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ARE SOIL CARBON CREDITS A HUGE OPPORTUNITY OR POTENTIALLY HIGH RISK?

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Abstract

Soil carbon is complex, existing in a continuum of decomposing organic compounds that transform and cycle across the biosphere and atmosphere over periods ranging from days to centuries or longer. There is wide agreement amongst agronomists and soil scientists that soils high in organic matter will generally be healthier and more productive, but there are divergent views on the value of soil carbon sequestration as a climate change mitigation strategy. Sequestration in soil counts as abatement when carbon is stored long-term (‘permanently’) in stable forms so that it represents a net removal of carbon dioxide from the atmosphere. The complexity of soil carbon dynamics and influence of multiple landscape, climate, and management variables contribute to differing interpretations of the role of carbon sequestration and of the value of soil carbon offsets in “carbon farming” market mechanisms. Inconsistent use of terminology and measurement methods are also significant challenges. Process understanding and prospects for accurate, cost-effective monitoring are improving, but to date there are very few data quantifying soil carbon stock changes over multiple decades to the standards required to ensure verifiable high-quality carbon offsets that can have credibility in carbon markets. In 2014, the Australian Emissions Reduction Fund (ERF) was the first government scheme to make methods for crediting and payment for soil carbon sequestration, with the first credits (Australian Carbon Credit Units, ACCUs) being issued for a soil carbon project in 2019. Soil carbon sequestration is expected to play a role in Australia’s 2030 and 2050 Paris Agreement target, but here and globally better understanding is needed of the sequestration potential and the carbon and non-carbon co-benefits or trade-offs for soil carbon positive practices to inform climate change mitigation policies and investment. Land managers interested in participating in carbon credit schemes, and potentially income from sale of offsets, also need context-specific information for their local conditions, farming systems and management history. Opportunities and risks differ regionally, but experience with implementation of the ERF in Australia may help inform consideration of land management for soil carbon sequestration elsewhere, including in countries with less extreme climates, higher quality soils and more intensive management systems such as New Zealand.

Introduction

The top three metres of the world’s soil hold around 2500 Gt (10^9t) carbon (Jansson et al. 2021), which is two to three times as much carbon as in vegetation and the atmosphere combined. Even a small percentage changes in such a large pool can significantly affect the net carbon dioxide (CO_2) balance in the atmosphere, and this has led to intense interest in carbon sequestration in soils as a potential climate change mitigation solution.

The primary pathway by which carbon enters the soil pool is via photosynthesis which fixes carbon dioxide from the atmosphere into plant organic matter. Soil organic matter (SOM) mainly from plant residues, root exudates and microbial necromass is about 58% carbon by mass. Like photosynthesis, respiration (the pathway by which biological carbon cycles back to the atmosphere) is a large CO_2 flux. More than 90% of organic carbon entering the soil returns to the atmosphere as CO_2 relatively rapidly – within a couple of decades. Soil organic carbon (SOC) sequestration occurs when inputs of organic matter to the soil exceed loss through microbial and plant respiration and a fraction of total organic matter is stored long-term in the soil. Jansson et al. (2021) estimated that for photosynthetic uptake of 123 Gt C yr^{-1}, respiration returned 120 Gt C yr^{-1} back to the atmosphere with net sequestration into soil being equal to 3 GT C yr^{-1}. This is a net removal of CO_2 from the atmosphere to the soil that may be recognised as climate change abatement in carbon credit schemes. One carbon credit is equivalent to one tonne CO_2 removed from the atmosphere, i.e., each additional tonne of carbon sequestered in soil is able to earn 3.67 (44/12) carbon credits.

Soil organic carbon credits

Influences on SOC sequestration: Within the soil, organic matter undergoes chemical and physical changes under the influence of microbes. SOM exists as a continuum of degradation products, from more recently added particulate organic matter (POM) (2mm to 0.053mm in size) to humus (<0.053mm). The fine fraction is more stable and may be protected from microbial action in soil aggregates as mineral associated organic matter (MAOM) (Lavellee et al. 2020).

