

MANAGING SOIL ORGANIC MATTER

A PRACTICAL GUIDE



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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.

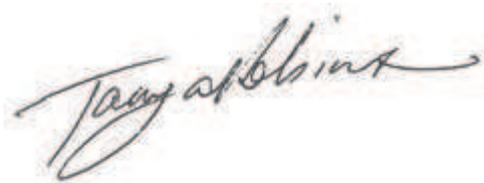
When selecting farming practices to maximise the benefits of soil organic matter it is important to consider the most important functions that soil organic matter provides to your crop and how that will bring benefits to your soil health and future crops.

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

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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

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.

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.

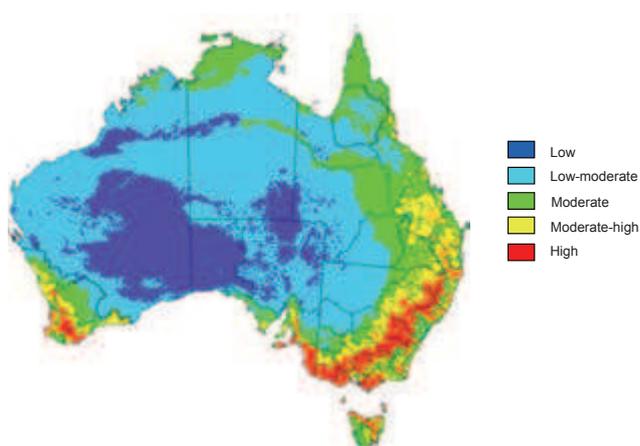


Figure 1.1 Potential for soil organic matter gain resulting from a combination of effective rain (considering amount and availability) and residue carbon, which reflects plant and livestock removals of organic matter (Baldock et al. 2009).

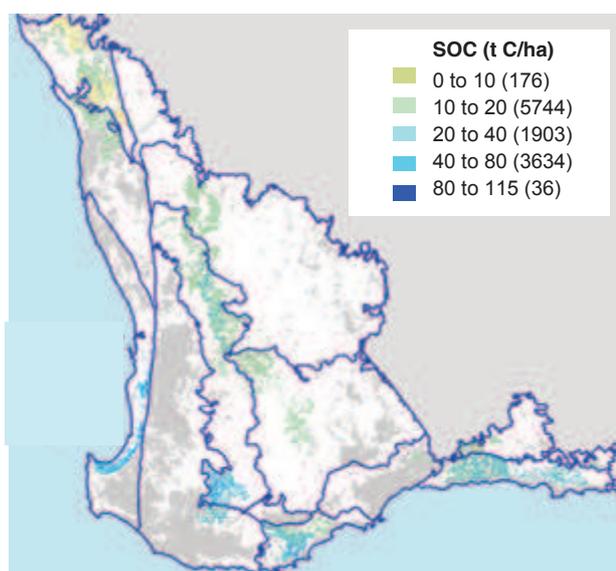


Figure 1.2 Soil organic carbon (tonnes per hectare) stocks in surface layers (0-10 cm) for south west Western Australia. Areas of low confidence (e.g. subsystems that only have one site) are masked out in white. Lines constitute agricultural soil zones: grey is remnant vegetation (Griffin et al. 2013).



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 percent 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.

