific enough to target specific organisms.

SOIL FAUNA

Soil fauna influence organic matter transformations (e.g. loss of organic matter, nitrogen pathways) in concert with changes in soil moisture and temperature, which influence the abundance and diversity of different functional groups (Osler 2007). The impact of soil fauna on organic matter decomposition rates suggests their contribution is greatest on the poorest quality litter (Osler 2007). Larger soil fauna such as earthworms and insects are primarily associated with fragmentation and redistribution of organic matter (see Plate 2.1), breaking down larger pieces through ingestion or transporting and mixing them through the soil. In the process they recycle energy and plant nutrients and create biopores.

> Biopores are channels or pores formed by living organisms that help water drain more freely and can improve the ability of roots to penetrate hard soil layers.

In low fertility, sandy textured soils typical of extensive areas of Australian agriculture, an increasing diversity of soil fauna has been linked to higher carbon dioxide respiration, soil organic carbon and mineral nitrogen production above that of soils containing only bacteria and fungi (Kautz and Topp 2000).

Earthworms

Earthworms are generally considered positive for the health of broadacre agricultural soils, but quantifying their impact on soil function has not been extensively studied in Australia. Since earthworms do not have teeth they ingest both organic matter and soil, using the soil to help grind up organic residues internally. Their waste (worm casts) is a resultant mix of strongly aggregated soil and organic residues that are rich in plant available nitrogen (0.6 per cent) and phosphorus (2.8 mg/100 g). The carbon content of these casts is on average 1.5 times that of the bulk soil (Bhadauria and Saxena 2010).

Significant numbers of earthworms are required to stimulate an improved soil structure. For example, Fonte et al. (2012) determined the equivalent of 144 worms per m^2 in the top 10 cm of a soil that also had high fungi and bacteria numbers and actively growing roots, was required before a six per cent increase in aggregate stability was measured. This has led to estimates of drainage rates up to 10 times faster and infiltration rates six times faster in soil with earthworms compared to those without earthworms.

Significant numbers of earthworms are required to stimulate an improved soil structure.

In Australian cropping soils, only a few species of earthworms are associated with improved plant growth (Blackmore 1997). Current estimates of earthworm populations in Australian agriculture are between 4/m^2 and 430/m^2, although higher populations have been observed in some pasture systems (Buckerfield 1992; Mele and Carter 1999; Chan and Heenan 2005). In north-eastern Victoria and southern New South Wales, the density of earthworms across 84 crop and pasture sites averaged 89 earthworms/m^2, with a low species richness of 1-2 per site (Mele and Carter 1999). This is similar to the average abundance (75 earthworms/m^2) reported by Chan and Heenan (2006).

Earthworm populations generally increased in wetter environments above 600 mm annual rainfall and were three times higher in pasture sites than cropping paddocks (Mele and Carter 1999). Zero-tillage combined with stubble retention was also shown to support earthworm populations up to seven times higher than in disturbed systems where residues were burnt (Chan and Heenan 2006). Variability in earthworm numbers has also been noted within seasons, increasing during the winter months to between 160/m^2 and 501/m^2 for crop and pasture systems respectively and between seasons (Chan and Heenan 2006).

Earthworms are not readily supported in some soils, including very coarse sands or acidic soils (pH_{Ca} less than 4.5), and are often absent regardless of management. In part this is due to low levels of calcium in these soils, which is required continuously by earthworms.

Soil-borne plant pathogens

Organisms that attack living plant tissue and cause plant diseases are called pathogens. In soil, undesirable organisms include a range of insects, parasitic nematodes, protozoa, viruses, bacteria and fungi, which may be present even where there are no visible symptoms. For a disease to develop several criteria must be met. There must be a suitable host plant, a pathogen and an environment suited to its growth. Climatic patterns also affect the types of fungal pathogens that are dominant in a region. Disease outbreaks can be caused by an increase in the population of the pathogen, or by an increase in susceptibility of the plant, which is affected by factors such as its age and nutritional status, environmental stress, crop type or variety. The degree of root damage will generally relate to the number and type of disease pathogens present.

Undesirable organisms influence soil health and production through their influence on root and plant vigour and changes in the soil food web. A high incidence of pathogens can slow root growth and decrease the ability of roots to acquire water and nutrients, decreasing grain and pasture yields, and constraining organic matter inputs into soil. In doing this, the addition of fresh organic inputs that favours the growth of a diverse range of beneficial organisms (as compared to pathogens) is constrained.

Soils with high levels of soil organic matter and biological activity seem to prevent pathogens from taking hold due to increased competition for resources, which constrains pathogen activity, or

by sheltering antagonistic or predatory microbes. For example, a decline in plant-parasitic nematodes and an increase in saprophytic nematodes were observed with the use of diverse rotational sequences, addition of organic matter, cover crops, green manures, composts and other soil amendments (Widmer et al. 2002).

Suppressive soils

Suppressive soils are those that naturally suppress the incidence or impact of soil-borne pathogens. Disease suppression can develop over 5-10 years and is a function of the population, activity and diversity of the microbial biomass (Roget 1995, 2006). In southern Australia, sites with high levels of disease suppression to rhizoctonia (*Rhizoctonia solani*) and take-all (*Gaeumannomyces graminis* var. *tritici*) have been associated with higher inputs of biologically available carbon and greater competition for food resources (Roget 1995, 2006).

The increase in available carbon at these sites was associated with intensive cropping, full stubble retention, limited grazing, no cultivation and high yielding crops. However, the adoption of these practices does not always result in suppression of soil pathogens as evidenced by the many instances in which disease continues to be prevalent. To date there are no indicator species associated with the development of suppression in agricultural soils, though research in this area is progressing.

ORGANIC MATTER TURNOVER TIMES

The 'turnover' or decomposition rate of organic matter refers to the time taken for organic matter to move into and through the various organic matter pools, including living, actively decomposing and stable. This movement is a continual process and is vital to the functioning of all ecosystems. As new organic matter enters the soil it supports biological processes, releases nutrients through decomposition and contributes to soil resilience.

The difference between organic matter inputs and outputs and the rate at which they are transformed determines the size and stability of the organic matter pools (see Chapter 1). Soil biological function is less sensitive to the total amount of organic matter than the rate at which organic matter turns over, which is related to the size and nature of the soil organic matter pools and soil depth (Dalal et al. 2011). Understanding and quantifying the mechanisms driving turnover of organic matter between the pools is critical to the capacity to increase and maintain soil organic carbon in different soils and climates.

The resistant soil organic matter fraction can take several thousand years to turn over and is relatively inert, while the stable humus pool generally takes decades or centuries. In contrast, the actively decomposing pool, which includes the particulate and dissolved organic fractions, has a turnover time of less than a few hours through to a few decades. As organic matter is decomposed and moves from the rapidly decomposing fraction through to the stable humus or resistant organic matter fractions, it becomes both more resistant to decomposition and increasingly nutrient rich (i.e. the carbon to nitrogen ratio declines).

Organic matter characteristics

The carbon to nitrogen ratio of the organic matter being decomposed has a significant influence on the rate and amount of nutrient release (see Chapter 1). As the ratio decreases, organic matter is generally decomposed more rapidly and there is greater potential for a net release of plant-available nutrients.

The chemical composition of plant residues strongly influences the rate at which organic matter is decomposed. Soluble sugars, metabolic carbohydrates and amino acids are rapidly decomposed, while more resistant plant material such as lignin, cellulose and polyphenols take significantly longer to break down. This differential in decomposition rate, results in residues with a similar carbon to nitrogen ratio, but different chemical composition having widely variable decomposition rates. For example, Lefroy et al. (1994) found the decomposition rate of Asian pea leaf residues was more than double that of medic hay due to differences in the chemical composition of the residues.

Suppressive soils are those that naturally suppress the incidence or impact of soil-borne pathogens.

The physical location of organic residues within the soil and the level of soil disturbance also influence the rate at which organic matter is broken down or mineralised. For example, Hoyle and Murphy (2011) found nitrogen was mineralised more rapidly as residues were incorporated with increasing intensity into a red-brown earth compared to being left on the soil surface.

Soil characteristics

The way in which a soil is constructed (i.e. its architecture) can influence soil organic matter accumulation or loss. Protection of organic matter in soil is most often associated with soil texture, specific surface area and mineralogy, which influence how organic carbon may be adsorbed. Other chemical and physical attributes of the soil such as pH, soil water and porosity can also modify the rate of organic matter decomposition and therefore the rate at which nutrients and carbon are cycled within the soil (see Table 2.1).

Table 2.1 Soil factors that can influence the rate of organic matter turnover.

Decrease soil organic matter turnover	Increase soil organic matter turnover
Increasing soil depth	Surface litter
Nutrient deficiency	Nutrient rich
High lignin and wax content	High carbohydrate content
Waterlogged (anaerobic) soil	Free draining soils
Low temperatures	High temperatures
Clay textures	Sandy textures
Aggregation	Unstructured soils
Variable charge surfaces	Low charge surfaces

Soils with increasing clay content can often retain organic matter for longer than coarse textured sandy soils by restricting access to organic residues. This is associated with a greater proportion of small pore sizes, which house smaller organic particles that microbes can't get to, and increasing soil aggregation which can encase organic particles and prevent access. While this effectively increases the retention of soil organic matter for longer it does not necessarily remove it from the decomposing pool. For example, management practices or events that expose this protected material then leave it vulnerable to decomposition. Therefore management practices that change the structure of a soil can influence the breakdown of organic matter fractions.

Climate

In moist soils, higher temperatures increase the turnover rate of organic matter. For example, Hoyle et al. (2006) showed the mineralisation rate of organic matter doubled with each 10°C increase in average soil temperature between 5-40°C in soil held at 45 per cent water holding capacity. Adequate amounts of water and oxygen are also required for decomposition to occur.

Rainfall and soil porosity determine available soil water. Changes in the water filled pore space

influence carbon mineralisation, with higher decomposition rates associated with an increasing proportion of soil pores larger than 3 mm in size. Therefore, sandy soils with a high porosity have a faster rate of decomposition than clay soils. While the amount of carbon mineralised at optimal water content is similar, the latter can vary between soil types. For example, the optimum water filled pore space for carbon mineralisation was determined at 45 per cent on sand with 10 per cent clay, compared to a water filled pore space of 60 per cent on a heavier soil with 28 per cent (Franzleubbers 1999).

Location in the soil profile

In Australian soils, about 60 per cent of the microbial biomass in the top 30 cm is located just below the surface (0-10 cm). Large soil biota such as earthworms, mites, termites and ants, which actively break-up large organic residues are also present in higher concentration near the soil surface. As a result, the turnover rate of organic material in surface soil (0-10 cm) is almost double that below this depth.

ECOSYSTEM SERVICES

Global carbon balance

Biological processes in soil contribute to fluxes in greenhouse gas emissions (see Chapter 7). The influence of these processes on soil organic matter is therefore critical to the global carbon balance. As soil organisms break down soil organic matter they release carbon dioxide, which when lost to the atmosphere is a potential source of greenhouse gases. In Australia, up to 75 per cent of the carbon in fresh organic residues may be released as carbon dioxide during the first year of decomposition depending on climate and as much as 90 per cent over the long-term. Soils also represent the largest ‘sink’ or store for organic carbon. Therefore, the balance between accumulation of carbon resulting from organic inputs and losses of carbon resulting from the decomposition of organic matter is critical to mitigating greenhouse gas emissions.

Soil buffering

Overall, adequate amounts of soil organic matter maintain soil quality, preserve sustainability of cropping systems and help to decrease environmental pollution (Fageria 2012). Adding organic matter to soils can decrease the toxicity of heavy metals to plants through absorption and decrease the contamination of waterways and ground water by pesticides through adsorption (Widmer et al. 2002).

Soil acidification which occurs widely across a range of agricultural soils is primarily associated with the removal of agricultural produce and high rates of nitrification, which contribute to leaching. Soil organic matter can contribute to in-situ soil acidification as humic and fulvic acids accumulate in soil, but can also have a buffering effect against the process depending on the quality of the organic matter. While the incorporation of high inputs of organic matter is thought to help neutralise soil acidity this effect is most pronounced when residues have been burnt. The application of lime to low pH soils to meet minimum targets in surface (> pH_{Ca} 5.5) and sub-surface soils (> pH_{Ca} 4.8) as recommended for Western Australian soils remains the most effective amelioration strategy (targets may vary by region).

THE CARBON CYCLE

AT A GLANCE

- Soil organic matter content is determined first by soil type then by climate and then by management.
- Increasing stable soil organic matter pools is a long-term focus in agricultural systems. It isn't going to happen overnight.
- In many instances less than 15 per cent of carbon inputs eventually contribute to the soil organic carbon pool.
- Soil function can be constrained when soil has less than one per cent organic carbon.

Carbon cycling between the soil, plants and atmosphere involves the continuous transformation of organic and inorganic carbon compounds by plants and organisms (see Figure 3.1). Soil represents a reservoir able to both store and release carbon within the global carbon cycle and as such is considered both a sink and source for carbon.

Soils contain carbon in both organic and inorganic forms, with the exception of calcareous soils, which is largely held as soil organic carbon. This organic carbon continually enters and leaves the soil resulting in both carbon accumulation and loss. At any one time the amount of organic carbon in soil represents the balance between inputs and losses.

Since carbon turnover can be constrained by available nutrients as suggested by the carbon to nutrient ratio, it is likely that more fertile soils will lose organic matter at a faster rate than lower nutrient content soils.

A significant amount of the organic carbon accumulated in soils has resulted from photosynthesis where plants convert atmospheric carbon dioxide into above-ground shoot growth and below-ground root growth. As primary productivity increases, organic inputs resulting from shoots, roots and micro-organisms grow and contribute to a build-up in soil organic carbon.

Carbon emissions from soil back to the atmosphere occur in the form of carbon dioxide, largely as a result of agricultural practices driving changes in microbial processes. These emissions have resulted primarily from the decomposition of organic matter, reflecting the historical declines that have been measured in soil organic matter for many agricultural soils and contributed to the measured increases in atmospheric carbon dioxide resulting from human activities.

CARBON BALANCE IN SOILS

Soil organic carbon is in a constant state of flux, slowly responding to environmental or management changes and moving to reach a new equilibrium level after changes occur (see Figure 3.2). For example, in systems where plant production is constrained, organic matter inputs decline and soil biota increasingly deplete stored soil organic carbon for energy. This results in declining soil organic carbon levels until a lower limit, determined by soil texture and a decline in biological activity, which is essentially starved of decomposable carbon, is reached. In contrast, systems with increasing organic inputs to soil can attain a higher level of soil organic

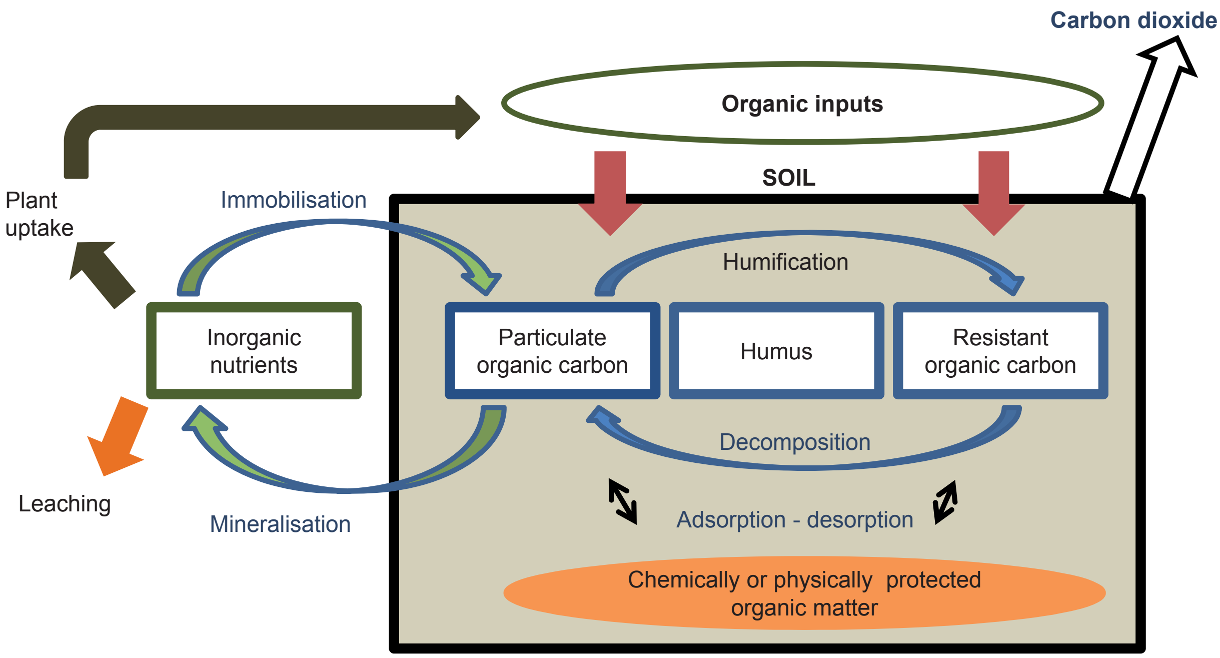


Figure 3.1 Organic carbon cycling in soils.

carbon for which the upper limit is determined by soil texture and climate. In most environments, soil organic carbon fluctuates both within and between seasons and may occur at a greater or slower rate as influenced by land management (see Figure 3.2).

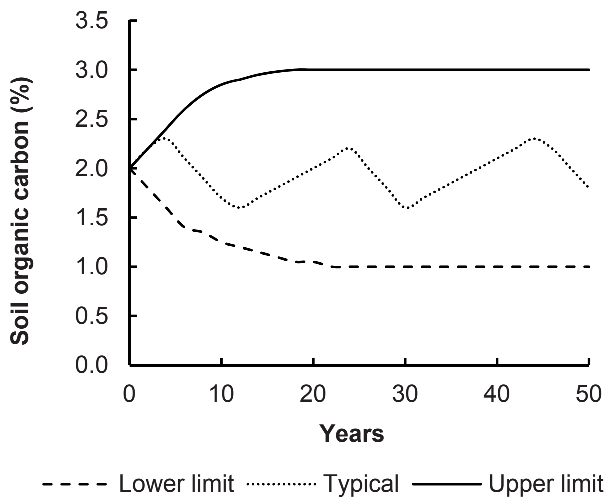


Figure 3.2 Theoretical changes in soil organic carbon (%) representing an upper and lower limit, or a more typical state of flux.

