Managing the carbon cycle

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Abstract
Organic carbon in soils is a heterogeneous mixture of organic materials decomposing at different rates. The amount of carbon found in a soil can be viewed as a balance between organic matter inputs (plant production and residue handling) and losses due to decomposition. In this paper, the carbon cycle and the ways various components of soil carbon can be affected by soils, climate and management practices are explained. Also discussed are the relationships between the potential, attainable and actual levels of carbon in soils, and the factors that influence them. Because soil organic matter content changes slowly, computer-based models are used to examine potential long-term influences of management practices. The RothC carbon model has been calibrated to allow the dynamics of total organic carbon and the particulate organic carbon, humus organic carbon and recalcitrant organic carbon (charcoal) fractions under Australian conditions to be predicted. Using data collected from a native pasture site at Yass, NSW, the relationship between pasture productivity and soil organic carbon content was explored. This highlighted the challenges of making significant increases in soil carbon in grazing systems, at least over reasonable time scales.

Key words
Soil organic carbon, management practices, residues, pasture.

Forms of organic carbon in soil

Soil organic carbon is found in a complex and heterogeneous mixture of organic materials. These organic materials vary in their physical size, chemical composition, degree of interaction with soil minerals and extent of decomposition. Although determining the impact of management practices on total soil organic carbon contents is useful and important, it does not tell us anything about the type of organic carbon present. For example, is the organic carbon dominated by pieces of plant residue or the more recalcitrant charcoal? It is therefore important to determine the composition of soil organic carbon to gain an appreciation of the implications of management practices on changes in organic carbon content.

We now recognise four different types of soil organic matter:

- Plant residues – shoot and root residues >2 mm residing on and in soil
- Particulate organic carbon (POC) – individual pieces of plant debris that are smaller than 2 mm but larger than 0.053 mm.
- Humus (HUM) – decomposed materials less than 0.053 mm that are dominated by molecules stuck to soil minerals
- Recalcitrant organic carbon (ROC) – dominated by pieces of charcoal

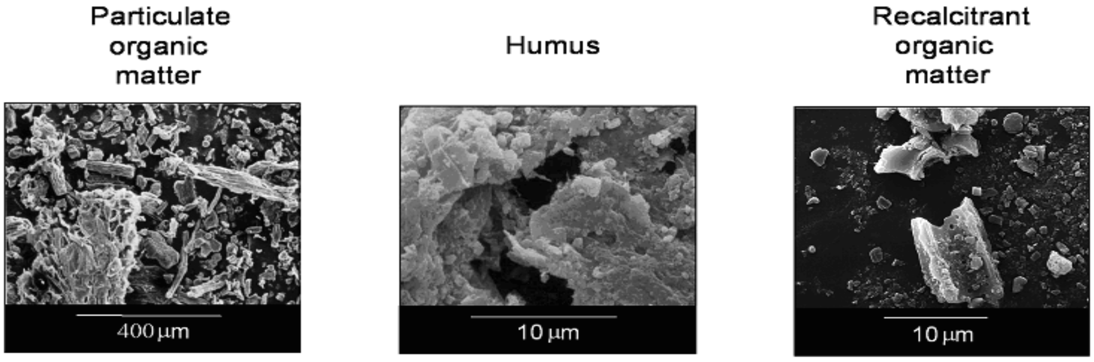

Figure 1. Types of organic matter found in soils.

Pictures of the POC, HUM and ROC forms of soil organic carbon are shown in Figure 1. Pieces of organic material with structures similar to plant residues dominate the POC fraction. For the HUM fraction the carbon consists predominantly of molecules attached to the surfaces of mineral particles, with little evidence of pieces of plant debris. The charcoal fragments visible in the ROC fraction are small (<0.053 mm) and have an average age typically >500 years. Large soil charcoal contents occur in regions that were historically grasslands and burned regularly. Soils in local depressions in the landscape also tend to accumulate charcoal.