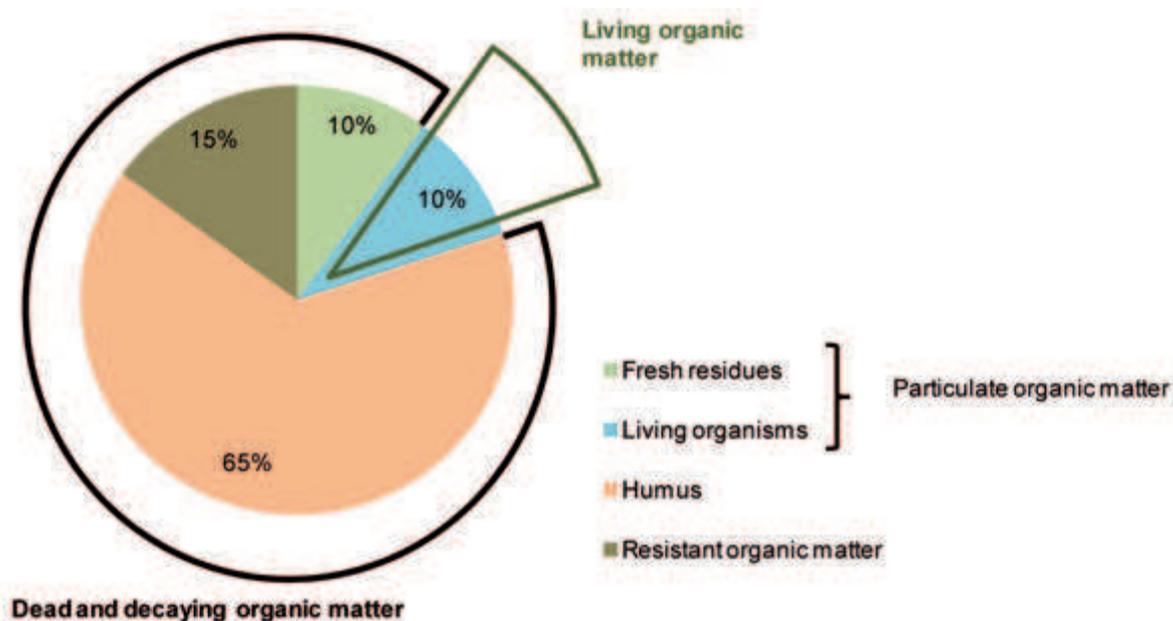


Figure 1.3 Proportional make-up of organic matter in an agricultural soil.

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

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.

- 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 µm) 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.

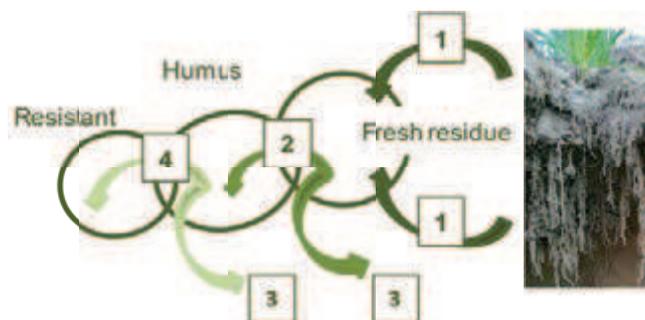


Figure 1.4 Pattern of organic matter transformation in soils (figure adapted from University of Minnesota extension publication WW-07402).

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:

$$\text{Organic matter (\%)} = \text{total organic carbon (\%)} \times 1.72$$

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:

$$\begin{aligned} & (\text{Total organic carbon per cent} \times 1.72) \times \text{soil mass (tonnes per hectare)} \\ & = [(1.2 \times 1.72)/100] \times 1200 \text{ (for a soil with a bulk density of 1.2 to 10 cm depth)} \\ & = 24.8 \text{ tonnes organic matter per hectare} \end{aligned}$$

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).

is not known how this relationship would differ when considering clay applied to soils for the treatment of non-wetting.

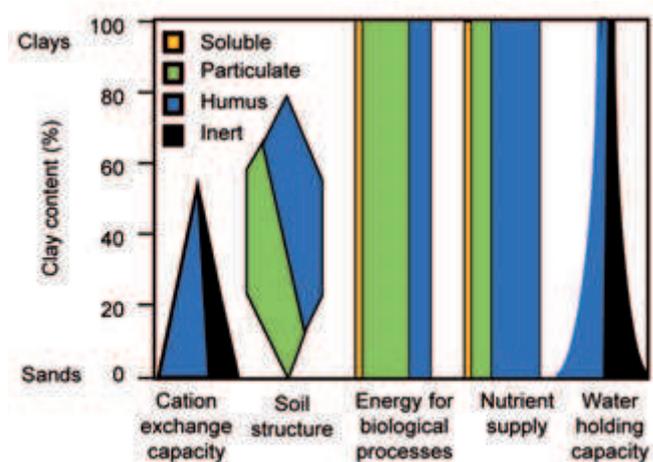


Figure 1.5 A conceptual representation of the role of soluble, particulate, humus and resistant (inert) organic matter fractions for a range of soil functions (from Hoyle et al. 2011).

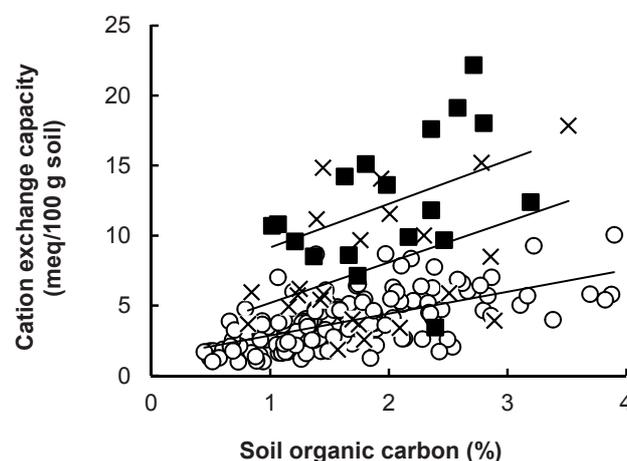


Figure 1.6 The influence of soil organic carbon on cation exchange capacity for Young River, Western Australia in soils with clay content between 0-10% (o), 10-20% (x) and 20-30% (■). Sourced from www.soilquality.org.au.

