Building soil carbon for productivity and implications for carbon accounting

Jeff Baldock, CSIRO Land and Water, Adelaide, SA

KEY MESSAGES

Composition of soil organic carbon

- Soil organic carbon is composed of a wide range of different materials with different chemical and physical properties and different extents of decomposition.

Functions of organic carbon/organic matter in soil

- Soil organic matter contributes to a variety of biological, chemical and physical properties of soils.
- Chemical—cation exchange, pH buffering, reduces effects of sodicity.
- Physical—water retention, soil structural stability, soil wettability, soil temperature.
- Biological—energy for microbes, provision of nutrients and resiliency.
- Increasing soil organic carbon content can result in an increase in the ability of a soil to hold water and thereby lead to enhanced productivity.

Calculating changes in soil organic carbon content

- Soil carbon content represents the balance between inputs and outputs.
- Values are required for the depth, bulk density and carbon content of the soil layer you are interested in to determine how much carbon is present.
- Changes in soil carbon content are slow and typically require at least 5 years to be detectable.
- Simulation models can be used to predict the likely outcomes of management practices on soil carbon content.

$$ from sequestration—fact or fiction?

- Maximising crop productivity will maximise carbon inputs and soil organic carbon content.
- At current prices, it is hard to justify modifying management practices for the sole purpose of selling carbon credits.

SOIL ORGANIC CARBON: WHAT IS IT?

Soil organic carbon is a complex and heterogeneous mixture of materials. These 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 soil organic carbon contents is 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 more recalcitrant charcoal? It is therefore important to determine the composition of soil organic carbon to gain an appreciation for the implications of management practices and changes in organic carbon content on soil productivity.

We now recognise four different types of soil organic carbon:

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

FUNCTIONS OF ORGANIC CARBON/ORGANIC MATTER IN SOIL

Organic carbon/organic matter contributes to a variety of functions in soils. These functions can be broadly classified into three types: biological, chemical and physical (Figure 1). Strong interactions (represented by the grey arrows) often exist between these different functions. For example, the biological function of providing energy that drives microbial activity also results in improved structural stability and creates organic materials that can contribute to cation exchange and pH buffering.

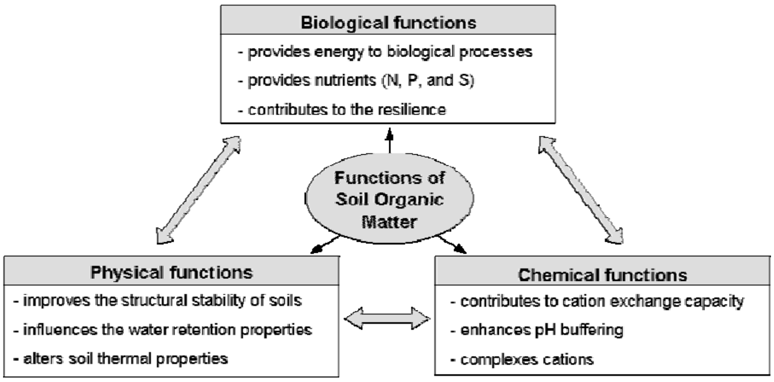

Figure 1 Functions performed by organic matter present in soils.

Future predictions of climate change suggest that most regions of Australia will be become warmer and drier based on increases in the concentrations of greenhouse gases (carbon dioxide, methane and nitrous oxide) in the atmosphere. Under such conditions it will become even more important than it currently is to be able to maximise the storage of plant available water in soils. The amount of plant available water a soil can hold is determined by two parameters:

1. the lower limit—the amount of water in the soil that plants cannot extract; and
2. the upper drained limit—the amount of water that can be held against drainage.

The difference between the upper and lower limit defines the potential available water holding capacity (PAWC) of a soil. If this value can be increased even marginally it will help to maintain or enhance potential productivity by allowing the soil to retain more water each time it rains.

In the absence of subsoil constraints such as salinity, the lower limit is defined by soil clay content and increases with increasing clay content (Figure 2). Evidence from WA sands suggests that increases in organic carbon content can also increase the amount of water present at the lower limit. The upper limit is also affected by the content of clay and organic carbon clay (Figure 2). For any given clay content, as organic carbon increases the upper limit, and therefore PAWC, of the soil increases. An analysis of the influence of increasing soil organic carbon content by 1% of total soil mass (e.g. from 0.7% to 1.7%) on the soil PAWC was completed using data collected from red brown earths of the mid-north region of SA. This analysis indicated that such an increase in carbon content in the surface 0–10 cm soil layer would increase PAWC from its original value by 2 to 4 mm with the effect diminishing as soil clay content increased (Figure 3). Although the change in PAWC for sandy-low clay content soils is predicted to be larger than for clay soils, it would be much more difficult to increase soil carbon content on sands relative to clays.