Labile and stable fractions of SOM each provide valuable overlapping functions in soil. Recent attention has tended to focus on the role of stable organic carbon storage in climate change mitigation efforts, while the relatively rapid turnover of POM has long been recognised as essential for healthy soil and its provision of services such as energy for microbial populations and the release of nutrients for plant growth. Management strategies that enhance sequestration are those that can accrue more, and more persistent, SOC by enhancing inputs of SOM and/or affecting the net balance of inputs and loss. More inputs rely primarily on more plant growth, i.e., higher net primary productivity (NPP). Constraints on NPP include location specific factors such as climate and soil nutrient status. The persistence of organic carbon is influenced by soil properties, notably clay content, that affect its bioavailability to microbial degradation. Nitrogen is often a limiting factor for crop and pasture yield in agricultural soils and can also limit persistence due to the requirement for maintaining chemical stoichiometry. Climate variations such as drought and management strategies, such as fallowing or high grazing pressure, that result in disturbance and exposure of SOM affect the rate of loss. Because gain and loss processes tend to be asymmetric, with loss occurring faster than gains, maintaining a higher level of SOC is challenging in agricultural soils, especially those under cultivation. In summary, the dynamics of SOC are complex with fractions representing a range of decomposition products differing in their distribution in the soil profile, vulnerability to disturbance loss, effects on soil fertility and agricultural yields, and contribution to climate change mitigation.

Measuring SOC sequestration: Research on SOM is not new and long-term field experiments, some established more than a century ago such as those at Rothamsted Research Station, provide exceptionally valuable insights into SOC dynamics (Henry et al. 2022). Measurement of SOC concentration in topsoil (usually 0 – 5cm or 0 – 10cm) was used to estimate SOM content for research on the role of soil in plant growth and crop yields and for informing agronomic decisions. However, while a valuable agronomic metric, on its own the %SOC in topsoil cannot quantify carbon sequestration, and unsuitable measurement protcols have been one factor leading to inconsistencies in reports of the potential for climate change mitigation and earning credits (Moinet et al. 2023). The following points summarise key requirements for accurate quantification of SOC credits due to improved management strategies:

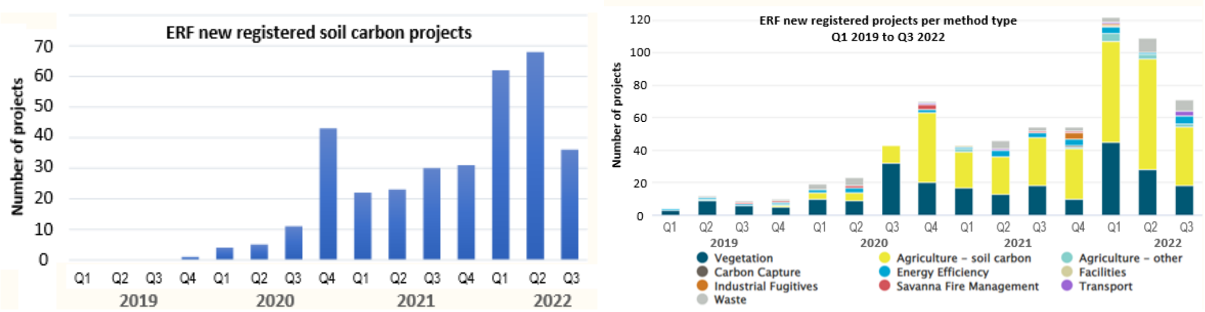
- Measurements of SOC concentration and bulk density to a nominated depth, which by international convention is ≥ 30cm, are used to estimate SOC stocks, the mass of C in a known volume of soil, expressed as mass per unit area (t C ha^{-1}).
- Sequestration, the rate of mass accumulation of C, is measured as the change in SOC stocks over time to give, most accurately expressed as the stock change in an equivalent soil mass.
- The precision of sampling and analysis, spatial variability and typically slow rate of change mean that soil scientists commonly recommend a period of at least 5 years between measurements to ensure a detectable difference that is meaningful in the long-term.
- For carbon credits an increase in SOC stocks must be 'permanent' so monitoring must be a multi-decadal commitment in order to demonstrate that the new management regime is continuing to maintain a higher level of organic carbon.

Meeting these requirements means that, with traditional accurate technologies, monitoring, reporting and verification (MRV) for soil C credits is time-consuming and costly. Newer proximal and remote sensing methods or model-supported monitoring are now being used by researchers and starting to become more accessible for land managers (Paustian et al. 2019, Smith et al. 2020). However, while their reliability is growing, they require calibration and validation data from field sampling and laboratory analysis to provide confidence in C credit markets.