The amount of each of these different types of organic matter in Australian agricultural soils varies significantly (Figure 2a) and can be affected by management practices (Figure 2b). In the study shown in Figure 2a, plant residues accounted for the smallest proportion of organic carbon, except at Harden. In cropping systems, the humus material was the largest component, but in pasture systems (Hamilton and Waikerie pasture-wheat) the particulate material accounted for as much or more of the soil organic carbon than the humus (Figure 2b). It is also important to note that the amount of carbon contained in the recalcitrant fraction varies across locations. This is consistent with the finding that ROC is dominated by charcoal (a compound that is resistant to decomposition). Results obtained for a wider range of soils than presented here, have indicated that charcoal can account for between 0 and 60% of the organic carbon present in a soil. Given the relatively inert nature of charcoal, it is important to identify soils with high charcoal contents to understand what fraction of the soil organic carbon is available to microorganisms.

How can soil organic carbon content be changed?
The amount of organic matter in a soil results from the balance of inputs (plant residues) and outputs (mineralisation). A simple example of the soil carbon cycle is shown in Figure 3. The majority of carbon enters the soil as plant residues. Fire can also contribute by converting plant dry matter into charcoal which enters the recalcitrant fraction and can survive in the soil for thousands of years. Inputs are controlled by the type of plants grown, the amount of dry matter they accumulate over the growing season and the environmental factors governing production. Under the water-limited conditions of most Australian agricultural regions (without irrigation), inputs of plant residues are restricted by climate (principally rainfall) and stubble-handling practices (e.g. burning or baling).

Losses of soil organic carbon result from decomposition and mineralisation of carbon contained in the plant residues and soil organic fractions to carbon dioxide. The rate of loss is determined by the nature of the residues entering the soil, climatic conditions and soil clay content. The final organic carbon content of a soil is a result of the balance of these two processes over many years. Given enough time, the inputs and losses will become balanced and soil organic carbon content will remain relatively stable, with small deviations occurring due to the variable effects of climate on productivity.

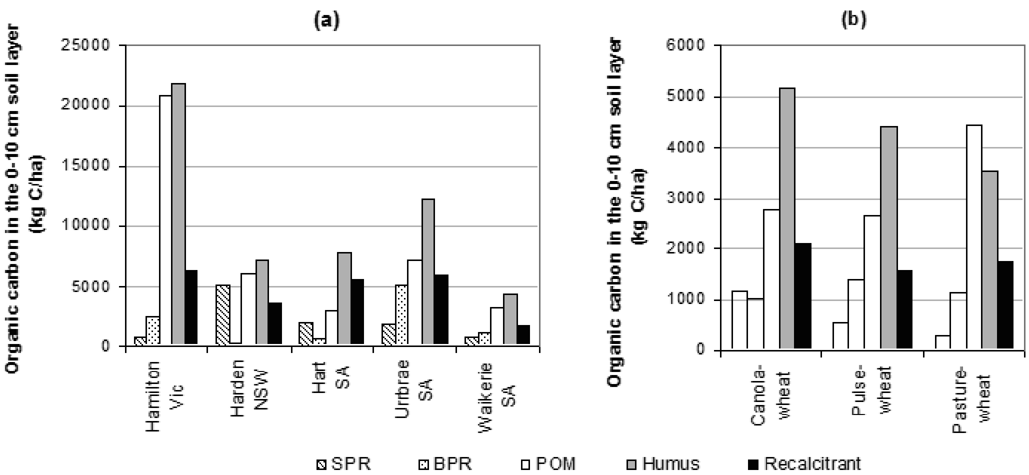

Figure 2. Amounts of each type of soil organic carbon found in the 0-10 cm soil layer at several locations within southern Australia (a) and within different crop rotations at a single location (b). (SPR: plant residues on the soil surface, BPR: plant residues buried in the soil, POM: particulate organic material)

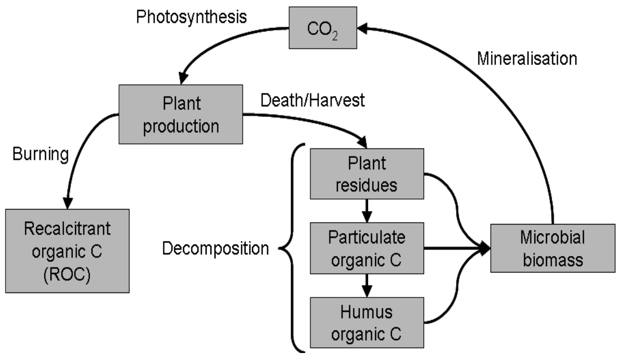

Figure 3. The soil organic carbon cycle.

