The low down on soil carbon

J.A. BALDOCK
CSIRO Land and Water, PMB 2, Glen Osmond, SA 5064, Australia
jeff.baldock@csiro.au

Abstract

Soil organic carbon consists of a mixture of different materials exhibiting various stages of decomposition and decomposing at different rates. Four different fractions are now recognised: plant residues, particulate organic carbon, humus carbon and recalcitrant organic carbon. Allocation of carbon to the various fractions allows more accurate assessment of the implications of management practices on soil carbon content and vulnerability to change. Quantifying the amount of carbon in each fraction is expensive, but a mid-infrared spectroscopic technique appears to offer a rapid and cost-effective alternative. 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, the humus and recalcitrant organic carbon 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 estimated.

Keywords: soil carbon fractions, management practices, residues, pasture, modelling

Introduction

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). 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. Most studies determine the total amount of organic carbon present and have not attempted to quantify the allocation of carbon to the different forms present. Although total organic carbon provides an important baseline measurement, 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 determining 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 changes in each of these soil organic carbon fractions in progressing from an intensive wheat/fallow cropping system to a less intensive continuous pasture system at year 33 are shown in Figure 1. Examining the total carbon values, it is evident that a rundown of carbon occurs during the initial wheat/fallow system and then a build up occurs on conversion to a continuous pasture. At two points in time (15 and 43 years) the same total carbon values were obtained and one could suggest that 18 years of intensive wheat could be offset by 10 years of pasture. The composition of the organic materials, however, is quite different. There is less humus (the more stable and nutrient rich component of soil organic carbon) and more particulate organic carbon (the fraction that is most susceptible to decomposition) in the continuous pasture than in the wheat/fallow system. Thus the behaviour of the carbon and its vulnerability to subsequent change at the 15 and 43 year points are quite different even though total organic carbon contents are similar. It is anticipated that by measuring the composition of soil organic carbon, our ability to better predict the influence of management practices on soil carbon contents will occur. Variations in the amount of carbon found in each fraction across several Australian soils are presented in Figure 2.

Fractionation of soil organic carbon requires the use of specialised equipment. As well, it is very labour intensive, time consuming and therefore expensive. 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,

Figure 1 Influence of management on the allocation of carbon to the different fractions.

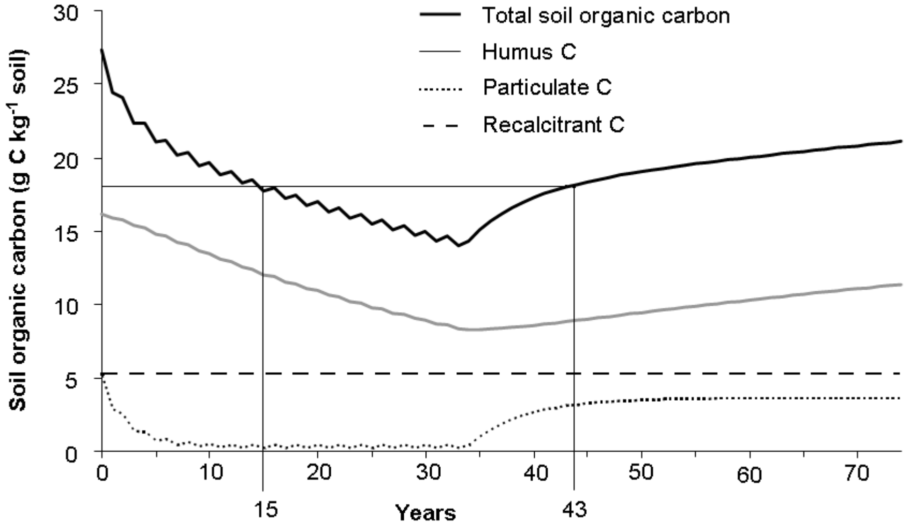
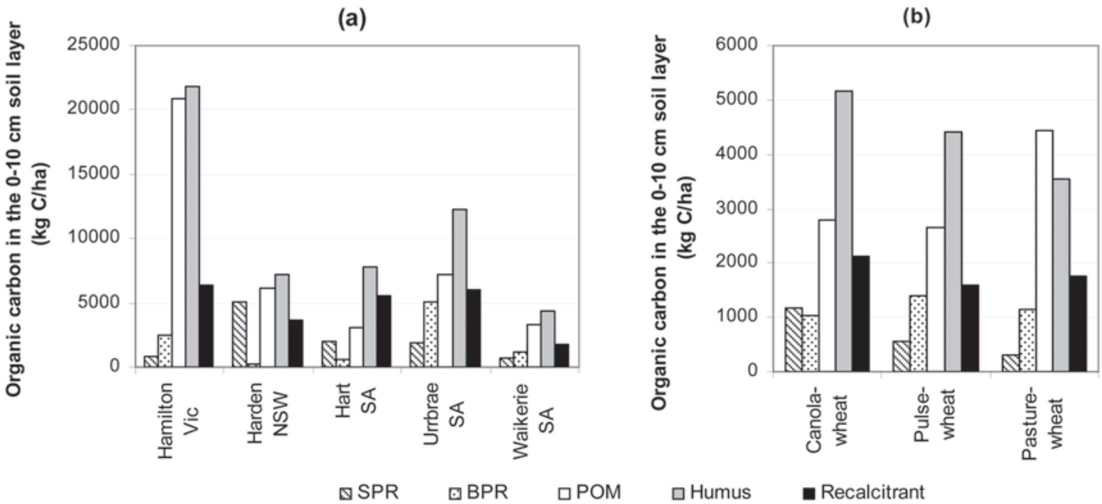


