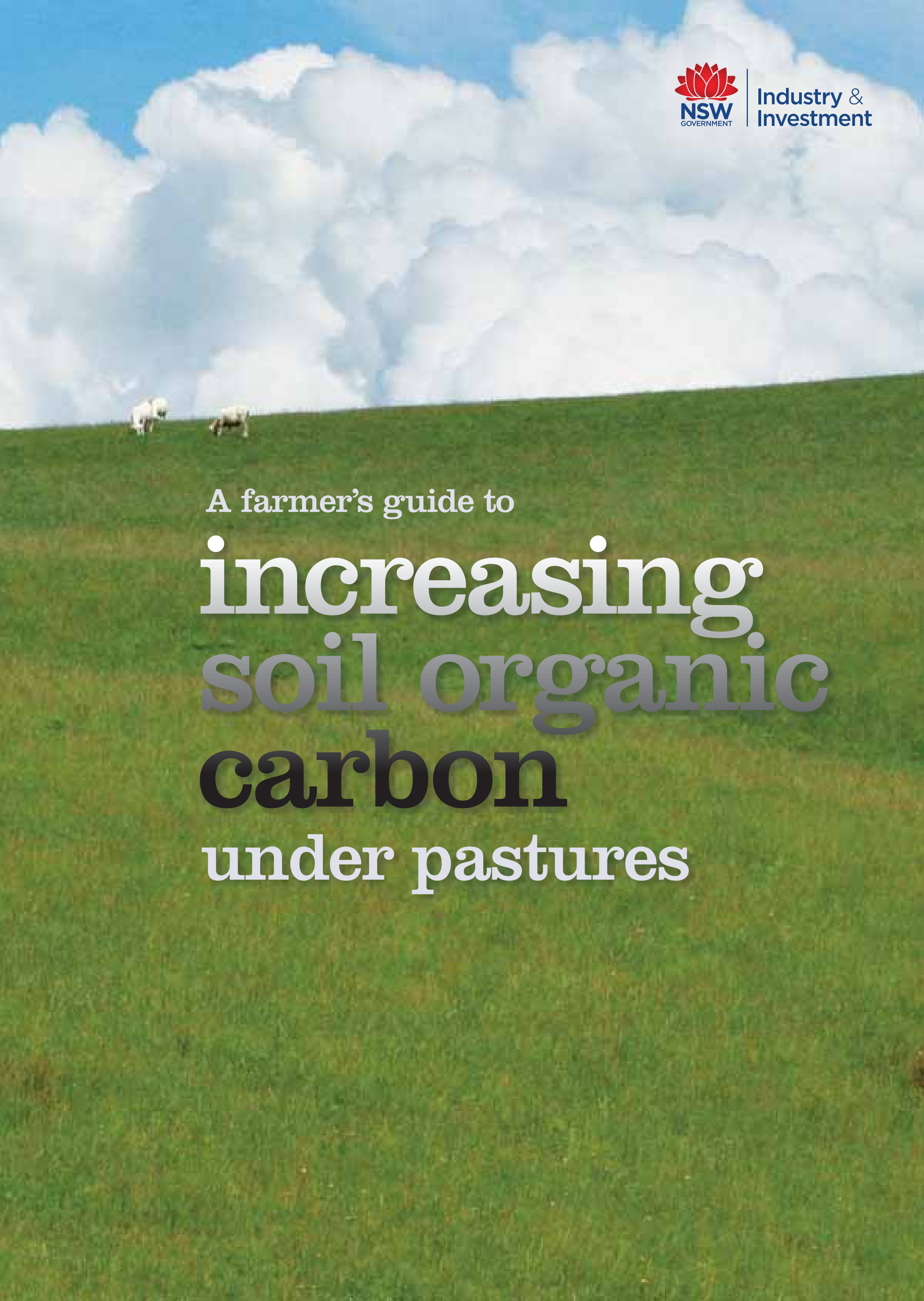

NSW GOVERNMENT | Industry & Investment

A farmer's guide to

increasing soil organic carbon under pastures

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:

- Dr Yin Chan, Richmond
- Albert Oates, Wagga Wagga
- Dr De Li Liu, Wagga Wagga
- Dr Guangdi Li, Wagga Wagga
- Ros Prangnell, Wagga Wagga
- Graeme Poile, Wagga Wagga
- Dr Mark Conyers, Wagga Wagga and
- Dr Brian Murphy, Department of Environment, Climate Change and Water, Cowra

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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.

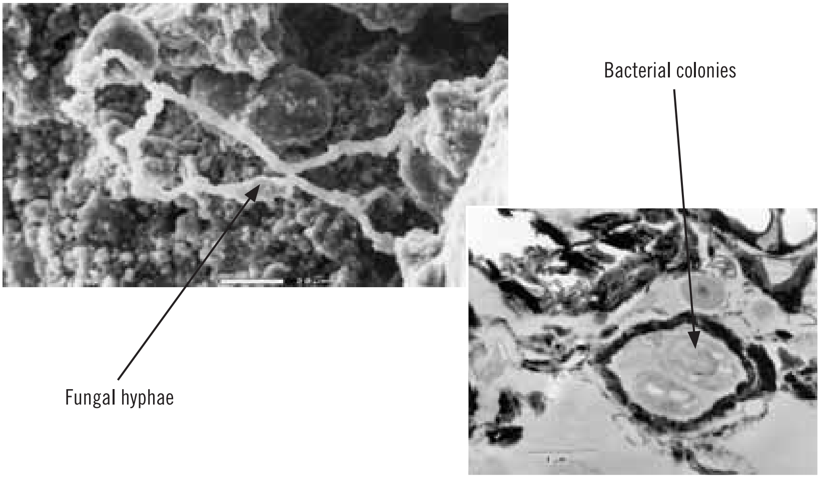


Figure 1a. Soil micro-organisms are part of SOM – scanning electron micrographs showing fungal hyphae and bacterial colonies living in soil.

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%

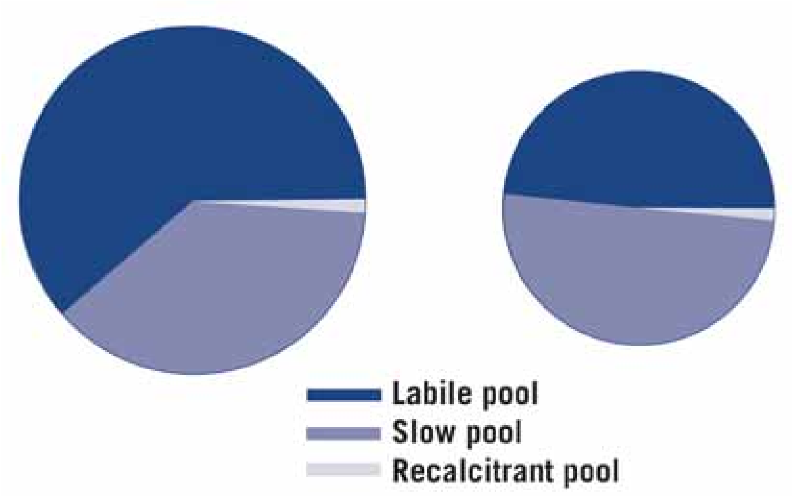


Figure 2. Carbon pools in two contrasting soils.

