Journal of Environmental Management 330 (2023) 117142

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation?

Carsten Paul [a,*], Bartosz Bartkowski [b], Cenk Dönmez [a,i], Axel Don [c], Stefanie Mayer [d], Markus Steffens [e], Sebastian Weigl [a], Martin Wiesmeier [d,f], André Wolf [g], Katharina Helming [a,h]

[a] *Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374, Müncheberg, Germany*
[b] *UFZ – Helmholtz Centre for Environmental Research, Department of Economics, Permoserstraße 15, 04318, Leipzig, Germany*
[c] *Thünen Institute of Climate Smart Agriculture, Bundesallee 65, 38116, Braunschweig, Germany*
[d] *Chair of Soil Sciences, TUM School of Life Sciences, Technical University of Munich, Emil-Ramann-Straße 2, 85354, Freising, Germany*
[e] *Department of Soil Sciences, Research Institute of Organic Agriculture (FiBL), Ackerstrasse 113, 5070, Frick, Switzerland*
[f] *Bavarian State Research Center for Agriculture, Institute for Organic Farming, Soil and Resource Management, Vöttinger Straße 38, 85354, Freising, Germany*
[g] *UFZ – Helmholtz Centre for Environmental Research, Department of Environmental and Planning Law, Permoserstraße 15, 04318, Leipzig, Germany*
[h] *Faculty of Landscape Management and Nature Conservation, University of Sustainable Development (HNEE), Schicklerstr. 5, 16225, Eberswalde, Germany*
[i] *Cukurova University, Landscape Architecture Department, Remote Sensing and GIS Lab, 01330 Adana, Turkey*

ARTICLE INFO

Keywords:
Carbon sequestration
Emission offset
CDR
Permenence
Agriculture
Private governance

ABSTRACT

Increasing soil organic carbon (SOC) stocks in agricultural soils removes carbon dioxide from the atmosphere and contributes towards achieving carbon neutrality. For farmers, higher SOC levels have multiple benefits, including increased soil fertility and resilience against drought-related yield losses. However, increasing SOC levels requires agricultural management changes that are associated with costs. Private soil carbon certificates could compensate for these costs. In these schemes, farmers register their fields with commercial certificate providers who certify SOC increases. Certificates are then sold as voluntary emission offsets on the carbon market.

In this paper, we assess the suitability of these certificates as an instrument for climate change mitigation. From a soils' perspective, we address processes of SOC enrichment, their potentials and limits, and options for cost-effective measurement and monitoring. From a farmers' perspective, we assess management options likely to increase SOC, and discuss their synergies and trade-offs with economic, environmental and social targets. From a governance perspective, we address requirements to guarantee additionality and permanence while preventing leakage effects. Furthermore, we address questions of legitimacy and accountability.

While increasing SOC is a cornerstone for more sustainable cropping systems, private carbon certificates fall short of expectations for climate change mitigation as permanence of SOC sequestration cannot be guaranteed. Governance challenges include lack of long-term monitoring, problems to ensure additionality, problems to safeguard against leakage effects, and lack of long-term accountability if stored SOC is re-emitted. We conclude that soil-based private carbon certificates are unlikely to deliver the emission offset attributed to them and that their benefit for climate change mitigation is uncertain. Additional research is needed to develop standards for SOC change metrics and monitoring, and to better understand the impact of short term, non-permanent carbon removals on peaks in atmospheric greenhouse gas concentrations and on the probability of exceeding climatic tipping points.

1. Introduction

Agriculture is both affected by and contributing to climate change. In Europe, 11% of greenhouse gas emissions are attributed to the agricultural sector, mainly nitrous oxide (N_2O) emissions from fertilizers and methane (CH_4) from ruminants. Additionally, drainage and agricultural use of organic soils causes substantial carbon dioxide (CO_2) emissions, which are reported under the category Land Use, Land Use Change and Forestry (LULUCF) (EEA, 2021).

Agricultural greenhouse gas emissions are mostly a result of

---

* Corresponding author.
E-mail address: paul@zalf.de (C. Paul).

https://doi.org/10.1016/j.jenvman.2022.117142
Received 14 October 2022; Received in revised form 9 December 2022; Accepted 22 December 2022

biological processes. Based on available and emerging technologies, it will not be possible to completely avoid them by 2050, the target year for Europe's carbon neutrality (European Union, 2020). Therefore, carbon offsets are required. In a carbon neutral-world, these will have to take the form of carbon dioxide removals (CDR). CDR are part of all IPCC scenarios that succeed in limiting global warming to 1.5 °C relative to pre-industrial times (IPCC et al., 2018). While it is usually assumed that the sequestration of one ton of CO_2 will offset the same amount of emissions, findings by Zickfeld et al. (2021) indicate that climate response may be asymmetric, requiring sequestration to be higher than emissions.

Soils constitute the largest terrestrial carbon pool, storing nearly three times as much carbon as aboveground biomass and twice the amount of carbon present in the atmosphere (Scharlemann et al., 2014). Agricultural soils, in particular croplands, are typically carbon depleted compared to soils under native vegetation such as forests (Poeplau et al., 2011). Agricultural management fostering carbon sequestration (carbon farming) can partly reverse this loss. Increasing the organic carbon content in agricultural soils is considered to have a high potential for CDR (Rumpel et al., 2020). Since agricultural land makes up 37% of the habitable land worldwide (FAO, 2021), even slight increases in their organic carbon stock could significantly contribute to climate change mitigation (Minasny et al., 2017). However, agricultural management in many parts of the world still has the opposite effect. For example, cropland soils in the EU are estimated to lose about 7.4 million tons of carbon per year (EC, 2021a). A strong source of carbon losses in many countries are former peatland soils that are artificially drained for agricultural production (Tiemeyer et al., 2020). The new EU Soil Strategy 2030 aims to implement measures for increasing soil organic carbon (SOC) stock to achieve land-based climate neutrality in the EU by 2035 and to contribute to a climate-neutral Europe by 2050 (EC, 2021a). The strategy includes plans for a legislative proposal on carbon removal certification in 2022, in order to promote a new green business model that rewards land managers for climate-friendly practices (EC, 2021b).

A challenge to increasing SOC stock is presented by the dynamics of soil carbon sequestration: under constant climatic conditions and constant management, SOC contents will approach a site-specific equilibrium where carbon inputs from plants and organic fertilizers are equal to carbon losses as CO_2 due to microbial respiration (Wiesmeier et al., 2019). Achieving increases in SOC therefore requires management changes. Such changes offer economic, ecological and social co-benefits (Tang et al., 2016), such as decreased risk of yield failure (Droste et al., 2020), increased resilience against droughts and heavy rainfalls (Hamidov et al., 2018), improved nutrient use efficiency, increased below-ground biodiversity and an increase in the supply of ecosystem services. However, they are also associated with costs to the farmers. In addition to public funding, such as payments for agri-environmental and climate measures (AECM) under the second pillar of European Union's Common Agricultural Policy, private governance instruments have recently emerged in the form of certification schemes for soil carbon sequestration. Farmers can register some or all of their fields with commercial providers who certify SOC increases achieved within a set period of time and sell these certificates to companies who want to market their products as climate neutral, or to individuals who wish to offset their private greenhouse gas emissions. This provides additional income to farmers ("carbon farming") and highlights their contribution to climate change mitigation. However, to offset emissions and have a genuine climate impact, carbon removals need to be permanent and additional to what would have happened anyway (without carbon certificates).

Markets for soil carbon certificates already exist in the United States (Marks, 2020), Europe (Cevallos et al., 2019), and Australia (Cevallos et al., 2019; Baumber et al., 2020). Australia is a special case insofar as certificates are also purchased by the government in order to reach the targets of the 2015 Paris Agreement (Baumber et al., 2020). In other world regions, soil carbon certificates seem to be less common, though markets have been reported in New Zealand (Marks, 2020), Colombia (Cevallos et al., 2019), Nepal (Schmidt et al., 2017) and Kenya (Shames et al., 2012). Comprehensive reviews of markets and trade volumes for soil carbon certificates are lacking. Compiling them would be challenging due to the high number of private companies and state-run approaches involved, for example in Germany (Nitsch and Schramek, 2020) and USA (Bomgardner and Erickson, 2021).

Certificates for carbon sequestration are already well established in the forestry sector (Marion Suiseeya and Caplow, 2013) where they are sold on the voluntary offset-market, and also contribute to public governance schemes, such as the Kyoto Protocol's Clean Development Mechanism (CDM), or the REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries) approach (UNFCCC, 2006; Otto, 2019). Multiple of these certification schemes credit both sequestration in wood biomass and in soils (Otto, 2019; Khatri-Chhetri et al., 2020). Principles developed to ensure the quality of forest-based carbon certificates are also useful for evaluating the more novel certification schemes for agricultural soils.

While there is overwhelming consensus that increasing the carbon content of agricultural soils is desirable and contributes to climate change mitigation, and while private investment to support management changes is considered helpful, it is uncertain whether private soil carbon certificates sold as voluntary emission offsets are a suitable instrument. Comprehensive assessments are lacking that consider underlying soil carbon dynamics, co-benefits and trade-offs, as well as questions of governance pertaining to the design of certification schemes. To close this knowledge gap, we assessed private soil carbon certificates sold on the voluntary offset market from the following perspectives.

- *Soil sciences*, focussing on soil processes, SOC sequestrations capacities and options for measuring SOC changes,
- *Agricultural soil management*, focussing on available measures to foster increases in SOC stocks and on their respective synergies and trade-offs, and
- *Soil governance*, focussing on the ability of private contracts to guarantee additionality and long-time sequestration of carbon, and to limit unwanted side-effects.

