Opportunities to build Soil Organic Carbon in a challenging environment; climate change and shifting paradigms

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Abstract: *Soil organic carbon (SOC) is fundamental to soil health and agricultural production. There has been an increasing interest in SOC as a land-based solution to climate change. While this is a win-win opportunity, too often the discussion focuses on the uncertainty of measurement, rather than using what we have learnt over the past two decades to focus on action, traction and implementation. In our paper, we address three frequently asked questions around historic decline in SOC concentrations; increasing productivity and SOC levels simultaneously and the vulnerability of SOC to loss under a changing climate, to move the conversation forward. The purpose of our arguments are to provide a thought-provoking paper providing context and understanding for practitioners, advisers and scientists alike, rather than a rehash of basic science facts. There is evidence that soil OC can be increased in agricultural soils. Regional, landscape and local specificity will be key enablers of change to increase SOC. We need to use local knowledge and practitioner expertise to identify strategies that increase SOC for a given locality, soil type and farming system. These strategies will include grazing management (time, timing and intensity), crop and pasture rotations, practices with a focus on improved agronomy and nutrient management and restoration of degraded soils. New innovations of organic amendments, biochar, biological inoculants and biodiverse plantings show promise. The role of scientists in supporting producers to regenerate the landscape by increasing SOM in soils is critical.*

Key words: Carbon sequestration, humus, plant nutrition, microbial processes, biomass production, decomposition

Introduction

Soil organic carbon (SOC) is fundamental to healthy, functioning soils and landscapes, and underpins agricultural production (Loveland and Webb 2003; Murphy 2013). Increasing organic carbon in agricultural soil also plays an important role in mitigating climate change (Batjes 1996; Minasny et al. 2017) and making farming systems more resilient. Despite a considerable focus on identifying strategies to increase SOC and methods to more accurately measure and monitor changes in SOC stocks, three frequently asked questions are:

1. Are we still experiencing a decline in organic carbon in Australian agricultural soils?
2. Can we sequester carbon in Australian agricultural soils while continuing to feed and clothe a growing population?
    a. Do agricultural practices provide opportunities to sequester carbon in Australian soils?
    b. Can we maintain or increase SOC levels thereby improving soil condition and supporting increases in agricultural production?
3. If we increase SOC, how vulnerable is it to loss under our changing climate?

As is the case for many such rhetorical questions, the most accurate answer is, "*It depends*". In this paper we address these three perpetual questions to move the discussion forward and we highlight the opportunities to build SOC on Australian farms and why we should be enabling producers to do so.

Are we still experiencing a decline in organic carbon in Australian agricultural soils?

The decline in SOC from agricultural soil has been considerable in Australia, largely due to overgrazing, cultivation and continuous cropping in a dry climate on often highly weathered soils. It is estimated that SOC concentration has decreased by up to 70 % in the surface 10 cm since converting native vegetation to agricultural land use (Luo et al. 2010 and Sanderman et al 2010). There are several reasons for this decline, including: i) reduced biomass production and/or organic matter (OM) supply to the soil, ii) increased rate of OM decomposition and mineralisation associated with tillage and altered soil aeration, moisture and temperature, iii) movement of SOC down the profile due to tillage and OM incorporation, iv) reduced capacity to protect OM in soil due to structural degradation and v) increased soil erosion by wind and water. Realistically, it is likely that a combination of these factors has resulted in SOC decline.

However, the initial sharp decline in SOC has been partially reversed by improved land management practices (Figure 1) such as crop rotations, nutrient application (e.g. superphosphate), inclusion of pasture phases (e.g. grasses with fibrous root systems and legumes with high nitrogen content) in cropping rotations, erosion control and conservation farming practices (Hamblin and Kyneur 1993; Williams and Lipsett 1961; Russell 1960; Pratley and Rowell 2003; Nichols et al. 2012; Packer et al. 1992; Freebairn et al. 1993). By increasing biomass production, replacing soil nutrients and reducing the loss (erosion) or degradation (soil respiration associated with cultivation) of soil organic matter (SOM), the level SOC has been partially restored. Pastures have proven an effective and productive strategy to increase SOC (Table 1) and withstand limitations imposed by climate, especially variable and low levels of available soil moisture. For example, at the MASTER trial site located near Wagga Wagga (see Figure 2), despite seasonal fluctuations in SOC stocks and the millennium drought (2000-2010), overall there was a mean increase in SOC of 0.5 t C/ha (0-30cm). Here we feel it is important to highlight that pasture alone is not a guarantee of increasing SOC. Accumulating SOC still depends on the biomass production (including appropriate management of pasture utilisation) and OM supply to the soil, and protection of the soil surface (i.e. groundcover). If pasture establishment is poor, nutrient deficient or if grazing management is suboptimal then SOC levels can be less than for a crop (Valzano et al. 2005). While this is a real consequence, producers can use nutrient inputs and grazing management to maximise carbon sequestration under pastures.