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).

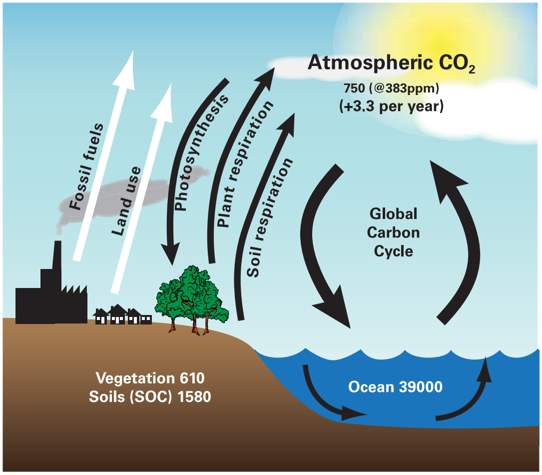


Figure 3. The carbon cycle (all numbers in giga tonnes (Gt)).

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

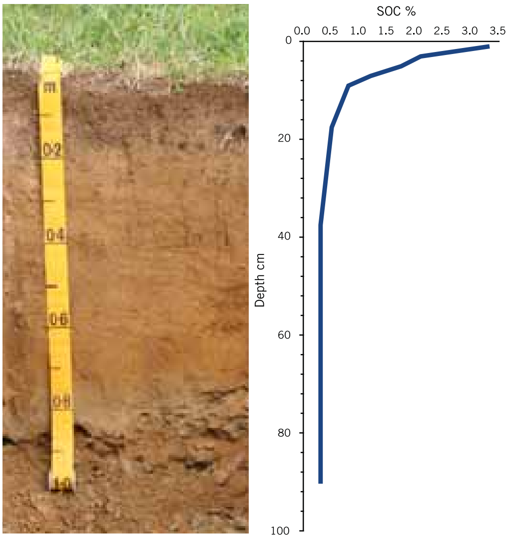


Figure 5. This graph shows the dramatic drop in SOC levels with depth in this soil under pasture.

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.

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.

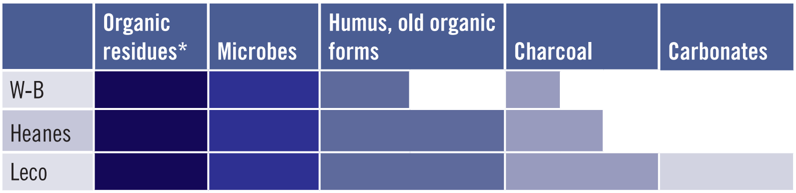


Figure 7. Carbon pools measured in the different soil carbon tests.
* includes fresh and partly decomposed organic matter.

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.

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).

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

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'.

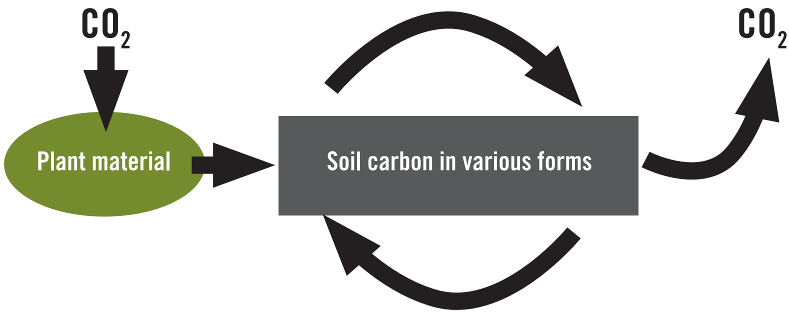


Figure 8. Modelling soil carbon using a model: inputs → carbon model → outputs.

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

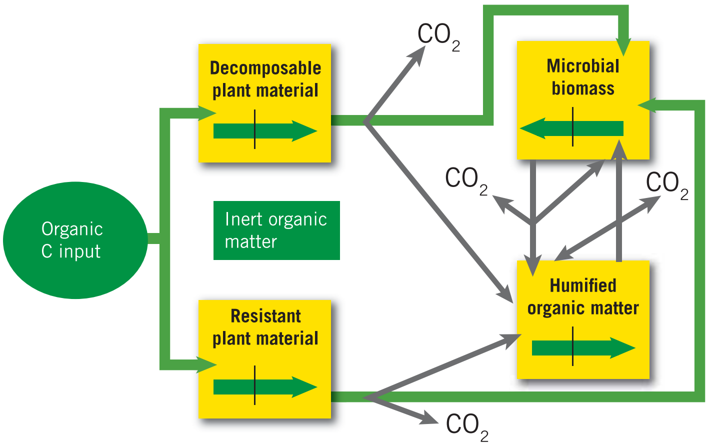


Figure 9. The structure of C flow in ROTHC-26.3 carbon turnover model.

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

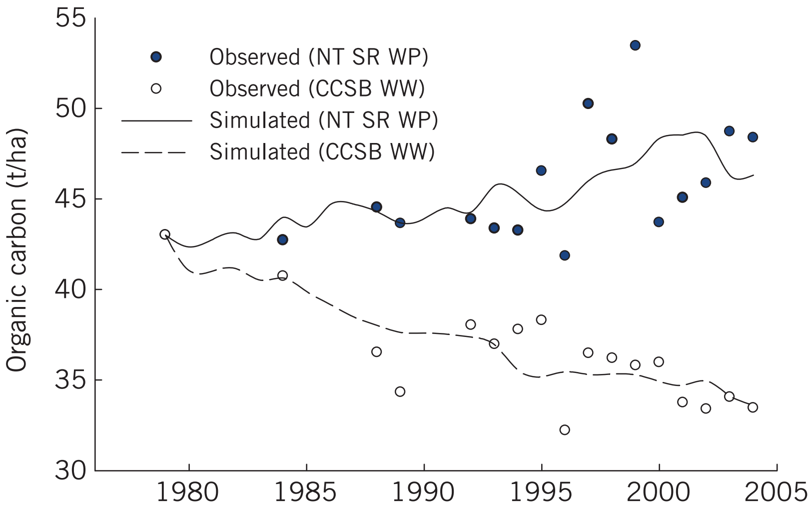


Figure 10. Comparison between measured SOC and simulated SOC by the ROTHC model for two contrasting farming systems. (NT SR WP = no tillage, stubble retained and wheat/pasture rotation; TT SB WW = traditional tillage, stubble burnt wheat/wheat rotation).