2. Material & methods

2.1. Analytical approach: system boundaries

We restrict our assessment to arable farming systems on mineral soils in industrialized countries of the temperate zone. This affects, for example, the relevance of synergies and co-benefits or the dynamics of carbon sequestration and respiration. We also restrict our analysis to certificates issued by private companies and sold on the voluntary carbon offset market. For the context of policies affecting soil carbon certificates, we focus on Europe while examples of certification schemes are based on certification providers active in Germany (see Supplement 1).

2.2. Analytical frame and literature review

We developed a matrix combining seven criteria with the perspectives of soil science, agricultural management and governance (Fig. 1). General principles such as quantification, additionality, permanence, additional emissions and the consideration of leakage have already been derived in the context of afforestation and reforestation projects under the CDM. They are also reflected in current standards for soil carbon certification, such as The Gold Standard Foundation's *Soil organic carbon framework methodology* (2020) or the *Methodology for improved agricultural land management* approved by Verra (2020), and they are to be considered in a planned European framework for carbon removals (EC, 2021b). We added the two criteria "Transparency, Legitimacy & Accountability" and "Synergies & Trade-offs" to better reflect

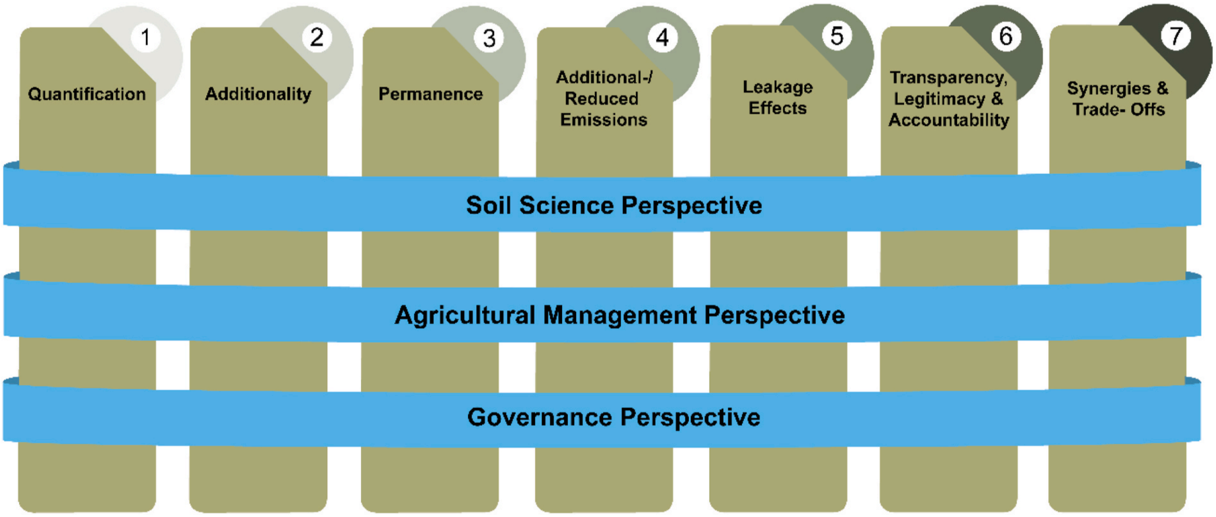


Fig. 1. Analytical approach to the suitability assessment of soil carbon certificates in agricultural systems.

implications for governance and agricultural management. All criteria are briefly characterized below. Carbon certificates sold as emission-offsets need to meet requirements in all criteria in order to function as an instrument for climate change mitigation.

To assess the state of knowledge, we analysed peer-reviewed publications for each criterion, applying a snowball sampling approach and drawing on the authors' respective expertise in soil sciences, agricultural sciences, economics, and law.

2.2.1. *Quantification of SOC changes*

SOC changes need to be quantified reliably. The high spatial and temporal variability of SOC stocks need to be accounted for, as even within a single agricultural field large variations are possible (Goidts et al., 2009). Moreover, the cultivated crop, its development stage and the time since last fertilization need to be considered as factors that influence SOC levels. The variability in SOC stocks adds to measurement and modelling uncertainties, precluding the reliable detection of very small changes.

2.2.2. *Additionality*

To offset greenhouse gas emissions, compensations must be additional to what would have happened without the mitigation measure (Leifeld et al., 2019). To assess the additionality of SOC increases in the context of soil carbon certificates, a scenario with carbon certificates should be compared to a counterfactual scenario without them (Bartkowski, 2021). These scenarios need to consider that numerous SOC increasing measures are routinely employed in organic farming systems, while several are also typical in conventional farming. Furthermore, some SOC increasing measures are part of the cross-compliance requirements for payments under the EU's Common Agricultural Policy.

Carbon farming measures that would be economically unviable without the sale of carbon certificates are not necessarily additional, as farmers' decisions are based on both economic and social considerations (Bartkowski and Bartke, 2018; Thamo and Pannell, 2016). Some measures may be implemented due to personal preferences, to improve long-term soil health, or out of considerations for the environment. Furthermore, increasing SOC stocks improves the resilience against climate change impacts (Hamidov et al., 2018) and farmers may invest into carbon farming to safeguard long-term yield stability.

The fact that the potential for carbon storage in soils is limited also has implications for the assessment of additionality. Total CO_2 removal is identical irrespective of whether SOC increases occur today or in the future when some carbon farming measures may already be mandatory or general practice (Thamo and Pannell, 2016). However, earlier removals are desirable as they may help to reduce peak concentrations and lower the risk of reaching climatic tipping points (Bossio et al., 2020). To strike a balance, the counterfactual scenario should go beyond the present situation and also account for potential changes in the near future.

2.2.3. *Permanence*

To provide climate change mitigation and offset emissions, removals of CO_2 from the atmosphere must be permanent. However, in contrast to measures based on emission reductions, soil-based carbon removals are usually reversible. With regard to soils, the commonly used term carbon sequestration is imprecise, because carbon is not simply "stored" in soils. Instead, the SOC content at any given time represents the result of two dynamic, antagonistic processes, namely organic matter entering the soil (e.g., via roots, above ground crop residues and organic fertilization), and macro- and microorganisms converting it to CO_2 as part of their metabolism. Even where SOC levels remain constant, carbon always needs to be replenished by inputs. In this paper, we use the term sequestration in spite of these caveats because of its importance in policy discussions of soil-related climate change mitigation.

The higher the SOC content, the higher the microbial activity and the higher also the amount of organic carbon inputs needed to maintain it. As a consequence, a high SOC content built up over many years may be lost if management changes or climatic effects lead to lower inputs of organic carbon or increased microbial activity.

2.2.4. *Additional emissions or emission reductions caused by carbon farming*

Management measures for increasing SOC may cause additional emissions, or result in emission reductions. Additional emissions may arise in multiple forms, such as CO_2 from diesel fuel where additional tractor work is required, CH_4 from higher numbers of ruminants that provide organic fertilizers, or N_2O from additional application of fertilizers for cover crops. In the long term, very high SOC levels may also cause increased N_2O emissions due to soil microbial processes (Lugato et al., 2018; Gu et al., 2017). These N_2O emissions are hard to predict since they are influenced by temperature, pH, soil moisture and soil texture (Wiesmeier et al., 2020).

Overall, carbon farming causing additional emissions are problematic, since management measures need to be continued indefinitely to prevent a re-release of carbon. However, after a soil's storage potential has been reached, no additional carbon will be stored and the net impact on global climate will then become negative.

2.2.5. *Leakage effects*

Leakage effects denote a process where improvements in one location cause deteriorations in one or multiple other locations (Paul and Helming, 2019). To assess the net impact of measures, both negative and positive consequences in all affected locations need to be accounted for. For example, if farmers apply more organic fertilizers on certified fields, the SOC content is likely to increase there. However, as long as the total amount of organic fertilizers in the region is not increased, this only transfers carbon from one field to another (Olson, 2013; Jacobs et al., 2020). Furthermore, where measures strongly reduce food production without a corresponding reduction in food demand (such as large-scale conversions of arable land), they may contribute to indirect land use change (iLUC), ultimately resulting in the conversion of natural ecosystems into arable land to counter the supply-demand imbalance (Leifeld et al., 2019). This may cause very high greenhouse gas emissions and offset the positive climate impacts of the original measures (Searchinger et al., 2008).

2.2.6. *Transparency, legitimacy & accountability*

To ensure transparency, documentation of the procedures used for assessing SOC increases need to be freely available (Demenois et al., 2022), and certified SOC increases should be traceable to the field where they occurred. This also reduces the risk of double counting (Schneider et al., 2019). Transparency strongly contributes to the accountability and legitimacy of governance instruments and is crucial for them to effectively and reliably serve their purpose. For legitimacy, the respective motivations of farmers, certifiers and buyers of certificates (including perceptions of fairness) need to be considered, and the positioning of a scheme within the broader governance framework and its relation to other policy instruments need to be addressed. Finally, accountability depends on how liabilities are regulated if certified carbon removals are re-emitted.

2.2.7. *Synergies and trade-offs*

For an overall assessment of soil carbon certificates, co-benefits and trade-offs with other societal targets (e.g., adaptation to climate change, biodiversity protection, water retention, farming system resilience) need to be considered. These may arise either from the certificates themselves, from increased SOC levels, or from specific management measures. Please note that synergies and trade-offs related to climate change mitigation are not considered here because they are already addressed in category 2.2.4 (additional emissions).

