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Understanding and fostering soil carbon sequestration

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Creating frameworks to foster soil carbon sequestration

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1 Introduction

It is now widely acknowledged that if the world is to avoid the worst of the projected impacts of climate change, then, in addition to urgent actions to reduce emissions of greenhouse gases (GHGs) to the atmosphere, removals are also needed (IPCC 2019, Rockström et al. 2017). Of the removal or 'negative emissions' technologies, natural climate solutions are an attractive option (Griscom et al. 2017). Soil organic carbon (SOC) sequestration, the process of removal of atmospheric carbon dioxide (CO_2) and storage as organic matter in soils, has immediate and broad applicability, offers potential for substantial climate change mitigation (Minasny et al. 2017, Paustian et al. 1997, Sanderman et al. 2010, Sanderman et al. 2017), and can contribute co-benefits for food security, ecosystem services and achievement of multiple Sustainable Development Goals (SDGs) (Keesstra et al. 2016, Keesstra et al. 2018, Paustian et al. 2016).

A systematic review of the literature has indicated that sequestration of soil carbon may contribute to removals of as much as 5 Gt CO_2 year^{-1} (Fuss et al. 2018). However, sequestration is variable across agro-ecological areas (Bossio et al. 2020) and will be highly dependent on levels of adoption of SOC-positive practices by landholders at scale. Past studies indicate that barriers to uptake can be substantial, and may include insufficient clarity on the impacts

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of recommended practices on agricultural productivity, yields and profitability; poor or unknown compatibility of actions with farm operations; and uncertainty in whether any significant increase in SOC stocks will occur and, whether it is practical to measure the change (Box 1). Even where there is strong scientific evidence for positive productivity and environmental outcomes of carbon-sequestering practices, uptake among land managers has generally remained low (Paustian et al. 2019).

Policy frameworks that can provide information, training and financial or other incentives to adopt more sustainable practices represent an opportunity for governments or private organisations to invest in increasing soil carbon sequestration for climate change and other objectives. In this chapter, we explore how creation of national- or regional-scale frameworks appropriately linked to broader farm and forestry management, and supported by research, governance and rigorous practical measurement, reporting and verification (MRV) systems, can foster adoption of soil carbon sequestration practices. Frameworks can take a range of forms, but in this context, they would be expected to set out objectives, procedures, and incentives to guide soil management decisions for climate change, food security and sustainability benefits.

Box 1 Evolution of soil carbon research informing future action

Some of the earliest scientific reports of the eighteenth and nineteenth centuries focused on the role of soils and atmosphere in enabling plant growth. The early history was reported by Sir John Russell of Rothamsted Research Station in his landmark book 'Soil Conditions and Plant Growth' (Russell 1912). A mix of speculation, observation and experimentation over the prior two centuries helped resolve controversies on how soil, water, nutrients and atmospheric carbon interacted to control plant growth (see Keating and Thorburn (2018) for a more detailed summary). Over the past 70 years, research on soil organic matter and measurement of soil carbon content have evolved in a way that provides a context for current understanding of how good practice for soil carbon sequestration may be fostered more effectively (Fig. 1).

The founders of Rothamsted Experimental Station (JH Gilbert and JB Lawes) were pioneers in what we know now as soil fertility and crop agronomy science, and the long-term trials they established in the 1840s are still continuing to the present day. Some of these trials have been important for building and testing soil carbon models (Jenkinson 1990).

Building on these centuries of studies on soil fertility and crop yields, intensive research on SOC and climate change mitigation began in earnest during the 1990s (Barnwell et al. 1992, Paustian et al. 1997).

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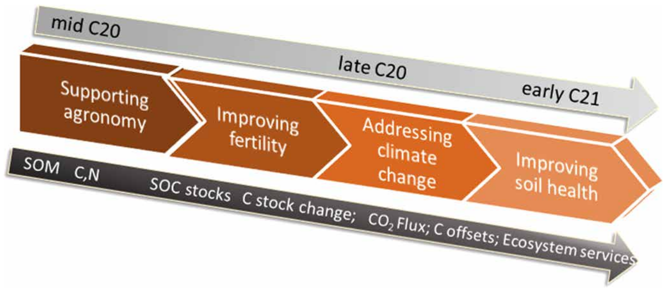

Figure 1 Illustrative timeline of research and monitoring of organic matter and carbon in soils, showing the evolution of interest driving research and development of metrics.

The initial focus was on understanding the contribution of land conversion and land use to increasing atmospheric CO_2 (e.g. Dalal et al. 2021a, Guo and Gifford 2002, Henry et al. 2018, Murphy 2020). By the late 1990s, research on rates of SOC sequestration moved towards assessing the value of management practices that increase soil organic matter (SOM) in diverse land uses and eco-regions as a climate change mitigation strategy. A variety of practices in croplands (Paustian et al. 1997, Lal 2004, Johnson et al. 2005, Franzluebbers 2005, Ogle et al. 2005, Causarano et al. 2006, Balkcom et al. 2013, Martens et al. 2005), such as the inclusion of cover crops (Causarano et al. 2006, Lal 2015a,b,c, Poeplau and Don 2015, Sainju et al. 2008), and in grazing lands (Conant et al. 2001, Schuman et al. 2002, Franzluebbers and Stuedemann 2009) and forestry and biofuel planting (Liebig et al. 2008, Follett et al. 2012) have been evaluated. As noted in the review by Stockmann et al. (2013), the results of field trials extending over periods of decades, and preferably for at least 100 years (referred to in this article as the 'permanence' period for storage) are more valuable than the outcomes of short-term experiments (Johnston et al. 2009, Powlson et al. 2011). Long-term monitoring enables the comparison of soil carbon under different practices over the time scales that are needed to understand the dynamics of SOC stock changes and their contribution to climate change mitigation.

2 Designing a framework to foster soil organic carbon sequestration

The key considerations in a framework for incentivising soil carbon sequestering actions by land managers include:

1 Sound scientific basis linking a management practice to soil carbon stock change, and real and achievable sequestration with permanence (long-term stability). It is essential that the evidence accounts for the

full system-wide consequences in terms of changes in SOC stocks or greenhouse gas emissions elsewhere, that is, avoids leakage, limits other environmental trade-offs and does not have negative socio-economic impacts;

2 Policy and legal instruments to enable payments or other incentivisation;
3 MRV and auditing protocols to provide appropriately rigorous accounting for soil carbon sequestration claims, credits and incentive payments; and
4 Consultation on socio-economic and cultural barriers to adoption of new practices, provision for training and education on the synergies or antagonisms with existing farm operations, and co-benefits of increasing SOC stocks.

This list is not exhaustive but is intended to facilitate discussion on how frameworks can be designed to improve opportunities for soil carbon sequestration in managed lands (Fig. 2).

2.1 Evidence linking practices to soil carbon outcomes

The evolving focus of soil science research for multiple benefits is expanding the body of evidence on the pivotal role of SOM and SOC in ecosystem

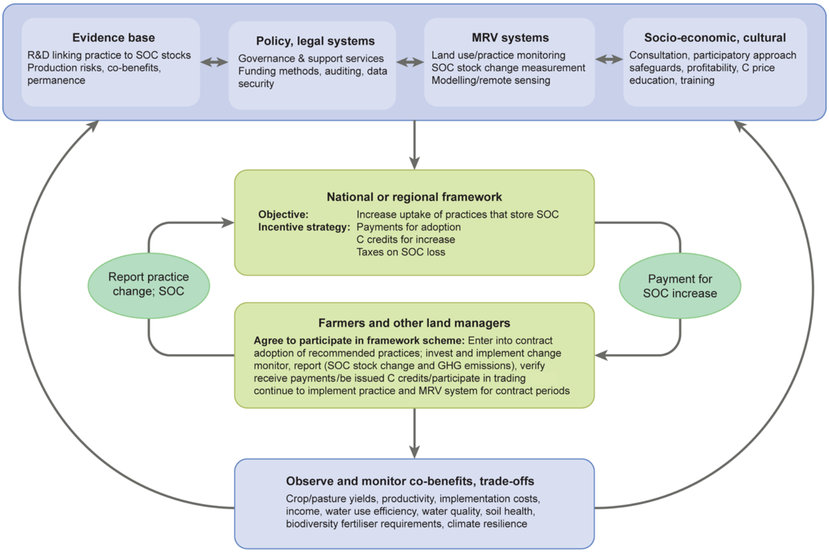

Figure 2 Schematic of a framework to foster adoption of management practices that increase sequestration of SOC in agricultural and other lands at the national or regional scale.