While 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

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

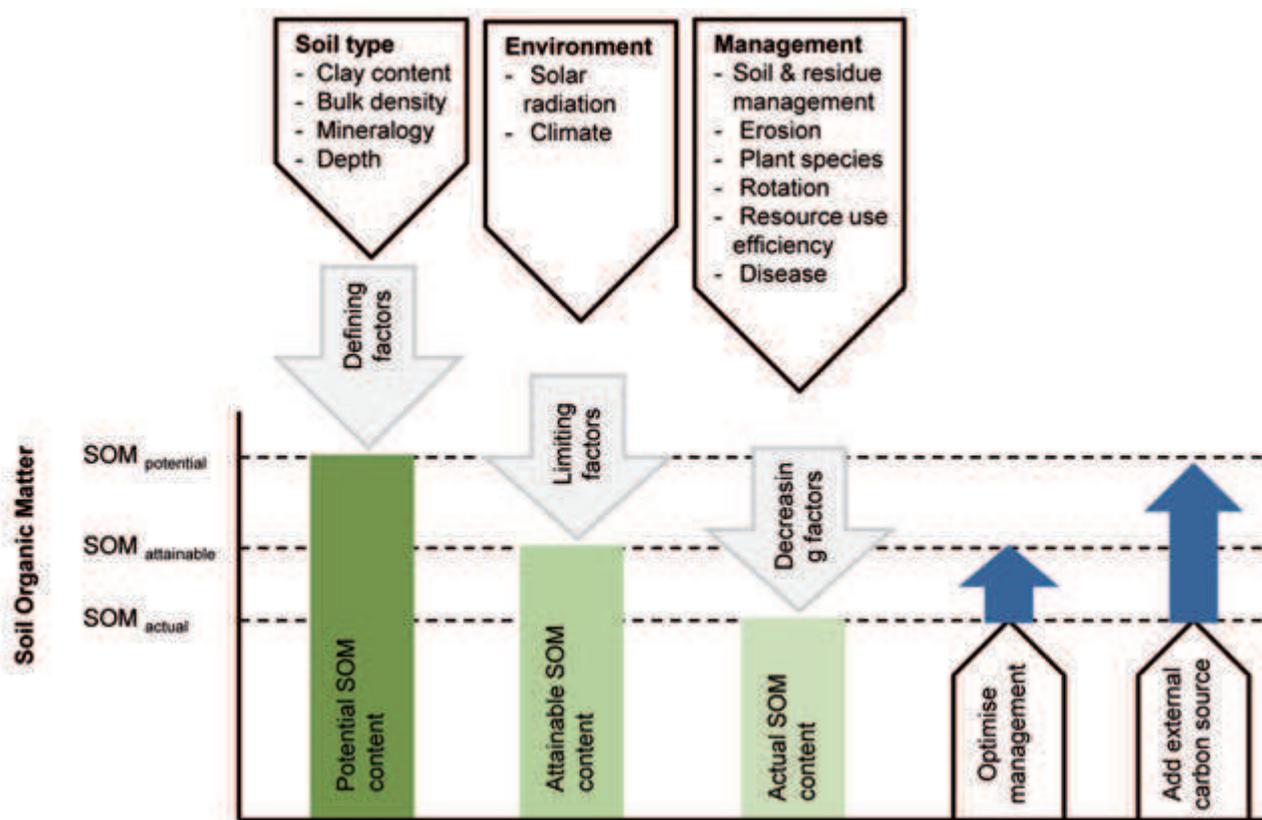


Figure 1.7 The influence of soil type, climate and management factors on potential soil organic matter content (Ingram and Fernandes 2001).

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.
 $1350 \text{ kg carbon} \div 120 = 11.25 \text{ kg nitrogen in organic matter}$

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.

$405 \text{ kg carbon} \div 12 = 34 \text{ kg N}$

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 (CO₂). 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.



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 m² 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.

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/m² and 501/m² 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

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/m² and 430/m², 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/m², with a low species richness of 1-2 per site (Mele and Carter 1999). This is similar to the average abundance (75 earthworms/m²) reported by Chan and Heenan (2006).



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.

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

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



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 ($> \text{pH}_{\text{Ca}} 5.5$) and sub-surface soils ($> \text{pH}_{\text{Ca}} 4.8$) 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

