Soil organic matter – what the science tells us

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Take home messages

- Stocks of soil organic matter (SOM) and the associated carbon and nutrient flows are key to healthy, sustainable, and resilient agricultural systems
- Declining SOM impacts the soil's ability to support key soil functions, including the capacity to deliver N
- Estimates of soil organic carbon (SOC) accumulation rates following relatively modest management changes in Australian cropping and pasture systems typically range from 0.1 to 0.3 tonnes C/ha/yr (also expressed as Mg or Megagram C/ha/yr)
- Building SOM stocks at higher rates is possible through bold management changes that maximise carbon inputs and minimise loss pathways
- Expenditure and opportunity costs need to be evaluated on an individual basis
- A long term (decadal) cyclical approach to management of SOM and nitrogen budgeting will ensure that future productivity is not compromised by short term (annual) approaches that don't capture the value of banking SOM for use in subsequent seasons
- SOM and SOC mean different things and are explained in this paper.

Introduction

Soil organic matter (SOM) is a key component of productive soils and resilient agricultural systems. SOM supports soil structure, moisture and nutrient sorption/retention, and biological processes central to nutrient cycling and to disease suppression. However, it is widely recognised that agricultural production leads to a decline in SOM stocks. For Australian agricultural soils, SOM decline in the top 10 cm is estimated between 20% and 70%, with average SOM stocks about half that of native system soils (Baldock 2019). Declining SOM content can lead to more vulnerable production systems, impairing the ability of the soil to perform key soil functions, including nitrogen supply through the growing season.

There is considerable interest in identifying management practices that build SOM. The principles of conservation agriculture typically align with goals of retaining and building SOM. These include minimising disturbance, maximising crop diversity/rotation, minimising fallow/bare ground, and integrating livestock where possible. Although changes in land-use (e.g. cropping to pasture) are commonly shown to change SOM content, it remains difficult to identify individual practices within a production system that have a consistent effect on SOM across different soil environments.

Accumulation of SOM depends on many factors including climate, soil type, topographic position, land management, and the current SOM equilibrium state. Changes to management are implemented in different ways; different paddocks have varying production constraints that can lead to inconsistent effects of management on input (biomass production) and output (decomposition) pathways.

In this paper we consider:

- The requirements for measuring changes in SOM and the linkages between carbon and nitrogen
- The reported rates of SOC accumulation within the Australian agricultural context and the difficulties in transferring one scenario across a broader context
- How to estimate potential changes in SOC given a change to carbon (crop biomass) inputs; conversely, to estimate the plant biomass production change that would be required to support an aspirational increase in SOC stock.

SOM vs SOC – carbon with or without nutrients

SOM and soil organic carbon (SOC) are often used interchangeably. SOM is not measured directly but calculated following measurement of the SOC content. On average SOM contains 58% carbon (C) and is bound to other essential elements including nitrogen (N), phosphorus (P), and sulphur (S). SOM values are thus on average 1.72 higher than SOC values. Some analytical laboratories report SOC content (mg/g), while others report SOM content. When comparing analytical results, it is important to check what has been reported and to convert data to comparable values if required.

Soil carbon accounting schemes require that changes in SOC content are measured as stocks in the top 30 cm. SOC stocks are expressed as tonnes per hectare (Megagram (Mg) or tonnes/ha), requiring a calculation that accounts for the carbon concentration (g/kg air dried soil <2mm), the depth to 30 cm, soil bulk density (g/cm^3), and accounts for gravel (> 2mm) content.

$$\text{SOC stock} = \left[\begin{matrix}\text{carbon}\\ \text{content}\end{matrix} \times (1+\theta_m)\right] \times \text{depth} \times \begin{matrix}\text{bulk}\\ \text{density}\end{matrix} \times \left[1 - \begin{matrix}\text{gravel}\\ \text{proportion}\end{matrix}\right] \times 0.10$$

SOC accumulation rates are expressed as tonnes of C per hectare per year (t C/ha/year). Scientists often express this in SI units, where Megagram (Mg) is the same as a tonne (Mg C/ha/year). These rates can be estimated in two ways:

- **A relative change in SOC stocks:** where measurements are made X years after contrasting management practices have been implemented (Figure 1 e.g. A3-A2). The relative difference between the starting and finishing levels is then divided by the number of years to provide an estimate of the annual difference in carbon stocks under the management practices. A positive difference may be due to a sequestration of carbon, an avoided emission, or a combination of both.
- **A temporal change in SOC stocks:** where a baseline measurement is made prior to management change, and subsequent sampling X years later is used to determine the rate of change (D-C in Figure 1). In this approach a positive difference is due only to a sequestration of carbon in soil (scenario C) and is dependent on the equilibrium state of the soil when the management change was implemented.