WHAT FACTORS DRIVE CHANGES IN THE CARBON BALANCE?

Soil, climate and management all interact to determine what extent the potential to store soil organic carbon is achieved (see Chapter 1).

1. Soil architecture and clay content = *potential*

The potential amount of organic carbon that soil can store varies with clay content and soil architecture. In general, well aggregated soils or those with increasing clay content, with the exception of cemented soils, have a greater capacity to store, protect or adsorb organic carbon in soil. Sandy soils provide little protection against decomposition and as a result it is more difficult to increase soil organic carbon on coarse textured soils.

2. Soil architecture and clay content PLUS climate = *attainable*

Rainfall and temperature interact with soil architecture to determine net primary productivity (inputs) and decomposition rates (losses).

3. Soil architecture and clay content PLUS climate PLUS management = *actual*

On-farm soil, agronomy and residue management influences the extent to which actual organic carbon storage reaches the attainable organic carbon storage (see Figure 1.5 in Chapter 1). Increasing levels of ground cover can protect soil organic carbon from losses due to erosion. Sub-soil constraints and surface soil sodicity will restrict the potential for plant productivity and thus limit the contribution of organic inputs to soil.

To sequester carbon in soil, the carbon dioxide removed from the atmosphere through plant photosynthesis and biomass production must be stored for long periods of time (i.e. 100 years). Newly incorporated organic material is about seven times more decomposable than older soil organic carbon and as a result only a relatively small proportion of the carbon contained in fresh organic residues will contribute to these more stable soil carbon pools.

WHAT IS THE RATE OF CHANGE?

Historic and future long-term changes in soil organic matter content are more influenced by the speed at which organic matter is lost after a change in land use (i.e. the rate of turnover) rather than the absolute amount of organic matter. Since carbon turnover can be constrained by available nutrients as suggested by the carbon to nutrient ratio, it is likely that more fertile soils will lose organic matter at a faster rate than lower nutrient content soils. In addition, soil disturbance can increase the rate of loss of carbon from soils and result in long-term losses in soil organic carbon compared to uncultivated soils.

While soil type and microbial efficiency influence what percentage of carbon in organic matter ends up in the soil, as a rule less than 15 per cent of carbon inputs eventually contribute to the soil organic carbon pool (Chan et al. 2010). Grace et al. (2006) simulated the influence of cation exchange capacity (which has a strong positive relationship with clay content) on the retention of organic carbon in soil. This relationship can be used to calculate how much carbon might be added to soil organic carbon stores on the addition of organic residues (Figure 3.3). While soil type and microbial efficiency influence what percentage of carbon in organic matter ends up in the soil, as a rule-of-thumb less than 15 per cent of carbon inputs eventually contribute to the soil organic carbon pool (Chan et al. 2010).

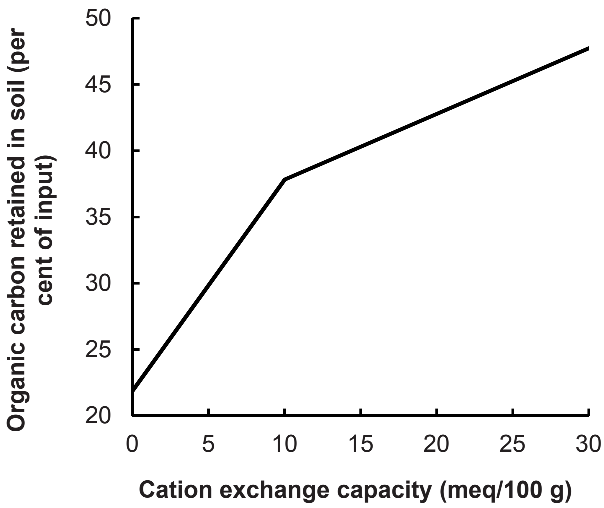


Figure 3.3 A model simulation showing the influence of cation exchange capacity (CEC) on the capacity of soil to retain soil organic carbon (Grace et al. 2006).

For example, a soil with a cation exchange capacity of 5 meq per 100 grams soil (e.g. typical of a sandy soil) might be expected to retain 30 per cent of the carbon added, so one tonne of dry plant material contains 450 kg carbon, but will only retain about 135 kg of organic carbon in the soil. If the soil had a background organic carbon content of 10 tonnes carbon per hectare in the top 10 cm this would reflect a change in organic carbon of just over 0.01 per cent. Therefore, increasing soil organic carbon is normally a slow, incremental process and inputs must be sustained to maintain these changes. It is also why it is difficult to detect short-term (less than 10 years) measureable changes in soil organic carbon.

O'Halloran et al. (2010) suggest a rule for irrigated mixed farming systems where the retention of an extra tonne of organic matter every year for 10 years will increase soil organic carbon by nearly 0.3 per cent — as occurred in northern Victoria and southern New South Wales. In their study, the extra organic matter includes the contribution from above-ground shoot and below-ground root biomass. In Western Australia, the potential of a sandy soil to store organic carbon was evaluated in the low rainfall zone (less than 350 mm annual rainfall). In this study, 60 tonnes of organic matter added as chaff over a period of eight years to a continuous cropping system resulted in an additional eight tonnes of carbon per hectare measured to 30 cm (Liebe Group unpublished). This reflects a retention factor of approximately 30 per cent. While we do not propose that this is an economic or logistical reality, it does demonstrate the potential to increase soil organic matter to an attainable potential determined by soil type and climate (see Chapter 1).

HOW STABLE IS ORGANIC MATTER?

The chemical compounds in organic matter break down at different rates. The first organic compounds to be broken down are those that have simple cellular structures such as amino acids and sugars. Cellulose breaks down more slowly and phenols, waxes and lignin remain in the soil for long periods of time due to the complex structure of the molecules.

Plant stems and leaves break down at different rates due to the differences in their molecular structure and the strength of their chemical bonds. Leaves generally have more cellulose, which is a simple molecule that decomposes rapidly, and less lignin which has a complex structure and breaks down more slowly. Specialised enzymes which increase the decomposition rate are required for their degradation. When lignin is associated with cellulose within plant cells it becomes more difficult to degrade. Under most conditions it might take three times as long to degrade stem material as it does to degrade leaves.

The chemical compounds in organic matter break down at different rates.

The stability of organic carbon is also related to the soil organic matter fraction in which it resides. In this respect, soil organic carbon can be partitioned into fractions based on the size and breakdown rates of the soil organic matter in which it is contained (see Chapter 1). Carbon sources in the active pool, including fresh plant residues, particulate organic

matter and the soil microbial biomass, are relatively easy to break down and have a turnover time ranging from days to less than 10 years. The humus fraction is more stable and has a turnover time of decades to less than 100 years. Resistant organic matter has a turn over time of hundreds to thousands of years.

IS ORGANIC MATTER WORTH BUILDING UP?

There are two primary considerations to managing soil organic matter (carbon being a component of this) that are relevant in Australian agriculture. The first is the contribution of soil organic matter in supporting a productive and profitable farming system that also serves to enhance or protect the soil resource (see Chapter 10). The second is the viability of managing soil organic matter in the context of a global carbon market (see Chapter 7).

Managing soil organic matter to optimise agricultural production systems

Benefits from increasing soil organic matter on crop production systems can be hard to measure as changes occur slowly, particularly in the resistant fractions and can often be the result of indirect effects, which are difficult to separate from other factors. Fisher et al. (2007) provided reasonable evidence for growers of the potential financial gains in increasing soil organic matter where paddocks with high organic matter out-yielded those with low organic matter content. Further attribution of changes in soil function as a result of increasing soil organic matter and its role in supporting various production or ecosystem services are presented in Table 3.1.

Either individually or in combination these factors can contribute to higher crop and pasture yields, more reliable production, increased resilience to dry periods, improved land asset value, the potential to reduce fertiliser use over the long-term and where associated with higher levels of soil cover and less soil disturbance a decreased erosion risk.

While organic carbon levels will vary with soil type, climate, land use and management, the soil's capacity to perform key functions is constrained where soil organic carbon content is below one per cent (Kay and Angers 1999). Prior work has suggested this is sufficient to constrain landholders from reaching their water limited potential yield (Kay and Angers 1999).

Table 3.1 The influence of soil organic matter on soil attributes and functions.

Soil attribute or function	Mode	Impact	Quantification
Soil architecture	Microbial by-products such as bacterial glues and fungal hyphae can increase soil aggregation and stability of soil structure.	Can improve water infiltration, soil porosity and the exchange of water and oxygen.	Minimal impact on coarse textured sands.
Soil fertility	Decomposition of organic matter determines nutrient supply.	Increased plant productivity. Decreased input costs.	Up to 80 per cent of nitrogen uptake results from the turnover of organic matter. Soils can supply between 50-100 kg nitrogen per hectare each year. Organic matter also contains phosphorous and sulphur.
Water infiltration	Microbial by-products such as bacterial glues and fungal hyphae increase potential for soil aggregation. Increasing organic matter can be associated with development of water repellence on soil with less than 15 per cent clay.	Decreases moisture loss from run-off, evaporation. More water enters the soil profile. Increased soil porosity helps the exchange of water and oxygen.	Increasing the rate of entry will lead to a greater potential for more available water.
Water holding capacity (or ‘bucket size’)	Soil organic matter can hold several times its own weight in water.	Increased plant available water and decreased deep drainage below the root zone. Supports higher productivity.	A one per cent increase in soil organic carbon stores the equivalent of a maximum 5.6 mm of soil water in the top 10 cm. Depending on soil type only a proportion of this will be plant available.
Soil biological processes	Organic matter is the primary source of energy required by soil microorganisms for growth and reproduction.	Influences nutrient cycling and availability, soil diversity, resilience and impact of stress events (i.e. pathogen impact, recovery).	The microbial efficiency influences what percentage of organic matter is retained in soils. A greater proportion of carbon is retained in soils with increasing clay content. In Australia, typically less than 30 per cent of carbon is retained (can be up to 50 per cent).
Buffers soil pH (helps maintain acidity at a constant level)	Organic matter is alkaline in its nature.	Large amounts of residues or a concentration of burnt residues can increase soil pH.	Burnt residues can have a liming effect (e.g. often observed on burnt windrows) resulting in higher yielding areas. Burning residues will result in less labile carbon entering the soil.
Soil resilience — defined as the ability of a soil to recover to its initial state after a stress event	Increasing organic matter supports an increasing diversity of microorganisms, many of which can undertake similar roles allowing for some redundancy.	Increased ability of soil to recover soil function after a disturbance.	Less than 10 per cent of the population is active at any time. It is estimated that losses of up to 20 per cent of the microbial biomass would have little impact on soil function.

SOIL ORGANIC MATTER AND NUTRIENT AVAILABILITY IN AGRICULTURE

AT A GLANCE

- Organic matter contains a large store of nutrients.
- As a general rule, for every tonne of carbon in soil organic matter about 100 kg of nitrogen, 15 kg of phosphorus and 15 kg of sulphur becomes available to plants as the organic matter is broken down.
- Between 2-4 per cent of soil organic matter is decomposed each year.
- Organic matter contributes significantly to cation exchange capacity in sandy soils.

Soil organic matter has a reservoir of nutrients bound within its organic structure, which are released into the soil solution as soil microorganisms mineralise (break down) the organic matter for their own metabolism and growth.

The amount of nutrients provided to plants via microbial breakdown of organic matter depends on the type of material that is being mineralised and its ratio of carbon and other nutrients such as nitrogen, phosphorus and sulphur.

As a rule, for every tonne of carbon in soil organic matter about 100 kg of nitrogen, 15 kg of phosphorus and 15 kg of sulphur becomes available to plants as organic matter is broken down. As well as releasing plant nutrients, the microbes also release between 50-90 per cent of the carbon in organic matter as carbon dioxide.

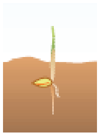
The rate at which organic matter is broken down determines how rapidly the nutrients within the organic structure become available to plants. The particulate organic matter fraction breaks down rapidly, so its nutrients are made readily available to plants and microbes. In contrast, the humus fraction breaks down over decades and provides a large but slow-release supply of plant-available nutrients. Other more recalcitrant forms of carbon are relatively inert, taking hundreds to thousands of years to break down and having little influence on the amount of nutrients released into the soil solution.

Stages of wheat development (average number of weeks after sowing)

Zadok's growth stage

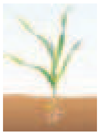
Source: GRDC, Top Crop

1. Germination (2 weeks)
   Zadok's Z10

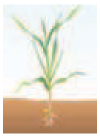


2. Seedling growth (2-3 weeks)
   Zadok's Z10 to Z19

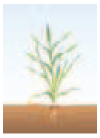
3. Tillering (4-12 weeks)
   Zadok's Z20 to Z29



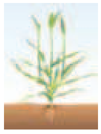
4. Stem elongation (12-16 weeks)
   Zadok's Z30 to Z39



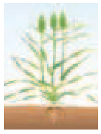
5. Booting (15-18 weeks)
   Zadok's Z40 to Z49



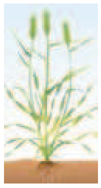
6. Ear emergence (16-19 weeks)
   Zadok's Z50 to Z59



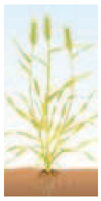
7. Flowering (18-21 weeks)
   Zadok's Z60 to Z69



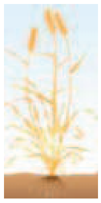
8. Milk development (25 weeks)
   Zadok's Z70 to Z79



9. Dough development (26 weeks)
   Zadok's Z80 to Z89



10. Ripening (28 weeks)
    Zadok's Z90 to Z99



Organic matter and cation exchange

The ability of a soil to hold positively charged cations such as calcium, magnesium, potassium, sodium, hydrogen and aluminium at a given pH determines its cation exchange capacity. Cation exchange measures the ability of a soil to hold on to and supply nutrients to plants. The cation exchange capacity of a soil provides information on its structural stability, resilience, nutrient status and pH buffering capacity. Sodium and aluminium are negatively correlated with plant growth. Soil test results are expressed either in milliequivalents per 100 grams soil (meq/100 g) or centimoles of charge per kilogram (cmol/kg).

Soils have variable cation exchange capacity ranging from sands, with a very low cation exchange capacity often less than 3 meq/100 g, to vermiculite, which may hold up to 200 meq/100 g. Kaolinitic clays have a moderate cation exchange capacity of about 10 meq/100 g, while other clays such as illite and smectite have a higher exchange capacity (Purdie 1998).

Table 4.1 contains information on the cation exchange of clay minerals.

Table 4.1 Indicative cation exchange capacity of different clay minerals in soil (Moore et al. 1998).

Clay mineral	Cation exchange capacity (meq/100g)
Kaolinite	3-15
Illite	10-40
Montmorillonite	70-100
Smectite	80-150
Vermiculite	100-150

Humified organic matter has a very high cation exchange capacity from 250-400 meq/100 g. Therefore, in soils with low clay content the amount of humus and resistant soil organic matter is increasingly important to nutrient exchange because its large surface area gathers (adsorbs) cations from the soil solution, holding nutrients that would otherwise leach. Williams and Donald (1957) estimate that each percentage increase in soil organic carbon is the equivalent of 2.2 meq/100 g cation exchange and in some soils contributes as much as 85 per cent of the cation exchange capacity (Helling et al. 1964; Turpault et al. 2005; Hoyle et al. 2011).

The contribution of organic matter to soil cation exchange capacity declines with soil depth, decreasing soil pH (i.e. increasing soil acidity) and with increasing clay content (see Table 4.2).

Table 4.2 Indicative cation exchange capacity for different soil textures and organic matter.

Soil texture	Cation exchange capacity (meq/100g)
Sand	1-5
Sandy loam	2-15
Silt loam	10-25
Clay loam/silty clay loam	15-35
Clay	25-150
Organic matter	40-200
Humified organic matter	250-400

NITROGEN, PHOSPHORUS, SULPHUR AND ORGANIC MATTER

Organic matter contains a large store of nutrients — the majority of which are unavailable for plant uptake. It estimated that 2-4 per cent of soil organic matter is decomposed each year (Rice 2002). Using an average three per cent turnover and based on a carbon to nutrient ratio of 1000 (C):100 (N):15 (P):15 (S), this suggests for a soil which has 1400 tonnes of soil per hectare and a soil organic carbon content of 2.1 per cent, there would be a release of about 88 kg nitrogen, 13 kg phosphorous and 13 kg sulphur each year from organic matter.

Nitrogen supply

In most soils, while nearly all nitrogen is present in organic form, plants are generally better able to take up inorganic (mineral) nitrogen forms such as ammonium (NH_4^+) and nitrate (NO_3^-). Nitrate is the dominant form of nitrogen taken up by agricultural plants.

The conversion of organic nitrogen to inorganic nitrogen is a biological process associated with the mineralisation (decomposition) of organic matter. Mineralisation results in the production of ammonium, which is predominantly taken-up by and immobilised within soil microbes and then transformed via nitrification to nitrate. These processes can be limited by soil pH_{Ca} less than 5.5, poor soil permeability resulting in water-logged soils, carbon availability, drying soils and temperatures below 20°C (Mengel and Kirkby 1987).

Soil biological processes are also integral to the

availability of the majority of inorganic fertilisers applied to soil, which are transformed into nitrate by soil microbes before being taken up by plants. This includes urea which is either decomposed by enzymes or chemically hydrolyzed to produce ammonia and carbon dioxide. The ammonia is then converted by microbes into ammonium and subsequently converted into nitrate by specialist microorganisms through a process known as nitrification.

In Australia, inorganic mineral fertilisers often make up as little as 20 per cent of crop uptake due to relatively low fertiliser applications and poor nitrogen use efficiency. Biological processes supply the remainder and in some cases contribute up to 80 per cent of crop nitrogen uptake (Angus 2001).

