Received: 7 October 2022 | Accepted: 17 November 2022

DOI: 10.1111/gcb.16570

Global Change Biology WILEY

OPINION

Carbon for soils, not soils for carbon

Gabriel Y. K. Moinet[1] | Renske Hijbeek[2] | Detlef P. van Vuuren[3,4] | Ken E. Giller[2]

[1]Soil Biology Group, Wageningen University, Wageningen, The Netherlands

[2]Plant Production Systems, Wageningen University, Wageningen, The Netherlands

[3]PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands

[4]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands

Correspondence
Gabriel Y. K. Moinet, Soil Biology Group, Wageningen University, Wageningen, The Netherlands.
Email: gabriel.moinet@wur.nl

Funding information
Wageningen University

Abstract

The role of soil organic carbon (SOC) sequestration as a 'win-win' solution to both climate change and food insecurity receives an increasing promotion. The opportunity may be too good to be missed! Yet the tremendous complexity of the two issues at stake calls for a detailed and nuanced examination of any potential solution, no matter how appealing. Here, we critically re-examine the benefits of global SOC sequestration strategies on both climate change mitigation and food production. While estimated contributions of SOC sequestration to climate change vary, almost none take SOC saturation into account. Here, we show that including saturation in estimations decreases any potential contribution of SOC sequestration to climate change mitigation by 53%–81% towards 2100. In addition, reviewing more than 21 meta-analyses, we found that observed yield effects of increasing SOC are inconsistent, ranging from negative to neutral to positive. We find that the promise of a win-win outcome is confirmed only when specific land management practices are applied under specific conditions. Therefore, we argue that the existing knowledge base does not justify the current trend to set global agendas focusing first and foremost on SOC sequestration. Away from *climate-smart soils*, we need a shift towards *soil-smart agriculture*, adaptative and adapted to each local context, and where multiple soil functions are quantified concurrently. Only such comprehensive assessments will allow synergies for land sustainability to be maximised and agronomic requirements for food security to be fulfilled. This implies moving away from global targets for SOC in agricultural soils. SOC sequestration may occur along this pathway and contribute to climate change mitigation and should be regarded as a co-benefit.

KEYWORDS
climate change mitigation, food security, soil carbon sequestration, soil multifunctionality, trade-off

1 | INTRODUCTION

Keeping global warming below 1.5°C (consistent with art. 2 of the Paris Agreement) requires immediate action to reach net-zero carbon dioxide (CO_2) emissions in the coming decades (IPCC WG3, 2022). Net-zero CO_2 emissions are achieved when anthropogenic emissions are balanced by anthropogenic CO_2 removal. To limit global warming to 1.5°C, nearly all scenarios rely on the removal of CO_2 from the atmosphere. This is also the case for many scenarios limiting global warming to well below 2°C (IPCC WG1, 2021), confirming earlier assessments (van Vuuren et al., 2013).

In the discussions on carbon dioxide removal (CDR) techniques, SOC sequestration has gained significant societal and scientific attention in recent years. The exact climate change mitigation potential of SOC sequestration is strongly debated, but unlike other CDR techniques, SOC sequestration is claimed to be a 'no regret' or a 'win-win' option because its implementation provides numerous co-benefits and few trade-offs (IPCC WG1, 2021). Indeed, management interventions aiming at SOC sequestration have long been claimed to enhance soil fertility and productivity, increase soil biodiversity, improve water retention and purification, and reduce erosion, compaction, runoff and water pollution (Lal, 2004; Paustian et al., 1997, 2016; Smith, 2012). Improvement of these 'soil functions' would lead to larger and more stable yields globally, thus safeguarding global food security and adaptation of global agricultural production to climate change (Lal, 2004; Rumpel et al., 2019). Increasing enthusiasm is pushing towards ever more optimistic predictions, with, for example, claims that SOC sequestration would be key to supporting five (FAO, 2017), seven (FAO, 2019) and up to 12 Sustainable Development Goals (Smith et al., 2019). As a result, several recent papers (Amelung et al., 2020; Chabbi et al., 2017; Kopittke et al., 2022; Rumpel et al., 2019) and high-level international initiatives (the '4p1000 initiative' launched during the COP21 in 2015, the Koronivia workshops held during the COP23 in 2018 and FAO's RECSOIL program) call for rapid upscaling and implementation of SOC sequestration practices to solve concurrently the challenges of climate change and food security.

Yet already more than 15 years ago, Janzen (2006) highlighted that a trade-off exists between *storing C* in soils for the benefit of climate change mitigation, and *using soil C* during soil organic matter (SOM) decomposition for the release of nutrients to support plant production. In parallel, both climate change (Smith, 2012) and food security (Giller, 2020) have been described as 'wicked problems', highlighting their daunting complexity and the formidable international social, political, economic and scientific interdisciplinary effort that is required to offer even partial solutions. In such a context, claims that a blanket solution can solve climate change and food insecurity concurrently should prompt some degree of scepticism. Like any ongoing scientific discussion, it needs relentless and rigorous examination.

Starting from this perspective, we re-examine the terminology and concepts underlying climate mitigation through SOC sequestration and the empirical evidence supporting the promised win-win with food security. We critically review estimates of the global SOC sequestration potential and quantify the potential contribution of SOC sequestration to reaching net-zero CO_2 emissions in a 1.5°C target climate scenario for the 2100 horizon. While we focus here on the technically achievable SOC sequestration potential, we also acknowledge that many large social, economic and political barriers exist to the implementation of SOC sequestration practices that cast yet more doubt on the global mitigation potential of SOC sequestration (Amundson & Biardeau, 2018; Bradford et al., 2019). Then, we review the existing evidence on the effect of increasing SOC stocks on above-ground plant production. Here, we focus on plant production as a key soil function because of its obvious link to food security, although we acknowledge that other functions are also key.

2 | SOC SEQUESTRATION: CONCEPTS AND TERMINOLOGY

Soils are the largest reservoir of C in the terrestrial biosphere, containing 1700 Gt C in the top meter, that is, four times as much C as global vegetation, twice as much as the atmosphere and 160 times as much as the current annual anthropogenic CO_2 emission rate (Friedlingstein et al., 2022). Soils also contain a significant amount of inorganic C (Lal et al., 2021), but here we focus exclusively on SOC, claimed to hold the largest climate change mitigation potential and to benefit numerous soil functions.

Small changes in global SOC stocks (a few tenths of a percent) could lead to proportionally large contributions to global CO_2 emissions (tens of percent; Paustian et al., 2016). This makes soil both a prime candidate to lock up CO_2 from the atmosphere, and a major threat as poor land management practices and environmental changes release CO_2 from soils and enhance global warming. For a given area, net sequestration of SOC is the difference between inputs of C to the soil and the release of C into the atmosphere as CO_2 (or methane) from the decomposition of accumulated organic matter by soil heterotrophic organisms. SOC sequestration can therefore be defined as a state of the soil in which the soil C inputs exceed the soil C release, leading to an increase in SOC stocks. Therefore, it follows that SOC sequestration may be achieved by either increasing inputs to the soil or decreasing losses.

Although this definition is widely accepted, it is worth highlighting some common misconceptions. For example, SOC sequestration in a given soil is commonly implied to contribute to climate change mitigation (Chenu et al., 2019). However, this is only true when sequestration results from a net gain of C from the atmosphere (Powlson et al., 2011). As such, increasing C inputs from photosynthesis is the most effective climate change mitigation strategy. Increasing organic amendment application, which represents a transfer of C from one place to another, leads to a net atmospheric decrease only when the soil stabilisation of the added material is more effective at the application site than at the site from where it is exported (Kirschbaum et al., 2020). Furthermore, the emission of other greenhouse gases such as nitrous oxide (N_2O), can negate or exceed the benefit of sequestering SOC in some conditions (Guenet et al., 2021; Lugato et al., 2018). Agriculture is responsible for approximately 70% of global anthropogenic N_2O emissions (Tian et al., 2020), largely due to the inefficient use of nitrogen fertilisers. We, therefore, argue that a lack of consideration for nitrogen use efficiency is a missed opportunity to strongly reduce the greenhouse gas footprint of agriculture as much as it is a trade-off with SOC sequestration (Powlson et al., 2011). Another misconception arises from the lack of distinction between SOC stocks and *changes* in SOC stocks. It is critical to stress that while SOM and SOC remain the most commonly measured soil variables (Bünemann et al., 2018), they provide little insight into SOC sequestration and the role of soils in mitigating climate change. First, SOC stocks measured at a given point in time provide no information on a trend—SOC sequestration involves a dynamic change in SOC stocks that can be quantified only by monitoring the stocks over time or by quantifying the balance between soil C uptake and release. Second, 'measuring SOC' often entails measuring concentrations (in unit mass of C per unit mass of soil), which do not inform on the quantities of SOC stored in the soil. Concentrations need to be converted to stocks (in unit mass of C per unit of land area to a sufficient depth to avoid the effects of soil compaction). This is usually done by multiplying the concentration by the soil bulk density, which may change over time as a result of changing management practices. More accurate methods exist that account for changing bulk densities, such as the equivalent soil mass basis (Wendt & Hauser, 2013).

3 | CLIMATE CHANGE MITIGATION POTENTIAL OF SOC SEQUESTRATION

3.1 | Estimates of global soil organic carbon sequestration potential

Several methods can be used to quantify the global potential of soil to sequester atmospheric CO_2.