Demand for soil carbon credits: Globally, investment in more accurate and cost-effective measurement technologies and understanding of SOC sequestration across scales has grown over the past decade in parallel with climate change concerns and strengthening emissions reduction commitments under the 2015 Paris Agreement. Analysis of Nationally Determined Contributions (NDCs) in late 2022 showed that 107 of 164 countries referred to SOC or SOC-related measures in their NDCs. Of these, 36 referred to SOC explicitly and 23 (14% of parties) referred to SOC in mitigation measures (Rose et al. 2020). Paris Agreement targets are, therefore, starting to be accompanied by policies or programs to encourage actions for increasing or maintaining SOC. Demand for carbon offsets, including soil carbon offsets, is forecast to increase further as private organisations and sub-national governments set 'net zero' targets. Carbon markets have grown almost exponentially, and the global compliance carbon market annual trading value exceeded US$850 billion in 2021 (IETA 2022).

Case study: Australia's soil carbon credit method

Policy settings: Legislation in 2011, the Carbon Credits (Carbon Farming Initiative) Act 2011 (Cth) (CFI Act) established Australia's carbon farming policy, and enabled Australia to introduce the first national government SOC crediting method under the Emissions Reduction Fund (ERF) in 2014. More detail on the methods and framework are available online (https://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-the-land-sector/Agricultural-methods) and in Henry et al. (2022) and Macintosh et al. (2019). The subsequent seven years experience in method development and soil carbon project implementation provides a useful case study for how agricultural land managers can earn SOC credits in a voluntary scheme. Since 2021, soil carbon offsets have been highlighted in both policy and research initiatives to support climate change commitments. Notably, Australia's "Net Zero Plan" that supports policy to achieve net zero emissions by 2050 includes an expectation that soil carbon sequestration would provide 20% of the abatement required in 2050. Government investment in new method development and innovative measurement technologies aims to reduce impediments to voluntary participation by farmers and other land managers in the ERF. Interest amongst stakeholders has accelerated over the three years to 2022, with the number of projects registered with the Clean Energy Regulator (CER), the body that administers the ERF, increasing at a higher rate than any other project type, approaching 450 by early February 2023 (Figure 1, CER 2022).



A **B**

Figure 1. New soil carbon projects registered under the Emissions Reduction Fund has grown rapidly over the three years from 2020 to 2022 (A) to be the fastest growing project type in the scheme (B).

Soil carbon methods: Two ERF methods are in force under which projects can be registered with a view to earning carbon credits for increases in soil carbon stocks in agricultural soils:

1. The 2015 model-based soil carbon method (*Carbon Credits (Carbon Farming Initiative—Estimating Sequestration of Carbon in Soil Using Default Values*) Methodology Determination 2015) enables land managers who adopt one of three eligible activities to earn carbon credits using regionally specified model-based default values. After seven years there have been no projects registered under this method with prospective participants indicating that reasons include the conservative estimates of sequestration and the narrow eligible activities.
2. The 2021 Measure-Model method for soil carbon sequestration in agricultural systems (Carbon Credits (*Carbon Farming Initiative - Estimation of Soil Organic Carbon Sequestration using Measurement and Models*) Methodology Determination 2021) has a measurement-only option with quantification by field sampling and laboratory analysis or proximal estimation, and a hybrid module which aims for more cost-effective monitoring by combining less frequent soil core measurements with process modelling. The measurement option improves on, and replaces, two earlier measurement methods made in 2014 and 2018. The 2021 method was developed with a view to attracting more projects through greater flexibility in eligible activities (see Box 1) and ease of reporting.

Other features of the 2021 method include the requirement for a land management strategy at registration that sets out the eligible activity that will be implemented and how the new practice fits within a business plan that continues through the permanence period. Land managers must also engage a soil technician to ensure an appropriate sampling protocol and correct procedures for taking samples and their analysis. These requirements add to the sampling costs but improve credibility. In the *measurement only approach*, each carbon estimation area (CEA) is sampled at least once every 5 years and in the *hybrid approach*, at least once every 10 years. Elements of methods, including those for eligibility, contracting and MRV, are highly technical, and a farmer or other land manager generally has to engage a specialist carbon service provider to participate.