> Although direct uptake of ammonium fertilisers by plants can occur most nitrogen fertilisers applied in an ammonium (NH_4+) form are converted to nitrate (NO_3-) by the soil microbes and are then taken-up by plants in this form.

Inorganic nitrogen moves readily in soil and is required in relatively large amounts at critical stages in crop growth such as terminal spikelet, which occurs about eight weeks after sowing, and during grain fill. In wheat, nitrogen deficiency early in the season limits tiller formation and spikelet and floret number, which in turn reduces yield potential. Later in the season nitrogen deficiency can result in smaller or fewer grain and where sufficient moisture during grain filling in lower grain protein.

Nitrogen cycling

Soil nitrogen is primarily determined via biological processes, which are influenced by rate limiting factors such as soil pH, tillage, soil moisture and temperature. Ammonium released from organic matter mineralised by soil microbes determines the supply (rate and amount) of inorganic nitrogen. The rate at which nitrogen is immobilised within soil microbes and converted to nitrate is directly proportional to microbial demands for nitrogen (Murphy et al. 2003) and determines the net amount (or surplus) of soil nitrogen that becomes available for plant uptake. While both plants and microorganisms can use ammonium a large proportion of it is converted into nitrate. Once dissolved in solution, nitrate is more readily taken-up by plants, but is also easily leached (see Figure 4.1).

Plant-available nitrogen originates from fertiliser input, nitrogen fixation and mineralisation of organic matter. The fate of mineral nitrogen within the profile is the result of immobilisation, plant uptake, leaching and gaseous losses.

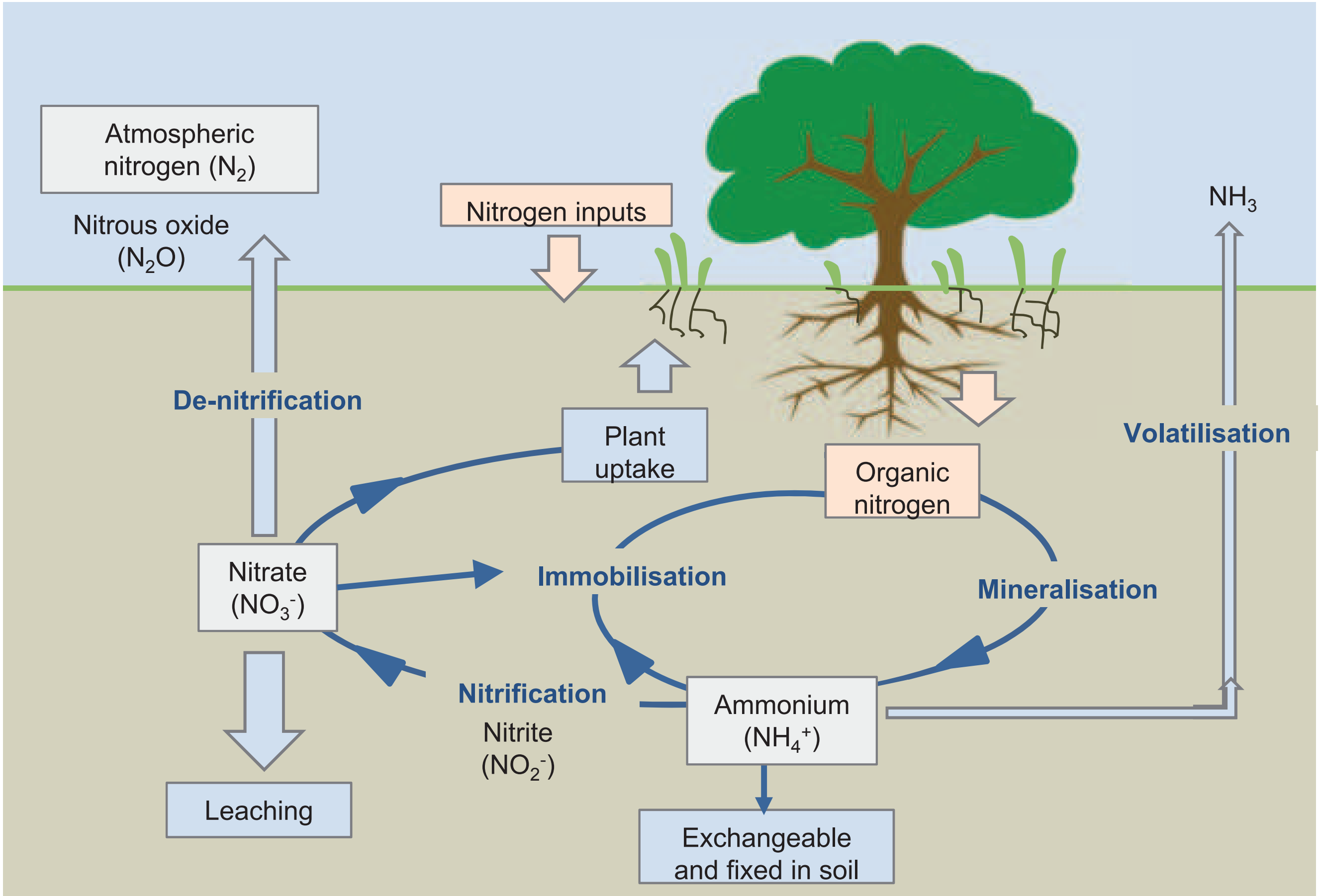


Figure 4.1 Nitrogen cycling in soil.

The influence of organic inputs on soil nitrogen supply

The ratio of carbon to nitrogen in organic matter influences how much nitrogen will eventually become available to plants through microbial decomposition (Hoyle and Murphy 2011). For example, when organic matter with a carbon to nitrogen ratio greater than 25:1 is broken down by microbes much of the nitrogen contained in the organic matter is taken-up and immobilised by the microbial population resulting in relatively little nitrogen being made available to plants (see Chapter 1). Increasingly poor quality residues such as wheat straw, with an even wider carbon to nitrogen ratio (more than 50:1), result in microbial uptake and immobilisation of existing plant-available nitrogen. This can lead to nitrogen deficiency during periods of high crop demand, which contrasts with high quality residues with a carbon to nitrogen ratio less than 25:1 where surplus nitrogen is released to the soil (see Figure 4.2).

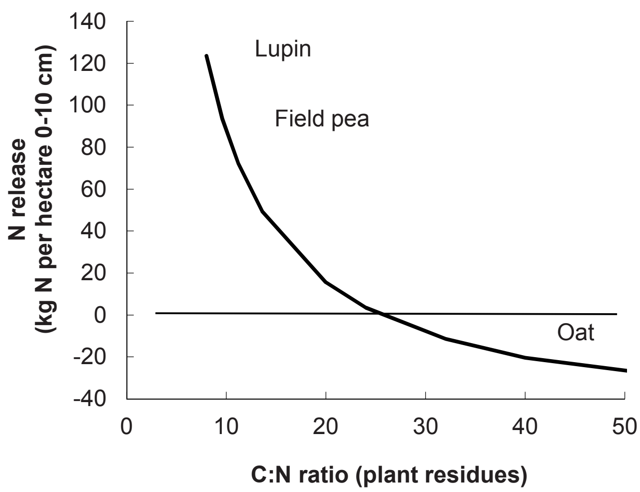


Figure 4.2 Nitrogen release in soil resulting from the decomposition of plant residues with a range of carbon to nitrogen (C:N) ratios. Adapted from Hoyle et al. (2011).

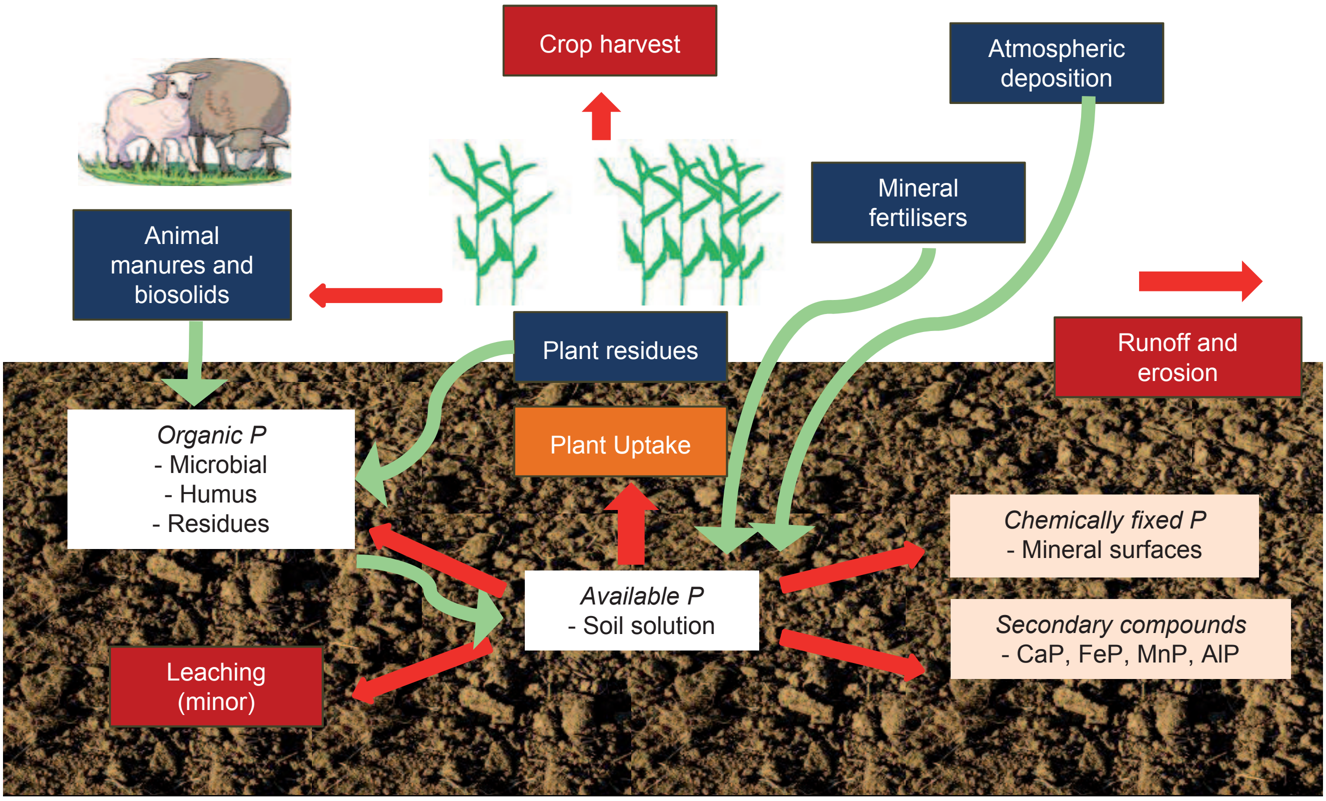


Figure 4.3 Phosphorus cycle in agricultural systems.

While the sustained release of nitrogen associated with organic sources might be expected to more effectively raise grain protein than inorganic nitrogen fertiliser applied at the start of the season, environmental and management factors make it difficult to predict when the organic nitrogen will become available and matching organic nitrogen supply to crop demand is not straightforward.

The polyphenol and lignin content of organic matter also influence the amount of nitrogen released from organic residues, with increasing amounts of these substances limiting microbial access and nitrogen release (Ha et al. 2008).

PHOSPHORUS

Phosphorus is required for cell growth during early plant development. Demand for phosphorus increases once phosphorus reserves in the seed have been exhausted following plant establishment.

Australian soils are inherently low in phosphorus and significant amounts of inorganic phosphorus fertiliser have been historically added to agricultural soils to support profitable crop and pasture production. Very soon after application, inorganic phosphorus reacts with clays and iron or aluminium oxides rendering it ‘fixed’ and unavailable to plants (see Figure 4.3).

Precipitation also results in a range of insoluble secondary phosphorous compounds forming in the soil and as a result as little as five per cent of the phosphorus applied is available to crops in the year of application due to these processes. These are distinguishable from direct losses such as product removal, run-off and leaching because the phosphorous though relatively unavailable remains in the soil (see Figure 4.3). Plant-available phosphorus in the soil solution is dominated by negatively charged orthophosphate ions (H_2PO^{4-} and HPO_4^{2-}) though small quantities of soluble organic phosphorus compounds might also be present. As a consequence, plant growth responses to phosphorus fertiliser are common despite soil phosphorus levels appearing adequate.

Highly weathered soils such as those in Western Australia have low levels of soil phosphorus (less than 10 mg/kg in sandy soils and less than 15 mg/kg in other soils) and rely on maintenance applications of fertiliser to support production. By comparison, in some areas soils with a long history of phosphorus fertilisation demonstrate surplus phosphorus levels have built up beyond crop and pasture requirements. In Victoria, New South Wales and Queensland for example, high levels of available soil phosphorus have been measured in some vertosols (cracking clay soils), despite phosphorus having been removed continuously in crop and pasture products. This is likely due to the mobilisation of insoluble phosphorus or redistribution of phosphorus from deeper in the soil profile.

Phosphorus and organic matter

Soil phosphorous can be divided into three pools, each differing in its availability to plants:

1. Soil organic phosphorus bound to organic compounds.
2. Inorganic compound phosphorus (phosphorus combined with Ca, Mg, Fe, Al or clay minerals).
3. Organic and inorganic phosphorus compounds associated with living cells.

Soil phosphorus moves between each of these pools via mineralisation (break down of organic matter), immobilisation and redistribution of phosphorus between microbes, organic matter and plants. Phosphorus is immobilised (made unavailable to plants) when it is incorporated into the living microbial biomass. Redistribution of phosphorus occurs when phosphorus is released from microbial cells (when they die and decompose) and transferred into other phosphorus pools. Phosphorus mineralisation and immobilisation occur simultaneously in soil. While mineralisation of soil organic phosphorus to inorganic phosphorus increases the availability of phosphorus to plants and microorganisms, a large proportion (between 15-80 per cent) of soil phosphorus remains in organic form and is unavailable to plants.

Plant residues, manures and grazing animal by-products contribute phosphorus to both the inorganic (soluble) and organic phosphorus pools. Harvest residues such as wheat straw and cotton trash typically have a lower concentration of phosphorus (less than 0.5 per cent) and therefore contribute less than animal manures, which contain between 0.5-3 per cent. Up to 70 per cent of the phosphorus in residues is water-soluble and rapidly released when the residues are incorporated into soil (Martin and Cunningham 1973; Ha et al. 2008). As organic residues decompose phosphorus is released more slowly.

The carbon to phosphorous ratio of organic matter can be used to predict whether phosphorus will be mineralised (released) or immobilised during organic matter decomposition. Net immobilisation of inorganic phosphorus is more likely if residues added to soil have a ratio of more than 300:1 (Brady and Weil 1996). As the ratio declines, phosphorus is in excess of microbial requirements, resulting in a net release of plant-available phosphorus. Microbial decomposition of crop residues available phosphorus. Microbial decomposition of crop residues with a phosphorus content more than 0.24 per cent results in a net increase of phosphorus mineralisation, while crop residues with a phosphorus content lower than 0.07 per cent result in net phosphorus immobilisation (Iqbal 2009).

Managing organic phosphorous

Removing plant biomass in the form of hay and grain and increasing frequency of leguminous crops in rotation, results in the export of phosphorus from farming systems. While burning stubbles tends to conserve soil phosphorus it removes carbon and nitrogen over the long-term. As phosphorus generally does not move more than a few millimetres in soil, its position within the soil profile influences plant uptake. The capacity of crop roots to explore soil is critical for effective plant uptake of phosphorus because phosphorus concentrated in upper soil layers can become less available to plants, especially in minimum tillage systems where phosphorous may be spatially isolated from plant roots and when soil becomes dry.

Plant adaptations have been noted in some plant species such as the white lupin (*L. Albus*), which releases organic compounds from their roots that mobilise soil-bound phosphorus and make it available to plants. Mycorrhizal associations with crop roots can also reportedly increase phosphorus uptake by increasing the effective root area. Despite their potential to contribute to phosphorus uptake in calcareous or phosphorous fixing soils (Li et al. 2005, 2006), mycorrhizal associations are not always beneficial to Australian crops. Crop responses are often dependent on background soil phosphorous status and the hosting ability of different plant types. Under low or sufficient phosphorus status mycorrhizal associations have been known to cause yield penalties (Ryan et al. 2002, 2005).

> Arbuscular mycorrhizal fungi have a symbiotic (defined in the broadest terms as two or more organisms living together) association with the root of a living plant and are primarily responsible for nutrient transfer.

Organic phosphorus sources are relatively slow-release, but it is not easy to predict exactly when soluble phosphorus will become available. To ensure a more reliable supply of phosphorus it is best to apply a combination of mineral and organic sources. Soils with a high tendency to adsorb or fix phosphorus are likely to require phosphorus fertiliser application to meet crop requirements even when soil tests suggest sufficient levels of phosphorus exist.

Diffusive Gradient in Thin-Films (DGT) is a new method of measuring soil phosphorus (Mason et al. 2010) and is shown to be more accurate than other conventional methods in estimating the phosphorus requirement of crops. It provides an improved measure of the phosphorus available for plant uptake and determines the likely yield response from additional fertiliser (see http://soilquality.org.au/factsheets/dgt-phosphorus for further information).

SULPHUR

Sulphur is essential for plant protein production and sulphur deficiency can lower grain quality. Sulphur is also critical for effective nitrogen fixation in legumes. Cereals typically require twice the amount of sulphur as phosphorus. As sulphur is relatively immobile in plants, a sustained supply of the mineral is required from the soil.

Sulphur and organic matter

Most sulphur in soil is bound in soil organic matter for surface soils (0-10 cm). The ratio of carbon to nitrogen to phosphorous to sulphur in soil organic matter is usually about 108:8:1:1 (108 units of carbon, eight units of nitrogen and one unit of phosphorous and sulphur). Many soils also contain gypsum in their subsoil layers.

Sulphate (SO_4^{-2}) is mineralised when soil organic matter is broken down and is the most plant-available form of sulphur in well aerated soils. Sulphate is made available to plants from organic matter with a carbon to sulphur ratio of less than 200:1. Residues with a carbon to sulphur ratio of more than 400:1 usually result in sulphur immobilisation (Delgado and Follet 2002). Sulphate not taken up by plants is vulnerable to leaching and in coarse textured soils under high rainfall sulphur is often deficient.