3. Theoretical background of SOC accumulation in agric. soils

3.1. *SOC accumulation*

Soil carbon sequestration is based on organic matter (OM) entering the soil and on stabilization mechanisms protecting it from mineralization. OM can be present in the soil in many different forms and degrees of degradation at the same time. It is a source of nutrients and energy for soil organisms and is successively broken down by them. The contained SOC is either incorporated into new microbial biomass or respired and released. Various mechanisms can protect SOC from degradation in the short or long term, including (1) inclusion of OM in soil aggregates, spatially separating it from decomposers, (2) stabilization of OM by binding to clay minerals or iron oxides (organo-mineral associations), and (3) selective preservation of organic compounds due to their chemical structure (recalcitrance) (von Lützow et al., 2006). Under constant environmental conditions, the SOC stock approaches a long-term equilibrium between OM inputs (e.g., crop residues, roots and root exudates, organic fertilizers) and OM degradation. This dynamic equilibrium can be shifted by changes in soil management. To increase SOC stocks, the existing SOC must be preserved and more carbon must be bound (Chenu et al., 2019).

Build-up and decomposition of SOM occur as nonlinear processes (Chenu et al., 2019; Poeplau et al., 2011). The rate of SOC accumulation decreases over time as an increase of SOC stock also increases the rate of degradation. This means that SOC accumulation is faster when carbon farming measures are newly initiated (high effectiveness of carbon inputs) than shortly before reaching the new equilibrium. The quantitative relationship between turnover rates and SOM quantity is site-specific, e.g., higher in coarse-textured soils or warmer climates than in fine-textured soils or colder climates. Likewise, the period until a new equilibrium is reached depends on site conditions and management measures and can vary considerably.

Due to different soil characteristics (e.g., parent material, texture, mineralogy, structure, humidity), soils have different SOC storage potentials (Wiesmeier et al., 2019), which cannot be exceeded even with optimized management. In general, fine-textured soils with high silt and clay contents can store higher amounts of SOC than coarse-textured soils (Hassink, 1997). Soils that are depleted in SOC, e.g., due to long-term intensive management, can therefore store more additional carbon than soils that are already carbon-rich (Sanderman et al., 2017b). To keep the SOC stock constant at the new level, a higher carbon input than before the start of the measure must be permanently maintained.

3.2. *Agricultural management options*

Agricultural management strategies for carbon sequestration include crop choices, crop rotations, cover crops, retention of crop residues, use of organic fertilizers, agroforestry systems, addition of biochar, or change of tillage regime. Most strategies are based on increasing the amount of carbon entering the soil: perennial crops such as alfalfa or miscanthus can deliver higher carbon inputs than annual crops because of the longer vegetation time and continuous soil cover (Kantola et al., 2017; Poeplau and Don, 2014). Deep rooting crops (e.g., canola, hemp) use a larger soil volume to deliver carbon (He et al., 2021) than shallow rooting crops (e.g., maize, sunflower). Legumes (e.g., soy, lupine) enrich SOC stocks because of their specific microbiome (Watson et al., 2017). With the design of a diverse crop rotation (crop sequences, intercrops, cover crops) farmers can stimulate SOC stock increase by combining crops with complementary root systems, growth seasons, and soil coverage (Dynarski et al., 2020). Incorporating crop residues such as stubble or straw into the soil or the application of organic fertilizers (slurry, manure, compost or digestate) increases carbon inputs and thus SOC stocks. However, the application of external organic fertilizers typically only relocates carbon as these fertilizers would have been used on agricultural land anyway (Powlson et al., 2008). This constitutes a leakage effect (see section 2.1.5). Agroforestry systems that integrate woody species in agricultural land increase SOC stocks due to increased carbon inputs by pruning residues, litterfall, root turnover and rhizodeposition (Mayer et al., 2022; Drexler et al., 2021).

The addition of biochar to agricultural soils contributes to carbon sequestration by adding organic matter with a high stability against microbial degradation (Lehmann et al., 2006; Wang et al., 2016). In contrast to all other types of carbon inputs, biochar additions do not substantially increase microbial activity, and SOC increases caused by them are not limited by a soil's capacity and are maintained even if the measure is stopped. Reducing tillage may increase SOC levels in the topsoil by reducing the decomposition rate of SOC due to decreased disruption of soil aggregates (Balesdent et al., 2000). However, while this will raise the SOC content in the uppermost soil layers, less organic matter is incorporated into lower layers. If the entire soil profile is considered, reduced tillage may not lead to SOC increases but only induce a vertical redistribution of carbon (Haddaway et al., 2017; Luo et al., 2010; Meurer et al., 2018; Powlson et al., 2014). In contrast, deep inversion tillage in soils with compacted subsoil layers (e.g., hard or plough pan) or for pasture renewal may be an effective measure to foster carbon sequestration (Alcántara et al., 2016; Schiedung et al., 2019). The burial of C-rich topsoil (usually below 60 cm depth) results in reduced decomposition of organic matter, while fresh carbon inputs into the newly exposed, carbon-depleted subsoils may be effectively stabilized.

Overall, SOC accumulation mainly depends on the amount and quality of additional carbon inputs into the soil. It is influenced by pedoclimatic conditions, such as the initial SOC content, soil texture and structure, and climatic conditions such as temperature, rainfall patterns and soil moisture regimes. Consequently, average annual carbon accumulation rates differ widely, ranging from less than 0.1 ton for measures such as grassland management and set aside to more than 10 tons for the restoration of histosols (Paustian et al., 2016). The FAO series "Recarbonizing global soils – A technical manual of recommended management practices" provides global data for the potential of different carbon farming measures to increase SOC (FAO & ITPS, 2021).

4. Results and discussion

4.1. Are soil carbon certificates a suitable instrument for climate change mitigation?

4.1.1. Quantification of SOC changes

Measurement-based, model-based and remote sensing-based options for quantifying SOC changes are available. Measurement-based methods are well established and automatically account for site-specific effects such as soil type, structure or local climate. They also capture the effects of external influences such as droughts or heavy rainfalls. Due to the typically high spatial heterogeneity in soils, multiple sampling points are required to represent the SOC content of larger areas (FAO, 2020). At least initially, bulk density and rock fragment content need to be measured (Wiesmeier et al., 2020). The sampling should be carried out either in spring (in arable soils preferably in winter crops) before tillage and fertilization, or in autumn, in order to minimize interfering factors such as fresh organic matter from organic fertilizers. The sampling depth should at least comprise the tillage depth and be maintained in subsequent re-sampling even where carbon farming measures reduce tillage depth, to avoid biased interpretation of results. The SOC content (mass % or mg g^{-1}) of the samples should be determined for the fine soil (<2 mm) and carried out in the laboratory, preferably by combustion in CN analysers. SOC stocks (kg m^{-2} or Mg ha^{-1}) are then calculated, taking into account SOC content, bulk density and rock fragment content (Poeplau et al., 2017). To quantify SOC stock changes over time, identical sampling locations have to be re-sampled under similar field conditions. Intervals between samplings should be at least 3–5 years, in line with recommendations by FAO & ITPS (2020) who consider positive impacts of soil management measures to be observable typically within 4–8 years. Measurement-based options significantly reduce farmers' economic benefit from carbon certificates due to costs for sampling and laboratory analyses. Long-term monitoring for a climate-relevant time frame of 25 years or more would be economically unviable under current conditions.

Several providers of certificates use models to calculate SOC increases. While this approach is typically much cheaper than sampling, and while modelling capabilities are rapidly expanding due to progress in data science and artificial intelligence (Lischeid et al., 2022), precision depends on the quality of the input data, the complexity of the model, and on model calibration. In particular, the initial SOC stock and several years of agricultural management data are required as inputs for reliable model performance. Management data can be difficult to obtain and typically relies on self-information by the farmer. For example, in the European Union, field-specific management data on type and rate of organic fertilizer application are considered sensitive information and are therefore not publicly available. However, digitalisation in agriculture may make it easier in the future to obtain this data and feed the models if the farmers provide permission (Basso and Antle, 2020). In model-based approaches there is also the risk that external influences which reduce or reverse SOC sequestration, such as climate change or extreme weather events, are not adequately accounted for. Model-based approaches could be used for long term monitoring of SOC levels, though continuously collecting management and weather data for 25 years or more would also incur high costs. Combinations between measurement and model-based approaches are possible. The regulating authority for the Australian Emissions Reduction Fund has recently approved a method for long-time monitoring SOC levels where these two approaches alternate (Clean Energy Regulator, 2022).

Finally, remote sensing data could be used to cost-effectively map the SOC content in topsoils over large areas. However, a precise estimation requires bare soil conditions, a low water content and a uniform SOC content throughout the plough layer. Factors such as vegetation, crop residues, surface roughness and atmospheric disturbances hamper real world applications (Zepp et al., 2021; Castaldi et al., 2019) and studies have yet to show successful applications for detecting field specific SOC trends. Overall, at the current state of knowledge, model-based or remote sensing-based approaches seem to have a limited potential in the context of carbon certificates as evidence regarding their ability to precisely detect SOC changes is insufficient and extensive input data is required for regional calibration and validation. Satellite data could, however, be used in long-term monitoring to ascertain whether or not specific carbon farming measures are maintained.

Soil-carbon certification schemes are currently not regulated in Europe. While methods exist to reliably determine SOC changes, certification providers are not required to use them and may instead choose easier or cheaper alternatives. For example, in Germany one provider currently awards certificates based solely on default values for specific carbon farming measures, without consideration or measurement of soil properties and dynamics.

4.1.2. Additionality

Additionality is often poorly addressed in certification schemes. Whether management changes or SOC increases would have occurred even without the certification is typically not investigated. While several certifiers in Germany argue that management changes would be economically unviable and therefore would not have been implemented without carbon certificates, this argument is based on a simplistic view of farmers' decision making by focussing only on economic motives (Brown et al., 2021). Furthermore, it only considers the current situation while agricultural management is typically dynamic and adapting to changing driving forces (Mitter et al., 2020). For Germany, we found no example of certifiers addressing the issue of future changes to agricultural driving forces such as policies, prices and consumer demand, which could make agricultural management changes mandatory or economically viable in the near future. For example, the European Commission has defined the improvement of soil health as an essential mission and provides substantial funding through its research framework program 2021–2027. It is expected that this will improve the knowledge base about SOC increasing management and result in a more widespread uptake (EC, 2021a), even without certificates.

