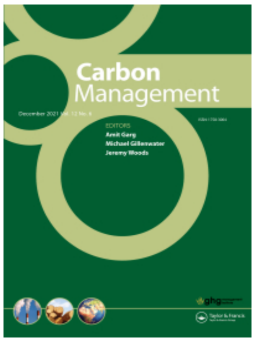

Carbon Management

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tcmt20

Greenhouse gas mitigation on croplands: clarifying the debate on knowns, unknowns and risks to move forward with effective management interventions

Emily E. Oldfield, Jocelyn M. Lavallee, Jennifer Blesh, Mark A. Bradford, Micah Cameron-Harp, M. Francesca Cotrufo, Alison J. Eagle, Lisa Eash, Rebecca J. Even, Sara E. Kuebbing, Eric A. Kort, Tyler J. Lark, Catharina Latka, Yang Lin, Megan B. Machmuller, Brendan O'Neill, Anna M. Raffeld, Taniya RoyChowdhury, Joseph Rudek, Jonathan Sanderman, Christine D. Sprunger, Theodore P. Toombs, Nazli Uludere Aragon, Marti Vidal, Dominic Woolf, Tamara J. Zelikova & Doria R. Gordon

CARBON MANAGEMENT
2024, VOL. 15, NO. 1, 2365896
https://doi.org/10.1080/17583004.2024.2365896

COMMENT

Greenhouse gas mitigation on croplands: clarifying the debate on knowns, unknowns and risks to move forward with effective management interventions

Emily E. Oldfield[a,c*], Jocelyn M. Lavallee[a,e*], Jennifer Blesh[b], Mark A. Bradford[c], Micah Cameron-Harp[d], M. Francesca Cotrufo[e], Alison J. Eagle[a], Lisa Eash[c], Rebecca J. Even[e], Sara E. Kuebbing[c], Eric A. Kort[f], Tyler J. Lark[g], Catharina Latka[h,i], Yang Lin[j], Megan B. Machmuller[e], Brendan O'Neill[b], Anna M. Raffeld[a], Taniya RoyChowdhury[k], Joseph Rudek[a], Jonathan Sanderman[k], Christine D. Sprunger[l], Theodore P. Toombs[a], Nazli Uludere Aragon[m], Marti Vidal[n], Dominic Woolf[o], Tamara J. Zelikova[e] and Doria R. Gordon[a,p]

[a]Environmental Defense Fund, New York, NY, USA; [b]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA; [c]The Forest School, Yale School of the Environment & Yale Center for Natural Carbon Capture, Yale University, New Haven, CT, USA; [d]Department of Agricultural Economics, Kansas State University, Manhattan, KS, USA; [e]Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, USA; [f]Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA; [g]Nelson Institute Center for Sustainability and the Global Environment, University of WI-Madison, Madison, WI, USA; [h]Environmental Markets Lab (emLab), University of California, Santa Barbara, CA, USA; [i]High Meadows Environmental Institute, Princeton University, Princeton, NJ, USA; [j]Department of Soil, Water, and Ecosystem Sciences, University of Florida, Gainesville, FL, USA; [k]Woodwell Climate Research Center, Falmouth, MA, USA; [l]W.K. Kellogg Biological Station, Department of Plant, Soil, and Microbial Sciences, and Plant Resilience Institute, Michigan State University, East Lansing, MI, USA; [m]Numerical Terradynamic Simulation Group (NTSG), University of Montana, Missoula, MT, USA; [n]Plant Production Systems Group, Wageningen University and Research, Wageningen, Netherlands; [o]School of Integrative Plant Sciences, Cornell University, Ithaca, NY, USA; [p]Department of Biology, University of Florida, Gainesville, FL, USA

ABSTRACT
The opportunity of agricultural management practices to sequester soil organic carbon (SOC) is recognized as an important strategy for mitigating climate change. However, there is low confidence when it comes to understanding the *magnitude* of the climate benefit we can expect from SOC sequestration or how best to achieve it. Several issues are often confounded when it comes to the mitigation potential of SOC sequestration and greenhouse gas (GHG) reductions from agriculture, creating confusion and making it difficult to clearly identify the knowns, unknowns and risks to implementing policy and practice recommendations. Here, we identify and explain four major areas of uncertainty: (1) the expected changes in soil carbon or GHG emissions resulting from agricultural management practice changes; (2) the extent to which social, environmental and economic factors constrain mitigation potential; (3) the ability to execute reliable measurement, monitoring, reporting and verification (MMRV) frameworks; and (4) the perception of risk associated with different ways of promoting practice adoption (e.g., voluntary carbon markets fueled by the private sector, pay-for-practice programs funded by public investment). We aim to pinpoint knowledge gaps and areas of disagreement to help right-size expectations and guide effective investment in GHG removals and reductions from agriculture.

ARTICLE HISTORY
Received 26 December 2023
Accepted 3 June 2024

KEYWORDS
Carbon markets; climate adaptation; climate smart agriculture; regenerative agriculture; soil organic carbon; soil carbon sequestration

There is strong disagreement among scientists surrounding the role that agricultural soils can play in mitigating climate change [1–4]. While some believe more robust scientific evidence is necessary to support claims of carbon sequestration and net greenhouse gas (GHG) mitigation from agriculture, others feel the urgency of the climate crisis demands a "learning-by-doing" approach to help shift agricultural production systems to incorporate more climate-friendly practices [5–7] even if the exact outcomes are uncertain. Expert review of the science underlying soil carbon sequestration as a natural climate solution concluded that more research is needed to resolve the scientific uncertainty around measurement of soil organic carbon and its long-term stability as well as the magnitude of unconstrained fluxes of other potent GHGs associated with agriculture (e.g. N_2O and CH_4) [8].

CONTACT Emily E. Oldfield eoldfield@edf.org Environmental Defense Fund, New York, NY, USA
*Joint first authors

Box 1. Technological developments for measuring SOC.

