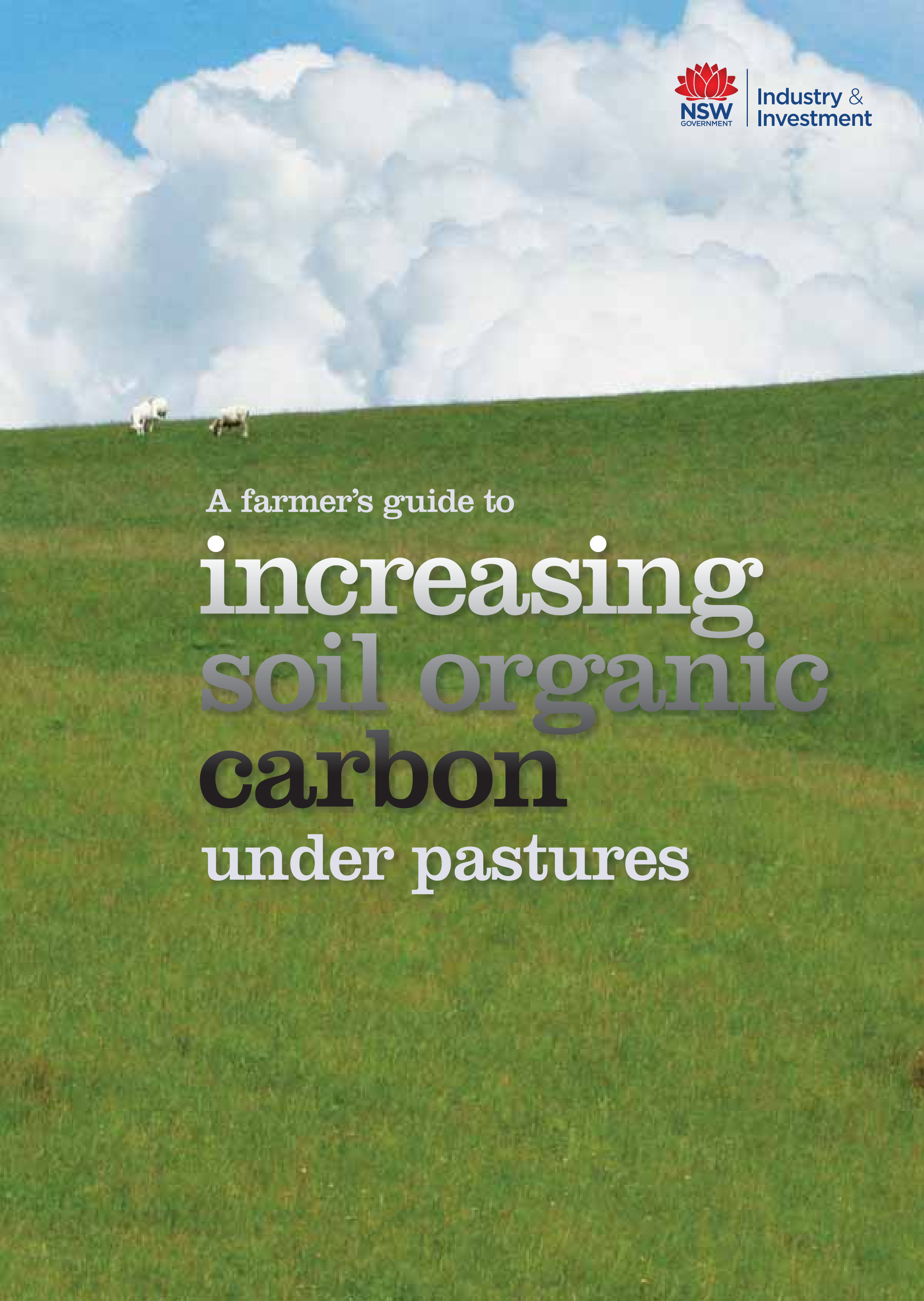

A farmer's guide to

increasing soil organic carbon under pastures

NSW GOVERNMENT
Industry & Investment

Cover photo: Sheep grazing on pasture.

A farmer's guide to increasing soil organic carbon under pastures

NSW GOVERNMENT | Industry & Investment

This book is based on findings from a three year project investigating soil carbon levels in pastures under different management practices in south east NSW. It is designed to be of practical use to farmers who want to increase their soil carbon levels. It includes basic information on soil carbon and reports the project's findings regarding the impact of pasture management on soil carbon.