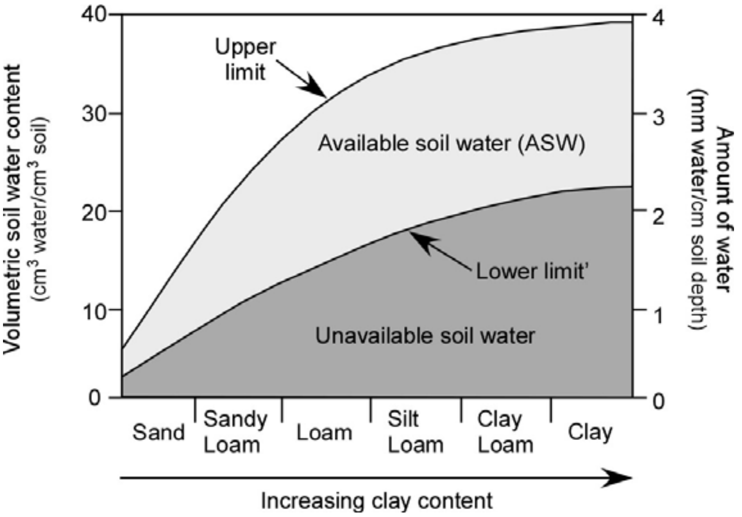

Figure 2 Changes in upper and lower limits of soil water content with changes in clay content. The light grey area defines the plant available water holding capacity of the soil.

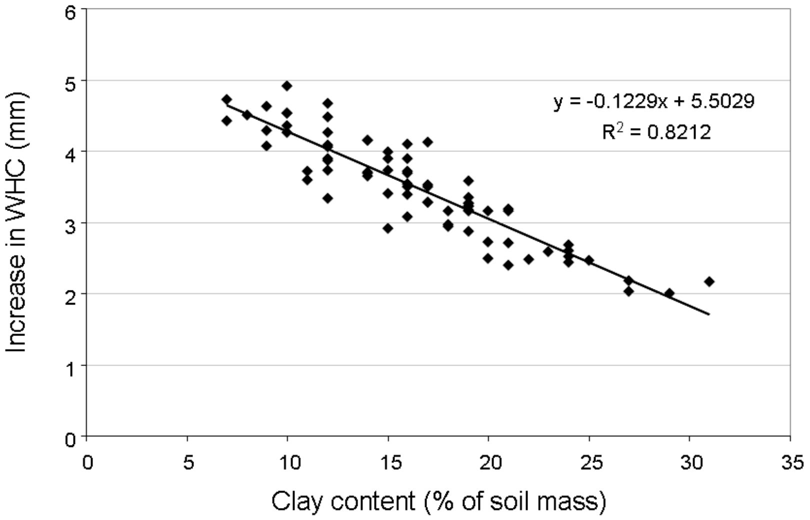

Figure 3 Change in soil water holding capacity (WHC) induced by increasing soil organic carbon content by 1% of total soil mass for red-brown earths of the mid-north of SA.

WHAT DETERMINES SOIL ORGANIC CARBON CONTENT?

The amount of carbon in a soil results from the balance between inputs (plant residues) and losses (microbial decomposition and associated mineralisation). Figure 4 the bucket represents the amount of carbon a soil could potentially hold. This amount will vary with factors such as soil clay content, soil depth, and bulk density and is not influenced by management. The bucket will be smaller for a sand than a clay soil.

Figure 4 Inputs and losses define soil organic carbon content.

To increase the content of organic carbon in soil, the input of residues must be increased and/or the rates of loss of carbon must be decreased.

Inputs are controlled by the type and amount of plant residue added to the soil. Any practice that enhances productivity and the return of plant residues (shoots and roots) to the soil opens the input tap and will result in an increase in soil carbon. For example, appropriate use of fertilisers to maximise productivity also maximise returns of organic residues to the soil. However, an upper limit to the input of residues exists in Australian dryland agriculture because of the limitation that the availability of water places on potential plant productivity. Maximum soil carbon contents will be obtained for any management system if productivity and capture of carbon are maximised by attaining 100% water use and nutrient use efficiencies.