In response to the unique challenges of quantifying SOC, the public and private sectors are investing in various efforts to reduce the costs of measurement, monitoring and verification without sacrificing accuracy. For example, the U.S. Department of Energy's ARPA-E SmartFarm Program is investing in technology to advance MMRV capabilities. Funded projects range from soil sensors building off advances in soil spectroscopy to combined process-based model and remote sensing approaches to quantify field-level GHGs. Advances in spectroscopy present an alternative to dry combustion methods and can address the need for long-term monitoring at a reduced cost [46,64,65]. Already a well-established technology in the research domain, private sector startups are capitalizing on these advancements to present the business case for spectroscopy as a scalable SOC MMRV solution.

Remote sensing technologies are also under discussion as scalable solutions to MMRV but are still in early phases of development. For instance, some remote sensing products can track agricultural yields and adoption of conservation agricultural practices such as no-till and winter cover cropping [66–68]. This information could be useful for parameterizing models, as well as for determining additionality and leakage for SOC sequestration projects. With the proliferation of higher-resolution, satellite-based sensors, there is growing research linking these remotely sensed spectral signatures over bare ground to measured SOC data [69]. This work generally shows promise for mapping the spatial distribution of surface SOC concentrations under ideal conditions [70]; however, vegetation, crop residues and variable soil moisture conditions all confound the direct use of remote sensing to estimate SOC. So while there is limited but growing success in mapping surface SOC concentration over bare fields, there has been no demonstrated proof that remote sensing alone can account for changes in SOC stocks to at least 30 cm over time thus far. It is critical that these efforts be evaluated in terms of their efficacy of achieving accuracy and precision when it comes to detecting changes in SOC.

Box from Oldfield et al. [46]

Indeed, the public and private sectors are investing in various efforts to reduce the cost of measurement, monitoring and verification without sacrificing accuracy to help reduce these uncertainties (Box 1). The rapidly developing voluntary carbon markets selling credits for soil carbon sequestration in some geographies (e.g., U.S., Australia) adds urgency and complexity to this debate. Despite differences of opinion, broad scientific consensus exists with respect to the following: (1) continued land use conversion to cropland and soil degradation derived from "business-as-usual" cropland management present a major threat to climate stability and livelihoods; (2) agricultural practices (often cited as climate smart or regenerative) that increase organic matter inputs to the soil, limit soil disturbance and maximize soil cover can provide environmental benefits (e.g., erosion control, water quality and nutrient retention) and beneficial GHG outcomes when compared to "business-as-usual" approaches; (3) land-based GHG removals are necessary to reach our climate goals, but they should not delay or justify avoidance of broad-scale decarbonization [5]. So, why the controversy?

When it comes to soil organic carbon (hereafter, SOC) sequestration and its climate-change mitigation potential, several issues are often confounded, which can create confusion and make it difficult to conduct clear discussions around knowns, unknowns, and risks. We see these issues occupying four major areas of uncertainty: (1) uncertainties regarding the magnitude of GHG mitigation benefits resulting from agricultural management interventions; (2) the extent to which social, environmental and economic factors constrain mitigation potential; (3) the ability to execute accurate measurement, monitoring, reporting and verification (MMRV) frameworks; and (4) the perception of risk associated with different ways of promoting practice adoption (e.g., voluntary carbon markets fueled by the private sector, pay-for-practice programs funded by public investment). Often, differing opinions on or understandings of these issues lurk implicitly in debates around the mitigation potential of SOC sequestration, hindering consensus on how to proceed or whether to proceed at all. Here, we describe these uncertainties with the goal of clarifying the conversation and pinpointing the key knowledge gaps and areas of disagreement that must be resolved to right-size expectations and guide appropriate investment in GHG emission reductions and removals from agriculture. While we recognize these uncertainties pertain to agriculture writ large (crop and livestock systems), our focus in this article is on row crop agriculture.

What is the magnitude of impact of management interventions on SOC sequestration and net GHG emissions?

While we have confidence in the opportunity of some agricultural management interventions for GHG mitigation benefits [5], we have less confidence when it comes to understanding the *magnitude* of those benefits, in particular at the smaller farm-scale. Context matters when it comes to GHG reductions from agriculture, but currently there is no consensus on whether we have sufficient empirical data to pinpoint what combination of management interventions, soil types, and climate are most likely to lead to beneficial GHG outcomes.

No one disputes that agricultural practices that increase inputs of organic material into the soil or decrease losses of SOC from decomposition can lead to SOC accrual. Practices such as cover cropping, agroforestry, perennialization, reduced tillage, and crop system diversification have all been demonstrated to increase surface (0–30 cm) SOC relative to business-as-usual practices on average, across broad geographical contexts [9,10]. These practices also tend to have important co-benefits for agricultural productivity, erosion reduction, preventing soil nutrient losses, and resilience against both drought and excess moisture [11,12]. However, insufficient empirical data on SOC stock changes through space and time across different soil types, soil depths (>30 cm), climates, management scenarios and cropping systems prohibit scientific consensus around the specific contexts under which we can expect positive responses *versus* negligible or negative responses [13]. We also have very limited understanding of the GHG tradeoffs of agricultural interventions and do not know what the impacts of long-term practice adoption are on net CO_2, N_2O and CH_4 emissions [14,15]. Hence, pinpointing exactly where, how and over what timeframe SOC stocks, N_2O and CH_4 will respond to management interventions is difficult and is associated with a large degree of variability and uncertainty.

Much of our current evidence base has been collected from long-term agricultural research trials in small strips and plots, and there are mixed opinions as to whether data from controlled research trials are representative of the outcomes observed on real working farms. For instance, the magnitude of impact of specific practices quantified in controlled research experiments may be larger than on working farms where farmers are not necessarily adhering to continuous no-till or adding substantial amounts of organic amendments to their fields [16,17]. Furthermore, we know almost nothing of the full life-cycle implications of specific practices as they are implemented on working farms including (among others) the extent to which practices increase or decrease the need for external non-renewable inputs (e.g., mineral N fertilizer) and the GHG implications related to greater herbicide use for cover crop termination or weed control in no-till systems. Uncertainties are even larger for geographic areas traditionally underrepresented in research, where even controlled research experiments are lacking [18].

