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Review

The Role of Soil Carbon Sequestration as a Climate Change Mitigation Strategy: An Australian Case Study

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Abstract: Soil carbon sequestration (SCS) is a key priority in the Australian government's Long-Term Emissions Reduction Plan. Under the government's Emission Reduction Fund (ERF), farmers are encouraged to change to a management practice that will increase their soil carbon (C) stock and earn Australian Carbon Credit Units (ACCUs). The projections of net C abatement nationally range from 17 to 103 Mt carbon dioxide equivalent annually up to 2050. This huge range reflects the uncertainties in achieving net SCS due to biophysical constraints, such as those imposed by the paucity and variability of Australian rainfall and the difficulty of measuring small changes in soil C stock. The uptake by farmers is also uncertain because of compliance costs, opportunity costs of a practice change and the loss of business flexibility when a farmer must commit to a 25-year permanence period. Since the program's inception in 2014, only one soil C project has been awarded ACCUs. Nevertheless, an increase in soil C is generally beneficial for farm productivity. As a voluntary C market evolves, the government is expecting that farmers will sell their ACCUs to businesses seeking to offset their greenhouse gas emissions. The risk is that, in buying cheap offsets, businesses will not then invest in new energy-efficient technologies to reduce their emissions at source.

Keywords: soil carbon; sequestration; carbon credits; Emission Reduction Fund; farm productivity; climate mitigation

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1. Introduction

Over the past decade, agriculture has gone from sinner to saviour in the context of global warming. For example, the World Bank [1] reported in 2012 that "Some 30 percent of global greenhouse gas (GHG) emissions are attributable to agriculture and deforestation driven by the expansion of crop and livestock production for food, fiber and fuel." However, an awareness of the potential of, and advocacy for, soils to sequester CO_2 from the atmosphere has been gathering momentum, propelled by the proposal at the 21st Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) for the soil carbon content (SOC) of soils globally to be increased by 0.4% per annum (www.4p1000.org, accessed on 20 March 2022). The same World Bank report hoped that, in the global debate about climate change mitigation, "the 'triple win' of soil carbon sequestration for increased productivity, improved climate resilience, and enhanced mitigation" would become an integral part of the dialogue.

The World Bank's call has been taken up by various international consortia such as The Adaptation of African Agriculture [2], Living Soils of the Americas [3] and Advancing Climate Action in the Americas [4]. However, actual mechanisms by which land managers can be rewarded for genuine GHG abatement through soil carbon sequestration (SCS) have been primarily the focus of government or private-sector action in North America and Australia. In these regions, schemes have been developed (see Table 1) whereby land managers are encouraged to implement practices to draw down CO_2 from the atmosphere and store it in soil organic matter (SOM), described as a negative emissions strategy [5]. For a defined area of land, SCS represents the balance between the transfer of atmospheric

CO_2 to soil through photosynthetic products, and carbon (C) losses primarily through soil respiration [6]. When the balance favours C accretion (i.e., is positive), net SCS occurs, which is measured by sampling the soil to a specific depth, normally 0.3 m as recommended by the Intergovernmental Panel for Climate Change (IPCC) [7], and measuring the soil C concentration and bulk density of the fine soil mass (particles < 2 mm equivalent diameter, which excludes gravel). Bulk density is necessary because this property can change with time under different soil managements. Because of this, estimates of the soil C stock over time are best based on an equivalent soil mass [7], but are usually scaled up to a C content per unit area (e.g., tonnes (t) per hectare (ha)).

Plant product removal, soil erosion and leaching of dissolved organic C may also deplete the soil C stock, and this will be reflected in its measured value. However, the success of SCS as a negative emissions strategy requires not only that net SCS be positive, but also that net SCS exceeds any increases in emissions of other GHGs that might occur during the operation of the project [8]; that is, net C abatement occurs.

Although the original COP21 proposal referred to an 0.4% increase in soil C in world soils, it is clear from subsequent references [9] that the proposal was focused on agricultural soils and their management. As indicated above, implementation schemes (called protocols) for SCS are now available in several countries [6,10]. One of the longest running schemes is the Emission Reduction Fund (ERF) of the Australian government (www.cleanenergyregulator.gov.au/ERF, accessed on 20 March 2022), under which soil C projects are strongly promoted. If a project achieves genuine net abatement, the landholder is rewarded with Australian Carbon Credit Units (ACCUs). One ACCU is the equivalent of one tonne of carbon dioxide equivalent (CO_2-e) of net C abatement.