There are a range of buffers and discounts built into ERF sequestration methods to manage the risk of over-crediting and ensure that estimates of carbon abatement are conservative. For example, the ‘risk of reversal buffer’ imposes a 5% reduction in carbon credits issued to protect the ERF against temporary losses of carbon and residual risks that cannot be managed by the other permanence arrangements. Projects may choose a 25 year permanence period rather than 100 years in return for a 20% discount in credits received. To guard against over-crediting in the initial sequestration estimate, 25% of the credits calculated for the first reporting period are withheld until the subsequent report.

Box 1

Eligible activities under the ERF 2021 soil carbon method:

- applying nutrients to address a material deficiency.
- applying lime to remediate acid soils.
- applying gypsum to remediate sodic or magnesic soils.
- undertaking *new irrigation.*
- re-establishing or rejuvenating a pasture by seeding or pasture cropping.
- re-establishing, and permanently maintaining, a new pasture (e.g., on crop or fallow land).
- altering the stocking rate, duration or intensity of grazing.
- retaining stubble after a crop is harvested.
- converting from intensive to reduced or no tillage.
- modifying landscape or landforms to remediate land.
- mechanically add or redistribute soil through the profile (e.g., clay delving).
- using legume species in crop or pasture systems.
- using cover crops.

Provisions of the CFI Act have been designed to ensure that (Australian Carbon Credit Units, ACCUs) issued under the ERF will be of high quality. Of critical importance at the scheme level, is that the Act includes a set of Offsets Integrity Standards[1] for the purpose of ensuring that credits are awarded only for abatement that is real and additional and that cause no adverse environmental outcomes. An independent committee assesses whether methods, including the soil carbon methods, meet all six Integrity Standards before they can be made.

Observations on opportunities for soil carbon credits in agricultural land

Opportunities and impediments: The Australian example of supporting legislation and soil carbon crediting methods demonstrates that an incentivisation framework to reward land managers for sequestration in agricultural soils can be successful in encouraging adoption of good practices. It also illustrates that for soil carbon credits, balancing useability and integrity of methods is challenging and complex.

Requirements and rules for quantifying carbon credits are detailed and technologically complex to the extent needed to provide confidence in their value in carbon markets. The experience in Australia shows that the result of simplification as in the 2015 default factor method can be that land managers perceive the eligible practices to be so restrictive and the quantification of credits so conservative that participation is unattractive and unlikely to be economically viable. On the other hand, the high up-front cost of measurement combined with the uncertainty in achievable sequestration was seen as a barrier to participation in the 2014 measurement method (Macintosh et al. 2019). Expanding the options for quantification, the range and flexibility for eligible activities for sequestering carbon in the 2021 method, combined with an increasing carbon credit price in primary (government) and secondary (commercial) markets saw a rapid growth in new soil carbon project registrations (Figure 1). Future reporting under these projects will

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[1] Carbon Credits (Carbon Farming Initiative) Act 2011 (Cth) (CFI Act), s 133.

provide insights into rates of sequestration achievable in agricultural soils for different management activities and regional conditions. Understanding of context specific constraints is expected to grow. In advance of project data becoming available, observations can be made on key factors that more generally represent opportunities and risks for projects seeking to earn soil carbon credits.

Co-benefits and trade-offs: Implementing practices with a view to increasing carbon sequestration is sometimes presented as a win-win-win for environmental, economic and social objectives, but experience from soil carbon projects shows both benefits and trade-offs are possible (White 2022, Rumpel et al. 2022). In addition to up-front financial outlays for implementation and measurement, there can be potentially high opportunity costs associated with project activities, e.g., with conversion from cropping to grassland. There is evidence of co-benefits, including improved productivity, resilience to climate and other disturbances, and enhanced soil water holding capacity in some contexts. Conversely trade-offs may also occur associated with irrigation, resource allocation or with nutrient status. For example, an increase in stable SOM content may result in lower plant-available soil nitrogen, and practices to increase stored SOM may divert resources, e.g., pasture biomass, from production (livestock feed). Understanding context-specific co-benefits and trade-offs for SOC sequestering practices is necessary to identify the most regionally and economically appropriate options.

Additionality: The ERF, like many carbon crediting schemes, has a requirement for ‘additionality’, i.e., the implementation of a ‘new or materially different’ practice that goes beyond business-as-usual management. This may exclude ‘good’ farmers who have been early adopters of practices to improve soil health and land condition especially where there are productivity co-benefits, such as incorporating legumes in pastures.