Despite the lack of consensus regarding the sufficiency of the evidence base supporting agricultural GHG mitigation opportunities, most would agree that having more data across a diversity of agricultural contexts across longer timeframes and larger scales is critical for reducing uncertainties around the potential for GHG emission reductions and removals from croplands. While soils are generally recognized as an essential part of climate mitigation efforts moving forward, implementation of presumably beneficial farming practices without a solid scientific foundation risks ineffectiveness or harm *via* inaccurate assumptions of negative emissions.

How and to what extent do environmental, social and economic conditions constrain adoption of management systems that can mitigate cropland GHGs (i.e. what is the realizable magnitude)?

Another layer of complexity within the debate around SOC sequestration as a climate mitigation pathway comes from differing consideration of how broader biophysical realities and socioeconomic factors constrain estimates of the realizable or realistic mitigation potential [1,18,19]. The largest estimates of mitigation potential, which are based solely on biophysical potential, cannot be fully realized because they sometimes ignore constraints from land available for practice adoption, rates and timing of practice adoption and social, political and economic factors. Right-sizing expectations of the mitigation potential for net SOC sequestration (new carbon stored minus any increased GHG emissions resulting from the management intervention) *via* practice adoption compared to business-as-usual farming is key to avoiding over-reliance on a climate strategy that cannot deliver as promised.

Proposed annual estimates for global cropland SOC sequestration potential under “best management practices” range from 0.3 to 6.8 petagrams (Pg) CO_2e per year [20]. The higher end of these estimates tends to take mean sequestration rates from long-term agricultural research and extrapolate them to the full spatial extent of regional, national or global cropland. Such estimates do not capture whether certain areas are unsuitable for a given practice (e.g., cover cropping is not feasible in all climates), areas where certain practices are not compatible (e.g., organic farmers may rely on tillage for weed control), or areas where land use change is imminent. For example, in the U.S., it is estimated that such constraints mean the actual area of croplands available for multi-decade adoption of cover cropping practices is only 32–44% of total cropland area [21]. In the EU, as of 2016, it is estimated that only 23% of arable land is currently left bare during wintertime and therefore suitable for cover cropping [22].

The higher biophysical estimates of global mitigation potential also do not take into account factors related to the pace and scale of practice adoption. For example, they may assume immediate and simultaneous adoption of climate-smart practices on all global croplands and ignore the social and economic realities that limit or slow new practice adoption. Exposure to and experimentation with new practices or technologies necessarily takes time, and even then, widespread and consistent implementation of a given practice is not assured [23,24]. Factors like land tenure, uncertainty surrounding market and other economic drivers, regulatory frameworks, access to technical assistance, cultural barriers, social networks and demographics influence the adoption rates of agricultural practices that affect SOC sequestration in croplands [18,19,25–27]. Uncertainty about impacts on profitability for farmers, high variability in costs and benefits and historical/current systems that fail to de-risk implementation of climate-smart practices add further challenges [28–30]. Insufficient research on the individual, structural and institutional factors that facilitate and constrain practice adoption [31,32] and the lack of integration of diverse theoretical perspectives to inform adoption has resulted in a lack of holistic understanding of realistic mitigation potential of SOC sequestration. As such, researchers are discouraging publications that focus solely on technical potentials without consideration of socioeconomic factors [33].

Can we measure and verify changes in net GHGs in row crop systems reliably at relevant spatial and temporal scales?

Many agree that building confidence in our understanding of the GHG impact of agricultural management interventions requires accurate and direct observations to quantify outcomes [34]. Yet, there is no consensus on what constitutes sufficient rigor for MMRV. In measuring and estimating agriculture-related GHGs, there are challenges related to expense (collecting and processing soil samples is time intensive and expensive), methodological inconsistencies (e.g., depth of soil sampling, lab processing of soil samples), timescales necessary for detecting change and the durability of removal that contribute to uncertainty and a lack of confidence surrounding cropland management as a natural climate solution.

The ways in which we measure SOC sequestration versus N_2O and CH_4 emissions are fundamentally different, which makes GHG accounting in cropland systems particularly challenging. Detecting change in SOC stocks requires intensive episodic (i.e., every 5–10 years) sampling, which has often been assumed unrealistic in terms of time and resources but is increasingly demonstrated to be feasible at larger population-level scales (i.e., measuring average SOC stock changes across many fields (e.g., >30) versus at the individual field level) [35]. In contrast, the microbial processes that produce N_2O and CH_4 are highly dynamic over space and time (i.e., hot spots and hot moments). The resources (time and money) required to achieve intensive, accurate and direct measurements are often viewed as prohibitive. As a result, reliance on process-based biogeochemical models (e.g., DayCent, DNDC) and/or emission factors to estimate changes in SOC and N_2O and CH_4 emissions has become common for scaling quantification [36,37].

The use of process-based models for agricultural GHG projects generally entails evaluation of model performance (termed "validation" in many protocols) using existing datasets deemed representative of project activities and context, followed by use of the validated model to make new predictions for the project area [38]. The datasets available for such validation efforts are highly limited because there are very few high-quality time series data on paired control and treatment plots in agricultural systems for any given practice change, especially under different contexts [39]. This raises the key question of whether model validation datasets are truly representative of the conditions under which a project is occurring with respect to soil types, climates and practices [40]. If a dataset consisting mainly of sites where conditions are favorable for SOC accrual is used to validate a model that is then applied to a project area where sites tend to have less favorable conditions for SOC accrual, there is a clear risk of overestimation [39]. Recent model validation exercises have shown large variances in differences between measured and modeled outcomes (i.e., changes in SOC, N_2O or CH_4 relative to a baseline); and due to limitations in the validation data, the types of conditions under which the variance is higher or lower often cannot be precisely determined [38,41,42]. Therefore, it is difficult to know exactly how well a model will perform and whether validation-based estimates of uncertainty are reliable when the models are applied to new sites.