This article discusses the soil C protocol of the ERF as a case study. The constraints imposed by biophysical and environmental factors on the efficacy of the protocol are examined. The integrity of the scheme is evaluated in terms of the rigour of monitoring, reporting and verification, the concepts of additionality, prevention of leakage, risk-of-reversal buffer and expectations for abatement outcomes. Income from ACCUs earned is compared with compliance costs and the opportunity costs of changing land management. Socioeconomic influences on landholder uptake of projects are also discussed, together with an assessment of the possible co-benefits of successful SCS. A conclusion is reached about the true role of SCS in the plethora of approaches for the mitigation of climate change.

Table 1. Examples of protocols for soil carbon sequestration recognized in the USA.

Protocol	Additionality Requirement	Permanence Period	Risk-of-Reversal	Leakage	Considers Other GHGs
Climate Action Reserve Enrichment v.1.0	Yes, performance and legal requirement tests	Yes, 100 years or tonne-year accounting for a shorter period	Percentage of credits to a buffer pool	Yes, for displacement of livestock and lower crop yields	Yes, uses modelling or emission factors
Nori Croplands Methodology v.1.1	Yes, project must show increase in SCS over baseline	10 years	Yes, restricted tokens are used for any deliberate reversals	Verify if SOC gains cause losses outside of project boundary	No
Gold Standard Soil Organic C Methodology v 1.0	Yes, performance and legal requirement tests	Permanence within crediting period (5–20 years)	Yes, a percentage of credits go to a buffer pool	Yes, accounts for shifting crop production	Yes, modelling or emission factors if emissions > 5% of baseline
BCarbon	Credits issued for C added after initial testing	10 years, renewable after credits issued	10% of credits to a buffer pool	Potential leakage assessed by life cycle analysis	No

Table 1. *Cont.*

Protocol	Additionality Requirement	Permanence Period	Risk-of-Reversal	Leakage	Considers Other GHGs
Regen Network Grassland Protocol	Yes, eligible practices must be new and additional to business-as-usual	25 years	Yes, a percentage of credits to a buffer pool	Potential sources of leakage tracked over time	Yes, net emissions accounted for using accepted factors
Carbon Credits—Measurement of SCS in Agricultural Systems Methodology	Yes, requires at least one new eligible management activity	25 or 100 years, deduction of 20% of credits for 25-year period	Yes, risk-of-reversal buffer of 5% of credits	Yes, accounts for organic materials derived from outside the project area or new irrigation water	Yes, emission factors used if project emissions are greater than those of the baseline

Adapted from Appendix A of [10].

2. Practical Implementation of a Soil Carbon Negative-Emission Strategy

2.1. Additionality and Leakage

For effective net abatement to occur, business-as-usual is not acceptable—there must be a change in the land management practice so that, for a defined area of land, net SCS is increased. This embodies the concept of additionality. The basic function of the practice change is to increase the supply of shoot residues (as litter or straw) and root material (as exudates and dead roots) that are deposited in the soil, and to minimize the rate at which these materials are decomposed by microorganisms. Furthermore, as soil C builds up in the soil, its capacity to sequester C diminishes as mineral surfaces approach saturation and the C compounds are less well protected from microorganisms [10].

Consistent with many other protocols for SCS, the ERF identifies a range of management practices that are eligible for a soil C project to be registered with the Clean Energy Regulator (CER) (www.cleanenergyregulator.gov.au/ERF, accessed on 20 March 2022). These practices are listed in Box 1. A farmer needs to introduce one or more of these practices that is new or materially different from what was done in the project's prior period. An eligible activity already being carried out does not need to cease: merely that a new or materially different activity must be added.

Many of these activities, such as minimizing soil disturbance due to tillage, retention of crop residues and crop diversification, including cover cropping, are drawn from the practices of conservation agriculture [11–14]. Others, such as the use of compost and manures, are consistent with a tenet of regenerative agriculture, whereby synthetic fertilizers are replaced by organic materials such as compost and manure [15]. However, such a substitution runs the risk of leakage, which describes the situation where sites from which the organic materials are derived suffer a loss of C inputs. In this case, there is no net gain in SCS for the landscape; or it can be that, with the removal of material from the site of origin, an increase occurs in the release of other GHGs; or as a result of the removal, extra land is cleared for agriculture, which causes a net increase in emissions [16].