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processes and their potential role in the societal response to climate change and towards meeting the SDGs (Keesstra et al. 2016, 2018). In general, government programmes require sound scientific evidence in order to have the high level of integrity that is expected for public funding (Macintosh et al. 2019, Schneider and La Hoz Theuer 2019). Similarly, private investment in markets for carbon offsets requires confidence that the activities and practices being implemented will result in genuine climate abatement.

An incentivisation framework based on sound evidence for recommended practices will help manage the risk to participants in terms of non-achievement of SOC increase and a resultant loss of the confidence needed to continue implementing the practice, but it cannot eliminate the uncertainty entirely. Importantly, the range of prospective practices identified in experimental trials (Sanderman and Baldock 2010, Dalal et al. 2021b) cannot be assumed to apply uniformly, due to the heterogeneity in natural and human systems across global or national climatic, geographical, socio-economic and cultural landscapes (Johnston et al. 2009, Rumpel et al. 2020). In addition, there remain gaps in data and process understanding of how current and future climate, land use, management and edaphic factors will interact to influence the stocks and stability of SOC (Stockmann et al. 2013, Sun et al. 2020). Hence, systems and procedures are needed within the framework design to manage the risks in changing management practices, including the uncertainties around achieving soil carbon storage that is above the business-as-usual baseline, and the relationships with agricultural or forestry yields. An approach that incorporates flexibility in enabling instruments to allow incorporation of improved data, nascent knowledge and/or emerging technologies is recommended due to evolving knowledge and data (Arrouays et al. 2014, de Gruijter et al. 2018).

Chenu et al. (2019) discussed the potential to increase carbon stocks in agricultural soils and the prospective practices shown to influence organic matter dynamics, such as conservation agriculture (including no-tillage), deep-rooting crops, organic manures, irrigation (where available) and balanced fertilisation. They highlighted the existence of knowledge gaps and summarised key research questions relevant to the design of a framework to equip farmers with the confidence and accounting capacity needed for investment in fostering good practices for SOC increase:

- What practices can increase soil carbon stocks, what is the rate of increase and for how long would the rate of increase continue?
- Where should soil carbon stock increase be prioritised?
- How should potential gain in carbon be estimated?

There is now an improved understanding of the biophysical processes that follow implementation of practices such as conversion to reduced tillage, increasing irrigation, applying chemical fertiliser or organic amendments (including biochar), and rotational grazing (Paustian et al. 2019, Dalal et al. 2021b). Access to local data to inform farm management decisions is also expanding, and these improvements flow through to refinement of farm-scale simulations of SOC sequestration for crediting schemes. Process models now allow for predictions of longer-term outcomes under rising atmospheric carbon dioxide levels and climate changes such as warming soils and more severe droughts (Dalal et al. 2021a), but further research is needed to resolve outstanding questions (Amundson et al. 2015, Dalal et al. 2021a). The areas of active research include the role of microorganisms in stabilising organic matter applied to soil and the risk of 'leakage.' Organic amendments *per se* add carbon that was produced elsewhere; but its constituent nutrients such as nitrogen (N) and phosphorus (P) may contribute to enhanced carbon sequestration via increased biomass production as well as via a C:N:P stoichiometry approach (Chenu et al. 2019). These complex dynamics present accounting challenges (e.g. Australian Government 2018), as also do uncertainties in the extent of change in SOC storage in deeper soil layers (Murphy et al. 2019). Some differences in reported outcomes for management implementation likely reflect the lack of consistent definitions of practices and the absence of standardised measurement and verification protocols at the spatial and temporal scales required for quantifying change.

The most valuable insights come from long-term experimental trials, but they are costly to maintain and monitor (see Box 1). Globally, there are few continuous multi-decadal trials, and most are in temperate agricultural regions (Poulton et al. 2018, Powlson et al. 1998). For other regions, many of the assumptions on the dynamics of SOC have necessarily been derived from local short-term experiments. The risk of extrapolating rates of sequestration from short-term monitoring and across climatic zones can be illustrated by data from studies over different durations in eastern Australia. A five-year pilot study in the central-west region of New South Wales examining the potential for farmers to earn carbon credits from implementation of new practices, measured rates of increase in SOC as high as 1.2 Mg C ha^{-1} $year^{-1}$ in carbon-depleted land converted from cropping to permanent pasture (Badgery et al. 2020). In contrast, three longer-term trials (13–25 years) in permanent pastures near Wagga Wagga, a somewhat more arid area of New South Wales, also with low initial SOC concentrations, suggested that improved soil nutrient and grazing management may increase sequestration by only 0.5–0.7 Mg C ha^{-1} $year^{-1}$ (Chan et al. 2011). Such comparisons suggest that caution is needed in assuming that the initially high rates of SOC storage following management change can be maintained. While this may be due to sequestration slowing as a new equilibrium SOC level is approached, the results also point to the risk of extrapolation to other locations or practices.

The evidence base required to establish soil carbon sequestration frameworks should also extend beyond the site-specific soil biophysical processes to socio-economic impacts (Poulton et al. 2018; see Section 2.4) and systemic consequences, including for greenhouse gas emissions associated with practice changes such as irrigation (Kong et al. 2009, Trost et al. 2013), fertilisation (Rumpel et al. 2020, Van Groenigen et al. 2017) or livestock management (Chang et al. 2021, Harrison et al. 2021). Soil carbon sequestration activities that involve changes in land use or management, such as shifting from intensive crop production to reduced cropping intensity and pasture or 'set-aside' transitions can have wider land-use consequences (Gil et al. 2018). Further, the framework development phase should seek to understand any limitations to landholder participation due to legal (e.g. land rights) and policy issues.

2.2 Policy and governance requirements

2.2.1 The policy context for incentive frameworks

A primary objective of SOC sequestration policy frameworks and programmes is to incentivise increases in SOC stocks above the business-as-usual baseline while ensuring an improvement in the net greenhouse gas balance. Consideration is generally given to the global context by seeking consistency with international climate change agreements as well as domestic policy priorities. The United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol established a system of national communications and greenhouse gas inventory reporting, to be compiled by parties and published by the UNFCCC. Under the 2015 Paris Agreement, 194 countries and the European Union (UNFCCC 2021) have signed up to taking action to limit global warming to less than 2°C, and preferably no more than 1.5°C, and to report progress against a Nationally Determined Contribution (NDC). For countries (120 at the time or writing) who have committed to achieving net-zero emissions before the second half of this century, carbon sequestration in vegetation and soil is needed to offset 'hard-to-abate' emissions. This effectively embeds frameworks to encourage SOC storage in policy and carbon market contexts (Table 1). At the global scale, the multi-stakeholder '4 per 1000' initiative (https://www.4p1000.org/) which was launched at UNFCCC COP21 in 2015 seeks to galvanise action to improve soil carbon storage and soil health as set out in the *Soils for Food Security and Climate* vision (Rumpel et al. 2020).

The effectiveness of these policies, programmes and initiatives to foster adoption of practices that increase SOC storage will help to determine how much of the biophysical potential sequestration will be achieved in practice (Sanderman et al. 2017).

Table 1 Examples of policies and programmes which credit soil organic carbon offsets

Policy or Programme	Credit name	Scope	Reference
Australian Emissions Reduction Fund (ERF)	Australian Carbon Credit Unit (ACCU)	Australia	Macintosh et al. (2019)
Alberta Emissions Offset Program (AEOP)	Alberta Emissions Offset Credit (AEOC)	Alberta, Canada	Goddard (2008)
The Gold Standard	Verified Emissions Reduction (VER)	International (non-government)	Gold Standard (2020)
Verified Carbon Standard	Verified Carbon Unit (VCU)	International (non-government)	Verra (2012)

2.2.2 Insights from existing frameworks and programmes

Frameworks or programmes that incentivise SOC sequestration through carbon credit mechanisms commonly include functions for: (i) developing and approving/legislating methods or standards to quantify credits; (ii) reviewing, registering and auditing projects against the method or standard requirements; and (iii) issuing, transferring and operating a registry of offset credits (Broekhoff et al. 2019). It is crucial that policy frameworks aiming to incentivise new practices for credible increases in soil carbon consider:

- *permanence* (considered to be ≥ 100 years) of the SOC sequestration, including the risk of reversal through changes in land management or natural events such as drought;
- *additionality* beyond business-as-usual management and baseline SOC stocks when credits are to be counted as offsets;
- *leakage* risk, that is, whether eligible SOC practices lead to increased emissions elsewhere; and
- *accuracy and uncertainty* in the SOC stock change, allowing for assessment of bias or errors, data limitations, modelling assumptions or projected future values.