The first one is based on calculations of historical C losses from cultivated soils (comparing C stocks from 'virgin' and cultivated soils on similar soil types and land use) and 'assuming a recovery of one-half to two-thirds of historical C losses as a reasonable upper limit' (Paustian et al., 1997). Early estimates of historical C losses varied widely, from 40 Gt C (148 Gt CO_2) to as much as 537 Gt C (1989 Gt CO_2) (Lal, 2001). The most recent estimate (using data-driven statistical modelling) puts global C losses at 116 Gt C (430 Gt CO_2) over the last 12,000 years of human land use (Sanderman et al., 2017), suggesting a global SOC sequestration potential of 285 Gt CO_2 under the two-thirds recovery assumption.

The second and most common method uses 'bottom-up' approaches where average SOC sequestration rates are estimated for different management practices over varied experimental duration, from 5 to more than 80 years (Paustian et al., 1997). Then, these estimated rates are extrapolated to regional or global scale by multiplying the rate with the estimated land area available for a given practice. The management practices, referred to as natural climate solutions (NCS) (Griscom et al., 2017), include many agricultural practices such as no-till, cover-cropping, improved nutrient, water, and grazing management, agroforestry, as well as interventions in other land-use sectors such as forestry and wetland management and peat restoration. Bottom-up estimates vary widely in the literature, from 0.4 (IPCC, 2019) up to 9.1 Gt CO_2 year^{-1} (Lal, 2018). The variety of underlying assumptions used to estimate the availability of land area for specific practices contributes greatly to this variability (Fuss et al., 2018). Moreover, different studies focus on different subsets of practices, from large ranges of NCS (Bossio et al., 2020), to agriculture and forestry (Minasny et al., 2017), agricultural lands only (IPCC WG3, 2022; Smith et al., 2008) or croplands only (Zomer et al., 2017). Whether biochar application should be included in estimates from agricultural management is also debated (Smith, 2016). Most recently, SOC sequestration in croplands, grasslands, agroforestry and biochar was estimated between 1.8 and 4.1 Gt CO_2 year^{-1} (IPCC WG3, 2022). We also observe that depth is inconsistently reported in review papers. As mentioned above, SOC stocks (and therefore sequestration rates) are usually measured to a constant depth and then converted per unit surface area (implicitly to this constant depth). These reviews, therefore, potentially combine estimates of sequestration rates that are not directly comparable (i.e. sequestration rates estimated to a depth of 2 m cannot be averaged directly with sequestration rates estimated to 30 cm depth; Knotters et al., 2022). This also contributes to the discrepancies between global estimates. Bossio et al. (2020) calculated recently the contribution of soils to the total mitigation potential of 20 NCS across different land-use sectors with stringent limits on the area availabilities to safeguard biodiversity and food security (leaving sufficient area available for food production; Griscom et al., 2017). The authors found a global technical SOC sequestration potential of 3.3 Gt CO_2 year^{-1}, far less than previous estimates which did not constrain the available land area (Fuss et al., 2018), and with greater recognition of the need to use multiple solutions and address multiple objectives concurrently.

As an alternative approach, Janzen et al. (2022) argued that global SOC sequestration is most constrained by photosynthesis, the primary source of soil C inputs. The authors estimated global photosynthetic C inputs and, from this, estimated a global SOC sequestration potential of around 0.52 Gt CO_2 year^{-1}.

Interpreting global SOC sequestration estimates in terms of their climate change mitigation potential is problematic because of a number of well-known limitations as briefly mentioned in the previous section (Baveye et al., 2018; Powlson et al., 2011; Rumpel et al., 2019). In the following sections, we emphasise two aspects—saturation and non-permanence—that we deem particularly underrated and critical to the interpretation of SOC sequestration potentials.

3.2 | Saturation

SOC sequestration saturates over time (Six et al., 2002; Smith, 2012). This 'sink saturation' is due to either a finite availability of mineral surfaces and other physico-chemical properties responsible for the persistence of C in soils, defining a maximum storage capacity, or to environmental constraints on C input stabilisation and decomposition rates leading to a new equilibrium value for SOC and defining an 'effective' storage capacity (Stewart et al., 2007). Therefore, converting estimated SOC sequestration rates into total SOC sequestration potential requires the time taken to reach a new equilibrium to be defined. Twenty years is often mentioned as a standard (Fuss et al., 2018; Smith et al., 2016), but other values are used, ranging from 5 to 50 years (Lal et al., 2018) and up to 85 years (Mayer et al., 2018). Furthermore, both the maximum and effective stabilisation capacities of soils depend on pedoclimatic conditions (Angers et al., 2011; McNally et al., 2017), suggesting that both the timespan of SOC accumulation and the rate of decrease in SOC sequestration are highly context dependent. A notable exception is peat and other organic soils such as mollisols, which are not bound to a maximum storage capacity, but require very specific conditions over large time spans to accumulate SOC. In mineral soils, texture is particularly influential, with sandy soils generally showing lower C storage capacities than heavier soils (Angers et al., 2011; McNally et al., 2017).

Most critically, the concept of sink saturation suggests not only a limited storage capacity but also that the rate of SOC sequestration decreases as SOC approaches the maximum or effective storage capacity (Poulton et al., 2018; Stewart et al., 2007). Saturation, therefore, implies not only that SOC sequestration is time-limited but also that sequestration rates decrease exponentially as soon as SOC stocks start to increase (Baveye et al., 2018). Most studies, however, with one notable exception (namely, Sommer & Bossio, 2014), assume a constant sequestration rate over the defined time period required to reach a new equilibrium (Bossio et al., 2020; Fuss et al., 2018). Some assessments provide only an annual rate in a specific year and compare this to other negative emission or emission reduction options. By doing so, the IPCC WG3 (2022) ranks SOC sequestration as the fourth most effective option in 2030, just behind the solar and wind energy transition. This is misleading and an unfair comparison because the potential of SOC sequestration will decline and reach zero over time, while it will be continued through time for most other options, including transitioning to non-CO_2 emitting energy production.

Here, we use the estimate of Bossio et al. (2020) as a starting value for SOC sequestration rates and illustrate the large overestimations in C sequestration potentials arising when C saturation is ignored. We compare the effect of three assumptions on the evolution of observed sequestration rates over time and illustrate their consequence for global SOC sequestration potential estimates: (1) a constant sequestration rate over time, (2) a rapid exponential decrease in sequestration rates with a 10-year exponential decay half-life; previously observed from converting croplands to grassland, which is arguably the fastest way to sequester SOC through land-use change (Baveye et al., 2018), and (3) a slow exponential decrease in sequestration rates: with a 30-year half-life (Figure 1a). The impact of these assumptions on global SOC sequestration potential is striking (Figure 1b): for the 2100 horizon, they are 257, 121 and 49 Gt CO_2 for constant, slowly decreasing and rapidly decreasing rates, respectively. This suggests that SOC sequestration potentials estimates that disregard saturation are overestimated by 53%–81%.

Finally, it is important to note that soils are not static: soil is formed at the soil-bedrock interface (saprolite) at the bottom of the soil column (mostly on centennial to millennial timescales), and soil is transported by erosion, exposing subsoil layers at the eroded site and burying topsoil layers where the eroded soil is deposited. Full accounting of these processes would be required to understand the carbon balance at larger temporal and spatial scale (Kirkels et al., 2014). Reviewing knowledge on the creation and redistribution of soils on SOC storage is beyond the scope of this article, but it is worth mentioning as it exposes yet another layer of complexity in the prediction of SOC sequestration.

3.3 | Non-permanence

SOC sequestration is also reversible. This means that improved management practices must be maintained for SOC stocks to remain at their maximum potential after the new equilibrium has been reached (Smith, 2012). Although some authors argue that this is realistic (Rumpel et al., 2019), SOC remains vulnerable to losses and is sensitive to a range of environmental factors. This vulnerability remains poorly understood. Particularly, the reappraised role of aggregation, organo-mineral interactions and microbial eco-physiology in regulating soil C dynamics (Lehmann & Kleber, 2015; Liang et al., 2017) questions knowledge of SOC sensitivity to factors such as temperature (Bradford et al., 2016; Conant et al., 2011; Moinet et al., 2018, 2020, 2021) and water availability (Moinet et al., 2016). The large variability in the responses of SOC stocks to soil warming (van Gestel et al., 2018) suggests a context-dependent response and a highly uncertain future for newly sequestered SOC, even when best management practices are maintained. Arguably, the residence time of sequestered SOC is less than that of the C stored in fossil fuel reservoirs (millennia). This implies that, in the long-term, avoiding CO_2 emissions is much more effective at limiting global warming than removing atmospheric CO_2, a fact referred to as 'asymmetry' in IPCC terminology (IPCC WG1, 2021).

Grasping the potential impact of SOC sequestration on climate change necessitates a comparison with the reductions in CO_2 concentrations that are required. This has been done, for example, by comparing estimated SOC sequestration potentials to CO_2 emitted from anthropogenic activities (Minasny et al., 2017; Sommer & Bossio, 2014). Following this approach, the most optimistic global potential estimate of ca. 454 Gt CO_2 (Lal, 2018) represents a little under 12 years of global CO_2 emissions at the current rate of 39 Gt CO_2 year^{-1}, and 3.5 years of global CO_2 emissions under our assumption of a fast decreasing SOC sequestration rate. The more realistic estimate from Bossio et al. (2020) represents 1.2–4.2 years of global emissions. Such comparisons have been used to illustrate that SOC sequestration would allow 'buying time' while low-carbon technologies are being developed (Minasny et al., 2017). We contend that this is misleading because of the reversibility of SOC sequestration and the large uncertainties surrounding its timespan. SOC sequestration cannot substitute emission reductions, even temporarily, nor does it delay the need for immediate and aggressive cuts in greenhouse gas emissions if we are to keep global warming under 1.5 or well-below 2°C (Anderson et al., 2019).