Because of possible leakage, under the ERF soil C protocol, restrictions are imposed on the use of compost and manure (non-synthetic fertilizers (NSF)) and biochar. If these materials are obtained from outside the Carbon Estimation Area (CEA), the amounts are limited to 100 kg C/ha/year: no quantity limits exist if they are derived from within the CEA or a designated waste stream. However, in the case of NSF, its C content must be deducted from the soil C stock when the latter is measured less than two years after the application of the NSF; after that period, it is assumed to have decomposed. This is not the case with biochar, which is resistant to decomposition, so that any biochar C must be deducted from any increase in soil C stock in calculating the net abatement [17]. The rationale for these tortuous regulations seems to be that the added organic materials should stimulate the growth of crop or pasture through the supply of nitrogen (N) and phosphorus (P), and hence predispose to the deposition of more shoot and root residues in the soil. Whether this leads consistently to an increase in SCS is currently debatable [18].

Box 1. List of activities currently eligible to be registered as a soil C project with the CER.

- Applying nutrients to the land in the form of a synthetic or non-synthetic fertilizer to address a material deficiency. For example, applying compost or manure; applying lime to remediate acid soils; applying gypsum to remediate sodic or magnesic soils.
- Undertaking new irrigation. Applying new or additional irrigation obtained through improving the efficiency of on-farm irrigation infrastructure and/or management practices within your project area.
- Re-establishing or rejuvenating a pasture by seeding or pasture cropping.
- Re-establishing, and permanently maintaining, a pasture where there was previously no or limited pasture, such as on cropland or bare fallow.
- Altering the stocking rate, duration, or intensity of grazing to promote soil vegetation cover and/or improve soil health.
- Retaining stubble after a crop is harvested.
- Converting from intensive tillage practices to reduced or no tillage practices.
- Modifying landscape or landform features to remediate land. For example, practices implemented for erosion control, surface water management, drainage/flood control, or alleviating soil compaction. Practices may include controlled traffic farming, deep ripping, water ponding or other means.
- Using mechanical means to add or redistribute soil through the soil profile. For example, clay delving or clay spreading.
- Using legume species in cropping or pasture systems.
- Using cover crops to promote soil vegetation cover and/or improve soil health.

2.2. Permanence and Risk of Reversal

The concept of using SCS as a net abatement strategy is predicated on the assumption that the extra soil C will be retained permanently. In practice, the UNFCCC has set the permanence period at 100 years, being the same period for which the global warming potential of GHGs is calculated [10].

Protocols offered by USA registries (some of which are international) are variable in this requirement, with "permanence" periods as short as five years in the first instance [10]. Table 1 summarizes some of these protocols.

The Australian ERF offers permanence periods of 25 or 100 years [17]. Because landholders commit to maintaining an approved practice for the duration of the permanence period, the shorter period offers more flexibility in their business management (see Costs and Benefits below). However, there is a discount of 20% for ACCUs generated in a 25-year project. According to the CER's register, all soil C projects are for 25 years, which means that the net income derived from such projects is reduced by at least 20% (www.cleanenergyregulator.gov.au/ERF, accessed on 20 March 2022).

Another consideration for a soil C project is the possible loss of stored C due to unpredictable environmental changes or singular events such as wildfires. Hence, in the ERF, an extra 5% discount is applied to all ACCUs to provide a risk-of-reversal buffer for any such events.

3. The Potential for Increasing Soil C Sequestration

Projections for the Australian Landscape

For an ERF soil C project, operating an approved management practice, the critical issue is by how much can the rate of C inputs be increased relative to the rate of C losses. The main factors governing these input and output processes have been discussed by many authors [6,7,9,12,16,19].

In the lead-up to COP26, the Australian government's Long-Term Emissions Reduction Plan [20] (p. 55) identified soil C as one of the key low-emission strategies for attaining net zero by 2050. Soil carbon sequestration was envisaged as a mechanism by which emissions from industry that were hard to reduce could be offset by SCS that provided genuine net abatement. Soil C projects were estimated to have the potential to provide at least 17 Mt CO_2-e of accredited offsets annually by 2050, in addition to CO_2 drawn from the atmosphere without accreditation.