Can we sequester carbon in Australian agricultural soils while continuing to feed and clothe a growing population?

Carbon comprises approximately 58 % of SOM by weight (Baldock and Skjemstad 1999) and SOC is an indicator of soil health and soil condition (Loveland and Webb 2003; Murphy 2015). To build SOC, the supply of OM (through stubble, pasture phases, cover crops and composts etc) needs to be greater than the loss of OM through decomposition and erosion. Increasing biomass production through good agronomy, and grazing and residue management is consistent with increasing agricultural productivity and having a net increase in the supply of OM; therefore building SOC.

Pastures and their management provide an important opportunity to sequester carbon in agricultural soils, as shown in Table 1. While the rate of carbon sequestration varies due to starting SOC levels, management, soil type and climate, evidence clearly supports a rate of change typically between 0.3 to 1.0 t C/ha/yr (0-30cm) for well managed pastures. Based on the literature, practices most likely to achieve increases in SOC stocks include converting degraded cropping paddocks to pasture and renovating or manipulating sub-optimal pasture paddocks to improve productivity (Hackney et al 2020). Contingent for the success of such remediation is implementation of management practices to overcome soil constraints to plant growth (e.g. acidity and sodicity), grazing management (duration, timing and intensity; Chen et al 2015) and improved nutrient management (Table 1).

To understand the optimum conditions for soil carbon sequestration and rate of change, knowledge of the capacity of the soil type and climate to sequester and store SOC is essential. Soil with OC concentrations that are well below the expected levels, are most likely to have a detectable change in SOC with practice change. Thus, in many cases degraded soils may offer the best opportunities for carbon sequestration (Govers et al 2013). That said, practices that focus on regenerating the landscape to improve soil function, and those that start from a healthy resource base may offer new opportunities to build SOC where existing levels may be moderate to high (HLPE 2019).

It is timely to consider the basic principles to increase SOC which are:

i) Increase the amount of above- and below-ground OM inputs to soil,
ii) Influence the location of OM inputs in the soil profile (with deeper horizons being less saturated in carbon, typically having a greater capacity to protect carbon through organo-mineral associations, and where the rate of decomposition is likely to be slower than surface soil layers),

iii) Influence the rate of fresh OM conversion to more stable forms of SOM (such as humus) through nutrient management and microbial processes, and

iv) Increase protection of OM through protecting the soil surface and enhancing soil aggregation.

While we talk of SOC, it is often SOM that is driving the processes that support agricultural production and enhance soil condition. For example, increasing SOM enhances the physical condition of the soil and plays a pivotal role in nutrient cycling (Janzen 2006). Meyer et al (2015) valued the increased pasture production associated with higher SOM on average to be between $26 and $95/ha/yr, attributing most of this value in the low rainfall zone to be through increased plant available water, and in the high rainfall zone through nitrogen mineralisation ($85–$105/ha). Similarly, Ringrose Voase et al (1997) estimated that a 1 % increase in SOC (e.g. increasing SOC from 1 to 2 %) increased gross margins by more than $100/ha/yr in some Riverina soils in NSW. Carbon trading offers the ability to diversify farm income and incentivise practice or land use change, however there are clear economic and environmental arguments supporting the increase in SOM for agricultural production.

If we increase soil organic carbon, how vulnerable is it to loss under our changing climate?

Two major drivers of SOC stocks and flows are rainfall (frequency, intensity and duration) and temperature. Soil organic carbon may be 'lost' due to decomposition (microbial degradation of SOM) or erosion (physical removal of OM and soil particles with SOC associated). (Introduction to the following dot points?)

