Soils in a Carbon Accounting System

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ABSTRACT

Soil organic carbon consists of a mixture of different materials exhibiting various stages of decomposition, and decomposing at different rates. Recent work has identified four biologically significant types of organic carbon in soils: plant residues, particulate organic carbon, humus carbon and recalcitrant organic carbon (dominated by charcoal). Although measures of total organic carbon are of use, identification of the allocation of carbon to the various fractions provides and improved capability to predict the response of soil carbon levels to current and alternative management practices. Quantifying the amount of soil carbon contained in each fraction is difficult and expensive, but a mid-infrared spectroscopic technique when combined with a statistical analysis appears to offer a rapid and cost-effective alternative. Various options exist to change soil carbon contents but the basic requirement is to enhance the return of plant residues to the soil. Under rainfall limited conditions carbon return will be maximised for any production system if the amount of carbon fixed by photosynthesis per mm of rain is maximised. In designing a system to achieve this goal, it is important to consider both the amount and distribution of rain. Practices that work in regions that experience significant amounts of summer rain may not be applicable to other regions where summer rain is more limited. The potential of adding biochar as a means of enhancing soil productivity and sequestering carbon is also being examined. It is important to define the properties of the biochar in order to ensure that the biochar can achieve the desired outcomes. 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 POC, HUM and ROC fractions under Australian conditions to be predicted. The influence of changes in wheat production on the amount of carbon stored in the soil was estimated.

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

FORMS OF ORGANIC CARBON IN SOIL

Soil organic matter contributes positively to a number of chemical, physical and biological soil properties (e.g. cation exchange capacity, structural stability and nutrient availability and storage). Carbon is the major element present in soil organic matter accounting for approximately 58% on a mass basis. However, other elements such as oxygen, hydrogen, nitrogen, phosphorous and sulphur also contribute. Methods of analysis have focused on the measurement of soil organic carbon content with a factor of 1.72 being used to convert soil organic carbon content into soil organic matter content.

The organic carbon present in a soil exists as a complex and heterogeneous mixture of organic materials varying in physical size, chemical composition, degree of interaction with soil minerals and extent of decomposition. Each of these different types of organic carbon will make different contributions to the soil properties. For example, the decomposition of cereal residues will tend to temporarily tie up nutrients; while decomposition of the more decomposed soil carbon fractions will result in a release of plant available nutrients.

Until recently, most studies have focused on determining the total amount of organic carbon presdsnt in a soil and have not attempted to quantify the allocation of carbon to the various different forms present. Although total organic carbon provides an important baseline measurement for assessing the influence of land use on the direction of any induced carbon change, 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, nutrient rich materials or the more recalcitrant charcoal? It is now apparent that detgermining the composition of soil organic carbon can provide a more detailed assessment of the implications of management practices on both the dynamics and functioning of soil carbon.

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

The amount of carbon found in each of these fractions is defined using the fractionation scheme given in Figure 1. The surface plant residues, buried plant residues and particulate organic carbon all consist of pieces of plant residue differing in size and extent of decomposition. The Humus fraction t consists predominantly of molecules attached to the surfaces of mineral particles but may also have small (<53µm diameter) particles. The recalcitrant fraction is typically dominated by small pieces of charcoal with average ages >500 years. Large contents of charcoal occur in regions that were historically grasslands and burned regularly and in local depressions. In a recent GRDC project, the allocation of soil carbon to the various fractions was measured. The amounts of each type of carbon was found to vary across locations (Figure 2a) and to be influenced by management practices at individual locations (Figure 2b).

The fractionation scheme presented in Figure 1 requires the use of specialised equipment, is very labour intensive, time consuming and therefore is expensive to complete. A more rapid and cost effective alternative based on the use of mid-infrared (MIR) spectroscopy is currently being examined and developed. With the MIR technology, estimates of the amount of total carbon, particulate organic carbon and charcoal carbon can be obtained rapidly (3-5 minutes) and the content of humus can be calculated as the difference between the total carbon and the sum of particulate and recalcitrant carbon. Although the values obtained using MIR spectroscopy are only predictions, an acceptable level of correspondence between measured and predicted values (Figure 3) provides confidence in the values obtained. Currently the amount of Humus carbon is calculated by subtracting the amounts of particulate and recalcitrant from the total carbon. With further work and continued analysis of Australian soils, this technology may be able to provide a rapid and routine means of quantifying both the total organic carbon as well as the allocation to biologically meaningful fractions.