As modelling for the Plan acknowledges [21] (p. 79), there is a wide range of estimates for SCS in Australian farmland, depending on assumptions about the effects of biophysical and environmental factors over time, uptake rates by farmers and the costs relative to the benefits (see Costs and Benefits below). For example, with advanced technology (unspecified) and an abatement incentive of AUD80 per t CO_2-e, SCS in Australian farmland was projected to account for 26 Mt CO_2-e annually to 2050. Previously, the first Low Emissions Technology Statement (LETS) [22] (p. 23) referred to a Commonwealth Scientific and Industrial Research Organization (CSIRO) review [23] that noted the potential for 35–90 Mt CO_2-e per annum to be drawn down from the atmosphere through improved management of one quarter of Australia's crop and grazing lands.

Estimates of SCS made by some commercial aggregators are considerably higher. For example, Agriprove's analysis, quoted in the Plan (agriprove.io), indicated that the potential across 36.58 Mha of cropping land and 28.95 Mha of grazing land (not including rangelands receiving <300 mm rainfall) could be at least 103 Mt CO_2-e annually [20] (p. 56). In an Australian Broadcasting Corporation Science Show of 19 September 2020 [24], Matthew Warnken of Agriprove stated that some 30 Mha of pasture land would be suitable for "proving" the levels of SOC, delivering approximately 130 Mt of abatement each year.

The data in Box 2.4 of the Plan [20] (p. 56) can be broken down to show the potential rate of SCS according to the area of cropping and pasture land in each of five rainfall zones. The results are shown in Table 2.

Table 2. Potential carbon sequestration in Australian cropping and pasture land according to rainfall zones.

	Cropping Land			Pasture Land		
Rainfall (mm)	**Area (Mha)**	**CO_2-e (Mt) per Year**	**SCS (t/ha/year)**	**Area (Mha)**	**CO_2-e (Mt) per Year**	**SCS (t/ha/year)**
300–600	28	22.40	0.22	8.375	12.562	0.41
600–900	7.976	9.97	0.34	15.745	39.362	0.68
900–1200	0.305	0.488	0.44	3.510	11.583	0.90
1200–1500	0.085	0.178	0.57	0.705	3.032	1.17
>1500	0.210	0.472	0.61	0.615	2.768	1.23

Adapted from Box 2.4 in the Long-Term Emissions Reduction Plan [20].

Several points should be noted about the data in Table 2.

1. For both cropping and pasture land, SCS is highly dependent on rainfall. This is primarily because, the higher the rainfall, the more vegetation that can be grown, and hence the more root and shoot residues that can be deposited in the soil.
2. For any rainfall range, the rate of SCS under pasture is approximately twice that of cropping. There can be differences in the yield of vegetation, but the main factor is the lack of soil disturbance under pasture, especially permanent pasture, which means that the rate of C loss is reduced.
3. The effect of rainfall notwithstanding, the potential for SCS is greatest in the 300–900 mm zone because of the greater area of cropping and pasture land in this zone. However, rainfall variability is also greater in the low rainfall zones of Australia, so that plant growth is more seasonally variable and annual increases in SCS are less certain there.
4. The projections of SCS assume 100% uptake of soil C projects in the land areas identified, which is unlikely to be achieved in practice.

4. Field Measurements of Soil Carbon Sequestration

4.1. Technical and Financial Considerations

In the field, soil C content varies both spatially and temporally, which creates difficulties for measurement. Once an area of land is delineated (the CEA), soil cores must be sampled to at least 0.3 m depth and the samples analyzed for the organic C concentration. At the same time, soil bulk densities must be measured so that the mean C content per unit volume of equivalent soil mass (the C stock) can be calculated (gravel must be excluded). This is the baseline sampling round. A second round of soil sampling for analysis must be undertaken within five years so that the change in soil C stock can be estimated.

Smith et al. [7] suggested that, under some land managements, sampling to more than 0.3 m may be necessary to accurately measure C change in the soil profile. For example, under no-till farming, a decrease in soil C at depth may counterbalance an increase in soil C within the top 0.3 m [25]. Although the Food and Agriculture Organization has recommended sampling to 1 m [7], this requires specialized equipment and makes the measurement of soil C change prohibitively expensive [10].