In Figure 4, the influence of altering management practices on the increase or decrease in the inputs of organic residues can be seen. If the change in management practice imposed at 20 years does not change the amount or nature of residues returned to the soil, soil organic carbon content will remain constant (solid black line of Figure 4). If the amount of residue returned increases, soil organic carbon contents will increase to a new higher value, with the extent of the increase being related to the increase in the amount of residues returned (dotted and dashed black lines of Figure 4). Conversely, if residue returns decrease, soil organic carbon levels will also decrease (dotted and dashed grey lines of Figure 4).

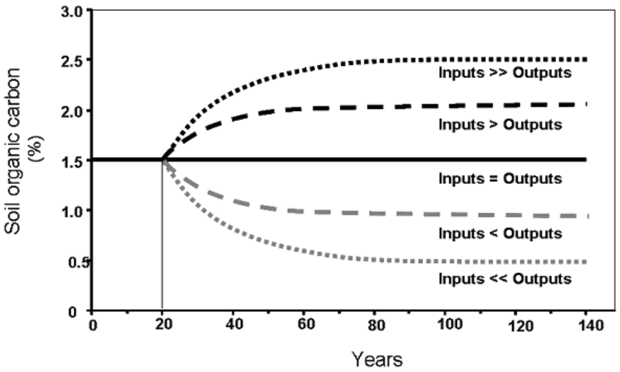

Figure 4. Influence of the relationship between inputs and losses on soil organic carbon content.

How much organic matter is it possible to retain in soil?

Because of the limitation placed on plant dry matter production and decomposition rates by climate and soil properties, there are specific levels of SOM that can be reached for any system in a particular geographic region and soil type. This is described in Figure 5, where three soil organic carbon (SOC) levels are shown: $SOC_{potential}$, $SOC_{attainable}$ and SOC_{actual}. $SOC_{potential}$ is the SOC level that could be achieved if there were no limitations on the system except soil type. Soil type has an influence because surfaces of clays and other minerals will influence how much organic C can be protected against decomposition. For a soil to actually attain $SOC_{potential}$, inputs of carbon from plant production must be sufficiently large to both fill the protective capacity of a soil and offset losses due to decomposition.

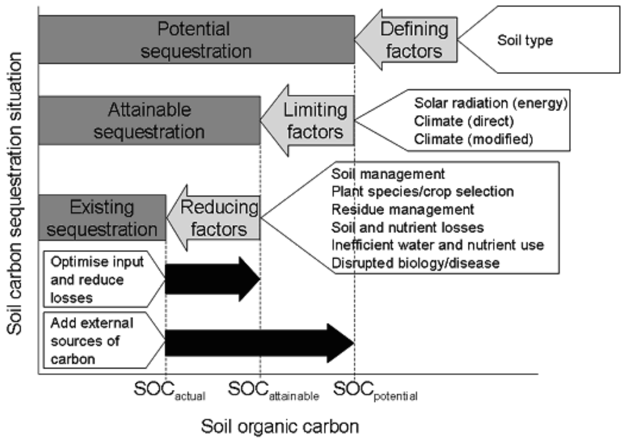

Figure 5. The influence of several factors on the level of SOC that can be reached in a given soil.

The potential amount of crop/pasture material that can be produced at a given location is defined by factors such as the amount of solar radiation, temperature range and availability of water. Under most conditions these factors, referred to as limiting factors, are out of the control of the farmer, with the possible exception of water where irrigation is an option. The amount of crop/pasture production possible after taking these limiting factors into account may be either greater or less than the amount required to allow the $SOC_{potential}$ to be attained. Where crop/pasture productivity is greater than the value required to achieve $SOC_{potential}$ (e.g. under irrigation or where mechanisms of protection are absent or of minor importance) then the attainable soil organic carbon content ($SOC_{attainable}$) will be greater than $SOC_{potential}$. However, under the dry-land agricultural conditions prevalent over most of Australia, the availability of water sets an upper limit on plant productivity below that required to attain the $SOC_{potential}$. As a result, the $SOC_{potential}$ cannot be attained, and a lower value defined as $SOC_{attainable}$ results.