Furthermore, double funding is not always precluded in certification schemes, allowing farmers to receive payments for the same measures from additional sources, such as funding for agri-environment-climate measures under the European Common Agricultural Policy (CAP).

Finally, where natural fluctuations in carbon stocks occur, SOC changes on a certified site may not represent the effect of carbon farming measures. Certification schemes will then either under- or overestimate the additional carbon removal. Badgery et al. (2020) report such a case for low rainfall farming systems in Australia. These authors suggest to analyse benchmark sites where carbon farming is not practiced in addition to the certified fields. This would allow to separate the additional effect of carbon farming measures from naturally occurring SOC changes.

4.1.3. Permanence

SOC levels in soils represent a balance between organic inputs into the soil and carbon losses from microbial respiration (see 3.1 above). To prevent a re-release of stored carbon, farmers need to maintain SOC-increasing measures forever (Thamo and Pannell, 2016). Some management measures have a higher likelihood to be maintained, in particular measures that would entail high costs to undo, such as the implementation of agroforestry systems (Mayer et al., 2022). Nevertheless, a permanent continuation of measures typically cannot be guaranteed by private certification schemes with a limited contract length. An exception may be measures that cannot be reversed due to a legal protection status, such as the planting of hedgerows which are protected under European Union law. However, even where management is maintained, climatic change may reduce the SOC content due to increased warming-induced mineralization of SOC and/or reduced C inputs as a result of reduced precipitation and droughts (Walker et al., 2018). Results of a modelling study on global agricultural SOC dynamics between 1919 and 2018 already indicate substantial SOC losses due to climate change for all climatic zones (Poeplau and Dechow, 2022).

Several certification schemes address the issue of non-permanence by withholding part of the payment for SOC increases to the farmers, making them conditional on SOC levels being maintained for 2–3 years after the certification. However, these control periods are far too short to guarantee permanence in the context of climate change mitigation. Other certificate providers keep a share of certificates as an unsold buffer to account for possible re-emissions (Murray et al., 2007). As it is impossible to calculate the risk of management changes within the next 25 years or to predetermine effects of climate change on SOC at the local level during that time, buffer values are arbitrary and likely too low when considering the risk of a complete re-emission of sequestered carbon. Overall, guaranteeing permanence appears to be an insurmountable challenge for private certifiers.

4.1.4. *Additional emissions or emission reductions caused by carbon farming*

High site-specific SOM contents in soils can lead to increased N_2O emissions, reversing the climatic benefits of carbon sequestration in the long term (Lugato et al., 2018). However, carbon farming measures implemented in the context of soil carbon certificates typically do not achieve these high SOC levels. As a precaution, certificate providers could define soil-specific maximum SOC contents.

Some carbon farming practices reduce mineral fertilizer use through the use of organic fertilizers or cultivation of legumes. This could avoid emissions from the energy-intensive production of mineral fertilizers (Ramirez and Worrell, 2006; Amenumey and Capel, 2014). On the other hand, cultivation of legumes or the inclusion and fertilization of intercrops may increase the total nitrogen input into the soil and cause additional N_2O emissions. Furthermore, changes in field traffic and ploughing regime may affect the consumption of diesel and the associated CO_2 emission. To account for these effects, certificate providers need to assess farm management data. Emissions and emission reductions can be estimated from default values based on published life cycle assessments (LCA), though differentiated management practices are only starting to be accounted for in LCAs (Peter et al., 2017).

It is important to note that emission or emission reduction categories may already be covered by other governance instruments. In the EU, industries producing nitrogen fertilizers are part of a cap- and trade regulated Emission Trading Scheme (European ETS). A reduction in production-related emissions is therefore unlikely to affect total emissions. Within this context, carbon farming measures reducing mineral nitrogen fertilizer use can not be considered to create an additional climate benefit. Likewise, diesel emissions and emissions from fertilizer application are covered by the European Effort Sharing Decision (ESD) which sets mandatory emission reduction targets for EU Member States. Arguably, certificate providers may not need to account for emissions as long as public governance mechanisms are responsible for offsetting them, though in this case farmers would be remunerated for climate benefits they provide, while the burden of greenhouse gas emissions they cause in the process would be shifted to the public.

4.1.5. *Leakage effects*

Leakage effects may arise within or beyond the borders of a farm. Internal leakage effects occur where certificates motivate farmers to focus carbon farming measures, such as organic fertilization or the cultivation of SOC building crops, onto their certified fields while reducing these measures elsewhere. This risk could be avoided if certification were to require farmers to participate with all their fields, and if carbon gains would be balanced against carbon losses. However, for large farms this would require a very strong commitment.

External leakage effects arise where the certification motivates farmers to buy organic inputs such as manure or compost from external sources, thereby reducing the supply for other farmers. Certification schemes could be designed to prohibit farmers from increasing the use of external organic inputs, or they could decline to reward SOC increases based upon those. While the first option may be unattractive to farmers due to limiting their management options, the second option would be very difficult to implement in measurement-based certification schemes, since with multiple carbon farming measures taken in parallel it is not possible to quantify their respective contributions. For model-based certification schemes, this does not constitute a problem.

Finally, where carbon farming results in strongly reduced yields, indirect land use changes (iLUC) need to be considered. While the mechanism of iLUC is well understood, reliable models to predict iLUC are still lacking and there is no consensus on how to link them to small scale management changes. As a precautionary measure, The Gold Standard's *soil organic carbon framework methodology* (The Gold Standard Foundation, 2020) aims to exclude projects assumed to significantly reduce production, and to account for iLUC where unexpected decreases in production occur. However, since different crops in a rotation are characterized by different yield levels, detecting yield reductions within the typical time frame of a certification scheme (3–5 years) is challenging, especially if the implementation of carbon farming includes a change of crop rotation. As a proxy for detecting declines in production, the area used for food production in combination with yield levels relative to a regional benchmark could be used. In this way, both loss of productive area and a shift of production to less fertile lands could be detected.

4.1.6. *Transparency, legitimacy & accountability*

Certifiers typically provide farmers and customers with information on their methods for assessing SOC increases. Where soil sampling and standardized laboratory methods are used, transparency can be easily achieved. However, the use of models for calculating SOC increases is less transparent since they are complex and require extensive calibration. In such cases, the model code and description should be openly accessible. Ideally, models described in peer-reviewed scientific literature should be used.

To enable back-tracing of sold certificates, information on the fields where the SOC increase occurred could be added. While technically easy to implement, private data protection requirements may become an issue as not all farmers may want information on their fields to be published.

Beyond transparency, the effectiveness of certification schemes as a private governance instrument requires that all involved parties are convinced of the scheme's legitimacy and believe that their respective interests will not be violated (Juerges et al., 2018). In this context, the role of soil carbon certificates within the broader framework of climate, agricultural and environmental policy is of central importance. Hyams and Fawcett (2013) refer to the concept of a 'carbon management hierarchy', according to which offsets are considered a 'measure of last resort' in climate mitigation policy. Given the above-discussed issue of permanence, it is questionable whether soil carbon certificate schemes are suited for incorporation into larger governance systems (such as emissions trading), unless a credit/debit mechanism is introduced (van Kooten, 2009). Since potential certificate buyers usually cannot use the certificates as formal offsets to avoid paying carbon taxes or in an emissions trading market such as European ETS, the main purpose of soil carbon offsets from their perspective lies in corporate social responsibility (CSR) and similar 'signalling' activities. There is a potential conflict between the buyers' motivation (often criticized as greenwashing) and their (potential lack of) interest in high standards of certification schemes (Hyams and Fawcett, 2013). A lack of transparent and rigorous standards may affect how consumers who buy products sold by the offset buyers perceive these certification schemes, thereby challenging the legitimacy of the schemes and the "social license" under which they operate (Baumber et al., 2022). Another issue related to legitimacy is the perceived fairness of the instrument (see also Baumber et al., 2022). In particular, there is a trade-off between additionality (requiring to only reward management changes that would not have happened in the absence of certification) and common perceptions of fairness, as land users who already invested in soil carbon sequestration without certification will not be rewarded. This could even create perverse incentives to downgrade one's land before enrolling in a certification scheme. As perceived unfairness affects perceptions of legitimacy, strong additionality criteria could result in low participation in certification schemes. For a discussion of the additionality-fairness trade-off, see Jeffery and Verheijen (2020) and Bartkowski (2021).

Where certified SOC increases are not permanent and carbon is rereleased to the atmosphere, the question of accountability arises. From a legal perspective, both the contract between farmer and certifier, and the contract between certifier and buyer of certificates can easily be designed in a way that precludes liability. For example, instead of making statements regarding contributions to climate change mitigation, contracts can be limited to define how SOC increases in the certification scheme are determined, including information on the length of a potential monitoring period. On the other hand, where companies buy soil carbon certificates to offset their emissions and advertise their products as climate neutral, consumers will understand this claim to mean a permanent offset of emissions. If the carbon removals the claim is based on are however non-permanent, this constitutes false advertising over which consumers or consumer organizations may sue. A reference to the specifics of the certification scheme is not sufficient in this case, because advertising is considered misleading where it intentionally makes the customer believe in product properties that do not exist.

In Europe, double counting of soil carbon certificates is not considered a significant problem, because certificates are currently not eligible to be included in public climate change mitigation schemes, such as the European ETS or the UNFCCC's Clean Development Mechanism (CDM) (Bossio et al., 2020; Schneider et al., 2019). This is different for Australia's Emissions Reduction Fund which is used both by industries to offset accountable emissions and by the government to contribute to reduction targets under the Paris Agreement. Here, questions of double counting are highly relevant (Keenor et al., 2021).