- Rate of SOM decomposition is a factor of soil biology, type of OM, land management, soils protective capacity (clay%, mineralogy, depth and structure) and environmental conditions (temperature, rainfall, soil water content and atmospheric balances). These are the same factors that drive productivity; some can be changed (e.g. plant type and soil structure) and others cannot easily be changed (e.g. clay content and soil depth).
- Vulnerability of soil to wind erosion is determined by ground cover, soil moisture, wind speed and aerodynamic roughness. Vulnerability of soil to water erosion is determined by rainfall intensity/amount (erosivity), soil type (erodibility), ground cover, slope length and slope steepness. It is important to account for loss of SOC via erosion when considering changes in SOC content and stocks. The amount of SOC removed due to erosion is a factor of the rate of loss and the enrichment ratio (that is, SOC content of the eroded fraction). Figure 3 (from Chappell et al 2019) presents global hot spots for loss of SOC via wind erosion. This figure highlights the impact of climate on carbon loss from soils and draws attention to the important role that practices which increase ground cover could play in the Australian rangelands.

Due to climate change, NSW is becoming hotter and drier with changing patterns of temperature, rainfall, fire, drought and heavy rainfall all of which impact on the stocks and flows of SOC. For example (DECCW 2010) in NSW:

- Mean summer temperatures are expected to increase by 1.5 to 2.0°C in central and north west NSW (e.g. Narrabri, Guyra, Murrurundi and Dubbo) and by 2.5 to 3.0°C in the Riverina (e.g. Corowa, Mildura and Deniliquin) by 2050. Such increases have the potential to increase the rate of decomposition of SOM.
- Mean winter rainfall is expected to decrease by between 20 to 80 mm/yr depending on location by 2050. This has the potential to reduce the biomass production necessary for accumulating SOC.

Climate change may increase the vulnerability of the more labile fraction of SOC to loss but this doesn't have to mean a decline in SOC. Producers and their land management will play a key role in keeping carbon in agricultural soil. Grazing management is a key driver of the provision of ground cover which protects the thin skin of soil that has the highest SOC concentration. Cropping practices which use minimal disturbance and that retain residues also protect the soil surface. Deep rooted perennial pastures enhance aggregate-protected SOM, regulate fluctuations in temperature and moisture and have the capacity to add SOC deeper in the soil profile through their fibrous roots and associations with microbes. Legumes and their associated rhizobia supply biologically fixed nitrogen which can enhance grass growth as well as build SOC through contributing OM with narrow C:N ratios. While currently not regarded as an economically viable option in many broadacre systems, we know increasingly more about nutrient management to create stabile SOC (building humus), optimising compost production and the pyrolysis of OM to make stable char (biochar). In addition, innovations in the field of optimising water use efficiency through rotations, species selection and diverse plantings offer opportunities to be flexible under changed soil water regimes.

Conclusion: it is possible build soil organic carbon!

There is evidence in the peer reviewed literature that you can increase OC in agricultural soils. There is no dispute that increasing SOM is important for agricultural production, soil condition, resilient farming systems and mitigating climate change. Measuring SOC concentration (% or g/100g soil) is cheap and provides valuable information on soil condition particularly when considered within the context of the region, or soil type and climate. We need to focus on action, traction and implementation as soon as possible to realise the full potential for increasing SOC in our soils.

Regional, landscape and local specificity will be key enablers of change to increase SOC. It is at the landscape and local scale where there are opportunities to improve the knowledge and understanding of SOC dynamics and measurement, and the influence of SOM on the water and nutrient cycle. We need to use local knowledge and practitioner expertise to identify strategies that increase SOC for a given locality, soil type and farming system. The effects of grazing duration, timing and intensity on soil carbon sequestration offer an opportunity to increase SOC, while improvements in crop and pasture rotations and practices with a focus on improved agronomy and nutrient management offer another. Implementation of these practices at the operational level needs to be undertaken by producers with nuance to maximise benefits in diverse and often complex landscapes. Restoration of degraded soils is also an area for carbon sequestration that can be better utilized. Incorporation of organic amendments (Badgery et al 2020), biological inoculants (Mukasa Mugerwa 2017) and biodiverse plantings (Yang et al 2019) are promising innovations in the field of SOC sequestration science. We need a greater level of understanding of these practices through replicated trials across different climates and soil types. The role of scientists to support producers to regenerate the landscape by increasing SOM in soils is critical.

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Table 1. Example of published soil carbon sequestration rates for NSW.

