Check for updates

Received: 26 June 2023 | Revised: 27 September 2023 | Accepted: 27 September 2023
DOI: 10.1111/gcb.16983

REVIEW

Global Change Biology WILEY

Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls

Axel Don[1] | Felix Seidel[1] | Jens Leifeld[2] | Thomas Kätterer[3] | Manuel Martin[4] | Sylvain Pellerin[5] | David Emde[1] | Daria Seitz[1] | Claire Chenu[6]

[1]Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany
[2]Climate and Agriculture Group, Agroscope, Zurich, Switzerland
[3]Department of Ecology, Swedish University of Agricultural Sciences, Upsala, Sweden
[4]Info&Sols Unit, INRAE, Orléans, France
[5]ISPA, Bordeau Sciences Agro, INRAE, Villenave d'Ornon, France
[6]Ecosys, Université Paris-Saclay, INRAE, AgroParisTech, Palaiseau, France

Correspondence
Axel Don, Thünen institute of Climate-Smart Agriculture, Braunschweig, Germany.
Email: axel.don@thuenen.de

Funding information
European Union Horizon 2020 Research and Innovation Programme, Grant/Award Number: 862695

Abstract

The term *carbon (C) sequestration* has not just become a buzzword but is something of a siren's call to scientific communicators and media outlets. *Carbon sequestration* is the removal of C from the atmosphere and the storage, for example, in soil. It has the potential to partially compensate for anthropogenic greenhouse gas emissions and is, therefore, an important piece in the global climate change mitigation puzzle. However, the term *C sequestration* is often used misleadingly and, while likely unintentional, can lead to the perpetuation of biased conclusions and exaggerated expectations about its contribution to climate change mitigation efforts. Soils have considerable potential to take up C but many are also in a state of continuous loss. In such soils, measures to build up soil C may only lead to a reduction in C losses (C loss mitigation) rather than result in real C sequestration and negative emissions. In an examination of 100 recent peer-reviewed papers on topics surrounding soil C, only 4% were found to have used the term *C sequestration* correctly. Furthermore, 13% of the papers equated C sequestration with C stocks. The review, further, revealed that measures leading to C sequestration will not always result in climate change mitigation when non-CO_2 greenhouse gases and leakage are taken into consideration. This paper highlights potential pitfalls when using the term *C sequestration* incorrectly and calls for accurate usage of this term going forward. Revised and new terms are suggested to distinguish clearly between C sequestration in soils, SOC loss mitigation, negative emissions, climate change mitigation, SOC storage, and SOC accrual to avoid miscommunication among scientists and stakeholder groups in future.

KEYWORDS
C removal, C sequestration, climate mitigation, negative emissions, soil carbon, soil organic carbon

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2023 The Authors. *Global Change Biology* published by John Wiley & Sons Ltd.

1 | INTRODUCTION

At the 21st United Nations Framework Convention on Climate Change (COP21) in Paris, socio-environmental challenges arising from the anticipated effects of global warming, such as increased risk of droughts and flooding, were identified and nature-based solutions for combating these effects were discussed (IPCC, 2021). The reduction of greenhouse gas (GHG) emissions through sustainable management of ecosystems is regarded as a key component in strategies for achieving this goal. Agricultural land, forests and wetlands have become increasingly prominent as land-use types that have the potential to store additional C in soils and biomass, thereby decreasing atmospheric CO_2 concentration and helping to mitigate climate change (Griscom et al., 2017). This focus has resulted in programs such as the 4per1000 initiative and various carbon (C) farming schemes (Minasny et al., 2017; Rumpel et al., 2020) aiming at increasing terrestrial C storage in managed ecosystems. Together, these ecosystems are seen as an actionable basis for achieving net zero GHG emissions by 2050 and preventing the rise of global temperatures beyond 2°C (IPCC, 2021).

Soil organic carbon (SOC) is dynamic in time and space and is continuously built up but also continuously decomposed and mineralised. Both SOC and soil inorganic carbon (SIC) occur in soils but this paper's focus is on SOC, since this is the main area of discussion in science and politics. SOC comprises all organic matter in soils that is dead. Changes in SOC stocks are small relative to existing large SOC stocks. Biomass in the form of aboveground and belowground litter, including woody material such as dead roots is entering the soil, thereby renewing parts of the SOC pool. Simultaneously, microbes decompose SOC, releasing a portion of carbon as respired CO_2 into the atmosphere. Observed changes in SOC stocks are thus mostly the consequence of two major fluxes: the fraction of net primary production entering the soil, for example, as litter and the respiration flux releasing C from the soil (Bondeau et al., 2007). The difference between the two fluxes is referred to as the net C balance of the soil. The net balance changes over time as a result of temporal variations in these two fluxes depending on various drivers. If the net C balance is positive soil takes up C. If soil C is increased relative to initial SOC as a result of reducing atmospheric carbon (e.g., via photosynthetic pathways), C sequestration is achieved.

What is ultimately of importance in relation to climate change mitigation is the SOC stock change on annual, decennial or centennial timescales, and the spatial domains in which this change occurs. In addition to the difficulty of measuring this net balance, the misuse of the terms related *to C sequestration in soils* can lead to misunderstandings and biased and unrealistic expectations of the role of agricultural and forest soils in their ability to contribute to climate change mitigation. Not every local or field-scale increase in terrestrial C stocks amounts to C sequestration, and not all C sequestration is a negative emission that contributes to climate change mitigation. Assessing the climate change mitigation potential of additional SOC stocks requires accounting for leakage effects (Lugato et al., 2018). Leakage describes additional GHG emissions caused by climate change mitigation measures that either reduce the strength of a C sink, or turn these measures into sources of GHGs.

The results and discussion surrounding C sequestration have implications beyond discipline-specific research circles, including for stakeholders such as politicians and farmers. There are risks of miscommunication if the terminology around C sequestration is not adequately defined and correctly used. Therefore, the aim of this paper was to revisit existing definitions of the terms *C sequestration*, *SOC sequestration*, *climate change mitigation*, *negative emissions*, *SOC storage*, and *SOC accrual*, with the goal of clarifying their meaning and ensuring their appropriate and accurate usage going forward. The results are presented of an evaluation of 100 recent peer-reviewed publications that use the term *C sequestration* or *SOC sequestration* in relation to soils in order to explore current use of the term, identify pitfalls associated with use of these terms based on their definitions, and outline a pathway for accurate communication in the field of C sequestration and negative GHG emissions.

2 | DEFINITION OF C SEQUESTRATION: NET UPTAKE OF CO_2 FROM ATMOSPHERE

Carbon sequestration is defined by the IPCC as the process of increasing the C content of a C pool other than the atmosphere (IPCC, 2001). Furthermore, for soil specifically, *C sequestration in soils* is described by Olson et al. (2014) as the "process of transferring CO_2 from the atmosphere into the soil of a land unit through plants, plant residues and other organic solids, which are stored or retained in the unit as part of the soil organic matter" (Table 1). The term *SOC sequestration* is frequently used with the same meaning despite it not being entirely correct since it involves the sequestration of atmospheric CO_2 rather than soil organic carbon (SOC). This means that for C sequestration in soils to occur, CO_2 must be drawn from the atmosphere and be converted into organic C via autotrophs metabolic activities, and then must enter the soil either directly (plant matter and plant residues produced on the same site) or indirectly (plant-derived organic matter such as manure or compost that derive mostly from other sites) in sufficient quantities to outweigh losses caused by respiration and lead to a net C stock increase in the soil (see example in Figure 1a). Consequently, as this C is derived from atmospheric CO_2, there is a commensurate net removal of C from the atmosphere, referred to here as *negative emissions* if the emission of other greenhouse gases (GHGs) is not simultaneously enhanced and the sum of all GHG fluxes (in CO_2 equivalent) is negative. To produce negative emissions, a measure needs to change the soil from a GHG source to a GHG sink, considering possible leakage.

C sequestration in soils is a term often used in the context of *climate change mitigation* because it is the process responsible for determining the flux of atmospheric C entering soils and turning them into C sinks. *Climate change mitigation* has been defined as "a human intervention to reduce emissions or enhance the sinks of greenhouse gases" (IPCC, 2021). Prior and post states of GHG fluxes need to be

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 Proposed definitions of key terms.

Term	Definition
C sequestration in soils	Process of transferring C from the atmosphere into the soil through plants or other organisms, which is retained as soil organic carbon resulting in a global C stock increase of the soil (based on IPCC, 2001; Olson et al., 2014)
SOC loss mitigation	An anthropogenic intervention to reduce SOC losses compared to a business-as-usual scenario
Negative emission	Net removal of CO_2-equivalents of greenhouse gases from the atmosphere
Climate change mitigation	An anthropogenic intervention that reduces the sources or enhance the sinks of greenhouse gases (based on IPCC, 2021)
SOC storage	The size of the SOC pool (i.e., SOC stock or SOC content)
SOC accrual	An increase in SOC stock at a given unit of land, starting from an initial SOC stock or compared to a business-as-usual value (does not always result in climate change mitigation or C sequestration in soils)

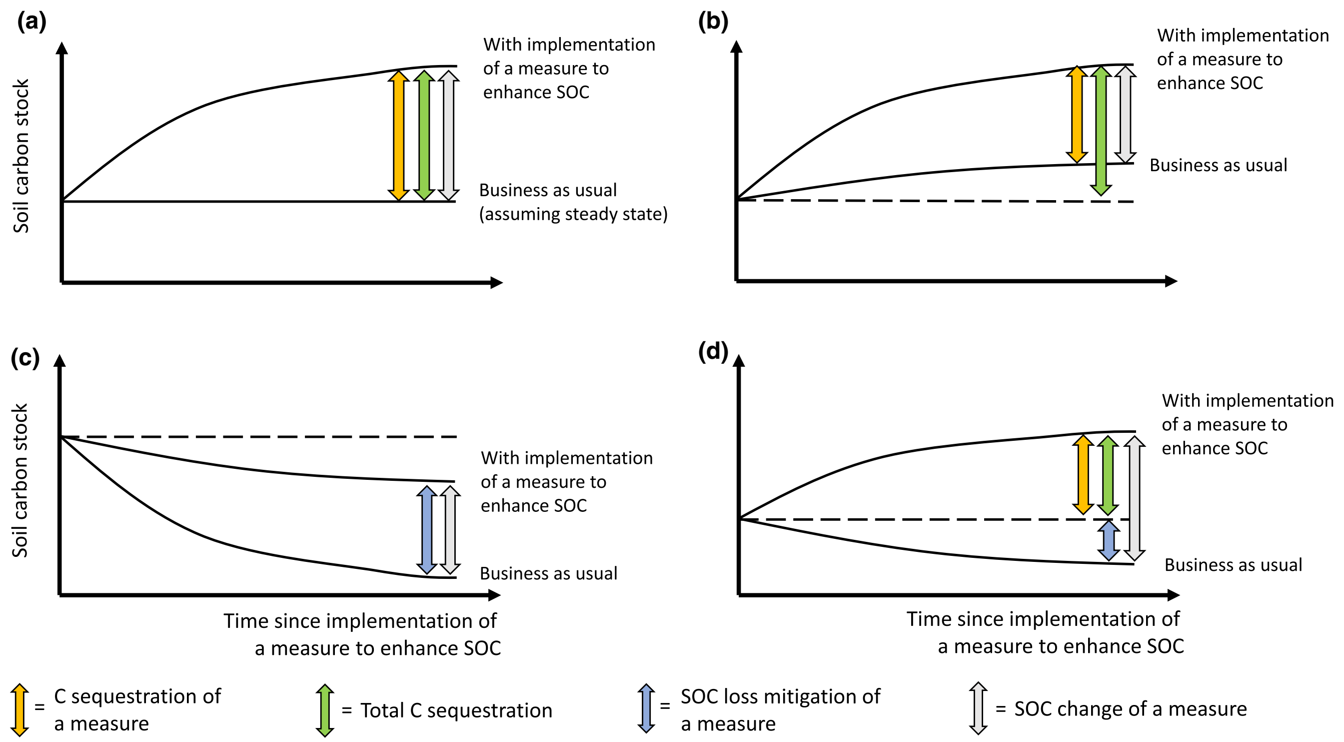

FIGURE 1 Possible trends in soil organic carbon (SOC) stocks in business-as-usual (BAU) scenarios and following implementation of C sequestration measures. (a) SOC stocks are assumed to be in steady state with no change in a BAU scenario, (b) SOC stocks are predicted to increase even without C sequestration measures in the BAU scenario, (c) SOC stocks are expected to decline in the BAU scenario despite the implementation of C sequestration measures, and (d) SOC stocks are expected to decline if no C sequestration measures are implemented. "SOC change of a measure" is relative to the BAU scenario. The dashed line indicates zero change. Calculations are provided in the Data S1.