The project team

The project team comprised researchers from the Primary Industries branch of Industry & Investment NSW:

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INTRODUCTION

Introduction

For a long time, both farmers and scientists have been aware of the importance of soil organic carbon to soil health and sustainable agriculture. Recently there has also been an increasing interest in the possible role of soil organic carbon as a carbon sink for the mitigation of climate change and therefore the possibility of its inclusion in emission trading schemes.

However, there is a lack of scientifically based data on soil carbon stocks in our agricultural soils under different management practices. In addition, there is a need for farmers to be better informed of the facts about soil carbon in agriculture so they can make sense of the many but often confusing claims appearing in the media.

This booklet aims to provide a practical guide to soil carbon under pastures. It is the product of a three year project looking at soil carbon levels under pastures, and the researchers have taken the opportunity to expand it from a simple report of project results to include further information on soil carbon that will be of interest to farmers, particularly graziers.

SECTION A:

Soil carbon basics

1. Soil organic carbon

Soil organic carbon (SOC) refers to the carbon associated with soil organic matter (SOM). Soil organic matter is the organic fraction of the soil and is made up of decomposed plant and animal materials as well as microbial organisms (Figure 1a), but does not include fresh and undecomposed plant materials, like straw and litter lying on the soil surface (Figure 1b). Soil carbon can also be present in inorganic form as carbonates, e.g. limestone.

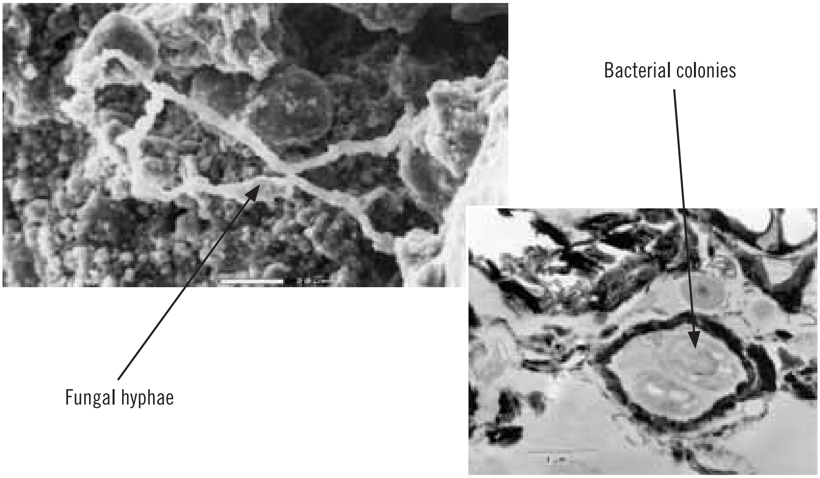

Figure 1a. Soil micro-organisms are part of SOM – scanning electron micrographs showing fungal hyphae and bacterial colonies living in soil.

Figure 1b. Fresh and undecomposed plant residues are not part of SOM.

2. Soil carbon pools

Chemically SOC is very complex, containing organic materials at all stages of decomposition.

Put simply SOC is made up of the following forms.

- *partly decomposed organic matter*; organic materials at an early stage of decomposition.
- *microbial biomass*; microscopic living organisms.
- *humus*; old organic material whose original form is no longer recognisable.
- *charcoal*; burnt organic material, in varying states of oxidation.

NOTE: *Fresh organic materials;* namely fallen leaves and stubble, senesced roots and dung, are technically not part of SOC because much of their carbon is likely to be lost as carbon dioxide as a product of decomposition with only a relatively small proportion entering the soil. These materials are generally either avoided at sampling or removed by sieving. If they are not avoided or removed, they will be measured by all common laboratory techniques as SOC. This can be a big source of error when measurements are taken over time.

Conveniently, SOC has been divided into a number of pools according to their stability; namely labile, slow and recalcitrant pools in increasing order of stability. The labile pool includes partly decomposed organic matter and microbial biomass, the slow pool includes humus, while charcoal represents the recalcitrant pool.

Different forms (pools) of SOC serve different functions (Table 1) and are found in different proportions in soil of different fertility levels (Figure 2).

The three pools of organic carbon serve different functions in the soil ecosystem (Table 1), so SOC is a good indicator of soil health. The proportion of the different pools indicate how healthy the soil is (Figure 2). Attributes like increased water holding capacity, higher infiltration rates and higher nitrogen availability arising from increased SOC can make farming systems more resilient to climate change.