SECTION B:

Pastures and soil organic carbon

1. Role of pastures in Australian farming systems

The primary purpose of growing pastures is to supply feed for livestock for meat and wool production. However, in Australia, pastures also play an important role in improving soil chemical, physical and biological properties of soils used for cropping.

Figure 11. Mixed farming of pasture/crop rotation is common in Australia.

In traditional pasture/crop systems, SOC declines under cropping but increases under pasture phase (Figure 12).

Pastures are grown alternately with crops to:

- replenish soil organic matter and plant nutrients
- manage disease
- increase water holding capacity
- improve water infiltration and drainage
- enhance biodiversity
- provide enterprise diversity

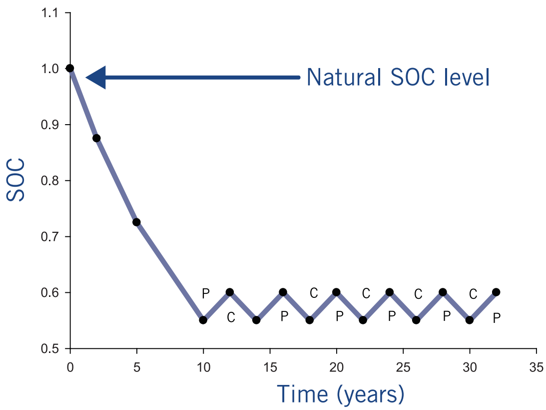


Figure 12. An example of soil organic carbon levels under pasture (P) and crops (C) rotation.

The pasture phase therefore plays the vital role of maintaining long term SOC and the long term fertility status of agricultural soils in Australia. However, this cyclic fluctuation may be at values well below the local carbon sequestration potential as indicated by the natural SOC level in Figure 12.

Reasons for higher SOC under pasture

Soils under pastures tend to have higher SOC than cropped soils because they:

- have a higher root to shoot ratio than many crops
- are not disturbed
- have lower rates of decomposition.

Higher root to shoot ratio

The root to shoot ratio (R/S) is the ratio of the plant's root biomass (below ground) to its shoot biomass (above ground).

> The R/S range in temperate grasses is between 0.4-3.7.
> The R/S in crops can be as low as 0.1.

Perennial pastures usually have higher R/S than annual pastures. For example, the R/S of phalaris is 1.0; the R/S of subclover is 0.45.

Minimal soil disturbance

When soils are undisturbed, SOC is able to reach an equilibrium level. Disturbing soils with tillage is the main cause of SOC loss in agricultural soils. Turning over the soil exposes SOC to air and microbial attack, resulting in increased decomposition rates.

Lower decomposition rate

As discussed earlier, soil moisture content affects the rate of SOC decomposition. Since soils under pasture are usually drier than cropping soils, especially when the latter are under fallow, SOC in pasture soils generally decomposes more slowly compared with cropping soils.

Therefore, SOC is higher under pastures than under cropping and the difference becomes larger as the rainfall increases (Figure 13).

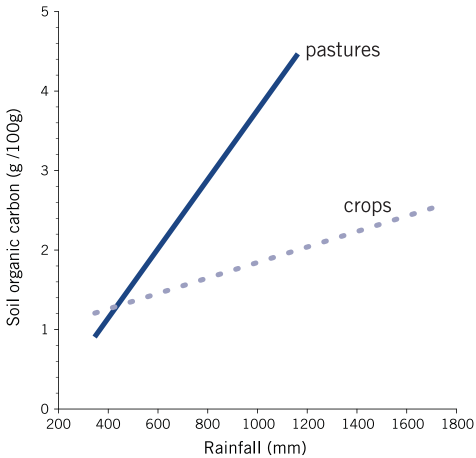


Figure 13. SOC levels in pasture soils compared with cropping soils (0-10 cm) as a function of rainfall in NSW (Gibson et al. 2003).

2. Pasture types

Annual pastures

In Australia, annual pastures are often used in the pasture phase in ley farming systems. The ideal annual pasture should have more than 40% legumes to provide protein and energy rich feed for ruminants and to fix nitrogen in the soil for following crops and grasses. A well managed legume-based pasture can potentially accumulate large amounts of nitrogen (30-200 kg N/ha annually) with the potential to substantially improve crop yields in the short term. In much of southern Australia's acid soil country, subterranean clover is the major species used in short term rotations. Use of annual legume-pastures may accelerate soil acidification if the soil nitrate nitrogen is leached below the root zone.

Perennial pastures

Perennial pastures (e.g. Phalaris, Figure 14) are less acidifying than annual pastures because there is less nitrate leaching. Their long-lived deep root systems take up soil water more effectively than annual pastures reducing soil acidification and the risk of dryland salinity. They use soil water from the deeper part of the soil profile and can respond quickly to out of season rainfall such as summer storms. They may not produce more biomass than equally well managed annual pastures but the seasonal production of that material may better meet the needs of the livestock grazing them.

There is currently little data available on the carbon sequestration potential of annual and perennial pastures. We do know that annual pastures return all of their shoot and root biomass to the soil every year when they die, and that carbon stored in perennial root systems deep in the soil is less easily decomposed than soil carbon close to the surface. However we do not have enough information about the relative effectiveness of the two pasture types in sequestering SOC.

Figure 14.   Phalaris provides the perennial component to the perennial pasture (above left). Both pastures contain annual species such as subterranean clover, annual ryegrass, barley grass and silver grass.

Native pastures

Soil beneath undisturbed native pastures (Figure 15) is sometimes used as a benchmark for natural SOC levels, but these pastures may not provide the best estimate of a district's soil carbon sequestration potential, particularly if the native system is deficient in essential plant nutrients. Unimproved native pasture has the potential for increases in SOC for many years if improved pasture management practices are used. A small increase of SOC per hectare on these unimproved pastures would result in considerable SOC sequestration given the large areas of unimproved native pasture in NSW. Improved pastures generally have higher ability to sequester more carbon in the soil than unimproved native pastures because of their higher productivity. These improved pastures will include legumes such as subterranean clover but the grass component may be exotic species such as phalaris and ryegrass or native species such as danthonia and microlaena. Fertilisers, (usually P fertilisers) are often needed to increase pasture production. However, if fertiliser is added to increase carbon sequestration under pastures, it must be continued regularly to maintain the higher level of forage production. Without these continual inputs, the sequestered soil carbon will eventually be lost.