The effect of spatial variability on the precision of each soil C mean can be reduced by increasing the number of samples taken in the CEA. For example, for a 50-ha field, Oldfield et al. [10] calculated the number of independent samples needed to estimate with 95% certainty a change of 0.05% in mean soil C concentration over 5 years (corresponding to a sequestration rate of 0.3 t C/ha/year to 0.3 m depth in a soil of bulk density 1 Mg/m^3). For field variabilities ranging from 0.3 to 0.7 standard deviations, the number of samples required ranged from 12 to 62 per ha. The effect of spatial variability, which may be exacerbated by seasonal changes from year to year, can be moderated to an extent by ensuring that samples are taken at the same time each year. However, the sampling intensity required for a 95% level of certainty remains high, so the ERF sets the confidence level for accepting a significant difference between means at 60% [26].

More intensive soil sampling incurs greater costs. For example, for a 68ha cropping field in central-west New South Wales (NSW), Singh et al. [27] reported an all-in cost of AUD37/ha (in 2011 dollars) to measure the soil C stock (to 0.3 m) with a standard error $\leq$2 t/ha. Under its Technology Investment Roadmap [22] (p. 24), the Australian government proposed the ambitious "stretch goal" of reducing the cost of measurement to AUD3/ha. Hence, much effort has been devoted to developing techniques that are cheaper, with an acceptable degree of precision, such as near- and mid-infrared spectroscopy [7,28]. However, such methods require calibration against soil C concentrations measured by dry-combustion analysis. Other methods, the so-called hybrid methods, seek to reduce the cost of monitoring by coupling direct measurements of soil C with a model of soil C dynamics, as advocated by Powlson and Neal [29].

A new ERF protocol, released at the end of 2021 [26], involves using less frequent soil sampling and measurements that are used to check the output of a C model. Other approaches involve the use of remote sensing, in particular, spectral bands [7,30]. Such a method may have some application for bare soil, but not vegetated land, other than for estimating above-ground plant biomass, which may provide an input variable to a soil C model. Prior remote sensing may also be helpful in determining the most effective selection of sites for soil sampling. Oldfield et al. [10] discuss some of the limitations of these "advanced" technologies.

4.2. Examples of Field Measurements of SCS in Australia

Converting cropland to permanent pasture is one of the most promising, eligible changes in land management under the ERF (see Box 1). For example, Badgery et al. [31] reported on trials on farms in the Cowra Trough, central-west NSW (rainfall 673 mm). Farms were selected on the basis of the soil C increase predicted from a Soil Carbon Calculation Tool [32] when the farmers changed their management in accordance with ERF requirements. Soil C stock was measured in 2012 according to the ERF protocol (baseline sampling) and again in 2017. Table 3 gives the results for five farms where the management change was from cropping to pasture without organic amendments.

Table 3. Changes in soil carbon stock after a change from cropping to pasture in a 5-year on-farm trial in the Cowra Trough, NSW [31].

Farm Identifier (All Farms > 200 ha)	Initial Soil C Stock (t C/ha to 30 cm)	Predicted Change in Soil C Stock (t C/ha/year)	Measured Change in Soil C Stock (t C/ha/year) [1]
LA0690	27.1	0.41	1.01 ± 0.16
LA0700	28.2	0.3	0.58 ± 0.43
LA0725	31.9	0.2	0.78 ± 0.29
LA0934	20.9	0.5	1.13 ± 0.16
LA0734	28.6	0.3	1.33 ± 0.18
Means	27.3	0.34	0.97

[1] Mean and standard error derived from a minimum of 10 composite samples according to a stratified random design.

The following points should be noted.

- The initial soil C stocks were low, which increased the likelihood of a faster initial rate of C accumulation when management was changed [33]. Similarly, Doran-Browne et al. [34] reported a significant potential to sequester C in a degraded soil when management was changed.
- There was considerable variation in the measured means for soil C change, reflecting the spatial variability of soil C in the field.
- The mean increase in soil C stock over the first five years of 0.97 t C/ha/year is at the upper end of expectations. A previous survey of farm paddocks converted from cropping to pasture in the region found an average increase of 0.78 t C/ha/year over five years [35].
- The rate of soil C increase is likely to slow with time as the soil approaches a new steady-state equilibrium [19]. For example, in a similar region of NSW, but for longer term trials of 13 and 25 years, Chan et al. [36] reported increases of 0.40 and 0.26 t C/ha/year, respectively.