Figure 2 Amounts of each type of soil organic carbon found in the 0-10 cm soil layer at several locations within southern Australia (a) and within different crop rotations at a single location (b). (SPR: plant residues on the soil surface, BPR: plant residues buried in the soil, POM: particulate organic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



estimates of the amount of total carbon and its allocation to the different fractions can be obtained. The relationship between measured and MIR predicted values are shown in Figure 3.

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 after fires. The plant residues are decomposed by soil organisms and progress through the various fractions. During decomposition the majority of carbon ultimately makes its way back to CO_2 via respiration. Charcoal carbon is more stable in soils than plant residues and can persist for >1000 years. As a result, interest exists in using biochar as a means of sequestering carbon.

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. Reductions in extent of cultivation have been reported to increase soil carbon content. In Australia, increases in soil carbon associated with reductions in extent of cultivation do not always

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.

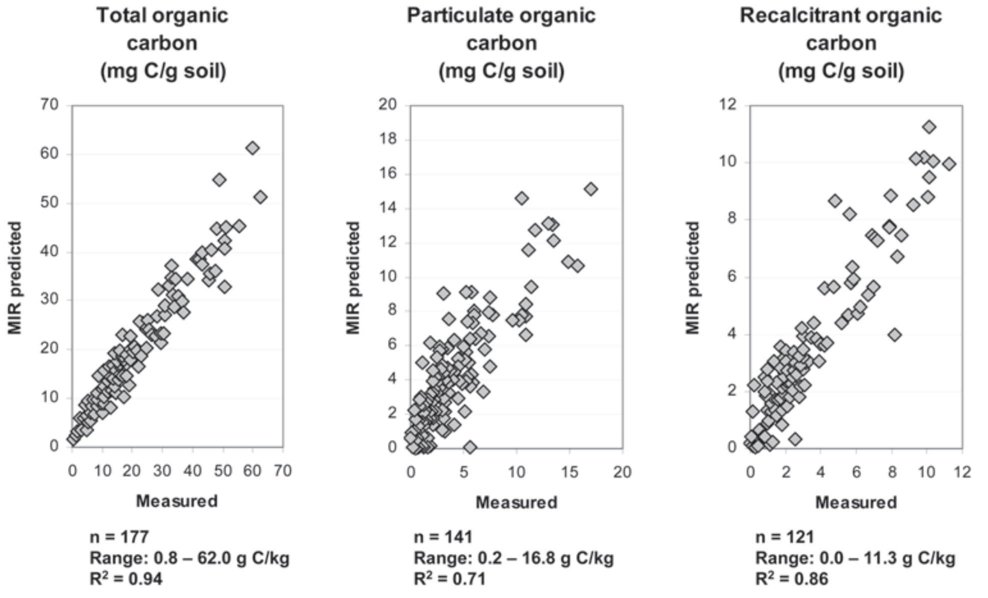
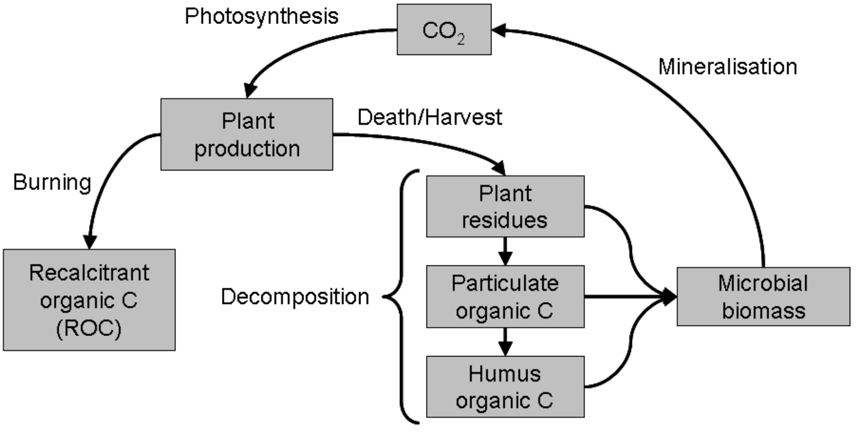