As an alternative representation of the contribution of SOC sequestration to reaching the goals of the Paris agreement, we made some simple calculations. Current policies are expected to stabilise emission levels at the current rate (39 Gt CO_2 year^{-1}), while scenarios focusing on current trends typically show a modest increase (IPCC WG3, 2022). Under these circumstances, cumulative emissions would reach close to 3500 Gt CO_2 (range of 3000–4000 Gt

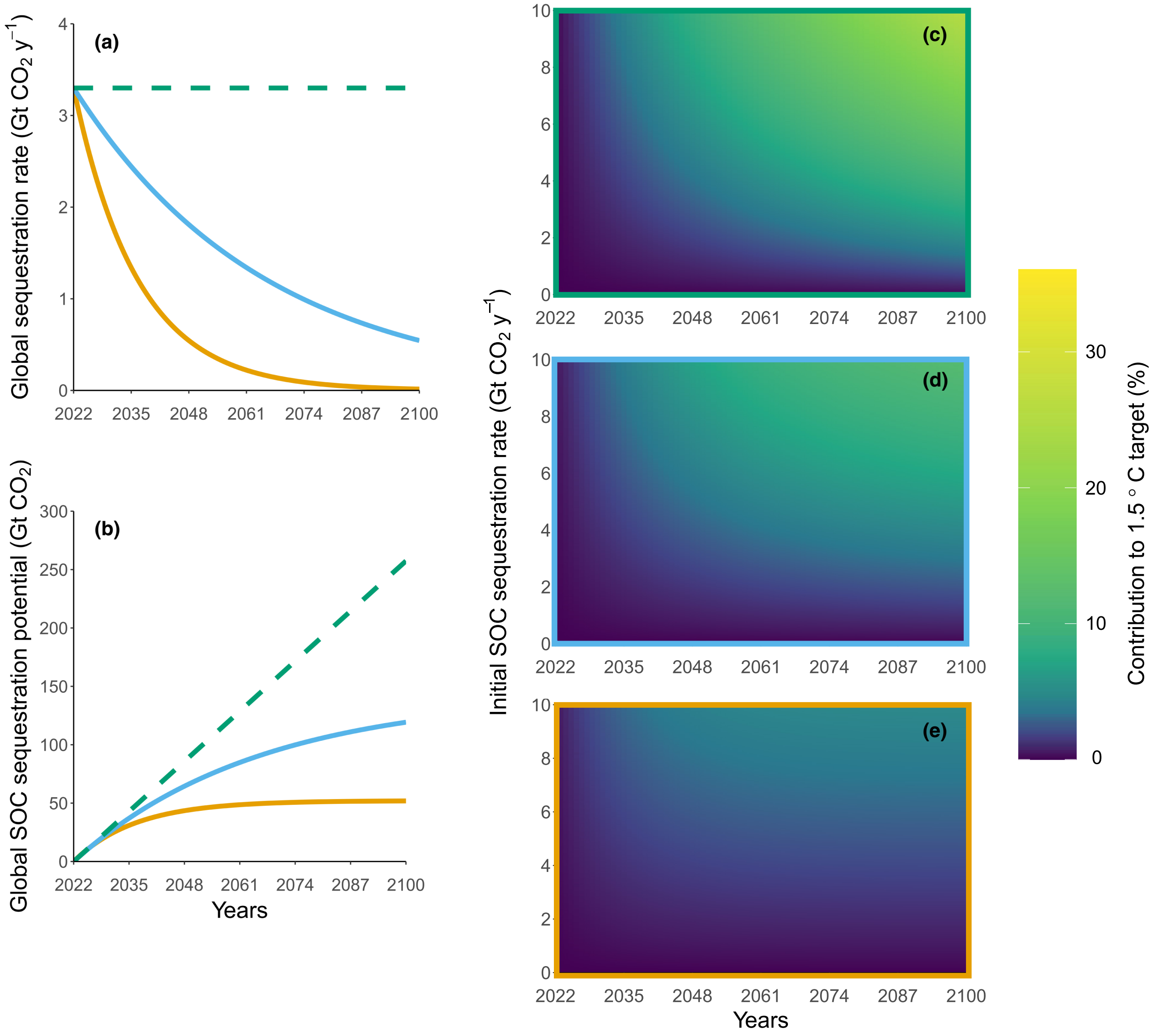

FIGURE 1 Visualisation of the impact of three different assumptions regarding C saturation on global soil organic carbon (SOC) sequestration and its potential to mitigate climate change to the horizon 2100. The three assumptions are as follows: An unrealistic constant sequestration rates over time, that is, no saturation limit (green dotted lines and frame); slow exponential decrease in sequestration rates (30 years exponential decay half-life; blue lines and frame); and fast exponential decrease in sequestration rates (10 years half-life; orange lines and frame). For the three assumptions, the temporal dynamics of global sequestration rates (a) and global SOC sequestration potential (b) are depicted for the example of the estimate from Bossio et al. (2020). The contribution of SOC sequestration to a pathway to 1.5°C target is represented for the whole range of literature estimates of sequestration rates in panels (c), (d) and (e), each panel corresponding to one assumption on saturation as indicated by the colours.

CO_2) by the end of the century. The total carbon budget to meet the 1.5°C target is estimated at 500 Gt CO_2 from early 2020 to 2100 (IPCC WG1, 2021). This implies a total net reduction in emissions of around 3000 Gt CO_2. Avoiding positive emissions (e.g. by decarbonisation and demand reduction) will be the main pathway. CDR can contribute to meeting the target by offsetting positive emissions before net-zero is reached (e.g. from hard-to-abate sectors) or by contributing to net negative emissions. In this context, the possible contribution of SOC sequestration alone, under the unrealistic assumption of an unlimited sequestration potential, would range from 1.0% (IPCC, 2019) to 23.7% (Lal, 2018) of the efforts towards a 1.5°C target for the horizon 2100 (Figure 1c; taking 0.4 and 9.1 Gt CO_2 year^{-1} as initial rates). Contributions decrease to 11.1% and 4.5% for the most optimistic SOC sequestration rate estimate (Lal et al., 2018) under the fast and slow assumptions, respectively; and to 4.0% and 1.6% for the more realistic initial SOC sequestration rate (3.3 Gt CO_2 year^{-1} by Bossio et al., 2020; Figure 1d,e). The most recent estimated initial SOC sequestration rate (0.52 Gt CO_2 year^{-1} by Janzen et al., 2022) would suggest an insignificant contribution of between 0% and 1%.

4 | CONTRIBUTION OF SOC SEQUESTRATION TO SOIL FERTILITY AND CROP YIELDS

Crops do not take up C from the soil. Therefore, the mechanisms through which SOC affects crop biomass and yield are always indirect. Such mechanisms include an increased supply of nutrients from mineralisation of SOM, enhanced retention and buffering of nutrient stocks through increased cation exchange capacity, improved water infiltration and better soil structure (and thus increased water and nutrient availability), or through shifts in the composition and structure of soil organism communities which may positively impact nutrient cycling and pest and disease control (Johnston et al., 2009; Watts & Dexter, 1997).

While seemingly sound, the generality of this narrative has been contested, both theoretically (Janzen, 2006) and empirically (Terrer et al., 2021), as mentioned in the introduction. So, what is the empirical evidence for a causal link between SOC sequestration and improved crop biomass production and yields? In recent years, a large number of meta-analyses assessed the benefits of either SOC sequestration or management practices that lead to SOC sequestration, on crop yields. To shed more light on the premise that SOC sequestration for climate change mitigation will also increase plant production, we reviewed 21 of those meta-analyses, the methods they employed, the outcomes, the validity and the limitations of the studies (Table 1). This exercise led us to three main conclusions, successively elaborated in the following sections: (i) establishing causality between SOC sequestration and crop yield is problematic, (ii) the response variables used vary among the studies and all have limitations, and (iii) the outcomes vary with space, time and methods used. Altogether, the meta-analyses provide no convincing empirical support that there is a general positive correlation between SOC sequestration and improvements in crop yield.

4.1 | Establishing causality is problematic

The most straightforward method to assess the effect of SOC on crop yields is a space for time substitution (as done by Han et al., 2018; Oelofse et al., 2015; Oldfield et al., 2019; Schjønning et al., 2018). Such studies compare crop production at several locations, some with larger SOC content than others, and assess differences in yields. Implicitly, a similar yield difference is assumed to occur when the SOC would have changed over time in one location. Interpretation is problematic, however, as soil texture and climate are strong confounding factors. Soil texture and climate affect SOC stocks (Burke et al., 1989; Feller & Beare, 1997; Hoyle et al., 2016; Miller et al., 2004) but also affect crop yields directly (van Ittersum & Rabbinge, 1997). Furthermore, if SOC can affect crop yield through the mechanisms mentioned earlier, the reverse may also be true: larger crop yields may lead to increased biomass inputs to the soil, through crop residues, roots and stubble, and may therefore positively affect the soil C balance. The direction of the causality in a correlation observed between SOC stocks and crop yields is therefore contested, both in spatial and time series observations (Figure 2).