4.1.7. Synergies and trade-offs

Soil carbon certificates can be linked to multiple synergies and trade-offs with objectives beyond climate change mitigation. We discuss them by first addressing effects of the certificates themselves, then effects of SOC level changes and finally effects from specific management measures.

Synergies related to the certification itself may arise where the sale of soil carbon certificates contributes to a diversification of farm income, leads to a more positive perception of farmers by society, or motivates farmers to re-think their management and implement more environmentally friendly practices. Synergies of increased SOC levels are likely to occur because SOC improves soil structure, aggregate stability, and belowground biological activity. This in turn leads to improved nutrient turnover and plant growth (Sanderman et al., 2017a), increased yield stability (Droste et al., 2020), increased water retention capacities and drought resistance, as well as higher water infiltration rates which reduce the risk of flooding and water erosion after heavy rainfalls (Hamidov et al., 2018). Increasing SOC levels has therefore always been the key principle of sustainable agriculture, and it may also play a key role in climate change adaptation.

A number of synergies are also caused by specific carbon farming measures. Longer and more diversified crop rotations and agroforestry systems lead to increased above-ground biodiversity (Tscharntke et al., 2012) and improved pollination services and pest control (Tamburini et al., 2020). The cultivation of catch crops and reduced tillage practices create a continuous soil cover which may reduce erosion (Hösl and Strauss, 2016; Cerda et al., 2022) and lower the risk of groundwater contamination with fertilizers (Klages et al., 2020, 2022). Increasing the share of legumes also contributes to a higher domestic production of plant-based proteins. Overall, increasing SOC is a cornerstone for a systemic transformation towards climate-friendly, more resilient cropping systems.

A trade-off applying to all emission offsets is that buyers of certificates may reduce their efforts to decrease or avoid emissions due to "moral licensing" or rebound effects (Paul et al., 2019). Consequences may be aggravated if the global climate reacts more strongly to the emission of greenhouse gases than to their removal via carbon sequestration, as findings by Zickfeld et al. (2021) indicate. Where farmers receive a certification for environmentally friendly behaviour, this could also contribute to complacency and reduce the motivation to implement further, not remunerated environmental measures ("motivational crowding out"; see Rode et al., 2015).

Increased SOC levels in agricultural soils are typically not considered to cause trade-offs, though high site-specific SOC levels with associated high microbial turnover rates could result in an excess of mineral nitrogen in the soil with negative consequences for the environment.

Under the current price system for agricultural products, carbon farming measures tend to reduce farmers' economic returns, though carbon certificates could help to overcome this problem, especially in light of rising carbon prices. Reduced tillage may result in higher applications of herbicides to compensate for the lack of mechanical weeding, with negative impacts on biodiversity (Schröder et al., 2020). Several carbon farming measures, such as planting hedges, the inclusion of short rotation coppice, intercropping, or the incorporation of plant residues into the soil may also result in a lower production of food (e.g., through a reduction of the area used for food production or where plant residues could alternatively be used as feed). This may contribute to leakage effects and indirect land use changes which not only cause greenhouse gas emissions as addressed in 4.1.3, but also have negative implications for biodiversity preservation.

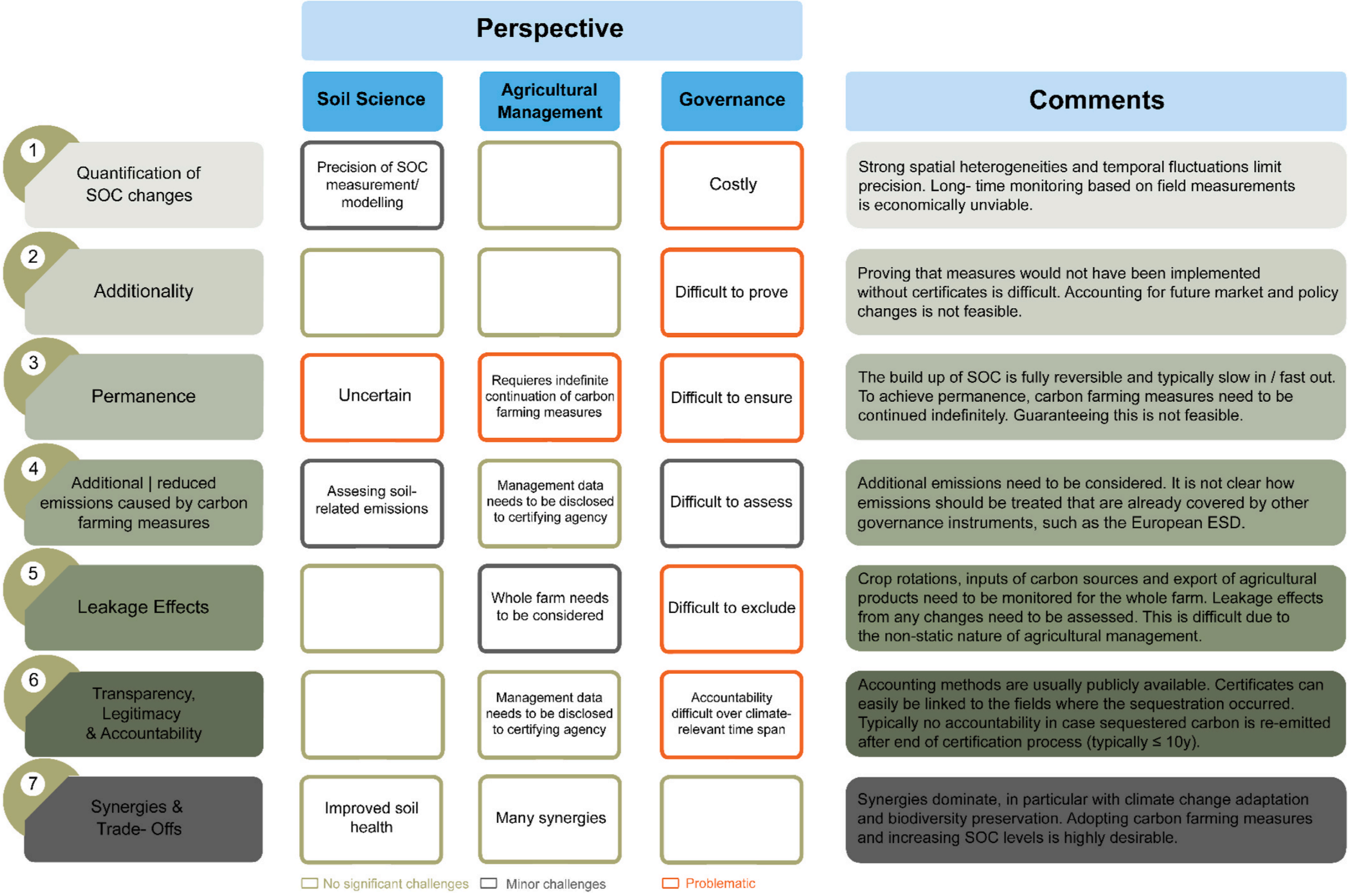
4.2. Overview of challenges

Fig. 2 provides an overview of the identified challenges from the perspectives of soil science, agricultural management and governance. It highlights that most problems regarding the use of private carbon certificates as an instrument for climate change mitigation relate to issues of governance, though ensuring permanence of carbon sequestration is considered problematic under all three perspectives.

Reasons for why governance of these certificates is particularly challenging mostly relates to economics and time. For private companies, the cost of long-term monitoring, or of rigorous controls to ensure additionality and prevent leakage effects are economically unviable, particularly if due to the lack of legal requirements or common standards, certificates with laxer requirements can be marketed as well. Furthermore, delaying the sale of certificates or providing guarantees over climate relevant time-frames of several decades is challenging, especially for start-ups or small companies.

4.3. Knowledge gaps and future perspective

The mechanisms linking carbon removals and atmospheric CO_2 concentrations are still insufficiently understood. While carbon offsets



	Perspective			
	Soil Science	Agricultural Management	Governance	Comments
1 Quantification of SOC changes	Precision of SOC measurement/ modelling		Costly	Strong spatial heterogeneities and temporal fluctuations limit precision. Long- time monitoring based on field measurements is economically unviable.
2 Additionality			Difficult to prove	Proving that measures would not have been implemented without certificates is difficult. Accounting for future market and policy changes is not feasible.
3 Permanence	Uncertain	Requieres indefinite continuation of carbon farming measures	Difficult to ensure	The build up of SOC is fully reversible and typically slow in / fast out. To achieve permanence, carbon farming measures need to be continued indefinitely. Guaranteeing this is not feasible.
4 Additional | reduced emissions caused by carbon farming measures	Assesing soil-related emissions	Management data needs to be disclosed to certifying agency	Difficult to assess	Additional emissions need to be considered. It is not clear how emissions should be treated that are already covered by other governance instruments, such as the European ESD.
5 Leakage Effects		Whole farm needs to be considered	Difficult to exclude	Crop rotations, inputs of carbon sources and export of agricultural products need to be monitored for the whole farm. Leakage effects from any changes need to be assessed. This is difficult due to the non-static nature of agricultural management.
6 Transparency, Legitimacy & Accountability		Management data needs to be disclosed to certifying agency	Accountability difficult over climate-relevant time span	Accounting methods are usually publicly available. Certificates can easily be linked to the fields where the sequestration occurred. Typically no accountability in case sequestered carbon is re-emitted after end of certification process (typically ≤ 10y).
7 Synergies & Trade- Offs	Improved soil health	Many synergies		Synergies dominate, in particular with climate change adaptation and biodiversity preservation. Adopting carbon farming measures and increasing SOC levels is highly desirable.