compared (including C sinks) to quantify the *climate change mitigation* effect of such interventions. At the same time it is clear, a reduction of emissions does not equate to *negative emissions* but only of C sinks, and *C sequestration* in soils may not always lead to *climate change mitigation*, depending on past sink strength or past GHG emissions.

Furthermore, the terms *C sequestration* and *SOC storage* are often used synonymously, but have different implications (Baveye et al., 2023). *SOC storage* is used as either (i) a quantity, that is, the amount of SOC (e.g., SOC stock) or (ii) a process, that is, an increase in SOC stocks over time for a given land unit. The former is not associated with net removal of C from the atmosphere, and thus does not constitute actual *C sequestration in soils* (Chenu et al., 2019; Guenet et al., 2021), while the latter implies it. In order to reduce miscommunication potential, it is proposed that clear definitions of the terms are used. We propose definitions in Table 1. Mathematical formulations of the definitions are presented in Data S1 .

3 | CURRENT USE OF THE TERM *C SEQUESTRATION*

Use of the term *C sequestration* in the context of soils was surveyed and analyzed in 100 recent peer-reviewed publications with the aim of comparing the broader use of the term in current scientific literature with the definitions outlined above (Table 1). With this review we wanted to get a representative overview of how the term *C sequestration* is currently used. Publications were selected using the search string ("soil") AND ("carbon sequestration" OR "C sequestration") in the title or abstract in the Web of Science database on 12 October 2022. This produced 10,601 peer-reviewed publications, dated between 1945 and 2022, covering the fields of environmental sciences (28%), soil science (22%), ecology (12%), agronomy (8%), forestry (7%), plant sciences (6%), geosciences (6%), agriculture (5%), biodiversity conservation (3%) and other multidisciplinary sciences (3%). The top ten countries publishing 8794 (84%) of these studies were China (26%), USA (23%), Germany (7%), Australia (5%), India (5%), Canada (5%), UK (4%), Spain (3%), France (3%), and Italy (3%), with the remaining 16% of studies published in other countries. The 100 most recent publications covering April 2022 to October 2022 were then selected (see Data S1). The broad range of scientific disciplines and countries represented in the search results indicates the importance of the term *C sequestration* in soils across scientific communities, and the urgent need for standardization of the terminology surrounding the uptake, storage, and release of C in and from soils. Subsequently, based on the definitions given above, the following nine aspects were looked at when surveying the literature (Table 2).

After surveying the selected papers, it was found that 93% referred specifically to *SOC sequestration* or *C sequestration in soils* in the title or abstract, while 7% referred to *C sequestration* where the word *soil* is mentioned independently in the abstract. The majority of studies either focused on agricultural management

TABLE 2 Overview of the study details and survey criteria considered for 100 peer-reviewed studies involving carbon (C) or soil organic carbon (SOC) sequestration. The criteria (right column) are mutually exclusive.

	Aspect	Criteria
i.	Is C or SOC addressed?	• Only C sequestration mentioned OR • C/SOC sequestration in soils is mentioned
ii.	Is C/SOC sequestration in soils the major topic (regardless of definition)?	• C/SOC sequestration is mentioned but no related data or discussion is presented OR • Specific or related data are presented (e.g., soil organic matter data) or discussed
iii.	Representativeness	• Only a subunit of soil is considered (e.g., sequestration in aggregates) OR • a representative unit of soil (e.g., fine soil <2 mm) is considered
iv.	Soil depths considered?	• Not mentioned OR • Only top soil (<30 cm) OR • Subsoil also considered (>30 to ≤100 cm)
v.	Relative C increase vs. C sequestration in soils	• Higher C stock compared to a business-as-usual (BAU) scenario in steady state (relative C increase) OR • SOC increase compared to a dynamic BAU scenario or initial C stock
vi.	Usage of SOC storage as a mass or a flux?	• Only SOC stock/ SOC content reported OR • C flux or stock increase compared with a control treatment reported
vii.	Long-term storage (permanence) considered and ensured?	• Not mentioned OR • Mentioned OR • Accounted for OR • Accounted for and ensured (e.g., by incorporating C in recalcitrant products such as biochar where C sequestration is not easily reversible)
viii.	Time considered?	• C sequestration value provided without time dimension OR • C sequestration rate provided
ix.	Is leakage considered and accounted for in the greenhouse gas balance (e.g., N_2O emissions, loss of yield)?	• Not mentioned OR • Mentioned OR • Partially accounted for OR • Fully accounted for

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

practices that have the potential to increase C storage in soils (39%) or quantified the C sequestration potential of whole ecosystems (20%; Figure 2). Surprisingly, 42% of the 100 papers appeared to use the term C or SOC sequestration only to apply a broader context to their study. While the topics of these papers often included C or soil C, there was insufficient data, context, and meaningful C or SOC sequestration related discussion linked to the term C sequestration.

Soils are generally a relatively thin layer between the atmosphere and bedrock; however, in some regions they can be several decameters deep. The highest SOC stocks are found in topsoils which are also most susceptible to SOC changes because of their proximity to the atmosphere as well as anthropogenic impacts (Poeplau & Don, 2013). In 72% of the 100 analyzed papers representative soil units were studied. Subunits, such as aggregates, that are not necessarily representative of either topsoil or total soil were studied in 8% of the publications. The remaining 20% did not mention the soil unit that was analyzed (e.g., sieved <2 mm). Further, most papers referred only to the topsoil to 30 cm soil depth (55%) or made no mention of the soil depth for which their results were reported (34%). Only 11% of the studies explicitly included subsoils below 30 cm soil depth, demonstrating the systematic neglect of subsoil's contribution to soil C dynamics (Börjesson et al., 2018).

Following the definitions given in Table 1, none of the 42 papers that only used C sequestration in soils to put their study into a broader context without data or discussion of the topic applied the term correctly and, of the 58 remaining publications involving soil C-related topics, only 7% applied the term correctly (Figure 3b).

As many as 67% of the 100 papers compared experimental soil C values to a BAU scenario assuming that SOC stock is in a steady state. This assumption is oversimplified and unrealistic in most cases since SOC stocks change over time (Minasny et al., 2017; Sanderman et al., 2017). Thus, it is unclear whether they are showing a net SOC increase (*C sequestration*) or a relative increase compared to a reference treatment or BAU scenario. Finally, for 29% of the 100 papers no distinction could be made between correct or incorrect use of the term *C sequestration* as SOC was not the main topic of these papers and the information necessary to make this distinction was not given.

Overall, almost two-thirds of 100 recent peer-reviewed publications referred to *SOC storage* as an *SOC stock increase*, while 13% referred to *SOC storage* as *SOC stocks*. The remaining 25% of studies did not mention SOC stocks or SOC stock changes, despite discussing C sequestration (Figure S1a). These proportions did not change significantly when excluding publications in which C sequestration in soils was only used to put their study into a broader context without data or discussion of the topic (75%, 12% and 14% respectively, Figure S1b).

A value for total C sequestration within a time period (e.g., in Mg C ha^{-1}) was found in 40% of 100 recent peer-reviewed publications, while 57% gave a C sequestration rate (e.g., in kg C ha^{-1} year^{-1}) and 3% did not give any information at all. No large differences were found after excluding those publications that only used C sequestration in soils to put their study into a broader context without data or discussion of the topic (47%, 51% and 2%, respectively).

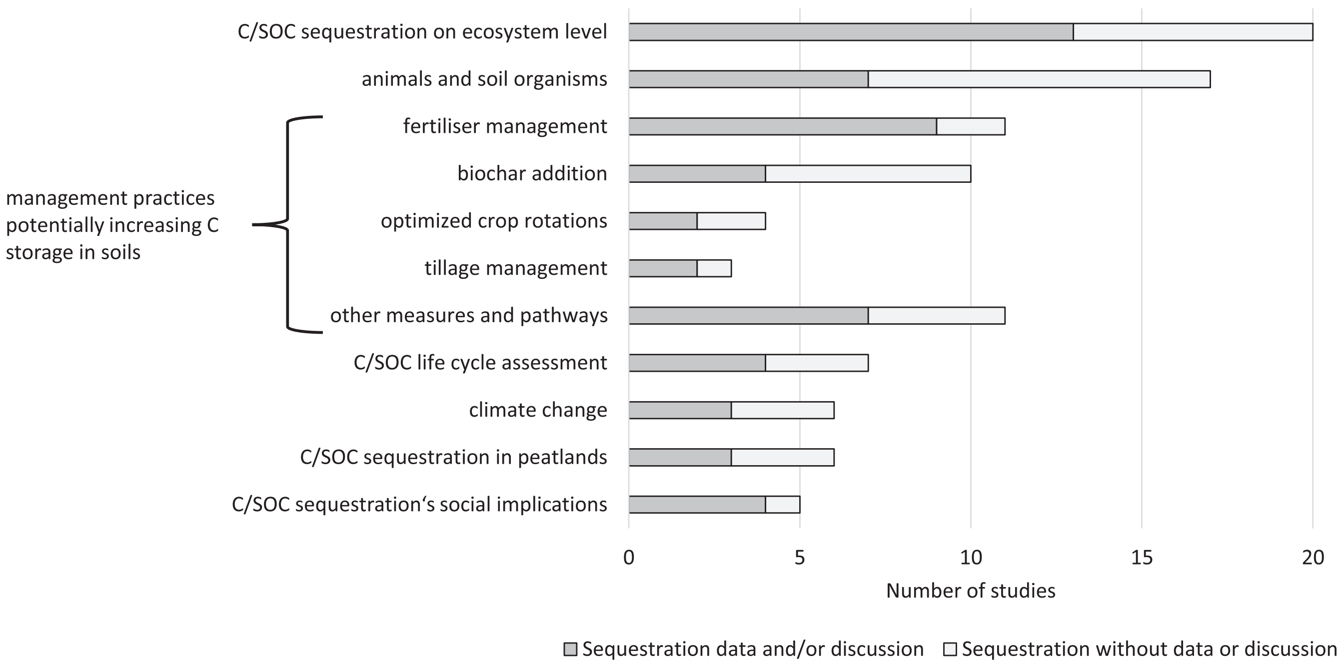

FIGURE 2 Main topics of 100 recent peer-reviewed publications following the search string (“soil”) AND (“C sequestration” OR “carbon sequestration”) in the title or abstract and divided into two groups: “C sequestration data and/or discussion of the topic” (dark bars) and “C sequestration used without data or discussion of the topic” (light bars).