Correlating crop yields to a change in SOC stocks (or to a management practice that enhances SOC stocks) over time in the same location (as done by Alvarez et al., 2017; Chen et al., 2018; Cooper et al., 2016; Dawe et al., 2003; Du et al., 2020; Han et al., 2018; Islam et al., 2022; Jeffery et al., 2017; Kuyah et al., 2019; Li et al., 2021; Luo et al., 2018; Soussana et al., 2019; Wei et al., 2016; Zavattaro et al., 2017) is not subject to such confounding environmental factors but has other limitations. To increase SOC stocks (relative to a control treatment) in an experimental field, a change in management practices is required. Yet management changes not only affect SOC but may also influence crop yields directly (Figure 2). For example, cultivation of a cover crop can increase SOC stocks and, at the same time, can reduce N losses, thereby increasing soil N supply and possibly crop yields (Thapa et al., 2018). Another example is that of biochar, for which beneficial effects on crop yields are mainly observed in tropical acid soils (Jeffery et al., 2017), most likely due to the amelioration of aluminium toxicity (Shetty et al., 2021).

4.2 | Limitations of response variables used

An additional complication that arises when assessing the contribution of SOC sequestration to crop yields is the composition of SOM, which changes over time. Often, adding organic amendments to soil is assumed to be representative of SOC sequestration (Dawe et al., 2003; Islam et al., 2022; Wei et al., 2016) as additional C inputs favour a positive soil C balance. However, fresh organic amendments are not equivalent to a long-term change in SOC stocks. Fresh organic amendments contain large amounts of nutrients (such as N, phosphorus [P] and potassium [K]), which are more readily available for crops than the nutrients contained in older, stabilised SOM. Fresh organic amendments may therefore have larger benefits for crop yields than older and more stable SOM. When analysing field experimental data, such NPK effects can be excluded by assessing yield response curves to N application in the presence of sufficient P and K supply and calculating the difference in attainable crop yields (as done by Hijbeek et al., 2017; Oelofse et al., 2015; Schjønning et al., 2018). In such cases, attainable crop yields are the plateau of the yield response curve. An increase in the plateau suggests improvements in other soil functions, beyond nutrient supply, that stimulate crop yields.

Alternatively, one can assess the influence of an increase in SOC on agronomic N use efficiency or N recovery (as done by Oelofse et al., 2015; Ravensbergen et al., 2021; Schjønning et al., 2018; Vanlauwe et al., 2011). These indicators assess the additional yield or crop N uptake per additional kg N applied. An increase would confirm the hypothesis that larger SOC stocks lead to improved soil structure, water holding capacity, or soil quality in general (although we acknowledge that the term is controversial; Bünemann et al., 2018), leading to more plant production per unit N applied.

TABLE 1 Overview of direction and size of mean effects of SOC sequestration on crop yields, depending on the assessment method used, across 21 meta-analyses

Correction of NPK supply?	Meta-analysis	Location	# data points	Management practice	Response variable	Significant mean effect
Observed yield effects—corrected for N, P and K contributions	Oelofse et al. (2015), figure 5a,b	Denmark	869	Spatial comparison	N recovery (wheat)	−0.17 (kg N/kg N)/% soil C
					N recovery (spring barley)	−0.16 (kg N/kg N)/% soil C
					Attainable yield	0 (t/ha)/% soil C
	Schjønning et al. (2018), figure 7	Denmark	975	Spatial comparison	Agronomic N use efficiency	−3.95 (kg grain yield/kg N) per 0.01 kg soil C/kg minerals
					Attainable yield	−630 kg grain yield/ha per 0.01 kg soil C/kg minerals
	Hijbeek et al. (2017)	Europe	107 (20)	Organic amendments	Δ attainable yield	0%
	Ravensbergen et al. (2021), figure 6a	Nigeria	676	Spatial comparison	N recovery	0 (kg N/kg N)/g/kg soil C
	Cooper et al. (2016)	N-America & Europe	1079 (26)	Reducing tillage	Δ yield (vs. deep inversion tillage)	−7.6%
					Δ yield (vs. shallow inversion tillage)	0%
Uncertain in some cases	Zavattaro et al. (2017)	Europe	310 (80)	Organic amendments	Δ yield	0%
	Chen et al. (2018), figure 2b, figure S1b	Global	329 (132)	Organic amendments	Δ yield (average over period)	0%
					Δ yield (last experimental year)	5.3%
	Dawe et al. (2003)	Asia	75 (25)	Organic amendments	Δ yield	0%
					Δ yield trends	0%

TABLE 1 (Continued)

Correction of NPK supply?	Meta-analysis	Location	# data points	Management practice	Response variable	Significant mean effect
Observed yield effects -possibly including N, P or K contributions	Wei et al. (2016)	China	38 (32)	Organic amendments	Δ yield	7.6%
					Δ yield trends	26.9%
	Vanlauwe et al. (2011), figure 6a	SSA	721 (90)	Residues I, III, IV	Δ agronomic N use efficiency	−36%
				Residues II	Δ agronomic N use efficiency	0%
				FYM or compost	Δ agronomic N use efficiency	28%
	Jeffery et al. (2017)	Global	1125 (109)	Use of biochar	Δ yield (temperate)	0%
					Δ yield (tropics)	25%
	Luo et al. (2018)	Global	226 (106)	Organic amendments	Δ yield	27%
	Han et al. (2018)	China	75 (70)	Straw	Δ yield	13.4%
				Spatial comparison	Yield	267–414 kg grain yield/g soil C/kg soil
	Pan et al. (2009)	China	National statistics	Time series	Yield	0.43 t grain yield/% soil C
	Soussana et al. (2019), figure 1	Africa, Asia & L-A	151 (32)	Diverse	Δ yield	3.25% grain yield/% change in % soil C
	Alvarez et al. (2017), figure 5	Argentine Pampas	67 (62)	Legume cover crop	Δ yield (maize)	6.70%
				Non-legume cover crop	Δ yield (maize)	0%
				Cover crop	Δ yield (soybean)	−2.50%
	Kuyah et al. (2019)	SSA	397 (61)	Agroforestry (divers)	Δ yield	100%
	Li et al. (2021)	Upland China	622 (160)	Organic amendments	Δ yield (org only)	0%
					Δ yield (org + fert)	8.3%–8.7%
	Du et al. (2020)	China	774 (141)	Manure	Δ yield	7.60%
	Oldfield et al. (2019), figure 1	Global	834 (90)	Spatial comparison	Yield	equation Table 1 (Oldfield et al., 2019)
	Islam et al. (2022), figure 2	China	1071 (177)	Straw	Δ yield (monocropping)	11.80%
					Δ yield (double cropping)	5.50%

Note: Red indicates a mean significant negative yield effect, orange indicates no significant yield effect and blue indicates a mean significant positive yield effect. Data points indicate the number of yield observations. If yield observations differ from the amount of field experimental locations, the latter is placed within brackets. An earlier (more limited) review of meta-analyses was published as a conference proceeding by Hijbeek et al. (2018).

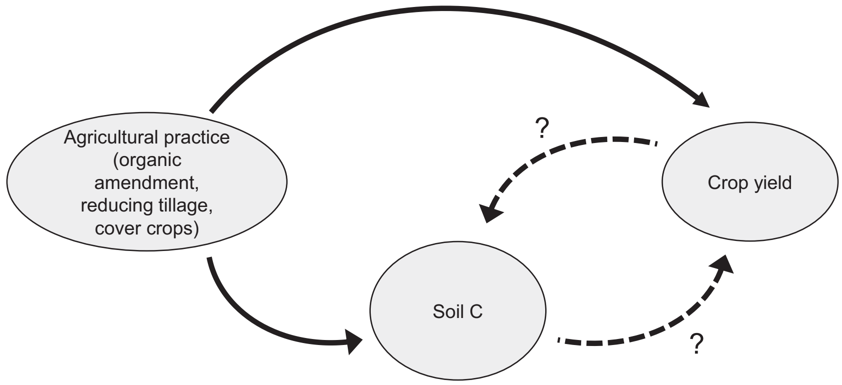

FIGURE 2 Illustration of the complexity of unravelling causal relations between an increase in soil organic carbon (SOC) stocks and crop yields. Agricultural practices that increase SOC stocks may also enhance crop yields, suggesting that the evolution of SOC and yield in time may correlate with no causal link between them. Moreover, even if a causal link exists, determining which SOC or yield is the cause, and which is the effect, is problematic.

When experimental treatments receive sufficient P and K application, a change in agronomic N use efficiency is also representative of the long-term effect of SOC on crop yield.

Among the meta-analyses reviewed, some studies tried to correct for NPK effects on crop yields by assessing the ratio of N, P and/or K between treatments or aiming to standardise nutrient supply (Chen et al., 2018; Dawe et al., 2003; Zavattaro et al., 2017). At the same time, the authors acknowledged that this approach is ambiguous as a control treatment with equal NPK supply from mineral fertiliser is required, while relative nutrient mineralisation rates of organic amendments vary strongly with the quality of the amendment and across locations (Schröder, 2005). As a result, it is unclear whether findings from those studies represent the effect of old or fresh organic matter. In Table 1, such studies are classified as 'uncertain in some cases'.

4.3 | Conflicting evidence

Findings of the recent meta-analyses vary from negative to neutral to positive yield effects of increasing SOC (or organic amendments; Table 1). It is striking that neutral or negative effects are found much more often when studies correct for N, P and K supply (Table 1, top section). By contrast, a majority of the studies in which N, P and K supply was included found a positive effect of SOC on crop yields (Table 1, bottom section). Based on the previous section, we argue that these latter yield effects are not representative of expected yield increases when sequestering carbon over long periods of time in more persistent forms, as required to mitigate climate change.