Other results from Chan et al. [36] are relevant to another of the eligible practices (see Box 1). For the mixed farming belt of central-west NSW, these authors found that improved soil nutrient inputs and grazing management could lead to increases of 0.5–0.7 t C/ha/year. They added the proviso that the initial soil C levels should be well below the steady-state contents that would be expected after such improved management. Similarly, for crop-pasture rotations with stubble retention under annual rainfall of 330–700 mm in Victoria, Robertson and Nash [37] projected increases in the soil C store of 0.3–0.9 t C/ha/year over 25 years; but they cautioned that such increases could take 10–25 years to be measured with certainty.

The above measurements and estimates of the rate of SCS under Australian conditions are consistent with the range of 0.3–0.6 t C/ha/year reported by Sanderman et al. [23]. However, the only soil C project that has been awarded ACCUs by the CER has recorded much higher values. This project was based on a renovated pasture on a 100-ha field of a farm in West Gippsland, Victoria, which receives an annual rainfall of 1000 mm (www.cleanenergyregulator.gov.au/ERF, accessed on 24 March 2022). Within the first five years of the project, 1904 ACCUs were awarded, which, allowing for a combined 25% discount for its 25-year permanence period and risk-of-reversal buffer, amounted to a net 25.39 t CO_2-e/ha sequestered over two years, or an average rate of 3.46 t C/ha/year (the change in other GHG emissions was negligible). Note that this value is much higher than the potential value of 0.9 t C/ha/year given for the 900–1200 mm rainfall zone in Table 2. Up to April 2022, no additional ACCUs had been recorded, and the reasons for this exceptional result remain unexplained.

4.3. Monitoring, Reporting and Verification (MRV)

Currently, the ERF requirements for monitoring soil C are based on measurements of soil C stock to at least 0.3 m depth. A qualified technician must carry out the sampling and the C analyses done in an approved laboratory. A previous version of the protocol allowed estimates of soil C change to be obtained from FullCAM modelling [38]. However, the model estimates were conservative and were not at a high spatial resolution, so few projects were registered under this protocol. In the recently released 2021 protocol, a hybrid modelling-soil sampling method is available. This still requires rigorous baseline sampling, but the frequency of further sampling and soil analysis can be reduced to once every 10 years.

All the registered soil C projects have chosen a 25-year permanence period during which a report must be submitted to the CER at least once every five years. The project results need to be independently audited three times during the crediting period of 25 years.

Smith et al. [7] acknowledged that there is much variation in the capacity of different C credit protocols globally to apply rigorous MRV. However, because of their strict MRV, ACCUs so far are recognized to be of high integrity [10].

5. Costs and Benefits of a Soil C Project

As indicated above, there are significant compliance costs involved in a soil C project. These include the cost of an areal survey to delineate a CEA, baseline sampling, soil C analysis and bulk density measurement, data collection and analysis to estimate changes in all GHG emissions over time, report preparation and auditing. If CEAs are large, or small CEAs are aggregated, these costs can be reduced on a per ha basis. The Australian government is offering a AUD5000 advance payment per project to help defray start-up costs. Because of the method's complexity, several commercial aggregators offer a start-up and management service. To cover the initial survey, soil sampling and analysis, the start-up cost can be as high as AUD5000 for farm properties <1000 ha, but lower for larger properties. The on-going service fee, which may cover subsequent measurement, reporting and auditing, can amount to 30% per ACCU (Professor R. Eckard, personal communication).

However, as White et al. [8] showed, the major potential cost is the opportunity cost of changing land management, measured as the change in gross margin of the farming business from before to after the change. The decreased gross margin was especially marked in changing from dryland cropping to grazing livestock, based on data for gross margins from the NSW Department of Agriculture (reported in White and Davidson [39], adjusted from Australian Bureau of Agricultural and Resource Economics and Sciences survey data in *Agricultural Outlook*—Department of Agriculture). A sensitivity analysis revealed little effect of a 50% reduction in sampling and analysis costs, or a 50% increase in the value of an ACCU, or a 100% increase in the rate of SCS. Clearly, the result of this analysis will also depend on input costs relative to the value of products, a relativity that can change with time. In this context, a halving of the crop yield or a doubling of livestock yield per ha could produce a positive change in gross margin.