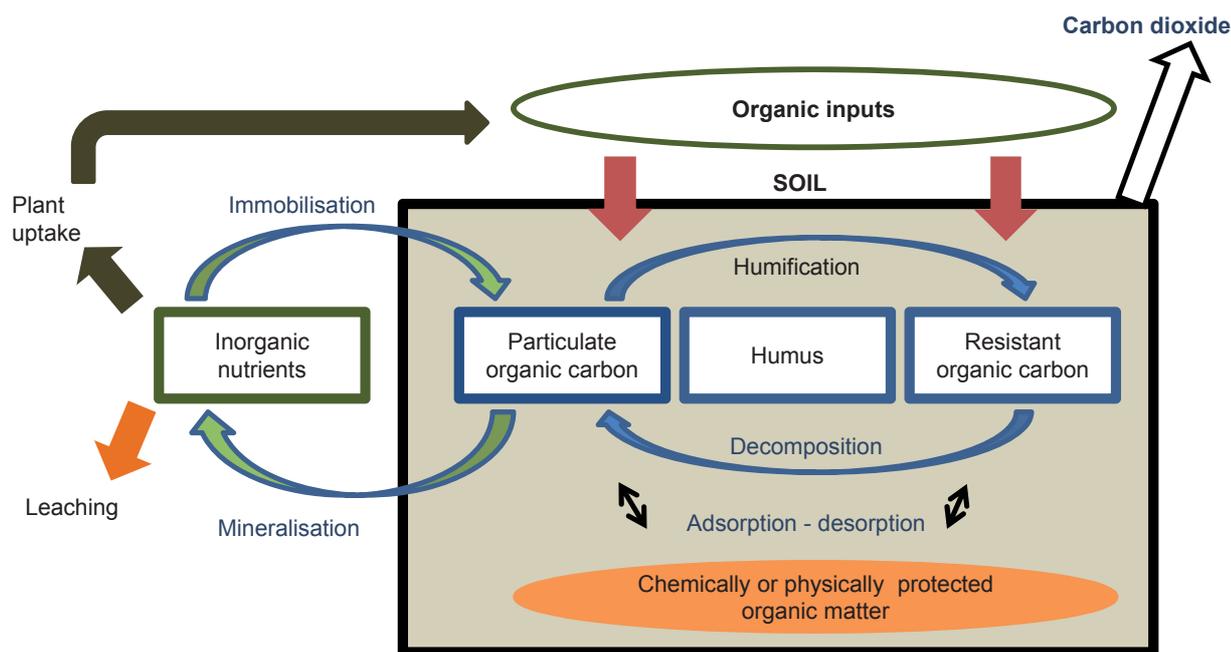


Figure 3.1 Organic carbon cycling in soils.

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).

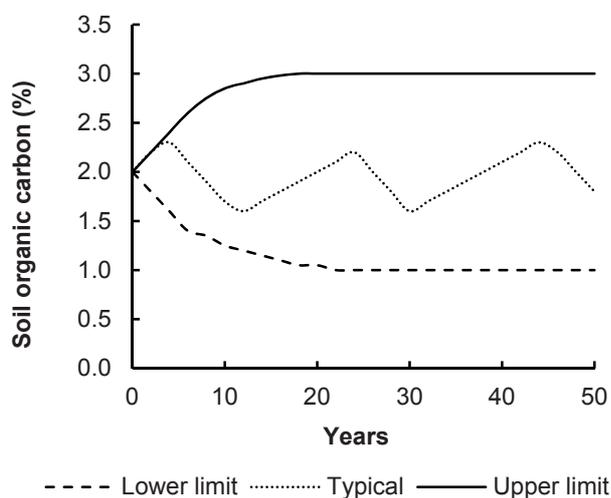


Figure 3.2 Theoretical changes in soil organic carbon (%) representing an upper and lower limit, or a more typical state of flux.

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).

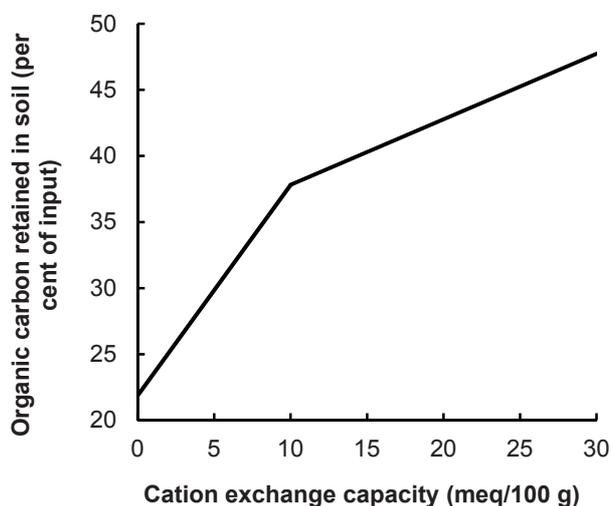


Figure 3.3 A model simulation showing the influence of cation exchange capacity (CEC) on the capacity of soil to retain soil organic carbon (Grace et al. 2006).

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.



04

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



6. Ear emergence (16-19 weeks)

Zadok's Z50 to Z59



2. Seedling growth (2-3 weeks)

Zadok's Z10 to Z19



7. Flowering (18-21 weeks)

Zadok's Z60 to Z69



3. Tillering (4-12 weeks)

Zadok's Z20 to Z29



8. Milk development (25 weeks)

Zadok's Z70 to Z79



4. Stem elongation (12-16 weeks)

Zadok's Z30 to Z39



9. Dough development (26 weeks)

Zadok's Z80 to Z89



5. Booting (15-18 weeks)

Zadok's Z40 to Z49



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 is 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.