Carbon pools in soils under different management practices

The diagram below compares the total carbon and the different carbon pools of a red earth soil which had undergone two contrasting management regimes from a long term trial at Wagga Wagga. The size of the circles indicates the relative amounts of SOC. The circle segments represent the different carbon pools.

After 20 years, the SOC of the degraded soil (three pass tillage and stubble burnt under continuous wheat without nitrogen fertiliser) was only 60% of the well-managed soil (no tillage, stubble retained for 20 years under a wheat/lupin rotation) (1.5% vs 2.5%). Most of the loss was from the labile fraction, showing the effect of management practices on this pool of SOC.

Well managed soil (no tillage, stubble retained for 20 years under a wheat/lupin rotation)	Degraded soil (three pass tillage and stubble burnt under continuous wheat with no nitrogen fertiliser for 20 years)
SOC = 2.5%	SOC = 1.5%

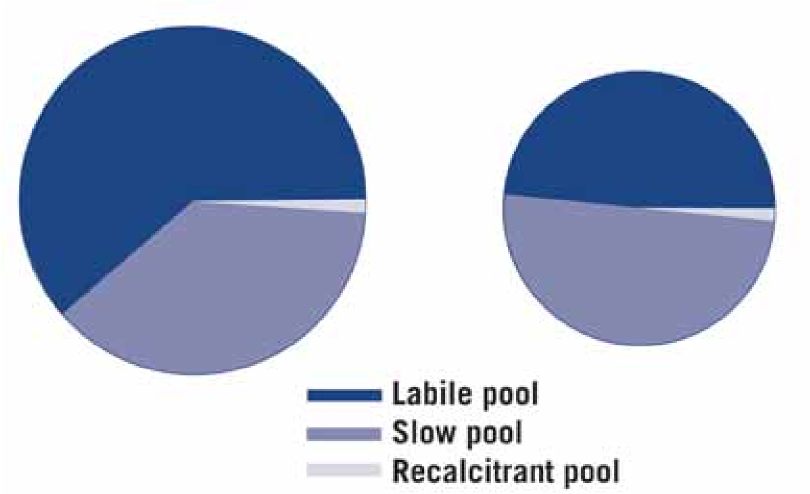

Figure 2. Carbon pools in two contrasting soils.

3. Soil organic carbon and soil fertility

Soil organic carbon is the basis of soil fertility. As shown in the following table, it enhances chemical, physical and biological fertility.

Soil fertility	Effects of SOC	C pools
Chemical fertility Provides nutrients available to plants	Microbial decomposition of SOM releases nitrogen, phosphorus and a range of other nutrients for use by plant roots.	Labile, slow
Physical fertility Improves soil structure and water holding capacity	In the process of decomposition, microbes produce resins and gums that help bind soil particles together into stable aggregates. The improved soil structure holds more plant available water, allows water, air and plant roots to move easily through the soil, and makes it easier to cultivate	Labile, slow
Biological fertility Provides food for soil organisms	Organic carbon is a food source for soil organisms and micro-organisms. Its availability controls the number and types of soil inhabitants and their activities which include recycling nutrients, improving soil structure and even suppressing crop diseases.	Labile
Buffers toxic and harmful substances	SOC can lessen the effect of harmful substances by sorption of toxins and heavy metals, and degradation of harmful pesticides.	Slow and recalcitrant

Table 1. Importance of SOC to soil health and the carbon pools responsible.

4. Soil organic carbon and greenhouse gases

SOC is the largest component of the terrestrial carbon pool (Figure 3), approximating to twice the amount of atmospheric carbon and that of vegetation biomass (Table 2).

Carbon pool size	
Vegetation	610 Gt
Atmosphere	750 Gt
Soil	1,580 Gt
Ocean	39,000 Gt
Carbon changes due to human activities	
Fossil fuel use	+ 5.5 Gt/year
Land use	+ 1.6 Gt/year
Rate of C increase in the atmosphere	
	+ 3.3 Gt/year

Table 2. Carbon pool size and changes due to human activities (Kasting 1998).

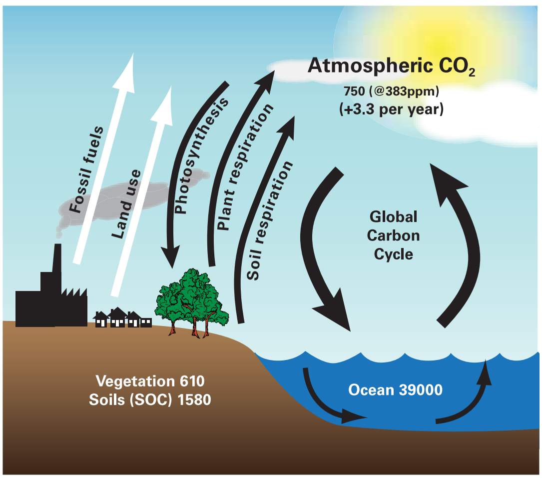

Figure 3. The carbon cycle (all numbers in giga tonnes (Gt)).