In short, increasing SOC stocks does not always increase crop yields, and can also negatively affect them. Terrer et al. (2021) showed a trade-off between SOC sequestration and plant biomass production in a meta-analysis of 108 elevated CO_2 experiments across forests and grassland ecosystems, most likely due to competition for N between soil and plants. This was affirmed by another recent study (van der Pol et al., 2022), who found that converting a fallow-grain crop rotation to a continuous grain crop rotation increased grain yield and SOC stocks only when a legume crop was also included in the rotation (enhancing inputs from biological N_2 fixation). Competition for nutrients (particularly for N) is therefore a strong candidate explanation for observed negative yield effects.

Another critical point to stress is the context specificity of the relationship between SOC and yield. From the eight meta-analyses which gave insights into the longer-term effect of SOC sequestration on soil fertility and crop yields (i.e. correcting for NPK supply), four studies investigated the role of soil texture (Chen et al., 2018; Hijbeek et al., 2017; Oelofse et al., 2015; Zavattaro et al., 2017) and one investigated the role of climate (Chen et al., 2018). Considering soil type, three studies consistently found greater benefits on sandy soils. Only one study (Oelofse et al., 2015) found unclear effects across eight soil types, with borderline positive effects on coarse sandy loam and fine sandy clay loam soils but negative effects on fine sandy soils. A clearer picture was obtained by Zavattaro et al. (2017) who found significantly more benefits on light than on medium-textured soils (response ratio of 1.051 vs. 0.866). Similarly, whereas Hijbeek et al. (2017) found no overall yield effects of organic amendments, attainable crop yields were increased on soils with smaller clay content (an additional 0.13% increase in attainable yields when using organic amendments for 1% less clay particles). Finally, when assessing the yield change in the final years of experiments, Chen et al. (2018) found a positive yield difference for sandy soils, but not for any of the other soils investigated (clay, loam or silty soils) when standardising NPK supply. Using the same data selection, the authors also found a positive yield effect in tropical climates, with no significant yield differences in the final experimental year in the other climate zones (subtropical and continental).

Beyond pedo-climatic conditions, the initial SOC stocks are also critical. This was very clearly demonstrated in the meta-analysis of Oldfield et al. (2019), who showed that the yield effect of SOC saturates, with no further increase beyond a SOC content of approximately 2%.

5 | SOIL-SMART AGRICULTURE

Two key points emerge from our review: (i) the climate mitigation potential of SOC sequestration is modest, at best, on a global scale, and context-specific, and (ii) correlations between SOC sequestration and crop yield are strongly context dependent and it is highly uncertain whether a causal link exists. Therefore, SOC sequestration is most certainly not a win-win option under all conditions.

Nevertheless, reaping the win-win between enhancing SOC and crop yields where and when possible is laudable. From this perspective, agendas that promote region-specific (or even more localised) assessments, as proposed recently (Amelung et al., 2020), seem appropriate. Yet even when and where SOC sequestration can go hand-in-hand with improved soil fertility and crop yields, strategies to promote one may not be the best suited to promote the other. The influence of soil type is particularly illustrative of this conflict (Rusinamhodzi et al., 2013). As discussed, clay soils have the largest potential to store SOC, and those that are depleted offer the greatest opportunity to increase SOC stocks (Angers et al., 2011; Kirschbaum et al., 2020; McNally et al., 2017), but it is in sandy soils that the effect of increasing SOC on crop yield may be the largest (Chen et al., 2018; Hijbeek et al., 2017; Zavattaro et al., 2017). In

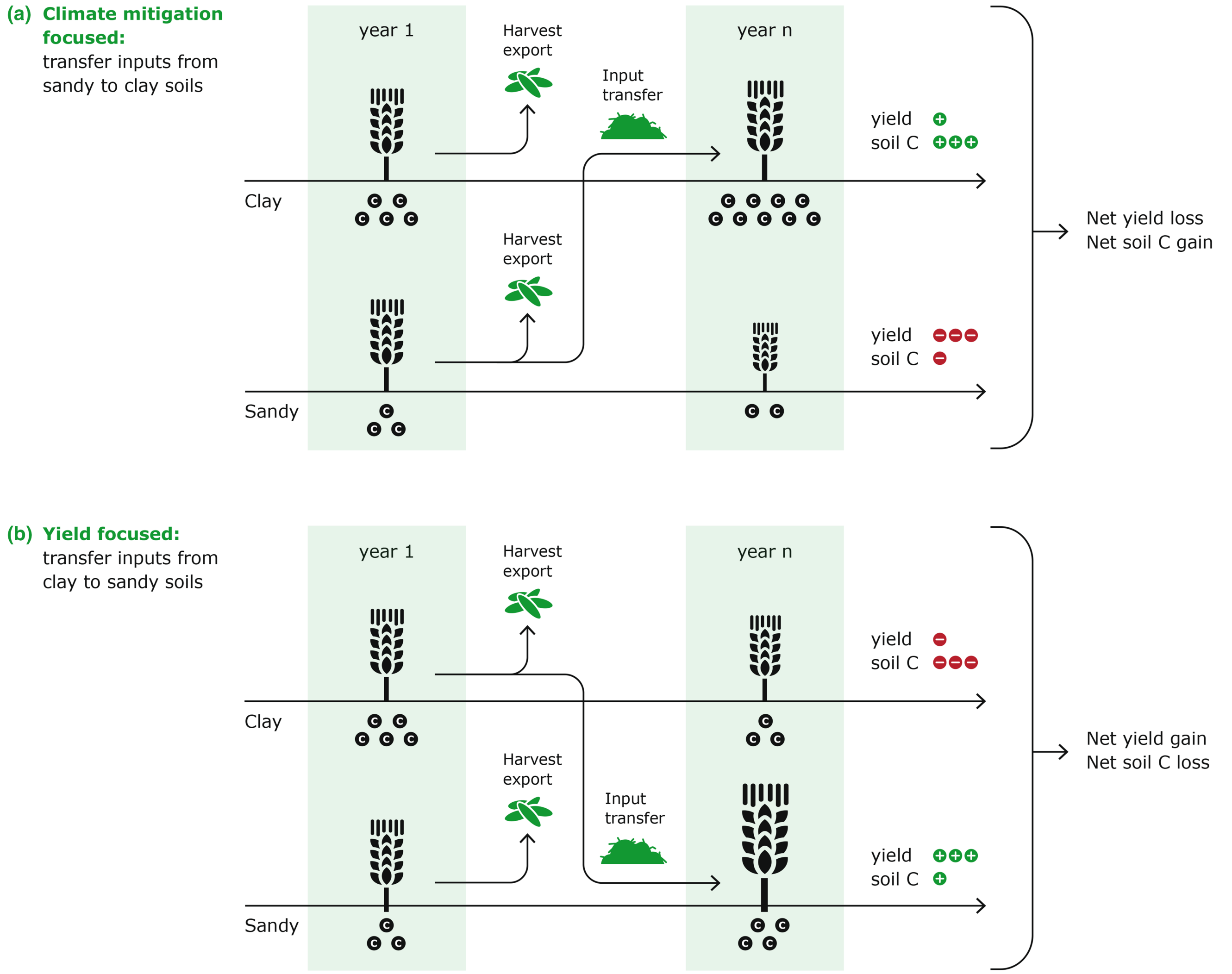

FIGURE 3 Conceptual figure illustrating potential conflicts between soil organic carbon (SOC) sequestration and food production. The figure depicts two hypothetical cases in which crop residues are removed from one field after harvest to be applied as OM inputs to another crop field. In panel a, residues are transferred from a sandy soil to a clay soil. After some years, a new equilibrium for SOC stock is reached. The clay soil gains more SOC than the sandy soil loses, due to its higher C stabilisation capacity (Kirschbaum et al., 2020). Therefore the net overall effect is that C is sequestered, to the benefit of climate (provided that no additional N_2O or CH_4 emissions would arise). The clay soil also sees crop yield increasing, but not as much as the yield in the sandy soil decreases, due to the stronger yield effect of organic amendments in sandy than clay soils (Hijbeek et al., 2017; Zomer et al., 2017). The net effect for yield is that less crops are produced overall. The reciprocal transfer, in panel b, leads to mirrored effects: Small yield loss in the clay soil and high yield gain in the sandy soil, and large CO_2 emissions in clay soil and small SOC sequestration in the sandy soil with an overall SOC loss and aggravated climate change, but more food produced overall. Importantly, assuming that each field is owned by a different farmer, someone always loses. This clearly illustrates that local win-win scenarios can occur at the expense of fertility elsewhere.

a context where organic resources are expensive and in high demand (Giller et al., 2008), a strategy targeted at maximising overall SOC storage for climate change mitigation would dictate that organic matter should preferably be diverted from sandy soils to clay soils (Kirschbaum et al., 2020), at the expense of the fertility of the sandy soils. By contrast, a primary focus on soil fertility and yield improvement would dictate organic matter to be diverted from clay soils to sandy soils, at the expense of overall SOC storage (Figure 3). Importantly, in the former case, an overall yield decrease would mean that more land is needed overall to maintain food production constant, leading to more deforestation or less reforestation and therefore SOC and above-ground C losses elsewhere.

Ensuring global food security in a stabilised climate is a tremendously complex endeavour. Our findings build on a wealth of knowledge showing the importance of local knowledge, of developing locally suited adaptative methods focusing on a wide set of environmental outcomes, and calling attention to social acceptability and economic viability (Giller et al., 2015; Pretty, 2018; Pretty et al., 2011). For example, while it is doubtful that increasing food production in Europe or North America would yield any benefit for global food security (Loos et al., 2014), the link between food production and food security is absolutely critical for smallholder African farmers (Giller et al., 2021), with an estimated 7% reduction in poverty for every 10% increase in yield (Pretty et al., 2011). The hard reality is that difficult choices must be made, and these choices have to be made locally.