Figure 4 The soil organic carbon cycle. The combined total of plant residues, particulate organic C, humus C, microbial biomass and recalcitrant organic C make up the total soil organic C present.

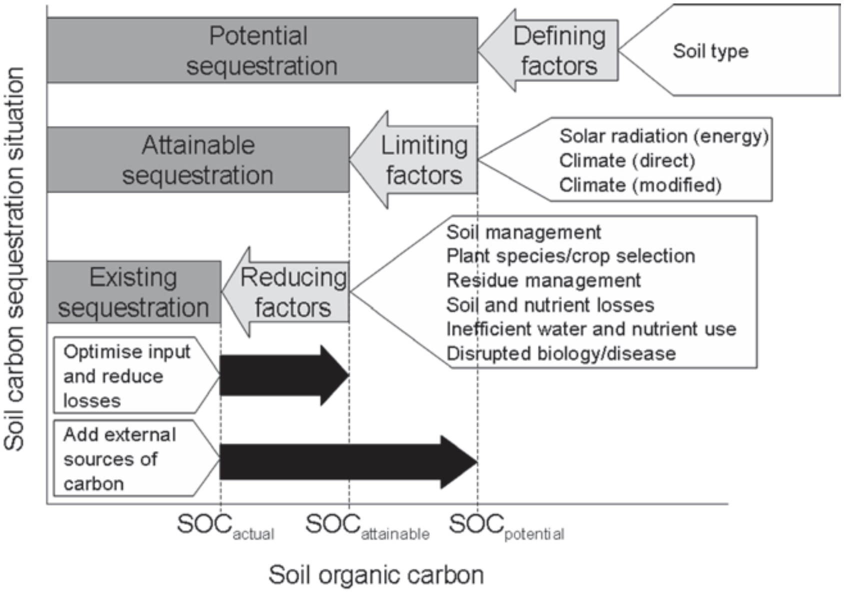


occur. Often it is the influence of management on the amount of stubble returned to the soil that is most influential on soil carbon content. To maximise soil carbon content under any given agricultural system, maximising productivity and retaining as much residue as possible will maximise soil carbon for that system. Options do exist to alter management and accumulate more carbon in soils. However, the design of crop and/or 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 Blenheim, NZ will not be viable or may not work as efficiently under the drier conditions of the Australian Mallee region. 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 New Zealand's or Australia's agricultural regions.

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

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



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. Some New Zealand soils, particularly those containing allophanic minerals have a high capacity to protect carbon 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.