I Gt = 1,000,000,000 tonnes = 1 billion tonnes = 10^9 tonnes

The natural C cycle has been thrown out of balance by human activities (white arrows in Figure 3). Our use of fossil fuels, clearing of vegetation and soil disturbance have all added CO_2 to the atmosphere, resulting in a 37% increase in atmospheric CO_2 since 1750. This elevated concentration of atmospheric CO_2, together with other greenhouse gases, is believed to be the cause of global warming and climate change. The situation is expected to get worse with time. If we store more carbon in the soil as organic carbon, we will reduce the amount of carbon in the atmosphere, and therefore help alleviate global warming and climate change. Storing carbon in soil is called soil carbon sequestration. It has been estimated that 78 giga tonnes (Gt) of carbon has been lost from agricultural soils worldwide since the industrial revolution.

The challenge is to find out the answers to the following questions.

1. How big is the soil carbon sink in NSW?
2. How can we increase soil carbon levels in agricultural soils?
3. Where are the carbon sinks in agriculture?
4. How can soil carbon sequestration occur effectively and profitably for farmers?

In NSW, more than 80% of agricultural land is under pastures, so it is particularly important to understand how pasture soils can sequester soil carbon and combat climate change.

Figure 4. More than 80% of agricultural land in NSW is under pasture.

5. Soil organic carbon levels

Soil organic carbon levels are dynamic. They vary according to the season, location and soil depth. SOC generally declines with soil depth (Figure 5) because most sources of organic matter from which it is derived are on or near the soil surface, and because plant roots are less dense deeper in the soil. However, the actual distribution of SOC down the soil profile varies with soil type and other factors.

Factors affecting soil organic carbon levels

In natural ecosystems, the SOC level at a given location depends on a number of factors:

- climate – temperature, rainfall, evaporation
- soil factors - texture, pH, fertility etc
- vegetation
- time

Temperature

Temperature determines the rate of decomposition. Decomposition is slow in colder temperatures, and increases rapidly at higher temperatures. In hot and wet areas such as the tropics, decomposition rates are so high that almost all organic carbon is decomposed, so SOC levels are low despite high plant productivity.

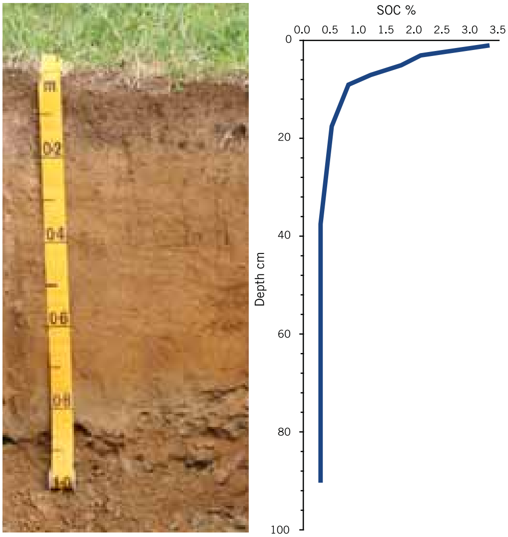

Figure 5. This graph shows the dramatic drop in SOC levels with depth in this soil under pasture.

Rainfall

Rainfall, along with other climatic factors such as evaporation, determines plant growth and therefore carbon inputs to soil. Rainfall also affects soil water content which determines the rate of decomposition by soil organisms. Decomposition is faster in moist soil than dry soil.

Soil factors

Soil fertility affects plant productivity. Soil texture, particularly clay content, influences the availability of organic substances for decomposition, which then affects the rate of decomposition. Clay surfaces and clay micro-aggregates protect organic materials from decomposition by either holding them tightly as complexes or by physically trapping them, thus rendering them unavailable to the microorganisms. A sandy soil tends to hold less soil organic carbon than a clay soil.

Soil acidity and aeration affect decomposition rates because microorganisms do not survive well in acid or anaerobic soils.

Time

Over time, SOC levels at a given location reach an equilibrium level where the soil has no more capacity to store SOC. This represents the maximum capacity of the soil to retain carbon at the given location and conditions. However, once disturbed, SOC levels will move to a new equilibrium. This can be a very slow process, sometimes taking hundreds to thousands of years.