The Australian 2018 soil carbon accounting scheme requires temporal measurements with at least two measurement timepoints. Where more temporal measurements are made, the SOC stock change is estimated by basing the rate of change on a regression over time. For carbon accounting, changes in SOC stocks are converted to carbon dioxide equivalents (CO_2e, t/ha), which are 3.67 times the value of the SOC stock (t/ha). It is important to take note of the measurement units when comparing results, and to convert data to comparable units.

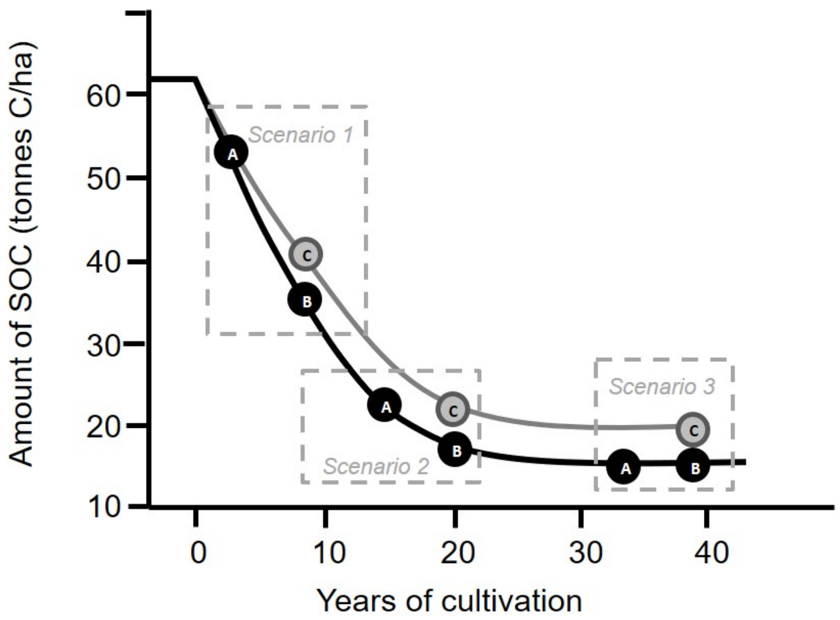

Figure 1. Schematic indicating the differences in SOC stocks (tonnes/ha) under a management change scenario indicating that: relative differences between management practices (C-B) can result from sequestration of carbon (scenario 3) or an avoided emission (scenario 2); temporal differences (C-A) are dependent on equilibrium state of the soil when the management change was implemented, and will only be positive where sequestration has occurred (scenario 3). Graphic modified from Sanderman and Baldock 2010.

SOC accumulation in Australian agricultural systems

There remains debate around achievable SOC accumulation rates and the stability/permanence of new SOC in Australian agricultural environments. There are many individual examples of positive, negative, or neutral changes in SOC that result from management. Collating data across the literature, a previous review of SOC sequestration potential for Australian agriculture reports relative gains for a range of management comparisons (Table 1; source Sanderman et al. 2010). For ease of comparison these SOC accumulation rates are reported as both SOC and SOM in Table 1. The data demonstrate the largest relative changes in stocks are achieved where greater management changes are implemented, for example converting cultivated land to permanent pastures (0.3 - 0.6 t C/ha/yr). Where modest management changes are implemented within cropping or pasture systems, the relative changes in SOC stocks are likely to be smaller (0.1 - 0.3 t C/ha/yr). Taking environmental factors into account, these values are broadly in line with rates of SOC change in the broader international literature.

The review does however acknowledge that the available field data captures a narrow range of management options, and that there is limited data to inform SOC change potential under more radical management changes. Recent successes within the Australian government Emissions Reduction Fund (now Climate Solutions Fund) demonstrate that much higher rates of SOC accumulation (~3 t C/ha/yr) can be achieved under the right growing conditions. These individual examples are important in demonstrating the potential to increase SOM and improve overall productivity. However, before investing in management change initiatives it is important to be able to estimate realistic accumulation targets for individual scenarios based on local expert knowledge of the environment, system constraints, and production opportunities.

Table 1. Relative changes in soil organic carbon (SOC) or soil organic matter (SOM) across management comparisons, where: improved cropping practices included enhanced rotation, minimum till, and stubble retention; and improved pasture included additional fertiliser, liming, sowing alternative species, and irrigation. SOC data is sourced from Sanderman et al. (2010) and converted to SOM with a multiplication factor of 1.72.