The design of effective frameworks also requires appropriate consideration of the risks and complexities for landholders and jurisdictions associated with practice change. Risks to jurisdictions depend on context-specific factors including priorities and budgets (COWI 2021, Peng et al. 2021), and the nature of individual and industry behavioural resistance to existing options available for soil carbon management (Alexander et al. 2015). Experience shows that diverse economic, social, cultural and psychological barriers will need to be overcome for uptake of practices to increase carbon storage – whether primarily for climate mitigation or to rehabilitate degraded, SOM-depleted lands (Alexander et al. 2015, Amundson et al. 2015, Lal et al. 2003, Lal 2015a, Rumpel et al. 2018). For example, policy design must consider whether change in land management to increase sequestration could potentially have social and environmental consequences such as reduced community access to productive agricultural land for food and fibre crops or could encroach on land valued for natural ecosystems and conservation reserves. The design challenge is exacerbated because research undertaken to inform policy frameworks may identify these issues poorly, if at all, in projections focussed on mitigation potential (Dooley et al. 2018). Nevertheless, these authors suggest that cross-disciplinary consultation and research can lead to a better understanding of the links between land use and climate change mitigation and support analysis of multiple objectives and interests to clarify how limited land resources can optimally be managed.

A significant design question for SOC frameworks is how to provide incentives which ensure that the adoption of new practices results in a long-term commitment to achieving genuine and sustained increases in SOC storage and minimises the risks of reversal of gains. This is only possible if the framework includes provisions for measurement and verification of changes in SOC stocks. Key technical considerations in the development of an MRV strategy include: (i) the purpose of measurement and level of confidence required; (ii) how to balance trade-offs between accuracy and measurement costs; and (iii) the extent to which the intensity and frequency of measurement and reporting may act as a barrier to voluntary participation. There is an expanding number of carbon-offset programmes (Table 1), each having its own rules for crediting and level of quality assurance, and this provides a sometimes confusing array of complex information that land managers need to weigh up before committing to practice change. The situation is exacerbated for frameworks or schemes that seek to create credits with value across jurisdictions or markets. From a policy perspective, more rigorous MRV systems will be required for recognition of offset credits as fungible commodities certified as representing a reduction of one metric tonne of carbon dioxide-equivalent emissions (t CO_2-e) (Schneider et al. 2019). The requirements and challenges for farm- or field-scale MRV to quantify SOC stock change are discussed in more detail below.

2.2.3 Common policy features in soil carbon sequestration programmes

The structure of frameworks varies between international, centralised schemes such as the Clean Development Mechanism (CDM), schemes that are private and independent (including some that issue credits that can be used in public or private compliance or market mechanisms) and domestic programmes with responsibilities to government. Here, a short overview is provided of the policy elements common to most programmes.

Governance, administration and strategic direction: A framework requires some form of governing body and administrative support, whose responsibilities could include developing the rules or methods and guidelines and approving, registering and overseeing implementation of projects and credit issuance. Some of these roles could be delegated, for example, in the not-for-profit organisation Verra, which is guided by a board of directors while private advisory committees develop standards and methodologies (Verra 2012). In all cases, a formal process is needed to establish eligibility of activities and projects and to maintain an account and registry of projects and credits to aid credibility.

Integrity: A process is needed to explicitly ensure that the GHG abatement (increased SOC sequestration less any associated emissions) is genuine and additional to what would occur under business-as-usual management practices, that is, in the absence of the incentive offered by the programme. Concepts related to ensuring environmental integrity include baseline setting, additionality, permanence of abatement/sequestration, avoidance of double counting and not causing other environmental harm such as negative impacts on biodiversity or loss of agricultural productivity leading to food insecurity.

MRV systems, tools and protocols: To ensure that policies support transparency and accountability in the issuance of carbon credits, offsets must be quantified in a way that is conservative and verifiable. The aim is to provide confidence that each offset corresponds to a real increase in SOC sequestration for the nominated 'permanence' period and represents a fungible unit (t CO_2-e) for offset markets. However, balancing cost-effective practical monitoring and reporting at farm scale with accuracy is challenging, as discussed below.

Stakeholder engagement: Actively engaging stakeholders (including farmers and advisers) in the scheme design process and regularly consulting during implementation can be effective in increasing uptake and commitment. Economic incentives are an important attractor for farmers but consulting on simplifying design or minimising initial baseline measurement costs have also been shown to influence participation (Macintosh et al. 2019). Integrating training and advisory opportunities into the scheme from the outset facilitates farmer learning and encourages adoption, especially if combined with raising awareness of the co-benefits of SOC sequestration for the farming business and as a societal approach to climate change mitigation.

Carbon pricing instruments and market mechanisms: Carbon market instruments may be voluntary or legislative. Policy issues for national

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frameworks to foster soil carbon sequestration extend across scales from transnational (e.g. market distortions) to farmer behaviour (Sampson and Sedjo 1997). Further, the policy design may include the capacity to generate demand for credits through linkage with other pricing or market instruments. Industries are increasingly adopting action on climate change as part of business risk management, which is creating a demand for eligible offset credits (e.g. TFCD 2021). Emissions trading systems, at the national or regional scale, are enabling trade in emission permits and offset credits issued for SOC sequestration. Alternatively, jurisdictions may link their policy instruments to allow permits or credits to be traded across borders. The scope of trades may expand through the provision for international transfers to achieve country targets under Article 6 of the Paris Agreement (Müller and Michaelowa 2019, Schneider and La Hoz Theuer 2019).

Co-benefits and trade-offs: Recognising the co-benefits such as biodiversity enhancement, water retention capability and reduced soil erosion, through ecosystem services credits (Lal et al. 2015, DES 2020, Flores-Rios et al. 2020) enhances farmers' ability to see value in improving their management practices to increase carbon sequestration (COWI 2021). There may also be trade-offs which should be identified. However, in general, few holistic assessments account for both benefits and trade-offs between agricultural, environmental, economic and social dimensions in land-use policies. While model-based holistic assessments can be challenging to formulate and fraught with uncertainties (Bishop and Welsh 1992, Harrison et al. 2012a,b), they can provide some cross-discipline evaluation for informing decision-makers about potential trade-offs and co-benefits and inform assessment of the possible opportunity costs of achieving environmental goals. The economic estimates of the minimum value of carbon sequestration credits and other environmental goods can assist a policy framework to achieve a net gain in social welfare, and opportunities for payments for ecosystem services credits (Baumber et al. 2019, DES 2020) may provide additional incentives for practice change by farmers (Lal et al. 2015, Kragt et al. 2016). Across these elements, policy and governance requirements for frameworks must take into consideration the objectives and the geographical and temporal scope of the desired carbon stock increase, and include explicit measures for ensuring environmental integrity and long-term maintenance of management changes.

2.3 Measurement, reporting and verification (MRV) systems for frameworks to incentivise practice change

While measurements of the carbon or organic matter content of soils (percentage SOC or SOM) have informed agronomic decisions over many decades (Box 1, Paustian et al. 2019), recent imperatives for greenhouse-gas-reporting and project-scale-monitoring to enable crediting of soil carbon offsets necessitate more rigorous quantification of SOC stocks and stock change. Policy frameworks or market mechanisms specify appropriately accurate estimation at field or farm scale, which together with the reporting and verification requirements aim to ensure consistency, reliability and integrity. If implemented properly, the framework will issue high-quality SOC sequestration offsets that have credibility in market mechanisms, demonstrate genuine long-term removal of atmospheric CO_2 (Chenu et al. 2019), and ideally, be consistent with national targets and inventory reporting. To achieve this, an MRV system for offsets must also include protocols to account for CO_2, nitrous oxide (N_2O) and methane (CH_4) emissions arising from new land management activities.

2.3.1 Overview of MRV approaches for soil organic carbon sequestration

There are challenges in designing MRV systems that balance accuracy, cost and practicality in a way that enables accounting that is fit-for-purpose (Paustian et al. 2019). Recognizing that access to resources and capacity for MRV can limit participation in incentive schemes, some have rewarded the adoption of SOC sequestering practices by action-based payments calculated on the expected result, rather than on measures of ex-post changes in SOC, as required in a result-based scheme such as Australia's ERF (Baldock and Burgess 2017) or Canada's Alberta Offset System (Goddard 2008). A framework providing government grants or payments for SOC management that is based on overall conservation benefits and could include improving soil health, ecosystem function and farm productivity (Govaerts et al. 2009) would normally require less rigorous quantification and lower MRV costs. However, the European experience has shown that action-oriented schemes not only have higher uncertainty (Burton and Schwarz 2013) but can be less successful in building confidence in the value of good practice over the long term (COWI 2021).