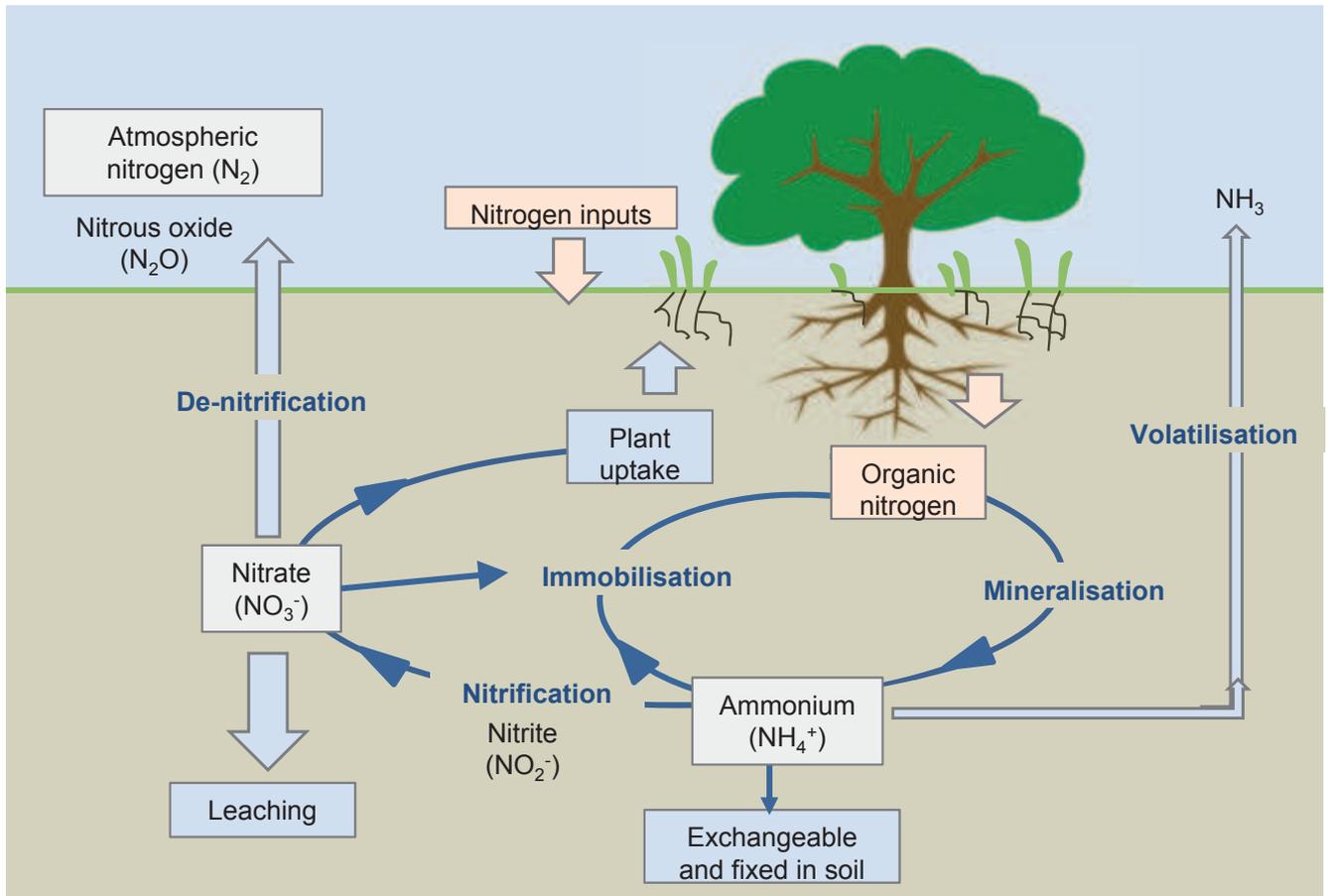


Figure 4.1 Nitrogen cycling in soil.

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).

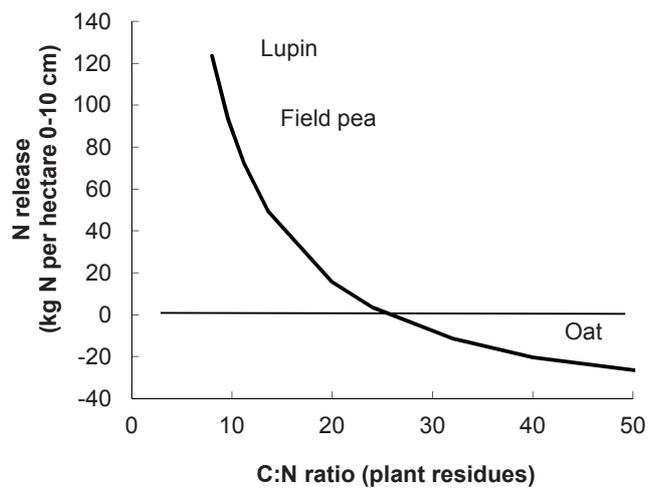


Figure 4.2 Nitrogen release in soil resulting from the decomposition of plant residues with a range of carbon to nitrogen (C:N) ratios. Adapted from Hoyle et al. (2011).