6. Impact of agricultural practices on soil organic carbon

In agricultural systems soil organic carbon levels dropped when natural areas were cleared and used for agricultural production. Past cropping practices tended to lose soil carbon, so SOC levels in many agricultural soils are much lower than the saturation SOC level. In the Australian wheatbelt, it has been estimated that >60% of SOC in 0-10 cm layer has often been lost. This represents a significant opportunity for additional soil carbon sequestration.

New equilibrium levels depend on climate, soil, time and management practices. The challenge is to turn agricultural land into a carbon sink by improving farming systems and management practices.

The change in SOC is the balance of organic carbon inputs over losses. Generally, soil organic carbon can be increased by increasing organic carbon inputs and/or reducing losses.

Increase SOC inputs

- Increase crop yield.
- Optimise rotations to increase carbon inputs per unit land area.
- Retain stubble.
- Grow more pastures.
- Return manure & recycled organic materials to the soil.

Reduce SOC losses

- Reduce tillage - because excessive tillage accelerates SOC decomposition and encourages erosion losses.
- Minimise stubble burning because it reduces organic matter inputs.
- Minimise fallowing because it accelerates SOC decomposition.
- Reduce erosion because it carries off SOC in the topsoil.
- Avoid overgrazing because it reduces the productive capacity of pastures.

As a rule of thumb, only 5-15% of carbon inputs eventually become SOC. For example, using an average of 10%, 1 tonne of dry plant material contains 450 kg C, but will add only about 45 kg of SOC to the soil.

7. Soil organic carbon sequestration rates in agriculture

Many management practices increase SOC stocks of agricultural soils.

Agricultural activity	Management practice	Carbon sequestration rate (t C/ha/yr)
Cropping	increase soil fertility improve rotations irrigate eliminate fallows use precision agriculture	0.05-0.15 0.10-0.30 0.05-0.15 0.10-0.30 not available
Conservation tillage	retain stubble reduce tillage use no- till systems	} 0-0.40
Grazing	use fertilisers manage grazing time irrigate introduce legumes	0.30 0.35 0.11 0.75
Addition of organic amendments	add animal manure add biosolids	0.1-0.6 1.0
Land conversion	convert degraded cropland to pasture	0.8-1.1

Table 3. Management practices that can increase soil organic carbon and the average SOC sequestration rates associated with these practices (adapted from Chan et al. 2008).

As this table shows, the average SOC sequestration rates

- vary with management practices
- vary widely for the same management practice
- are generally less than 1 t C/ha/yr, mostly around 0.3 t C/ha/yr

Furthermore, there is a finite capacity of SOC for a given situation and in most cases the saturation capacity for agricultural land will be reached in 50-100 years.

8. Sampling soil organic carbon in the paddock

Choose representative locations

Soil organic carbon varies with location. SOC levels will be higher in header trails, windrows, stock-camps etc, so it is important to avoid sampling in areas that are not typical of most of the paddock (Figure 6).

Figure 6. Soil sampling for soil organic carbon by avoiding "unrepresentative" areas, e.g. close to the fence (A), old tree stumps (B), visibly disturbed areas (C) and areas close to existing trees (D).

Control sampling depth

SOC levels decrease sharply with depth, so sampling needs to be done carefully as small errors in soil sampling can result in big errors in the soil test. For example, when sampling moist soils at 0-10 cm, it is easy to push the soil corer into the soil, compressing the surface and potentially including soil from 10-12 cm depth. This dilutes the apparent soil C level in the top 10 cm of soil. Conversely, when the soil is dry and hard the corer might only penetrate to 9 cm, resulting in an artificially elevated apparent soil C for the 0-10 cm depth.

Sample number

A large number of cores should be included in any composite soil sample. The actual number of samples depends on the specific location and the level of accuracy required. We recommend at least 20 cores from a defined sampling area. A large number of representative cores plus care with depth control are necessary for obtaining a representative composite sample for estimating the soil C at a particular site.

9. Soil carbon tests

There are currently several methods used to analyse SOC levels in soil. All of them differ slightly in what they measure, so the purpose of the sampling will determine the technique to be used. There are no absolute levels on which to interpret SOC so it is important to monitor levels over time as SOC is an indicator of sustainability, particularly for:

- increases/decreases in carbon sequestration
- soil N availability
- soil structure
- nutrient holding capacity.