☐ No significant challenges ☐ Minor challenges ☐ Problematic

Fig. 2. Overview of the challenges associated with using soil carbon certificates as privately traded, voluntary emission offsets.

typically assume that one tonne of carbon sequestered cancels out on tonne of CO_2 emitted, natural buffers such as the worlds' oceans may lead to asymmetric responses of the climate system (Zickfeld et al., 2021). For effective climate policy, it is imperative to improve our understanding of the effects of CO_2 removals and emissions, potential interlinkages, and the timing of effects, especially considering climatic tipping points.

Additional knowledge gaps pertain to the lack of permanence. Where carbon farming measures are discontinued, elevated SOC levels will revert back to original levels and CO_2 will be re-released. While some certification schemes maintain a buffer of unsold certificates to account for this, the size of these buffers is arbitrary. Models or projections are lacking that could estimate the percentage of farmers who continue specific carbon farming measures as a function of time after the end of the certification process.

Even practices that remove carbon only temporarily can make a contribution to climate change mitigation (Leifeld and Keel, 2022). Determining the typical duration of soil-based carbon removals and establishing models to quantify the mitigation effect of temporary sinks may be a way forward to consider carbon farming measures in certification schemes and climate accounting. Standardized methods, indicators, and monitoring systems that account for measurement errors and model uncertainties are needed to establish transparent, comparable, and reliable schemes.

5. Conclusion and recommendations

Increasing the SOC content of agricultural soils is highly desirable, contributing not only to climate change mitigation but also to climate change adaptation. Carbon farming measures that can achieve such increases are well known and likely to come with multiple co-benefits such as improved yield stability and biodiversity preservation. While soil carbon certificates could provide a financial incentive for measures that are currently economically unviable, their use as voluntary emission offsets is highly problematic: Private certification providers cannot effectively guarantee permanence of carbon sequestration over climate relevant time-frames. Furthermore, claims of additionality tend to be based on the assumption that farmers' management decisions are solely guided by economic short-term considerations; and only the current situation is used for a counterfactual scenario, while possible future market, technology and policy changes are not considered. Assessing and preventing leakage effects is very challenging due to the dynamic, interconnected and complex nature of agricultural systems. Finally, where SOC increases are reversed through discontinuation of carbon farming measures or external influences, the re-emission of CO_2 may not even be detected due to a lack of long-time monitoring. Neither farmers nor certificate providers will typically be liable for this if it occurs after the end of the certification contract. However, where companies use soil carbon certificates to market their products as climate neutral, this constitutes false or misleading advertising in case of non-permanence. While in theory consumers could sue, it would be difficult to prove non-permanence in the absence of long-term monitoring.

In the long tem, soil carbon certificates are likely to fall short of providing the certified emission offsets, and funds for climate change mitigation should therefore be used more effectively elsewhere, ideally by supporting emission reductions.

Private investment can however make an important contribution towards a sustainable transformation of agriculture towards more climate- and environmentally friendly management and increased resilience. Development of alternative schemes and labels to support this are highly desirable. Incentives for farming measures that increase SOC could for example focus on benefits such as improved soil health, biodiversity preservation, or climate change adaptation. Research and development of private business models and public governance options to encourage carbon farming should be increased.

Credit author statement

Carsten Paul: Conceptualization, Methodology, Investigation, Writing – original draft preparation, Visualization, Writing- Reviewing and Editing, Supervision; Bartosz Bartkowski: Investigation, Writing – original draft preparation, Writing- Reviewing and Editing; Cenk Dönmez: Investigation, Writing – original draft preparation, Writing- Reviewing and Editing; Axel Don: Investigation, Writing – original draft preparation, Writing- Reviewing and Editing; Stefanie Mayer: Investigation, Writing – original draft preparation, Writing- Reviewing and Editing; Markus Steffens: Investigation, Writing – original draft preparation, Writing- Reviewing and Editing; Sebastian Weigl: Investigation, Writing – original draft preparation, Writing- Reviewing and Editing; Martin Wiesmeier: Conceptualization, Investigation, Writing – original draft preparation, Writing- Reviewing and Editing, Supervision; André Wolf: Investigation, Writing – original draft preparation, Writing- Reviewing and Editing; Katharina Helming: Conceptualization, Methodology, Investigation, Writing – original draft preparation, Visualization, Writing- Reviewing and Editing, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors would like to thank K.C. Meier for improving the layout of the figures and S. Abulkosimova for help with organizing the references. We would also like to thank the editor and seven anonymous reviewers for their helpful comments and suggestions. Part of this work was funded by the German Federal Ministry of Education and Research (BMBF) under the grant scheme BonaRes – Soil as a Sustainable Resource for the Bioeconomy, numbers 031B0511A, 031B0511B and 031B0511C.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.117142.

References

Alcántara, V., Don, A., Well, R., Nieder, R., 2016. Deep ploughing increases agricultural soil organic matter stocks. Global Change Biol. 22 (8), 2939–2956. https://doi.org/10.1111/gcb.13289.

Amenumey, S.E., Capel, P.D., 2014. Fertilizer consumption and energy input for 16 Crops in the United States. Nat. Resour. Res. 23, 299–309. https://doi.org/10.1007/s11053-013-9226-4.

Badgery, W.B., Mwendwa, J.M., Anwar, M.R., Simmons, A.T., Broadfoot, K.M., Rohan, M., Singh, B.P., 2020. Unexpected increases in soil carbon eventually fell in low rainfall farming systems. J. Environ. Manag. 261, 110192 https://doi.org/10.1016/j.jenvman.2020.110192.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53 (3), 215–230. https://doi.org/10.1016/S0167-1987(99)00107-5.

Bartkowski, B., 2021. Don't throw efficiency out with the bathwater: a reply to Jeffery and Verheijen (2020). Environ. Sci. Pol. 122, 72–74. https://doi.org/10.1016/j.envsci.2021.04.011.

Bartkowski, B., Bartke, S., 2018. Leverage points for governing agricultural soils: a review of empirical studies of European farmers' decision-making. Sustainability 10 (9), 3179. https://doi.org/10.3390/su10093179.

Baumber, A., Waters, C., Cross, R., Metternicht, G., Simpson, M., 2020. Carbon farming for resilient rangelands: people, paddocks and policy. Rangel. J. 42 (5), 293–307. https://doi.org/10.1071/rj20034.

Basso, B., Antle, J., 2020. Digital agriculture to design sustainable agricultural systems. Nat Sustain 3, 254–256. https://doi.org/10.1038/s41893-020-0510-0.

Baumber, A., Cross, R., Waters, C., Metternicht, G., Kam, H., 2022. Understanding the social licence of carbon farming in the Australian rangelands. Sustainability 14, 174. https://doi.org/10.3390/su14010174.

Bomgardner, M., Erickson, B., 2021. Carbon farming gets off the ground. Chem. Eng. News 99 (18), 22–28.

Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R.J., von Unger, M., Emmer, I.M., Griscom, B.W., 2020. The role of soil carbon in natural climate solutions. Nat. Sustain. 3, 391–398. https://doi.org/10.1038/s41893-020-0491-z.

Brown, C., Kovács, E., Herzon, I., Villamayor-Tomas, S., Albizua, A., Galanaki, A., Grammatikopoulou, I., McCracken, D., Olsson, J.A., Zinngrebe, Y., 2021. Simplistic understandings of farmer motivations could undermine the environmental potential of the Common Agricultural Policy. Land Use Pol. 101, 105136 https://doi.org/10.1016/j.landusepol.2020.105136.

Castaldi, F., Chabrillat, S., Don, A., van Wesemael, B., 2019. Soil organic carbon mapping using LUCAS Topsoil database and Sentinel-2 data: an approach to reduce soil moisture and crop residue effects. Rem. Sens. 11 (18), 2121. https://doi.org/10.3390/rs11182121.

Cerda, A., Franch-Pardo, I., Novara, A., Sannigrahi, S., Rodrigo-Comino, J., 2022. Examining the effectiveness of catch crops as a nature-based solution to mitigate surface soil and water losses as an environmental regional concern. Earth Syst Environ 6, 29–44. https://doi.org/10.1007/s41748-021-00284-9.

Cevallos, G., Bellassen, V., Grimault, J., 2019. Domestic Carbon Standards in Europe-Overview and Perspectives. I4CE Institute for Climate Economics. Research report. https://tinyurl.com/49bvvscs. (Accessed 12 August 2022). Accessed.

Chenu, C., Angers, D.A., Barré, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations. Soil Tillage Res. 188, 41–52. https://doi.org/10.1016/j.still.2018.04.011.

Clean Energy Regulator, 2022. Estimating Soil Organic Carbon Sequestration Using Measurement and Models Method. Clean Energy Regulator. Australian Government. https://tinyurl.com/yc5p785z. (Accessed 10 December 2022). Accessed.

Demenois, J., Dayet, A., Karsenty, A., 2022. Surviving the jungle of soil organic carbon certification standards: an analytic and critical review. Mitig. Adapt. Strategies Glob. Change 27 (1), 1–17. https://doi.org/10.1007/s11027-021-09980-3.

Drexler, S., Gensior, A., Don, A., 2021. Carbon sequestration in hedgerow biomass and soil in the temperate climate zone. Reg. Environ. Change 21 (3), 1–14. https://doi.org/10.1007/s10113-021-01798-8.

Droste, N., May, W., Clough, Y., Börjesson, G., Brady, M.V., Hedlund, K., 2020. Soil carbon insures arable crop production against increasing adverse weather due to climate change. Environ. Res. Lett. 15 (12), 124034 https://doi.org/10.1088/1748-9326/abc5e3.

Dynarski, K.A., Bossio, D.A., Scow, K.M., 2020. Dynamic stability of soil carbon: reassessing the "permanence" of soil carbon sequestration. Front. Environ. Sci. 8 https://doi.org/10.3389/fenvs.2020.514701.