The value of $SOC_{attainable}$ is the realistically best-case scenario for any production system. To achieve $SOC_{attainable}$, no constraints to productivity (e.g. low nutrient availability, weed growth, disease, subsoil constraints, etc.) must be present. Such situations virtually never exist, and these constraints typically result in lower crop/pasture productivities than required to attain $SOC_{attainable}$. This second set of factors is referred to as reducing factors, which may well be under the control of farmers. Decreased productivity, induced by the reducing factors, leads to lower returns of organic carbon to soil and lower actual organic carbon contents (SOC_{actual}). Optimising agricultural management will allow SOC contents to move from SOC_{actual} values towards $SOC_{attainable}$. Where all constraints to productivity can be removed, $SOC_{attainable}$ may actually be achieved. Under conditions where $SOC_{attainable} < SOC_{potential}$, the only way to move SOC content beyond $SOC_{attainable}$ towards $SOC_{potential}$ is through the addition of an external source of organic matter to the soil, since the level of crop/pasture production required is beyond that which is possible under the ambient environmental conditions.

Predicting the amount of organic carbon that can be present in a soil.

Soil organic carbon content changes very slowly. When this fact is considered, along with the annual variability in rainfall normally experienced at any given location, measurements of soil organic carbon over several decades may be required to accurately define the effects of particular management treatments on soil organic carbon contents. Using data from long term cropping, crop/pasture rotations and continuous pasture trials from around Australia, the RothC soil carbon model (Figure 6) has been calibrated to Australian conditions. By running this model for long time frames using soil and crop/pasture production data, estimates of the potential soil organic carbon content that will eventually be reached (SOC_{actual}) can be derived.

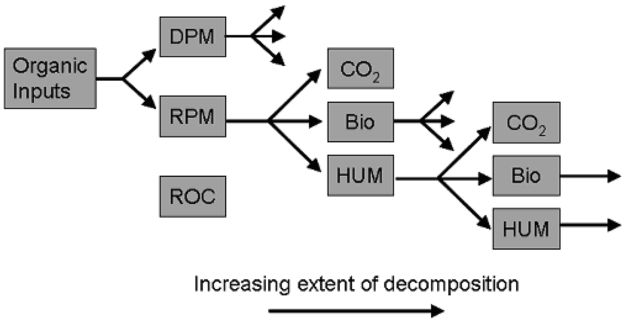

Figure 6. RothC soil carbon model.

By using this model, along with the climatic data and the contents of soil organic carbon and its fractions measured for a grazing experiment at Yass, estimates of the long-term effect of different levels of pasture production on soil organic carbon content can be predicted (Figure 7). In this experiment, based on a native grassland with naturalised subclover present, pasture and animal production were measured over 5 years at either nil or increasing levels of superphosphate and lime application (Garden *et al.* 2003). To complete the carbon calculations, the following assumptions were made:
• the root:shoot ratio for the pasture was 0.8 (kg root dry matter/kg shoot dry matter)
• 50% of the pasture shoot dry matter was consumed by grazing animals and 50% was returned directly to the soil
• 33% of the consumed pasture shoot dry matter was returned to the soil as faeces and 67% was lost in the form of weight gain, respiration, methane release and wool production.
• the carbon content of the pasture shoot and root material was 45% (g C/100 g dry matter).

These assumptions meant that 33.5% of the carbon associated with the shoots was removed from the plant/soil system. Therefore, the net returns of carbon to the plant/soil system amounted to 66.5% of the shoot carbon plus 100% of the root carbon.

The results of these simulations indicate that a sustained productivity of between 4 and 6 tonnes shoot dry matter/ha/year of the grass/legume mixture is required to maintain the current soil carbon content (~2%) at the Yass site. To double soil carbon content from 2% to 4% would require an increase in shoot dry matter production to 10 tonnes/ha/yr, which is above the level of attainable production at this site, and this production would have to be sustained for approximately 200 years. To attain the same doubling of soil organic carbon over a 10 year period would require shoot dry matter production rates in excess of 25 tonnes/ha/yr over the 10 year period. Since the average dry matter production over 5 years at this site (even with application of superphosphate and lime) was considerably less than this (average 6700 kg/ha/yr; range 3200-9200), the difficulty in making a significant impact on soil carbon levels in grazing systems is evident.