Figure 15. Both pastures contain microlaena and danthonia but the improved pasture (above left) has a strong legume component which boosts its productivity. Note the exposed bare soil in the native pasture (above right).

3. Overgrazing

Historically, overgrazing has been a major cause of widespread land degradation in Australia, and on occasion has contributed to the collapse of livestock industries.

Overgrazing can seriously damage the pasture sward and the soil beneath it. Desirable species can be grazed out and replaced by less desirable weeds. Frequently these weeds species are not only less productive but provide less protection to the top soil. For example, cape-weed rapidly decomposes at the end of spring leaving the soil exposed to erosion.

Overgrazing occurs when the stocking rate is higher than the pasture base can withstand. It may occur in continuous grazing systems such as set-stocked grazing where there is less opportunity for pastures to rest and recover after grazing. This is the traditional grazing management practice in Australia.

Heavy-hooved animal traffic on wet soil can be worse than tillage, not only disturbing and exposing the soil but also causing serious compaction problems. Cattle and sheep are especially hard on soil. Intensively trafficked areas often become bare and are sources of soil erosion, leading to significant losses of topsoil, nutrients and organic matter, while the less obvious soil compaction of larger areas can reduce the productive capacity of the pasture system.

Overgrazed pasture not only cannot sequester much soil carbon but is vulnerable to losses due to erosion (Figure 16). It is therefore important to maintain adequate ground cover to protect the soil surface from wind and water erosion.

Figure 16. Overgrazed pasture with exposed soil surface (Photo: I Packer).

4. Rotational grazing

Rotational grazing systems have a large number of animals graze a limited area for a short time, after which the paddock is rested for several weeks or months before the animals return.

These systems increase competition between animals for forage and force them to consume plants that they would otherwise ignore. In addition, rotational grazing can be used to manage the height of pasture to optimise both pasture and livestock production and to rest pastures at times critical for plant reproduction or persistence. During the resting period, both the soil and pasture have time to recover from grazing disturbance. This can be used to foster the persistence of desirable and more productive species. Overall, rotationally grazed systems have the potential to increase pasture biomass production over time and so ultimately lead to higher soil carbon levels. However, little information is available on the magnitude of the SOC increase, if any, due to this improved management practice. Promoters of rotational grazing assert that the additional costs and management issues with rotational grazing are outweighed by the benefits of the system.

Figure 17. Rotational grazing: showing a flock of approximately 2000 sheep left on the paddock for short periods of time during the year. The paddock is rested for the remainder of the year allowing pasture growth, suppression of weeds and general repair of soil structure (Photo: I Packer).

5. Pasture cropping

Pasture cropping refers to an intercropping technique first developed in the central west of New South Wales and involves the direct drilling of winter-growing cereals into the predominantly summer-growing native perennial pastures.

From the perspective of soil carbon sequestration, the system may have the potential to increase SOC. There is less soil disturbance in the cropping phase compared with full cultivation, so lower SOC losses. Where pasture cropping successfully re-colonises run-down pastures or cropped soils with well-adapted native pastures, the role of pastures in sequestering soil carbon may be restored or enhanced.

However, while there have been claims that soil organic carbon under pasture cropping should be higher than of that under pasture of conventional ley/crop systems, there is little scientific data currently available.

Figure 18. Pasture cropping: sowing of oats into a winter dormant pasture of red grass (Bothriochloa macra) in central west NSW.

SECTION C:

The SOC pasture project 2006-2009

1. Project background

In 2006 NSW Department of Primary Industries (now Industry & Investment NSW) began research in south eastern NSW to find out more about soil carbon stocks under pastures and to evaluate the effects of different pastures and pasture management practices on soil carbon levels.

The project objectives were to:

- quantify SOC stocks under pastures for a range of management practices
- identify management practices that can increase soil carbon under pastures.

To do this we investigated historical SOC data from two long-term field trial sites, and conducted on-farm paired paddock comparisons of SOC under pastures.

The long term trial sites are near Wagga Wagga on the south-west slopes of NSW and both have had pasture systems in place for more than 15 years. We looked at historical soil carbon and agronomic data from the sites to investigate long term trends in SOC under different management practices and as inputs for testing the soil carbon model, ROTHC.

Figure 19. Hydraulic soil corer for obtaining ‘intact’ soil cores used in the project.

2. Long term trial sites

SATWAGL (Sustainable Agriculture Through Wheat and Good Legumes)

SATWAGL was established in 1979 at the Wagga Wagga Agricultural Institute, Wagga Wagga, New South Wales, Australia on a Kandosol. Average annual rainfall at the site was 554 mm. The surface A horizon was brown to greyish brown clay loam which gradually changed to a light to medium reddish brown clay at about 20 cm. Soil pH of the A horizon (0-12 cm) was acidic, about 4.9 in 0.01 M $CaCl_2$. The objective of the experiment was to monitor changes in agronomic performance and soil quality under a range of tillage, stubble management and rotation practices. Soil and plant samples were collected yearly for analyses and archived. The trial was discontinued in 2005 due to lack of funding.

Figure 20. The SATWAGL field trial (1979-2005).

MASTER (Managing Acid Soils Through Efficient Rotations)

The field trial was located at Book Book, 40 km south-east of Wagga Wagga in a 650 mm rainfall zone. The soil was a Subnatric Yellow Sodosol. Two types of pastures, perennial and annual, each with or without limestone, were established in 1992. The perennial pasture was sown to phalaris, cocksfoot, lucerne and subterranean clover. The annual pasture was sown to annual ryegrass and subterranean clover. Lime was applied to maintain an average pH_{Ca} of 5.5 in the 0-10 cm depth over the six year liming cycle. Phosphorus (P) was applied at 15 kg P/ha as single superphosphate every year. Pastures were grazed with a 2½-week grazing period and a five week spell throughout the year except for the period of the autumn break when annual species emerged and the period of rapid growth in spring where a one week grazing and two week spell regime was used. The stocking rate was adjusted to achieve the optimum pasture and animal productivity. More information about the trial is available at: www.dpi.nsw.gov.au/agriculture/resources/soils/acidity

Figure 21. The MASTER long term trial at Book Book, close to Wagga Wagga, NSW.

3. Soil carbon under pasture survey

In this survey we compared SOC in paddocks on 23 farms from Gulgong in the north to south of Albury (Figure 22). We undertook five different comparisons as shown below.

1. Native perennials vs introduced perennials
2. Annual vs perennial pastures
3. Continuous grazing vs rotational grazing management
4. Pasture cropping vs control
5. Improved vs unimproved pastures

We selected 4-5 paired-paddocks for each of these comparisons based on the following criteria to minimise variability and ensure that variations in SOC were due to the factors being studied.