Without a doubt, soils have a critical role to play, and SOM, with the carbon it contains, is fundamental to maintaining soil fertility and supporting plant production. Furthermore, SOM is central to the numerous functions delivered by soils (Kopittke et al., 2022). This, we do not question. However, our review demonstrates that the importance of SOC does not imply that *increasing* SOC stocks necessarily leads to an increase in yield. More generally, relationships between the multiple functions of soil are context-specific and numerous trade-offs exist (Schulte et al., 2014; Vazquez et al., 2021; Zwetsloot et al., 2021). It is increasingly recognised that greater scientific knowledge and concurrent management of these soil functions will be critical (Kopittke et al., 2022; Schulte et al., 2014). We conclude that, if we are to ensure food security in a changing climate, let alone other sustainable development goals, SOC sequestration is simply not up to the challenge. SOC sequestration is indeed one of many approaches, one small piece of a very large puzzle, and it should be treated as such. We argue that including SOC sequestration in the narrative of global climate change mitigation is ill-suited and we call for a soil-smart approach, which will not always be 'climate-smart'.

ACKNOWLEDGMENTS

We thank Marie Zwetsloot, Jan-Willem van Groenigen, Jantiene Baartman and Rachel Creamer for internal reviews of draft manuscripts and suggestions for improvement. We thank Hein ten Berge, Andy Whitmore and Martin van Ittersum for the exchange of ideas on how to measure the effect of SOC sequestration on crop yields in earlier years. We also thank Thom Kuyper for creating the course 'the carbon dilemma—a soil perspective' at Wageningen University, and the MSc students that took part in this course for the lively class discussions which gave inspiration for the writing process.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Gabriel Y. K. Moinet https://orcid.org/0000-0002-5347-8847
Renske Hijbeek https://orcid.org/0000-0001-8214-9121
Detlef P. van Vuuren https://orcid.org/0000-0003-0398-2831
Ken E. Giller https://orcid.org/0000-0002-5998-4652

REFERENCES

Alvarez, R., Steinbach, H. S., & De Paepe, J. L. (2017). Cover crop effects on soils and subsequent crops in the pampas: A meta-analysis. *Soil and Tillage Research*, *170*, 53–65. doi:10.1016/j.still.2017.03.005

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nature Communications*, *11*(1), 1. Scopus. https://doi.org/10.1038/s41467-020-18887-7

Amundson, R., & Biardeau, L. (2018). Opinion: Soil carbon sequestration is an elusive climate mitigation tool. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(46), 11652–11656. https://doi.org/10.1073/pnas.1815901115

Anderson, C. M., DeFries, R. S., Litterman, R., Matson, P. A., Nepstad, D. C., Pacala, S., Schlesinger, W. H., Shaw, M. R., Smith, P., Weber, C., & Field, C. B. (2019). Natural climate solutions are not enough. *Science*, *363*(6430), 933–934. https://doi.org/10.1126/science.aaw2741

Angers, D. A., Arrouays, D., Saby, N. P. A., & Walter, C. (2011). Estimating and mapping the carbon saturation deficit of French agricultural topsoils. *Soil Use and Management*, *27*(4), 448–452. https://doi.org/10.1111/j.1475-2743.2011.00366.x

Baveye, P. C., Berthelin, J., Tessier, D., & Lemaire, G. (2018). The "4 per 1000" initiative: A credibility issue for the soil science community? *Geoderma*, *309*, 118–123. https://doi.org/10.1016/j.geoderma.2017.05.005

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. *Nature Sustainability*, *3*(5), 391–398. https://doi.org/10.1038/s41893-020-0491-z

Bradford, M. A., Carey, C. J., Atwood, L., Bossio, D., Fenichel, E. P., Gennet, S., Fargione, J., Fisher, J. R. B., Fuller, E., Kane, D. A., Lehmann, J., Oldfield, E. E., Ordway, E. M., Rudek, J., Sanderman, J., & Wood, S. A. (2019). Soil carbon science for policy and practice. *Nature Sustainability*, *2*(12), 1070–1072. https://doi.org/10.1038/s41893-019-0431-y

Bradford, M. A., Wieder, W. R., Bonan, G. B., Fierer, N., Raymond, P. A., & Crowther, T. W. (2016). Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change*, *6*(8), 751–758. https://doi.org/10.1038/nclimate3071

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality—A critical review. *Soil Biology and Biochemistry*, *120*, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Burke, I. C., Yonker, C. M., Parton, W. J., Cole, C. V., Flach, K., & Schimel, D. S. (1989). Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. *Soil Science Society of America Journal*, *53*(3), 800–805. https://doi.org/10.2136/sssaj1989.03615995005300030029x

Chabbi, A., Lehmann, J., Ciais, P., Loescher, H. W., Cotrufo, M. F., Don, A., SanClements, M., Schipper, L., Six, J., Smith, P., & Rumpel, C. (2017). Aligning agriculture and climate policy. *Nature Climate Change*, *7*, 307–309. https://doi.org/10.1038/nclimate3286

Chen, J., Sun, X., Zheng, J., Zhang, X., Liu, X., Bian, R., Li, L., Cheng, K., Zheng, J., & Pan, G. (2018). Biochar amendment changes temperature sensitivity of soil respiration and composition of microbial communities 3 years after incorporation in an organic carbon-poor dry cropland soil. *Biology and Fertility of Soils*, *54*(2), 175–188. https://doi.org/10.1007/s00374-017-1253-6

Chenu, C., Angers, D. A., Barre, 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

Conant, R. T., Ryan, M. G., Ågren, G. I., Birge, H. E., Davidson, E. A., Eliasson, P. E., Evans, S. E., Frey, S. D., Giardina, C. P., Hopkins, F. M., Hyvönen, R., Kirschbaum, M. U. F., Lavallee, J. M., Leifeld, J., Parton, W. J., Steinweg, J. M., Wallenstein, M. D., Wetterstedt, J. Å. M., & Bradford, M. A. (2011). Temperature and soil organic matter decomposition rates—Synthesis of current knowledge and a way forward. *Global Change Biology*, *17*(11), 3392–3404. https://doi.org/10.1111/j.1365-2486.2011.02496.x

Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., Peigné, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegher, A., Döring, T. F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., … Mäder, P. (2016). Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: A meta-analysis. *Agronomy for Sustainable Development*, *36*(1), 22. https://doi.org/10.1007/s13593-016-0354-1

Dawe, D., Dobermann, A., Ladha, J. K., Yadav, R. L., Bao, L., Gupta, R. K., Lal, P., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., & Zhen, Q.-X. (2003). Do organic amendments improve yield trends and profitability in intensive rice systems? *Field Crops Research*, *83*(2), 191–213.

Du, Y., Cui, B., Zhang, Q., Wang, Z., Sun, J., & Niu, W. (2020). Effects of manure fertilizer on crop yield and soil properties in China: A meta-analysis. *Catena*, *193*, 104617. https://doi.org/10.1016/j.catena.2020.104617

Feller, C., & Beare, M. H. (1997). Physical control of soil organic matter dynamics in the tropics. *Geoderma*, *79*(1–4), 69–116. https://doi.org/10.1016/S0016-7061(97)00039-6

Food and Agriculture Organisation of the United Nations (FAO). (2017). Soil organic carbon: The hidden potential. https://www.fao.org/3/I6937EN/i6937en.pdf

Food and Agriculture Organisation of the United Nations (FAO). (2019). Recarbonization of global soils—A dynamic response to offset global emissions. http://www.fao.org/3/i7235en/I7235EN.pdf

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Bates, N. R., Becker, M., Bellouin, N., … Zeng, J. (2022). Global carbon budget 2021. *Earth System Science Data*, *14*(4), 1917–2005. https://doi.org/10.5194/essd-14-1917-2022

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., Garcia, W. d. O., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., Dominguez, M. d. M. Z., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Giller, K. E. (2020). The food security conundrum of sub-Saharan Africa. *Global Food Security*, *26*, 100431. https://doi.org/10.1016/j.gfs.2020.100431

Giller, K. E., Andersson, J. A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., & Vanlauwe, B. (2015). Beyond conservation agriculture. *Frontiers in Plant Science*, *6*, 14.

Giller, K. E., Delaune, T., Silva, J. V., van Wijk, M., Hammond, J., Descheemaeker, K., van de Ven, G., Schut, A. G. T., Taulya, G., Chikowo, R., & Andersson, J. A. (2021). Small farms and development in sub-Saharan Africa: Farming for food, for income or for lack of better options? *Food Security*, *13*, 1431–1454. https://doi.org/10.1007/s12571-021-01209-0

Giller, K. E., Leeuwis, C., Andersson, J. A., Andriesse, W., Brouwer, A., Frost, P., Hebinck, P., Heitkönig, I., van Ittersum, M. K., Koning, N., Ruben, R., Slingerland, M., Udo, H., Veldkamp, T., van de Vijver, C., van Wijk, M. T., & Windmeijer, P. (2008). Competing claims on natural resources: What role for science? *Ecology and Society*, *13*(2), 34. https://www.jstor.org/stable/26267992

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. https://doi.org/10.1073/pnas.1710465114

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. https://doi.org/10.1111/gcb.15342

Han, X., Xu, C., Dungait, J. A. J., Bol, R., Wang, X., Wu, W., & Meng, F. (2018). Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: A system analysis. *Biogeosciences*, *15*(7), 1933–1946. https://doi.org/10.5194/bg-15-1933-2018

Hijbeek, R., van Ittersum, M. K., ten Berge, H. & Whitmore, A. P. (2018). Evidence review indicates a re-think on the impact of organic inputs and soil organic matter on crop yield. Paper presented to the International Fertiliser Society at a Conference in Cambridge, UK, 7th December 2018. Proceeding 826. International Fertiliser Society.