Management comparison	**Stock change (t /ha/yr)**	
	SOC	**SOM**
Cropping: improved compared to conventional	0.2 - 0.3	0.34 - 0.52
Pasture: improved compared to current	0.1 - 0.3	0.17 – 0.52
System conversion: cultivated to permanent pasture	0.3 - 0.6	0.52 – 1.03

Soil carbon inputs: visibility and (un)certainty

In order to manage SOM stocks, we need to consider input and output pathways in the carbon cycle. Inputs of organic carbon to soils include plant biomasses and organic amendments, such as manure. Losses include decomposition/mineralisation and erosion. Maximising plant inputs, while minimising erosion loses, represent two of the most important management levers when aiming to build SOM stocks.

Considering both above- and below- ground inputs are important. Inputs from above-ground crop residues can be estimated from yields based on harvest index (HI) data across a range of Australian cropping scenarios (Unkovich et al. 2010). Local expert knowledge of the cropping systems may be useful in fine tuning values.

Although below ground inputs are less frequently measured, they are important drivers contributing to SOM stocks and overall biological fertility. Estimates of root biomass can be made based on general root:shoot ratios, but these numbers tend to be more uncertain compared to shoot biomass inputs. In addition to root biomass that can be readily seen, roots also add a significant amount of carbon in forms that are unseen. Fine root hairs, sloughed root cells and root exudates supply a steady flow of carbon to the rhizosphere through the growing season. These carbon forms are easily used by the microbial community and commonly referred to as rhizodeposits. It is generally considered that the microbial community can be relatively efficient in using rhizodeposits. The microbial community is key to converting these labile carbon forms into more stable carbon that contribute to more persistent soil carbon pools.

Estimating SOC accumulation rates: let's make some assumptions

A useful cross-check in evaluating target sequestration rates is to consider how much extra crop biomass would be needed to support carbon accumulation in the soil. This provides a tool to question and moderate expectations around rates of SOC change based on local understanding of the extent to which plant biomass inputs can be changed through management. Although this does not account for potential changes in the loss pathways, changing carbon inputs can often be the dominant driver in achieving SOC gains.

A theoretical SOC stock change potential (Figure 2) can be estimated through calculations based on carbon input and loss factors informed by published literature (Table 2). The input factors can be moderated based on local expert knowledge of the farming environment and the changes that can be achieved. Here we estimate the theoretical SOC stock change potential of a cereal system based on changes to carbon inputs including:

1. **plant biomass (roots + shoots):** this approach aligns with input factors used in traditional soil carbon modelling. Shoot biomasses can be approximated based on the yield and harvest index (0.37 for cereals); root biomass approximated based on a root:shoot ratio of 0.5

(cereals); the soil carbon input is estimated using the total plant biomass (shoots plus roots, t/ha) and approximate carbon content (44%); and finally we estimate a retention factor for the biomass-C (RF^b) into SOC at approx. 30 %.

$$\textbf{SOC } \Delta^{B} = \left[\begin{array}{c} \text{shoot + root} \\ \text{biomass} \end{array} \right] \times \begin{array}{c} \text{carbon content} \\ \text{(proportion)} \end{array} \times RF^{b}$$

2. **plant biomass (roots + shoots) plus rhizodeposits**: this approach recognises that traditional soil carbon models don't explicitly account for labile carbon inputs as a separate pool. Here we include rhizodeposition as equivalent to 50% of root biomass, and that these simple compounds are converted to SOM more efficiently (0.57 retained) by the microbial community compared to plant residues.

$$\textbf{SOC } \Delta^{B+R} = \left[\text{SOC } \Delta^{B} \right] + \left[\begin{array}{c} \text{root} \\ \text{biomass} \end{array} \times \begin{array}{c} \text{rhizodeposition} \\ \text{carbon factor} \end{array} \times RF^{r} \right]$$

Under these assumptions SOC stock change potential can be estimated for a given increase in plant biomass (Figure 2). Thus, a 0.5 t/ha change in SOC stock can be expected to require an approximate increase in crop biomass in the region of 2.5 t/ha when considering traditionally recognised shoot and root inputs, or 1.4 t/ha where rhizodeposits inputs are also included.

Figure 2. A theoretical SOC stock change potential (t/ha) for a given increase in crop biomass (t/ha) when considering crop biomass inputs (solid black), or crop biomass inputs plus estimated rhizodeposit (solid grey). Assuming steady state equilibrium before the implementation of management change, the calculation factors are listed in Table 2.

Table 2. Calculation factors, values, and references used to estimate the theoretical SOC stock change potential based on crop biomass inputs (SOC Δ^{B}) or biomass plus rhizodeposit inputs (SOC Δ^{B+R}) depicted in Figure 2. Factor values* can be updated based on local expert knowledge for a given management scenario.

