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State of the Science:

Cropland Soil Carbon Sequestration

Environmental Defense Fund
Natural Climate Solutions

About this report

This report summarizes Environmental Defense Fund's interpretation of the literature on cropland soil carbon sequestration. It explains areas of agreement and disagreement on such vital questions as: how much climate mitigation potential cropland soil carbon sequestration might provide, which agricultural practices increase soil carbon levels, what challenges remain for measuring net greenhouse gas mitigation, and what all of this means for soil carbon credits.

As interest in agricultural climate solutions grows, this state of the science provides a lay of the land to help researchers, environmental and agricultural organizations, policymakers and companies ensure that investments deliver the intended climate mitigation benefits.

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Executive summary

Natural climate solutions aim to avoid greenhouse gas emissions and increase long-term carbon storage in vegetation, soils, sediments and deep ocean water by conserving, restoring and improving the management of ecosystems. Understanding the potential contributions of these approaches, 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.

Market interest is running ahead of the foundational and carbon accounting science for many natural climate solutions pathways, which adds urgency to the challenge of addressing knowledge gaps. Lack of consensus on what is known and unknown about natural climate solutions and the broader array of other carbon dioxide removal strategies is a key barrier to progress toward the broad deployment of these strategies.

This report focuses on carbon sequestration through cropland management, one of multiple pathways for potential net GHG mitigation via natural climate solutions.

We obtained review of this summary from scientists in academia and nonprofits to obtain an initial indication of the current degree of consensus on the state of the science.

Thus far we have seen broad agreement about the overall state of the science on measurement and accounting for carbon sequestration. However, some reviewers suggested that EDF is conservative in concluding that market activity should wait for an improved scientific foundation in situations where the directionality of carbon fluxes likely leads to sequestration. Even so, all reviewers support EDF's advocacy for stronger standards for generating high-quality carbon credits.

We hope that the research that EDF and others will generate by 2025 will refine both our understanding of agricultural soil carbon sequestration and standards for sequestration credits.

Introduction

The foremost approach to address climate change is to reduce or avoid GHG emissions. However, all scenarios to keep the global temperature increase below 1.5 degrees Celsius[1] also require carbon dioxide removal from the atmosphere. Carbon dioxide removal proposals include, but are not limited to, land management strategies, enhanced mineral weathering, ocean alkalinization, and direct air capture and sequestration.

Natural climate solutions aim to avoid GHG emissions and sequester carbon dioxide away from the atmosphere in terrestrial soils and vegetation, and in marine biota, sediments and water by conserving, restoring and improving the management of ecosystems. Understanding the potential contributions and consequences of these approaches is critical for minimizing climate change and ensuring that investments achieve intended goals.

While natural climate solutions approaches appear to have significant potential to help reduce GHG emissions and draw down atmospheric carbon dioxide concentrations — as well as to generate critical co-benefits — we see serious gaps in the understanding, analysis and advocacy of potential natural climate solutions. For instance, there is no clear scientific consensus on the realizable net carbon sequestration potential of multiple carbon sinks.[2] Adding to the challenge of estimating sequestration potential are the difficulties associated with measurement and quantification of net fluxes from these total stocks. For systems like cropland soils, we need effective and economical methodologies for measuring and accounting for incremental changes in net carbon sequestered.

[1] IPCC, 2021, is one such example.

[2] In this context we use the term "net carbon sequestration" to denote the amount of new carbon stored minus any other increased GHG emissions resulting from the activity. This phrase is used instead of "net GHG mitigation" to draw attention to the negative emissions or carbon dioxide drawdown that is anticipated, as opposed to reduction of existing emissions.

[3] Download *Agricultural Soil Carbon Credits: Making sense of protocols for carbon sequestration and net greenhouse gas removals* at www.edf.org/soilcarbon.

Additionally, there is a lack of agreement on how to best address critical accounting elements. These include leakage (whether emissions reductions in one place cause increases in another), additionality (whether reductions would have happened without an incentive program), and permanence (maintenance of carbon stocks over time) at the appropriate scales to ensure that projects or programs result in real net GHG emission reductions overall.

Social and economic factors also play a critical role in determining mitigation potential. In croplands, socioeconomic issues (e.g., land tenure and access to technology, capital and markets) will determine the rate of adoption by farmers of agricultural practices that store carbon in cropland soils. These factors, especially those beyond the farm scale, must be considered when estimating the realistic soil carbon sequestration potential of cropland soils, which is likely to be much lower than the estimated maximum biophysical potential.