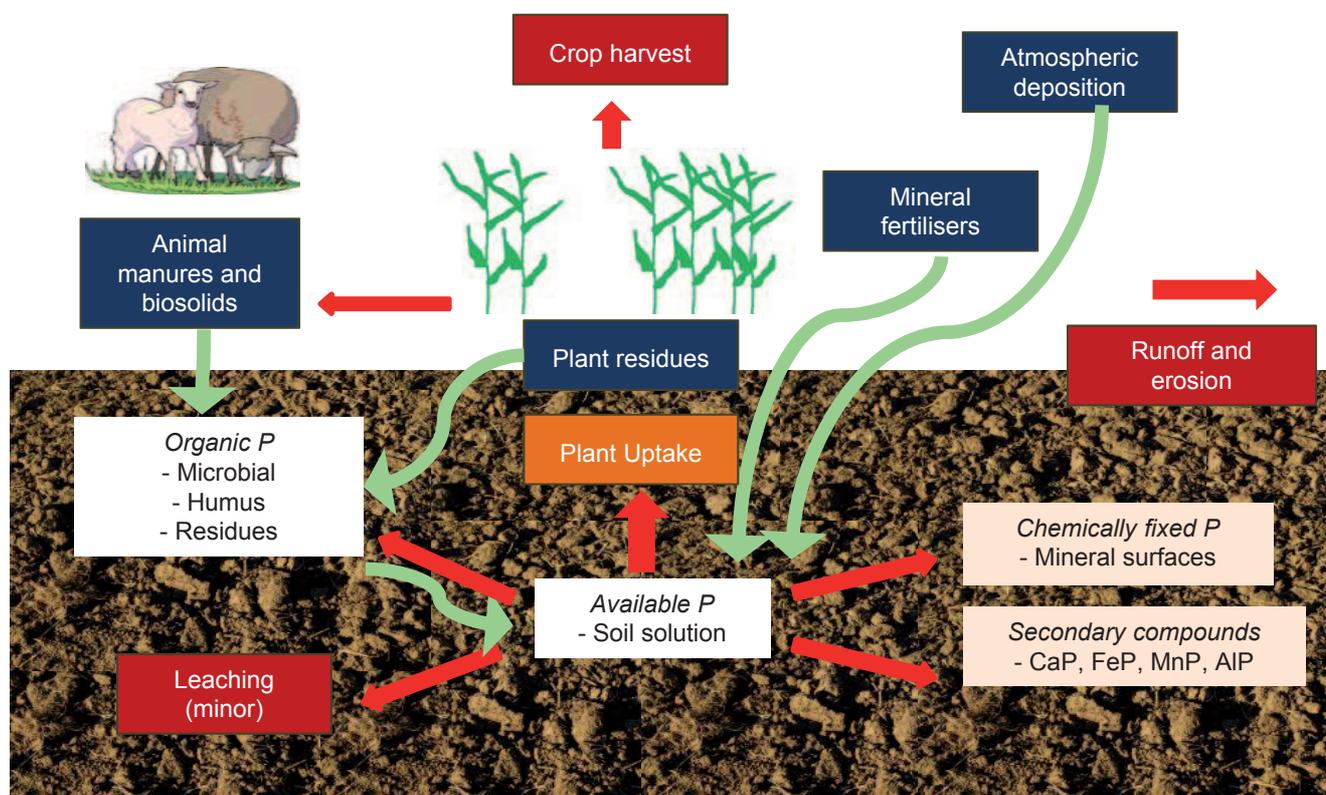


Figure 4.3 Phosphorus cycle in agricultural systems.

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 phosphorus 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 phosphorus 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 phosphorus

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 phosphorus 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 phosphorus fixing soils (Li et al. 2005, 2006), mycorrhizal associations are not always beneficial to Australian crops. Crop responses are often dependent on background soil phosphorus 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 phosphorus 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 phosphorus 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 phosphorus, 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).