Management	Region (NSW)	C seq rate (t C/ha/yr 0-30cm)	Years	Reference
Pastures - NSW				
Liming	Riverina	0.46 to 0.55	18	Chan et al 2011
Nutrient management	Southern Tablelands	0.41	>25	Chan et al 2010; Orgill et al 2014; Orgill et al 2017
Rotational grazing	Southern Tablelands	0.35	>25	Chan et al 2010
Grazing management (strategic & rotational)	Southern Tablelands & Western Division	1.04 to 1.46	>5	Orgill et al 2016; Orgill et al 2017
Nutrient mgmt & inc stocking rate (*60cm)	Southern Tablelands	0.60*	20	Coonan et al 2019
Organic amendments	Central West	1.09 to 2.47	5	Badgery et al 2020
Pastures - Australia meta-analysis				
Nutrient management		0.29	dns	Sanderman et al 2010
Irrigation		0.11		Sanderman et al 2010
Introduced perennial pastures		0.50	dns	Gifford et al 1992
Cultivated crop to pasture		0. 50 to 0.70	22	Young et al 2009; Chan et al 2011; Conyers et al 2015
Min till crop to pasture		0.78 to 1.33	5	Badgery et al 2020
Crop to pasture - Australia meta-analysis				

Nutrient mgmt, legumes, irrigation (*30cm+)		0.30 to 0.60	dns	Sanderman et al 2010
Crop with pasture in rotation - NSW				
Pasture rotations	Riverina	0.22 to 0.40	>13	Chan et al 2011; Helyar et al 1997
No till wheat with 2 yr pasture rotation	Riverina	0.26	25	Chan et al 2011
Crop rotation with 2-6 yr pasture rotation	Riverina	0.23	18	Helyar et al 1997
Crop with nutrients - NSW				
Nutrients + stubble & incorporated (*160cm)	South West Slopes	1.10*	5	Kirkby et al 2016
Organic amendments + direct drill crop	Central West	0.32 to 0.64	5	Badgery et al 2020

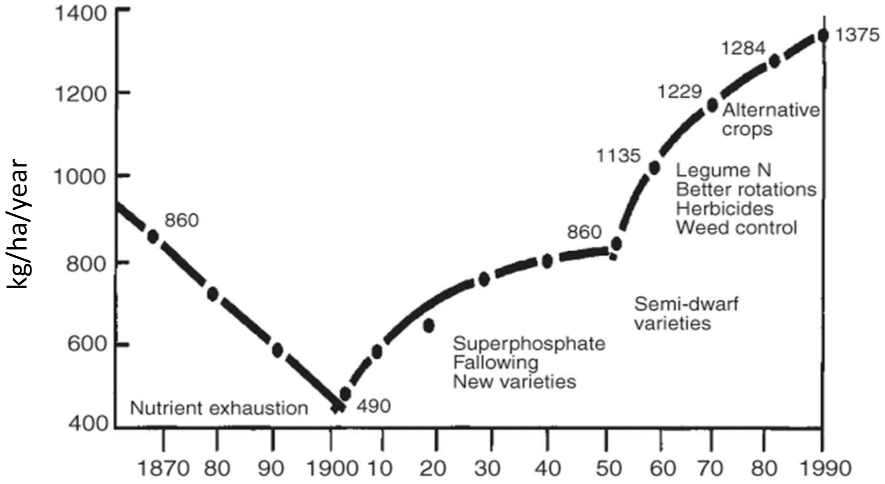

Figure 1. Trends in wheat yields (kg/ha/yr) since 1870 for Australia. (Adapted from Hamblin and Kyneur 1993).