This raises another key question: what level of unexplained variance in model predictions are we prepared to tolerate? There is no consensus on what constitutes an "acceptable" level of uncertainty for the use of process-based models in GHG accounting frameworks, and disagreements persist. On the one hand, the voluntary carbon market industry uses models specifically for generating offset credits, while on the other, some academics have deemed models inadequate for estimating SOC sequestration for reliable carbon crediting [40,43]. More broadly, the lack of clear and consistent guidance on important aspects of model application, including initialization, uncertainty partitioning and propagation, and potential confrontation with new measurements from a project may leave the door open to various interpretations of best practices and to the potential gaming of outcomes, leading many to criticize their current use in agricultural GHG mitigation projects.

These measurement and modeling challenges are seen by many as critical obstacles that must be overcome to realize robust MMRV [37,44]. However, it is important to avoid conflating the issues of measurement and verification challenges with the issue of what the evidence base shows regarding GHG effects of adopting more climate smart agricultural practices. Measurement challenges can be overcome with concerted research and development on approaches that can deliver economical and accurate data, but whether this is worthy of investment depends on whether improved management of agricultural lands can realistically deliver GHG benefits.

What is the risk tolerance associated with different incentive approaches for GHG reductions and removals?

In discussions around the unknowns and risks associated with GHG mitigation in croplands, some of the disagreement and disconnect can stem from different perspectives regarding implementation. That is, one's answers to the above questions and level of comfort with unknowns can depend on how practice changes might be implemented, for example through market incentives (e.g., voluntary carbon markets) versus pay-for-practice programs (e.g., subsidies for the costs of transition to more climate smart practices). Note we focus here on interventions targeted at the individual farmer (i.e., through incentives and subsidies for farmers) rather than on interventions related to interacting, cross-scale structural factors (e.g., public funding priorities, methods of conservation delivery, agricultural production processes and policies) that go beyond the individual scale. Interventions aimed at these structural factors and systemic interactions deserve much greater attention given that individuals are operating within complex, larger systems [31].

Carbon markets – both compliance and voluntary – are meant to deliver robust, durable credits representing tonnes of CO_2e sequestered. Whereas compliance markets are subject to regulation and oversight that establishes legal obligation on covered entities to offset emissions (usually aimed at energy intensive emitters), voluntary carbon markets function outside of any regulation with credits purchased by individuals or entities wanting to reduce their carbon footprint. In the U.S. to date, carbon credits for soil carbon sequestration in row-crop agricultural systems are only available through the voluntary carbon market [45]. The market landscape is evolving rapidly and the rules of the road for GHG accounting and the use of credits for achieving GHG targets are currently being written and revised. Within the voluntary carbon market, for example, a number of different protocols for generating agricultural soil carbon credits exist. A comprehensive synthesis of 12 publicly available protocols revealed substantial differences in their approaches to measuring and estimating SOC and net GHGs as well as important accounting issues such as additionality and permanence [37,46]. Additional to the voluntary carbon market are other voluntary standards for GHG accounting, which include the Science Based Targets Initiative (SBTi) and Greenhouse Gas Protocol Land Sector and Removals Guidance that provide guidance for companies seeking to reduce their GHG footprints [47,48].

Any nature-based C solution funded through a market approach needs a robust scientific foundation because these markets render fossil and biotic C equivalent, allowing fossil fuel emissions to be offset by increases in biological C sequestration [49]. Quantification challenges aside, designing a market around SOC sequestration demands assurance that credits are additional and durable, and that the market contains sufficient safeguards against reversals and leakage. SOC sequestration through carbon accrual is not permanent – carbon continuously cycles through the soil and so durability rests on continuing (and monitoring) the management practices that build and maintain

SOC stocks over time. Farmers are understandably wary about committing to requirements to maintain practices for decades into the future, making the design of effective incentives that meet durability standards difficult.

There are risks and limitations to compliance and voluntary carbon markets as strategies to deliver climate mitigation. First, there is a perception that these credits can let large industrial emitters "off the hook" from doing the work to decarbonize their own operations [50]. Second, if credits are poorly quantified or lack integrity (e.g., estimated CO_2 reductions are not truly additional), then there is real risk to the climate in that industrial emissions continue without additional CO_2 sequestration and GHG reductions coming from the credits. A growing body of evidence highlights this may be occurring in crediting projects across the globe [50–53]. Due to these challenges and since GHG emissions from agriculture are inevitable, some have argued that removals and reductions should be tracked and accounted for within agricultural supply chains through Scope 3 accounting (i.e., not sold as credits to offset GHG emissions outside of food and agriculture supply chains) to help mitigate agriculture's climate impact rather than offset emissions outside the sector [54]. Since these within-supply chain reductions and removals are not sold as offsets to industrial emitters, there is less of a perceived risk to the climate. Regardless, robust quantification and accounting of agricultural supply chain GHGs, just like offsets, are still necessary to ensure progress towards climate targets (Tables 1 and 2).

Programs that pay-for-practice may seem like a less risky approach to incentivizing GHG mitigation from agriculture because they do not rely on the quantification of GHG outcomes that could then be used to offset industrial emissions. However, this approach represents an indirect strategy for GHG mitigation and therefore may not necessarily be an efficient means of achieving GHG reductions and removals [55,56]. For instance, amenable contract timelines (1–10 years) typical of such programs (e.g., USDA's Environmental Quality Incentives Program and the Conservation Stewardship Program) may seem inadequate for ensuring durable GHG outcomes, which require long-term monitoring of the practice change to ensure SOC stock accrual and maintenance (upwards of 30 years). Furthermore, because GHGs are not directly quantified or verified under current pay-for-practice programs, uncertainties remain as to the magnitude of climate benefits these programs provide. If these investments, however, are not targeted to contribute to emission reduction goals, then pay-for-practice and subsidization of associated costs of practice transitions could be considered a good use of funds to support adaptation and resilience at the farm scale and of larger food systems (e.g., soil loss, drought resilience) that are perceived as comparably certain.