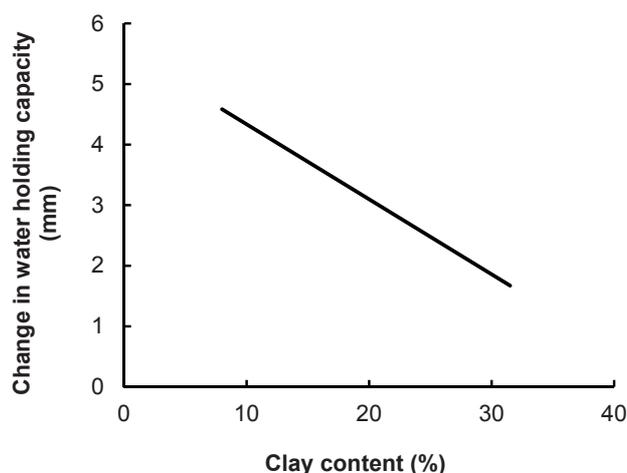


Figure 5.1 Change in water holding capacity for the 0-10 cm soil layer of South Australian red-brown earths, with a one per cent increase in soil organic carbon content (Hoyle et al. 2011).

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/cm³ 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	<p>Helps form soil aggregates with small pore size, which increases water holding capacity.</p> <p>Clay soils with a high level of exchangeable sodium are likely to disperse and have poor aggregate stability.</p>	<p>Increased yield potential. Small pores can make it more difficult for plants to extract soil water under drying conditions.</p> <p>Poor aggregate stability can result in surface crusting, hard-setting, waterlogging and less available water.</p>
Low clay or silt content (e.g. uniform, coarse textured soils such as deep sands, sandy earths)	<p>Results in poor aggregation.</p> <p>Water drains freely through profile.</p> <p>Low water and nutrient storage capacity within the root zone.</p>	<p>Crops and pastures can run out of water in a tight (dry) finish.</p> <p>More prone to developing water repellence, restricting water entry.</p>
Poor soil structure (e.g. dispersive, hard setting, naturally compacting soils)	<p>Poor water infiltration.</p> <p>Increased risk of erosion.</p> <p>Low water storage capacity.</p>	Crop yields often below potential due to lower water storage and restricted access to water.
Texture contrast soils (e.g. sand over clay duplex)	<p>Plant available water depends on:</p> <ul style="list-style-type: none"> • 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)	<p>Water preferentially flows into cracks, while areas between cracks remain dry due to the dense soil structure and rapid water flow.</p> <p>Increased but spatially variable water storage capacity.</p>	Water availability and yield potential determined by infiltration pattern and rooting depth.
High organic content soils	<p>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.</p> <p>Biological secretions, fungal hyphae and worm casts help to stabilise soil structure by bonding organic materials to soil minerals.</p>	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/cm³.

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/cm³

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 (cm³) = $3.14 \times r^2 \times h$

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 = $3.14 \times 3.5 \times 3.5 \times 10 = 385\text{cm}^3$

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 105°C 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/cm³) = dry soil weight (g)/soil volume (cm³)

can be adjusted accurately (see Figure 5.2). In this example, a soil with an initial bulk density of 1.2 g/cm³ 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/cm³, 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