The paired paddocks had to have:

- the same soil type
- the same aspect
- similar slope and topography
- at least 10 years history under the particular management
- be near each other (preferably across the fence).

However, we encountered some difficulties during site selection.

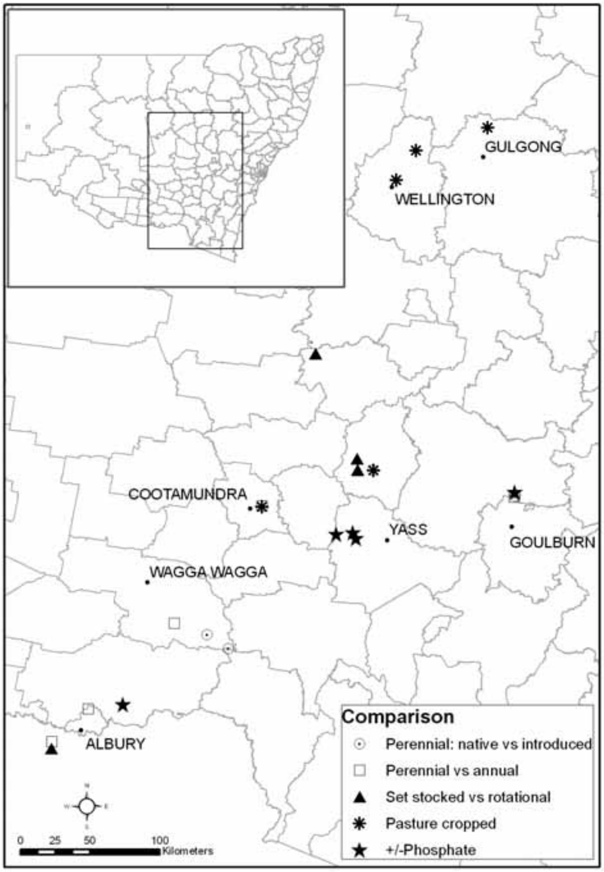


Figure 22. Location of the paired sites for the SOC survey.

Difficulties in site selection

Pasture types

Pastures were rarely pure. Both native and introduced perennial pastures generally also contained some annual grasses and clovers, particularly annual ryegrass and subterranean clover.

Annual pasture sites

Long-term annual pastures were rare on arable land, so one of the annual pastures sampled was under 10 years old.

Fertiliser and grazing management

Grazing management comparisons were inevitably made across-boundary-fences between neighbouring farmers, and therefore potentially confounded by differences in fertiliser history. We initially targeted set-stocking vs rotational grazing, but in practice some set-stockers proved to be loose rotational grazers. In all cases however, we compared relative non-grazed periods.

Pasture cropping sites

Pasture cropping comparisons were particularly problematic. In some cases, the pasture based cropped paddocks were compared against their un-cropped pasture counterparts. In one instance, we compared two pasture areas, each with the same cropping history with one area ‘traditionally farmed’ (disc plough) and the other pasture cropped. In another, both areas had been cultivated initially and the perennial pasture component was still very low. The final comparison was on a strong bothriochloa pasture with both areas pasture-cropped in the first year, with one area pasture-cropped every year thereafter and the other area just under pasture. In most cases, the history of pasture cropping was less than five years.

Improved pasture sites

Improved pastures were defined as those having a history of superphosphate and subterranean clover. Some of the unimproved pastures may have been fertilised with superphosphate in the past, but not for many years.

4. Soil sampling and analysis

Following the advice of a biometrician we adopted the following sampling scheme.

1. A uniform sampling area (20 m by 20 m) was selected from each side of the paired sites as shown below (Figure 23).
2. Each sampling area was subdivided into four 10 m x 10 m squares.
3. Within each square, 2 soil cores to 40 cm depth were taken at random with a hydraulic device (Figure 24).
4. Each core was individually cut into five depth increments of 0-5, 5-10, 10-20, 20-30 and 30-40 cm (Figure 25). Samples from the two soil cores of each 10 m x 10 m square were combined by depth intervals to form five composite samples.

This means that for each sampling area we took eight composite soil cores with a total of 20 soil samples for analysis.

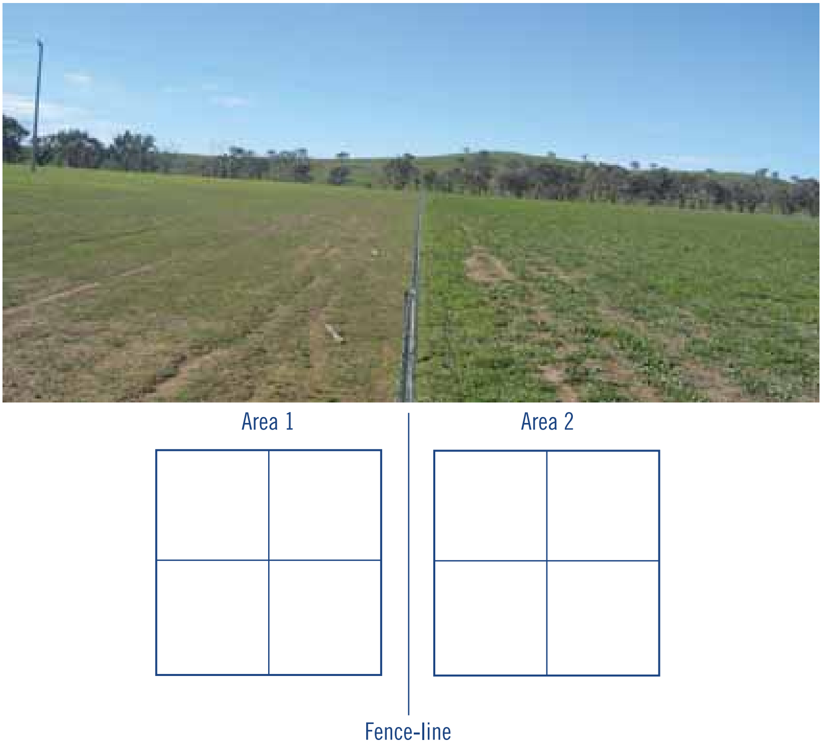


Figure 23. Soil sampling at each paired site.

Figure 24. Soil sampling using a hydraulic soil corer.

Figure 25. Intact soil core to be sectioned into 0-5, 5-10, 10-20, 20-30 and 30-40 cm increments.

Laboratory analysis

In the laboratory, all the soil samples were tested for total organic carbon using the Leco method. Bulk density of all the soil sections was also calculated.