EC: European Commission, 2021a. Reaping the Benefits of Healthy Soils for People, Food, Nature and Climate. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://tinyurl.com/4wx48rfw. (Accessed 12 August 2022). Accessed.

EC: European Commission, 2021b. Sustainable Carbon Cycles. Communication from the Commission to the European Parliament and the Council. https://tinyurl.com/4nj3ma4w. (Accessed 12 August 2022). Accessed.

EEA: European Environment Agency, 2021. Annual European Union Greenhouse Gas Inventory 1990 – 2019 and Inventory Report 2021. https://tinyurl.com/baxw29er. (Accessed 12 August 2022). Accessed.

FAO & ITPS, 2020. Protocol for the Assessment of Sustainable Soil Management. FAO, Rome.

FAO & ITPS, 2021. Recarbonizing Global Soils – A Technical Manual of Recommended Management Practices. Volume 1 – Introduction and Methodology. FAO, Rome. https://doi.org/10.4060/cb6386en.

FAO, 2020. A Protocol for Measurement, Monitoring, Reporting and Verification of Soil Organic Carbon in Agricultural Landscapes. GSOC-MRV Protocol, Rome. https://doi.org/10.4060/cb0509en.

FAO, 2021. Global, Regional and Country Trends 1990– 2019. FAOSTAT Analytical Brief Series No 28. In: Land Use Statistics and Indicators Statistics (Rome).

Goidts, E., Van Wesemael, B., Crucifix, M., 2009. Magnitude and sources of uncertainties in soil organic carbon (SOC) stock assessments at various scales. Eur. J. Soil Sci. 60 (5), 723–739. https://doi.org/10.1111/j.1365-2389.2009.01157.x.

Gu, J., Yuan, M., Liu, J., Hao, Y., Zhou, Y., Qu, D., Yang, X., 2017. Trade-off between soil organic carbon sequestration and nitrous oxide emissions from winter wheat-summer maize rotations: implications of a 25-year fertilization experiment in Northwestern China. Sci. Total Environ. 595, 371–379. https://doi.org/10.1016/j.scitotenv.2017.03.280.

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.-E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ. Evid. 6 (1), 1–48. https://doi.org/10.1186/s13750-017-0108-9.

Hamidov, A., Helming, K., Bellocchi, G., Bojar, W., Dalgaard, T., Ghaley, B.B., Hoffmann, C., Holman, I., Holzkämper, A., Krzeminska, D., Kværnø, S.H., Lehtonen, H., Niedrist, G., Øygarden, L., Reidsma, P., Roggero, P.P., Rusu, T., Santos, C., Seddaiu, G., Skarbøvik, E., Ventrella, D., Žarski, J., Schönhart, M., 2018. Impacts of climate change adaptation options on soil functions: a review of European case-studies. Land Degrad. Dev. 29 (8), 2378–2389. https://doi.org/10.1002/ldr.3006.

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soil 191 (1), 77–87. https://doi.org/10.1023/A:1004213929699.

He, W., Grant, B.B., Jing, Q., Lemke, R., St Luce, M., Jiang, R., Qian, B., Campbell, C.A., VanderZaag, A., Zou, G., Smith, W.N., 2021. Measuring and modeling soil carbon sequestration under diverse cropping systems in the semiarid prairies of western Canada. J. Clean. Prod. 328, 129614 https://doi.org/10.1016/j.jclepro.2021.129614.

Hösl, R., Strauss, P., 2016. Conservation tillage practices in the alpine forelands of Austria — are they effective? Catena 137, 44–51. https://doi.org/10.1016/j.catena.2015.08.009.

Hyams, K., Fawcett, T., 2013. The ethics of carbon offsetting. WIREs Climate Change 4 (2), 91–98. https://doi.org/10.1002/wcc.207.

IPCC, 2018. Summary for policymakers. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. World Meteorological Organization, Geneva, Switzerland, p. 32.

Jacobs, A., Heidecke, C., Jumshudzade, Z., Osterburg, B., Paulsen, H.M., Poeplau, C., 2020. Soil organic carbon certificates – potential and limitations for private and public climate action. Landbauforschung, J Sustainable Organic Agric Syst 70 (2), 31–35. https://doi.org/10.3220/LBF1605778405000.

Jeffery, S., Verheijen, F., 2020. A new soil health policy paradigm: pay for practice not performance. Environ. Sci. Pol. 112, 371–373. https://doi.org/10.1016/j.envsci.2020.07.006.

Juerges, N., Hagemann, N., Bartke, S., 2018. A tool to analyse instruments for soil governance: the REEL-framework. J. Environ. Pol. Plann. 20 (5), 617–631. https://doi.org/10.1080/1523908X.2018.1474731.

Kantola, I., Masters, M., DeLucia, E., 2017. Soil particulate organic matter increases under perennial bioenergy crop agriculture. Soil Biol. Biochem. 113, 184–191. https://doi.org/10.1016/j.soilbio.2017.05.023.

Keenor, S.G., Rodrigues, A.F., Mao, L., Latawiec, A.E., Harwood, A.R., Reid, B.J., 2021. Capturing a soil carbon economy. R. Soc. Open Sci. 8, 202305 https://doi.org/10.1098/rsos.202305.

Khatri-Chhetri, A., Juma, O.M., Wekesa, A., Recha, J., Radeny, M., 2020. Assessment of Adoption and Impact of Management Innovations in Agriculture Carbon Project in East Africa. Working Paper. https://hdl.handle.net/10568/110876.

Klages, S., Heidecke, C., Osterburg, B., 2020. The impact of agricultural production and policy on water quality during the dry year 2018, a case study from Germany. Water 12, 1519. https://doi.org/10.3390/w12061519.

Klages, S., Aue, C., Reiter, K., Heidecke, C., Osterburg, B., 2022. Catch crops in lower saxony—more than 30 Years of action against water pollution with nitrates: all in vain? Agriculture 12, 447. https://doi.org/10.3390/agriculture12040447.

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems – a review. Mitig. Adapt. Strategies Glob. Change 11 (2), 403–427. https://doi.org/10.1007/s11027-005-9006-5.

Leifeld, J., Keel, S.G., 2022. Quantifying negative radiative forcing of non-permanent and permanent soil carbon sinks. Geoderma 423, 15971. https://doi.org/10.1016/j.geoderma.2022.115971.

Leifeld, J., Müller, A., Steffens, M., 2019. Kriterien für die Zertifizierung von Kohlenstoffsenken in Landwirtschaftsböden. Agrarforschung Schweiz 10 (9), 346–349.

Lischeid, G., Webber, H., Sommer, M., Nendel, C., Ewert, F., 2022. Machine learning in crop yield modelling: a powerful tool, but no surrogate for science. Agric. For. Meteorol. 312, 108698 https://doi.org/10.1016/j.agrformet.2021.108698.

Lugato, E., Leip, A., Jones, A., 2018. Mitigation potential of soil carbon management overestimated by neglecting N2O emissions. Nat. Clim. Change 8 (3), 219–223. https://doi.org/10.1038/s41558-018-0087-z.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139 (1–2), 224–231. https://doi.org/10.1016/j.agee.2010.08.006.

Marion Suiseeya, K.R., Caplow, S., 2013. In pursuit of procedural justice: lessons from an analysis of 56 forest carbon project designs. Global Environ. Change 23 (5), 968–979. https://doi.org/10.1016/j.gloenvcha.2013.07.013.

Marks, A.B., 2020. (Carbon) Farming our way out of climate change. Denver Law Review 97 (3), 497–556.

Mayer, S., Wiesmeier, M., Sakamoto, E., Hübner, R., Cardinael, R., Kühnel, A., Kögel-Knabner, I., 2022. Soil organic carbon sequestration in temperate agroforestry systems – a meta-analysis. Agric. Ecosyst. Environ. 323, 107689 https://doi.org/10.1016/j.agee.2021.107689.

Meurer, K.H.E., Haddaway, N.R., Bolinder, M.A., Kätterer, T., 2018. Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—a systematic review using an ESM approach. Earth Sci. Rev. 177, 613–622. https://doi.org/10.1016/j.earscirev.2017.12.015.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.

Mitter, H., Techen, A.-K., Sinabell, F., Helming, K., Schmid, E., Bodirsky, B.L., Holman, I., Kok, K., Lehtonen, H., Leip, A., Le Mouël, C., Mathijs, E., Mehdi, B., Mittenzwei, K., Mora, O., Øistad, K., Øygarden, L., Priess, J.A., Reidsma, P., Schaldach, R., Schönhart, M., 2020. Shared socio-economic pathways for European agriculture and food systems: the eur-agri-SSPs. Global Environ. Change 65, 102159. https://doi.org/10.1016/j.gloenvcha.2020.102159.

Murray, B.C., Sohngen, B., Ross, M.T., 2007. Economic consequences of consideration of permanence, leakage and additionality for soil carbon sequestration projects. Climatic Change 80 (1–2), 127–143. https://doi.org/10.1007/s10584-006-9169-4.

Nitsch, H., Schramek, J., 2020. Strategien und Maßnahmen für den Klimaschutz bei der landwirtschaftlichen Flächennutzung im Rahmen der GAP, vol. 83. Institut für Ländliche Strukturforschung (IfLS) an der Goethe-Universität Frankfurt am Main, Frankfurt am Main.

Olson, K.R., 2013. Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: issues paper for protocol development. Geoderma 195–196, 201–206. https://doi.org/10.1016/j.geoderma.2012.12.004.

Otto, J., 2019. Precarious participation: assessing inequality and risk in the carbon credit commodity chain. Ann. Assoc. Am. Geogr. 109 (1), 187–201. https://doi.org/10.1080/24694452.2018.1490167.

Paul, C., Helming, K., 2019. Handbook of Soil-Related Impact Assessment. BonaRes Centre. https://doi.org/10.20387/bonares-6djm-e22m.