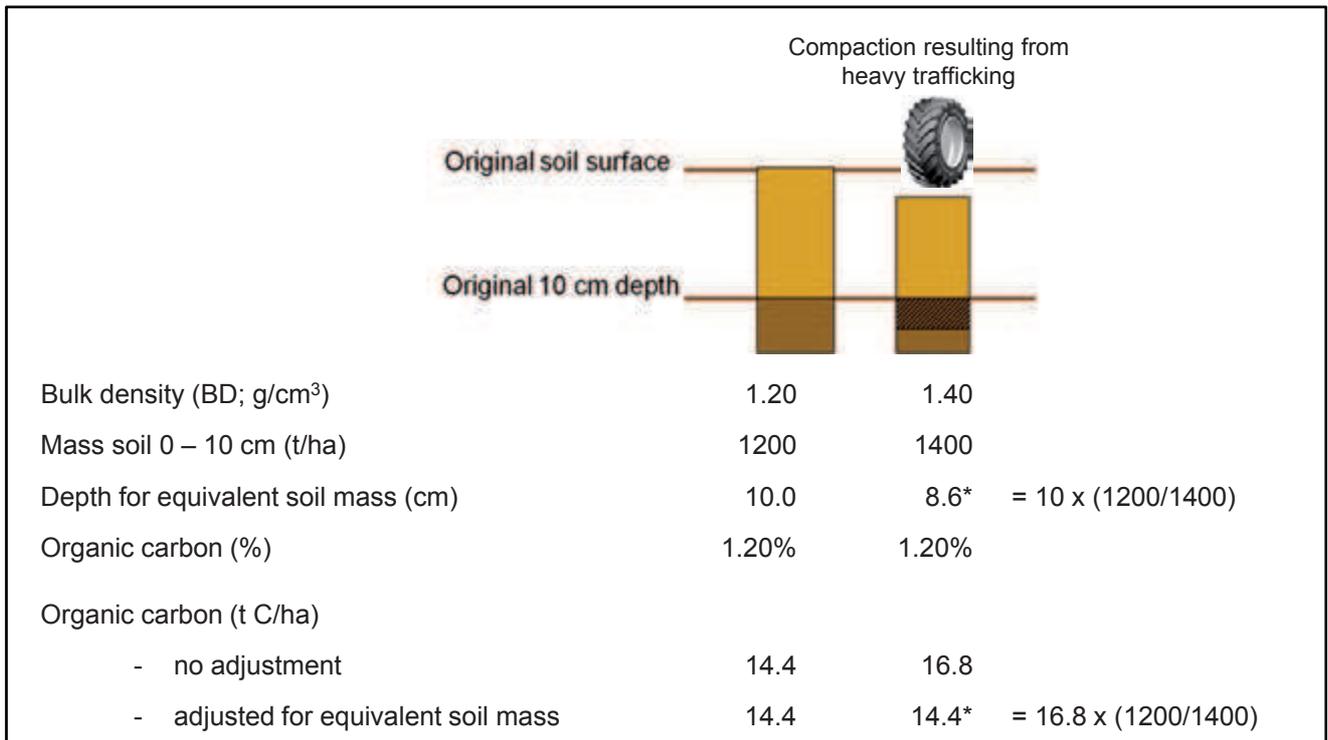


Figure 5.2 Adjustment of organic carbon content for an equivalent soil mass associated with changes in bulk density and sampling depth.

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/cm³ 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

$$= [0.01 \times (1.4 \times 100)] \times 4$$

$$= 1.4 \text{ kg/m}^2 \times 4$$

$$= 5.6 \text{ litres/m}^2 \text{ (or the equivalent of 5.6 mm)}$$

* While unlikely, if this change was observed to 30 cm then = $[0.01 \times (1.4 \times 300)] \times 4 = 16.8 \text{ mm}$

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/cm³ 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).

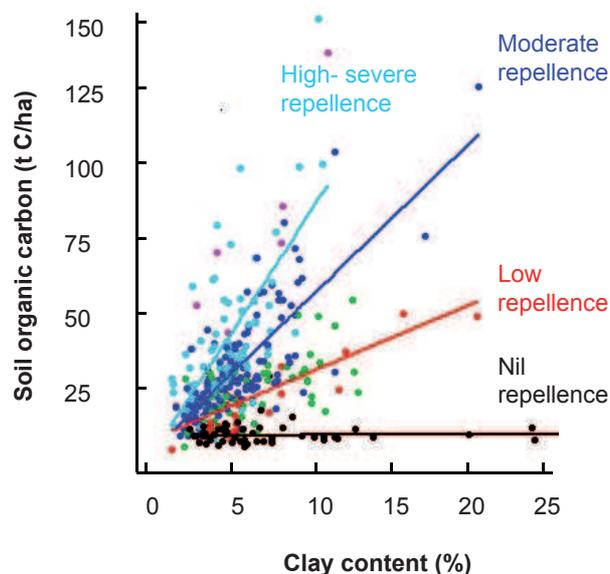


Figure 5.3 A complex relationship exists between soil organic carbon, clay content and the severity of water repellence as measured at 400 sites across Western Australia (Hoyle and Murphy unpublished) for MED severity (nil – black, very low – red, low – green, moderate – dark blue, severe – light blue, 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/cm³), 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.

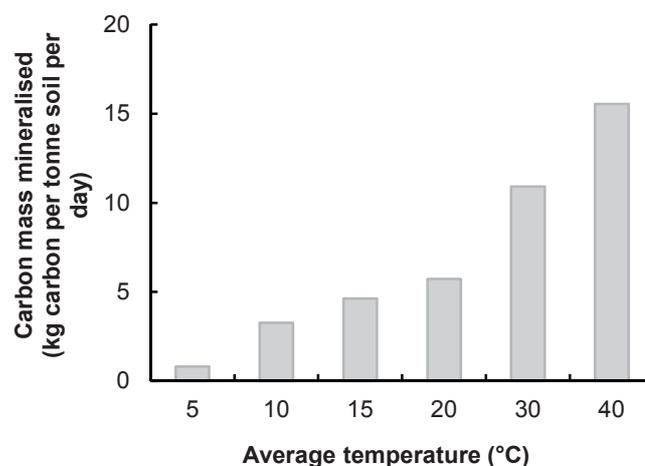


Figure 6.1 The effect of increasing temperature on the amount of carbon lost from soil (kg carbon per tonne of soil per day) where stubble has been retained (adapted from Hoyle et al. 2006).

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 µm) 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



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 (CO₂-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 (CH₄) from ruminant livestock digestion, nitrous oxide (N₂O) from soils and carbon dioxide (CO₂) 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 (CO₂-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 (CO₂-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 CO₂-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/cm³), 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 (N₂O) 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 (N₂O) 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 (NO₃⁻) to nitrogen gas (N₂), 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

(NH₄⁺) to nitrate (NO₃⁻), 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 (CH₄) 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 (CO₂-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)