Traditional in-field measurements using destructive sampling and laboratory analysis are still the most widely accepted methods to accurately quantify SOC sequestration, but high costs are a barrier to participation (Commonwealth of Australia 2020). Prospects for lower-cost alternative technologies for SOC quantification are being explored, but issues remain to be overcome to enable their routine use in SOC crediting schemes (Costa Jr et al. 2020, Paustian et al. 2019, Smith et al. 2020, Jackson Hammond et al. 2021). Promising approaches include spectroscopy (Australian Government 2018, Viscarra Rossel et al. 2016), flux measurements (FAO 2019, Mudge et al. 2020), indicator or proxy measures (Wiesmeier et al. 2019, Terrer et al. 2021) and modelling (Powlson et al. 1998, Smith et al. 1997). Modelling and hybrid methods that use a combination of direct measurement, modelling and remote sensing are being trialled as alternatives to direct measurement for practical quantification options with appropriate accuracy (Zhang et al. 2019, Jackson Hammond et al. 2021). Systems for SOC MRV are presented in detail elsewhere in this volume, while here we discuss issues for MRV relating specifically to national frameworks for fostering SOC-sequestering practices.

Quantifying SOC storage attributed to adoption of new management practices is challenging because it necessitates measuring a small percentage change in a much larger, dynamic pool (Batjes 2014) largely driven by climate and soil characteristics (Allen et al. 2013, Rabbi et al. 2015, Sun et al. 2020). As described by Paustian et al. (2019), targeting a potential annual stock change of 1% or less means that measurement intervals of 5 years or more are generally required to detect statistically significant cumulative SOC stock changes for a moderate sampling density. To encourage participation in frameworks, strategies may be needed to enable early payments before confidence in detected SOC stock change is established (Commonwealth of Australia 2020).

Table 2 summarises the main components of an MRV system relevant to carbon crediting frameworks and provides examples of how emerging measurement and modelling capabilities may, in future, be integrated into carbon-crediting frameworks.

While a key strategic need is for accessible, harmonised, globally reconciled SOC databases that include management history, improvements in MRV could be readily achieved at low cost with better integration of current sources of data and commitment to maintain and consistently monitor long-term and short-term field trials, investment in advancing modelling capability, analysis of uncertainty and bias in simulations, and evaluation of how to use the increasing spatially-explicit activity data and the higher resolution remote-sensing platforms now available (Angelopoulou et al. 2019). Together these would enable the development of more accurate spatial data for model inputs and validation data for land use and management. Smith et al. (2020) summarised the gaps and needs to achieve better SOC monitoring and MRV practice that would support frameworks to foster practice for SOC sequestration:

- the provision of long-term continuity and consistency of monitoring in MRV systems under changing conditions;
- scientifically and politically appropriate spatial and temporal resolution for measurements;
- quality assurance at all stages of measurement and monitoring;
- documentation and measurement of all potential drivers of change in SOC stocks and greenhouse gas emissions; and
- geo-referenced samples archived with associated (harmonised) data made accessible.

Table 2 Major components of MRV systems and their possible integration in an SOC incentivisation framework

Purpose	Component activity	Applications for SOC data (examples)
Measurement/ monitoring	Long-term field trials/ experiments	Impact of management/practices on yield; Soil health; SOM and SOC content
	Short-term experiments; On-farm soil tests	Process studies; Model calibration; Agronomic decisions
Measurement, Reporting	SOC/GHG models Calibration – short-, long-term data Validation – long-term data Verification – survey data, remote sensing	Deriving Tier 2 Emission Factors Tier 3 methodologies Process/predictive data for policy and planning
	Spatial data	Model inputs (e.g. climate, soils, land cover layers)
	Activity data	Management data at farm/paddock scale
Measurement, Verification	Spatial soil re-sampling survey Site/paddock re-sampling	Ground-truthing SOC change; activity data for models; ground-truthing remote sensing Project monitoring; SOC change/ verification
Measurement, Reporting, Verification (Current and Emerging)	Remote sensing Flux tower measurements Spectroscopy Process-based modelling Other new technologies	• Soils, vegetation data; Inputs to run or verify models • Verifying project activity; Non-destructive sampling • Higher-density, spatial sensor and satellite data layers

2.4 Economic, social and cultural considerations in incentivisation frameworks

Review of the literature indicates a greater focus on biophysical and technological aspects of frameworks to incentivise climate change mitigation actions by landholders than on economic aspects (Harrison et al. 2021), and still less evaluation of social and cultural barriers. This observation likely reflects the broader traditional pathway in which scientific research is conducted, from an initial focus on technological questions, followed by biophysical (productivity etc.), then economic, and lastly, social and cultural aspects (Alcock et al. 2015, Ho et al. 2014). However, it can be argued that the policies and design for frameworks intended to influence behavioural and management decisions by farmers over extended periods, such as for adoption of SOC sequestering practices, would benefit from more, and earlier, economic and social science research (Sykes et al. 2020).

2.4.1 Economic considerations

Proponents of frameworks to foster SOC increase argue that positive incentives to change land management can result in substantial carbon sequestration in agricultural soils at lower cost than many alternative abatement activities (Kragt et al. 2012). However, considerable differences currently exist between economic viability at the farm level and financial support in national programmes and policies (Sampson and Sedjo 1997). The economic potential of agricultural carbon storage activities is likely to be lower than the technical potential (Bangsund and Leistritz 2008, Sanderman et al. 2017).

Landholders are more likely to adopt carbon sequestration practices if they see a clear financial advantage (Morgan et al. 2015), but the economic benefit of participating in a soil carbon sequestration payment framework depends on site-specific opportunity costs of changing production practices, the price of each tonne of carbon stored (as t CO_2-e) and rates of sequestration and hence the carbon credits issued over time. For example, changing rotations in a crop–livestock farm in the Western Australian wheat belt to increase SOC stocks could mean foregoing more than A$80 in profit for every additional t CO_2-e stored, depending on the crop residue retention practices adopted (Kragt et al. 2012), a value three- to four-fold the average carbon price under Australia's ERF scheme (at the time of writing in mid-2021, one Australian dollar (A$1) was equivalent to approximately US$0.75). Economic incentives to encourage landholder adoption of SOC sequestration practices may take the form of payments or subsidies for increases in SOC stocks or penalties, such as taxes for SOC losses. A study of land use in France sought to compare the cost-effectiveness of approaches based on either payments to compensate for costs of implementing better practice, or taxes (Bamière et al. 2021). The study, which examined three SOC sequestration measures – no-till, extension of temporary grasslands and hedgerows – found a disparity between net SOC sequestration and costs of implementation. Hedgerows and extended pasture phases in mixed crop/pasture systems resulted in sequestration of, respectively, 14.5 and 1.6 Mt CO_2-e, but very different average costs of €75/t CO_2-e sequestered for the hedgerow option but – €259/t CO_2-e in the case of extended pasture phases. Bamière et al. (2021) found that increasing the carbon price from €50 to €100 per t CO_2-e shifted the viability of actions and the dominance of farming enterprise participation. At the higher carbon price, the area of fallow land entering the scheme increased at the expense of the least-cost carbon storage option of temporary grasslands. In a similar large-area land-use study, Nelson et al. (2008) examined trade-offs in land-use policies in the Willamette Basin (Oregon, USA) under three levels of economic stimulus using efficiency frontiers. In all cases, increasing payment amounts to private landholders to restore natural land cover simultaneously increased ecosystems services, biodiversity conservation and carbon sequestration (Nelson et al. 2008).

From a landholder perspective, the costs of participation and income from carbon are often the key determinants of entry into voluntary SOC sequestration schemes. Burton and Schwarz (2013) contend that result-oriented schemes with payments based on validated changes in measured SOC are likely to be more cost-effective than action-oriented schemes (payment for adopting sequestration practices), and that using competitive reverse-auction-based pricing further established cost-effectiveness in incentivisation payments. Directly linking payments to outcomes and offering contracts for bids that deliver higher sequestration benefits at lower cost have been identified as effective design options for incentivisation frameworks in other analyses (e.g. Latacz-Lohmann and Schilizzi 2007, Claassen et al. 2008, Matzdorf and Lorenz 2010). This approach has been adopted in the Australian ERF policy framework (Commonwealth of Australia 2020, Macintosh et al. 2019) and is under active consideration for the EU (COWI 2021) at the time of writing.