Despite these challenges and uncertainties, the voluntary market for cropland soil carbon sequestered through agricultural practices has increasing momentum, which adds urgency to the need to address these gaps. Carbon registries and private companies are developing carbon measurement, reporting and verification protocols to bring verified carbon credits into the market and to pay farmers and foresters for sequestering carbon.[3] Review of the scientific underpinning of this natural climate solutions pathway should help identify the scientific gaps that create risk and uncertainty in carbon credit development.

Definitions:

Carbon market: A market in which units — allowances or credits — are traded between entities. When units are used for voluntary purposes or where carbon credits are certified solely by voluntary programs or standards, the market is often referred to as a "voluntary" carbon market. When units are used to satisfy legal compliance obligations, the market is often referred to as a "compliance" market.

Carbon stock: The absolute mass of carbon in a sample of known volume — typically expressed in tonnes per hectare to a specific depth.

Measurement, reporting and verification: A system or protocol for tracking specific methods and outcomes, transparently communicating specific information, and validating that the information is accurate and complete. Often abbreviated as MRV.

Protocol: A guidance document that contains all relevant rules, standards, deductions, calculations and parameters for the calculation/estimation of emission reductions and removals, and for MRV of emission reductions and removals from an emissions crediting project.

Soil carbon sequestration: The net additional storage of carbon from atmospheric carbon dioxide in soil pools, after accounting for any GHG losses.

Soil organic carbon: The carbon contained within soil organic matter. Often referred to as soil carbon or abbreviated as SOC.

Carbon sequestration in cropland soils

Agricultural soils include a very wide variety of land uses, such as cropland, set-aside and field edges (i.e., the matrix within which cropland exists), pasture and rangeland. This report focuses on net carbon sequestration in active cropland (i.e., cropland that does not change to another land use or ecosystem type such as forest, grassland or wetland), in order to address the majority of current carbon protocol and market activity. The soil carbon sequestration potential for cropland restoration to wetlands, riparian buffers, reforestation and other conversion to perennials is more certain, with fewer challenges for MRV protocols. Pasture and rangeland may require more attention as we move forward.

Broad findings for cropland soils

- Practices that increase the quantity of carbon inputs into the soil by growing plants over a longer time period (i.e., cover crops grown after a season's cash crop), retaining crop residues, or otherwise increasing total above- and below-ground biomass have the potential to enhance soil carbon stocks. In addition, practices that decrease soil disturbance can reduce soil carbon losses.
- The degree to which these agricultural practices increase net carbon sequestration is likely to depend on baseline practice and starting soil carbon stocks, fertilizer management, and geographic, soil and climatic conditions.
- Soils store a significant amount of organic carbon at depths beyond the immediate tillage zone; however, we lack an understanding of how agricultural management practices impact soil carbon at depth since the majority of soil sampling has focused on the top 30 cm.
- Building soil carbon in agricultural soils has important co-benefits that can lead to improved water quality, reduced erosion, increased yields, and increased drought resilience through higher soil water holding capacity.
- Understanding the socioeconomic factors at regional or societal scales is necessary to understand the realistic mitigation potential of agricultural soil carbon sequestration. Realizing the biophysical potential for carbon sequestration would require practice adoption by hundreds of millions of individual farmers across the globe, all with different economic constraints, governance, land tenure, and access to inputs, technology and markets.
- Calculating the net climate effects of agricultural soil management, and thus carbon credits, requires accurate assessment of carbon dioxide captured and nitrous oxide and methane released. Nitrous oxide will

depend on nutrient management and other agricultural practices, while non-animal methane (i.e., from rice cultivation) may depend on water management. These GHGs are difficult to compare given that methane is a short-lived climate pollutant with much greater warming potential over shorter timeframes. (Over the first 20 years, methane is 84 times more potent than carbon dioxide).

- We lack efficient, scalable and cost-effective soil sampling methodologies to quantify net soil carbon sequestration accurately at the scale of individual fields.
- There is currently little agreement on what constitutes sufficient accuracy for estimating changes in soil carbon.
- We need models that accurately estimate net GHG reductions for crop fields aggregated to a suitable spatial and temporal scale under proposed management interventions for combinations of soils, cropping systems and climates.
- Models that estimate net GHG impacts must consider how real farms may differ in both practice and outcome from the research sites that are the source of model calibration data (e.g., total biomass produced).
- There are a lack of agreement and serious unresolved challenges in how soil carbon MRV protocols should account for permanence, reversals, additionality, uncertainty and leakage.
- There is a risk that the market will move toward protocols and marketplaces that provide the highest number of credits with the lowest overhead verification costs, which might edge protocols with the highest standards and highest quality credits out of the market and result in unreliable credits that do not deliver actual climate benefits.
- There needs to be consistent oversight to ensure environmental integrity in the generation of credits. Such oversight by a public or private entity could set consistent and transparent standards regarding baseline accounting, definitions of additionality, maintenance of sufficient buffers to mitigate against risk of reversal, and leakage accounting to guard against shifts in production.