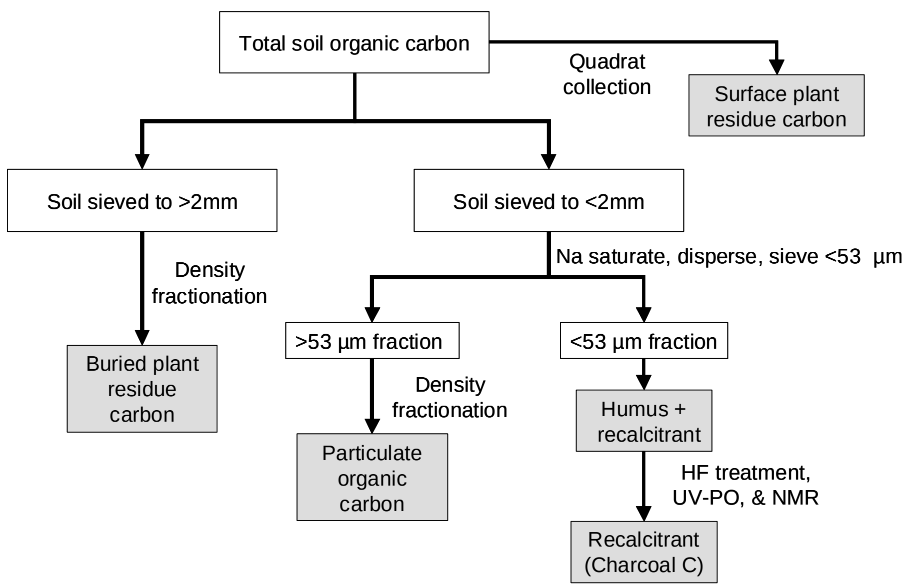


Figure 1. Fractionation scheme used to divide soil organic carbon up into biologically meaningful fractions. The resultant fractions are shaded grey and the Humus fraction is calculated as the difference between the (Humus+recalcitrant fraction) minus the (Recalcitrant fraction).

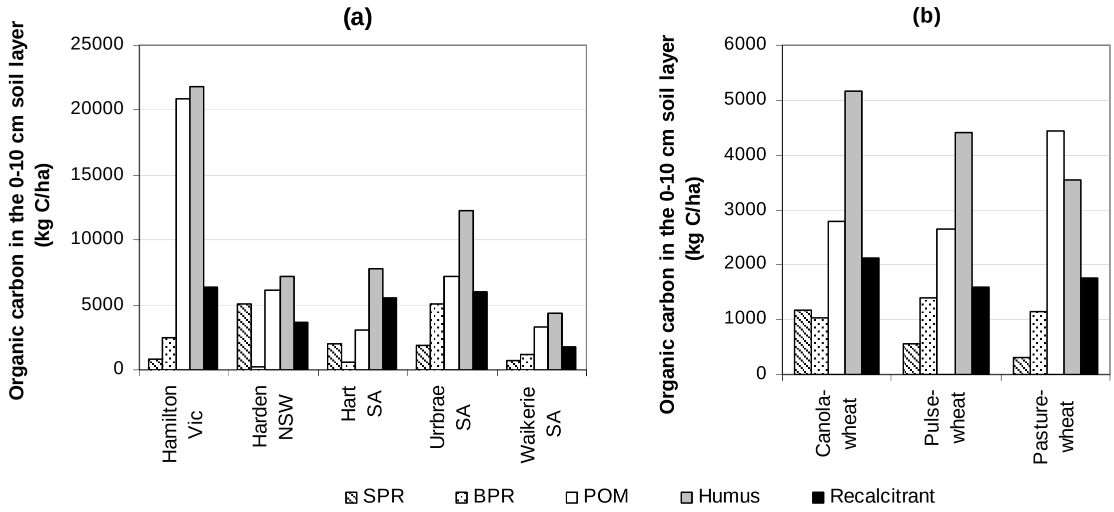


Figure 2. Amounts of each type of soil organic carbon found in the 0-10 cm soil layer at several locations within southern Australia (a) and within different crop rotations at a single location (b). (SPR: plant residues on the soil surface, BPR: plant residues buried in the soil, POM: particulate organic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