Walkley-Black (W-B) test

The Walkley-Black test used to be the most common soil test for carbon, but it only measures readily oxidisable/decomposable carbon, not total SOC. It measures, on average, about 80% of SOC. It fails to measure some old compounds but can measure some charcoal. W-B organic C is frequently converted to total organic C by a correction factor (eg 100/80 = 1.25).

However since the 80% is only an average correction across a range of soil depths and soil types, the measured value is best referred to as 'readily oxidisable' organic C.

Heanes test

The Heanes test is similar to Walkley-Black but includes a heating step that results in a measure close to total SOC. The Heanes method can measure up to 100% of the organic C in soil. This includes a proportion of the fine charcoal present in a sample.

Leco test

The Leco test uses high temperature combustion in an O_2 atmosphere. This is now the most common method for measuring carbon, but it measures total carbon which includes inorganic carbon (eg lime) as well as SOC so it can overestimate organic C present in a soil sample.

Other tests

Thermal gravimetric analysis and mid-infrared/near-infrared (MIR/NIR) methods are research tools for differentiating forms of soil carbon, and are not routinely available for farm soil testing.

What carbon is tested?

As stated at the beginning of this booklet, there are many pools of carbon in the soil. The pools used in carbon accounting models are sometimes different to those recognised by laboratory chemists. The diagram below (Figure 7) shows which pools are measured by the different tests.

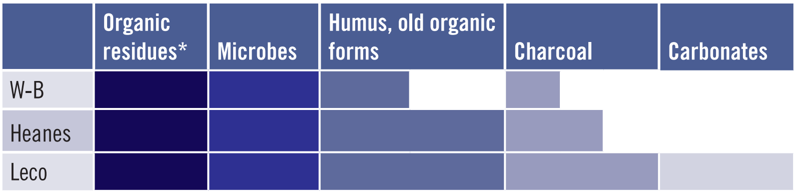

Figure 7. Carbon pools measured in the different soil carbon tests.
* includes fresh and partly decomposed organic matter.

The figure above shows that all methods will measure fresh organic residues if these are not avoided or removed. Hence there can be large apparent seasonal and annual variations in the apparent SOC% if care is not taken in sampling and testing.

> For the same soil sample, different methods will very likely give different SOC results. Therefore it is important to know the actual method used.
>
> For carbon accounting purposes, total carbon is needed and Leco test is the common method that can measure it.

10. Conversion of SOC to SOM

The carbon results in most commercial soil tests are usually expressed on a percentage basis, namely as SOC%. This is the number of grams of soil organic carbon per 100 grams of oven-dried soil. Depending on the purpose, SOC% can be expressed in a number of other forms.

There is often confusion between SOC% and SOM%. SOM% is grams of soil organic matter per 100 grams of oven-dried soil. SOM is composed of carbon, nitrogen, sulfur, phosphorus, oxygen, hydrogen and other elements, the same as fresh organic matter but in different proportions. SOC refers only to the carbon in SOM. On average SOM is about 57% carbon (range 50-58%), so this is the figure used in converting SOM to SOC.

To convert SOC% to SOM%, multiply SOC% by 100/57, or 1.75.

eg 3% SOC is equivalent to (3 x 1.75)% SOM, i.e. 5.25% SOM

To convert SOM% to SOC%, divide SOM% by 1.75

eg 6% SOM is equivalent to (6/1.75)% SOC, i.e. 3.43% SOC

Error factors

Leco method

If the Leco method is used to obtain SOC%, there could be an over-estimation of SOM% because the test includes any inorganic carbon in the soil sample.

Walkley-Black method

If the Walkley-Black method is used to obtain SOC%, the conversion factor used to obtain SOM% is 2.2 because this test tends to underestimate total SOC%. The conversion factor is the product of two factors (1.75 for carbon content and 1.25 for under-estimation of carbon).

In practice, both conversion factors vary widely so 2.2 is really only a very approximate average value.

To convert Walkley Black SOC% to SOM%, multiply W-B SOC% by 2.2 to obtain SOM%.

eg W-B 3% SOC x 2.2 is equivalent to 6.6% SOM

11. Soil carbon for carbon accounting

For carbon accounting purposes, we need to know how much carbon is stored as tonnes of carbon per hectare of land. To work this out, in addition to SOC%, we also need to know the bulk density of the tested soil and the depth of sampling.