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

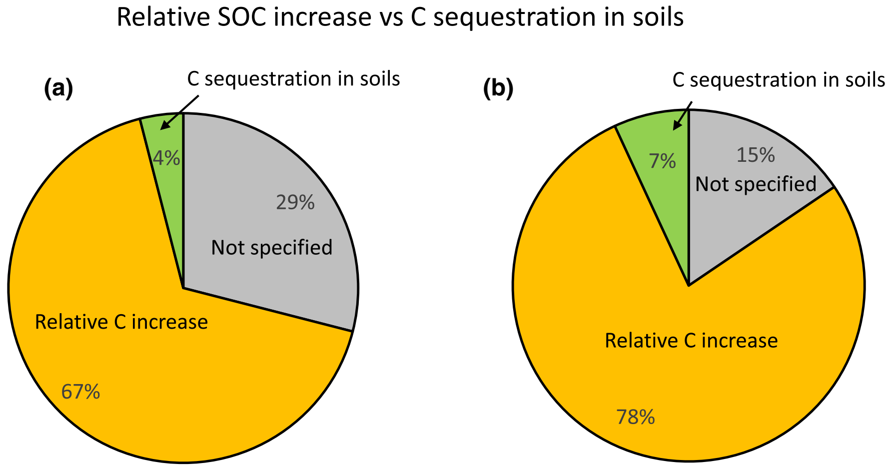

FIGURE 3 Use of the terms *carbon (C) sequestration* or *soil organic carbon (SOC) sequestration* in 100 recent peer-reviewed studies following the definitions shown in Table 1. In the studies, soil C was assessed either relative to a business-as-usual scenario in a steady state (orange) or as *C sequestration in soils* (green), as defined in this study for (a) all 100 publications and (b) a selection of 58 recent peer-reviewed publications excluding those that only use *C sequestration* without data or discussion of the topic. In all cases where study conditions could not be determined, these were considered "Not specified" (grey).

4 | PITFALLS OF USING THE TERM *C SEQUESTRATION* IN SOILS

The literature review underlines the cross- and intra-disciplinary confusion about the terms *C sequestration*, *negative emissions*, *climate change mitigation*, and *C storage* related to soil C. In this chapter, we want to show the pitfalls surrounding these words and how to avoid them.

4.1 | C sequestration in soils versus C loss mitigation

As a result of the definitions of IPCC (2021) and Olson et al. (2014) for the term *C sequestration in soils*, not every measure to enhance SOC will result in C sequestration and negative emissions with a net uptake of C from the atmosphere (Figure 4a). The SOC stocks of many agricultural soils are currently declining due to changes in land management, such as drainage, and historic land use changes but also to climate change (Ciais et al., 2010; Poeplau & Dechow, 2023; Sanderman et al., 2017). Agricultural measures can help reduce (Figure 4b) or stop this SOC loss or even achieve SOC build-up (Figure 4c,d) and thus true *C sequestration in soils* (Paustian et al., 2016). However, in cases where SOC losses are only reduced compared to a business-as-usual scenario (i.e., a SOC stock increase compared to a BAU scenario) this cannot be called *C sequestration in soils* as the soil is still losing SOC. Instead, use of the term *SOC loss mitigation* is proposed but also the term C stock protection is used (Whitehead et al., 2018; Figures 1c and 4b).

Previous literature referred to this as *relative C sequestration* (Peralta et al., 2022), but we considered this to be misleading since it does not represent a net removal of atmospheric CO_2 but uses the term *C sequestration*. Regardless of the underlying reasons for the decline in SOC, if SOC stocks do not increase over time true *C sequestration in soils* cannot be achieved. Therefore, a comparison of the difference in SOC stocks between a treatment that enhances SOC and a control treatment should not be interpreted as *C sequestration*; the initial SOC stock also needs to be considered. The difference in SOC stocks between SOC-enhancing treatments and a control treatment can instead be referred to as *SOC accrual* or *SOC increase*.

Some ecosystems are particularly SOC rich, such as peatlands and some grasslands and forests (Jobbagy & Jackson, 2000). The protection of their SOC stocks is important for climate change mitigation since many of them are actually C sources due to land use conversion or the agricultural use of peatland after drainage (Leifeld et al., 2019). Therefore, a business-as-usual scenario in which SOC is in decline needs to be defined in order to include measures to protect these SOC stocks as climate change mitigation measures, for example, if peatlands are rewetted to reduce or stop their CO_2 emissions compared to a business-as-usual scenario with drained peatlands (see Figure 1c). In these ecosystems the major aim is to achieve *climate change mitigation* by reducing GHG emissions rather than through *C sequestration*.

4.2 | C sequestration in soil, SOC storage or SOC stocks?

Only C that is additionally stored in soils or that is additional compared to a business-as-usual scenario can be relevant for climate change mitigation. Thus, C sequestration in soils is not the same as SOC stocks. Soil organic carbon sequestration refers to a net flux of C from the atmosphere to the soil. The rate unit should be mass C per area per time period, for example, $Mg\,C\,ha^{-1}\,year^{-1}$, while SOC stock is a mass per area, for example, $Mg\,C\,ha^{-1}$. In summary, the size of any C pool can be referred to as a C mass, C pool or C stock,

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

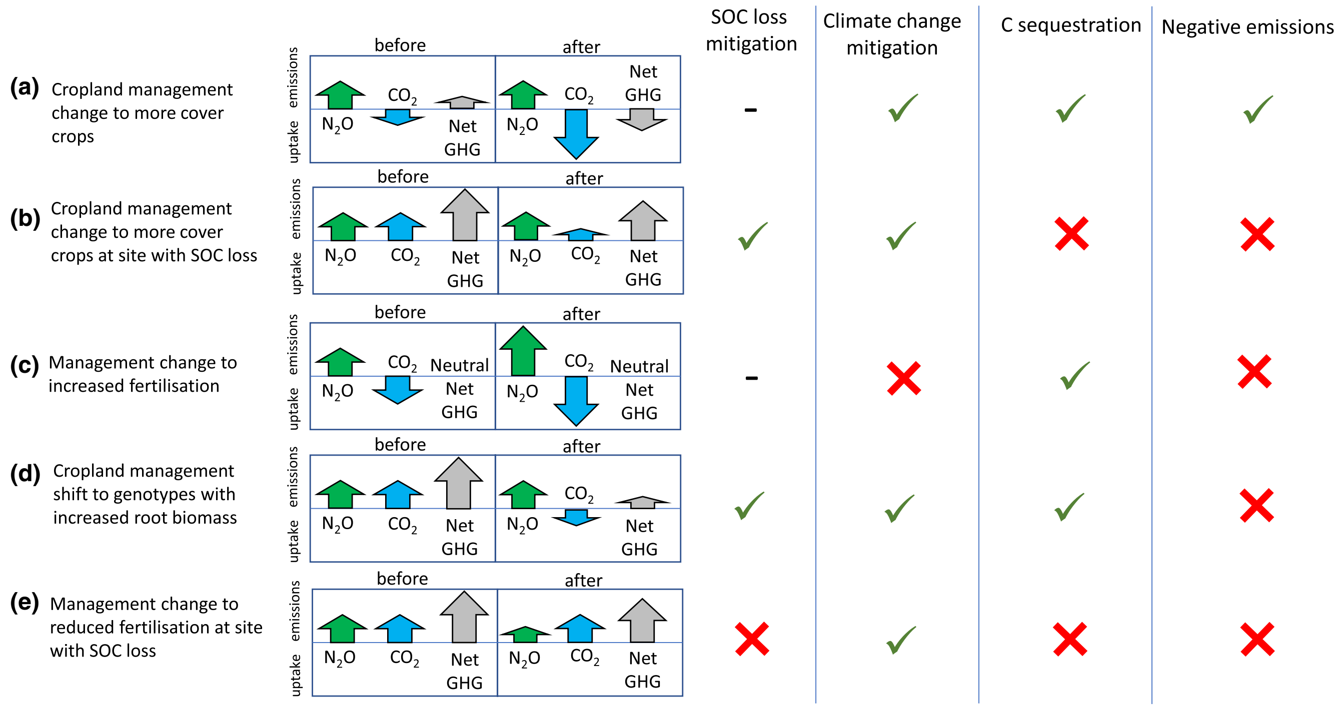

FIGURE 4 Theoretical examples of management changes (a–e) and their site-specific impacts on soil and atmospheric carbon pools and N_2O fluxes. Off-site fluxes (e.g., leakage) are not considered. Management examples are evaluated according to their effects on SOC loss mitigation, climate change mitigation, C sequestration and negative emissions. Arrow length represents the flux size in CO_2-equivalents. ✓: yes; ×: no; −: not applicable.

while C sequestration is the process of removing CO_2 from the atmosphere over time, which is always a C flux.

The present analysis showed that in 12% of the 58 publications that focused on C sequestration in soils, the term *SOC storage* was used synonymously with *SOC stocks*, while two thirds used it to describe an increase in SOC stocks (Figure S1). This highlights the potential for miscommunication resulting from a single term with two different definitions (as shown in Section 1). While the two uses are correct as storage describes both the act of storing or the state of being stored (Collin, 1982), we suggest that: (i) SOC content or stock is referred to as *SOC storage* and (ii) an increase in SOC stocks is referred to as *SOC accrual* (Table 1). While *SOC accrual* is related to *C sequestration in soils*, there is potential for differences in the source of C. Where *C sequestration in soils* requires the atmosphere to soil pathway of C accumulation, *SOC accrual* does not require atmospheric C as the source of C, and instead relates to any increase in SOC stocks at a given site. For example, *SOC accrual* can be due to eroded sediment that is deposited and increases SOC at one site. However, this is causing SOC depletion at another site where the sediment was derived from and thus, no net SOC increase (*C sequestration*) is achieved. Additionally, climate change mitigation effects were often claimed to be related to the size of the existing SOC stock at a single site (Baveye et al., 2023); however, the protection of existing SOC stocks is only a measure for climate change mitigation if in the business-as-usual scenario soils are losing SOC. In either case, *C sequestration in soils* is not achieved since there is no net uptake of C from the atmosphere.

4.3 | C flux or global warming potential

Differentiating between the global warming potential (GWP) of CO_2 and C mass is essential for understanding the effect of a measure on C fluxes and for climate change mitigation. The common unit to express the effect of GHGs on the climate is CO_2-equivalents (CO_2-eq). This converts N_2O and CH_4 emissions into equivalent units relative to the cumulative radiative forcing of CO_2 over a given period, usually 100 years. In contrast, *C sequestration in soils* refers to C mass which is representative of the number of C atoms removed from the atmosphere and is thus different from removals calculated in $CO_{2\text{-eq}}$, which are key when focusing on comparing the radiative effect of different GHGs. This is particularly important if methane (CH_4) is part of the evaluation, since it contains C but has a 28-fold higher global warming potential than CO_2 over a 100-year period. Paddy soils and peatlands are systems that emit large amounts of CH_4 (Jackson et al., 2020). Thus, C sequestration can be achieved with C removal from the atmosphere, but if CH_4 emissions increase at the same time, they can easily offset the climate change mitigation effect of C sequestration (Figure 5). Thus, C may be removed from the atmosphere (number of C atoms, Figure 5b) without negative emissions being achieved (unit $CO_{2\text{-eq}}$, Figure 5a). Although *C sequestration in soils* refers to C fluxes per number of C atoms, in the wider context of climate change mitigation the global warming effect of different greenhouse gases expressed as CO_2-equivalents is relevant.