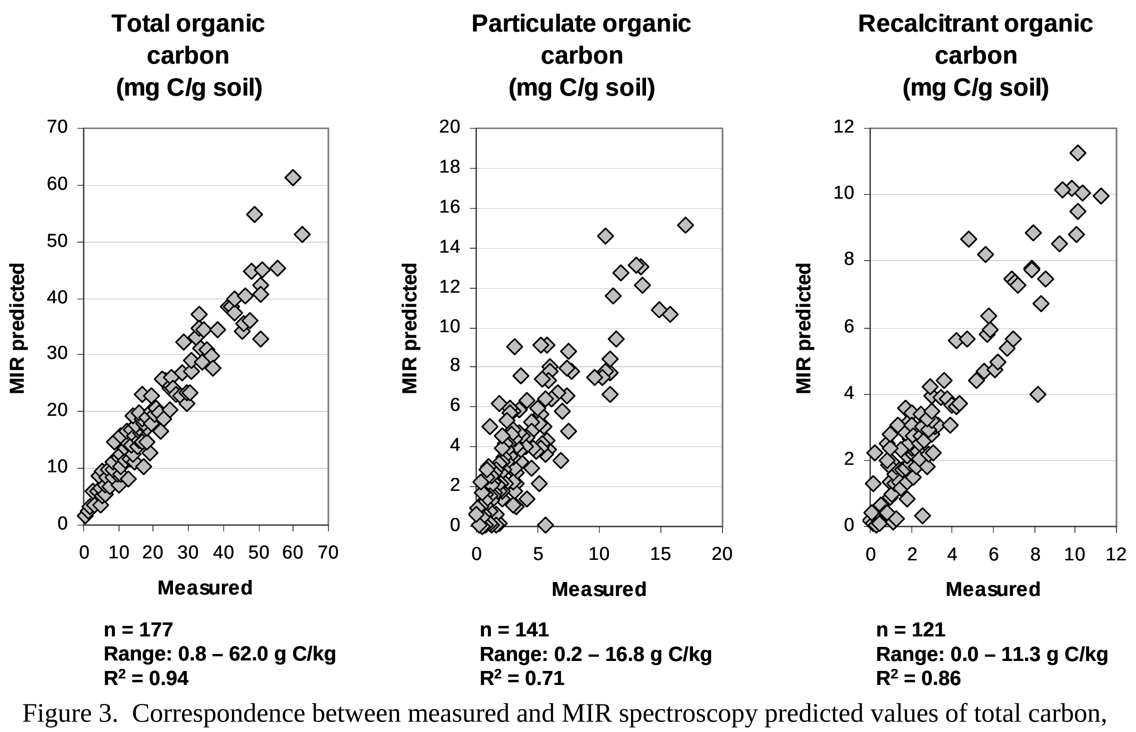


Figure 3. Correspondence between measured and MIR spectroscopy predicted values of total carbon, particulate carbon and recalcitrant (charcoal) carbon for surface layers of Australian soils.

HOW CAN SOIL ORGANIC CARBON CONTENT BE CHANGED?

A simple version of the soil carbon cycle is presented in
Figure **4**. Carbon enters the soil as either plant residues or potentially as charcoal (or charcoal like materials) after fires. The plant residues are decomposed by soil organisms and progress through the various fractions discussed above and in doing so the majority of this carbon ultimately makes its way back to CO_2 via respiration. Charcoal carbon is much more stable in soils than plant residues and can persist for >1000 years. As a result much interest exists in regards to using biochar as a means of sequestering carbon (see below).