More generally, when it comes to GHG mitigation opportunities in row crop agriculture and associated risks, an important distinction should be made between removals and reductions. As a removal strategy, SOC sequestration has received substantial attention and investment in the voluntary carbon market, while reduction strategies (e.g., reducing N_2O emissions through fertilizer management) have received less attention [57]. Reducing N_2O emissions, however, represents a less risky approach than CO_2 removal given that it is permanent and represents an immediate reduction in radiative forcing (most N_2O emissions occur the same year fertilizer is applied). The climate benefit derived from removals through SOC sequestration, on the other hand, takes years to develop, requires continued maintenance well into the future and is prone to reversal. Though incentivizing N_2O reductions also comes with its own challenges, which include quantifying N_2O (emissions are highly variable over space and time) and ensuring that any reductions in the use of mineral N fertilizer are not accompanied by losses in agricultural productivity. Existing research on the use of metrics such as nitrogen balance – the difference between nitrogen inputs and outputs – can

Table 1. Overview of the accounting issues associated with different incentive approaches for GHG reductions and removals.

Accounting issues	
Quantification	Accurate quantification of changes in soil organic C (SOC) stocks and associated GHGs (e.g., N_2O and CH_4) resulting from agricultural management interventions
Additionality	The concept that a project or intervention leads to emission reductions or removals that would not otherwise have occurred under a business-as-usual approach
Durability/Permanence	Continuing and monitoring the management practices that build and maintain SOC stocks over time to prevent losses; 100 years is the default timeframe per the IPCC
Leakage	Preventing loss of SOC or increases in other GHGs that may result from uptake of climate smart ag practices (e.g., converting more land into agriculture to make up for losses in production, fertilizing cover crops)

Table adapted from Ogle et al. [71]

Table 2. Classification of how/if different implementation strategies address accounting issues to help ensure GHG benefits, with (+) necessary (–) not necessary.

Incentive approaches	Quantification	Additionality	Durability/ Permanence	Leakage	Examples of protocols, guidance, programs	Justification or Explanation for classifications
Voluntary or compliance carbon markets	+	+	+	+	Registry-backed protocols including Climate Action Reserve's Soil Enrichment Protocol and Verra's VM0042	All issues are necessary to account for as individuals or companies are purchasing carbon credits to potentially offset emissions; to be considered fungible, credits must be accurately quantified, additional to what would have happened under business-as-usual, result in long-term sequestration and/or GHG reductions, and avoid leakage
Scope 3 accounting*	+	–	+	+	Within supply chain efforts (i.e., Scope 3) to reduce GHGs and increase SOC accrual; Greenhouse Gas Protocol's Land Sector and Removals Guidance	Standards for scope 3 accounting within the land sector are still being determined, and additionality requirements may differ situationally. For example, the inventory method as defined under the draft Land Sector and Removals Guidance from the GHG Protocol does not require additionality since GHG reductions and removals are accounted for on a year-on-year basis within a supply chain rather than generating credits used to offset emissions outside of their own supply chains.
Pay-for-practice	–	–	–	–	U.S. federal programs such as USDA's Conservation Stewardship Program and Environmental Quality Incentives Program	With pay-for-practice programs, highly accurate quantification of changes in C stocks and GHG emissions may not be necessary because the primary outcome is the practice, rather than a specific claim of decreased emissions. Accounting for additionality, durability and leakage would increase the likelihood these programs are generating climate impact but is generally not a requirement to participate in these programs; note, however, this could change under Nationally Determined Contribution (NDC) accounting.

Table adapted from Ogle et al. [71].
**Note*: We distinguish scope 3 inventory accounting as distinct from the generation of inset credits which are defined as credited reductions and removals within agricultural supply chains and follow criteria similar to scope 1 offsets under the voluntary carbon market.

help approximate on-farm N losses and help overcome some of the quantification challenges associated with measuring N_2O [58]. Targeting farms or larger areas (e.g., counties, regions) where N balance is high represents an opportunity to substantially reduce GHG emissions with little risk of yield impacts [59].

Much of the hesitation to advance SOC sequestration as a natural climate solution ultimately comes from the risk assessment of the implementation strategy and the context in which the variation and uncertainty associated with GHG outcomes is applied. To demonstrate this point, consider conversations around regenerative agricultural practices and environmental outcomes. Currently, many scientists encourage efforts to increase adoption of regenerative agricultural practices, seeing little risk and emphasizing that these practices deliver many benefits such as reduced erosion, drought resistance and resilience, improved water quality, or higher yield stability over time [60]. However, if these environmental benefits were traded such that heavy polluters could offset negative effects on water quality by purchasing "water quality" credits, there might be just as much hesitation from the scientific community due to the uncertainty in the quantitative links between soil health and environmental outcomes and their context specificity [61]. As the perceived severity of potentially adverse outcomes from interventions increases, so does one's perception of the need to reduce uncertainty in those outcomes.

Conclusion

The confusion and conflation of the different sources of uncertainty outlined above highlight the need for clearer discussions surrounding knowns, unknowns and risks of cropland GHG mitigation. These issues are being thrust into the spotlight as policy makers and market players invest in climate mitigation through incentivizing regenerative agricultural practices. To reduce these uncertainties and craft effective policy and investments, we must reconcile longer-term research efforts with shorter-term action for climate mitigation and adaptation efforts. To that end, we recommend the following actions that policy makers and researchers can take that can be implemented over short to medium timescales (0–5 years):

- Support and encourage the adoption of regenerative agricultural management practices for climate adaptation and co-benefits for which assessments are comparably certain, without accounting for their contribution to specific GHG targets as long as these are not verifiable/quantifiable with a sufficient level of certainty.
- Prioritize policy and market interventions for nitrogen and methane management to deliver higher permanence, lower uncertainty emission reductions.
- Develop a measurement and model standard for robust MMRV that can support a system of independent evaluation/certification of specific climate impacts.
- Now and into the future, expand upon existing and invest in additional research infrastructure (see reports by Hayes et al. [34] and Novick et al. [62]) designed to collect and track data to evaluate and quantify the impact of and reduce the uncertainties around management interventions on net GHG balances. The recently released US "Federal Strategy to Advance Measurement and Monitoring Greenhouse Gas Measurement for Agriculture and Forest Sectors" represents a step in the right direction.
- Invest in research networks to capture the impact of management interventions on working farms representative of local to regional agricultural systems (as opposed to small plot research). Concurrently, advance research to support integrated models that capture the interacting biophysical-socio-economic factors that can help provide more realistic estimates of achievable mitigation.
- From these expanded research networks, develop openly and freely accessible benchmarking and independent validation datasets to support evaluation of the impact of management interventions on GHG outcomes [63].