Sulphur deficiencies in the soil

Historically, sulphur deficiency has been rare in Australia because of the widespread use of superphosphate fertilisers containing sulphur. However, in recent years sulphur deficiency has become more evident with the switch to low-sulphate phosphate fertilisers and the increasing adoption of canola, which has a high sulphur requirement. Sulphur deficiency is particularly apparent in soils with high nitrogen availability, which increases yield potential and therefore sulphur demand. Removal of sulphur in organic matter via the harvest of crops and pastures can be rectified with a replacement strategy of between 2-5 kg of sulphur per tonne of grain or biomass removed (or in the case of canola 10 kg of sulphur per tonne of removed grain or biomass).

POTASSIUM

Between 95-98 per cent of the potassium in soil is unavailable to plants and exists as a structural component of soil minerals until broken down by weathering processes. Instead, plants largely acquire potassium in the form of exchangeable potassium, or dissolved potassium available in soil solution. Available soil potassium results from the net effects of supply processes, including mineral weathering, addition of fertilisers and mineralisation of organic inputs against losses associated with leaching, erosion, plant uptake and fixation.

Soil organic matter increases the soil's cation exchange capacity and in doing so increases the amount of soluble potassium, calcium and magnesium available for release during mineralisation (Delgado and Follet 2002). Potassium is also released relatively quickly from crop residues to contribute to the non-exchangeable, exchangeable and soil solution potassium pools. However, unlike nitrogen and phosphorous, available potassium in many situations appears more closely linked to soil type (clay complex) than soil organic matter.

SOIL ORGANIC MATTER AND PLANT AVAILABLE WATER

AT A GLANCE

- A one per cent increase in soil organic matter could potentially increase water holding capacity between 2-5 mm depending on soil type.
- A measure of bulk density is required to calculate soil organic carbon stocks (tonnes carbon per hectare) for carbon accounting frameworks.
- There is a link between increasing amounts of soil organic matter and increasing severity of water repellence across a range of soils, though most often observed in sandy soils.

Soil organic matter and in particular the humus fraction can hold several times its own weight in water. It seems logical, then, that increasing the organic matter content of soil would have a positive impact on the water holding capacity of a soil.

However, while there is indeed an established link between soil organic matter and water holding capacity, its importance declines with soil depth and increasing clay content (Hoyle et al. 2011). About 60 per cent of the organic matter in the top 30 cm of soil occurs in the surface layer (0-10 cm), so the influence of soil organic matter on soil water is most evident in the topsoil.

There is little influence of organic matter on plant available water late in the season when soil moisture is usually below 30 cm. Clay also functions to absorb soil water, decreasing the relative influence of soil organic matter on water holding capacity as the clay content of a soil increases (see Figure 5.1).

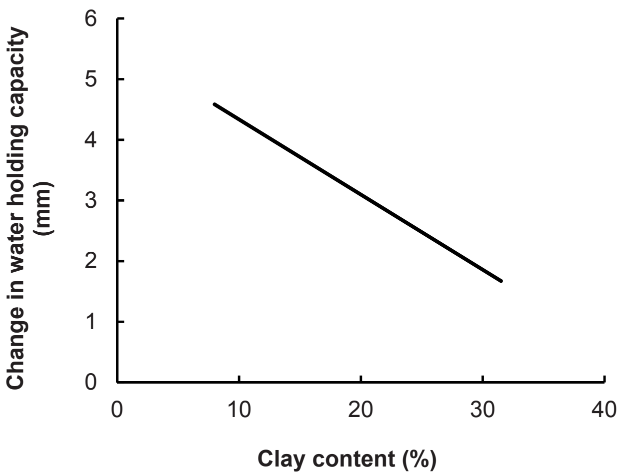


Figure 5.1 Change in water holding capacity for the 0-10 cm soil layer of South Australian red-brown earths, with a one per cent increase in soil organic carbon content (Hoyle et al. 2011).

The relative value of available soil water depends on the amount and frequency of rainfall in any one season. For example, any additional water holding capacity provided by soil organic matter is only likely to be beneficial when intermittent rainfall results in low, infrequent or variable soil water. In contrast, frequent or high in-crop rainfall is likely to diminish the impact of soil organic matter on soil water holding capacity. In addition, and depending on soil type, the amount of extra water held does not necessarily mean it will be available to plants due to its location in the profile relative to roots, or because it is held so tightly by the soil that it cannot be extracted by the plant.

Maximum amount of extra water stored from a 1% increase in soil organic carbon (SOC)
1% SOC = 14 t C ha* = 5.6 mm**

* Calculated to a depth of 10 cm in soil with a bulk density of 1.4
** Actual plant available water will be influenced by soil texture
** Assumes soil organic matter holds four times its weight in water

WHAT AFFECTS THE WATER HOLDING CAPACITY OF A SOIL?

The texture and structure of a soil determine its ability to form soil aggregates, which help determine water and nutrient storage (see Table 5.1). A soil organic carbon content of two per cent is considered optimal for aggregate stability (Kay and Angers 1999).

The spaces or pores that form between soil aggregates are capable of storing water and provide a home for soil biota. Soils with a wide range of particle sizes are unstable and are easily compacted to form dense, often impenetrable layers that constrain root growth. Organic matter helps to create and stabilise soil pores, promotes the formation of soil aggregates and contributes to soil water storage via its capacity to absorb water.

BARRIERS TO ROOT GROWTH

Physical, chemical and biological subsoil constraints can prevent plant roots from growing to depth. Pathogens, physical impediments or chemical barriers such as subsoil acidity and salinity can slow plant root growth and prevent access to subsoil moisture. Improving soil structure and removing these barriers to plant growth can improve the water storage capacity of the soil and increase the area and depth of soil available to plant roots for exploration.

Water and nutrients can move through compacted soil (see Plate 5.1), but often remain unavailable to plants because of restricted root growth. When soil strength measures about 2000 kilopascal (kPa), or has a bulk density higher than 1.7 g/cm^3 root growth typically stops, continues horizontally or occurs at a slower rate. Bulk density is influenced by soil organic

Table 5.1 Influence of soil characteristics on water storage capacity.

Soil characteristic	Effect on soil structure and water storage	Impact on crops
Increasing clay content	Helps form soil aggregates with small pore size, which increases water holding capacity. Clay soils with a high level of exchangeable sodium are likely to disperse and have poor aggregate stability.	Increased yield potential. Small pores can make it more difficult for plants to extract soil water under drying conditions. Poor aggregate stability can result in surface crusting, hard-setting, waterlogging and less available water.
Low clay or silt content (e.g. uniform, coarse textured soils such as deep sands, sandy earths)	Results in poor aggregation. Water drains freely through profile. Low water and nutrient storage capacity within the root zone.	Crops and pastures can run out of water in a tight (dry) finish. More prone to developing water repellence, restricting water entry.
Poor soil structure (e.g. dispersive, hard setting, naturally compacting soils)	Poor water infiltration. Increased risk of erosion. Low water storage capacity.	Crop yields often below potential due to lower water storage and restricted access to water.
Texture contrast soils (e.g. sand over clay duplex)	Plant available water depends on: • surface soil texture • depth to subsoil • nature and texture of subsoil • interface between surface and subsoil	Perched water table above dense clay subsoil can result in waterlogging.
Cracking clays (light clay texture throughout soil profile, with coarser material on the surface)	Water preferentially flows into cracks, while areas between cracks remain dry due to the dense soil structure and rapid water flow. Increased but spatially variable water storage capacity.	Water availability and yield potential determined by infiltration pattern and rooting depth.
High organic content soils	Fresh organic matter stimulates biological activity including soil fauna such as earthworms and termites, which in turn help form the soil pores that increase soil porosity, water infiltration and soil water capacity. Biological secretions, fungal hyphae and worm casts help to stabilise soil structure by bonding organic materials to soil minerals.	Higher yields when associated with increased soil water storage and nutrient cycling.

matter content, porosity and structure. Less dense, well-structured soils have a lower bulk density than poorly structured, low-organic or 'massive' soils (cemented in a large mass). Light textured sandy soils are prone to compaction and higher bulk density, both of which tend to increase with depth. Water movement is constrained at bulk densities higher than 1.6 g/cm^3.

A measure of bulk density is also needed to calculate 'stock' values of soil properties per unit area such as the amount of soil organic carbon per hectare and can be done as outlined on page 41.

Such calculations allow soil properties to be monitored accurately over time and ensure that when changes in bulk density occur the soil resource condition (e.g. soil organic carbon content)

Bulk density (BD) = soil mass per known volume of soil = g/cm^3

Measuring bulk density

This method works best for moist soils without gravel.

1. Prepare a flat, undisturbed surface at the depth you wish to sample.
2. Collect a known volume of soil (steel core or tube or PVC pipe; minimum 40 mm diameter and 100 mm depth) by pushing or gently hammering core into soil taking care not to compact it (see Plate 5.2).
3. Remove core, brush away any soil on the outside of tube, check soil is flush with core ends and place the soil from the core into a labelled plastic bag.
4. Record date, sample code and location of sample (if possible using GPS).
5. Weigh sample after drying to a constant weight and record soil weight.

Calculations

Soil volume

Soil volume (cm^3) = 3.14 x r^2 x h
h = height of the ring measured with the ruler in cm (e.g. 10 cm)
r = radius = half the diameter of the ring in cm (e.g. 7 cm ÷ 2 = 3.5 cm)
Soil volume = 3.14 x 3.5 x 3.5 x 10 = 385cm^3

Dry soil weight

To calculate the dry weight of the soil:

1. Weigh an ovenproof container such as a pie tin (record weight in grams = W1).
2. Carefully remove all soil from the bag into the container.
3. Dry the soil at 105ºC until a constant weight (usually 24-48 hours). Depending on size of the core and soil moisture this may take longer.
4. When dry, weigh the sample (record weight in grams = W2).
5. Record the dry soil weight (g) = W2 - W1

Bulk density calculation

Bulk density (g/cm^3) = dry soil weight (g)/soil volume (cm^3)

can be adjusted accurately (see Figure 5.2). In this example, a soil with an initial bulk density of 1.2 g/cm^3 and an organic carbon concentration of 1.2 per cent (14.4 tonnes organic carbon per hectare to 10 cm) was exposed to farming practices, which used over a period of 10 years resulted in topsoil compaction (see Figure 5.2). This increased the bulk density of the topsoil to 1.4 g/cm^3, but did not change the percentage of organic carbon in the soil. Without adjusting for the change in bulk density to an equivalent soil mass, a change in organic carbon stock of 2.4 tonnes per hectare would result. If the stocks are adjusted to an equivalent soil weight, then results show no change in organic carbon stocks (see Figure 5.2).

THE INFLUENCE OF SOIL ORGANIC MATTER ON SOIL WATER

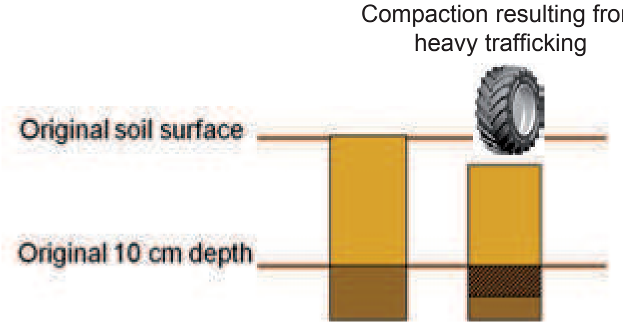
Plant residues that cover the soil surface prevent the soil from sealing and crusting. This can result in better water infiltration and decreased water losses associated with run-off. Evaporation is also decreased and up to 8 mm of soil water can be saved where more than 80 per cent of the soil surface is covered with residues compared with bare soil. If this water was available to plants it could return the equivalent of about 120 kg grain per hectare in wheat.

CALCULATING HOW MUCH WATER CAN BE STORED

While soil organic matter can hold between 2-5 times its weight in water, the impact of increasing soil organic matter on water holding capacity depends on the mineral composition of the soil, the depth to which organic matter has increased and the contribution of organic inputs to the various soil organic fractions (see Chapter 1).

As a general rule, each one percentage increase in soil organic matter increases water holding capacity in agricultural soils by an average of 2-4 per cent (0.8–8.0 percentage range; Hudson 1994). This is the equivalent of less than two per cent on average for a one per cent increase in soil organic carbon. For a soil that held 200 mm of soil water this would be equal to an additional 4 mm of water. However, as most of the soil organic matter will be in the top 10 cm of the soil, reports of increases in water holding capacity beyond 10 cm are likely to be an over-estimation.

Similarly, changes in water holding capacity should be considered in context to the likely changes in soil



Bulk density (BD; g/cm^3)	1.20	1.40	
Mass soil 0 – 10 cm (t/ha)	1200	1400	
Depth for equivalent soil mass (cm)	10.0	8.6*	= 10 x (1200/1400)
Organic carbon (%)	1.20%	1.20%	
Organic carbon (t C/ha)			
- no adjustment	14.4	16.8	
- adjusted for equivalent soil mass	14.4	14.4*	= 16.8 x (1200/1400)

Figure 5.2 Adjustment of organic carbon content for an equivalent soil mass associated with changes in bulk density and sampling depth.

Calculating the change in water-holding capacity due to organic matter

Scenario 1
A one per cent increase in soil organic carbon (SOC) in the top 10 cm of a sandy soil, with a bulk density (BD) of 1.4 g/cm^3 and no gravel or stone content.
Calculation (assuming one part soil organic carbon retains four parts water)
[SOC (%) x BD (kg soil/ha to 10 cm depth*)] x retention factor
= [0.01 x (1.4 x 100)] x 4
= 1.4 kg/m^2 x 4
= 5.6 litres/m^2 (or the equivalent of 5.6 mm)

** While unlikely, if this change was observed to 30 cm then = [0.01 x (1.4 x 300)] x 4 = 16.8 mm*

organic matter. For example, the likelihood of soil organic carbon being increased by more than one per cent is low because this level of change would require an additional 111 t/ha of organic matter to be added to the soil. This is calculated assuming a soil bulk density of 1.5 g/cm^3 to 10cm, carbon content of 45 per cent in plant material and a microbial efficiency of 70 per cent. Such an input level is highly unlikely in Australian agricultural systems even if considered over a 10-year time frame.

Often reported 'changes' in soil organic carbon stocks are inaccurate having not adjusted for changes in soil bulk density or stone content. Similarly, changes in the surface concentration (%) of organic carbon do not necessarily reflect a change in carbon stock over a deeper soil profile where the distribution of carbon within the profile may have altered.

Reported changes in soil water content due to increases in organic matter often relate to changes in water holding capacity and are not necessarily indicative of an increase in plant-available water. The difference between soil water holding capacity and plant-available water can vary widely depending on the mineral composition of the soil, the form and level of organic matter and whether associated changes in bulk density have been considered. In general, increasing soil organic matter will have a smaller effect on plant available water in soils with increasing clay content. It is therefore critical to take all these factors into account when assessing the potential impact of soil organic matter on soil water content.

HOW IMPORTANT IS 'EXTRA' WATER TO AGRICULTURAL PRODUCTION

The value of 'extra' soil water storage to crop and pasture yield depends on the amount and frequency of rainfall or irrigation as well as the water demand of the crop or pasture. If the water is available at a time when crops are otherwise water stressed, even a small amount of water could lift crop or pasture productivity. As a rule, each additional millimetre of rainfall (where water limited) can produce an additional 20 kg grain per hectare of wheat (French and Schulz 1984). However, where there is sufficient water availability or when soil constraints prevent plants accessing water then any extra soil moisture may not be used.

RELATIONSHIP BETWEEN ORGANIC MATTER AND WATER REPELLENCE

Organic matter is not always associated with improved water holding capacity because organic compounds that exhibit water repellent properties (see Plate 5.3 a) such as plant waxes can be implicated in the development of non-wetting soils (see Plate 5.3 b).

Although not restricted to any one climate or soil type, water repellence most often affects sands. An estimated 2-5 million hectares of agricultural land in southern Australia exhibits signs of soil water repellence (Roper 2004), with coastal sand-plain soils especially prone. Water repellence is a significant issue in agricultural systems because it slows water infiltration and constrains soil water storage. This often results in poor or uneven crop establishment and development, variable weed control, increased risk of soil erosion and decreased grain yield. Nationally, estimated losses for crop and pasture production due to water repellent soils is about $100-$250 million per year.

> An easy to use web-based tool for adjusting your soil carbon and nutrient concentration results for either bulk density or gravel/stone content is available at **www.soilquality.org.au/calculators/gravel_bulk_density**

WHAT CAUSES WATER REPELLENCE?

While all plants have waxes to prevent their desiccation, a range of more than 50 plant species including eucalyptus, acacia, clover and lupin and various organic compounds, including fungal derived sources, have been more closely associated with

water repellence. These materials break down and either mix with or coat soil particles making them hydrophobic, or water repellent. Most often water repellence is associated with the soil surface because this is where most of the organic matter is located.

Despite being associated with organic matter there is generally no direct relationship between total soil organic matter and water repellence. This is because organic matter content is one of several interacting variables that impact on the severity of soil water repellence (Harper et al. 2000). Rather it is a combination of the amount, type of organic matter present and soil texture that influences the susceptibility of soils to water repellence.

Blue lupins (*Lupinus consentinii*) are renowned for their capacity to cause severe water repellence. This is most likely not only associated with plant waxes, but also the large biomass associated with this plant type in many environments. For example, sandplain soils will develop moderate to severe water repellence following five years of continuous blue lupin production. Heavier soil types generally require higher amounts of organic matter to induce water repellence and as such it is less prevalent on these soil types. Sheep camps also tend to be more water repellent because they concentrate repellent organic matter and waxy substances that have not been broken down during sheep digestion. Similarly, in native vegetation a strong link exists between particular species such as *Eucalyptus astringens* (brown mallet), *E. patens* (blackbutt) and *Banksia speciosa* (showy banksia) and the occurrence of water repellence (Blackwell 1996).

Only a relatively small amount of organic matter (between 1-4 per cent of the soil mass) is required to inhibit water absorption and slow infiltration in sands. Water repellence has a similar impact on both deep and shallow sands in terms of limiting water entry (Moore 2001).