Losses of carbon from soil result from decomposition and conversion of carbon in plant residues and soil organic materials into carbon dioxide. Processes that accelerate decomposition open the losses tap further; while those that slow down the rate of decomposition will close the losses tap and help to maintain or increase soil carbon. Reducing the extent of cultivation has been suggested to result in enhanced soil carbon levels. Results from Australian studies suggest that while this may be true for some soils, for other soils such an effect has not been observed (Figure 5). It should also be noted that even shifting to a zero tillage system is unlikely to result in soil carbon values equivalent to those that would be obtained under a pasture system.

CALCULATING CHANGES IN SOIL ORGANIC CARBON CONTENT

The amount of organic carbon found in a soil can be calculated using values for the depth (cm) of the soil layer of interest, the soil bulk density (g/cm^3) and the soil carbon content (%) (Equation [1]). Using Equation [1], indicates that a 30 cm layer of soil having a bulk density of 1.2 g/cm^3 and a carbon content of 1.2% contains approximately 43 Tonnes of C/ha.

$$\text{Organic C (T C/ha)} = \text{Depth (cm)} \times \text{Bulk density (g/cm}^3) \times \text{Carbon content (\%)} \qquad [1]$$

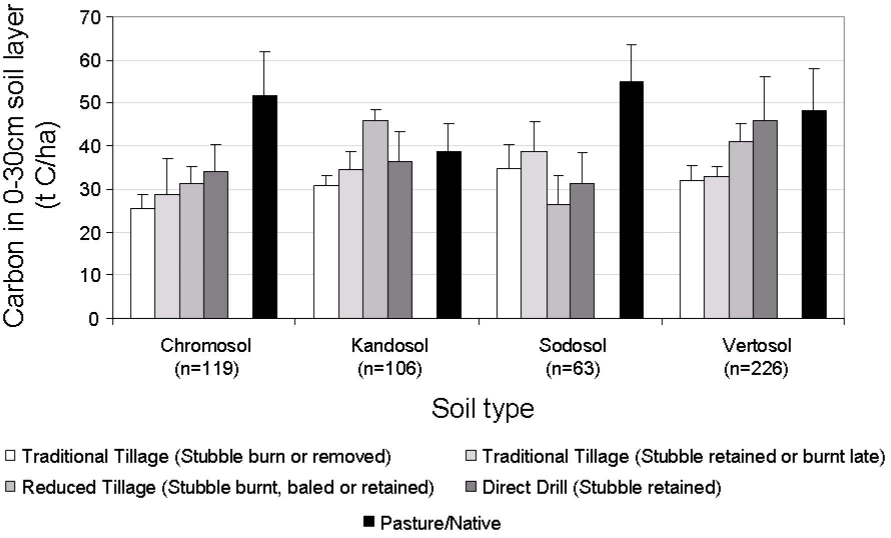

Figure 5 Change in soil carbon induced by different levels of tillage for several different Australian soil types. The number of samples of each type of soil are given by n.

Suggestions have been put forward that altering management practices can increase soil organic carbon content from 2% to 4% in 5 years. Is this really possible?

If we use the same bulk density as above (1.2 g/cm^3) and restrict our calculations to the top 10 cm of soil where organic carbon is most easily increased, at 2% carbon the soil would contain 24 tonnes C/ha. At 4% carbon the same soil layer would contain 48 tonnes C/ha. This indicates that 24 tonnes of C/ha would have to be added to the soil. Since plant residues contain approximately 45%C this would equate roughly to 50 tonnes/ha of dry matter (DM). If this increase was to occur over 5 years, then an additional 10 tonnes DM/ha/year **above that currently being added** would be required if no decomposition occurs. If half of the residues added were in the form of roots below ground, then we would have to add an additional 5 tonnes shoot DM/ha/year. Since we know that at least 50% of the added plant residues will decompose, annual additions of approximately 10 tonnes shoot DM/ha/year **above that currently being added** would be required to achieve an increase in soil organic carbon content from 2% to 4% in five years.

Under dryland conditions typical of the Australian cereal belt, increases in returns of shoot dry matter of this magnitude are unlikely and thus it is hard to substantiate such changes in C content. However, in specific locations where rainfall may not be used efficiently to produce agricultural crops/pastures (particularly regions with significant amounts of summer rainfall and where annual crops are being produced) significant increases in crop production and residue returns are possible by modifying existing management practices. Conversion of annual to perennial pastures and altering grazing practices from set stocking to rotational grazing will enhance plant dry matter production and increase soil carbon content.