2.4.2 Socio-cultural considerations

Social and cultural factors are the least explored areas with respect to frameworks to foster adoption of practices for SOC sequestration, but available studies indicate the relevant factors that include:

1. *Knowledge and trust:* Many farmers maintain conservative value systems, place importance on personal independence and have high regard for autonomy (as opposed to egalitarian views of authority and shared decision-making). Amundson and Biardeau (2018) suggest that farmers, even those practising innovative methods, may be wary of information from non-farming experts and a perceived government intervention through environmental schemes. They propose that farm advisors, who are local community members with relevant practical experience, may help lower cultural barriers to adoption, indicating that understanding people and how to motivate practice change is likely to be more important in terms of fostering farmer uptake than soil expertise.
2. *Human and social capital:* In his landmark work on the diffusion of innovations, Rogers (2004) proposed that every innovation relies on

human and social capital for adoption, depending on the innovation (here, national frameworks to foster uptake of SOC sequestering practices), communication channels, time and the social system and, further, that every innovation has some degree of status conferral. The provision of environmental capital through increased SOC stocks can be used to better establish social relationships that are beneficial over the long term (Bourdieu 1986, Burton and Schwarz 2013).

3 *Cultural assets and values of Indigenous peoples:* Important considerations in some regions are: (i) the need to obtain free and prior consent before developing a 'carbon farming' project; (ii) whether local Indigenous people have control over benefit-sharing; and (iii) whether traditional land owners will have increased quality of life as a result of projects (Robinson et al. 2016). It is plausible that carbon credit trading may present risks in commoditising indigenous cultural practices and landscapes (Gerrard 2008) and, therefore, the design of national frameworks for fostering SOC sequestration needs to define institutional and regulatory mechanisms to ensure appropriate incentives that respect indigenous values and achieve agreed, sustainable outcomes (Heckbert et al. 2008).

4 *Long-term behavioural change:* To be successful, any policy framework should foster not only shorter-term adoption of good practice for SOC increase but also beneficial long-term behavioural change (Matzdorf and Lorenz 2010). The design challenge is how to predict the level of [financial] incentive sufficient to elicit a desired behavioural change, in addition to what would occur in the ordinary course of events, due, for instance, to yield increase, but not so high as to attract a level of participation that is either not affordable under the scheme or, in a carbon market system, results in supply that exceeds demand, causing a drop in prices of carbon credits (Sampson and Sedjo 1997).

5 *Social and societal benefits of fostering SOC sequestration practices*: While landholders bear much of the direct costs of increasing SOC stocks, the associated ecosystem services are largely public goods (Brady et al. 2019), through contributions to water quality and climate regulation and providing resilience to future disturbances. There is a risk of trade-offs between private benefits, for example, higher yields, and wider societal benefits such as biodiversity and aesthetic services. A Swedish case study showed that the perceived value of conserving SOC stocks in agricultural land diverged between farmers and society in their decision-making, indicating that optimal conservation of soil natural capital from a societal perspective would benefit from innovative information systems and governance institutions as well as market mechanisms (Brady et al. 2019).

2.4.3 Multi-dimensional aspects in framework design

Incentives to foster SOC sequestration currently operating through government-sponsored frameworks and private market mechanisms usually focus on carbon stock change metrics aligned with IPCC accounting (Section 2.2). They may incorporate premium pricing for associated ecosystem services or social/economic credits (DES 2020, Verra 2012), and there is growing interest in considering more holistic approaches and interdisciplinary metrics in frameworks supporting sequestration (Chang-Fung-Martel et al. 2017, Rawnsley et al. 2016). Appropriately contextualised socio-economic and environmental 'bundling' of incentives for SOC-positive practices in policy frameworks may enhance their adoption. However, uptake may not increase if farmers and other stakeholders do not understand how multiple policy instruments that are operating concurrently can interact to affect their interests (Börner et al. 2017).

3 An Australian case study

This case study examines the theory and practice of a policy framework for government and industry action and provides an example of the design of a national approach to incentivising voluntary adoption of practice to increase soil carbon in agricultural lands. The historical context for the framework is provided in Box 2.

Box 2 Developing a framework to foster increase in SOC in agricultural land: Historical context 2000–2020

Climate change policy in Australia has been highly contested from a political perspective over the last two decades. There has been a litany of start, stop, revise, re-name and re-start of different policies, including a broad-based emissions trading system, a carbon tax, a direct-action program, a national energy guarantee (NEG) and many variations on these themes. Beneath the surface, however, there has been a broadly consistent program and policy development of national carbon accounts and emissions registers, and policy interventions to reduce the emissions intensity of different industry sectors and to incentivise carbon sequestration where possible. This consistent effort has been supported by technical capacity in policy departments and science agencies as well as a well-informed 'community of practice' in industry, particularly for agriculture and land management, and in the broader population.

Industry interest in carbon offsets was growing rapidly in the late 2000s and various voluntary carbon offset schemes were emerging internationally (e.g. Gold Standard https://www.goldstandard.org/; Verra https://verra.org/). There was also angst in land-based industries over the potential for emissions trading or carbon tax schemes to threaten industry viability in circumstances where the industry had few options for abatement action (e.g. technical options for CH_4 emissions reduction in the livestock sector seemed few and far between at that time). At the same time, some suggested government incentivisation was needed to encourage carbon sequestration in trees and soils. The term 'bio-sequestration' gained currency to the extent that the Department of Prime Minister and Cabinet (PMC) established an Inter-Departmental Committee (IDC) in 2009 to explore associated policy options.

3.1 Policy settings for Australian sequestration projects

The main policy and implementation elements underpinning Australia's carbon offset scheme are summarised below, followed by an overview of the ERF scheme legislated to incentivise actions to reduce GHG emissions or increase carbon sequestration across all sectors of the economy. The following sections explain how the ERF operates to incentivise adoption of soil carbon sequestering practices by landholders and highlights some of the lessons learnt in the six years that it has been in place.

3.1.1 Overview of policy, governance and implementation elements

3.1.1.1 National Greenhouse Accounts

The National Greenhouse Accounts are a series of databases and comprehensive reports (National Inventory Reports, NIR) that estimate and account for Australia's GHG emissions. The annual NIRs, which have fulfilled reporting requirements under the UNFCCC, its Kyoto Protocol and the Paris Agreement, are supported by a national spatial land sector program that in 1998 established a national carbon accounting system (NCAS) for land sector GHG emissions and carbon sequestration. The accounting system set up modelling tools and datasets centred on the Full Carbon Accounting Model (FullCAM), in which SOC is simulated in agricultural (including grazed native vegetation) and forest lands across Australia's total 769 million hectare land area through a sub-model based on the Roth C model (Jenkinson 1990).

3.1.1.2 NGER – National Greenhouse and Energy Reporting

The NGER scheme was established in 2007 as a national framework for reporting and disseminating company information, including GHG emissions, energy production and energy consumption.

3.1.1.3 CFI – Carbon Farming Initiative

The CFI was established through the *Carbon Credits (Carbon Farming Initiative) Act 2011* as a legislated project-based, baseline-and-credit offset scheme. Registered offset projects could generate certified offsets, Australian Carbon Credit Units (ACCUs), from land use, land-use change and forestry (LULUCF), agriculture and waste sectors. The CFI Act and its amendments are administered by the responsible Minister and Department.

3.1.1.4 CER – Clean Energy Regulator

The Clean Energy Regulator (CER) is an independent statutory authority that, since 2007, has administered schemes legislated by the Australian Government for measuring, managing, reducing or offsetting Australia's carbon emissions, including NGER, ERF and the Australian National Registry of Emissions Units which supports the CFI Act.

3.1.1.5 Climate Active

In 2019, Climate Active was formed as an update of the National Carbon Offsets Standard, which came into effect in 2010 to support the voluntary carbon offset market. This industry partnership, supported by government, aims to drive voluntary action towards carbon neutrality, based on the Climate Active Carbon Neutral Standard.

3.1.1.6 ERF – The Emissions Reduction Fund

The ERF was legislated in 2014 through the CFI Amendment Act to the *Carbon Credits (Carbon Farming Initiative) Act 2011*, to enable the CFI to extend voluntary abatement arrangements to all sectors of the economy (Box 3). The ERF was allocated A$2.55 billion in 2014 to purchase emissions reductions and extended by an additional A$2 billion in 2019 through the Climate Solutions Fund (CSF) to support international GHG emissions reduction targets.

3.1.1.7 ERAC – Emissions Reduction Assurance Committee

The 2011 *Carbon Farming Initiative (CFI Act)* established an independent expert committee to oversee the integrity of emissions abatement methodologies credited under the Act. Initially called the Domestic Offsets Integrity Committee (DOIC), and, after legislation of the ERF in 2014, the Emissions Reduction Assurance Committee (ERAC), this Committee assesses whether draft methods comply with the set of legislated offsets integrity standards (OIS; Box 4), designed to ensure that only genuine, additional abatement and sequestration is credited. Only if determined by ERAC as meeting all OIS can a drafted ERF method be made into legislation.