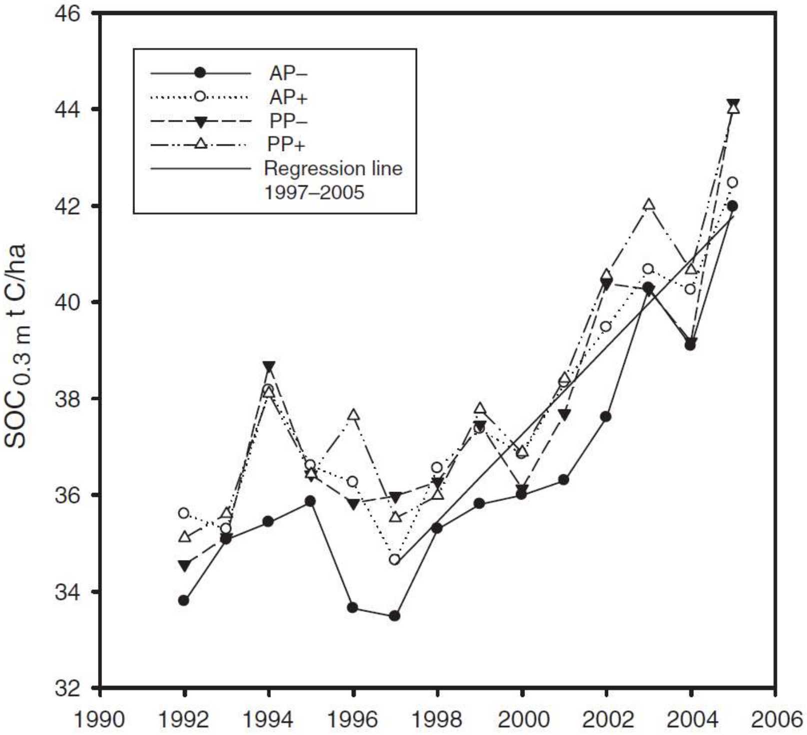

Figure 2. Trends in soil organic carbon stocks (t C/ha 0-30cm) 1992 – 2005 at the MASTER trial site near Wagga Wagga from Chan et al 2011. Annual Pasture (AP) and Perennial Pasture (PP) with (+) and without (-) lime. All plots rotationally grazed with sheep.

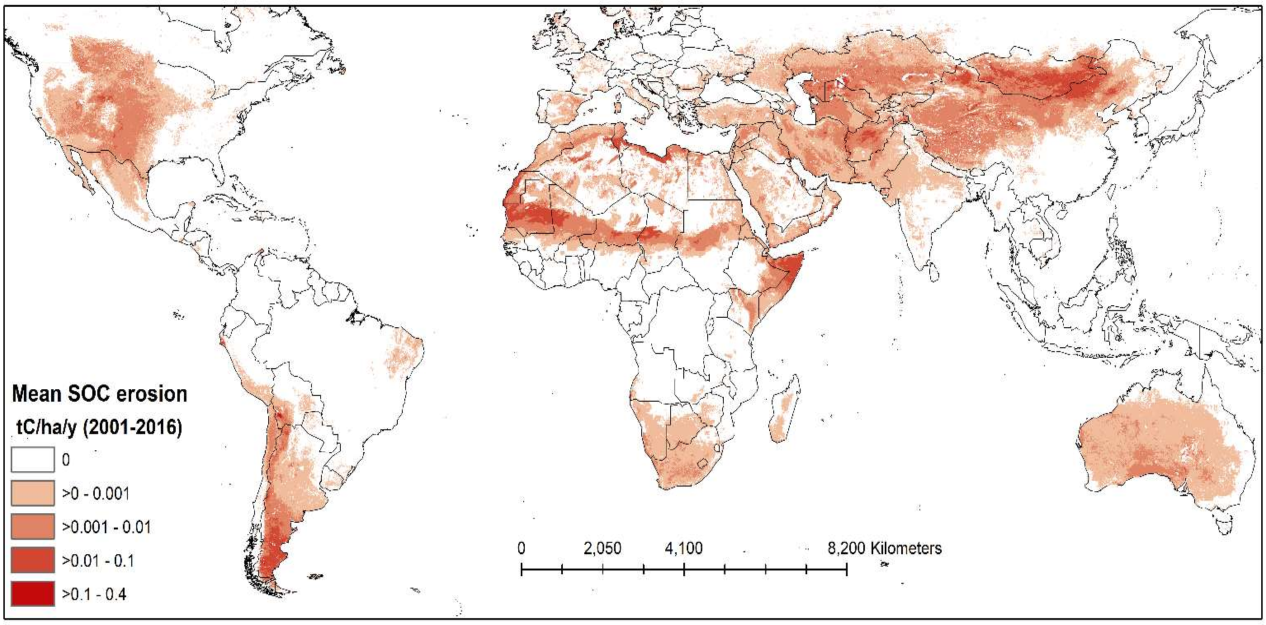

Figure 3. Mean soil organic carbon (SOC) loss in dust from Chappell et al (2019).