The amount of organic carbon in a soil results from the balance between inputs (plant residues) and losses (mineralisation of organic carbon to CO_2 during decomposition). To increase soil carbon, a requirement exists to increase the amount of plant residue returned to the soil, decrease the amount of carbon lost via decomposition or both. This can be achieved by enhancing plant growth or reducing stubble removal through gazing, baling or removal. Under the water-limited conditions of most Australian agricultural regions, without irrigation, inputs of plant residues are restricted by climate, principally the amount of rainfall received an how effectively that rain can be used to produce plant biomass. To maximise plant residue returns under any agricultural system (pasture, cropping or other) the goal is to maximise the amount of carbon captured by photosynthesis per mm of rainfall received.

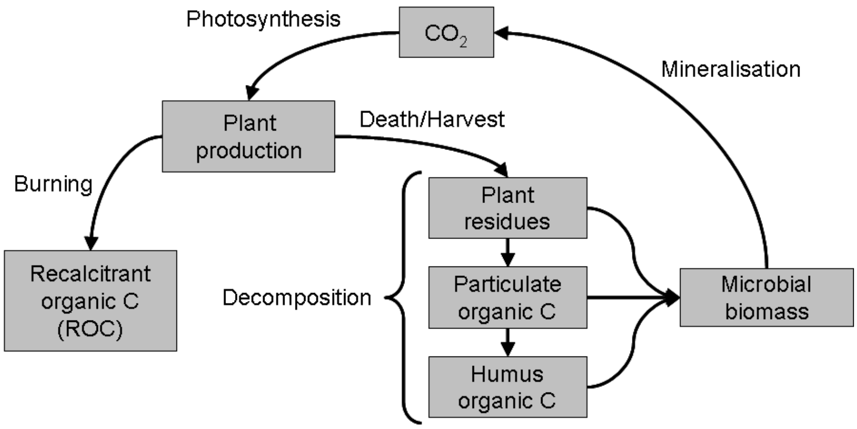
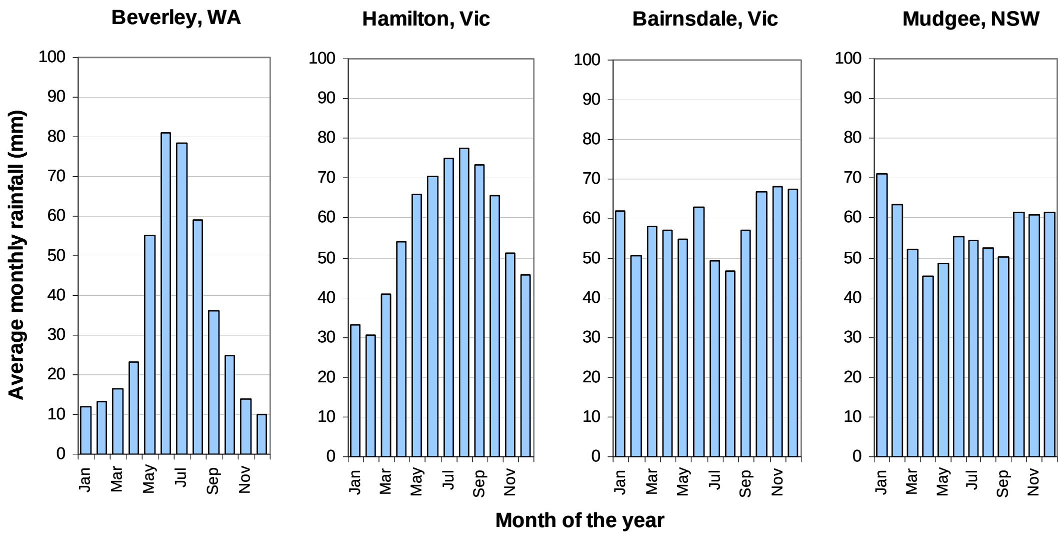


Figure 4. The soil organic carbon cycle. The combined total of plant residues, particulate organic C, humus C, microbial biomass and recalcitrant organic C make up the total soil organic C present.