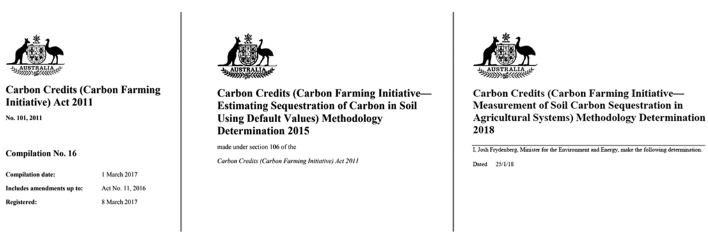
3.1.2 How the Emissions Reduction Fund (ERF) incentivises abatement

The ERF is a carbon crediting and pricing mechanism aimed at providing incentives for organisations and individuals to adopt new practices and technologies that reduce their emissions and/or increase sequestration (Fig. 4). Participation is voluntary. ERF methods set out the rules to enable projects to register under the scheme and to be issued with ACCUs. The ACCUs may be sold either through government reverse auctions or in private secondary markets as certified high-quality carbon offsets, providing income for participants. Activities that are eligible under ERF methods may provide public good through environmental, economic and social services as well as private good, for example through increased farm and forestry productivity, and social and financial benefits for Indigenous communities, and may attract additional value through other schemes (e.g. DES 2020). The ERF crediting, purchasing and compliance roles are summarised in Box 3.

Box 3 Summary: Emissions Reduction Fund (ERF) policy context

The Carbon Farming Initiative (CFI) Act 2011 was established to supply offsets to Australia's carbon pricing mechanism (Fig. 3).

In 2014, the CFI transitioned to the ERF through amendment to the Act, covering all sectors of the economy.



AUSTRALIA

Carbon Credits (Carbon Farming Initiative) Act 2011

No. 101, 2011

Compilation No. 16

Compilation date: 1 March 2017

Includes amendments up to: Act No. 11, 2016

Registered: 8 March 2017

AUSTRALIA

Carbon Credits (Carbon Farming Initiative—Estimating Sequestration of Carbon in Soil Using Default Values) Methodology Determination 2015

made under section 106 of the

Carbon Credits (Carbon Farming Initiative) Act 2011

AUSTRALIA

Carbon Credits (Carbon Farming Initiative—Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination 2018

I, Josh Frydenberg, Minister for the Environment and Energy, make the following determination.

Dated 25/1/18

Figure 3 ERF legislative instruments directly relevant to soil carbon sequestration projects are (left to right) the CFI Act 2011, the 2015 model-based soil carbon method and the 2018 measurement-based method for soil carbon sequestration in agricultural lands.

The three components of the ERF are:

- A *crediting scheme* for eligible offset projects, with one ACCU earned for each t CO_2-e abatement.
- A *purchasing scheme* enabling purchase of ACCUs through periodic reverse auctions from project owners who have voluntarily entered into a carbon abatement contract with the government.
- A *safeguard mechanism* that places legal emission obligations on major emitters (facilities emitting >100 000 t CO_2-e per year), which can be met through relinquishment of ACCUs (potentially supporting a market demand).

ERF methods set out the eligibility, legal and procedural requirements for activities and projects to be issued with credits. Two soil carbon sequestration methods are available at the time of writing (Fig. 3)

By March 2021, about 205 million tons of abatement had been contracted under the ERF over a total of 962 projects registered under the ERF, with about 80% from agriculture- and forestry- related activities.

Governance responsibilities for the ERF scheme are shared by the Minister, the relevant government department, the CER and the ERAC. The Minister is responsible for developing new methods, varying and revoking existing methods and, with consideration of Departmental advice, determining method-development priorities. The CER is responsible for developing new methods and method variations and administering the scheme, including registering and crediting projects, conducting auctions, managing the Safeguard Mechanism and providing the Secretariat role for the ERAC. An independent body, the Climate Change Authority (CCA), which was set up to provide expert advice on climate change policy, undertakes a review of the ERF at three-year intervals.

3.1.3 Integrity and practicality in the ERF

The set of integrity standards (the OIS) has remained at the core of the CFI legislation and its derivatives, which have broadened its scope, since inception in 2011 to the present day. These standards sit behind and guide the development of the approved methods and the governance structure that seeks to ensure practical arrangements to encourage participation. In this way, the ERF aims to provide opportunities for uptake of methods and income from credits that have high credibility in primary and secondary market mechanisms.

The OIS, legislated in Section 133 of the CFI Act, are intended to provide confidence that the offsets credited are: (i) additional; (ii) measurable and verifiable; (iii) able to provide abatement eligible to be counted towards

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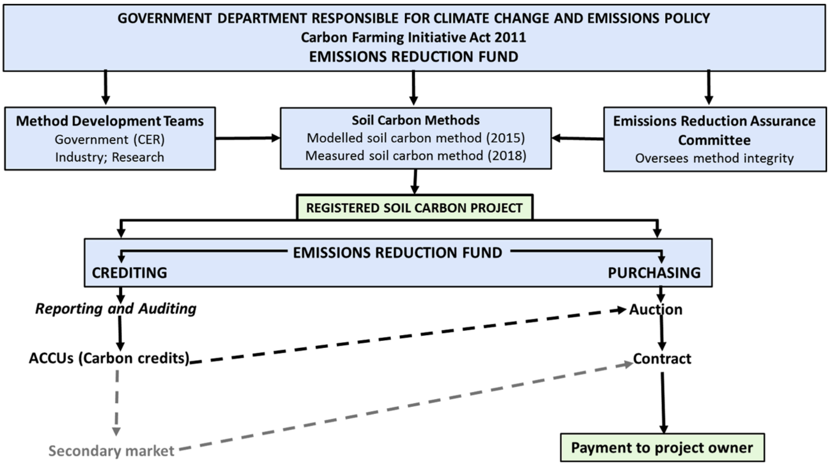

Figure 4 Schematic illustrating the steps for implementing an agricultural soil carbon project in Australia's ERF framework (Based on: http://www.cleanenergyregulator.gov.au/ERF).

Australia's international emissions reduction obligations; (iv) evidence based; (v) deducted for GHG emissions that result from project activities; and (vi) conservative. In interpreting the OIS to assess compliance of new and varied methods, the ERAC seeks consistency in its approach but considers requirements in individual methods against each standard (Box 4, ERAC 2021). The ERAC is also required to adopt an interpretation of the OIS that would best achieve the objects of the CFI Act:

- to remove GHGs from the atmosphere and avoid emissions of GHGs, in order to meet Australia's international mitigation obligations;
- to create incentives for people to undertake offsets projects; and
- to increase carbon abatement in a manner that is consistent with the protection of the natural environment and improves resilience to the effects of climate change; and to authorise the purchase by the government of units that represent carbon abatement.

Box 4 How the ERAC interprets the Offset Integrity Standards

The ERAC seeks to interpret the integrity standards to ensure projects registered under the scheme are issued with credits only for emissions reduction or sequestration that is real, additional and able to be measured accurately. A method must be assessed as complying with all six standards to be approved (ERAC 2021).

1. ***Additionality*****:** *A method should result in carbon abatement that is unlikely to occur in the ordinary course of events (disregarding the effect of the Act).*
   - At the method level, the general approach is to apply two tests for additionality:
     - Project test – Would the method activities occur without the incentive provided by the scheme?
     - Baseline test – What net emissions would be likely if the activities were not undertaken?
   - Three project-level additionality requirements set out in the Act must also be satisfied (Newness, regulatory additionality, and possible funding under another government program or grant).
2. ***Measurable and verifiable*****:** *Where a method results in emissions removal, reduction in emissions or emissions of greenhouse gases these should be measurable and capable of being verified.*
   - The method must provide a rigorous and reliable way to measure or estimate and verify removals, emissions reductions and project emissions. Each method specifies how verification is achieved, e.g. by audits, models, satellite imagery. Interaction with other OIS, particularly 'evidence-based' and 'conservative' is considered.
3. ***Eligible carbon abatement:*** *A method should provide abatement that is able to be used to meet Australia's international mitigation obligations.*
   - Interpretation of this standard requires the abatement to be from sources and sinks that are accounted for to meet Australia's mitigation targets under international commitments, notably the Paris Agreement.
4. ***Evidence-based:*** *A method should be supported by clear and convincing evidence.*
   - This standard is interpreted as requiring clear and convincing evidence on the impact of a method activity on emissions or sequestration, their measurement and verification, and for the approach to ensure no leakage.
5. ***Project emissions:*** *Material greenhouse gas emissions directly resulting from a project should be deducted.*
   - The project emissions standard requires methods to include appropriate deductions for all material project emissions, and their estimation to be consistent with the measurable and verifiable standard and evidence-based standard. Estimates of material project emissions (those that cumulatively exceed 5% of net project abatement) also must result in estimated net abatement being conservative.
6. ***Conservative:*** *Where a method involves an estimate, projection or assumption, it should be conservative.*

- Estimates, projections and assumptions that influence the calculation of net abatement for eligible projects are required to be conservative, that is, unlikely to be an over-estimation. However, requiring every estimate, projection and assumption to have a high probability of being an under-estimate, would be highly conservative and would be a disincentive for uptake of projects.
- In applying the conservative standard, the Committee also generally considers:
  - the potential for direct and indirect leakage to arise as a consequence of project activities;
  - the risk of non-permanence for sequestration projects and whether the permanence period discount is sufficiently conservative.