PREDICTING THE INFLUENCE OF MANAGEMENT ON SOIL CARBON CONTENT

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. We have used a soil carbon model (RothC) to predict the likely soil organic carbon content that would be obtained under wheat production using average climatic conditions and retaining all crop stubble. At Roseworthy the water limited grain yield was calculated using the French-Schultz approach (slope = 20 kg grain/mm water and slope = 110 mm water). To define the potential long term soil carbon content (equilibrium soil carbon content), wheat production was set to 75% of the water limited potential was used along with a harvest index of 0.37 and a root:shoot ratio of 0.43 to calculate the crop residue addition rate including roots. The equilibrium soil C content predicted for the 0–30 cm layer was 86 tonnes C/ha. It should be noted that in these modelling analyses a clay content of 15% was used.

In Figure 6 the estimated changes in the amount of soil organic carbon content stored in the 0–30 cm soil layer is presented for different levels of wheat production defined in terms of water use efficiency (WUE). The predicted wheat grain yields (for Roseworthy) are given in parentheses after each WUE value in the legend. The changes in soil carbon associated with a 25 year time frame are given in Table 1. The model predictions suggest that if we were to move wheat yields to an average of 4.5 t grain/ha (100% WUE), soil carbon would increase by about 11 tonnes C/ha over the 25 year period, and by about 32 tonnes C/ha if we could obtain wheat yields equivalent to 150% of current water use efficiencies. These data show that carbon changes will be slow but enhancing productivity, if it can be maintained, will result in increased soil carbon levels. Other management scenarios (e.g. conversion to pasture production) may provide larger increases; however, if such management changes are made, attempting to claim carbon credits in a carbon trading scheme will limit future options for land use because the new levels of carbon attained would have to be maintained.

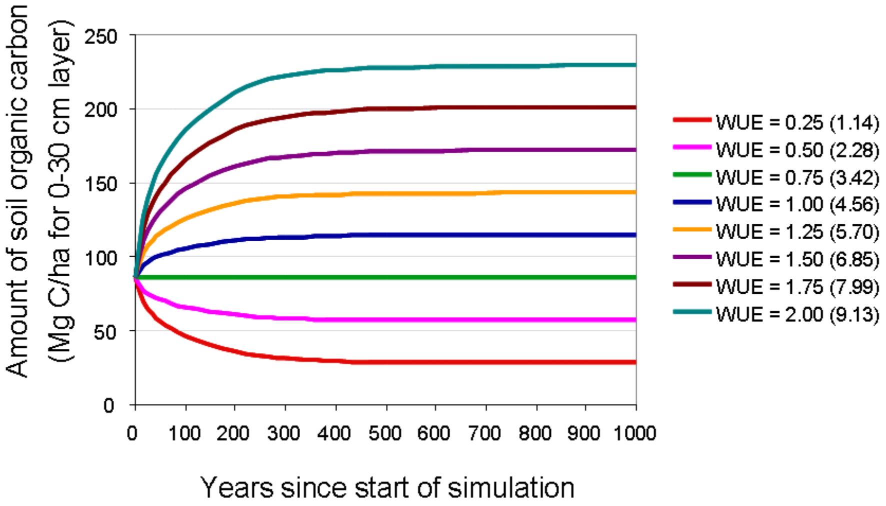

Figure 6 Changes in the amount of carbon stored in the 0–30 cm soil layer at Roseworthy, SA predicted using the RothC soil carbon cycling model for different water use efficiencies (WUE).

Table 1 **Change in soil carbon after 25 years for different levels of wheat productivity**

Wheat grain yield (t/ha)	**Water use efficiency (% water limited potential)**	**Total amount of carbon stored in the 0–30 soil layer (t C/ha)**		
		0 years	**25 years**	**Change**
1.1	0.25	86	65	-21
2.3	0.50	86	75	-11
3.4	0.75	86	86	0
4.6	1.00	86	97	11
5.7	1.25	86	107	21
6.8	1.50	86	118	32

$$ FROM SEQUESTRATION—FACT OR FICTION?

There is no doubt that soils could potentially hold more carbon. The challenge is to be able to do this while still maintaining an economically viable farm enterprise. Some potential options include:

- enhancing the proportion of perennial vegetation in pastures or conversion of portions of cropped paddocks that continually give negative returns to perennial vegetation;

- increased retention of crop residues, reduced stocking rates and increased use of green manure crops to return more plant material to the soil;
- optimise farm management inputs to maximise water use efficiency and thus maximise the return of crop residues to soil but be careful not to generate other greenhouse gases in the process which may offset any benefits.

At a price of < $20 per tonne of sequestered carbon and the slow potential rates of soil carbon change, it will be hard to economically justify modifying management practices for the purpose of selling carbon credits alone. Under such pricing, carbon credits should be considered as a secondary benefit that may be realised whilst attempting to enhance soil productivity by building soil carbon content.

Reviewed by: Bill Bowden