Paul, C., Techen, A.-K., Robinson, J.S., Helming, K., 2019. Rebound effects in agricultural land and soil management: review and analytical framework. J. Clean. Prod. 227, 1054–1067. https://doi.org/10.1016/j.jclepro.2019.04.115.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57. https://doi.org/10.1038/nature17174.

Peter, C., Helming, K., Nendel, C., 2017. Do greenhouse gas emission calculations from energy crop cultivation reflect actual agricultural management practices? – a review of carbon footprint calculators. Renew. Sustain. Energy Rev. 67, 461–476. https://doi.org/10.1016/j.rser.2016.09.059.

Poeplau, C., Dechow, R., 2022. The Legacy of One Hundred Years of Climate Change for Organic Carbon Stocks in Global Agricultural Topsoils. https://doi.org/10.21203/rs.3.rs-2126270/v1. Preprint (Version 1, 19 October 2022), Research Square.

Poeplau, C., Don, A., 2014. Soil carbon changes under Miscanthus driven by C4 accumulation and C3 decompostion–toward a default sequestration function. Gcb Bioenergy 6 (4), 327–338. https://doi.org/10.1111/gcbb.12043.

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach. Global Change Biol. 17 (7), 2415–2427. https://doi.org/10.1111/j.1365-2486.2011.02408.x.

Poeplau, C., Vos, C., Don, A., 2017. Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. Soils 3 (1), 61–66. https://doi.org/10.5194/soil-3-61-2017.

Powlson, D.S., Riche, A.B., Coleman, K., Glendining, M.J., Whitmore, A.P., 2008. Carbon sequestration in European soils through straw incorporation: limitations and alternatives. Waste Manag. 28 (4), 741–746. https://doi.org/10.1016/j.wasman.2007.09.024.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4 (8), 678–683. https://doi.org/10.1038/nclimate2292.

Ramirez, C.A., Worrell, E., 2006. Feeding fossil fuels to the soil: an analysis of energy embedded and technological learning in the fertilizer industry. Resour. Conserv. Recycl. 46 (1), 75–93. https://doi.org/10.1016/j.resconrec.2005.06.004.

Rode, J., Gómez-Baggethun, E., Krause, T., 2015. Motivation crowding by economic incentives in conservation policy: a review of the empirical evidence. Ecol. Econ. 117, 270–282. https://doi.org/10.1016/j.ecolecon.2014.11.019.

Rumpel, C., Amiraslani, F., Chenu, C., Cardenas, M.G., Kaonga, M., Koutika, L.-S., Ladha, J., Madari, B., Shirato, Y., Smith, P., Soudi, B., Soussana, J.-F., Whitehead, D., Wollenberg, E., 2020. The 4p1000 initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio 49 (1), 350–360. https://doi.org/10.1007/s13280-019-01165-2.

Sanderman, J., Creamer, C., Baisden, W.T., Farrell, M., Fallon, S., 2017a. Greater soil carbon stocks and faster turnover rates with increasing agricultural productivity. Soils 3, 1–16. https://doi.org/10.5194/soil-3-1-2017.

Sanderman, J., Hengl, T., Fiske, G.J., 2017b. Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. USA 114 (36), 9575–9580. https://doi.org/10.1073/pnas.1706103114.

Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag. 5 (1), 81–91. https://doi.org/10.4155/cmt.13.77.

Schiedung, M., Tregurtha, C.S., Beare, M.H., Thomas, S.M., Don, A., 2019. Deep soil flipping increases carbon stocks of New Zealand grasslands. Global Change Biol. 25 (7), 2296–2309. https://doi.org/10.1111/gcb.14588.

Schmidt, H., Pandit, B., Kammann, C., Taylor, P., 2017. Forest gardens for closing the global carbon cycle. The Biochar Journal 48–62, 2017. www.biochar-journal.org/en/ct/88. (Accessed 12 August 2022). Accessed.

Schneider, L., Duan, M., Stavins, R., Kizzier, K., Broekhoff, D., Jotzo, F., Winkler, H., Lazarus, M., Howard, A., Hood, C., 2019. Double counting and the Paris Agreement rulebook. Poor emissions accounting could undermine carbon markets. Science 366 (6462), 180–183. https://doi.org/10.1126/science.aay8750.

Schröder, J., Ten Berge, H.F.M., Bampa, F., Creamer, R.E., Giraldez-Cervera, J.V., Henriksen, C.B., Olesen, J., Rutgers, M., Sandén, T., Spiegel, H., 2020. Multi-functional land use is not self-evident for European farmers: a critical review. Front. Environ. Sci. 8, 156. https://doi.org/10.3389/fenvs.2020.575466.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319 (5867), 1238–1240. https://doi.org/10.1126/science.1151861.

Shames, S., Wollenberg, E.K., Buck, L.E., Kristjanson, P.M., Masiga, M., Biryahwaho, B., 2012. Institutional Innovations in African Smallholder Carbon Projects. https://hdl.handle.net/10568/21222.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6 (45), eaba1715. https://doi.org/10.1126/sciadv.aba1715.

Tang, K., Kragt, M.E., Hailu, A., Ma, C., 2016. Carbon farming economics: what have we learned? J. Environ. Manag. 172, 49–57. https://doi.org/10.1016/j.jenvman.2016.02.008.

Thamo, T., Pannell, D.J., 2016. Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage, and permanence. Clim. Pol. 16 (8), 973–992. https://doi.org/10.1080/14693062.2015.1075372.

The Gold Standard Foundation, 2020. Soil Organic Carbon Framework Methodology. Version 1.0. https://tinyurl.com/cf36uc6b. (Accessed 12 August 2022). Accessed.

Tiemeyer, B., Freibauer, A., Borraz, E.A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Ebli, M., Eickenscheidt, T., Fiedler, S., 2020. A new methodology for organic soils in national greenhouse gas inventories: data synthesis, derivation and application. Ecol. Indicat. 109, 105838 https://doi.org/10.1016/j.ecolind.2019.105838.

Tscharntke, T., Tylianakis, J.M., Rand, T.A., Didham, R.K., Fahrig, L., Batáry, P., Bengtsson, J., Clough, Y., Crist, T.O., Dormann, C.F., Ewers, R.M., Fründ, J., Holt, R. D., Holzschuh, A., Klein, A.M., Kleijn, D., Kremen, C., Landis, D.A., Laurance, W., Lindenmayer, D., Scherber, C., Sodhi, N., Steffan-Dewenter, I., Thies, C., van der Putten, W.H., Westphal, C., 2012. Landscape moderation of biodiversity patterns and processes - eight hypotheses. Biol. Rev. 87 (3), 661–685. https://doi.org/10.1111/j.1469-185X.2011.00216.x.

Union, European, 2020. Long-term Low Greenhouse Gas Emission Development Strategy of the European Union and its Member States. https://unfccc.int/documents/210328. (Accessed 12 August 2022). Accessed.

United Nations Framework Convention on Climate Change, 2006. Decisions Adopted by the Conference of the Parties Serving as the Meeting of the Parties to the Kyoto Protocol. 5/CMP.1 Modalities and Procedures for Afforestation and Reforestation. FCCC/KP/CMP/2005/8/Add.1. https://tinyurl.com/3jdndry5. (Accessed 12 August 2022). Accessed.

van Kooten, G.C., 2009. Biological carbon sequestration and carbon trading re-visited. Climatic Change 95 (3), 449–463. https://doi.org/10.1007/s10584-009-9572-8.

Verra: Verified Carbon Standard, 2020. VM0042 methodology for improved agricultural land management. Version 1.0. https://tinyurl.com/3emtwyey. (Accessed 12 August 2022). Accessed.

von Lützow, M., Kogel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. Eur. J. Soil Sci. 57 (4), 426–445. https://doi.org/10.1111/j.1365-2389.2006.00809.x.

Walker, T.W.N., Kaiser, C., Strasser, F., Herbold, C.W., Leblans, N.I.W., Woebken, D., Janssens, I.A., Sigurdsson, B.D., Richter, A., 2018. Microbial temperature sensitivity and biomass change explain soil carbon loss with warming. Nat. Clim. Change 8, 885–889. https://doi.org/10.1038/s41558-018-0259-x.

Wang, J., Xiong, Z., Kuzyakov, Y., 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8 (3), 512–523. https://doi.org/10.1111/gcbb.12266.

Watson, C.A., Reckling, M., Preissel, S., Bachinger, J., Bergkvist, G., Kuhlman, T., Lindström, K., Nemecek, T., Topp, C.F., Vanhatalo, A., 2017. Grain legume production and use in European agricultural systems. Adv. Agron. 144, 235–303. https://doi.org/10.1016/bs.agron.2017.03.003.

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschläger, U., Vogel, H.-J., Kögel-Knabner, I., 2019. Soil organic carbon storage as a key function of soils - a review of drivers and indicators at various scales. Geoderma 333, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026.

Wiesmeier, M., Mayer, S., Paul, C., Helming, K., Don, A., Franko, U., Steffens, M., Kögel-Knabner, I., 2020. CO2 certificates for carbon sequestration in soils: methods, management practices and limitations. BonaRes Series. https://doi.org/10.20387/bonares-ne0g-ce98.

Zepp, S., Heiden, U., Bachmann, M., Wiesmeier, M., Steininger, M., van Wesemael, B., 2021. Estimation of soil organic carbon contents in croplands of bavaria from SCMaP soil reflectance composites. Rem. Sens. 13 (16), 3141. https://doi.org/10.3390/rs13163141.

Zickfeld, K., Azevedo, D., Mathesius, S., Matthews, H.D., 2021. Asymmetry in the climate–carbon cycle response to positive and negative CO2 emissions. Nat. Clim. Change 11 (7), 613–617. https://doi.org/10.1038/s41558-021-01061-2.