Size of existing pool in cropland soils

The soil science community agrees that the vast majority of agricultural soils have lost soil carbon compared to their pre-agricultural state. The top 30 cm (~1 foot) of the world's cropland soils contains ~131 Pg of organic carbon (equivalent to 481 Pg CO_2e),[4] having lost an estimated 9.6 Pg C (6.8%) from anthropogenic land use changes over the last 12,000 years.[5,6]

In comparison, grasslands and savannas cover a greater total area and contain more than twice the total amount of organic carbon in the top 30 cm (275 Pg C), with estimated soil carbon losses over the same time period of 5.0% and 3.6% of their pre-agricultural totals, respectively.[7,8]

6.8%

Reduction in global soil carbon levels due to agriculture and other human-caused land use changes.

[4] Pg (petagram) is an SI unit equal to 1 × 1012 kg or 1 billion (109) metric tonnes. One Pg carbon (C) is also equal to 1 Gigaton of carbon (Gt C), a non-SI unit used in some contexts.

[5] These values combine cropland with cropland and natural vegetation mosaic.

[6] Sanderman et al., 2017.

[7] Ibid.

[8] While scientists tend to talk about carbon stocks in terms of the elemental units (i.e., C), the climate change conversation about emissions and mitigation more often refers to CO_2 or CO_2-equivalents (CO_2e). One Mg of carbon is contained within 3.67 Mg of CO_2, so these soil carbon values can be converted from C to CO_2e by multiplying by 3.67. As this report is oriented toward climate change mitigation, most subsequent mentions of carbon quantities will be in units of CO_2 or CO_2e.

20-50 YEARS

of practice changes: Point at which soil carbon levels reach a new equilibrium and gains are balanced by losses.

Practices that can sequester carbon in cropland soils

It is generally accepted that practices that increase the amount of carbon inputs into the soil by boosting overall plant productivity, retaining residues and/or keeping plants in the ground can build soil carbon. By preventing losses of existing soil carbon, reducing soil disturbance (e.g., with less tillage) can also result in greater overall soil carbon stocks than conventional management. In this way, even if reduced disturbance does not draw down carbon dioxide to create new soil carbon, it can provide real GHG emissions mitigation.

Practices that reduce soil disturbance include no-till (otherwise called direct seeding or direct drilling), strip tillage and conservation tillage. A critical unresolved question is how these practices impact soil carbon stocks at depth. Most research has focused on the top 30 cm of the soil profile, but some studies that have examined carbon dynamics down to 1 m depth have shown that certain practices such as no-till can lead to a re-distribution of soil carbon across the soil profile rather than net accrual.[9] On the other hand, soil carbon is much more stable at depth (i.e., it is less vulnerable to decomposition) and so strategies that can increase soil carbon stocks (e.g., deep-rooted crops) below the plow layer are important avenues for further research.

For cropland that remains cropland, and continues to produce a similar mix of commodities, the best options for sequestering new soil carbon include adding winter or fallow-season cover crops (where moisture and temperature conditions allow) and incorporating perennials into crop rotations.

Other opportunities to both store new carbon and reduce soil carbon losses include agroforestry, restoring wetlands, and planting other perennial vegetation at field edges and on marginal cropland. While these strategies have high carbon sequestration potential per unit area, they fall outside the scope of the current study due to the land use change involved over limited areas, if maintaining agricultural productivity and keeping most cropland as cropland. Further, a successful cropland soil carbon program relies on maintaining or increasing productivity within a designated project to provide commodities to meet the demand of global supply chains and to reduce leakage and other risks.

Uncertainty exists in the efficacy of these practices to sequester soil carbon and result in net GHG emission reductions. This uncertainty stems from diversity in climate and soil characteristics, differences in practice — and outcome — between research plots and commercial farms, and high variability in measured soil carbon and other GHG outcomes. In addition, expectations have been moderated by studies that found no-till reduced crop yield in some regions[10] and reduced soil carbon in deeper soil horizons.[11] For all practices, the removal of carbon dioxide into soil carbon is also time-limited, since soil carbon tends to approach a new equilibrium level after 20-50 years of change in practice (depending on the type of practice), after which gains are balanced by losses.[12]

Potential magnitude of carbon sequestration in cropland soils

We found a lack of consensus about the degree to which agricultural soils can be managed to sequester sufficient carbon dioxide to have an appreciable impact in

[9] Meurer et al., 2018.