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

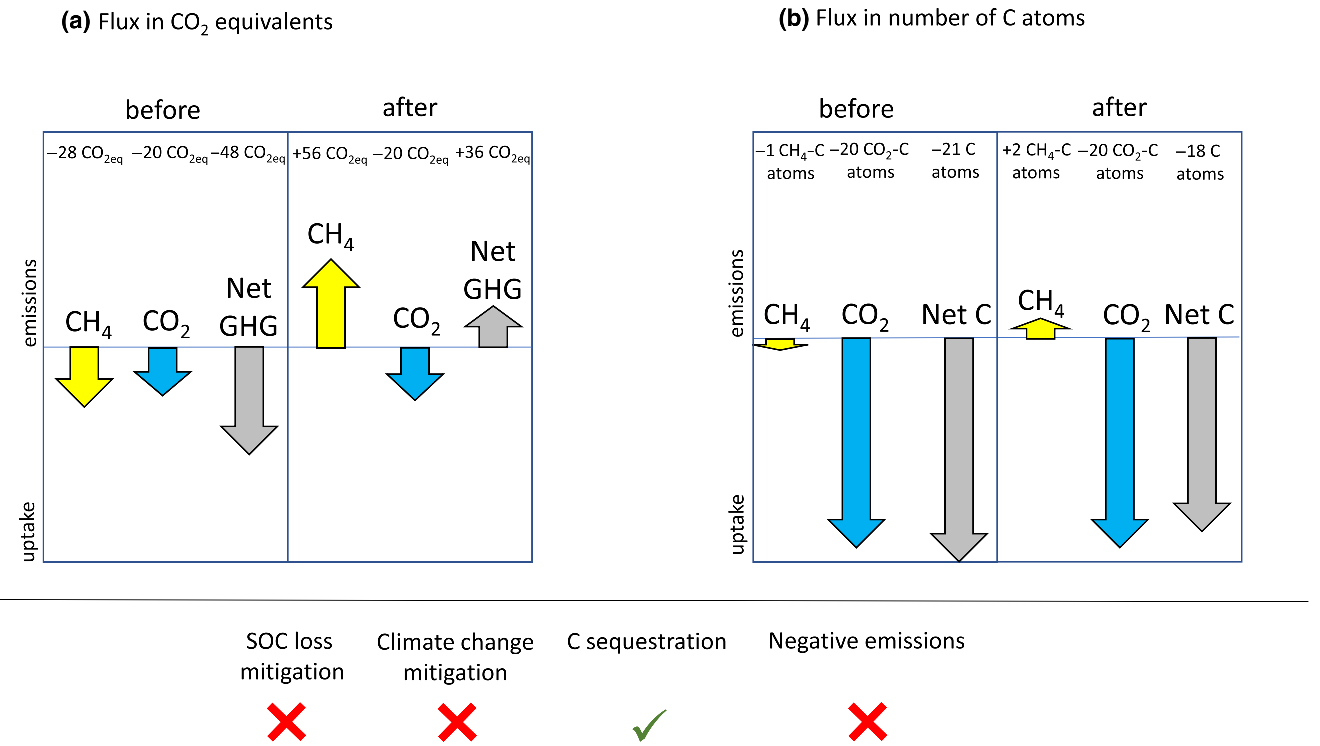

FIGURE 5 Net-exchange of methane (CH_4) and carbon dioxide (CO_2) between the soil and the atmosphere for a theoretical example of a management change and its site-specific impact in (a) CO_2-equivalents ($CO_{2\text{-eq}}$) and in (b) number of C atoms. Off-site fluxes (e.g., leakage) are not considered. Arrow lengths in (a) represent the flux size in CO_2-equivalents with a global warming potential of CH_4 of 28. CH_4 fluxes and CO_2 fluxes together result in the net greenhouse gas balance (net GHG) by assuming zero N_2O fluxes. By only considering the C in CH_4 and CO_2, we derived a net C balance (Net C). Arrow lengths in (b) represent the C flux size of CH_4-C and CO_2-C that together indicate SOC accrual (net C).

5 | FROM C SEQUESTRATION IN SOILS TO NEGATIVE EMISSIONS

5.1 | Permanence of additional SOC storage

There are diverging views on the conditionality of permanence for C sinks: CO2 storage in geological formations or the deep ocean is generally considered to stay for millennia whereas biomass C sinks in afforestations are considered as C sinks even though their storage time is often only measured in decades (Gren & Zeleke, 2016; Tyka et al., 2022). Thus, the permanence of C storage is context specific. Ideally, additional SOC is stored permanently but even temporary storage is beneficial. For instance, the climate benefit of SOC that is stored for 40 years before release is still 66% of that for SOC stored for 100 years before release (Leifeld & Keel, 2022). Thus, the time period for which additional SOC is stored is pivotal for its climate impact.

Carbon bound in soil organic matter is in a continuous flow. About 80%–90% of the C entering soils in the form of plant biomass is respired within a timespan of months to a few years in a temperate climate (Angers et al., 2022). Nevertheless, even such a dynamic C pool can be enhanced, and C stocks can probably be preserved in the long-term by adopting SOC increasing management practices (Johnston et al., 2017). Only 7% of 100 recent peer-reviewed publications considered or ensured long-term storage, for example, via stabilization as biochar. Furthermore, permanence was considered by 11%, at least mentioned by 46%, and not mentioned at all by 36% of all the studies considered. No notable differences were found when excluding publications that use C sequestration in soils only to put their study into a broader context without data or discussion of the topic (7%, 17%, 46%, 30%, respectively).

5.2 | Leakage can prevent C sequestration in soils from achieving climate change mitigation

Leakage of GHGs may determine whether or not an agricultural measure for C sequestration in soils is able to mitigate climate change or even achieve negative emissions. Leakage occurs if a measure to enhance SOC stocks leads to an increase in GHG emissions either on site (i.e., from the soil where SOC stocks are increased) or off site. Some agricultural measures for SOC accrual also increase on-site N_2O emissions to such an extent that the potential climate change mitigation effect of added SOC is completely negated or even reversed (Guenet et al., 2021; Lugato et al., 2018). This may be the case, for example, when SOC stock increases are obtained by promoting biomass production and thus C inputs to the soil as a result of additional N fertilization (Poeplau et al., 2018). Potential additional off-site emissions can be caused, for example, by increased energy consumption required for

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

fertilizer and machinery production and transport. Furthermore, leakage can occur due to indirect effects, for example, due to a reduced agricultural yield that may trigger the need for additional agricultural land and related C losses as a result of land-use changes. Such indirect land-use changes may even dominate the net GHG balance of agricultural measures for climate change mitigation and turn their balance from positive to negative (Kløverpris & Mueller, 2013; Searchinger et al., 2008). It is, therefore, not reasonable, or perhaps even possible, to fully account for all leakage effects in studies on C sequestration in soils due to the complexity of the topic. However, we encourage an increased awareness of such leakage effects when evaluating C sequestration measures.

Another form of leakage is the transfer of C from one site to another through organic amendments such as farm-yard manure or compost (Paustian et al., 2019). The level of these organic amendments is limited by the amount of biomass available to produce these organic fertilizers in the first place (Janzen et al., 2022). Thus, SOC cannot be increased with organic amendments at one site without a commensurate reduction of SOC from another site. Organic amendments are thus likely to enhance SOC stocks on a local scale (SOC accrual) without achieving SOC stock increases on a global scale (C sequestration in soils). Organic amendments can only boost SOC stocks globally if they are not returned to soil in the business-as-usual scenario (e.g., compost or sewage sludge that is currently incinerated) or some transformation increases the persistence of the resulting SOC. The latter is true for biochar, which has been shown to increase the mean residence time of organic C in soils significantly compared with its feedstock and therefore achieves C sequestration in soils (Schmidt et al., 2021). However, additional GHG emissions from processing of biochar and transport should be accounted for when evaluating its C sequestration potential.

Notably, of the 100 recent peer-reviewed publications reviewed, only 9% fully consider leakage by reporting a complete GHG balance, while 3% partially account for this (e.g., by accounting for just some GHGs but not all). Meanwhile, 20% mention that leakage effects exist or are possible, while the majority (68%) do not mention it at all. This does not change very much when excluding those publications that use C sequestration in soils only to put their study into a broader context without data or discussion of the topic (14%, 5%, 21% and 60%, respectively). Owing to the widespread potential for leakage in SOC-enhancing measures, spatially explicit accounting of SOC stock changes is not sufficient to capture the climate change mitigation potential of a measure, and therefore the global scale view is required to establish the true effect of C sequestration. That being said, for plot scale studies such global view is hardly possible and thus estimates on off-site and leakage effects may only be roughly estimated, discussed or mentioned.

5.3 | The temporal dimension of C sequestration: C stocks versus GHG fluxes

The implementation of management changes can induce SOC stock increases, but the achieved SOC accrual will decrease over time with SOC stocks approaching a new steady state between SOC formation and respiration (Chenu et al., 2019; Sommer & Bossio, 2014). Although the measure continues to be implemented, there is no further buildup of SOC once the new steady state is reached (Figure 1). In particular, if agricultural measures are implemented to increase SOC that also enhance GHG emissions such as N_2O (i.e., on-site leakage), the respective time scale for judging these agricultural measures on their potential to mitigate climate change or cause negative emissions is important (Lugato et al., 2018) and needs to be clearly reported. For illustration, here is one example. Reduced tillage can enhance SOC stocks mainly in dry regions (Bai et al., 2019). A total C sequestration in soils of 3 $Mg\,ha^{-1}$ (11 $Mg\,CO_2\,ha^{-1}$) may be reached after 30 years in the topsoil compared to a reference scenario with conventional ploughing (Lugato et al., 2018). Thus, each year 0.1 $Mg\,C\,ha^{-1}$ is sequestered for 30 years (0.37 $Mg\,CO_2\,ha^{-1}$). At the same time, reduced tillage leads to enhanced annual N_2O emissions by 0.2 $Mg\,CO_{2eq}\,ha^{-1}$ (Guenet et al., 2021). Over a 30-year period, this results in a ratio of 0.54 between additional N_2O emissions and additional CO_2 uptake (see also Figure 4c). Any ratio below 1 indicates climate mitigation effects. Thus, over a 30-year timescale, this agricultural measure would be considered to contribute to climate change mitigation (if there is no other leakage and if the reference scenario's SOC storage is in a steady state). This conclusion changes if the same example is viewed from a 100-year perspective, resulting in a ratio of 1.82 between N_2O and CO_2. While the C sequestration in soils ceases once the new steady state of C input and mineralisation is reached, N_2O may continue to be emitted. Thus, in this example reduced tillage would result in negative emissions if calculated from a mid-term perspective (30 years), but would result in additional emissions from a longer-term perspective. Although this example is a simplification regarding the time-dependency of the GWP, it illustrates that it is critical to consider timescales and leakage when evaluating a measure's climate change mitigation potential.