Co-Benefits

Soil carbon sequestration is usually promoted as a win:win strategy [9]. Under the ERF, C credits are expected to provide extra farm income, while the increase in SOM will improve the soil condition and farm productivity. For productivity and profitability to be achieved, not only does the overall benefit/cost ratio of the management change need to be favourable, but the farmer also needs the skills to implement the new practice successfully. In some instances, this may be a deterrent to change. Furthermore, as Janzen [40] has pointed out, there is a paradox in the objectives of achieving optimum sequestration and productivity outcomes. On the one hand, sequestration is most effective when C accumulates in recalcitrant compounds that decompose only very slowly, that is, it is considered permanent. On the other hand, added C residues are most effective in improving soil condition and promoting plant growth when the residues decompose quickly, soil microbial activity is stimulated, and essential elements such as N, P and sulfur (S) are recycled [29]. Even so, there is a current hypothesis that the necromass from stimulated microbial activity leads to enhanced mineral stabilization of soil C compounds [41,42]; however, Craig et al. [43] found that microbial growth and turnover were negatively correlated with the formation of mineral-stabilized SOC in six forest soils of the eastern USA. The necromass hypothesis is often linked to the concept that below-ground inputs of C are more effective in increasing SCS than above-ground inputs [15]. Confirming this concept requires more reliable estimates of root C inputs, which in cropland at least are relatively small [44], so Janzen's original paradox is yet to be resolved.

In existing soil C protocols, the concept of permanence is not fixed (see Table 1), so the effectiveness of sequestration is not assessed: only that soil C stock must increase over time [17]. However, increases in soil C that lead to improved soil condition are readily measured by the resultant increase in crop productivity. As Meyer et al. [33] demonstrated, the increased productivity can be measured in monetary value that in many cases exceeds any income from C credits.

Other benefits claimed for increased soil C are for ecosystem services and biodiversity. Kopittke et al. [45] stated that soils play a critical role in multiple ecosystems services through regulation of the global C pool. On a more modest scale, improved soil structure from increased SOM is one example of an ecosystem service benefit provided through better infiltration of rainfall, resulting in less runoff that produces surface erosion and soil loss—the water quality in receiving waterways should therefore be improved. This is more a public benefit than a private benefit and is difficult to quantify.

Biodiversity, like sustainability, is an omnibus term that has been applied widely. For example, Kopittke et al. [45] stated that soils are the most biologically diverse habitat on earth. While there is a broad correlation between SOM status and soil biological diversity [46], Kopittke et al. [45] acknowledged that the linkages between measures of biodiversity and specific soil functions are yet to be elucidated. Nevertheless, under the Australian government's pilot Carbon + Biodiversity program (Carbon + Biodiversity Pilot agriculture.gov.au), an improvement in soil condition could provide an indirect, but measurable, biodiversity benefit. This program is focused on farmers planting native tree species on degraded, unproductive land or productive land that can be improved by targeted tree planting. The biodiversity benefit will come from the tree plantation, the growth of which will also be eligible for C credits. However, there is an underlying expectation that the degraded soil will be improved under the trees, and it is possible that this new method may join others listed in Box 1 to be eligible for earning soil C credits.

Another co-benefit sometimes cited is better risk management—that with increased SOM, crops are less likely to be affected by adverse conditions. Such a benefit should be expressed through farm productivity, as noted above.

6. Abatement of National Emissions

As indicated in Section 4.2, SCS has made a negligible contribution to offsetting the national GHG emissions. However, the Australian government's Long-Term Emissions Reduction Plan [20] projects that, by 2050, SCS could be providing between 17 and 103 Mt CO_2-e per year of abatement nationally. This huge range in projections reflects the fact that the uptake rate of the 2021 soil C protocol and the success of participants in sequestering significant amounts of C are uncertain, given the known biophysical, climatic and socioeconomic constraints that exist. As pointed out by several authors in different countries [8,16,47–49], the enthusiastic advocacy, especially in Australia, for SCS as a climate mitigation strategy ignores this uncertainty. There is the consequent risk that businesses under pressure to reduce their GHG emissions will choose to offset those emissions by buying relatively cheap C credits, rather than invest in new, energy-efficient, emission-reducing technologies. The latter point is highlighted in a recent CSIRO report [50] on climate-related risk scenarios and how these might influence future investment decisions in Australia. For example, a scenario whereby transition actions are delayed up to 2030 results in a high reliance on negative emission technologies, rising to 9000 Mt CO_2-e, to achieve net zero by 2050. This is potentially unattainable, given that, from 31 December 2012 to 13 April 2022, only 109 million ACCUs for all ERF protocols had been issued (i.e., 109 Mt of abatement achieved), of which 77 Mt were delivered under government fixed contract (www.cleanenergyregulator.gov.au/erf, accessed on 24 April 2022).