3.2 Performance of the Australian Emissions Reduction Fund (ERF) scheme

3.2.1 ERF status and soil carbon projects

The following section reflects publicly available data as at April 2021, noting that ERF project and ACCU issuance data should be interpreted in the context of the scheme and method procedures and are subject to updating by government.

As at April 2021, there were 966 projects registered under the CFI Act (2011) including initial CFI projects and ERF projects (CER 2021a). Contracts were in place to deliver 205 billion t CO_2-e abatement with 92.7 million issued by the CER up to April 2021. Of the 966 registered projects, more than half (532) use vegetation and savannah ERF methods, that is, they relate to the LULUCF sector of the national greenhouse accounts. Of the remainder, 155 projects use agriculture methods, the majority for avoidance of emissions relating to livestock manure management and ruminant enteric fermentation. There has been a rapidly growing interest in project registrations to increase carbon sequestration in soil, with more than 80% of all agriculture sector projects using methods for soil carbon sequestration at April 2021.

Under the ERF, there are (as at mid-2021) two methods under which farmers can be issued with carbon credits for adopting new practices that increase soil carbon sequestration:

1 A model-based soil carbon method (2015) for grazing land soils – land managers who adopt one of three eligible activities can earn carbon credits using regionally specified model-based default values that

give conservative estimates of sequestration. This method has had no uptake.

2 A measurement method for soil carbon sequestration in agricultural systems (2018) developed to improve the 2014 measurement method. As at March 2021, there were approximately 130 projects registered under measurement methods.

The number of soil carbon ACCUs delivered up to mid-2021 is low – approximately 1900. This reflects the expected delay between a project start and first measurement and reporting of SOC stock change which, under the ERF method, is permitted to be up to five years. It may also be a function of the complexity of the method and expense of sampling and analysis. Early experience has led to discussions on modifications and additional incentives to reduce costs and improve usability, including forward payments for baseline soil carbon measurements. Nevertheless, registration of new projects has accelerated in 2020 and 2021 (Fig. 5), and stakeholder interest in participating in soil carbon sequestration projects is high. Development of a new method with reduced measurement costs and improved flexibility is a departmental priority for release in 2021.

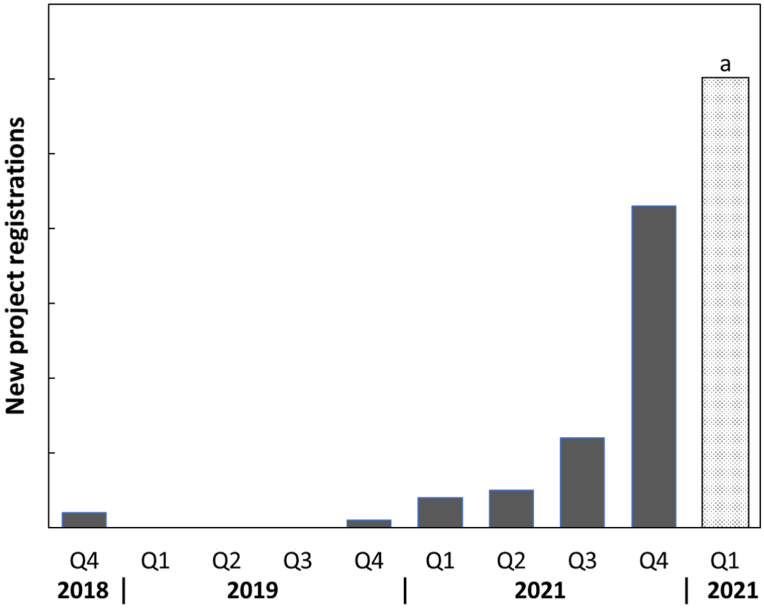

Figure 5 New registrations of ERF soil carbon sequestration projects in agricultural systems. Data for 2018 to 2020 from CER (2021b); a – Quarter 1, 2021 estimated from registrations http://www.cleanenergyregulator.gov.au/ERF; Accessed May 2021).

3.2.3 Practical issues limiting uptake of sequestration projects

The experience gained through implementation of the Australian ERF policy as an incentive framework for abatement actions highlights some of the practical issues for SOC practice adoption by land managers. It demonstrated the challenges in balancing the costs and rigorous integrity and MRV accuracy under the scheme, and also farmers' difficulty in understanding and applying technically complex methods and schemes without the help of specialist [sometimes costly] service providers. Several sequestration methods legislated in the ERF, including the modelled method for SOC, have had no uptake, with reasons including that they are not financially positive or that eligible activities are not compatible with managing a real-life farm enterprise as a profitable business. A review of uptake of ERF vegetation and soil sequestration projects by farmers (Macintosh et al. 2019) identified eight barriers to uptake: low carbon prices; perceived risk of rule changes affecting participation and crediting; uncertainty about future carbon prices; difficulties in getting third-party consents (land rights); permanence requirements; lack of awareness amongst farmers of carbon market opportunities; the scope of methods; and a lack of trust on behalf of farmers in parties offering carbon market information. Another key learning was that uptake could be improved if co-benefits to carbon sequestering activities were optimised and their value communicated to land managers.

The major constraints on participation in the ERF SOC model-based method (Australian Government 2015) reported by stakeholders concern the conservative nature of the default values and the method's narrow eligibility requirements. These problems reflect the state of knowledge in SOC sequestration rates for practices adopted on agricultural lands at the time the method was developed, and the requirements for integrity under the policy, including being evidence-based and using conservative assumptions to ensure high-quality carbon credits. In contrast, the main constraint on uptake of the less conservative measurement method has been the high costs of sampling and analysis. Stakeholders also cited the limited eligible practices and discounts applied to maintain conservativeness in the revised measurement method legislated in 2018 (Australian Government 2018) as barriers. More recently, greater confidence and higher prices for carbon offsets have resulted in accelerated participation in ERF projects.

This acceleration in participation is likely to continue as emerging techniques, such as spectrometry, remote sensing and flux measurements and new hybrid approaches using modelling capacity verified by accessible datasets, enable more cost-effective MRV for SOC sequestration methods in policy frameworks (Smith et al. 2020). Increased flexibility in MRV and in the range of eligible practices are being evaluated for an updated ERF SOC method, which is expected to be more attractive to stakeholders while maintaining the focus on integrity.

4 Conclusion and future trends in research

4.1 Opportunities and challenges to foster adoption of soil organic carbon practices

Lal et al. (2003) proposed that, with the implementation of suitable policy initiatives, substantial SOC sequestration potential could be realised for up to 30 years, or when the soil C sink capacity is filled. This would provide a valuable near-term contribution to restricting global warming to no more than 2°C, as specified in the Paris Agreement and supporting the Global Agenda for Sustainable Development set out in the SDGs. The challenges for design of national or regional frameworks relate not only to understanding the technical and biophysical potential for SOC sequestration but also to understanding the nature of behavioural resistance to practices and incentives already available for adoption. There is an urgent need for frameworks that enable investment in soil carbon mitigation to be practical and effective for achieving climate change mitigation, food security and ecosystem health benefits (Alexander et al. 2015).

Investment in research on biophysical and technological aspects of soil carbon sequestration and its climate change mitigation potential over more than a decade has provided strong evidence as a basis for action. More recently, research has accelerated as countries increase their ambition under the Paris Agreement, and as awareness is raised through initiatives such as '4 per 1000.' To support action, studies are being undertaken into the impacts of increasing SOC storage on agricultural yields and productivity, but economic, social and cultural opportunities and barriers to uptake of positive practices have generally received less attention (Harrison et al. 2021). Consideration of all four areas – biophysical, technological, economic and socio-cultural – will be essential for successful implementation of policy frameworks fostering adoption of good practice for long-term SOC management.