In general, coarse textured sands require less particulate organic material and develop repellence more rapidly than finer textured clay soils, but these may still exhibit water repellence (see Figure 5.3). It is also evident that increasing amounts of soil organic matter is associated with the development of more severe repellence for any given clay content (see Figure 5.3).

These results contrast to some extent with previous studies that found water repellence only occurred in soils with less than 10 per cent clay and was most severe in coarse textured sandy soils, with less than five per cent clay (Harper and Gilkes 1994).

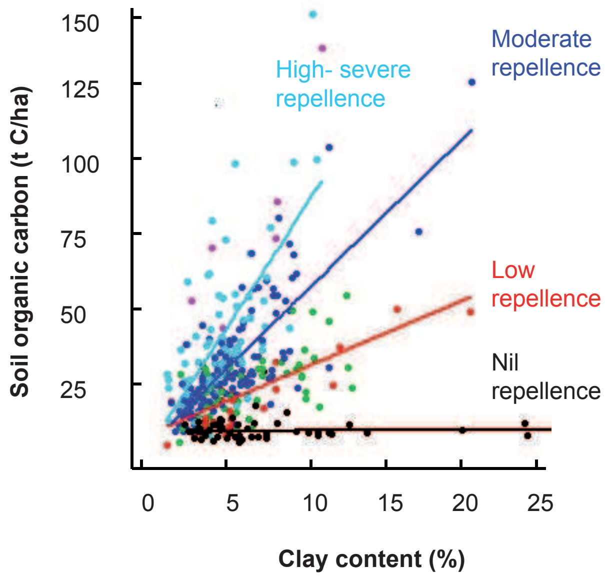


Figure 5.3 A complex relationship exists between soil organic carbon, clay content and the severity of water repellence as measured at 400 sites across Western Australia (Hoyle and Murphy unpublished) for MED severity (nil – black, very low – red, low – green, moderate – dark blue, severe – light blue, very severe – pink; King 1981).

Plate 5.1 A sub-surface compaction layer shows a dense impenetrable soil layer.
Source: Tim Overheu, DAFWA

Plate 5.2 Bulk density core.

Plate 5.3 a) Water droplet sitting on the surface of a non-wetting soil (Van Gool et al. 1999) and **b)** typical sub-surface dryness observed after rain in water repellent sand.

ORGANIC MATTER LOSSES FROM SOIL

AT A GLANCE

- Organic carbon in soil is concentrated at the soil surface (0-10 cm). Protecting this soil from loss is therefore critical to maintaining soil organic carbon levels.
- Much of the original loss of soil organic carbon was associated with the clearing and subsequent tillage of land for agricultural pursuits.
- Building soil organic carbon in coarse textured sandy soils is more challenging than in finer textured clay soils.
- Warm, moist soils increase the decomposition rate of soil organic matter.

When soils under natural vegetation are converted to agricultural land there is an important loss of soil organic carbon mainly in the form of carbon dioxide.

Organic matter levels in many Australian cropping soils have declined by between 10-60 per cent compared to pre-clearing levels (Dalal and Chan 2001). Based on a total arable soil area of 41 million hectares and assuming the carbon component of this organic matter measured between 30-60 tonnes carbon per hectare (top 30 cm of soil), the total historical loss in soil organic carbon is 646 million tonnes carbon (Chan et al. 2009). This represents the equivalent of nearly 2.4 billion tonnes of carbon dioxide emissions.

While soil forms and regenerates very slowly, it can degrade rapidly and could in essence be considered a non-renewable resource. Soil organic matter is in a constant state of turnover whereby it is decomposed and then replaced with new organic material. The balance between these additions and losses determines the relative flux and amount of soil organic matter present at any point in time.

Below-ground organic residues and root turnover represent direct inputs of organic matter into the soil system and have the potential to make major contributions to the soil organic matter stock (see Plate 6.1). The tight coupling between root distribution and the distribution of organic matter with depth is often cited as evidence of the importance of root inputs in maintaining stocks of soil organic carbon. In addition, roots generally decay more slowly than above-ground residue because of differences in litter quality and environmental factors (Sanderman et al. 2010).

DIRECT LOSSES

Soil erosion

In Australia, annual soil losses from erosion are negligible under a good pasture, but can be up to eight tonnes per hectare under planted crop. Erosion risk is strongly influenced by the amount of ground cover and the highest risk scenarios are most often associated with bare fallow, under which typical soil losses in a single year can reach between 60-80 tonnes per hectare. While less common, wind and water erosion resulting from single, high-intensity storms can erode up to 300 tonnes per hectare (see Plate 6.2). Since a 1 mm depth of soil weighs between 10-15 tonnes per hectare (assuming a bulk density of 1.0 to 1.5g/cm^3), erosion events in cropped soils represent a significant loss of topsoil along with its associated carbon and nutrient-rich fractions (Hoyle et al. 2011). Soil physical attributes associated with high organic matter content such as more stable soil aggregates, greater porosity, improved water infiltration and improved workability at high moisture content (plastic limit) all contribute to a lower risk of soil loss from erosion.

INDIRECT LOSSES

Losses of soil organic carbon occur primarily when organic matter is decomposed and mineralised to carbon dioxide. The rate at which organic matter is decomposed is driven by factors that regulate microbial activity, including climate (soil moisture and temperature), soil disturbance and the management of organic inputs.

Climate

In moist soils, organic matter breaks down more rapidly as average temperatures increase. As a general rule for every 10°C rise in average temperature between 5°C and 40°C the rate of mineralisation will nearly double where carbon substrates are not limited (see Figure 6.1; Hoyle et al. 2006). Therefore, it is more difficult to store large amounts of organic carbon in soils subject to high temperatures and even more difficult in soils exposed to high temperatures and extended periods of adequate soil water. In cooler environments, decomposition does not occur year-round and is constrained at low temperature.

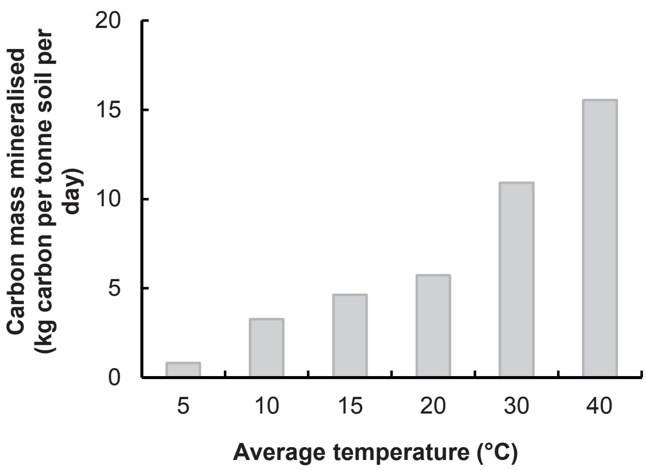


Figure 6.1 The effect of increasing temperature on the amount of carbon lost from soil (kg carbon per tonne of soil per day) where stubble has been retained (adapted from Hoyle et al. 2006).

Drying soils increasingly inhibit microbial activity and therefore decomposition of organic matter because there are fewer substrates and nutrients for microbial growth and reproduction. Soil moisture between 20-60 per cent of water holding capacity is considered optimal for microbial activity, with wetter soils inhibiting biological activity due to low oxygen availability.

As soils warm up in spring, the microbial biomass increases in size as well as activity. In general, population size and activity of soil microorganisms are highest during spring and lowest during winter. This means warm, moist environments can support high levels of microbial activity and soil organic matter can be lost quickly in these systems if organic inputs stop. Conversely, in soils with very low levels of soil microbial activity organic carbon can slowly accumulate and build to relatively high levels, despite being in an environment of poor productivity. For example, in highly acidic, waterlogged or clay soils, organic matter can accumulate but does not break down. Highly alkaline and in particular sodic soils do not support high organic carbon stocks.

Factors that control how sensitive organic matter is to decomposition include:

(1) *Physical protection.* Organic matter can be protected inside soil aggregates limiting access to it by microorganisms and their enzymes (Tisdall and Oades 1982). Micro-aggregates (53–250 mm) slow the turnover of soil organic matter, withstand physical disturbance and protect carbon more effectively than larger macro-aggregates (Angers et al. 1997; Six et al. 2002).

(2) *Chemical protection.* Organic matter can become adsorbed on to mineral surfaces protecting it from decomposition.

(3) *Drought.* Low soil moisture results in thinning or absent water films in soil, slowing the flow of extracellular enzymes and soluble carbon substrates. Organic compounds in dry or hydrophobic soils are isolated from degradation by water-soluble enzymes.

(4) *Flooding.* Flooding slows the diffusion of oxygen and constrains aerobic decomposition of organic matter.

(5) *Freezing.* The diffusion of substrates and extracellular enzymes within the soil below 0°C is extremely slow and this, in turn, slows the decomposition of organic matter (Davidson and Janssens 2006).

SOIL DISTURBANCE

Soil disturbance and cultivation can accelerate the decomposition of organic matter, increasing its rate of mineralisation. Cultivation and soil disturbance exposes previously protected organic matter to soil biota increasing its decomposition. Minimum tillage has the greatest potential to maintain, or perhaps increase levels of organic matter in Australian cropping soils over the long-term, especially in surface soils.

The increasing use of soil management practices such as mouldboard ploughing is likely to have a profound effect on the amount and distribution of soil organic matter and needs further study (see Plate 6.3).

MANAGEMENT OF ORGANIC RESIDUES

Soil organic carbon declines rapidly under fallow because of increased microbial attack on stored soil organic carbon supported by soil moisture conservation, a lack of plant production and, where practiced, due to cultivation for weed control which exposes previously protected organic matter to decomposition

Crop type, rotation and management influence soil organic carbon content. In general, soils under pasture have a higher soil organic content than those under cropping (Blair et al. 2006), while minimum tillage and stubble retention can either maintain or increase soil organic carbon in cropped soils (Chan and Heenan 2005). Applying inorganic fertilisers to low fertility soils can sometimes promote microbial activity and soil organic matter decomposition where nutrients are limiting, but also support greater plant productivity.

Loss of topsoil from erosion results in a direct loss of soil organic matter. Soil organic matter can also be affected indirectly by erosion when exposed sub-surface soil layers are subject to higher temperatures leading to an increase in organic matter mineralisation (Liddicoat et al. 2010).

Grazing can remove a significant amount of above-ground biomass — a proportion of which is returned to the soil as manure. Plant growth stage and grazing intensity can impact on the ability of pastures to recover and therefore the amount of above-ground biomass that makes its way into soil organic matter. Model estimates show a 10 per cent loss of organic carbon stocks over 30 cm associated with the net removal of 30 per cent of dry matter from an annual pasture paddock in Western Australia (Roth-C initialised at five per cent clay, 450 mm annual growing season rainfall, 75 tonnes carbon per hectare and no erosion loss).

THE FATE OF CAPTURED CARBON IN SOILS

The contribution of recently fixed carbon to soil carbon stocks depends on whether plant products stay on the land and are incorporated into soil, or are exported as hay and grain (see Plate 6.4).

In most farming systems a proportion of the carbon fixed during photosynthesis will be removed as grain. For grain crops, 30-50 per cent of the above-ground dry matter is typically removed from the farming system as grain or hay. Depending on how the stubble is managed the balance of the dry matter remains as above and below-ground (root) residues. Some carbon is transferred into the soil as root and mycorrhizal biomass and exudates.

Incorporating organic matter into the soil can, in some cases, increase the amount and persistence of organic carbon at depth. In farming systems, the majority of surface residues are mixed into soil during tillage. In natural systems, soil fauna such as earthworms and litter arthropods (e.g. mites and ants) fragment and mix surface residues into the soil. Upwards of 30 per cent of the mass of surface residues are leached into the soil. A proportion of this soluble organic carbon will be rapidly lost, while the remainder enters the soil to eventually become humus.

Plate 6.1 Canola roots contribute organic matter to soil.
Source: GRDC

Plate 6.2 Soil erosion resulting from poor ground cover and compaction.
Source: Paul Blackwell, DAFWA

Plate 6.3 Mouldboard plough in operation for the treatment of non-wetting soil.
Source: Evan Collis

Plate 6.4 The removal of products such as grain or hay can decrease organic matter inputs and contribute to soil acidification.
Source: Kondinin Group

07

GREENHOUSE GAS EMISSIONS

AT A GLANCE

- Methane, nitrous oxide and carbon dioxide are the main greenhouse gases associated with agricultural production.
- Greenhouse gas emissions are reported in carbon dioxide equivalents (CO_2-e).
- One tonne of carbon is equal to 3.67 tonnes of carbon dioxide.
- Soils act as both a source and sink for carbon.
- Increases in soil organic carbon must be permanent and verifiable to be traded.

Australia's greenhouse gas emissions are largely associated with methane (CH^4) from ruminant livestock digestion, nitrous oxide (N_2O) from soils and carbon dioxide (CO_2) from fossil fuel use and soils (Australian National Greenhouse Accounts 2011).

The contribution of different greenhouse gases to global warming is measured in carbon dioxide equivalents (CO_2-e), which allows all greenhouse gases to be compared with a common standard (that of carbon dioxide) and reflects how long the gases remain in the atmosphere and their ability to trap heat.

Globally, fossil fuel combustion, land use conversion, soil cultivation and cement manufacturing have largely been associated with a 36 per cent increase in atmospheric carbon dioxide concentrations from a pre-industrial level of 280 ppm to 380 ppm in 2006 (Lal and Follet 2009).

For example, over 100 years the global warming potential of:

- 1 tonne of methane = 25 tonnes of carbon dioxide
- 1 tonne of nitrous oxide = 298 tonnes of carbon dioxide

Source: IPCC, 4th Assessment 2007

In Australia, agricultural industries are the dominant source of methane (58 per cent) and nitrous oxide (77 per cent) emissions. In 2011, agricultural emissions were estimated at 84.1 million tonnes of carbon dioxide equivalents (CO_2-e) of which 65 per cent was methane and 19 per cent nitrous oxide. However, while agriculture contributes significantly to methane and nitrous oxide emissions it accounted for just 15.2 per cent of Australia's total greenhouse gas emissions in 2011. By comparison, the energy sector accounted for 76.4 per cent (417.4 Mt CO_2-e) of Australia's net emissions (Australian National Greenhouse Accounts 2011).

SOIL ORGANIC MATTER AND GREENHOUSE GAS EMISSIONS

Globally, soils are estimated to contain about three times as much carbon as that found in the world's vegetation. Soil organic matter and the carbon contained within it therefore play a critical role in the global carbon balance.

Historical conversion of native land to agricultural production has decreased the world's soil organic carbon stocks by between 40-60 per cent (Guo and Gifford 2002), or the equivalent of 78 Petagrams (Pg) of carbon (Lal 2004). These large losses coupled with concerns over rising atmospheric levels of carbon dioxide has driven interest in the possibility of the world's soils being used to store carbon and help mitigate climate change.

Agricultural soils have a high potential for carbon sequestration (albeit slowly in many cases) at relatively low cost. Increasing soil organic carbon could mitigate Australia's greenhouse gas emissions and the effects of climate change with co-benefits for productivity. Increasing soil organic carbon is also associated with biological resilience, which provides agro-ecosystems with the capacity to recover critical soil functions following short-term climate or environmental stresses.

A one per cent change in the amount of stored soil organic carbon equates to a change in atmospheric carbon dioxide concentration of about eight parts per million (Baldock et al. 2012).

Carbon dioxide

For every tonne of organic carbon that is decomposed, 3.67 tonnes of carbon dioxide is released to the atmosphere. Conversely, for every tonne of soil organic carbon created, 3.67 tonnes of carbon dioxide is removed from the atmosphere. For example, a one per cent increase in organic carbon in the top 30 cm of soil (with a bulk density of 1.2 g/cm^3), is equivalent to 36 tonnes per hectare of organic carbon or 132 tonnes carbon dioxide sequestered per hectare.

1 tonne of carbon is the equivalent of 3.67 tonnes of carbon dioxide.

One option available to lower atmospheric greenhouse gases is to remove carbon from the atmosphere by sequestering carbon dioxide in organic matter in a stable form (trees or soil carbon). Under current carbon accounting requirements the sequestered carbon must remain stored for at least 100 years and be verifiable for accounting purposes (Noble and Scholls 2001; Smith 2004).

Freshly deposited soil organic matter tends to readily oxidise to carbon dioxide unless it is converted to a more stable form. Stable forms of carbon take time to form and in many cases it can take years to rebuild a bank of stable carbon to previous levels.

The effect of nitrogen fertilisers on soil organic carbon stocks should be assessed on the net balance between increased carbon inputs from increased production versus increased decomposition if it occurs. In some cases, nitrogen inputs can actually slow down carbon loss because more carbon is stabilised. In other cases, nitrogen fertilisers can indirectly degrade soil organic carbon reserves because their addition stimulates a range of bacteria that feed on carbon for their growth and reproduction. For every tonne of fertiliser nitrogen applied, bacteria consume about 30 tonnes of carbon (based on a carbon to nitrogen ratio of 30 to 1).

Nitrous oxide

Nitrous oxide (N_2O) emissions account for about 10 per cent of global greenhouse gas emissions, with 90 per cent of these emissions derived from agricultural practices (Smith et al. 2007). The main source of nitrous oxide emissions worldwide is mineral nitrogen fertilisation and its influence on the nitrogen cycle.

As a consequence of its high global warming potential, nitrous oxide emissions from land can have a large bearing on the assessment of greenhouse gases from cropping systems (Australian National Greenhouse Accounts 2011). Barton et al. (2010) report nitrous oxide emitted after the application of synthetic nitrogen fertilisers to land under grain cropping systems to be 17 times lower than the Intergovernmental Panel on Climate Change (IPCC) default value of 1.0 per cent.

Nitrous oxide (N_2O) emissions account for about 10 per cent of global greenhouse gas emissions, with 90 per cent of these emissions derived from agricultural practices (Smith et al. 2007).