Soil bulk density is the measure of mass of soil solid particles divided by the volume they occupy. Different soils and, especially, different soil depths, have different bulk densities. Compacted soils with very few air spaces have a much higher bulk density than soils with plenty of air spaces. For example a tilled surface soil with plenty of air spaces in it might have a bulk density of 1.1 grams/cm^3 (numerically the same as in tonnes/m^3) while a compacted subsoil with few air spaces might have a bulk density of 1.5 grams/cm^3 (tonnes/m^3).

Table 4 shows an example of how the quantity of C stored in a hectare of soil to 10 cm depth varies with both the soil test value for SOC% and the bulk density of the soil.

The following shows how the calculation is done:

eg: To calculate the mass of SOC in 1 hectare of land over 0-10 cm depth for %SOC=2.0 if bulk density =1.5 tonnes/m^3

SOC%	Bulk density (tonnes per m^3)		
	1.1	1.3	1.5
1	11	13	15
2	22	26	30
3	33	39	45

Table 4. Quantities of SOC in 0-10 cm soil layer (in tonnes C per hectare).

Example

Area = 1 ha = 10000 m^2

Depth of 0-10 cm = 0.1 m

Volume of soil = 10000 m^2 x 0.1 m =1000 m^3

Since bulk density = 1.5 tonnes/m^3

Mass of soil = volume of soil x bulk density = 1000 x 1.5 = 1500 tonnes

Since SOC% = 2, which is the same as 2 tonnes SOC per 100 tonnes of soil, the mass of SOC in 1500 tonnes of soil = 2 x 1500/100 = 30 tonnes.

This is the mass of SOC present in 0-10cm of soil over one hectare of land.

The same calculation can be used to work out mass of SOC for other combinations of soil depth, bulk density and SOC%.

Following the above, mass of SOC in 1 hectare over 0-30 cm depth (as required under Kyoto Protocol) can be similarly calculated knowing the SOC% and bulk density over this soil depth.

12. Soil carbon equivalence to CO_2

Every tonne of carbon sequestered in the soil is a tonne of carbon not in the atmosphere, so good management of soil carbon is an important tool in the reduction of greenhouse gases in the atmosphere.

> Every tonne of C in the soil is equivalent to 3.67 tonne of CO_2.
> 1 tonne soil carbon is equivalent to 3.67 tonne CO_2e

The calculation for this figure is based on the atomic weight of carbon and oxygen.

- Atomic weight of carbon is 12 grams per mole
- Atomic weight of oxygen is 16 grams per mole
- Therefore 1 mole of carbon dioxide (CO_2) weighs 44 g (12 + 16 +16)
- Carbon is only 12 grams of the 44 gram weight of CO_2.
- The conversion factor of C to CO_2 is thus 44/12 = 3.67

Hence a tonne of soil C has a 'CO_2 equivalence' (CO_2e) of 3.67 tonne.

When talking about soil carbon in carbon accounting, it is important to make clear whether it is soil carbon (tonnes of C) or CO_2e (tonnes of CO_2) that is being discussed.

13. Predicting SOC using soil carbon models

A soil carbon model describes changes in soil carbon using a set of mathematical equations. Models are important tools because they help predict SOC changes for different management practice scenarios at a given location and other locations with different climates and soil types. The alternative to modelling is running long term field experiments which are expensive and slow to provide results. However, long term trials are still important for testing and calibrating the performance of the models.

All soil carbon models look at inputs to the model, and outputs over time (changes in soil organic carbon, carbon pools and carbon dioxide) (Figure 8). The accuracy of the modelled outputs depends on the quality of the input data and the ability of the mathematical equations to predict changes in soil carbon. Otherwise it will be a case of 'garbage in garbage out'.

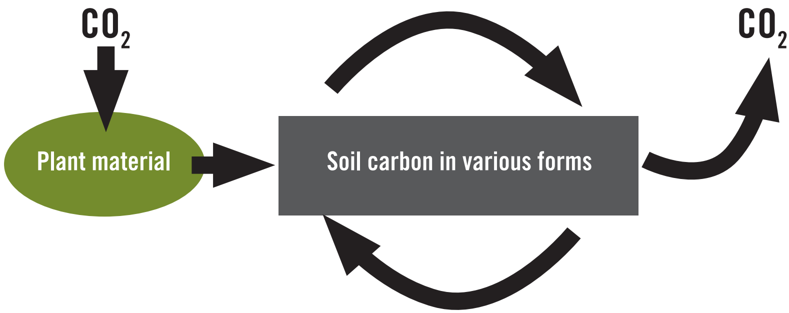

Figure 8. Modelling soil carbon using a model: inputs → carbon model → outputs.