Experience with soil carbon measurement methods in the Australian ERF policy has also highlighted the practical challenges of implementing outcome-based soil carbon projects, including the barrier imposed by lack of early income from credits to cover participation expenses such as baseline sampling and analysis as part of a financial incentive model. Not unexpectedly, there is a tension between the timing of reporting for earlier financial returns and integrity of carbon credits issued. Early reporting (i.e. within 1–2 years) of [often small] changes in SOC stocks challenges the legislated requirement for verifiable and conservative crediting. Scientists caution that a rapid rise in measured

SOC stocks following implementation of new practices, especially for soil with initially low SOC, may reflect an increase in the labile carbon pool that improves soil health but may not be sustained over a 25-year or 100-year period. Sequestration rates are also affected by climatic and soil nutrient variations over time. The rate of increase in SOC stocks generally decreases as a new equilibrium level is approached. Managing the risk of over-crediting through provisions for discounted or delayed payments to ensure total crediting under an SOC method is conservative and is unlikely to align with farmers' need to manage costs. Sampling and analysis for project reporting incur significant up-front cost and there may also be disappointment if crediting is lower than expected, due, for example, to climate factors such as drought.

There can also be a need to resolve knowledge gaps relating to policy design. For example, a policy requirement that estimates of sequestration are conservative is difficult until there is more scientific certainty about what a 'conservative' estimate means for practices. Research and long-term trials will improve confidence in the expected relationship between practice change and soil carbon stocks in various climates and soil types (e.g. Schlesinger and Amundson 2019). The limited period of operation of incentivisation frameworks, including the Australian ERF, highlights the need for more experience to better understand and overcome tensions that act to constrain adoption of SOC sequestering practices on the ground.

4.2 Future study in soil carbon research

Soil carbon research will continue to build the underpinning evidence base for investment in frameworks and promote sequestration for climate change mitigation and soil health. As experience better identifies knowledge and data gaps, research is evolving to meet biophysical process and data needs for recognition of high-quality soil carbon offsets in market mechanisms. At the same time, multi-dimensional collaborations are contributing to overcoming socio-economic and cultural barriers to adoption by land managers. Here we provide illustrative examples, specific to the needs for developing frameworks for fostering adoption of good practice. More detail on biophysical research questions is found in a number of review papers, including Chenu et al. (2019), Paustian et al. (2019) and Smith et al. (2020), and socio-economic and cultural issues are identified in Burton and Schwarz (2013) and COWI (2021).

SOC stabilisation: From a policy framework perspective, key questions relate to the processes of stabilisation of carbon in soils. This understanding is needed to foster those practices that are consistent with the long-term SOC sequestration essential for genuine removals to offset emissions of GHGs. The role of processes in aggregate stabilization must be elucidated to identify effective sequestration practices for storing carbon in soil.

Research on stabilising soil aggregates will help the understanding of how to increase the pool of protected carbon that is relatively inaccessible to microbes and hydrolysing enzymes, and yet allows sufficient biogeochemical cycling for production (Cotrufo et al. 2013, Wilpiszeski et al. 2019). Next, advances in soil carbon modelling are needed to incorporate practices such as soil microbiome-aggregate processes affecting the stocks and dynamics of organic carbon.

Co-benefits and trade-offs: A transdisciplinary research effort is needed to understand the links between SOC sequestration, ecosystem services, and agricultural productivity and food security, to avoid trade-offs and optimise co-benefits of SOC sequestration. For example, selecting crops on their partitioning of biomass between aboveground and belowground carbon is a strategy that may increase soil carbon storage. Perennial crops such as perennial rice and intermediate wheat grass, (Cox et al. 2006), which invest more carbon into the roots, are likely to sequester more carbon than annual crops. However, research shows this practice may also lead to low grain productivity. Therefore, they may not prove economical to grow and the practice would not be feasible for adoption by farmers.

MRV: Another priority for research investment is improved capacity for rigorous but practical measurement, modelling and verification systems for SOC stock change. The target areas for investment include:

- Commitment to maintain and monitor short- and long-term field trials to quantify SOC sequestration across scales and management practices;
- More harmonious integration and quality control of data sources; and
- Advances in modelling capability linked to strategic measurement of validation sites and high-resolution remote sensing (Angelopoulou et al. 2019) and accurate spatial data for model initialisation and validation for diverse land use and management options (Rumpel et al. 2020).

Multi-disciplinary aspects: To clarify and define SOC sequestering practices for agriculture and forestry, including agroforestry and conservation forestry, research targeting sociological and economic considerations is needed. This research is of specific importance in assistance-deserving communities but is generally relevant to the design of all frameworks intended to influence landholders' long-term management decisions for adoption of practices to increase SOC (Sykes et al. 2020). The potential for private and public co-benefits and trade-offs of such decisions are not well understood (Brady et al. 2019) across the diverse range of management systems, landscapes and climates. The lack of confidence in environmental, economic and social impacts is a major deterrent to participation by farmers in outcome-based frameworks to foster uptake of better practice. Multidisciplinary collaboration based on cooperative research to understand realistic expectations (Rumpel et al. 2020) is needed to achieve improvements (e.g. Vermeulen et al. 2019).

4.3 Lessons learned on the role of government as the catalyst for action

Reflecting on ten years of experience with Australian policy and outcomes of a national framework to promote emissions abatement and carbon sequestration, it is clear that there is a consistent dynamic at play between 'government action and control' and 'industry action and initiative.' The notion that, at least in many nations, government can only ever be a 'catalyst' for industry initiative and action is evidenced in distinct ways in the Australian case study. Method development, a key element of the framework, was initially open to all in order to stimulate industry engagement. Later, method development moved more 'in-house' to the government, to reduce the duplication and work associated with the numerous industry-initiated methods being proposed. More recently, modular methods are being developed which set the overall framework and integrity structures but allow industry and/or others from within the science community to proposed 'models' as sub-components of methods. The umbrella method, however, sets the validation standard and process for such sub-models. There has been a consistent effort at consultation and review from the potential 'user community' (www.cleanenergyregulator.gov.au).

In parallel with these dynamics of method development, the Australia experience provides some insights into the evolution in the carbon offsets marketplace. Pre-2010, the markets were small and limited to voluntary schemes being offered to individuals and businesses. The advent of the CFI and later ERF policies introduced a government-funded marketplace that has invested more than A$575 million since 2014, with another A$1.4 billion committed by government, in the purchase of ACCUs that are eligible to be counted in the national greenhouse inventory accounts (CER 2021a). More recently, the private sector marketplace has been strengthening, which is something the government scheme seeks to encourage. For example, owners of ACCUs contracted to the government scheme under an 'optional' contract can choose to sell them onto the private marketplace rather than deliver them to the government at a fixed contracted price. Increasingly, there is a discussion of the development of a 'Carbon Exchange' that can facilitate public and private buying and selling of carbon offsets (www.cleanenergyregulator.gov.au/ 28 April 2021).

Irrespective of all these developments in methods and markets, our overarching conclusion is that a focus on the integrity of the carbon offsets must remain central at all stages of any policy framework if it is to continue to meet its objectives.

5 Where to look for further information

Recent publications provide informative overviews of the practical potential for SOC sequestration (Rumpel et al.), the challenges and outlook for accurately quantifying SOC change (Smith et al.) and the status and gaps in research (Chenu et al.), while websites discuss incentive mechanisms and illustrate a national policy framework to foster SOC sequestration.

5.1 Key publications

- Chenu, C., Angers, D. A., Barré, P., Derrien, D., Arrouays, D. and Balesdent, J. (2019). Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil and Tillage Research* 188, 41–52.
- Rumpel, C., Amiraslani, F., Chenu, C., Cardenas, M. G., Kaonga, M., Koutika, L. S., Ladha, J., Madari, B., Shirato, Y., Smith, P. and Soudi, B. (2020). The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio* 49(1), 350–360.
- Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., Batjes, N. H., Van Egmond, F., McNeill, S., Kuhnert, M. and Arias-Navarro, C. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology* 26(1), 219–241.

5.2 Web resources

- Costa Jr, C., Dittmer, K., Shelton, S., Bossio, D., Zinyengere, N., Luu, P., Heinz, S., Egenolf, K., Rowland, B., Zuluaga, A., Klemme, J., Mealey, T., Smith, M. and Wollenberg, E. (2020). *How Soil Carbon Accounting Can Improve to Support Investment-Oriented Actions Promoting Soil Carbon Storage*. CCAFS Info Note. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Available at: https://ccafs.cgiar.org/resources/publications/how-soil-carbon-accounting-can-improve-support-investment-oriented.
- The Australian Emissions Reduction Fund – How it works. http://www.cleanenergyregulator.gov.au/ERF/About-the-Emissions-Reduction-Fund/emissions-reduction-fund-schematic.
- The Australian ERF Measurement of soil carbon sequestration in agricultural systems method. http://www.cleanenergyregulator.gov.au/ERF/Pages/Choosing%20a%20project%20type/Opportunities%20for%20the%20land%20sector/Agricultural%20methods/The-measurement-of-soil-carbon-sequestration-in-agricultural-systems-method.aspx.

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