Nitrous oxide in soils is associated with microbial processes associated with nitrogen transformations. Denitrification occurs under anaerobic (waterlogged) conditions and involves the reduction of nitrate (NO_3-) to nitrogen gas (N_2), with nitrous oxide as a by-product (de Klein and Eckard 2008). Nitrification contributes to a lesser extent to nitrous oxide emissions by oxidising ammonium (NH_4+) to nitrate (NO_3-), with nitrous oxide as a by-product. Nitrification can be favoured at high temperatures and inhibited at acid pH values (Mengel and Kirkby 1987).

The influence of organic matter on nitrous oxide emissions is related to substrate availability. Current evidence suggests this is most closely associated with the carbon to nitrogen ratio of the dissolved (soluble) organic matter fraction, which differs among species and decomposition stages. A lower carbon to nitrogen ratio provides more mineralisable nitrogen substrate for microbial nitrous oxide production and increases the bioavailability of dissolved organic carbon.

Methane

Despite a short residence time (about 10 years) in the atmosphere, methane is the main hydrocarbon present in the atmosphere and due to its ability to absorb infrared radiation has 20-30 times the global warming potential of carbon dioxide (Rodhe 1990). Nearly 16 per cent of Australia's greenhouse gas emissions are associated with methane production from agriculture. A large proportion (just over 67 per cent) of this comes from methane produced by Australia's cattle and sheep industries (National Greenhouse Gas Inventory 2010).

Methane (CH_4) is a natural by-product of ruminant digestion in animals, wetland rice paddy farming and anaerobic decomposition of biological material. Its global warming potential is 21 times that of carbon dioxide. In soils, methane emissions are the net result of two bacterial processes influenced by land use, management and soil type — methane production and methane consumption. Methane is produced by methanogens in anaerobic soils that constrain oxygen diffusion such as in water-logged soils and methane consumption in aerobic soils by methane-oxidizing bacteria (Le Mer and Roger 2012).

CARBON OFFSETS FOR GREENHOUSE GAS EMISSIONS AND CARBON TRADING

Global markets for greenhouse gas emissions

Carbon trading markets have been introduced in some countries as a response to climate change imperatives and typically greenhouse gas emissions are limited by tradeable permits. Hence, a price for a set amount of emissions is determined by market forces, which should promote changes in production towards a lower-emission producing industry. In a number of European Union (EU) countries this has operated as a mandatory cap and trade scheme, which despite initially high permit prices and because of the recession, in May 2013 is currently trading at around 3.5 Euros ($4.67 based on an exchange rate of 0.75 Euros per Australian dollar) per metric ton on London's ICE Futures Europe exchange. Each carbon credit represents one tonne of carbon dioxide equivalents (CO_2-e).

The Australian situation

The Carbon Farming Initiative (CFI) aims to help Australia meet its international greenhouse gas obligations by undertaking land sector abatement projects that generate saleable carbon credits (Australian carbon credit units, ACCUs) or offsets. These offsets are either Kyoto compliant and can contribute towards Australia's national inventor, or be exchanged for Kyoto consistent credits and exported overseas, or are non-Kyoto compliant and commonly termed 'voluntary' carbon credits.

The Australian government introduced a fixed price of $23 per tonne of carbon dioxide for permits in July 2012 and is set to increase by five per cent a year through 2015 before shifting to a cap and trade system linked to the EU market. In Australia, around 500 companies have a mandatory obligation to pay for, or offset their direct emissions using carbon credits.

Currently, soil organic carbon can also be traded via voluntary carbon trading schemes both in Australia and internationally to offset greenhouse gas emissions. In an emissions trading framework, the term 'offset' describes the reduction or removal of greenhouse gas emissions in a 'non-covered' sector (i.e. not mandatory). Until very recently, the agricultural sector remained uncovered and constituted the primary opportunity for landholders to engage in the creation of carbon offsets.

Trading in voluntary carbon offsets may provide additional benefits to companies, including promotion and strengthening of environmental credentials, and promoting a perception within the community that they are taking responsibility for their emissions. Landholders wanting to participate in voluntary offset schemes are encouraged to seek legal and financial advice.

Afforestation and reforestation activities, which are included under Article 3.3 of the Kyoto Protocol, can be traded internationally and attract a premium over voluntary trading markets. These activities include as an example the establishment of planted trees of at least 2m in height in an area greater than 0.2 hectare that has been previously cleared of natural vegetation post December 31, 1989.

Should agriculture become a covered sector, landholders taking part would need to consider the whole farm implications of participating in carbon markets as they may then be required to report not only sequestration and mitigation gains, but also 'leakages' and losses from the system (i.e. increasing use of nitrogen fertilisers associated with nitrous oxide emissions and livestock methane emissions), which may result in a negative carbon balance overall.

In May 2013, the Australian government elected to include reporting of activities which include cropland management, grazing land management and revegetation towards their national greenhouse gas reduction target during the second commitment phase of the Kyoto protocol. This means that for an approved methodology developed under the Carbon Farming Initiative (CFI), these activities will be able to generate and sell Kyoto-compliant CFI credits. They also remain eligible for use in voluntary markets.

Offsets are assessed against internationally recognised standards to ensure real and verifiable abatement, including:

- Additionality (projects only happened because the offsets market was available)
- Permanence (carbon store must be maintained for 100 years)
- Accounting for leakage (emissions from elsewhere that nullify abatement must be accounted for)
- Measureable and auditable
- Conservative
- Internationally consistent
- Supported by peer reviewed science (where estimation methods are different to those used in Australia's National Greenhouse Accounts, peer reviewed science must support the estimation methods)

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/cm^3 bulk density; 1.2% organic carbon

10,000 m^2 in one hectare x 0.1m soil depth x 1.3 g/cm^3 bulk density x (1.2/100)
= 15.6 tonnes carbon hectare

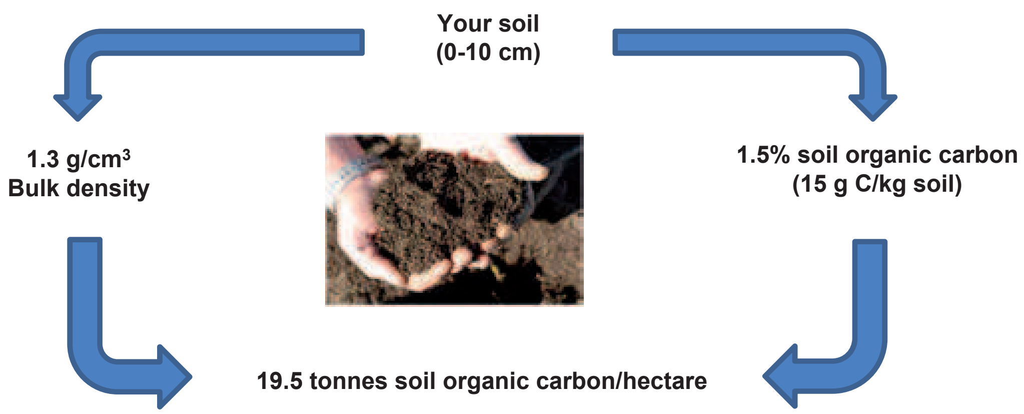
III) USING SOIL CARBON VALUES ADJUSTED FOR BULK DENSITY TO MEASURE TEMPORAL CHANGES IN SOIL ORGANIC CARBON OVER TIME

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 m^2 in one hectare x 0.1 m soil depth x 1.3 g/cm^3 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

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

10

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).

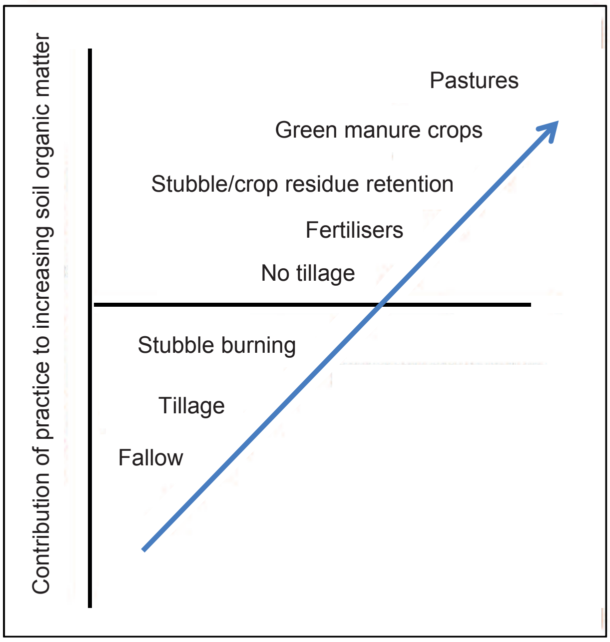


Figure 10.1 Summary of the relative effect of different management practices on soil carbon levels (Cotching 2009).

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

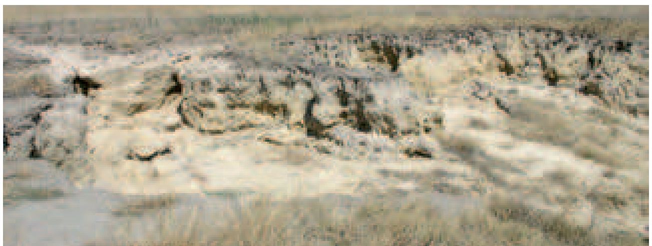


Plate 10.5 Soil collapse and erosion resulting from dispersion on a sodic soil.

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).

BEST ESTIMATE PREDICTIONS FOR AUSTRALIA

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

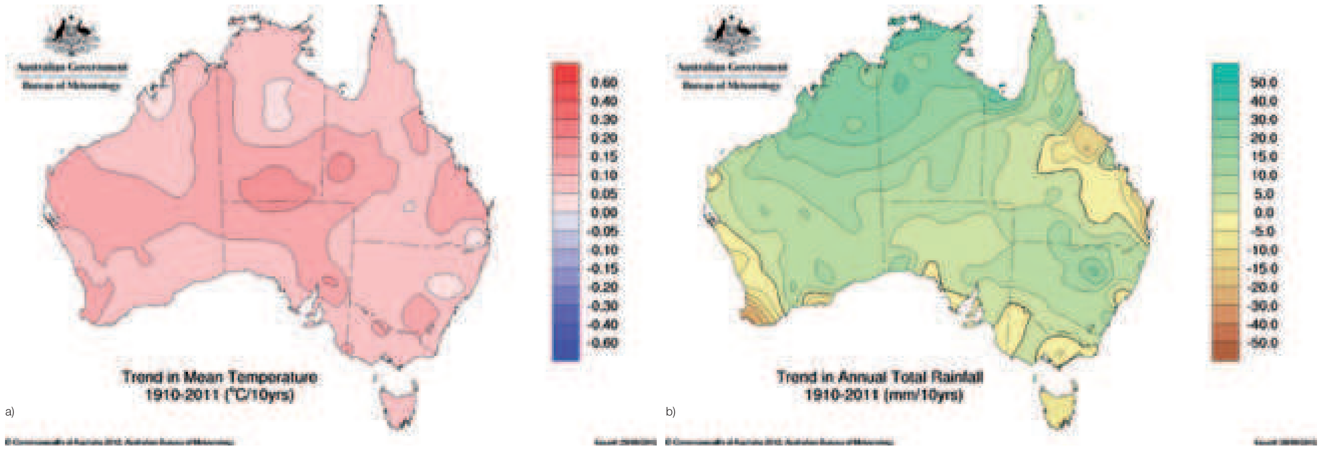


Figure 11.1 The trend in **a)** average temperature (°C) and **b)** annual total rainfall (mm) across Australia from 1910 to 2011 (Australian Bureau of Meteorology 2012).

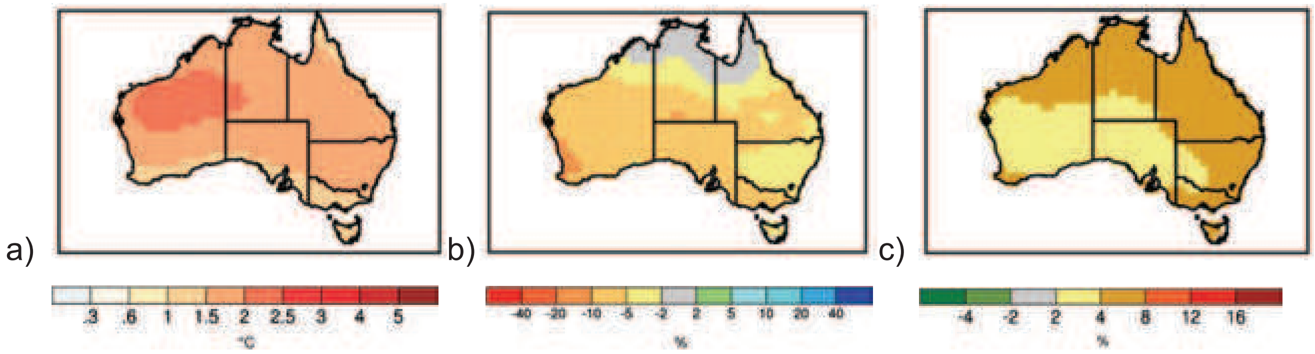
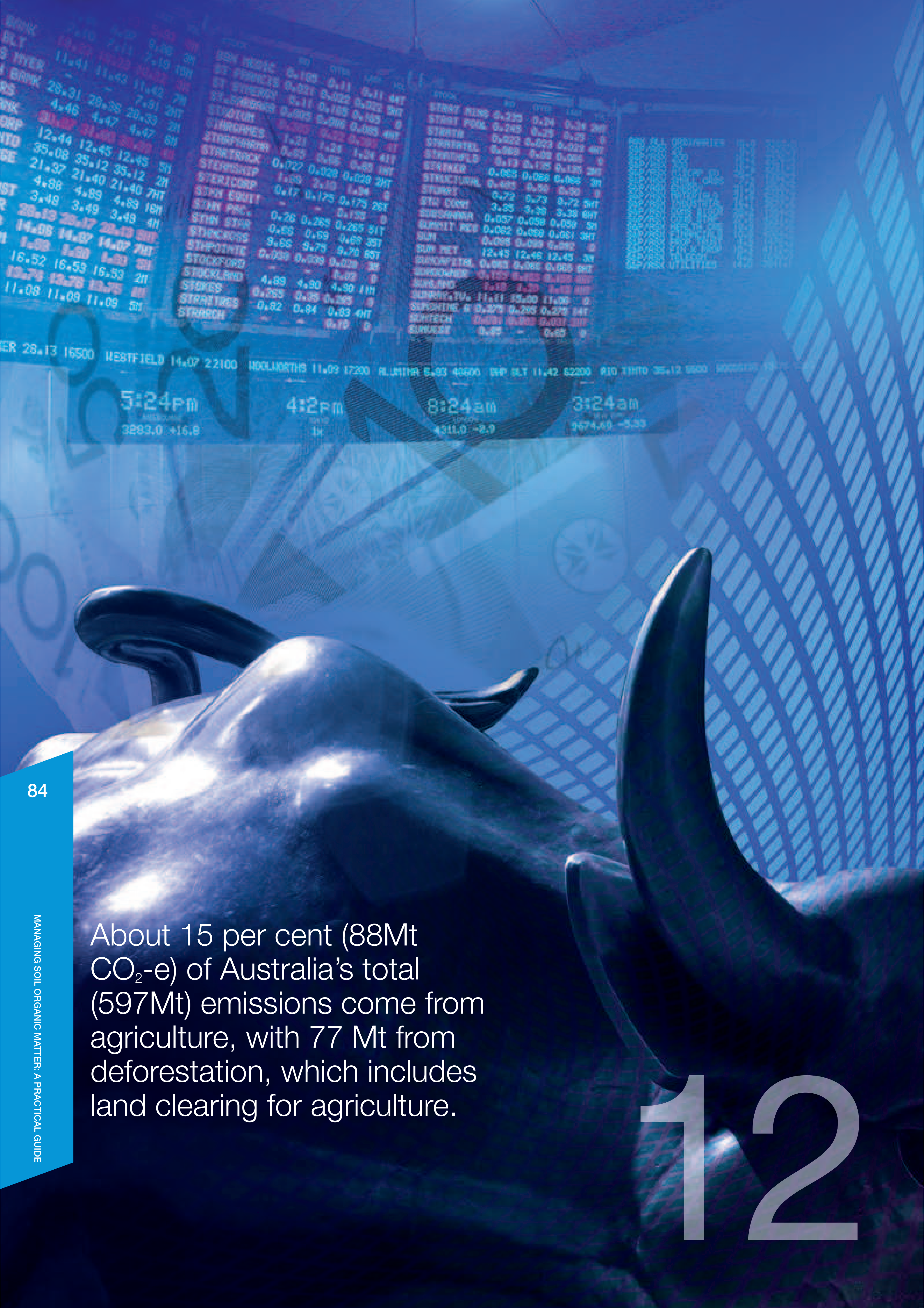


Figure 11.2 Climate change projections for average annual **a)** temperature **b)** rainfall and **c)** potential evapotranspiration (source: http://climatechangeinaustralia.com.au) for 2050 under a moderate emissions scenario (IPCC Special Report on Emission Scenarios 2000, A1B).

in traditional pasture-based systems in the south-west of Western Australia could stimulate a shift to grain production and a decline in organic inputs. In contrast, areas with increased summer rainfall could adopt summer cropping or feed opportunities that result in larger and more frequent organic matter inputs. However, under decreasing annual rainfall net primary production and soil organic matter content are expected to decline.

A decline in winter rainfall is less likely to have a significant impact on soil organic matter decomposition unless soil moisture falls below that required to support biological activity. Increased soil moisture during summer is expected to result in faster rates of organic matter decomposition in New South Wales, western Queensland and the northern tropics. In contrast, higher temperatures combined with drier soils are likely to slow organic matter decomposition.

Despite grain growing areas experiencing a 20 per cent decline in rainfall over the past 30 years, nearly two thirds of Western Australian agricultural businesses have kept growing (Kingwell et al. 2013). This suggests that when climate change is relatively gradual, access to improved crop genetics, farming technology, knowledge and business tools will enable farmers to adapt successfully to new production constraints (Kingwell et al. 2013). Adapting to climate change over the next few decades will more likely depend on dealing successfully with seasonally significant events such as flood, frosts, drought and price fluctuations.



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.