[10] Sun et al., 2020.

[11] Powlson et al., 2014; Du et al., 2017.

[12] Minasny et al., 2017.

mitigating climate change.[13] Estimates of the global potential for soil carbon sequestration vary dramatically and are associated with substantial uncertainty.[14]

Estimates of the potential for climate mitigation through increasing the carbon stored in global agricultural soils vary by more than an order of magnitude. For instance, a recently published estimate of carbon dioxide removal potential for cropland soils alone (i.e., excluding grassland) is 6.8 Pg CO_2 per year over 20 years.[15] The IPCC assessed the carbon dioxide removal potential for cropland and grassland soils to be between 0.4 and 8.6 Pg CO_2 per year.[16] Others have estimated that 1.5 to 8 Pg CO_2 per year could be stored in the top 30 cm of agricultural soils over a 20 to 30 year period.[17] The high end is more than twice as large as the estimated human-caused loss of soil carbon (down to 30 cm) over the last 12,000 years.[18]

Crucially, these are estimates of maximum biophysical potential carbon sequestration. They do not account for the practical challenges of making management changes that sufficiently increase biomass and reduce soil disturbance at the farm scale. These include finding markets for any new crops (whether secondary, cover or rotation); accessing equipment, labor and sufficient cover crop seed; figuring out seeding and harvest timing to maintain productivity; and getting cover crops or other new species to grow well, all while dealing with uncertain weather.

Nor do they account for other socioeconomic factors that affect adoption rates of new agricultural practices, such as farmer identity or the realities that even the most sequestration-minded farmers face when considering practice changes — access to information, social pressures, authority over land contracts or land ownership issues, for example. Depending on the price of carbon alone, the realizable potential is estimated to be between 27% and 72% of the biophysical potential.[19] Others estimate that adoption rates of practices likely to increase soil carbon will limit the global realizable potential to 60% of biophysical potential on croplands.[20]

These types of limiting factors must be considered before we can estimate the realistic magnitude of carbon sequestration in cropland soils.

Measuring net soil carbon sequestration in cropland soils

We lack efficient and scalable methodologies to accurately quantify changes in net soil carbon sequestration. Soil carbon can vary significantly over small scales, even down to the centimeter, and it accrues very slowly. The annual change in soil carbon concentration might be 0.01% under realistic implementation of agricultural practices (e.g., cover crops and reduced tillage).

Current measurement techniques can detect changes of 0.05%,[21] and the documented average detection from commercial laboratories is 0.1%.[22] The inability to detect annual carbon sequestration in agricultural soils is why

27-72%

How much of the biophysical potential for soil carbon gains could be achieved based on the price of carbon alone.

13 VandenBygaart, 2016; Schlesinger and Amundson, 2019; Bradford et al., 2019

14 Minasny et al., 2017; Bossio et al., 2020.

15 Zomer et al., 2017.

16 IPCC, 2019.

17 Sanderman et al., 2017; NASEM, 2019.

18 Sanderman et al., 2017.

19 Smith et al., 2008.

20 Sommer and Bossio, 2014.

21 Jon Sanderman, Woodwell Climate Research Center, pers. comm, 2021.

22 Jimenez and Ladha, 1993.

MRV protocols that require soil sampling generally stipulate that soil samples be collected every five years. Low precision in the soil carbon analysis leaves little to no room for any field or analytical error in order to detect a change of 0.05% over five years.

Measurement techniques that allow for greater density of soil samples at a lower analytic cost may improve our ability to detect changes in soil carbon. One such approach is soil spectroscopy, which can provide accurate measures of soil carbon at a fraction of the cost of traditional lab analysis.[23]

Underscoring the heterogeneity of soils and slow pace of soil carbon accumulation, research analyzing data from 13 field trials across the U.S. Midwest demonstrated that it can take between 11 and 71 years to detect statistically significant soil carbon stock changes in agricultural field trials.[24] As a result, it is difficult to detect change at the temporal and spatial scales of interest for GHG reduction programs that credit individual farmers without collecting and analyzing a cost-prohibitive number of soil samples. Soil carbon crediting protocols therefore rely on process-based biogeochemical models and less on field measurements to issue credits in the short term.