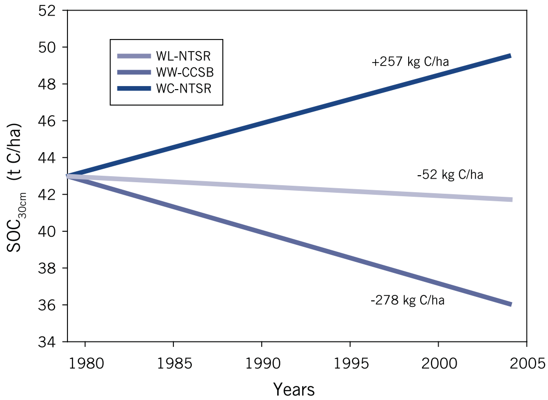
From these data, soil carbon stocks per ha to 30 cm depth were calculated from the data of each of the sampling squares.

Soil carbon stocks between paired comparisons were then compared statistically to see if they were different.

5. Key findings

Key Finding 1: Pastures maintain and increase SOC

SATWAGL long term trial (1979-2004)



NT = no tillage
TT = traditional tillage (3 passes)
SR = stubble retention
SB = stubble burnt
WL = wheat/lupin rotation
WW = continuous wheat
WC = wheat/clover rotation

Figure 26. Changes in SOC stocks with time for three contrasting management systems in SATWAGL long term trial.

In this long term trial, we found SOC stocks varied with the kind of rotation, tillage and stubble management practices (Figure 26).

Declining SOC

Under continuous wheat cropping with stubble burning and traditional tillage (three passes), SOC declined at a rate of 278 kg/ha/yr.

Static SOC

Under wheat/lupin rotation, even with the most conservative management, no tillage and stubble retention, at best SOC remained relatively unchanged.

Increasing SOC

Under wheat/clover rotation (1:1), we found SOC actually increased at a rate of 257 kg C/ha/yr when no tillage and stubble retention were practised under cropping and pasture was mown and returned.

These findings highlight the importance of the pasture phase in sequestering carbon.

MASTER long term trial (1992-2004)

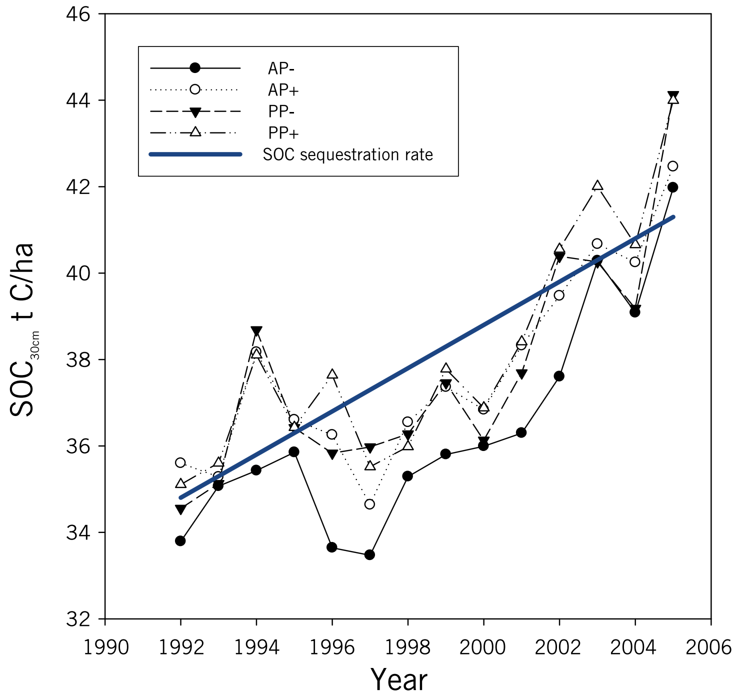


Figure 27. Changes in SOC stocks (to 30 cm depth) with time under different pastures and lime treatments in MASTER long term trial
(AP = annual pasture PP = perennial pasture - = unlimed + = limed)

Before the trial commenced, the site was a degraded pasture, but in the 15 years since then, SOC has increased at a rate (when averaged over all treatments) of about 500 kg C/ha/yr. The increase was due to improved management of the pastures, which increased annual dry matter production from 4 t/ha before the trial to a mean of 6 t/ha. There was no statistically significant difference in SOC stocks between pasture types (PP vs AP) or lime treatment (unlimed vs limed).

These results highlight the importance of improved pasture management in increasing SOC. The results also highlight the year to year variation which can occur within a long-term trend. Short-term changes in soil carbon based on only a couple of samplings can be misleading because they may be very different from changes measured over ten or twenty years (Figure 27).

Key Finding 2: Additional potential for SOC sequestration

The SOC stock under pastures did not vary with rainfall within the rainfall zone studied. Instead, average SOC stocks (0-30 cm) varied between 29 to 55 t C/ha across all sites and at individual sites with the same rainfall, SOC varied by up to 25 t/ha (Figure 28). This therefore indicates considerable additional potential in SOC sequestration under pastures in the region. We need to identify the factors restricting SOC sequestration at some of these sites.

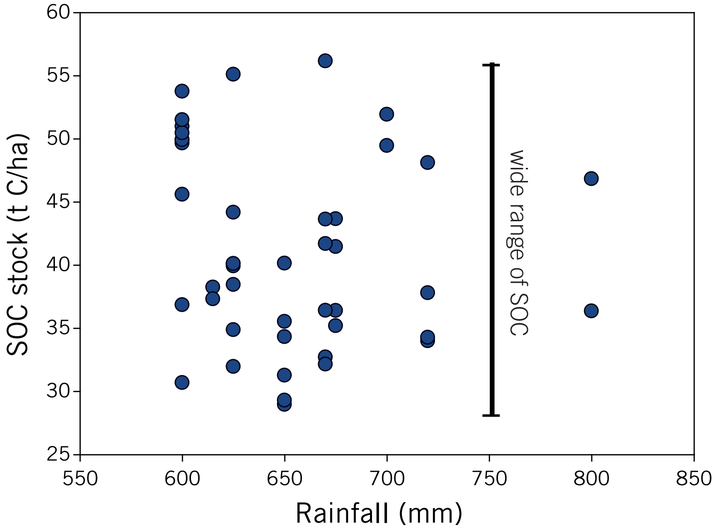


Figure 28. Average soil organic carbon stock (0-30 cm) at all the different sites as a function of annual rainfall.

Key Finding 3: Pasture types do not affect SOC

We found no significant difference in SOC stocks between introduced and native perennial pastures, or between annual and perennial pastures.