12

ECONOMIC CONSIDERATIONS AND IMPLICATIONS IN A CARBON TRADING ENVIRONMENT

In 2011 the Australian government introduced the Carbon Farming Initiative (CFI). The initiative allows farmers and land managers to earn carbon credits by storing carbon or reducing greenhouse gas emissions on the land. These credits can then be sold to people and businesses wishing to offset their emissions. The CFI operates independently of Australia's Kyoto Protocol target and includes abatement from uncovered sectors such as soil and tree carbon, which previously have been traded primarily in voluntary domestic markets.

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

i) The diffuse nature of emissions and sinks associated with farming system.
ii) The wide range of climates and production systems within the Australian agricultural sector.
iii) The high costs associated with compliance and auditing of greenhouse gas emissions, which requires accounting across whole farming systems for carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4).

Recent changes to the Kyoto Protocol stipulate that emissions resulting from natural causes can no longer be counted towards a country's Kyoto targets. In response to this the Australian government has elected to account for the greenhouse gas emissions associated with crop and grazing land management and revegetation during our second commitment phase of the Kyoto protocol from May 2013. This means that with an approved methodology developed under the Carbon Farming Initiative (CFI) these activities can now be used to generate and sell Kyoto-compliant CFI credits. The activities also remain eligible for use in voluntary markets.

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.

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.

13

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).

REFERENCES

CHAPTER 1

Baldock J, Grundy M, Wilson P, Jacquier D, Griffin T, Chapman G, Hall J, Maschmet D, Crawford D, Hill J, Kidd D (2009); Identification of areas within Australia with the potential to enhance soil carbon content; results of a multi-criterion analysis undertaken by CSIRO, state and territory agencies; CSIRO Land & Water.

Cork S, Harper P, Joy R, Kanowski P, Mackay R, McKenzie N, Ward T, Wienecke B (2011); Australia State of the Environment Report; Commonwealth of Australia.

Griffin T, Hoyle FC, Murphy DV (2013); Report Card on Sustainable Natural Resource Use in Agriculture; Department of Agriculture and Food.

Hoyle FC, Murphy DV, Fillery IRP (2006); Temperature and stubble management influence microbial CO_2–C evolution and gross N transformation rates; *Soil Biology & Biochemistry 38*; pp. 71–80.

Hoyle FC, Baldock J, Murphy DV (2011); Soil Organic Carbon – Role in Rainfed Farming Systems; *Rainfed Farming Systems* (Eds. P Tow, I Cooper, I partridge, Birch); pp. 339-361.

Ingram JSI, Fernandes ECM (2001); Managing carbon sequestration in soils: concepts and terminology; *Agriculture, Ecosystems and Environment 87*; pp. 111–117.

CHAPTER 2

Chan KY, Heenan DP (2006); Earthworm population dynamics under conservation tillage systems in south-eastern Australia; *Soil Research 44*; pp. 425-431.

Bhadauria T, Saxena KG (2010); Role of earthworms in soil fertility maintenance through the production of biogenic structures; *Applied and Environmental Soil Science 2010*; Article ID 816073.

Buckerfield JC (1992); Earthworm populations in dryland cropping soils under conservation-tillage in South Australia; *Soil Biology and Biochemistry 24*; pp. 1667-1672.

Dalal RC, Allen DE, Wang WJ, Reeves S, Gibson I (2011); Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation; *Soil and Tillage Research 12*; pp. 133-139.

Franzleubbers AJ (1999); Microbial activity in response to water-filled pore space of variably eroded southern Piedmont soils; *Applied Soil Ecology 11*; pp. 91-101.

Hoyle FC and Murphy DV (2011); Influence of organic residues and soil incorporation on temporal measures of microbial biomass and plant available nitrogen; *Plant and Soil 347*; pp. 53-64.

Kautz G, Topp W (2000); Acquisition of microbial communities and enhanced availability of soil nutrients by the isopod Porcellio scaber (Latr.); *Biology and Fertility of Soils 31*; pp. 102-107.

Krull E, Baldock J, Skjemstad J (2001); Soil texture effects on decomposition and soil carbon storage; *NEE Workshop Proceedings*; pp. 103-110.

Mele PM, Carter MR (1999); Species abundance of earthworms in arable and pasture soils in south-eastern Australia; *Applied Soil Ecology 12*; pp. 129-137.

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).

BEST ESTIMATE PREDICTIONS FOR AUSTRALIA

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

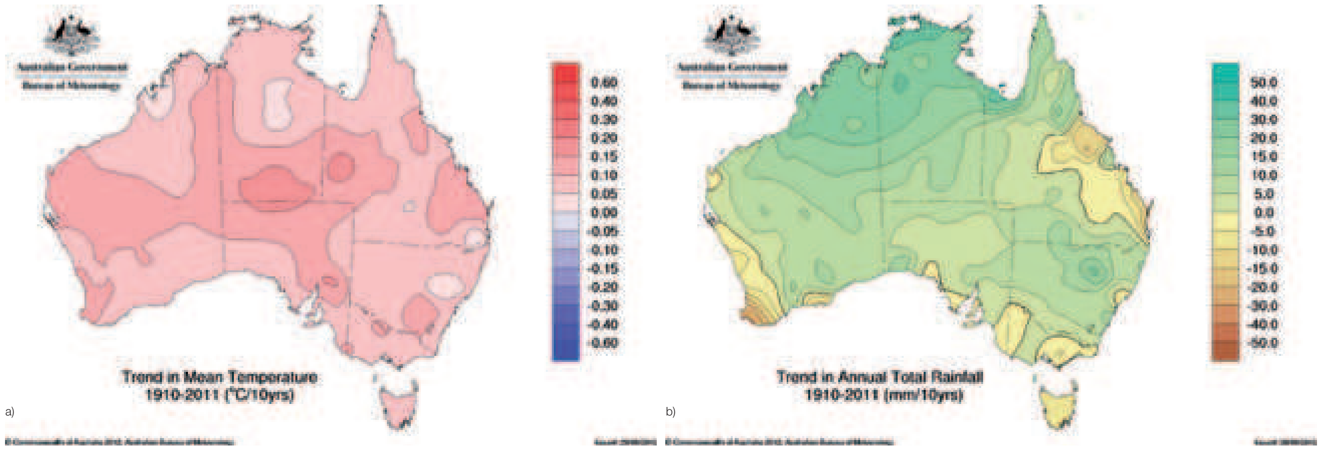


Figure 11.1 The trend in **a)** average temperature (°C) and **b)** annual total rainfall (mm) across Australia from 1910 to 2011 (Australian Bureau of Meteorology 2012).

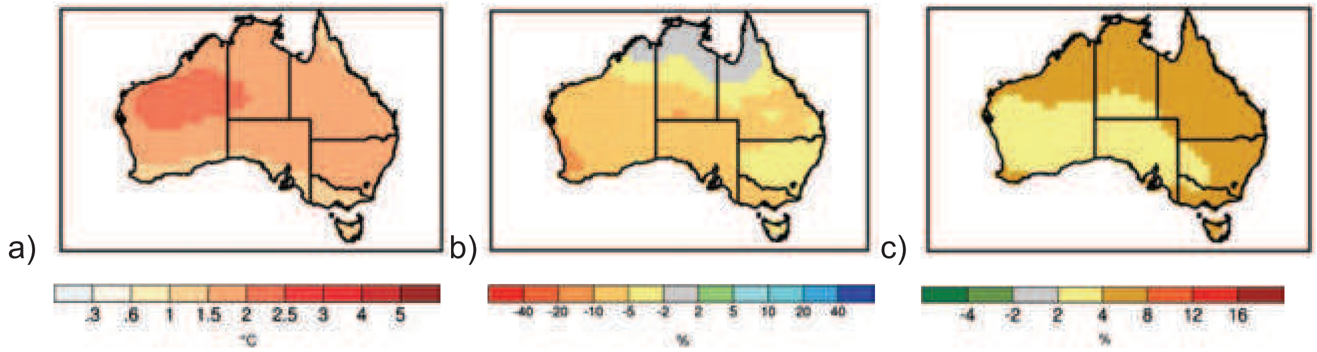
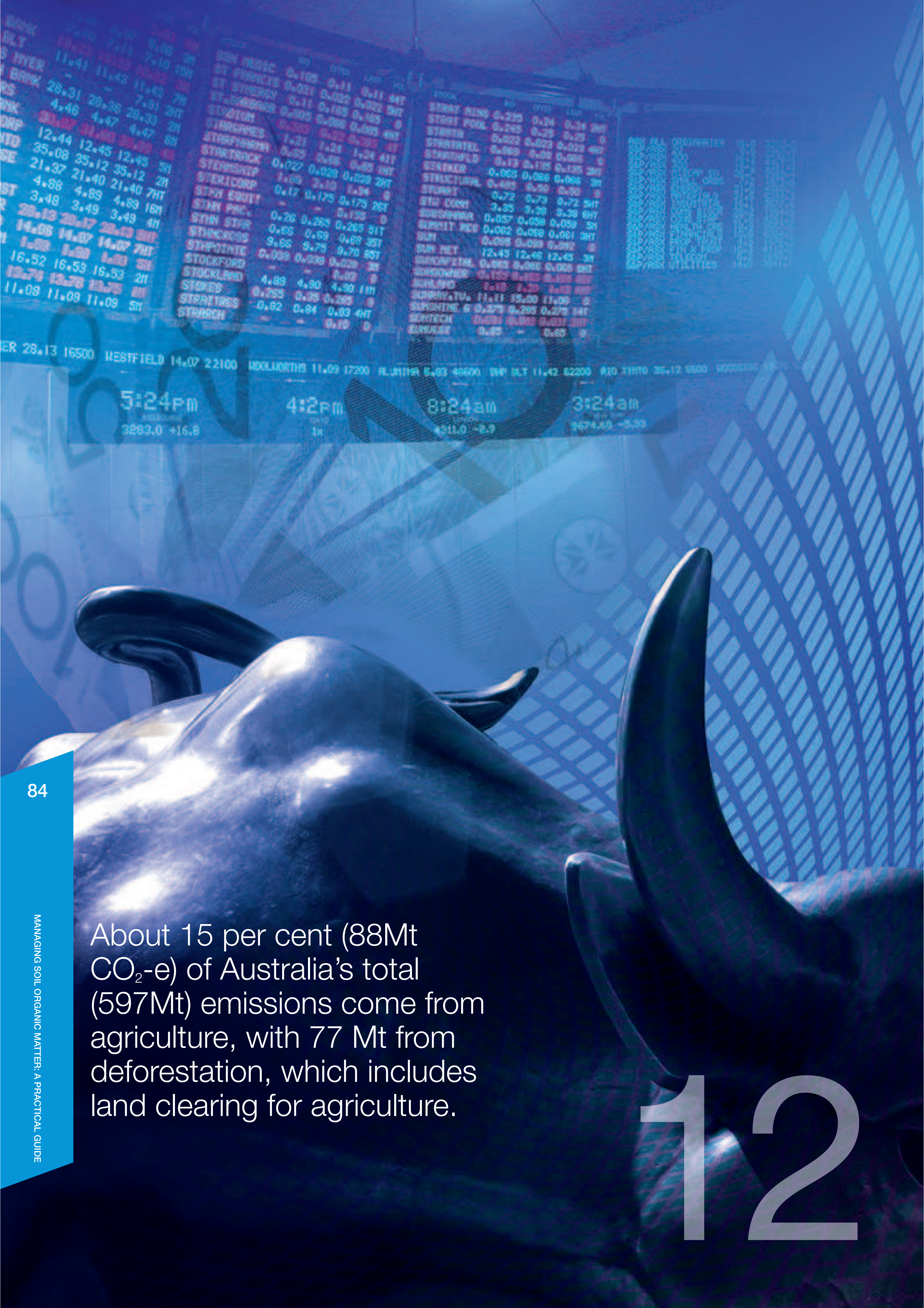


Figure 11.2 Climate change projections for average annual **a)** temperature **b)** rainfall and **c)** potential evapotranspiration (source: http://climatechangeinaustralia.com.au) for 2050 under a moderate emissions scenario (IPCC Special Report on Emission Scenarios 2000, A1B).

in traditional pasture-based systems in the south-west of Western Australia could stimulate a shift to grain production and a decline in organic inputs. In contrast, areas with increased summer rainfall could adopt summer cropping or feed opportunities that result in larger and more frequent organic matter inputs. However, under decreasing annual rainfall net primary production and soil organic matter content are expected to decline.

A decline in winter rainfall is less likely to have a significant impact on soil organic matter decomposition unless soil moisture falls below that required to support biological activity. Increased soil moisture during summer is expected to result in faster rates of organic matter decomposition in New South Wales, western Queensland and the northern tropics. In contrast, higher temperatures combined with drier soils are likely to slow organic matter decomposition.

Despite grain growing areas experiencing a 20 per cent decline in rainfall over the past 30 years, nearly two thirds of Western Australian agricultural businesses have kept growing (Kingwell et al. 2013). This suggests that when climate change is relatively gradual, access to improved crop genetics, farming technology, knowledge and business tools will enable farmers to adapt successfully to new production constraints (Kingwell et al. 2013). Adapting to climate change over the next few decades will more likely depend on dealing successfully with seasonally significant events such as flood, frosts, drought and price fluctuations.



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.

12

ECONOMIC CONSIDERATIONS AND IMPLICATIONS IN A CARBON TRADING ENVIRONMENT

In 2011 the Australian government introduced the Carbon Farming Initiative (CFI). The initiative allows farmers and land managers to earn carbon credits by storing carbon or reducing greenhouse gas emissions on the land. These credits can then be sold to people and businesses wishing to offset their emissions. The CFI operates independently of Australia's Kyoto Protocol target and includes abatement from uncovered sectors such as soil and tree carbon, which previously have been traded primarily in voluntary domestic markets.

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

i) The diffuse nature of emissions and sinks associated with farming system.
ii) The wide range of climates and production systems within the Australian agricultural sector.
iii) The high costs associated with compliance and auditing of greenhouse gas emissions, which requires accounting across whole farming systems for carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4).

Recent changes to the Kyoto Protocol stipulate that emissions resulting from natural causes can no longer be counted towards a country's Kyoto targets. In response to this the Australian government has elected to account for the greenhouse gas emissions associated with crop and grazing land management and revegetation during our second commitment phase of the Kyoto protocol from May 2013. This means that with an approved methodology developed under the Carbon Farming Initiative (CFI) these activities can now be used to generate and sell Kyoto-compliant CFI credits. The activities also remain eligible for use in voluntary markets.

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.

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.

13

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).

REFERENCES

CHAPTER 1

Baldock J, Grundy M, Wilson P, Jacquier D, Griffin T, Chapman G, Hall J, Maschmet D, Crawford D, Hill J, Kidd D (2009); Identification of areas within Australia with the potential to enhance soil carbon content; results of a multi-criterion analysis undertaken by CSIRO, state and territory agencies; CSIRO Land & Water.

Cork S, Harper P, Joy R, Kanowski P, Mackay R, McKenzie N, Ward T, Wienecke B (2011); Australia State of the Environment Report; Commonwealth of Australia.

Griffin T, Hoyle FC, Murphy DV (2013); Report Card on Sustainable Natural Resource Use in Agriculture; Department of Agriculture and Food.

Hoyle FC, Murphy DV, Fillery IRP (2006); Temperature and stubble management influence microbial CO_2–C evolution and gross N transformation rates; *Soil Biology & Biochemistry 38*; pp. 71–80.

Hoyle FC, Baldock J, Murphy DV (2011); Soil Organic Carbon – Role in Rainfed Farming Systems; *Rainfed Farming Systems* (Eds. P Tow, I Cooper, I partridge, Birch); pp. 339-361.

Ingram JSI, Fernandes ECM (2001); Managing carbon sequestration in soils: concepts and terminology; *Agriculture, Ecosystems and Environment 87*; pp. 111–117.

CHAPTER 2

Chan KY, Heenan DP (2006); Earthworm population dynamics under conservation tillage systems in south-eastern Australia; *Soil Research 44*; pp. 425-431.

Bhadauria T, Saxena KG (2010); Role of earthworms in soil fertility maintenance through the production of biogenic structures; *Applied and Environmental Soil Science 2010*; Article ID 816073.

Buckerfield JC (1992); Earthworm populations in dryland cropping soils under conservation-tillage in South Australia; *Soil Biology and Biochemistry 24*; pp. 1667-1672.

Dalal RC, Allen DE, Wang WJ, Reeves S, Gibson I (2011); Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation; *Soil and Tillage Research 12*; pp. 133-139.

Franzleubbers AJ (1999); Microbial activity in response to water-filled pore space of variably eroded southern Piedmont soils; *Applied Soil Ecology 11*; pp. 91-101.

Hoyle FC and Murphy DV (2011); Influence of organic residues and soil incorporation on temporal measures of microbial biomass and plant available nitrogen; *Plant and Soil 347*; pp. 53-64.

Kautz G, Topp W (2000); Acquisition of microbial communities and enhanced availability of soil nutrients by the isopod Porcellio scaber (Latr.); *Biology and Fertility of Soils 31*; pp. 102-107.

Krull E, Baldock J, Skjemstad J (2001); Soil texture effects on decomposition and soil carbon storage; *NEE Workshop Proceedings*; pp. 103-110.

Mele PM, Carter MR (1999); Species abundance of earthworms in arable and pasture soils in south-eastern Australia; *Applied Soil Ecology 12*; pp. 129-137.

Osler G (2007); Impact of Fauna on Chemical Transformations in Soil; *Soil Biological Fertility* (Eds. L Abbott, DV Murphy); pp. 17-35.

Peoples MB (2002); Biological fixation, contributions to agriculture; *Encyclopedia of Soil Science* (Ed. R Lal); Marcel Dekker, New York.

Roget DK (1995); Decline in root rot (Rhizoctonia solani AG-8) in wheat in a tillage and rotation experiment at Avon, South Australia; *Australian Journal of Experimental Agriculture 35*; pp. 1009-1013.

Roget DK (2006); Lift soil microbial activity to reduce disease; *Farming Ahead 168*; pp. 28-30.

Widmer TL, Mitkowski NA, Abawi GS (2002); Soil organic matter and management of plant-parasitic nematodes; *Journal of Nematology 34*; pp. 289-295.