Hijbeek, R., van Ittersum, M. K., ten Berge, H. F. M., Gort, G., Spiegel, H., & Whitmore, A. P. (2017). Do organic inputs matter—A meta-analysis of additional yield effects for arable crops in Europe. *Plant and Soil*, *411*(1–2), 293–303. https://doi.org/10.1007/s11104-016-3031-x

Hoyle, F. C., O'Leary, R. A., & Murphy, D. V. (2016). Spatially governed climate factors dominate management in determining the quantity and distribution of soil organic carbon in dryland agricultural systems. *Scientific Reports*, *6*(1), 31468. https://doi.org/10.1038/srep31468

IPCC. (2019). *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, …, J. Malley (Eds.)]. Cambridge University Press, 896 pp. https://doi.org/10.1017/9781009157988

IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the* intergovernmental panel on climate change [V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.)]. Cambridge University Press, in press. https://doi.org/10.1017/9781009157896

IPCC. (2022). *Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate hange* [P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley (Eds.)]. Cambridge University Press. https://doi.org/10.1017/9781009157926

Islam, M. U., Guo, Z., Jiang, F., & Peng, X. (2022). Does straw return increase crop yield in the wheat-maize cropping system in China? A meta-analysis. *Field Crops Research*, *279*, 108447. https://doi.org/10.1016/j.fcr.2022.108447

Janzen, H. H. (2006). The soil carbon dilemma: Shall we hoard it or use it? *Soil Biology and Biochemistry*, *38*(3), 419–424. https://doi.org/10.1016/j.soilbio.2005.10.008

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. https://doi.org/10.1016/j.geoderma.2022.115810

Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, *12*(5), 053001. https://doi.org/10.1088/1748-9326/aa67bd

Johnston, A. E., Poulton, P. R., & Coleman, K. (2009). Chapter 1 soil organic matter. In *Advances in agronomy* (Vol. *101*, pp. 1–57). Elsevier. https://doi.org/10.1016/S0065-2113(08)00801-8

Kirkels, F. M. S. A., Cammeraat, L. H., & Kuhn, N. J. (2014). The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes—A review of different concepts. *Geomorphology*, *226*, 94–105. https://doi.org/10.1016/j.geomorph.2014.07.023

Kirschbaum, M. U. F., Moinet, G. Y. K., Hedley, C. B., Beare, M. H., & McNally, S. R. (2020). A conceptual model of carbon stabilisation based on patterns observed in different soils. *Soil Biology and Biochemistry*, *141*, 107683. https://doi.org/10.1016/j.soilbio.2019.107683

Knotters, M., Teuling, K., Reijneveld, A., Lesschen, J. P., & Kuikman, P. (2022). Changes in organic matter contents and carbon stocks in Dutch soils, 1998–2018. *Geoderma*, *414*, 115751. https://doi.org/10.1016/j.geoderma.2022.115751

Kopittke, P. M., Berhe, A. A., Carrillo, Y., Cavagnaro, T. R., Chen, D., Chen, Q.-L., Román Dobarco, M., Dijkstra, F. A., Field, D. J., Grundy, M. J., He, J.-Z., Hoyle, F. C., Kögel-Knabner, I., Lam, S. K., Marschner, P., Martinez, C., McBratney, A. B., McDonald-Madden, E., Menzies, N. W., … Minasny, B. (2022). Ensuring planetary survival: The centrality of organic carbon in balancing the multifunctional nature of soils. *Critical Reviews in Environmental Science and Technology*, *52*, 1–17. https://doi.org/10.1080/10643389.2021.2024484

Kuyah, S., Whitney, C. W., Jonsson, M., Sileshi, G. W., Öborn, I., Muthuri, C. W., & Luedeling, E. (2019). Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agronomy for Sustainable Development*, *39*(5), 47. https://doi.org/10.1007/s13593-019-0589-8

Lal, R. (2001). World cropland soils as a source or sink for atmospheric carbon. In *Advances in agronomy* (Vol. *71*, pp. 145–191). Academic Press. https://doi.org/10.1016/S0065-2113(01)71014-0

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Lal, R. (2018). Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Global Change Biology*, *24*(8), 3285–3301. https://doi.org/10.1111/gcb.14054

Lal, R., Monger, C., Nave, L., & Smith, P. (2021). The role of soil in regulation of climate. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1834), 1834. Scopus. https://doi.org/10.1098/rstb.2021.0084

Lal, R., Smith, P., Jungkunst, H. F., Mitsch, W. J., Lehmann, J., Nair, P. K. R., McBratney, A. B., Sá, J. C. M., Schneider, J., Zinn, Y. L., Skorupa, A. L. A., Zhang, H.-L., Minasny, B., Srinivasrao, C., & Ravindranath, N. H. (2018). The carbon sequestration potential of terrestrial ecosystems. *Journal of Soil and Water Conservation*, *73*(6), 145A–152A. https://doi.org/10.2489/jswc.73.6.145A

Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. *Nature*, *528*(7580), 60–68. https://doi.org/10.1038/nature16069

Li, P., Li, Y., Xu, L., Zhang, H., Shen, X., Xu, H., Jiao, J., Li, H., & Hu, F. (2021). Crop yield-soil quality balance in double cropping in China's upland by organic amendments: A meta-analysis. *Geoderma*, *403*, 115197. https://doi.org/10.1016/j.geoderma.2021.115197

Liang, C., Schimel, J. P., & Jastrow, J. D. (2017). The importance of anabolism in microbial control over soil carbon storage. *Nature Microbiology*, *2*(8), 17105. https://doi.org/10.1038/nmicrobiol.2017.105

Loos, J., Abson, D. J., Chappell, M. J., Hanspach, J., Mikulcak, F., Tichit, M., & Fischer, J. (2014). Putting meaning back into "sustainable intensification". *Frontiers in Ecology and the Environment*, *12*(6), 356–361. https://doi.org/10.1890/130157

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

Luo, G., Li, L., Friman, V.-P., Guo, J., Guo, S., Shen, Q., & Ling, N. (2018). Organic amendments increase crop yields by improving microbe-mediated soil functioning of agroecosystems: A meta-analysis. *Soil Biology and Biochemistry*, *124*, 105–115. https://doi.org/10.1016/j.soilbio.2018.06.002

Mayer, A., Hausfather, Z., Jones, A. D., & Silver, W. L. (2018). The potential of agricultural land management to contribute to lower global surface temperatures. *Science Advances*, *4*(8), eaaq0932. https://doi.org/10.1126/sciadv.aaq0932

McNally, S. R., Beare, M. H., Curtin, D., Meenken, E. D., Kelliher, F. M., Pereira, R. C., Shen, Q., & Baldock, J. (2017). Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. *Global Change Biology*, *23*(11), 4544–4555. https://doi.org/10.1111/gcb.13720

Miller, A. J., Amundson, R., Burke, I. C., & Yonker, C. (2004). The effect of climate and cultivation on soil organic C and N. *Biogeochemistry*, *67*(1), 57–72. https://doi.org/10.1023/B:BIOG.0000015302.16640.a5

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. https://doi.org/10.1016/j.geoderma.2017.01.002

Moinet, G. Y. K., Cieraad, E., Hunt, J. E., Fraser, A., Turnbull, M. H., & Whitehead, D. (2016). Soil heterotrophic respiration is insensitive to changes in soil water content but related to microbial access to organic matter. *Geoderma*, *274*, 68–78. Scopus. https://doi.org/10.1016/j.geoderma.2016.03.027

Moinet, G. Y. K., Dhami, M. K., Hunt, J. E., Podolyan, A., Liáng, L. L., Schipper, L. A., Whitehead, D., Nuñez, J., Nascente, A., & Millard, P. (2021). Soil microbial sensitivity to temperature remains unchanged despite community compositional shifts along geothermal gradients. *Global Change Biology*, *27*(23), 6217–6231. https://doi.org/10.1111/gcb.15878

Moinet, G. Y. K., Hunt, J. E., Kirschbaum, M. U. F., Morcom, C. P., Midwood, A. J., & Millard, P. (2018). The temperature sensitivity of soil organic matter decomposition is constrained by microbial access to substrates. *Soil Biology and Biochemistry*, *116*, 333–339. Scopus. https://doi.org/10.1016/j.soilbio.2017.10.031

Moinet, G. Y. K., Moinet, M., Hunt, J. E., Rumpel, C., Chabbi, A., & Millard, P. (2020). Temperature sensitivity of decomposition decreases with increasing soil organic matter stability. *Science of the Total Environment*, *704*. Scopus, 135460. https://doi.org/10.1016/j.scitotenv.2019.135460

Oelofse, M., Markussen, B., Knudsen, L., Schelde, K., Olesen, J. E., Jensen, L. S., & Bruun, S. (2015). Do soil organic carbon levels affect potential yields and nitrogen use efficiency? An analysis of winter wheat and spring barley field trials. *European Journal of Agronomy*, *66*, 62–73. https://doi.org/10.1016/j.eja.2015.02.009

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *The Soil*, *5*(1), 15–32. https://doi.org/10.5194/soil-5-15-2019

Pan, G., Smith, P., & Pan, W. (2009). The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. *Agriculture, Ecosystems & Environment*, *129*(1), 344–348. https://doi.org/10.1016/j.agee.2008.10.008