The distribution of rainfall varies across Australian agricultural regions with winter rains dominating in the west and shifting towards a more even distribution in the east (Figure 5). The implication of this is that in the west, annual winter crops and pastures will be present and active during the part of the year when the majority of rain falls. Only 13% of the annual rain falls outside of the winter growing season and is not available to produce plant biomass. However, in the east, almost 40% of the annual rain falls in the summer months when evaporation demands are high. Although some of this rain may be stored in deeper soil layers and made available to subsequent crops or pastures, the majority of it (>75%) would be lost through evaporation and not be available to capture carbon and produce plant biomass. As a result the introduction of perennial vegetation to maintain actively growing plants over the summer period would offer the potential to increase the amount of plant biomass produced per mm of rain received and increase the return of carbon to the soil. It should be noted however, that it is not just the distribution of rain alone that is important, but also the amount of rain needs to be sufficient to allow the plants to survive and capture carbon throughout as much of the summer period as possible in order to optimise the capture and return of carbon to the soil.

What becomes apparent after considering this issue is that the design of crop and pasture systems to enhance the capture of carbon and return of residues to soil needs to be tailored to the environmental and soil conditions of any given site. It is entirely likely that a system designed to optimise carbon return to a soil located near Bairnsdale, Vic. may not be viable or may not work as efficiently at Beveley, WA. Caution must be exercised in translating the results of particular management practices obtained at one location to another or inappropriately suggesting that similar results could be obtained across the Australia's agricultural regions.

In Figure 6, 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 6). 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 6). Conversely, if residue returns decrease, soil organic carbon levels will also decrease (dotted and dashed grey lines of Figure 6).



	Beverly, WA	Hamilton, Vic	Bairnsdale, Vic	Mudgee, NSW
Total annual rain (mm)	**411**	**650**	**639**	**606**
Winter rain (Apr-Oct) (mm)	**358**	**482**	**394**	**368**
Summer rain (Nov-Mar) (mm)	**54**	**168**	**244**	**238**
% summer rain	**13**	**26**	**38**	**39**

Figure 5. Average monthly rainfall distribution, average annual, winter and summer quantities of rain received and the percentage of annual rain that falls in the summer for several locations across southern Australia over the period of 1900 – 2007.

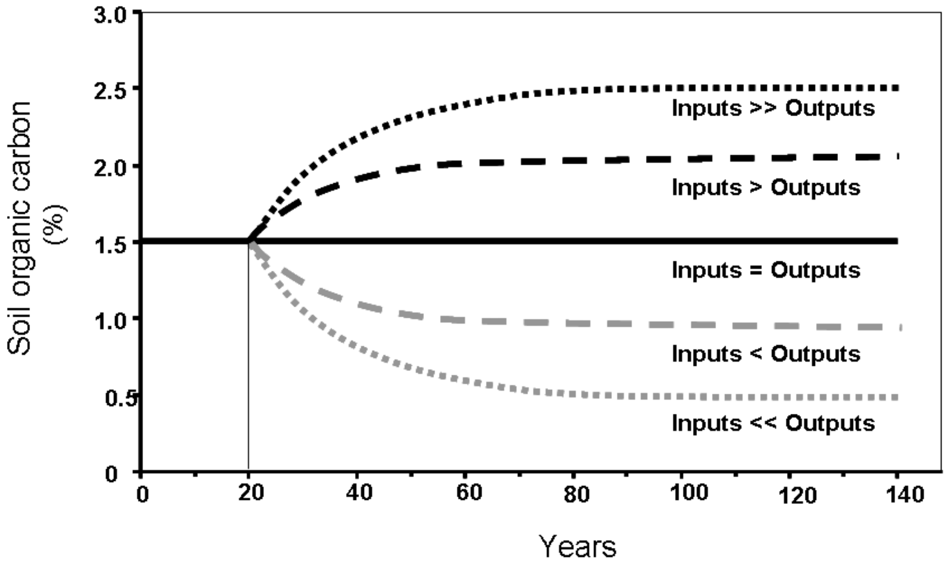


Figure 6. Influence of the relationship between inputs and losses on soil organic carbon content.