7. Financial Outcomes

The Long-Term Emissions Reduction Plan [20] (p. 55) suggested that Australian farmers could earn AUD400 million from the sale of soil C credits in 2050. Taking the Plan's modest estimate of annual abatement at 17 Mt CO_2-e by 2050 (see above), this implies an average ACCU price of AUD23.53. Farmers with a soil C project may enter into a contract through a twice-yearly reverse auction to sell their ACCUs to the CER at a fixed price, currently AUD17.35 per unit. Alternatively, farmers may decide to sell all or part of their units on the voluntary or secondary market, where the price is higher but fluctuates markedly according to supply and demand (recently between AUD29 and AUD57 per unit (www.reputex.com, accessed on 24 April 2022)). Because of this differential in price, the Australian government is now allowing farmers, who were contracted to the CER, to sell all their credits on the voluntary market. Taking advantage of this change, commercial facilitators are encouraging more farmers to engage in a soil C project, but the biophysical and financial constraints identified above remain.

When ACCUs are sold to the government under contract, they are "retired", but can count towards the farm's attaining C neutrality. Although a farmer may achieve a higher price on the more volatile voluntary market, the ACCUs sold there become the property of the buyer and cannot count towards the farm's C neutrality. Several international companies also offer soil C credits in Australia. However, these credits, although possibly of higher value than ACCUs, are of variable integrity [10]. Moreover, if credits are sold overseas, they cannot be counted as offsets in the national GHG inventory.

8. Conclusions—A Take-Home Message

Australia's approach to achieving net zero emissions by 2050 is based on "technology not taxes" [20] (p. 11). The first LETS [22] (p. 6) identified five key priorities, one of which was soil C. The mechanism for implementing SCS is through the Carbon Farming Initiative of the ERF. Since its inception in 2014, soil C projects have been singularly unsuccessful in providing C credits, with only one project receiving ACCUs in 2018–2020. Even this result is questionable, because the imputed rate of SCS is more than three times greater than that expected for pasture under a 1000 mm rainfall.

A key priority is to reduce the cost of soil C measurement to less than AUD3/ha, such as through remote sensing technology backed up by modelling and less frequent soil sampling. However, as Oldfield et al. [10] pointed out, remote sensing technologies have not yet been shown to work on vegetated land, nor are they able to measure soil C down to 0.3 m. Further research is required to achieve this goal without compromising the integrity of the C credits.

Notwithstanding the government's priority, the main barriers to greater uptake of soil projects are the opportunity costs associated with a change in management practice [8], the inflexibility for a farm business of commitment to a permanence period of at least 25 years [51], and the uncertainty of achieving a significant increase in soil C stock and maintaining it, given the variability of Australia's climate [37]. The last point is underscored by the need to grow large amounts of plant biomass (requiring substantial inputs of major nutrients such as N), which then provide the residues to power SCS [49]. Nevertheless, as demonstrated by Meyer et al. [33], there are considerable productivity gains to be made from increasing SOM, which are most readily achieved on degraded soils [34], provided climatic conditions are suitable.

Ultimately, as indicated in Section 6, the focus on delivering soil C credits, rather than on farm productivity gains, could have the most undesirable effect of diverting businesses in the mining, manufacturing and transport industries from taking real measures to reduce their own emissions.

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Abbreviations

ACCU	Australian Carbon Credit Unit
CEA	Carbon Estimation Area
CER	Clean Energy Regulator
COP	Conference of Parties
CSIRO	Commonwealth Scientific and Industrial Research Organization
ERF	Emissions Reduction Fund
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel for Climate Change
LETS	Low Emissions Technology Statement
MRV	Monitoring, Reporting and Verification
NSF	Non-Synthetic Fertilizer
NSW	New South Wales
SOC	Soil Organic Carbon
SCS	Soil Carbon Sequestration
SOM	Soil Organic Matter
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

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