6 | CONCLUSIONS

The window for preventing climate change from reaching an irreversible tipping point is closing and action needs to be taken to keep the effect of anthropogenic global warming under +2°C. Nature-based solutions that enhance soil C storage can contribute to climate change mitigation. In order to identify and quantify these measures and their climate change mitigation potential, multiple stakeholder groups need to be able to work together and communicate unambiguously. This kind of collaboration is only possible when key terms are carefully defined and accurately employed. It is therefore a priority for the scientific literature to be clear about definitions of important terms in order to guide discussions in the political world and wider society. This analysis of 100 recently published peer-reviewed research papers clearly demonstrates that the terms *C sequestration* and *SOC storage* are either used ambiguously or have multiple interpretations. Thus, a more rigorous use of the term *C sequestration*

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

and related vocabulary is needed in order to avoid misunderstandings and biased perception of the true potential of nature-based solutions. Clearer definitions of such terms are proposed and new terms outlined to distinguish clearly between *C sequestration in soils*, *SOC loss mitigation*, *negative emissions*, *climate change mitigation*, *SOC storage*, and *SOC accrual*. In addition, based on examples, this paper highlights the pitfalls of inaccurately applying terminology associated with SOC storage, and provides guidance on the proper use of the more clearly defined terms suggested. Furthermore, it highlights the importance of transparent communication regarding the permanence of additional SOC and leakage effects. Without correct use of these key terms, misleading conclusions may be drawn regarding climate change mitigation strategies, ultimately leading to support for measures that do not have the intended benefits. By using a consistent vocabulary the foundations can be laid for much-needed climate change solutions.

AUTHOR CONTRIBUTIONS

Axel Don: Conceptualization; funding acquisition; supervision; visualization; writing – original draft. **Felix Seidel:** Conceptualization; formal analysis; visualization; writing – review and editing. **Jens Leifeld:** Conceptualization; writing – review and editing. **Thomas Kätterer:** Conceptualization; writing – review and editing. **Manuel Martin:** Writing – review and editing. **Sylvain Pellerin:** Writing – review and editing. **David Emde:** Visualization; writing – review and editing. **Daria Seitz:** Conceptualization; writing – review and editing. **Claire Chenu:** Conceptualization; writing – review and editing.

ACKNOWLEDGEMENTS

This study has received funding from the European Unions' Horizon 2020 research and innovation programme under grant agreement No. 862695 EJP SOIL. We thank the soil organic matter working group at the Thünen-Institute of Climate-Smart Agriculture for fruitful discussions about the paper. Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare to have no competing interests.

DATA AVAILABILITY STATEMENT

Publications used in the paper analysis are listed as Data Sources below.

ORCID

Axel Don https://orcid.org/0000-0001-7046-3332
Felix Seidel https://orcid.org/0000-0002-6176-0017
Jens Leifeld https://orcid.org/0000-0002-7245-9852
Thomas Kätterer https://orcid.org/0000-0002-1751-007X
Manuel Martin https://orcid.org/0000-0003-2041-932X
Sylvain Pellerin https://orcid.org/0000-0003-4388-8460
David Emde https://orcid.org/0000-0002-7311-3159
Daria Seitz https://orcid.org/0000-0003-0702-2993
Claire Chenu https://orcid.org/0000-0001-9054-0489

REFERENCES

Angers, D., Arrouays, D., Cardinael, R., Chenu, C., Corbeels, M., Demenois, J., Farrell, M., Martin, M., Minasny, B., Recous, S., & Six, J. (2022). A well-established fact: Rapid mineralization of organic inputs is an important factor for soil carbon sequestration. *European Journal of Soil Science*, *73*(3), e13242. https://doi.org/10.1111/ejss.13242

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.-A., Tao, B., Hui, D., Yang, J., & Matocha, C. (2019). Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. *Global Change Biology*, *25*(8), 2591–2606. https://doi.org/10.1111/gcb.14658

Baveye, P. C., Berthelin, J., Tessier, D., & Lemaire, G. (2023). Storage of soil carbon is not sequestration: Straightforward graphical visualization of their basic differences. *European Journal of Soil Science*, *74*(3), e13380. https://doi.org/10.1111/ejss.13380

Bondeau, A., Smith, P. C., Zaehle, S., Scharphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., & Smith, B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, *13*(3), 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x

Börjesson, G., Bolinder, M. A., Kirchmann, H., & Kätterer, T. (2018). Organic carbon stocks in topsoil and subsoil in long-term ley and cereal monoculture rotations. *Biology and Fertility of Soils*, *54*(4), 549–558.

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 and Tillage Research*, *188*, 41–52. https://doi.org/10.1016/j.still.2018.04.011

Ciais, P., Wattenbach, M., Vuichard, N., Smith, P., Piao, S. L., Don, A., Luyssaert, S., Janssens, I. A., Bondeau, A., Dechow, R., Leip, A., Smith, P. C., Beer, C., Van Der Werf, G. R., Gervois, S., Van Oost, K., Tomelleri, E., Freibauer, A., Schulze, E. D., & Carboeurope Synthesis Team. (2010). The European carbon balance. Part 2: Croplands. *Global Change Biology*, *16*(5), 1409–1428. https://doi.org/10.1111/j.1365-2486.2009.02055.x

Collin, P. H. (Peter Hodgson), 1935. (1982). *Harrap's shorter French and English dictionary/edited by Peter Collin*. Harrap.

Gren, I. M., & Zeleke, A. A. (2016). Policy design for forest carbon sequestration: A review of the literature. *Forest Policy and Economics*, *70*, 128–136. https://doi.org/10.1016/j.forpol.2016.06.008

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(44), 11645–11650.

Guenet, B., Gabrielle, B., Chenu, C., Arrouays, D., Balesdent, J., Bernoux, M., Bruni, E., Caliman, J.-P., Cardinael, R., Chen, S., Ciais, P., Desbois, D., Fouche, J., Frank, S., Henault, C., Lugato, E., Naipal, V., Nesme, T., Obersteiner, M., … Zhou, F. (2021). Can N_2O emissions offset the benefits from soil organic carbon storage? *Global Change Biology*, *27*(2), 237–256.

IPCC. (2001). *Annex B - glossary of terms in climate change 2001: Impacts, adaptation, and vulnerability: Contribution of working group II to the third assessment report of the intergovernmental panel on climate change (Vol. 2)*. Cambridge University Press.

IPCC. (2021). Annex VII: Glossary. In J. B. R. Matthews, V. Möller, R. van Diemen, J. S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, & A. Reisinger (Eds.), *In climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change* (pp. 2215–2256). Cambridge University Press.

Jackson, R. B., Saunois, M., Bousquet, P., Canadell, J. G., Poulter, B., Stavert, A. R., Bergamaschi, P., Niwa, Y., Segers, A., & Tsuruta, A.

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

(2020). Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. *Environmental Research Letters*, *15*(7), 071002.

Janzen, H. H., van Groenigen, K. J., Powlson, D. S., Schwinghamer, T., & van Groenigen, J. W. (2022). Photosynthetic limits on carbon sequestration in croplands. *Geoderma*, *416*, 115810.

Jobbagy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(2), 423–436.

Johnston, A. E., Poulton, P. R., Coleman, K., Macdonald, A. J., & White, R. P. (2017). Changes in soil organic matter over 70 years in continuous arable and ley–arable rotations on a sandy loam soil in England. *European Journal of Soil Science*, *68*(3), 305–316. https://doi.org/10.1111/ejss.12415

Kløverpris, J. H., & Mueller, S. (2013). Baseline time accounting: Considering global land use dynamics when estimating the climate impact of indirect land use change caused by biofuels. *The International Journal of Life Cycle Assessment*, *18*(2), 319–330. https://doi.org/10.1007/s11367-012-0488-6

Leifeld, J., & Keel, S. G. (2022). Quantifying negative radiative forcing of non-permanent and permanent soil carbon sinks. *Geoderma*, *423*, 115971. https://doi.org/10.1016/j.geoderma.2022.115971

Leifeld, J., Wüst-Galley, C., & Page, S. (2019). Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. *Nature Climate Change*, *9*(12), 945–947.

Lugato, E., Leip, A., & Jones, A. (2018). Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. *Nature Climate Change*, *8*(3), 219–223. https://doi.org/10.1038/s41558-018-0087-z

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., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., … Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86.

Olson, K. R., Al-Kaisi, M. M., Lal, R., & Lowery, B. (2014). Experimental consideration, treatments, and methods in determining soil organic carbon sequestration rates. *Soil Science Society of America Journal*, *78*(2), 348–360. https://doi.org/10.2136/sssaj2013.09.0412

Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C sequestration as a biological negative emission strategy. *Frontiers in Climate*, *1*. https://doi.org/10.3389/fclim.2019.00008

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Peralta, G., Di Paolo, L., Luotto, I., Omuto, C., Mainka, M., Viatkin, K., & Yigini, Y. (2022). *Global soil organic carbon sequestration potential map (GSOCseq v1. 1)—Technical manual*. Food & Agriculture Organisation FAO.

Poeplau, C., & Dechow, R. (2023). The legacy of one hundred years of climate change for organic carbon stocks in global agricultural topsoils. *Scientific Reports*, *13*(1), 1–12.

Poeplau, C., & Don, A. (2013). Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. *Geoderma*, *192*, 189–201. https://doi.org/10.1016/j.geoderma.2012.08.003

Poeplau, C., Zopf, D., Greiner, B., Geerts, R., Korvaar, H., Thumm, U., Don, A., Heidkamp, A., & Flessa, H. (2018). Why does mineral fertilization increase soil carbon stocks in temperate grasslands? *Agriculture, Ecosystems and Environment*, *265*, 144–155. https://doi.org/10.1016/j.agee.2018.06.003

Rumpel, C., Amiraslani, F., Chenu, C., Garcia Cardenas, M., 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., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(36), 9575–9580.