Paustian, K., Andrén, O., Janzen, H. H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., & Woomer, P. L. (1997). Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management*, *13*(s4), 230–244. https://doi.org/10.1111/j.1475-2743.1997.tb00594.x

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

Poulton, P., Johnston, J., Macdonald, A., White, R., & Powlson, D. (2018). Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted research, United Kingdom. *Global Change Biology*, *24*(6), 2563–2584. https://doi.org/10.1111/gcb.14066

Powlson, D. S., Whitmore, A. P., & Goulding, K. W. T. (2011). Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *European Journal of Soil Science*, *62*(1), 42–55. https://doi.org/10.1111/j.1365-2389.2010.01342.x

Pretty, J. (2018). Intensification for redesigned and sustainable agricultural systems. *Science*, *362*(6417), eaav0294. https://doi.org/10.1126/science.aav0294

Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, *9*(1), 5–24. https://doi.org/10.3763/ijas.2010.0583

Ravensbergen, A. P. P., Chamberlin, J., Craufurd, P., Shehu, B. M., & Hijbeek, R. (2021). Adapting the QUEFTS model to predict attainable yields when training data are characterized by imperfect management. *Field Crops Research*, *266*, 108126. https://doi.org/10.1016/j.fcr.2021.108126

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. (2019). The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio*, *49*, 350–360. https://doi.org/10.1007/s13280-019-01165-2

Rusinamhodzi, L., Corbeels, M., Zingore, S., Nyamangara, J., & Giller, K. E. (2013). Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. *Field Crops Research*, *147*, 40–53. https://doi.org/10.1016/j.fcr.2013.03.014

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. https://doi.org/10.1073/pnas.1706103114

Schjønning, P., Jensen, J. L., Bruun, S., Jensen, L. S., Christensen, B. T., Munkholm, L. J., Oelofse, M., Baby, S., & Knudsen, L. (2018). The role of soil organic matter for maintaining crop yields: Evidence for a renewed conceptual basis. In *Advances in agronomy* (Vol. *150*, pp. 35–79). Elsevier. https://doi.org/10.1016/bs.agron.2018.03.001

Schröder, J. (2005). Revisiting the agronomic benefits of manure: A correct assessment and exploitation of its fertilizer value spares the environment. *Bioresource Technology*, *96*(2), 253–261. https://doi.org/10.1016/j.biortech.2004.05.015

Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C., & O'HUallachain, D. (2014). Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science & Policy*, *38*, 45–58. https://doi.org/10.1016/j.envsci.2013.10.002

Shetty, R., Vidya, C. S.-N., Prakash, N. B., Lux, A., & Vaculík, M. (2021). Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review. *The Science of the Total Environment*, *765*, 142744. https://doi.org/10.1016/j.scitotenv.2020.142744

Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, *241*(2), 155–176. https://doi.org/10.1023/A:1016125726789

Smith, P. (2012). Soils and climate change. *Current Opinion in Environmental Sustainability*, *4*(5), 539–544. https://doi.org/10.1016/j.cosust.2012.06.005

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, *22*(3), 1315–1324. https://doi.org/10.1111/gcb.13178

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J. C., Popp, A., Renforth, P., Vicente Vicente, J. L., & Keesstra, S. (2019). Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. *Annual Review of Environment and Resources*, *44*(1), 255–286. https://doi.org/10.1146/annurev-environ-101718-033129

Smith, P., House, J. I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P. C., Clark, J. M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M. F., Elliott, J. A., McDowell, R., Griffiths, R. I., Asakawa, S., Bondeau, A., Jain, A. K., … Pugh, T. A. M. (2016). Global change pressures on soils from land use and management. *Global Change Biology*, *22*(3), 1008–1028. https://doi.org/10.1111/gcb.13068

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 789–813. https://doi.org/10.1098/rstb.2007.2184

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

Soussana, J.-F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M., Wollenberg, E. (Lini), Chotte, J.-L., Torquebiau, E., Ciais, P., Smith, P., & Lal, R. (2019). Matching policy and science: Rationale for the '4 per 1000—Soils for food security and climate' initiative. *Soil and Tillage Research*, *188*, 3–15. https://doi.org/10.1016/j.still.2017.12.002

Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., & Six, J. (2007). Soil carbon saturation: Concept, evidence and evaluation. *Biogeochemistry*, *86*(1), 19–31. https://doi.org/10.1007/s10533-007-9140-0

Terrer, C., Phillips, R. P., Hungate, B. A., Rosende, J., Pett-Ridge, J., Craig, M. E., van Groenigen, K. J., Keenan, T. F., Sulman, B. N., Stocker, B. D., Reich, P. B., Pellegrini, A. F. A., Pendall, E., Zhang, H., Evans, R. D., Carrillo, Y., Fisher, J. B., Van Sundert, K., Vicca, S., & Jackson, R. B. (2021). A trade-off between plant and soil carbon storage

under elevated CO_2. *Nature*, *591*(7851), 7851–7603. https://doi.org/10.1038/s41586-021-03306-8
Thapa, R., Mirsky, S. B., & Tully, K. L. (2018). Cover crops reduce nitrate leaching in agroecosystems: A global meta-analysis. *Journal of Environmental Quality*, *47*(6), 1400–1411. https://doi.org/10.2134/jeq2018.03.0107
Tian, H., Xu, R., Canadell, J. G., Thompson, R. L., Winiwarter, W., Suntharalingam, P., Davidson, E. A., Ciais, P., Jackson, R. B., Janssens-Maenhout, G., Prather, M. J., Regnier, P., Pan, N., Pan, S., Peters, G. P., Shi, H., Tubiello, F. N., Zaehle, S., Zhou, F., … Yao, Y. (2020). A comprehensive quantification of global nitrous oxide sources and sinks. *Nature*, *586*, 7828. https://doi.org/10.1038/s41586-020-2780-0
van der Pol, L. K., Robertson, A., Schipanski, M., Calderon, F. J., Wallenstein, M. D., & Cotrufo, M. F. (2022). Addressing the soil carbon dilemma: Legumes in intensified rotations regenerate soil carbon while maintaining yields in semi-arid dryland wheat farms. *Agriculture, Ecosystems & Environment*, *330*, 107906. https://doi.org/10.1016/j.agee.2022.107906
van Gestel, N., Shi, Z., van Groenigen, K. J., Osenberg, C. W., Andresen, L. C., Dukes, J. S., Hovenden, M. J., Luo, Y., Michelsen, A., Pendall, E., Reich, P. B., Schuur, E. A. G., & Hungate, B. A. (2018). Predicting soil carbon loss with warming. *Nature*, *554*(7693), E4–E5. https://doi.org/10.1038/nature25745
van Ittersum, M. K., & Rabbinge, R. (1997). Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research*, *52*(3), 197–208. https://doi.org/10.1016/S0378-4290(97)00037-3
van Vuuren, D. P., Deetman, S., van Vliet, J., van den Berg, M., van Ruijven, B. J., & Koelbl, B. (2013). The role of negative CO_2 emissions for reaching 2°C—Insights from integrated assessment modelling. *Climatic Change*, *118*(1), 15–27. https://doi.org/10.1007/s10584-012-0680-5
Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., & Six, J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil*, *339*(1), 35–50. https://doi.org/10.1007/s11104-010-0462-7
Vazquez, C., de Goede, R. G. M., Rutgers, M., de Koeijer, T. J., & Creamer, R. E. (2021). Assessing multifunctionality of agricultural soils: Reducing the biodiversity trade-off. *European Journal of Soil Science*, *72*(4), 1624–1639. https://doi.org/10.1111/ejss.13019
Watts, C. W., & Dexter, A. R. (1997). The influence of organic matter in reducing the destabilization of soil by simulated tillage. *Soil and Tillage Research*, *42*(4), 253–275. https://doi.org/10.1016/S0167-1987(97)00009-3
Wei, W., Yan, Y., Cao, J., Christie, P., Zhang, F., & Fan, M. (2016). Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: An integrated analysis of long-term experiments. *Agriculture, Ecosystems & Environment*, *225*, 86–92. https://doi.org/10.1016/j.agee.2016.04.004
Wendt, J. W., & Hauser, S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *European Journal of Soil Science*, *64*(1), 58–65. https://doi.org/10.1111/ejss.12002
Zavattaro, L., Bechini, L., Grignani, C., van Evert, F. K., Mallast, J., Spiegel, H., Sandén, T., Pecio, A., Giráldez Cervera, J. V., Guzmán, G., Vanderlinden, K., D'Hose, T., Ruysschaert, G., & ten Berge, H. F. M. (2017). Agronomic effects of bovine manure: A review of long-term European field experiments. *European Journal of Agronomy*, *90*, 127–138. https://doi.org/10.1016/j.eja.2017.07.010
Zomer, R. J., Bossio, D. A., Sommer, R., & Verchot, L. V. (2017). Global sequestration potential of increased organic carbon in cropland soils. *Scientific Reports*, *7*(1), 15554. https://doi.org/10.1038/s41598-017-15794-8
Zwetsloot, M. J., van Leeuwen, J., Hemerik, L., Martens, H., Josa, I. S., de Broek, M. V., Debeljak, M., Rutgers, M., Sandén, T., Wall, D. P., Jones, A., & Creamer, R. E. (2021). Soil multifunctionality: Synergies and trade-offs across European climatic zones and land uses. *European Journal of Soil Science*, *72*(4), 1640–1654. https://doi.org/10.1111/ejss.13051

How to cite this article: Moinet, G. Y. K., Hijbeek, R., van Vuuren, D. P., & Giller, K. E. (2023). Carbon for soils, not soils for carbon. *Global Change Biology*, *29*, 2384–2398. https://doi.org/10.1111/gcb.16570