Understanding the realizable magnitude of GHG reductions and removals from agriculture, as well as risks and uncertainties, is critical for minimizing anthropogenic climate change and ensuring that investments in mitigation achieve intended goals without incurring adverse impacts. Given investments (both private and public) in agricultural management practices with the aim of climate mitigation are already occurring, it is essential to focus on the specific uncertainties as they relate to the questions posed above and the specific actions we can take to reduce those uncertainties. In clarifying uncertainties surrounding GHG mitigation potential from cropland management, we lay a foundation for productive discussions, clear research priorities, and effective policy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Environmental Defense Fund with awards from the Bezos Earth Fund, King Philanthropies, and Arcadia, a charitable fund of Lisbet Rausing and Peter Baldwin.

Data availability statement

No new data were collected for this manuscript, and there is no supplementary material.

References

1. Amundson R, Biardeau L. Opinion: soil carbon sequestration is an elusive climate mitigation tool. Proc Natl Acad Sci USA. 2018;115(46):11652–11656.
2. Bradford MA, Carey CJ, Atwood L, et al. Soil carbon science for policy and practice. Nat Sustain. 2019;2(12):1070–1072. doi: 10.1038/s41893-019-0431-y.
3. Janzen HH, van Groenigen KJ, Powlson DS, et al. Photosynthetic limits on carbon sequestration in croplands. Geoderma. 2022;416:115810. doi: 10.1016/j.geoderma.2022.115810.
4. Moinet GYK, Amundson R, Galdos MV, et al. Carbon for soils, not soils for carbon. Glob Chang Biol. 2023;30(1):e17010–2398. doi: 10.1111/gcb.16570.
5. IPCC.—IPCC [Internet]. AR6 synthesis report: climate change; 2022. Available from https://www.ipcc.ch/report/sixth-assessment-report-cycle/.
6. Paustian K, Lehmann J, Ogle S, et al. Climate-smart soils. Nature. 2016;532(7597):49–57. doi: 10.1038/nature17174.
7. Rumpel C, Amiraslani F, Koutika L-S, et al. Put more carbon in soils to meet Paris climate pledges. Nature. 2018;564(7734):32–34. doi: 10.1038/d41586-018-07587-4.
8. Buma B, Gordon DR, Kleisner KM, et al. Expert review of the science underlying nature-based climate solutions. Nat Clim Chang. 2024;14(4):402–406. https://www.nature.com/articles/s41558-024-01960-0. doi: 10.1038/s41558-024-01960-0.