It is also important to consider the nature of the organic carbon that is added to the soil. The most responsive fraction of soil organic matter is the particulate organic carbon fraction. During the first 5-10 years after altering a management strategy, almost all of the change (increase or decrease) in soil organic carbon content is related to the change in the particulate

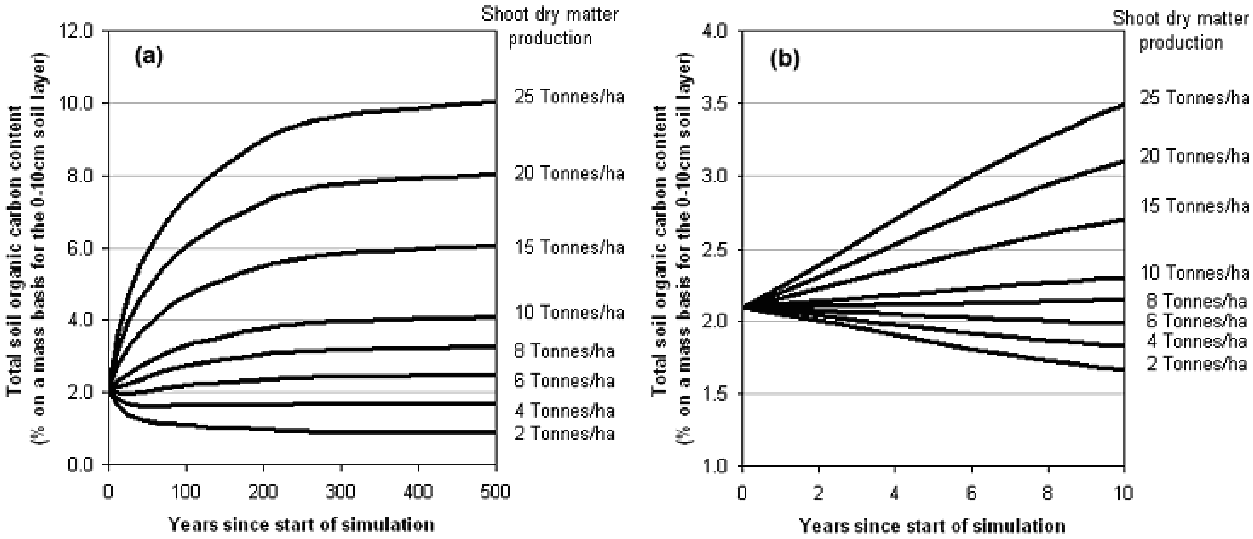

Figure 7. Changes in soil organic carbon content predicted using the RothC soil carbon cycling model for different levels of aboveground pasture dry matter production of native pasture at Yass, NSW. (a) Long-term simulations (up to 500 years), and, (b) scale increased to show the changes up to 10 years in more detail.

organic carbon fraction. The implication of this is that if one is building soil organic carbon, the carbon associated with the initial increase is the most labile form present in the soil and is highly vulnerable to decomposition. What maintains this labile carbon is the constant high input of residues. If this were to stop or be significantly reduced for a period of a few years, the soil organic carbon levels would drop rapidly, back to their values prior to initiating the change in management.

Conclusions

Organic matter is an important soil component that makes many positive contributions to soil health and potential productivity. Although measures of total soil organic carbon (or organic matter) are useful, measurement of the different forms of organic carbon present is required to correctly understand the dynamic nature of soil organic C and the implications of management practices. The quantity of organic carbon and its various fractions present in a soil is defined by the balance between inputs and losses. Increasing inputs via pasture and crop stubble management practices will lead to increased soil organic carbon contents. Using a carbon-cycling model calibrated to Australian conditions and current estimates of pasture utilisation efficiencies, soil carbon contents under different levels of pasture production were predicted. This exercise indicated that a pasture shoot dry matter production of >25 tonnes/ha would be required to change the current carbon content of 2.0% to 4.0% over a 10 year period. It was also estimated that a sustained pasture shoot production of 10 tonnes/ha would be required to accomplish this same doubling over 200 years, highlighting the inherently slow nature of increasing soil organic carbon content.

Reference

Garden DL, Ellis NJS, Rab MA, Langford CM, Johnston WH, Shields C, Murphy T, Holmberg M, Dassanayake KB, Harden S (2003) Fertiliser and grazing effects on production and botanical composition of native grasslands in south-east Australia. *Australian Journal of Experimental Agriculture* **43**, 843-859.