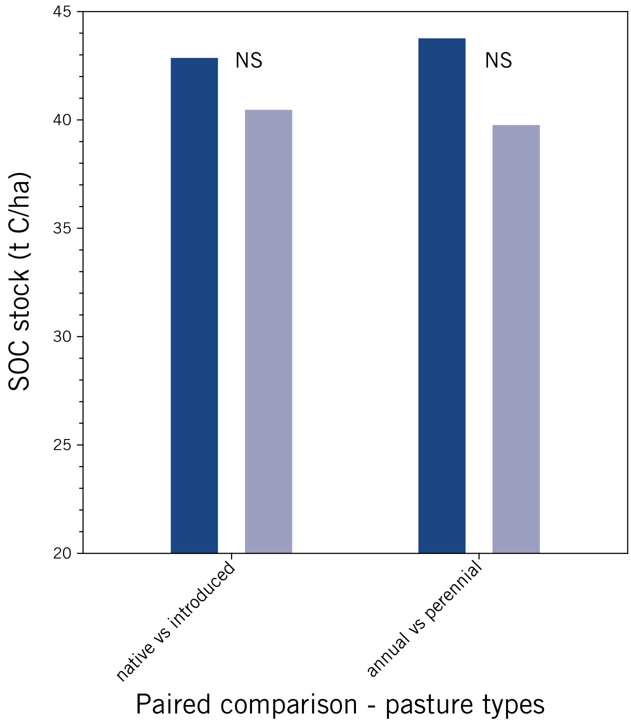


Figure 29. SOC stocks (0-30 cm) between different pasture types.
NS = not statistically different

Key Finding 4: Improved pastures increase SOC

We found significantly higher SOC under pastures improved with P fertiliser application than under unimproved pastures with no history of phosphorus application. Pastures with added P had an average of 10 tonnes of carbon per hectare higher than unimproved pastures.

The estimated long term rate of carbon sequestration due to pasture improvement ranged between 260 – 710 kg C/ha/yr (mean of 410 kg C/ha/yr).

We found no difference in SOC levels between set stocked vs rotational grazing or pasture cropping vs control.

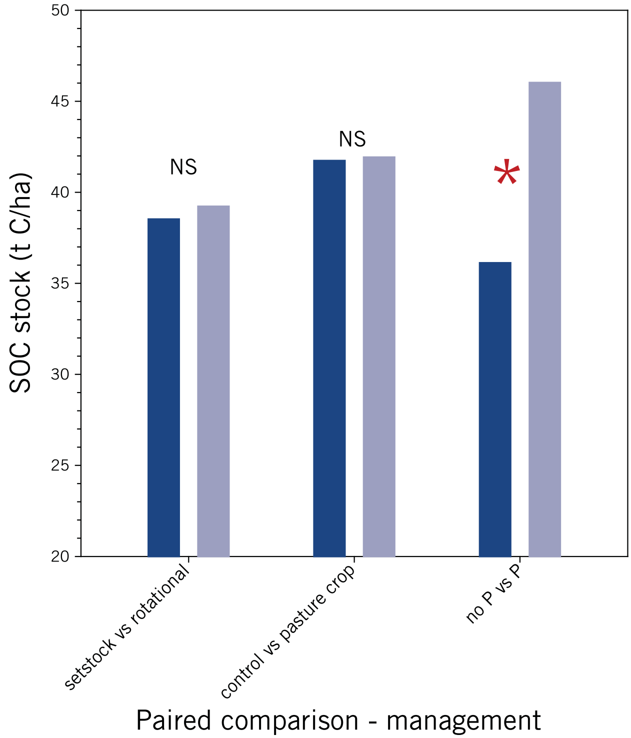


Figure 30. SOC stock (0-30 cm) under pastures of different management practices.
NS= not statistically different
* = statistically different

Key Finding 5: There is potential to store carbon in subsoil

Comparisons of soils with phosphorus and no phosphorus applications showed two distinct patterns in SOC at depth (Figure 31).

At some locations SOC increases were measured down to 30 cm (A) in soils fertilised with phosphorus. At others, increases in SOC were restricted to the top 10 cm (B).

This indicates that there is potential to store SOC in the subsoil layer where it is less prone to decomposition and therefore will stay in the soil for longer.

However, we need more research to understand why the different patterns of SOC sequestration occur.

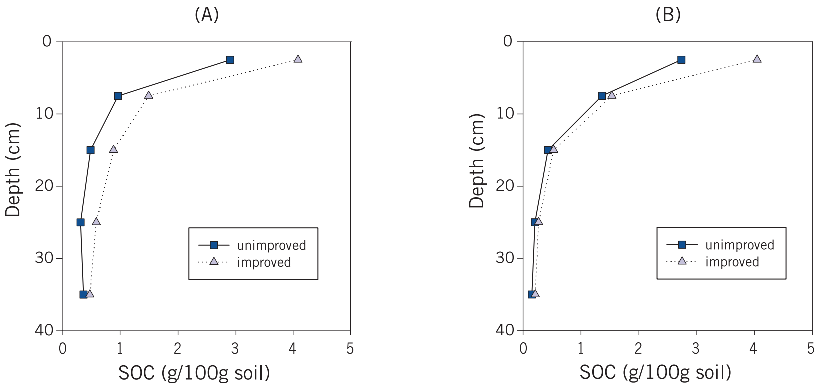


Figure 31. Soils varied in the depths at which they stored SOC. In comparison A SOC increased to 30 cm; in comparison B SOC increases only occurred in the top 10 cm.

Key Finding 6: SOC levels vary across the paddock

Our sampling showed that organic carbon levels vary spatially even in a seemingly uniform area (Figure 32).

Over the small area of 40 m by 40 m sampled, SOC levels varied between a maximum of 2.72% and a minimum of 1.44%. The mean value of the 20 soil samples was 2.02%.

Therefore, by collecting just one sample at random, any SOC value within this range is possible but this would not represent accurately the SOC status of the area.

This highlights the importance of sampling methodology to obtain accurate and verifiable SOC values.

This large field variability tends to mask any small real difference in SOC due to management practice and is probably the reason why we could not detect significant difference in SOC for some of the paired comparisons investigated in this project.