9. Lessmann M, Ros GH, Young MD, et al. Global variation in soil carbon sequestration potential through improved cropland management. Glob Chang Biol. 2022;28(3):1162–1177. doi: 10.1111/gcb.15954.
10. Prairie AM, King AE, Cotrufo MF. Restoring particulate and mineral-associated organic carbon through regenerative agriculture. Proc Natl Acad Sci USA. 2023;120(21):e2217481120. doi: 10.1073/pnas.2217481120.
11. Smith P, Adams J, Beerling DJ, et al. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annu Rev Environ Resour. 2019;44(1):255–286. doi: 10.1146/annurev-environ-101718-033129.
12. Won S, Rejesus RM, Goodwin BK, et al. Understanding the effect of cover crop use on prevented planting losses. American J Agri Economics. 2023;106(2):659–683. doi: 10.1111/ajae.12396.
13. Schlesinger WH. Biogeochemical constraints on climate change mitigation through regenerative farming. Biogeochemistry. 2022;161(1):9–17. doi: 10.1007/s10533-022-00942-8.
14. Kritee K, Nair D, Zavala-Araiza D, et al. High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. Proc Natl Acad Sci USA. 2018;115(39):9720–9725. doi: 10.1073/pnas.1809276115.
15. Lugato E, Leip A, Jones A. Mitigation potential of soil carbon management overestimated by neglecting N 2 O emissions. Nature Clim Change. 2018;8(3):219–223. doi: 10.1038/s41558-018-0087-z.
16. Aguilera E, Lassaletta L, Gattinger A, et al. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agricult Ecosyst Environ. 2013;168:25–36. doi: 10.1016/j.agee.2013.02.003.
17. Poulton P, Johnston J, Macdonald A, et al. 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. Glob Change Biol. 2018;24(6):2563–2584.
18. Buck HJ, Palumbo-Compton A. Soil carbon sequestration as a climate strategy: what do farmers think? Biogeochemistry. 2022;161(1):59–70. doi: 10.1007/s10533-022-00948-2.
19. Blesh J, Mehrabi Z, Wittman H, et al. Against the odds: network and institutional pathways enabling agricultural diversification. One Earth. 2023;6(5):479–491. doi: 10.1016/j.oneear.2023.03.004.
20. Roe S, Streck C, Obersteiner M, et al. Contribution of the land sector to a 1.5 °C world. Nat Clim Chang. 2019;9(11):817–828. doi: 10.1038/s41558-019-0591-9.
21. Uludere Aragon N, Xie Y, Bigelow D, et al. The realistic potential of soil carbon sequestration in U.S. croplands for climate Mitigation. Earth's Future. 2024;12(6):e2023EF003866.
22. Smit B, Janssens B, Haagsma W, et al. Adoption of cover crops for climate change mitigation in the EU [Internet]. Available from: https://publications.jrc.ec.europa.eu/repository/handle/JRC116730.
23. Pannell D, Zilberman D. Understanding adoption of innovations and behavior change to improve agricultural policy. Appl Eco Perspect Pol. 2020;42(1):3–7. doi: 10.1002/aepp.13013.
24. Thompson NM, Reeling CJ, Fleckenstein MR, et al. Examining intensity of conservation practice adoption: evidence from cover crop use on U.S. Midwest farms. Food Policy. 2021;101:102054. doi: 10.1016/j.foodpol.2021.102054.
25. Kathage J, Smit B, Janssens B, et al. How much is policy driving the adoption of cover crops? Evidence from four EU regions. Land Use Pol. 2022;116:106016. doi: 10.1016/j.landusepol.2022.106016.
26. Ranjan P, Wardropper CB, Eanes FR, et al. Understanding barriers and opportunities for adoption of conservation practices on rented farmland in the US. Land Use Pol. 2019;80:214–223. doi: 10.1016/j.landusepol.2018.09.039.
27. Van Der Pol LK, Tibbetts CA, Lin Hunter DE. Removing barriers and creating opportunities for climate-resilient agriculture by optimizing federal crop insurance. JSPG. 2021;18(02):1–9. doi: 10.38126/JSPG180213.
28. Bowman M, Poley K, McFarland E. Farmers employ diverse cover crop management strategies to meet soil health goals. Agricult Env Lett. 2022;7(1):1–6. doi: 10.1002/ael2.20070.
29. Dumbrell NP, Kragt ME, Gibson FL. What carbon farming activities are farmers likely to adopt? A best–worst scaling survey. Land Use Policy. 2016;54:29–37. doi: 10.1016/j.landusepol.2016.02.002.
30. Martins LB, Rejesus RM, Reberg-Horton C, et al. Understanding the market for cover crop seeds in the United States: background and potential policy directions. J Soil Water Conserv. 2021;76(5):83A–88A. doi: 10.2489/jswc.2021.0820A.
31. Prokopy LS, Floress K, Arbuckle JG, et al. Adoption of agricultural conservation practices in the United States: evidence from 35 years of quantitative literature. J Soil Water Conserv. 2019;74(5):520–534. doi: 10.2489/jswc.74.5.520.
32. Yoder L, Ward AS, Dalrymple K, et al. An analysis of conservation practice adoption studies in agricultural human-natural systems. J Environ Manage. 2019;236:490–498. doi: 10.1016/j.jenvman.2019.02.009.
33. Amundson R, Buck H, Lajtha K. Soil science in the time of climate mitigation. Biogeochemistry. 2022;161(1):47–58. doi: 10.1007/s10533-022-00952-6.
34. Hayes DJ, Ferruolo S, Gajardo D, et al. Data progress needed for climate-smart agriculture (Policy Lab: harvesting climate benefits from agriculture and forestry practices (808Y)) [Internet]. Stanford Law School Law & Policy Lab. Available from: https://law.stanford.edu/publications/data-progress-needed-for-climate-smart-agriculture/.
35. Bradford MA, Eash L, Polussa A, et al. Testing the feasibility of quantifying change in agricultural soil carbon stocks through empirical sampling. Geoderma. 2023;440:116719. doi: 10.1016/j.geoderma. 2023.116719.
36. Mathers C, Black CK, Segal BD, et al. Validating DayCent-CR for cropland soil carbon offset reporting

at a national scale. Geoderma. 2023;438:116647. doi: 10.1016/j.geoderma.2023.116647.