An alternative way of increasing soil carbon content and sequestering carbon in soils is through the production and application of biochar. The potential for creating and using biochar is being looked at favourably because it provides a means of producing carbon-neutral bio-energy, it offers a means of sequestering carbon in soils because of its apparent stability and several studies have shown that biochar application can increase soil fertility. Several important issues need to be considered with respect to the application of biochar to soils. Not all biochars are the same. The properties of biochars are dependent upon the nature of the materials used to create them and the extent of heating that they have been subjected to. Thus obtaining a plant growth response with one biochar does not mean that it would be obtained with all biochars. Biochars can carry nutrients (particularly P) and provide a liming potential (particularly for chars with high ash contents) but these characteristics will vary with the source materials used. For example, biochar created from wood would not be expected to have as high a nutrient content or liming potential as biochar created from legume crop residues or municipal green waste. It is important to define why particular biochars induce responses and characterise the properties of available biochars to ensure that intended responses are obtained.

A second consideration in the potential use of biochars is where the source material has originated. If crop residues are burnt in place or removed, burnt and returned to the soil, the biological properties of the soil will deteriorate. The occurs because the substrate that normally provides energy and nutrients to soil organisms (plant residues) has essentially been converted into a material that may no longer be able to meet these requirements. Additionally, if residues are removed from one place, used to create biochar and then applicated to a different location, the build up (or sequestration) of carbon at the application location will occur at the expense of a decrease in carbon at the source location.

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 7, 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.

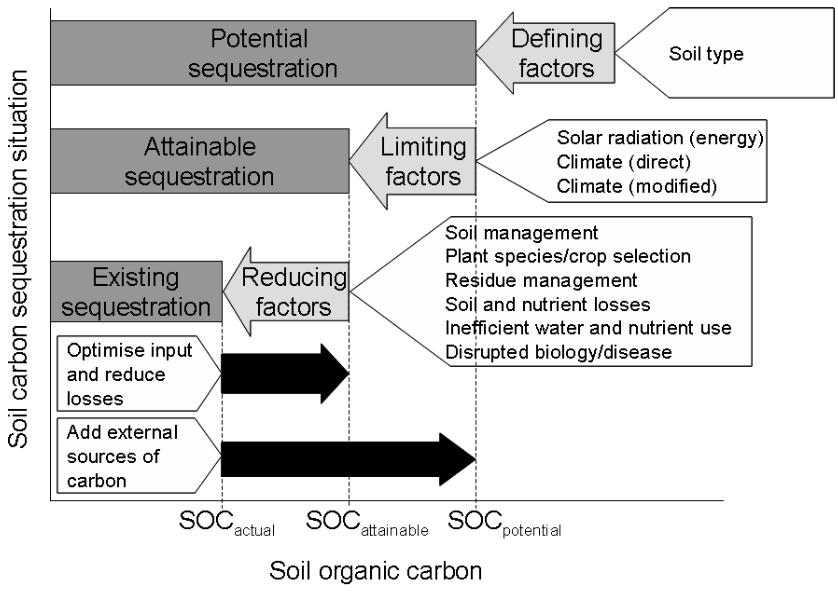


Figure 7. The influence of several factors on the level of SOC that can be reached in a given soil.

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 8) 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.

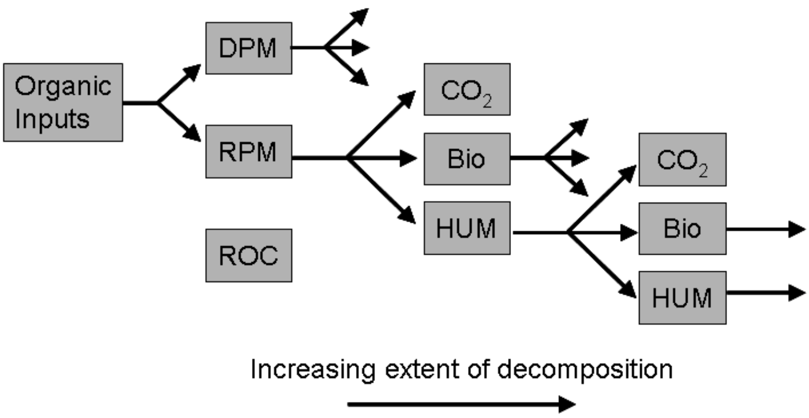


Figure 8. RothC soil carbon model

By using this model, along with the long term average climatic data for Dubbo, NSW, estimates of the long term effect of different levels wheat productivity on soil organic carbon content can be predicted (Figure 7). To complete these calculations the following assumptions were made:

1) crops had access to the rain that fell between April and October (winter crop)
2) wheat grain yield could be predicted using a French-Schultz approach with a slope of 20 kg grain/mm rain and an intercept of 90 mm rain
3) the starting amount of carbon in the soil was defined by that obtained when grain production attained water use efficiencies of (a) 50% and (b) 100%
4) the harvest index of the wheat crop was 0.37, the root:shoot ratio was 0.43 and the carbon content of shoots and roots was 45%
5) all stubbles were retained (no burning or grazing)
6) the soil had a clay content of 15%

The results of these simulations indicate that lifting grain yields by enhancing water use efficiency (WUE) can result in an enhanced soil organic carbon content. However, the increase in soil organic carbon is slow. In Figure 7a were the initial SOC content was set to that obtained for a WUE of 0.5, lifting the WUE to 1.0 (100% water use efficiency) over 25 years gives and additional 18.4 t soil carbon/ha (an average of 0.74 t C/ha/year). This should be considered the best possible case as it requires 100% water use efficiency year after year for the 25 years. In Figure 7b, where the soil organic carbon content was initially set to that predicted for a WUE =1, it would be much more difficult to lift soil carbon content.

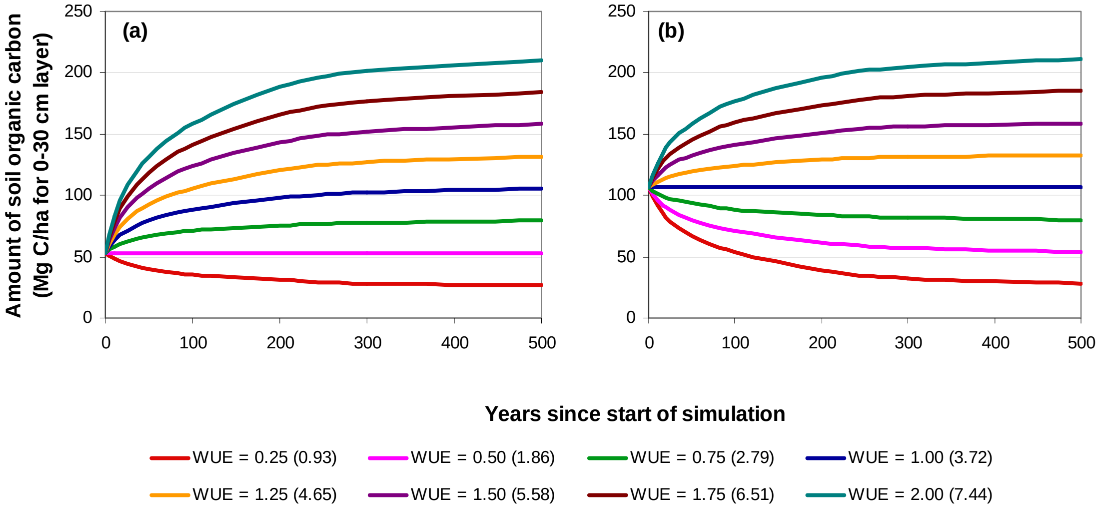


Figure 7. Predicted changes in the amount of organic carbon stored in a soil under different levels of wheat production at Dubbo, NSW using the RothC soil carbon cycling model. A WUE (water use efficiency) value of 1 means that all the crop used all growing season rainfall efficiently to product wheat grain. The corresponding wheat grain yields (t/ha) for each WUE are given in parentheses. (a) uses a starting soil organic carbon equivalent to that obtained with a WUE of 0.5 and (b) uses a starting soil organic carbon equivalent to that obtained with a WUE of 1.0.

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 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 was 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.

SUMMARY

Organic matter is an important soil component that potentially makes may 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. Potential options to consider include enhancing the perennial component of pastures and ensuring that plants maintain a significant soil cover through out the year to minimise direct evaporation of rain from the soil surface. Using a carbon cycling model calibrated to Australian conditions soil carbon contents under different levels of wheat production at Dubbo were predicted. This exercise indicated that significant increases in WUE would be required to shift soil organic carbon contents appreciably and even then the increases would be slow and vulnerable to change as the labile fractions build up first.