Schmidt, H.-P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T. D., Sánchez Monedero, M. A., & Cayuela, M. L. (2021). Biochar in agriculture – A systematic review of 26 global meta-analyses. *GCB Bioenergy*, *13*(11), 1708–1730. https://doi.org/10.1111/gcbb.12889

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

Sommer, R., & Bossio, D. (2014). Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*, *144*, 83–87. https://doi.org/10.1016/j.jenvman.2014.05.017

Tyka, M. D., Van Arsdale, C., & Platt, J. C. (2022). CO_2 capture by pumping surface acidity to the deep ocean. *Energy & Environmental Science*, *15*(2), 786–798. https://doi.org/10.1039/d1ee01532j

Whitehead, D., Schipper, L. A., Pronger, J., Moinet, G. Y. K., Mudge, P. L., Pereira, R. C., Kirschbaum, M. U. F., McNally, S. R., Beare, M. H., & Camps-Arbestain, M. (2018). Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. *Agriculture, Ecosystems & Environment*, *265*, 432–443. https://doi.org/10.1016/j.agee.2018.06.022

DATA SOURCES

Abebe, M. T., Degefu, M. A., Assen, M., & Legass, A. (2022). Dynamics of land use/land cover: Implications on environmental resources and human livelihoods in the Middle Awash Valley of Ethiopia. *Environmental Monitoring and Assessment*, *194*(11), 833. https://doi.org/10.1007/s10661-022-10498-7

Aguirre-Villegas, H. A., Larson, R. A., Rakobitsch, N., Wattiaux, M. A., & Silva, E. (2022). Farm level environmental assessment of organic dairy systems in the U.S. *Journal of Cleaner Production*, *363*, 132390. https://doi.org/10.1016/j.jclepro.2022.132390

Ahmad Bhat, S., Kuriqi, A., Dar, M. U. D., Bhat, O., Sammen, S. S., Towfiqul Islam, A. R. M., Elbeltagi, A., Shah, O., Al-Ansari, N., Ali, R., & Heddam, S. (2022). Application of biochar for improving physical, chemical, and hydrological soil properties: A systematic review. *Sustainability*, *14*(17), 11104. https://doi.org/10.3390/su141711104

Ali, A., Ahmad, W., Munsif, F., Khan, A., Nepal, J., Wójcik-Gront, E., Ahmad, I., Khan, M. S., Ullah, I., Akbar, S., Zaheer, S., & Jin, G. (2022). Residual effect of Finely-Ground Biochar inoculated with bio-fertilization impact on productivity in a Lentil–Maize cropping system. *Agronomy*, *12*(9), 2036. https://doi.org/10.3390/agronomy12092036

Almeida, J. P., Rosenstock, N. P., Woche, S. K., Guggenberger, G., & Wallander, H. (2022). Nitrophobic ectomycorrhizal fungi are associated with enhanced hydrophobicity of soil organic matter in a Norway spruce forest. *Biogeosciences*, *19*(15), 3713–3726. https://doi.org/10.5194/bg-19-3713-2022

An, Z., Bork, E. W., Olefeldt, D., Carlyle, C. N., & Chang, S. X. (2022). Simulated heat wave events increase CO_2 and N_2O emissions from cropland and forest soils in an incubation experiment. *Biology and Fertility of Soils*, *58*, 789–802. https://doi.org/10.1007/s00374-022-01661-w

Aravind, P. V., Champatan, V., Gopi, G., Vijay, V., Smit, C., Pande, S., van den Broeke, L. J. P., John, T. D., Illathukandy, B., Sukesh, A., Shreedhar, S., Nandakishor, T. M., Purushothaman, S. J., Posada, J., Lindeboom, R. E. F., & Nampoothiri, K. U. K. (2022). Negative emissions at negative cost-an opportunity for a scalable niche. *Frontiers in Energy Research*, *10*. https://doi.org/10.3389/fenrg.2022.806435

Audia, E., Schulte, L. A., & Tyndall, J. (2022). Measuring changes in financial and ecosystems service outcomes with simulated grassland restoration in a Corn Belt watershed. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.959617

Behrer, A. P., & Lobell, D. (2022). Higher levels of no-till agriculture associated with lower PM 2.5 in the Corn Belt. *Environmental Research Letters*, *17*(9), 94012. https://doi.org/10.1088/1748-9326/ac816f

Bernués, A., Tenza-Peral, A., Gómez-Baggethun, E., Clemetsen, M., Eik, L. O., & Martín-Collado, D. (2022). Targeting best agricultural practices to enhance ecosystem services in European mountains. *Journal of Environmental Management*, *316*, 115255. https://doi.org/10.1016/j.jenvman.2022.115255

Breg Valjavec, M., Čarni, A., Žlindra, D., Zorn, M., & Marinšek, A. (2022). Soil organic carbon stock capacity in karst dolines under different land uses. *Catena*, *218*, 106548. https://doi.org/10.1016/j.catena.2022.106548

Buck, H. J., & Palumbo-Compton, A. (2022). Soil carbon sequestration as a climate strategy: What do farmers think? *Biogeochemistry*, *161*(1), 59–70. https://doi.org/10.1007/s10533-022-00948-2

Chang, Q., Xu, W., Peng, B., Jiang, P., Li, S., Wang, C., & Bai, E. (2022). Dynamic and allocation of recently assimilated carbon in Korean pine (*Pinus koraiensis*) and birch (*Betula platyphylla*) in a temperate forest. *Biogeochemistry*, *160*(3), 395–407. https://doi.org/10.1007/s10533-022-00962-4

Chen, X., Zhang, J., Lin, Q., Li, G., & Zhao, X. (2023). Dispose of Chinese cabbage waste via hydrothermal carbonization: Hydrochar characterization and its potential as a soil amendment. *Environmental Science and Pollution Research International*, *30*(2), 4592–4602. https://doi.org/10.1007/s11356-022-22359-4

Chen, Y. Y., Yang, H., Bao, G. S., Pang, X. P., & Guo, Z. G. (2022). Effect of the presence of plateau pikas on the ecosystem services of alpine meadows. *Biogeosciences*, *19*(18), 4521–4532. https://doi.org/10.5194/bg-19-4521-2022

Chen, Z., Liu, F., Cai, G., Peng, X., & Wang, X. (2022). Responses of soil carbon pools and carbon management index to nitrogen substitution treatments in a sweet maize farmland in South China. *Plants (Basel, Switzerland)*, *11*(17), 2194. https://doi.org/10.3390/plants11172194

Chiriluș, G. V., Lakatos, E. S., Bălc, R., Bădărău, A. S., Cioca, L. I., David, G. M., & Roşian, G. (2022). Assessment of organic carbon sequestration from Romanian degraded soils: Livada forest plantation case study. *Atmosphere*, *13*(9), 1452. https://doi.org/10.3390/atmos13091452

Cipolla, G., Calabrese, S., Porporato, A., & Noto, L. V. (2022). Effects of precipitation seasonality, irrigation, vegetation cycle and soil type on enhanced weathering – Modeling of cropland case studies across four sites. *Biogeosciences*, *19*(16), 3877–3896. https://doi.org/10.5194/bg-19-3877-2022

Crichton, K. A., Anderson, K., Charman, D. J., & Gallego-Sala, A. (2022). Seasonal climate drivers of peak NDVI in a series of Arctic peatlands. *The Science of the Total Environment*, *838*(Pt 3), 156419. https://doi.org/10.1016/j.scitotenv.2022.156419

Cui, Y., Bing, H., Moorhead, D. L., Delgado-Baquerizo, M., Ye, L., Yu, J., Zhang, S., Wang, X., Peng, S., Guo, X., Zhu, B., Chen, J., Tan, W., Wang, Y., Zhang, X., & Fang, L. (2022). Ecoenzymatic stoichiometry reveals widespread soil phosphorus limitation to microbial metabolism across Chinese forests. *Communications Earth & Environment*, *3*(1). https://doi.org/10.1038/s43247-022-00523-5

Cunha, H. F. V., Andersen, K. M., Lugli, L. F., Santana, F. D., Aleixo, I. F., Moraes, A. M., Garcia, S., di Ponzio, R., Mendoza, E. O., Brum, B., Rosa, J. S., Cordeiro, A. L., Portela, B. T. T., Ribeiro, G., Coelho, S. D., de Souza, S. T., Silva, L. S., Antonieto, F., Pires, M., … Quesada, C. A. (2022). Direct evidence for phosphorus limitation on Amazon forest productivity. *Nature*, *608*(7923), 558–562. https://doi.org/10.1038/s41586-022-05085-2

Davidson, E. A. (2022). Is the transactional carbon credit tail wagging the virtuous soil organic matter dog? *Biogeochemistry*, *161*(1), 1–8. https://doi.org/10.1007/s10533-022-00969-x

Debska, B., Kotwica, K., Banach-Szott, M., Spychaj-Fabisiak, E., & Tobiašová, E. (2022). Soil fertility improvement and carbon sequestration through exogenous organic matter and biostimulant application. *Agriculture*, *12*(9), 1478. https://doi.org/10.3390/agriculture12091478

Diao, H., Chen, X., Wang, G., Ning, Q., Hu, S., Sun, W., Dong, K., & Wang, C. (2022). The response of soil respiration to different N compounds addition in a saline–alkaline grassland of northern China. *Journal of Plant Ecology*, *15*(5), 897–910. https://doi.org/10.1093/jpe/rtac006

Dong, D., Yang, W., Sun, H., Kong, S., & Xu, H. (2022). Effects of animal manure and nitrification inhibitor on N_2O emissions and soil carbon stocks of a maize cropping system in Northeast China. *Scientific Reports*, *12*(1), 15202. https://doi.org/10.1038/s41598-022-19592-9

Doyeni, M. O., Barcauskaite, K., Buneviciene, K., Venslauskas, K., Navickas, K., Rubezius, M., Baksinskaite, A., Suproniene, S., & Tilvikiene, V. (2023). Nitrogen flow in livestock waste system towards an efficient circular economy in agriculture. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *41*(3), 701–712. https://doi.org/10.1177/0734242X221123484

Fancourt, M., Ziv, G., Boersma, K. F., Tavares, J., Wang, Y., & Galbraith, D. (2022). Background climate conditions regulated the photosynthetic response of Amazon forests to the 2015/2016 El Nino-Southern Oscillation event. *Communications Earth & Environment*, *3*(1). https://doi.org/10.1038/s43247-022-00533-3

Feng, X., Zhang, T., Feng, P., & Li, J. (2022). Evaluation and tradeoff-synergy analysis of ecosystem services in Luanhe River Basin. *Ecohydrology*, *15*(8). https://doi.org/10.1002/eco.2473

Galán-Martín, Á., Del Contreras, M. M., Romero, I., Ruiz, E., Bueno-Rodríguez, S., Eliche-Quesada, D., & Castro-Galiano, E. (2022). The potential role of olive groves to deliver carbon dioxide removal in a carbon-neutral Europe: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, *165*, 112609. https://doi.org/10.1016/j.rser.2022.112609

Geethathanuja, K., & Karthikeyan, S. (2023). Application of soil amendments to enhance soil carbon and biological properties in a paddy field under elevated CO_2 conditions. *Archives of Agronomy and Soil Science*, *69*(10), 1860–1877. https://doi.org/10.1080/03650340.2022.2120195

Guillaume, T., Makowski, D., Libohova, Z., Elfouki, S., Fontana, M., Leifeld, J., Bragazza, L., & Sinaj, S. (2022). Carbon storage in agricultural topsoils and subsoils is promoted by including temporary grasslands into the crop rotation. *Geoderma*, *422*, 115937. https://doi.org/10.1016/j.geoderma.2022.115937

Guo, R., Qian, R., Yang, L., Khaliq, A., Han, F., Hussain, S., Zhang, P., Cai, T., Jia, Z., Chen, X., & Ren, X. (2022). Interactive effects of maize straw-derived biochar and N fertilization on soil bulk density and porosity, maize productivity and nitrogen use efficiency in arid areas. *Journal of Soil Science and Plant Nutrition*, *22*(4), 4566–4586. https://doi.org/10.1007/s42729-022-00881-1

Han, L., Mu, C., Jiang, N., Shen, Z., Chang, Y., Hao, L., & Peng, W. (2023). Responses of seven wetlands carbon sources and sinks to permafrost degradation in Northeast China. *Journal of Soils and Sediments*, *23*(1), 15–31. https://doi.org/10.1007/s11368-022-03271-3