37. Oldfield EE, Eagle AJ, Rubin RL, et al. Crediting agricultural soil carbon sequestration. Science. 2022;375(6586):1222–1225. doi: 10.1126/science.abl7991.
38. Lavallee JM, McConkey BG, Kyker-Snowman E, et al. Modeling soil carbon and greenhouse gas emissions: identifying challenges and advancing guidance for using process-based models in soil emission reduction and removal projects [Internet]. Environmental Defense Fund, New York, New York. Available from: https://www.edf.org/modeling-soil-carbon-emissions.
39. Tonitto C, Woodbury PB, McLellan EL. Defining a best practice methodology for modeling the environmental performance of agriculture. Environmental Science & Policy. 2018;87:64–73. doi: 10.1016/j.envsci.2018.04.009.
40. Garsia A, Moinet A, Vazquez C, et al. The challenge of selecting an appropriate soil organic carbon simulation model: a comprehensive global review and validation assessment. Glob Chang Biol. 2023;29(20):5760–5774. doi: 10.1111/gcb.16896.
41. Indigo Ag. Validation report DayCent-CR version 1.0.2 [Internet]; 2022. Available from: https://www.climateactionreserve.org/wp-content/uploads/2022/11/CAR1459_model_val_DayCentCR_1.0.2.pdf.
42. Regrow. DNDC validation report [Internet]; 2022. Available from: https://www.climateactionreserve.org/wp-content/uploads/2022/08/regrow_dndc_validation_report_carsep_20220804.pdf.
43. Le Noë J, Manzoni S, Abramoff R, et al. Soil organic carbon models need independent time-series validation for reliable prediction. Commun Earth Environ. 2023;4(1):1–8. doi: 10.1038/s43247-023-00830-5.
44. Smith P, Soussana J-F, Angers D, et al. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Glob Chang Biol. 2020;26(1):219–241. doi: 10.1111/gcb.14815.
45. USDA. A general assessment of the role of agriculture and forestry in U.S. carbon markets [Internet]. United States Department of Agriculture, Washington, D.C. Available from: https://www.usda.gov/sites/default/files/documents/USDA-General-Assessment-of-the-Role-of-Agriculture-and-Forestry-in-US-Carbon-Markets.pdf.
46. Oldfield EE, Eagle AJ, Rubin RL, et al. Agricultural soil carbon credits: making sense of protocols for carbon sequestration and net greenhouse gas removals [Internet]. Environmental Defense Fund, New York, NY. Available from: https://www.edf.org/sites/default/files/content/agricultural-soil-carbon-credits-protocol-synthesis.pdf.
47. WRI, WBCSD. Land sector and removals guidance. Part 1: accounting and reporting requirements and guidance [Internet]; 2022. Available from: https://ghgprotocol.org/sites/default/files/2022-12/Land-Sector-and-Removals-Guidance-Pilot-Testing-and-Review-Draft-Part-1.pdf.
48. SBTi corporate manual [Internet]; 2023. Available from: https://sciencebasedtargets.org/resources/files/SBTi-Corporate-Manual.pdf.
49. Carton W, Lund JF, Dooley K. Undoing equivalence: rethinking carbon accounting for just carbon removal. Front Clim. 2021;3:664130. doi: 10.3389/fclim.2021.664130
50. Badgley G, Freeman J, Hamman JJ, et al. Systematic over-crediting in California's forest carbon offsets program. Glob Chang Biol. 2022;28(4):1433–1445. doi: 10.1111/gcb.15943.
51. Macintosh A, Butler D, Larraondo P, et al. Australian human-induced native forest regeneration carbon offset projects have limited impact on changes in woody vegetation cover and carbon removals. Commun Earth Environ. 2024;5(1):1–11. doi: 10.1038/s43247-024-01313-x.
52. Randazzo NA, Gordon DR, Hamburg SP. Improved assessment of baseline and additionality for forest carbon crediting. Ecol Appl. 2023;33(3):e2817. doi: 10.1002/eap.2817
53. West TAP, Börner J, Sills EO, et al. Overstated carbon emission reductions from voluntary REDD + projects in the Brazilian Amazon. PNAS. 2020;117(39):24188–24194.
54. Greene S, Bateman A. Getting to 2050: transparency for setting and reaching supply chain climate goals. In: Sundaram AK, Hansen RG editors. Handbook of business and climate change. Northampton, MA: Edward Elgar Publishing; 2023. p. 340–358.
55. Mezzatesta M, Newburn DA, Woodward RT. Additionality and the adoption of farm conservation practices. Land Econ. 2013;89(4):722–742. doi: 10.3368/le.89.4.722.
56. Sawadgo W, Plastina A. Do cost-share programs increase cover crop use? Empirical evidence from Iowa. Renew Agric Food Syst. 2021;36(6):527–535. doi: 10.1017/S1742170521000132.
57. DeFries R, Ahuja R, Friedman J, et al. Land management can contribute to net zero. Science. 2022;376(6598):1163–1165. doi: 10.1126/science.abo0613.
58. Eagle AJ, McLellan EL, Brawner EM, et al. Quantifying on-farm nitrous oxide emission reductions in food supply chains. Earth's Future. 2020;8(10):e2020EF001504. Available from: https://onlinelibrary.wiley.com/doi/10.1029/2020 EF001504.s
59. McLellan EL, Cassman KG, Eagle AJ, et al. The nitrogen balancing act: tracking the environmental performance of food production. BioScience. 2018;68(3):194–203. doi: 10.1093/biosci/bix164.
60. Schulte LA, Dale BE, Bozzetto S, et al. Meeting global challenges with regenerative agriculture producing food and energy. Nat Sustain. 2021;5(5):384–388. doi: 10.1038/s41893-021-00827-y.
61. Wood SA, Blankinship JC. Making soil health science practical: guiding research for agronomic and environmental benefits. Soil Biol Biochem. 2022;172:108776. doi: 10.1016/j.soilbio.2022.108776.
62. Novick K, Williams C, Runkle BRK, et al. The science needed for robust, scalable, and credible nature-based climate solutions in the United States: full report [Internet]. Bloomington, Indiana: Indiana University. Available from: https://oneill.indiana.edu/doc/research/climate/climate-solutions-full-report.pdf.
63. Novick KA, Keenan TF, Anderegg WRL, et al. We need a solid scientific basis for nature-based climate solutions in the United States. Proc Natl Acad Sci USA. 2024;121(14):e2318505121. doi: 10.1073/pnas.2318505121.

64. Dangal S, Sanderman J, Wills S, et al. Accurate and precise prediction of soil properties from a large mid-infrared spectral library. Soil Syst. 2019;3(1):11. doi: 10.3390/soilsystems3010011.
65. Wijewardane NK, Hetrick S, Ackerson J, et al. VisNIR integrated multi-sensing penetrometer for *in situ* high-resolution vertical soil sensing. Soil Tillage Res. 2020;199:104604. doi: 10.1016/j.still.2020.104604.
66. Hagen SC, Delgado G, Ingraham P, et al. Mapping conservation management practices and outcomes in the corn belt using the operational tillage information system (OpTIS) and the denitrification–decomposition (DNDC) model. Land. 2020;9(11):408. doi: 10.3390/land9110408.
67. Surdoval A, Jain M, Blair E, et al. Financial incentive programs and farm diversification with cover crops: assessing opportunities and challenges. Environ Res Lett. 2024;19(4):044063. doi: 10.1088/1748-9326/ad35d8.
68. Deines JM, Guan K, Lopez B, et al. Recent cover crop adoption is associated with small maize and soybean yield losses in the United States. Glob Chang Biol. 2023;29(3):794–807. doi: 10.1111/gcb.16489.
69. Angelopoulou T, Tziolas N, Balafoutis A, et al. Remote sensing techniques for soil organic carbon estimation: a review. Remote Sens. 2019;11(6):676. doi: 10.3390/rs11060676.
70. Castaldi F, Hueni A, Chabrillat S, et al. Evaluating the capability of the Sentinel 2 data for soil organic carbon prediction in croplands. ISPRS J Photogramm Remote Sens. 2019;147:267–282. doi: 10.1016/j.isprsjprs.2018.11.026.
71. Ogle SM, Conant RT, Fischer B, et al. Policy challenges to enhance soil carbon sinks: the dirty part of making contributions to the Paris agreement by the United States. Carbon Manage. 2023;14(1):2268071. doi: 10.1080/17583004.2023.2268071.