CHAPTER 3

Chan KY, Conyers MK, Li GD, Helyar KR, Poile G, Oates A, Barchia IM (2010); Soil carbon dynamics under different cropping and pasture management in temperate Australia: results of three long-term experiments.; *Soil Research 49*; pp. 320-328.

Grace P, Ladd JN, Robertson GP, Gageet SH (2006); SOCRATES — A simple model for predicting long-term changes in soil organic carbon in terrestrial ecosystems; *Soil Biology & Biochemistry 38*; pp. 1172-1176.

Kay BD, Angers DA (1999); Soil Structure; *Handbook of Soil Science* (Ed. ME Sumner); CRC Press, Boca Raton, USA; pp. 229-276.

O'Halloran N, Fisher P, Aumann C, Rab A (2010); Relationship between organic matter retention and soil carbon in irrigated mixed farming systems; 19th World Congress of Soil Science, Soil Solutions for a Changing World, August 2010, Brisbane, Australia.

Perry MW, Belford RK (2000) The structure and development of the cereal plant. In: The Wheat Book Principles and Practice (Eds. WK Anderson, J Garlinge). Department of Agriculture and Food Western Australia. Bulletin 4443 pp.23-36.

CHAPTER 4

Angus JF (2001); Nitrogen supply and demand in Australian agriculture; *Australian Journal of Experimental Agriculture 41*; pp. 277-288.

Brady NC, Weil RR (1996); The nature and properties of soils; New Jersey, Prentice Hall.

Delgado JA, Follett RF (2002); Carbon and nutrient cycles; Journal of Soil and Water Conservation 57; pp. 455-464.

Ha KV, Marschner P, Bünemann EK (2008); Dynamics of C, N, P and microbial community composition in particulate soil organic matter during residue decomposition; P*lant and Soil 303*; pp. 253-264.

Helling CS, Chesters G, Corey RB (1964); Contribution of Organic Matter and Clay to Soil Cation-Exchange Capacity as Affected by the pH of the Saturating Solution; *Soil Science Society of America Journal 28*; pp. 517-520.

Iqbal SM (2009); Effect of crop residue qualities on decomposition rates, soil phosphorus dynamics and plant phosphorus uptake; PhD thesis, University of Adelaide.

Li CJ, Zhu YG, Marschner P, Smith FA, Smith SE (2005); Wheat responses to arbuscular mycorrhizal fungi in a highly calcareous soil differ from those of clover, and change with plant development and P supply; *Plant and Soil 277*; pp. 221–232.

Li H, Smith SE, Holloway RE, Zhu Y, Smith FA (2006); Arbuscular mycorrhizal fungi contribute to phosphorus uptake by wheat grown in phosphorus-fixing soil even in the absence of positive growth response; *New Phytologist 172*; pp. 536–543.

Martin JK, Cunningham RB (1973); Factors controlling the release of phosphorus from decomposing wheat roots; *Australian Journal of Biological Science 26*; pp. 715-727.

Mason S, McNeill A, McLaughlin MJ, Zhang H (2010); Prediction of wheat response to an application of phosphorus under field conditions using diffusive gradients in thin-films (DGT) and extraction methods; *Plant and Soil 337*; pp. 243-258.

Mengel K, Kirkby EA (1987); *Principles of plant nutrition* (4th Ed); IPI, Bern; pp. 687.

Moore G, Dolling P, Porter B and Leonard L (1998); *Soilguide: A handbook for understanding and managing agricultural soils* (Ed. G Moore); Agriculture Western Australia Bulletin No. 4343.

Murphy DV, Recous S, Stockdale EA, Fillery IRP, Jensen LS, Hatch DJ, Goulding KWT (2003); Gross nitrogen fluxes in soil: theory, measurement and application of 15 N pool dilution techniques; *Advances in Agronomy 79*; pp. 69-118.

Purdie B (1998); Understanding and interpreting soil chemical and physical data; Soilguide: A handbook for understanding and managing agricultural soils (Ed. G Moore); Agriculture Western Australia Bulletin No. 4343.

Rice CW (2002); Organic matter and nutrient dynamics; *Encyclopedia of Soil Science* (Ed. R Lal); Marcel Dekker, New York.

Ryan MH, Norton RM, Kirkegaard JA, McCormick KM, Knights SE, Angus JF (2002); Increasing mycorrhizal colonisation does not improve growth and nutrition of wheat on vertosols in south-eastern Australia; *Australian Journal of Agricultural Research 53*; pp. 1173-1181.

Ryan MH, Van Herwaarden A, Angus JF, Kirkegaard JA (2005); Reduced growth of autumn-sown wheat in a low-P soil is associated with high colonisation by arbuscular mycorrhizal fungi; *Plant and Soil 270*; pp. 275-286.

Turpault MP, Bonnaud P, Fighter J, Ranger J, Dambrine IE (2005); Distribution of cation exchange capacity between organic matter and mineral fractions in acid forest soils (Vosges mountains, France); *European Journal of Soil Science 47*; pp. 545-556.

Williams CH, Donald CM (1957); Changes in organic matter and pH in a podzolic soil as influenced by subterranean clover and superphosphate; *Australian Journal of Agricultural Research 8*; pp. 179-189.

CHAPTER 5

Blackwell P (1996); Managing water repellent soils; Department of Agriculture and Food Western Australia *Farmnote* 109/96.

French RJ, Schultz JE (1984); Water use efficiency of wheat in a Mediterranean-type environment: 1. The relationship between yield, water use and climate; *Australian Journal of Agricultural Research 35*; pp. 743-764.

Harper RJ, Gilkes RJ (1994); Soil attributes related to water repellency and the utility of soil survey for predicting its occurrence; *Australian Journal of Soil Research 32*; pp. 1109-24.

Harper RJ, McKissock I, Gilkes RJ, Carter DJ, Blackwell PS (2000); A multivariate framework for interpreting the effects of soil properties, soil management and land use on water repellency; *Journal of Hydrology 231-232*; pp. 371-383.

Hudson BD (1994); Soil organic matter and available water capacity; *Journal of Soil Water Conservation 49*; pp. 189-194.

King PM (1981); Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement; *Journal of Soil Research 19*; pp. 275-285.

Moore G (2001); Soilguide: A handbook for understanding and managing agricultural soils; Agriculture Western Australia Bulletin No. 4343.

Roper MM (2004); The isolation and characterisation of bacteria with the potential to degrade waxes that cause water repellency in sandy soils; *Australia Journal of Soil Research 42*; pp. 427-433.

Van Gool D, Tille P and Moore G (1999); Land evaluation standards for land resource mapping; Department of Agriculture and Food; Resource Management Technical Report #298 (3rd ed).

CHAPTER 6

Angers DA, Recous S, Aita C (1997); Fate of carbon and nitrogen in water-stable aggregates during decomposition of 13C 15N-labelled wheat straw in situ; *European Journal of Soil Science 48*; pp. 295-300.

Blair N, Faulkner RD, Till AR, Poulton PR (2006); Long-term management impacts on soil C, N and physical fertility Part 1: Broadbalk experiment; *Soil and Tillage Research 91*; pp. 30-38.

Chan KY, Heenan DP (2005); The effects of stubble burning and tillage on soil carbon sequestration and crop productivity in south-eastern Australia; *Soil Use and Management 21*; pp. 427-431.

Chan KY, Cowie A, Kelly G, Singh B, Slavich P (2009); Scoping Paper: Soil Organic Carbon Sequestration Potential for Agriculture in NSW; NSW Department of Primary Industries; ISBN 978 0 7347 1957 7.

Dalal R, Chan KY (2001); Soil organic matter in rained cropping systems of Australian cereal belt; *Australian Journal of Soil Research 39*; pp. 435-464.

Davidson EA, Janssens IA (2006); Temperature sensitivity of soil carbon decomposition and feedbacks to climate change; *Nature 440*; pp. 165-173.

Liddicoat C, Hayman P, Alexander B, Rowland J, Maschmedt D, Young M-A, Hall J, Herrmann T, Sweeney S (2012); Climate change, wheat production and erosion risk in South Australia's cropping zone: Linking crop simulation modelling to soil landscape mapping; South Australian Department of Environment, Water and Natural Resources.

Sanderman J, Farquharson R, Baldock J (2010); Soil Carbon Sequestration Potential: A review for Australian agriculture; report prepared for Department of Climate Change and Energy Efficiency; CSIRO.

Six J, Conant RT, Paul EA, Paustian K (2002); Stabilization mechanisms of soil organic matter: Implications for C saturation of soils; *Plant and Soil 241*; pp. 155-176.

Tisdall JM, Oades JM (1982); Organic matter and water-stable aggregates in soils; *Journal of Soil Science 62*; pp. 141-163.

CHAPTER 7

Australian National Greenhouse Accounts; National Inventory Report 2011; Australian Government Submission to the United Nations Framework Convention on Climate Change April 2013.

Baldock JA, Wheeler I, McKenzie N, McBrateny A (2012); Soils and climate change: potential impacts on carbon stocks and greenhouse gas emissions and future research for Australian agriculture; *Crop and Pasture Science 63*; pp. 269-283.

Barton L, Murphy DV, Kiese R, Butterbach-Bahl K (2010); Soil nitrous oxide and methane fluxes are low from a bioenergy crop (canola) grown in a semi-arid climate; *Global Change Biology Bioenergy 2*; pp. 1-15.

de Klein CAM, Eckard RJ (2008); Targeted technologies for nitrous oxide abatement from animal agriculture; *Australian Journal of Experimental Agriculture 48*; pp. 14-20.

Guo LB, Gifford RM (2002); Soil carbon stocks and land use change: a meta-analysis; *Global Change Biology 8*; pp. 345-360.Intergovernmental Panel on Climate Change (IPCC) Climate Change 2007; Fourth Assessment Report (AR4) of the United Nations.

Kingwell R, Anderton L, Islam N, Xayavong V, Wardell-Johnson A, Feldman D, Speijers J (2013); Broadacre farmers adapting to a changing climate; *National Climate Change Adaptation Research Facility*; pp. 171.

Lal R (2004); Soil carbon sequestration to mitigate climate change; *Geoderma 123*; pp. 1-22.

Lal R, Follett RF (2009); Introduction: Soils and climate change; *Soil carbon sequestration and the greenhouse effect second edition* (Eds. R Lal, R Follett); pp. 21-28; Soil Science Society of America, Madison WI.

Le Mer J, Roger P (2001); Production, oxidation, emission and consumption of methane by soils: A review; *European Journal of Soil Biology 37*; pp. 25-50.

Noble I, Scholes R (2001); Sinks and the Kyoto Protocol; *Climate Policy 1*; pp. 5-25.

Rodhe H (1990); A comparison of the contribution of various gases to the greenhouse effect; Science 248; pp. 1217-1219.

Smith P (2004); Monitoring and verification of soil carbon changes under Article 3.4 of the Kyoto Protocol; Soil Use Man 20; pp. 264–270.

CHAPTER 8

Blair GJ, Lefroy RDB, Lisle L (1995); Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems; Australian Journal of Agricultural Research 46, pp. 1459-1466.

Don A, Schumacher J, Scherer-Lorenzen M, Scholten T, Schulze ED (2007); Spatial and vertical variation of soil carbon at two grassland sites — Implications for measuring soil carbon stocks; *Geoderma 141*; pp. 272-282.

Heanes DL (1984); Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotomic procedure; *Communication in Soil Science and Plant Analysis 15*; pp. 1191-1213.

Holmes K, Wherrett A, Keating A, Murphy DV (2011); Meeting bulk density sampling requirements efficiently to estimate soil carbon stocks; *Soil Research 49*; pp. 680-695.Janik LJ, Skjemstad JO, Shepherd KD, Spouncer LR (2007); The prediction of soil carbon fractions using mid infra-red-partial least square analysis; *Australian Journal of Soil Research 45*; pp. 73-81.

Walkley A, Black IA (1934); An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method; *Soil Science 37*; pp. 29-37.

Zimmermann M, Leifeld J, Fuhrer J (2007); Quantifying soil organic carbon fractions by infrared-spectroscopy; *Soil Biology and Biochemistry 39*; pp. 224-231.

CHAPTER 9

Clapperton MJ, Chan KY, Larney FJ (2003); Managing the soil habitat for enhanced biological fertility; *Soil Biological Fertility – a key to sustainable land use in agriculture* (Eds. LK Abbott and DV Murphy); Dordrecht, Netherlands; Kluwer Academic; pp. 203-224.

CHAPTER 10

Australian Agricultural Assessment (2001); National Land and Water Resources Audit; http://www.anra.gov.au/topics/agriculture/pubs/natioal/agriculture_landscape.html

Bot A, Benites J (2005); The Importance of Soil Organic Matter: Key to Drought-resistant Soil and Sustained Food Production; Food and Agriculture Organisation; pp. 78.

Chan KY, Heenan DP, So HB (2003); Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: a review; *Australian Journal of Experimental Agriculture 43*; pp. 325-334.

Edmeades DC (2002); The effects of liquid fertilisers derived from natural products on crop, pasture and animal production: A review; *Australian Journal of Agricultural Research 53*; pp. 965-976.

Gupta VVSR, Grace PR, Roper MM (1994); Carbon and Nitrogen Mineralization as Influenced by Long-term Soil and Crop Residue Management Systems in Australia; *Soil Science Society of America Special Publication 35*; pp. 193-200.

Grace PR, Basso B (2012); Offsetting greenhouse gas emissions through biological carbon sequestration in north-eastern Australia; *Agricultural Systems 105*; pp. 1-6.

Harper RJ, Beck AC, Ritson P, Hill MJ, Mitchell CD, Barrett DJ, Smettem KRJ, Mann SS (2007); The potential of greenhouse sinks to underwrite improved land management; *Ecological Engineering 29*; pp. 329-341.

Hoyle FC, Murphy DV (2006); Seasonal changes in microbial function and diversity associated with stubble retention versus burning; *Australian Journal of Soil Research 44*; pp. 407-423.

Hoyle FC, D’Antuono M, Overheu T, Murphy DV (in press); Capacity for increasing soil organic carbon stocks in dryland agricultural systems. *Soil Research 51*

Johnston AE, Poulton PR, Coleman K (2009); Soil Organic Matter: Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes; *Advances in Agronomy 101*; pp. 1-57.

Kirkby CA, Kirkegaard JA, Richardson AE, Wade LJ, Blanchard C, Batten G (2011); Stable soil organic matter: A comparison of C:N:P:S ratios in Australian and other world soils; *Geoderma 163*; pp. 197-208.

Lal R (2008); Carbon sequestration; *Philosophical Transactions of the Royal Society B 363*; pp. 815-830.

Llewellyn RS, D’Emden FH (2010); How much is enough: the steep final steps to extensive no-tillage cropping in Australia; Proceedings of 15th Agronomy Conference 2010, Lincoln, New Zealand.

Luo Z, Wang E, Sun OJ (2010); Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments; *Agriculture, Ecosystem and Environment 139*; pp. 224-231.

McLauchlan K (2006); The nature and longevity of agricultural impacts on soil carbon and nutrients: A review; Ecosystems 9; pp. 1364-1382.

Moran KK, Six J, Horwath WR (2005); Role of mineral-nitrogen in residue decomposition and stable soil organic matter formation; *Soil Science Society of America Journal 69*; pp. 1730-1736.

Quilty J, Cattle S (2011; The use and understanding of organic amendments in Australian agriculture – a review; *Soil Research 49*; pp. 1-26.

Rumpel C (2008); Does burning of harvesting residues increase soil carbon storage; *Journal of Soil Science and Plant Nutrition 8*; pp. 44-51.

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O (2007); Agriculture in Climate Change 2007: Mitigation; contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Eds. B Metz, OR Davidson, PR Bosch, R Dave, LA Meyer); Cambridge University Press, Cambridge, United Kingdom and New York.

Wardle DA (1995); Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices; *Advances in Ecological Research 26*; pp. 105-185.

CHAPTER 11

Drake BG, Gonzàlez-Meler MA, Long SP (1997); More efficient plants: A consequence of rising atmospheric CO_2?; *Annual Review Plant Physiology and Plant Molecular Biology 48*; pp. 609–39.

Luo Y, Hui D, Zhang D (2006); Elevated CO_2 stimulates net accumulation of carbon and nitrogen in land systems: A meta-analysis; *Ecology 87*; pp. 53–63.

Grace PR, Post WM, Hennessy K (2006); The potential impact of climate change on Australia's soil organic carbon resources; *Carbon Balance and Management*; pp. 1-14.

Fang C, Smith P, Moncrieff JB, Smith JU (2005); Similar response of labile and resistant soil organic matter pools to changes in temperature; *Nature 433*; pp. 57-59.

Hungate BA, Holland EA, Jackson RB, Chapin III FS, Mooney HA, Field CB (1997); On the fate of carbon in grasslands under carbon dioxide enrichment; *Nature 388*; pp. 576-579.

IOCI (2004a); How has our rainfall changed? The South West Indian Ocean Climate Initiative Bulletin; http://www.ioci.org.au/publications/ioci-stage-3/doc_download/42-fact-sheet-1-how-was-climate-has-changed.html

IOCI (2004b); The future of WA's climate; The South West Indian Ocean Climate Initiative Bulletin; http://www.ioci.org.au/publications/ioci-stage-3/doc_download/43-fact-sheet-2-the-future-of-was-climate.html

Maracchi G, Sirotenko O, Bindi M (2005); Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe; *Climate Change 70*; pp. 117-135.

Ontl TA, Schulte LA (2012); Soil Carbon Storage; *Nature Education Knowledge*; pp. 3, 35.

Pataki DE et al. (2003); Tracing changes in ecosystem function under elevated carbon dioxide conditions; *BioScience 53*; pp. 805-818.

Zak DR, Pregitzer KS,Curtis PS, Holmes WE (2000); Atmospheric CO2 and the composition and function of soil microbial communities; *Ecological Applications 10*; pp. 47-59.

CHAPTER 12

Whittle L, Hug B, Heyhoe E, Ahammad H, Berry (2011); Possible short-run effects of a carbon pricing scheme on Australian agriculture; ABARES research report 11.10; Commonwealth of Australia.