Calculation factor	**Value***	**Reference**
Harvest Index (HI) cereal	0.37	Unkovich et al. (2010)
Root:Shoot (R:S) cereal	0.50	for pasture increase to 1
Carbon content of cereal biomass	0.44	
Retention Factor biomass (RF^{b})	0.30	Ladd et al. (1995)
Rhizodeposition C (proportion of root biomass)	0.50	Jones et al. (2009)
Retention Factor rhizodeposition (RF^{r})	0.57	Pausch and Kuzyakov (2018)

This estimate calculation does not provide a definitive answer on SOC change potential. It provides a tool to consider whether management changes have a big enough impact on plant inputs to support a target SOC stock gain. The harvest index can be updated for different crops with local knowledge or with values reported for a range of crops within Unkovich et al. (2010). It is also useful to consider how close to the water limited yield potential current yields are, and what factors are limiting closing the yield gap. Identifying the constraints in play, what it will take to overcome them, and estimating the gains in crop biomass inputs can be informative in helping to set realistic SOC change targets.

It is important to note the uncertainties and assumptions around this estimate calculation. The calculation assumes that the system is in steady state, not losing or gaining carbon under the current management practice (Figure 1, scenario C). If the system is losing carbon then changed management practices may lead to either a slower rate of SOC loss (avoided emission) but no measurable gain from a baseline (time zero) measuring point, or only a small sequestration gain.

SOM stocks and flows for resilient soil systems: the need for long-term nutrient budgeting

Soil health and fertility benefits from SOM result from decomposition or loss of SOM. Thus, it is equally important to recognise how management changes impact carbon and nutrient flows as much as SOM stocks. Matching fertiliser requirements to a larger yield target is important in ensuring that striving for a larger biomass does not come at the expense of mining the existing SOM for nutrients.

Soil organic carbon contents vary widely. However, the C:N ratio of soil is relatively consistent, commonly reported to be around 12 (12C:1N). For other nutrients, such as phosphorus, the ratio is more variable and less predictable. However, most of the N contained in soil (>95%) is associated with carbon in SOM. Therefore, if we know the SOC content, we can estimate the total N content of the soil. A decline in SOC content will also reduce the soil N stock and the ability of the soil to supply N through mineralisation.

For example, a 0.5% decline in SOC in a 10 cm layer of soil with a bulk density of 1.3 g/cm^3 (no gravel), equates to a loss of 540 kg N/ha. As SOM content declines, the ability to support N supply through the growing season declines, and the crop becomes more reliant on fertiliser N.

Norton (2016) previously demonstrated that current rates of fertiliser application are likely to result in mining of soil N - mineralisation of SOM that is not replaced through crop residue returns. In the long-term this results in a decline in soil N status over time, a reduction in the ability of the soil to supply N through mineralisation, and a growing dependence on fertiliser N. Part of the benefit of SOM-derived N is that it is made available through the growing season. Mineralisation will occur when the soil is wet and warm providing a certain amount of synchrony with times when crops are actively growing and have a requirement for N.

Baldock (2019) emphasise the importance of conducting N balance calculations over multiple seasons to not only manage soil N status but to manage SOM stocks. A long-term N balance approach allows for phases of building/replenishing SOM, and phases of using SOM so that the crop benefits from stored N. Other than fertiliser application, the main mechanism to enhance N status is a regular legume rotation to contribute to SOM stocks. Baldock (2019) promote the need for longer term (>10 years) economic analyses. The most profitable management approaches in the short-term will maximise the extraction of N from the soil (i.e. mine the soil N reserve) thereby reducing the cost of production. A long-term approach allows the true cost-benefit analysis associated with both building and using SOM in a cyclic manner to benefit crop production.

Conclusions

Productive and resilient agricultural systems require the careful management of SOM stocks and the associated carbon and nutrient flows. Conventional management practices and current rates of fertiliser addition are likely to favour SOM decline, reducing the ability of the soil to supply N through the growing season. Although there is considerable interest in building SOM stocks to support current and future productivity, the potential rates of accumulation are commonly debated.

Scientific literature estimates Australian SOC accumulation rates in cropping and pasture systems to be approximately 0.1 to 0.3 t C/ha/yr, while higher rates (0.3 to 0.6 Mg t C/ha/yr) are estimated when converting from cropping to pasture. It is however acknowledged that there is a lack of data to inform SOC accumulation rates under a broader range of alternative management practices. Building SOM stocks at higher rates is possible through bold management changes that maximise carbon inputs and minimise loss pathways, but expenditure and opportunity costs need to be evaluated on an individual basis. It can be useful to estimate SOM accumulation targets based on local knowledge of the potential changes to plant biomass production. Taking a long term (decadal) view on building and using SOM and the associated nutrient flows is critical to ensuring that future productivity will not be compromised to maximise short term (annual) profits.

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