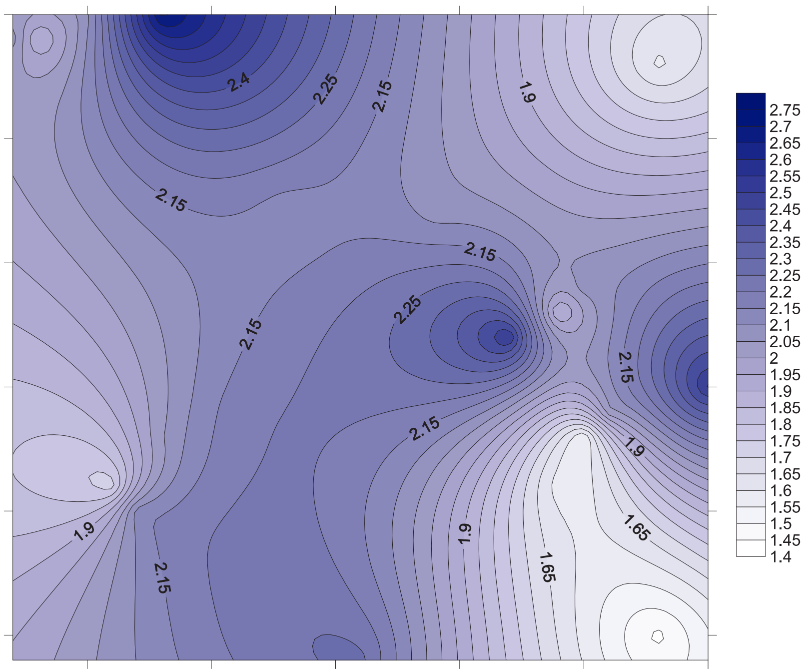


Figure 32. This 40 m x 40 m contour plot shows large variations in SOC concentration (%) as measured in 20 soil carbon samples collected from 0-5 cm depth.

Summary and conclusions

Soil organic carbon is the basis for sustainable agriculture. Increasing SOC of agricultural soil is a win-win strategy because it improves soil fertility and assists in mitigating climate change.

SOC levels are sensitive to management practices.

In agriculture, SOC levels are sensitive to management practices. To turn agricultural soils from a carbon source to an effective soil sink requires adopting improved management practices.

SOC levels are higher under pasture.

In pasture soils, SOC levels are generally higher than those under cropping and so management of pastures offers opportunities to increase SOC sequestration.

Higher rainfall areas have potential to sequester additional SOC.

We have identified considerable additional SOC sequestration potential under pastures in higher rainfall (>600mm) areas in central and southern NSW.

Applying P fertiliser is a useful practice to increase SOC under pastures.

We have also identified the use of P fertiliser on P deficient soil together with legumes to increase pasture production as an effective management practice to significantly increase SOC stocks under pastures. This also results in more productive and hopefully more profitable pasture enterprises.

More research is needed in SOC under pastures.

We did not detect any statistically significant difference in SOC stock due to other management practices included in the investigation, namely native perennial vs introduced perennial; annual vs perennial; continuous vs rotational grazing management or pasture cropping comparisons. Further research using other approaches, such as long term trials, is needed.

SOC levels are highly variable so a good sampling methodology is needed.

Due to high field variability of SOC, an appropriate sampling methodology is required to obtain accurate SOC values, particularly if soil carbon is to be included in carbon trading schemes.

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Glossary

Annual pasture

A pasture with species that complete their life cycle in one year. Typically, annual species germinate from seeds in autumn at the break of season and set seeds at the end of the growing season, normally in late spring. Pastures dominated by annual pasture species, such as annual ryegrass, subterranean clover or annual medics are called annual pastures. The ideal annual pasture should have more than 40% of legume component.

Bulk density

The ratio of the oven dried mass of a given soil sample to its bulk volume. The common unit for bulk density is Mg m^{-3}, i.e. tonnes m^{-3} which is numerically the same as g cm^{-3}.

C sink

The parts of the carbon cycle (see Figure 3) that store carbon in various forms are referred to as C sinks. Soil carbon, with a size more than twice that of vegetation is a C sink of considerable size.

Carbon neutral

Refers to achieving net zero carbon emissions by balancing a measured amount of carbon released with an equivalent amount sequestered or offset. The carbon neutral concept may be extended to include other greenhouse gases (GHG) measured in terms of their carbon dioxide equivalence.

CENTURY Soil Carbon Model

Another widely used soil carbon model developed in the US. It is part of a general plant soil ecosystem model which simulates carbon and nutrients dynamics for different types of ecosystems.

Continuous grazing

A grazing system in which little or no opportunity is provided for the pasture system to rest and recover after grazing. This is the traditional management grazing management practice in Australia. This term is used interchangeably with set stocked grazing.

Greenhouse effect

The heating of the surface of a planet or moon due to the presence of an atmosphere containing gases that absorb and emit infrared radiation. Greenhouse gases are almost transparent to solar radiation but strongly absorb and emit infrared radiation. Thus, greenhouse gases trap heat within a system.

Greenhouse gases

There are many gases which cause the atmosphere to retain heat. In order, Earth's most abundant greenhouse gases are: water vapor, carbon dioxide, methane, ozone.

Carbon dioxide from human activity is the greenhouse gas that contributes most of the warming effect. CO_2 is produced by fossil fuel burning and other human activities such as cement production and tropical deforestation.

CO_2 is the standard by which the relative impact of other gases is assessed. For example, methane (CH_4) is approximately 33 times worse than CO_2, so every tonne of CH_4 gas emitted is equivalent to 33 tonnes of CO_2. The worst gas emitted by agriculture is probably N_2O, which has approximately 298 times the warming potential of CO_2; hence 1 tonne of N_2O has a CO_2 equivalent of 298 tonnes.

Improved pasture

Grazing land permanently producing introduced or domesticated native forage species that receives varying degrees of periodic cultural treatment including fertiliser application to enhance forage quality and yields and is primarily harvested by grazing animals.

Overgrazing

Grazing livestock to the point of damage to the land. Overgrazing occurs when plants are exposed to intensive grazing for extended periods of time, or without sufficient recovery periods. It can be caused by either livestock in poorly managed agricultural applications, or by overpopulations of native or non-native wild animals.

Pasture cropping

Pasture cropping refers to an intercropping technique first developed in the Central West of New South Wales and involves the direct drilling of winter-growing cereals into the predominantly summer-growing native perennial pastures.

Perennial pasture

Species that can grow more than two years are called perennial species. Pastures dominated by perennial pasture species are called perennial pastures. Perennial pastures can be established from seeds or vegetative parts.

Perennial pastures can grow all year round depending on the availability of soil moisture. However, many perennial pasture species have mechanisms which provide dormancy when there is a lack of moisture. Perennial pastures can generally use soil moisture from deep in the soil profile and they may respond more quickly to out of season rainfall, such as summer storms.

Root shoot ratio

The ratio of root biomass to shoot biomass of a plant. Different plants have different R/S ratios. In general, grass species have higher R/S ratios than crop and tree species

e.g. Temperate pastures 0.4-3.7; crops 0.1 and trees 0.2-0.3.

Rotational grazing

Rotational grazing refers to the improved practice of scheduled movement of grazing animals from one pasture paddock to another during the year.

Soil carbon stock

The amount of soil carbon stored over a given depth of soil per unit area of land. The unit is t C/ha. Based on Kyoto protocol, the depth refers to 0-30 cm layer of surface soil.

Notes

Notes

Notes

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

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.

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