The ROTHC model

There are many soil carbon models around but a popular one in use in Australia is the ROTHC model (Figure 9) which was developed at Rothamsted Agricultural Institute in the UK.

Inputs

To predict changes in SOC, ROTHC model requires the following inputs.

- Monthly rainfall, evaporation and mean air temperature
- Soil clay content
- Monthly inputs of plant residues
- Soil depth

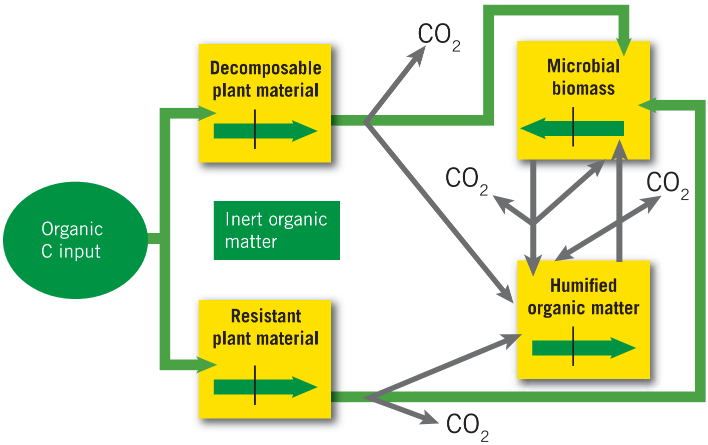

Figure 9. The structure of C flow in ROTHC-26.3 carbon turnover model.

Decomposition

The ROTHC model simulates decomposition of input plant material into different carbon pools with release of CO_2 over time for a given soil depth eg 30 cm.

Coarse carbon pools

Plant residues are assumed to enter two coarse SOC pools: decomposable plant material (DPM) and resistant plant material (RPM).

Fine carbon pools

These then further decompose into two other fine SOC pools, namely humified organic matter (HUM) and microbial biomass (BIO). The fifth pool, inert organic matter (IOM) is assumed to be inert and to not take part in the decomposition process.

Rates of decomposition

Decomposition of different pools and release of CO_2 into the air occurs at different rates which are modified by changing soil moisture and temperature conditions. Other factors, such as soil acidity, soil clay content and soil aeration, also affect the rate of decomposition.

Comparison of model and actual results

The graph below shows how the ROTHC model (lines) compares with actual results (dots) for two contrasting farming systems from the long term trial at Wagga Wagga (Figure 10). Both the actual measurements and model show that in the stubble burnt and cultivated continuous wheat system, the amount of soil carbon declines with time, while in a no tillage and stubble retained wheat/ pasture rotation, soil carbon increases with time.

The close relationship between the measured and modelled SOC shows that:

- the ROTHC model predicts SOC changes with time reasonably well
- the measured SOC data shows large variation, probably due to sampling and measurement errors
- modelling can offer an inexpensive way to obtain long term SOC trends

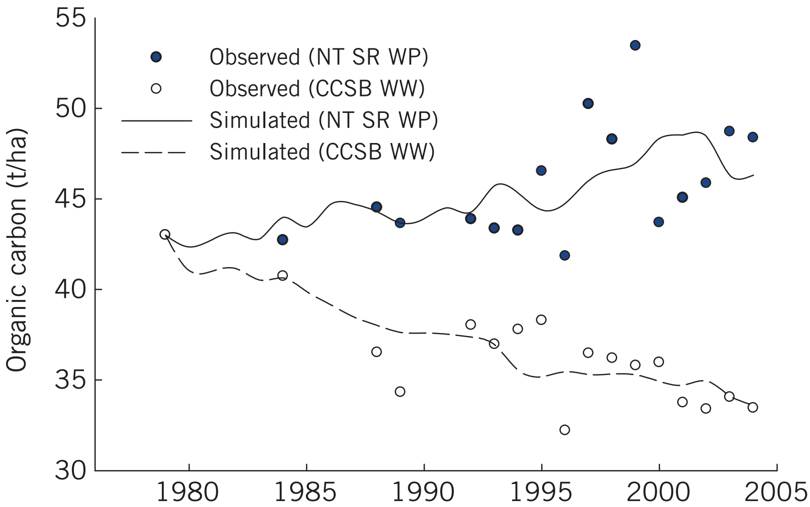

Figure 10. Comparison between measured SOC and simulated SOC by the ROTHC model for two contrasting farming systems. (NT SR WP = no tillage, stubble retained and wheat/pasture rotation; TT SB WW = traditional tillage, stubble burnt wheat/wheat rotation).