Hassan, W., Li, Y., Saba, T., Jabbi, F., Wang, B., Cai, A., & Wu, J. (2022). Improved and sustainable agroecosystem, food security and environmental resilience through zero tillage with emphasis on soils of temperate and subtropical climate regions: A review. *International Soil and Water Conservation Research*, *10*(3), 530–545. https://doi.org/10.1016/j.iswcr.2022.01.005

von Hellfeld, R., Hastings, A., Kam, J., Rowe, R., Clifton-Brown, J., Donnison, I., & Shepherd, A. (2022). Expanding the *Miscanthus* market in the UK: Growers in profile and experience, benefits and drawbacks of the bioenergy crop. *Global Change Biology. Bioenergy*, *14*(11), 1205–1218. https://doi.org/10.1111/gcbb.12997

Holka, M., Kowalska, J., & Jakubowska, M. (2022). Reducing carbon footprint of agriculture—Can organic farming help to mitigate climate change? *Agriculture*, *12*(9), 1383. https://doi.org/10.3390/agriculture12091383

Holliday, M. C., Parsons, D. R., & Zein, S. H. (2022). Microwave-assisted hydrothermal carbonisation of waste biomass: The effect of process conditions on hydrochar properties. *PRO*, *10*(9), 1756. https://doi.org/10.3390/pr10091756

de Jager, M., Schröter, F., Wark, M., & Giani, L. (2022). The stability of carbon from a maize-derived hydrochar as a function of fractionation and hydrothermal carbonization temperature in a Podzol. *Biochar*, *4*(1), 52. https://doi.org/10.1007/s42773-022-00175-w

Jayanthi, D., & Gokila, B. (2023). Continuous cropping and fertilization on vertical distribution of major nutrients, SOC dynamics through FT-IR spectroscopy and developing soil quality indices under Sandy clay loam soil. *Communications in Soil Science and Plant Analysis*, *54*(3), 356–377. https://doi.org/10.1080/00103624.2022.2112597

Jensen, J. L., Beucher, A. M., & Eriksen, J. (2022). Soil organic C and N stock changes in grass-clover leys: Effect of grassland proportion and organic fertilizer. *Geoderma*, *424*, 116022. https://doi.org/10.1016/j.geoderma.2022.116022

Jiang, P., Xiao, L. Q., Wan, X., Yu, T., Liu, Y. F., & Liu, M. X. (2022). Research progress on microbial carbon sequestration in soil: A review. *Eurasian Soil Science*, *55*(10), 1395–1404. https://doi.org/10.1134/S1064229322100064

Jin, S., Ma, H., Jia, L., Liu, X., Hussain, Q., Song, X., Cui, L., Wang, C., & Cui, D. (2022). Organic material additions have stronger effects on humic substances and enzyme activities than soil types. *Land Degradation & Development*, *33*(15), 2783–2794. https://doi.org/10.1002/ldr.4317

Johansson, E. L., Brogaard, S., & Brodin, L. (2022). Envisioning sustainable carbon sequestration in Swedish farmland. *Environmental Science & Policy*, *135*, 16–25. https://doi.org/10.1016/j.envsci.2022.04.005

Kan, Z.-R., Chen, Z., Wei, Y.-X., Virk, A. L., Bohoussou, Y. N., Lal, R., Zhao, X., & Zhang, H.-L. (2022). Contribution of wheat and maize to soil organic carbon in a wheat-maize cropping system: A field and laboratory study. *Journal of Applied Ecology*, *59*(11), 2716–2729. https://doi.org/10.1111/1365-2664.14265

Kok, D. D., Scherer, L., de Vries, W., Trimbos, K., & van Bodegom, P. M. (2022). Relationships of priming effects with organic amendment composition and soil

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

microbial properties. *Geoderma*, *422*, 115951. https://doi.org/10.1016/j.geoderma.2022.115951

Li, R., Chen, X., Wen, M., Vachula, R. S., Tan, S., Dong, H., Zhou, L., Gu, Z., & Xu, M. (2022). Phytolith-occluded carbon in leaves of Dendrocalamus Ronganensis influenced by drought during growing season. *Physiologia Plantarum*, *174*(5), e13748. https://doi.org/10.1111/ppl.13748

Li, T., Zou, Y., Liu, Y., Luo, P., Xiong, Q., Lu, H., Lai, C., & Axmacher, J. C. (2022). Mountain forest biomass dynamics and its drivers in southwestern China between 1979 and 2017. *Ecological Indicators*, *142*, 109289. https://doi.org/10.1016/j.ecolind.2022.109289

Liao, L., Wang, J., Lei, S., Zhang, L., Ye, Z., Liu, G., & Zhang, C. (2023). Differential effects of nitrogen addition on the organic carbon fractions of rhizosphere and bulk soil based on a pot experiment. *Journal of Soils and Sediments*, *23*(1), 103–117. https://doi.org/10.1007/s11368-022-03311-y

Liu, F., Ding, Z., Lu, Y., Li, R., & Shi, Z. (2022). Nano-scale investigation of organic C sequestration and distribution on Fe oxides during ferrihydrite transformation: Effect of Al-substitution. *Environmental Science: Nano*, *9*(10), 4007–4017. https://doi.org/10.1039/d2en00505k

Liu, H., Rezanezhad, F., Zak, D., Li, X., & Lennartz, B. (2022). Freeze-thaw cycles alter soil hydro-physical properties and dissolved organic carbon release from peat. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.930052

Liu, J., Zhen, B., Qiu, H., Zhou, X., & Zhang, H. (2023). Impact of waterlogging and heat stress on rice rhizosphere microbiome assembly and potential function in carbon and nitrogen transformation. *Archives of Agronomy and Soil Science*, *69*(10), 1920–1932. https://doi.org/10.1080/03650340.2022.2128190

Liu, M., Han, G., & Zhang, Q. (2022). Soil organic carbon sequestration following a secondary succession of agricultural abandonment in the karst region of Southwest China. *Environmental Earth Sciences*, *81*(19). https://doi.org/10.1007/s12665-022-10606-3

Loisel, J., & Gallego-Sala, A. (2022). Ecological resilience of restored peatlands to climate change. *Communications Earth & Environment*, *3*(1). https://doi.org/10.1038/s43247-022-00547-x

Luo, M., Moorhead, D. L., Ochoa-Hueso, R., Mueller, C. W., Ying, S. C., & Chen, J. (2022). Nitrogen loading enhances phosphorus limitation in terrestrial ecosystems with implications for soil carbon cycling. *Functional Ecology*, *36*(11), 2845–2858. https://doi.org/10.1111/1365-2435.14178

Lyu, H., Zhang, H., Chu, M., Zhang, C., Tang, J., Chang, S. X., Mašek, O., & Ok, Y. S. (2022). Biochar affects greenhouse gas emissions in various environments: A critical review. *Land Degradation & Development*, *33*(17), 3327–3342. https://doi.org/10.1002/ldr.4405

Marañón-Jiménez, S., Serrano-Ortíz, P., Peñuelas, J., Meijide, A., Chamizo, S., López-Ballesteros, A., Vicente-Vicente, J. L., & Fernández-Ondoño, E. (2022). Effects of herbaceous covers and mineral fertilizers on the nutrient stocks and fluxes in a Mediterranean olive grove. *European Journal of Agronomy*, *140*, 126597. https://doi.org/10.1016/j.eja.2022.126597

Maxwell, T. M., & Germino, M. J. (2022). The effects of cheatgrass invasion on US Great Basin carbon storage depend on interactions between plant community composition, precipitation seasonality, and soil climate regime. *Journal of Applied Ecology*, *59*(11), 2863–2873. https://doi.org/10.1111/1365-2664.14289

Mayer, A., & Silver, W. L. (2022). The climate change mitigation potential of annual grasslands under future climates. *Ecological Applications: A Publication of the Ecological Society of America*, *32*(8), e2705. https://doi.org/10.1002/eap.2705

Mehrab, N., Chorom, M., Norouzi Masir, M., Fernandes de Souza, M., & Meers, E. (2022). Effect of soil application of biochar produced from Cd-enriched maize on the available Cd in a calcareous soil. *Environmental Earth Sciences*, *81*(18). https://doi.org/10.1007/s12665-022-10586-4

Mirzaei, M., Gorji Anari, M., Razavy-Toosi, E., Zaman, M., Saronjic, N., Zamir, S. M., Mohammed, S., & Caballero-Calvo, A. (2022). Crop residues in corn-wheat rotation in a semi-arid region increase CO_2 efflux under conventional tillage but not in a no-tillage system. *Pedobiologia*, *93–94*, 150819. https://doi.org/10.1016/j.pedobi.2022.150819

Na, M., Hicks, L. C., Zhang, Y., Shahbaz, M., Sun, H., & Rousk, J. (2022). Semi-continuous C supply reveals that priming due to N-mining is driven by microbial growth demands in temperate forest plantations. *Soil Biology and Biochemistry*, *173*, 108802. https://doi.org/10.1016/j.soilbio.2022.108802

Niu, G., Yin, G., Mo, X., Mao, Q., Mo, J., Wang, J., & Lu, X. (2022). Do long-term high nitrogen inputs change the composition of soil dissolved organic matter in a primary tropical forest? *Environmental Research Letters*, *17*(9), 95015. https://doi.org/10.1088/1748-9326/ac8e87

Noirot, L. M., Müller-Stöver, D. S., Wahyuningsih, R., Sørensen, H., Sudarno, Simamora, A., Pujianto, Suhardi, & Caliman, J.-P. (2022). Impacts of empty fruit bunch applications on soil organic carbon in an industrial oil palm plantation. *Journal of Environmental Management*, *317*, 115373. https://doi.org/10.1016/j.jenvman.2022.115373

Nordström, E., Eckstein, R. L., & Lind, L. (2022). Edge effects on decomposition in Sphagnum bogs: Implications for carbon storage. *Ecosphere*, *13*(9), e4234. https://doi.org/10.1002/ecs2.4234

Nyang'au, J. O., Møller, H. B., & Sørensen, P. (2022). Nitrogen dynamics and carbon sequestration in soil following application of digestates from one- and two-step anaerobic digestion. *The Science of the Total Environment*, *851*(Pt 1), 158177. https://doi.org/10.1016/j.scitotenv.2022.158177

de Oliveira, D. C., Maia, S. M. F., de Cássia Alves Freitas, R., & Cerri, C. E. P. (2022). Changes in soil carbon and soil carbon sequestration potential under different types of pasture management in Brazil. *Regional Environmental Change*, *22*(3), 87. https://doi.org/10.1007/s10113-022-01945-9

Olofsson, F., & Ernfors, M. (2022). Frost killed cover crops induced high emissions of nitrous oxide. *The Science of the Total Environment*, *837*, 155634. https://doi.org/10.1016/j.scitotenv.2022.155634

Palsaniya, D. R., Kumar, T. K., Chaudhary, M., & Choudhary, M. (2023). Effect of reduced tillage and mulching on soil health in Sesbania alley cropping based rainfed food - fodder systems. *Archives of Agronomy and Soil Science*, *69*(10), 1750–1764. https://doi.org/10.1080/03650340.2022.2111025

Park, Y. J., Park, J.-E., Truong, T. Q., Koo, S. Y., Choi, J.-H., & Kim, S. M. (2022). Effect of Chlorella vulgaris on the growth and phytochemical contents of "Red Russian" Kale (Brassica napus var. Pabularia). *Agronomy*, *12*(9), 2138. https://doi.org/10.3390/agronomy12092138