Baseline SOC content and ‘saturation’: Soils do not have an infinite capacity to store stable forms of organic carbon. The rate of increase in SOC stocks from a baseline level after initiating practices for higher SOM inputs slows over time as stocks approach a steady state with the amount of increase dependent on the initial content relative to the natural saturation level. The hypothetical soil carbon saturation is a concept that defines the upper limit of stable SOC due to mineral protection, at which point inputs and loss of SOM are effectively in balance (Craig et al. 2021). It follows that the potential sequestration in mineral soils is a function of baseline SOC deficit relative to this natural location-specific equilibrium level Thus, baseline SOC stocks are critical to understanding the potential to earn soil carbon credits and also to calibrating models used to project sequestration. Measurements show that many of New Zealand’s agricultural lands, particularly grasslands, have a high SOC content. The average SOC content to a soil depth of 30 cm for New Zealand is close to 100 t C ha^{-1} (https://www.nzagrc.org.nz/), which is higher than the global average (62 t C ha^{-1}), reflecting favourable climatic and soil conditions, and a large proportion of land area with perennial vegetation that is largely undisturbed. In contrast, Australian soils have, on average, 29.7 t C ha^{-1} (Viscarra-Rossel et al. 2014), due to the large part of the continent with unreliable rainfall and weathered, nutrient-poor soils and, consequently, low NPP. High resolution spatial data on baseline SOC stocks are needed to better understand variations in baseline deficit relative to the saturation level in agricultural soils in both New Zealand and Australia to identify locations of greater sequestration potential.

Permanence: Climatic conditions and physiochemical characteristics of soil have a dominant influence on SOC dynamics but within these constraints, adoption of improved management can give a net increase in sequestered carbon (Rabbi et al. 2015). Importantly, this increase in SOC can also be reversed when inputs cease to be greater than respiratory losses, and the rate of loss is commonly more rapid than the increase. Trials indicate that the risk of reversal is greater where climate variability is high (Badgery et al. 2020), and that it is set to become even greater due to the impacts of climate change. Climate extremes and warming affect NPP and organic matter inputs to soil and can increase the rate of loss via soil respiration and changes to microbial biota. (Roxburgh et al. 2019). Provisions in ERF methods seek to manage the risks to government and participants due to the biophysical and financial uncertainty associated with permanency in sequestration projects but there remains a degree of uncertainty in whether sequestered SOC can be maintained to meet permanence period obligations. This risk is viewed as an impediment to ERF participation by land managers.

Conclusions

Within the constraints of climate, edaphic and landscape factors, land management practices can influence the stocks and dynamics of organic carbon in agricultural soils, providing for the potential for farmers to receive carbon credits for adopting SOC sequestering practices. The Australian ERF case study illustrates that carbon crediting frameworks and methods can be developed that attract land managers to participate in soil carbon sequestration projects. However, it is also clear that there are significant data and knowledge gaps that limit confidence in achievable, permanent SOC sequestration, and act as a barrier to action. Better understanding is needed of the regional opportunities for sequestration, the most effective management strategies, and context-specific costs, benefits and risk of reversal. There is also a need to develop more reliable, cost-effective, and accurate measurement technologies. The Australian example illustrates that, despite research investment and some promising innovations, current MRV costs and accuracy remain an impediment to uptake by farmers. Measurement protocols are needed not only for accurately monitoring SOC stock changes but to account for greenhouse gas emissions arising from project activities to ensure the number of carbon credits genuinely representing climate change mitigation can be quantified.

The potential for sequestration in agricultural soils is influenced by baseline SOC levels and their relationship to the ‘saturation’ level of stable SOC stocks. Investment in more spatially explicit baseline SOC data and understanding of the impacts of past management is needed to improve estimates of the potential to increase SOC stocks and evaluate the case for investment in carbon credit projects. In assessing the opportunities for soil carbon credits from improved management practices the risks to retaining any gains must also be considered. The risks to the ‘permanency’ of sequestered SOC are greater where climate variability is high and are projected to increase further due to anthropogenic climate change.

Regardless of the challenges and risks associated with adopting new practices with a view to increasing SOC sequestration and earning carbon credits, there is wide agreement amongst soil scientists and agronomists that managing agricultural soils in ways that increase SOM inputs and minimize loss will be beneficial for soil health, and may provide higher crop and pasture yields, more resilient production systems and enhanced ecosystem services.

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