At any given location, the amount of crop or pasture material that can be produced and returned to the soil will be defined by factors such as the amount of solar radiation, temperature range and availability of water. Under dryland conditions (no irrigation) these factors will place a limit on the amount of residue that can be added to a soil such that attaining the $SOC_{potential}$ is not possible 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 production 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 (Fig. 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.

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 (NSW,

Figure 6 RothC soil carbon model. DPM – decomposable plant material; RPM – resistant plant material; ROC – recalcitrant organic carbon; Bio – microbial biomass; Hum – humus.

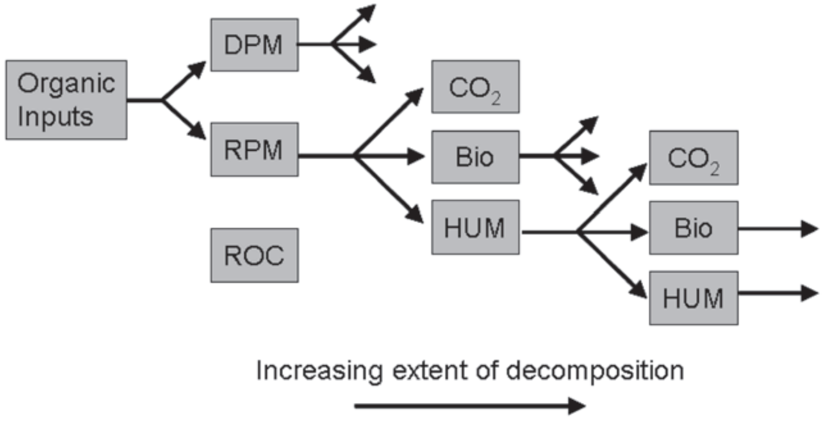
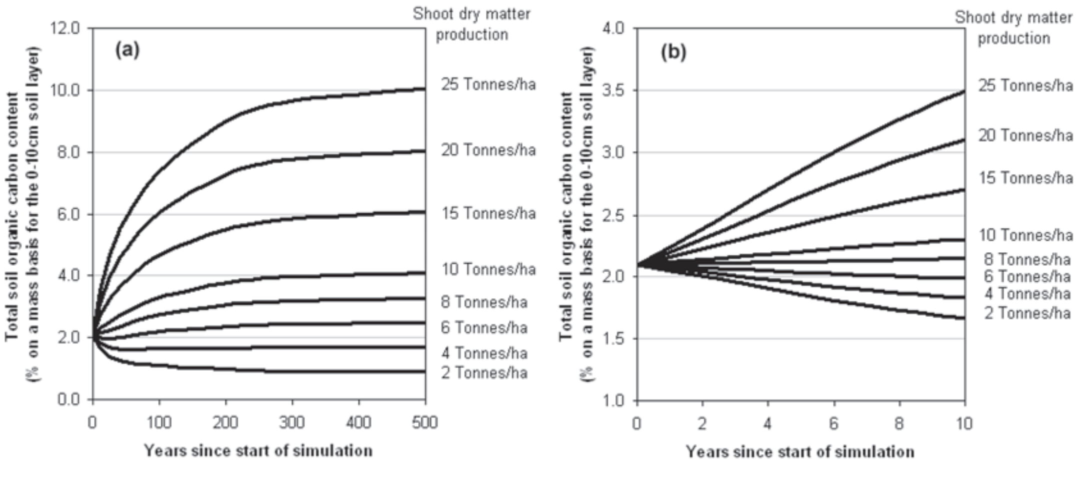


Figure 7 Changes in soil organic carbon content predicted using the RothC soil carbon cycling model for different levels of aboveground pasture dry matter production of native pasture at Yass, NSW; (a) Long-term simulations (up to 500 years), and (b) scale increased to show the changes up to 10 years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



Australia), estimates of the long term effect of different levels of pasture production on soil organic carbon content can be predicted (Fig. 7). In this experiment, based on a native grassland with naturalised subclover, pasture and animal production were measured over 5 years at either nil or increasing levels of fertiliser and lime application. To complete the carbon calculations the following assumptions were required:

- 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/yr 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 was considerably less than this (average 6700 kg/ha/yr; range 3200-9200), the difficulty in making a significant impact on soil carbon levels 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 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.