Qu, Z.-L., Li, X.-L., Ge, Y., Palviainen, M., Zhou, X., Heinonsalo, J., Berninger, F., Pumpanen, J., Köster, K., & Sun, H. (2022). The impact of biochar on wood-inhabiting bacterial community and its function in a boreal pine forest. *Environmental Microbiomes*, *17*(1), 45. https://doi.org/10.1186/s40793-022-00439-9

Rathore, S. S., Babu, S., El-Sappah, A. H., Shekhawat, K., Singh, V. K., Singh, R. K., Upadhyay, P. K., & Singh, R. (2022). Integrated agroforestry systems improve soil carbon storage, water productivity, and economic returns in the marginal land of the semi-arid region. *Saudi Journal of Biological Sciences*, *29*(10), 103427. https://doi.org/10.1016/j.sjbs.2022.103427

Ratul, S. B., Gu, X., Qiao, P., Sagala, F. W., Nan, S., Islam, N., & Chen, L. (2022). Blue carbon sequestration following mangrove restoration: Evidence from a carbon neutral case in China. *Ecosystem Health and Sustainability*, *8*(1), 2101547. https://doi.org/10.1080/20964129.2022.2101547

Rivière, C., Béthinger, A., & Bergez, J.-E. (2022). The effects of cover crops on multiple environmental sustainability indicators—A review. *Agronomy*, *12*(9), 2011. https://doi.org/10.3390/agronomy12092011

Rönnberg-Wästljung, A. C., Dufour, L., Gao, J., Hansson, P.-A., Herrmann, A., Jebrane, M., Johansson, A.-C., Kalita, S., Molinder, R., Nordh, N.-E., Ohlsson, J. A., Passoth, V., Sandgren, M., Schnürer, A., Shi, A., Terziev, N., Daniel, G., & Weih, M. (2022). Optimized utilization of Salix—Perspectives for the genetic improvement toward sustainable biofuel value chains. *Global Change Biology. Bioenergy*, *14*(10), 1128–1144. https://doi.org/10.1111/gcbb.12991

Rushimisha, I. E., Li, X., Han, T., Chen, X., Abdoul Magid, A. S. I., Sun, Y., & Li, Y. (2022). Application of biochar on soil bioelectrochemical remediation: Behind roles, progress, and potential. *Critical Reviews in Biotechnology*, 1–19. https://doi.org/10.1080/07388551.2022.2119547

Sasaki, T., Ishii, N. I., Makishima, D., Sutou, R., Goto, A., Kawai, Y., Taniguchi, H., Okano, K., Matsuo, A., Lochner, A., Cesarz, S., Suyama, Y., Hikosaka, K., & Eisenhauer, N. (2022). Plant and microbial community composition jointly determine moorland multifunctionality. *Journal of Ecology*, *110*(10), 2507–2521. https://doi.org/10.1111/1365-2745.13969

Shao, Y., Xiao, Y., & Sang, W. (2022). Land use trade-offs and synergies based on temporal and spatial patterns of ecosystem services in South China. *Ecological Indicators*, *143*, 109335. https://doi.org/10.1016/j.ecolind.2022.109335

Shen, Z., Tiruta-Barna, L., & Hamelin, L. (2022). From hemp grown on carbon-vulnerable lands to long-lasting bio-based products: Uncovering trade-offs between overall environmental impacts, sequestration in soil, and dynamic influences on global temperature. *The Science of the Total Environment*, *846*, 157331. https://doi.org/10.1016/j.scitotenv.2022.157331

Singh, A., Singh, P., Dhillon, G. P. S., Sharma, S., Singh, B., & Gill, R. I. S. (2023). Differential impacts of soil salinity and water logging on Eucalyptus growth and carbon sequestration under mulched vs. unmulched soils in South-Western Punjab, India. *Plant and Soil*, *482*(1–2), 401–425. https://doi.org/10.1007/s11104-022-05700-1

Song, J., Gao, J., Zhang, Y., Li, F., Man, W., Liu, M., Wang, J., Li, M., Zheng, H., Yang, X., & Li, C. (2022). Estimation of soil organic carbon content in coastal wetlands with measured VIS-NIR spectroscopy using optimized support vector machines and random forests. *Remote Sensing*, *14*(17), 4372. https://doi.org/10.3390/rs14174372

Wang, H., Dai, Z., Trettin, C. C., Krauss, K. W., Noe, G. B., Burton, A. J., Stagg, C. L., & Ward, E. J. (2022). Modeling impacts of drought-induced salinity intrusion on carbon dynamics in tidal freshwater forested wetlands. *Ecological Applications: A Publication of the Ecological Society of America*, *32*(8), e2700. https://doi.org/10.1002/eap.2700

Wang, W., Zhu, W., Li, X., & Ma, S. (2023). Long-term nitrogen addition increased soil microbial carbon use efficiency in subalpine forests on the eastern edge of the Qinghai–Tibet Plateau. *Plant and Soil*, *482*(1–2), 553–565. https://doi.org/10.1007/s11104-022-05710-z

Wang, Y., Sun, J., Hou, S., Tan, Y., Wang, Z., Chang, S., Chen, J., Qian, Y., Chu, J., & Hou, F. (2022). Plateau pika burrowing and yak grazing jointly determine ecosystem greenhouse gas emissions of alpine meadow. *Land Degradation & Development*, *33*(18), 3914–3925. https://doi.org/10.1002/ldr.4433

Wang, Y.-R., Buchmann, N., Hessen, D. O., Stordal, F., Erisman, J. W., Vollsnes, A. V., Andersen, T., & Dolman, H. (2022). Disentangling effects of natural and anthropogenic drivers on forest net ecosystem production. *The Science of the Total Environment*, *839*, 156326. https://doi.org/10.1016/j.scitotenv.2022.156326

Wang, Z., An, Y., Chen, H., Zhang, J., Zhang, H., Zhu, G., Chen, J., Li, W., Wang, J., Xu, H. J., Li, Y., & Zhang, Y. (2022). Effects of earthworms and phosphate-solubilizing bacteria on carbon sequestration in soils amended with manure and slurry: A 4-year field study. *Agronomy*, *12*(9), 2064. https://doi.org/10.3390/agronomy12092064

Wang, Z., Wang, C., & Liu, S. (2022). Elevated CO_2 alleviates adverse effects of drought on plant water relations and photosynthesis: A global meta-analysis. *Journal of Ecology*, *110*(12), 2836–2849. https://doi.org/10.1111/1365-2745.13988

Wei, L., Zhu, Z., Razavi, B. S., Xiao, M., Dorodnikov, M., Fan, L., Yuan, H., Yurtaev, A., Luo, Y., Cheng, W., Kuzyakov, Y., Wu, J., & Ge, T. (2022). Visualization and quantification of carbon "rusty sink" by rice root iron plaque: Mechanisms, functions, and global implications. *Global Change Biology*, *28*(22), 6711–6727. https://doi.org/10.1111/gcb.16372

Wu, J., Guo, X., Zhu, Q., Guo, J., Han, Y., Zhong, L., & Liu, S. (2022). Threshold effects and supply-demand ratios should be considered in the mechanisms driving ecosystem services. *Ecological Indicators*, *142*, 109281. https://doi.org/10.1016/j.ecolind.2022.109281

Wu, L., Wu, L., Bingham, I. J., & Misselbrook, T. H. (2022). Projected climate effects on soil workability and trafficability determine the feasibility of converting permanent grassland to arable land. *Agricultural Systems*, *203*, 103500. https://doi.org/10.1016/j.agsy.2022.103500

Xu, Y., Gao, X., Pei, J., Sun, L., & Wang, J. (2022). Crop root vs. shoot incorporation drives microbial residue carbon accumulation in soil aggregate fractions. *Biology and Fertility of Soils*, *58*(8), 843–854. https://doi.org/10.1007/s00374-022-01666-5

Yang, F., Huang, J., Zheng, X., Huo, W., Zhou, C., Wang, Y., Han, D., Gao, J., Mamtimin, A., Yang, X., & Sun, Y. (2022). Evaluation of carbon sink in the Taklimakan Desert based on correction of abnormal negative CO_2 flux of IRGASON. *The Science of the Total Environment*, *838*(Pt 1), 155988. https://doi.org/10.1016/j.scitotenv.2022.155988

Yu, J., Zhang, Y., Wang, Y., Luo, X., Liang, X., Huang, X., Zhao, Y., Zhou, X., & Li, J. (2022). Ecosystem photosynthesis depends on increased water availability to enhance carbon assimilation in semiarid desert steppe in northern China. *Global Ecology and Conservation*, *38*, e02202. https://doi.org/10.1016/j.gecco.2022.e02202

Yuan, Y., Li, J., & Yao, L. (2022). Soil microbial community and physicochemical properties together drive soil organic carbon in *Cunninghamia lanceolata* plantations of different stand ages. *PeerJ*, *10*, e13873. https://doi.org/10.7717/peerj.13873

Yuan, Y., Zhao, Y., Gao, Y., Gao, G., Ren, Y., & Hou, F. (2022). The effect of tree species on soil organic carbon recovery in a restoration project is associated with vegetation biomass: Evidence from the Pingshuo mine reclaimed ecosystem, North China. *Land Degradation & Development*, *33*(18), 3870–3881. https://doi.org/10.1002/ldr.4429

Zeng, X.-M., Feng, J., Yu, D.-L., Wen, S.-H., Zhang, Q., Huang, Q., Delgado-Baquerizo, M., & Liu, Y. R. (2022). Local temperature increases reduce soil microbial residues and carbon stocks. *Global Change Biology*, *28*(21), 6433–6445. https://doi.org/10.1111/gcb.16347

Zhang, J., Wang, J., Zhou, Y., Xu, L., Chen, Y., Ding, Y., Ning, Y., Liang, D., Zhang, Y., & Li, G. (2022). Reduced basal and increased topdressing fertilizer rate combined with straw incorporation improves rice yield stability and soil organic carbon sequestration in a rice-wheat system. *Frontiers in Plant Science*, *13*, 964957. https://doi.org/10.3389/fpls.2022.964957

Zhang, M., He, H., Zhang, L., Ren, X., Wu, X., Qin, K., Lv, Y., Chang, Q., Xu, Q., Liu, W., & Feng, L. L. (2022). Increased forest coverage will induce more carbon fixation in vegetation than in soil during 2015–2060 in China based on CMIP6. *Environmental Research Letters*, *17*(10), 105002. https://doi.org/10.1088/1748-9326/ac8fa8

Zhang, M., Yang, W., Yang, M., & Yan, J. (2022). Guizhou karst carbon sink and sustainability—An overview. *Sustainability*, *14*(18), 11518. https://doi.org/10.3390/su141811518

Zhou, J., Shao, G., Kumar, A., Shi, L., Kuzyakov, Y., & Pausch, J. (2022). Carbon fluxes within tree-crop-grass agroforestry system: 13C field labeling and tracing. *Biology and Fertility of Soils*, *58*(7), 733–743. https://doi.org/10.1007/s00374-022-01659-4

Zhou, X., Hu, C., & Wang, Z. (2022). Ecological response of urban forest carbon density to site conditions: A case study of a typical karst mountainous regions in Southwest China. *Forests*, *13*(9), 1484. https://doi.org/10.3390/f13091484

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., Emde, D., Seitz, D., & Chenu, C. (2024). Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *Global Change Biology*, *30*, e16983. https://doi.org/10.1111/gcb.16983

13652486, 2024, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/gcb.16983 by Swedish University Of Agricultural Sciences, Wiley Online Library on [26/01/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License