Given this reliance on modeled results of annual soil carbon sequestration, we need models that produce estimates of net soil carbon sequestration with high confidence — accounting for non-carbon dioxide GHGs — and meet standards of accuracy and uncertainty. Such standards of accuracy and uncertainty are not currently universally agreed upon.

Accounting for non-carbon dioxide GHGs is critical because the emissions of other GHGs may be influenced by the practices adopted for carbon sequestration. For example, if additional fertilizer is applied to improve establishment and productivity of cover crops, emissions of the potent GHG nitrous oxide may increase. No-till management is also known to generate increased nitrous oxide emissions in certain soil-climate zones because of impacts on soil moisture, especially in the first years after adoption.[25] Evidence suggests that the mitigation potential of no-till systems is only realized when practiced over longer timeframes.[26] Thus, accurate carbon accounting requires that both carbon sequestration gains and other emissions be included.

Currently, there is little evidence that existing models can accurately capture net GHG reductions at the field level under all proposed management interventions for all combinations of soils and climate.[27] While the basic soil management practices that are most likely to increase soil carbon are included in multiple models, validation of these models with high-quality field data is limited to only certain cropping systems and geographic conditions — generally the most common crops and most intensive cropland use.

Measurement, reporting and verification protocols

Addressing uncertainty, permanence, additionality, reversals and leakage in these heavily managed systems is also complicated. Published MRV protocols address these issues, but with varying thresholds (Table 1). In addition, some protocols do not incorporate trade-offs with non-carbon dioxide GHGs in

[23] Paul et al., 2019; Sanderman et al., 2020.

[24] Necpálová et al., 2014.

[25] van Kessel et al., 2013

[26] Six et al., 2004.

[27] Tonitto et al., 2018.

quantifying soil carbon credits. These differences mean that credits derived from different protocols may not be equivalent,[28] precluding application of these credits to nationally determined contributions or emission offsets.

Over time, the market may move toward protocols and marketplaces that provide credits with the lowest overhead verification costs, which might edge protocols with the highest standards and quality credits out of the market. This potential outcome underscores the need for consistent oversight to ensure environmental integrity in the generation of credits.

Carbon credit accounting

While there has been a growing amount of project development in the agricultural carbon space, no verified credits have been issued to date by any of the major registries: Climate Action Reserve, Verra and Gold Standard. Indigo Ag, LLC announced the first round of payments to 267 farmers with anticipated verification under Climate Action Reserve's Soil Enrichment Protocol in 2022. Indigo announced that it has secured buyers for all of the credits generated under this project. Other market activity includes the following:

- The Nori Carbon Removal Marketplace has sold 75,540 Nori Removal Tonnes (NRTs, issued for soil carbon sequestered only, as they do not account for other GHGs) and have 9,621 NRT available for purchase.
- Regen Registry has issued 118,957 credits under their Grasslands Methodology. Microsoft was among the companies that purchased these credits.
- Truterra, LLC's TruCarbon Program has a contract with Microsoft to develop/deliver 100,000 tonnes.
- The Ecosystem Services Market Consortium issued its first round of payments to farmers for ecosystem service credits under a pilot in Kansas in collaboration with General Mills and the Kansas Department of Health and Environment. The consortium released their soil sampling protocol in December 2021.

Consensus, gaps and disagreements around cropland soil carbon credits

We obtained six external reviews of this summary to highlight points of disagreement and areas that reviewers felt were missing important information. Generally, there was consensus among the reviewers with the main conclusions. Disagreement was raised in response to specific framing of issues (e.g., using variability in ecosystem carbon stocks to illustrate the challenge of detecting change in fluxes of soil carbon). In these circumstances, we have revised the document to provide more appropriate context to highlight points related to the uncertainty in cropland mitigation potential.

Some of the reviewers also felt the summary's language around the uncertainty of the agricultural soil carbon sequestration potential belies consensus surrounding the significant potential for climate abatement in agriculture. These reviewers felt that while uncertainty in projections of the magnitude of impact exists, this could result from differences in agricultural systems and interventions considered when estimating projections.

[28] Oldfield et al., 2021.

TABLE 1

Variation in structure and accounting in 10 MRV protocols used in the private or public sector [29]

Issue	Approach
Measurement	• Sampling • Modeling • Sampling + modeling (hybrid) • Sampling + remote sensing
Additionality	• New practices are not already implemented on a percentage of land area • Legally required practices are not accepted • Modeling demonstrates carbon storage above business as usual • Practices must be proven to be new and additional to business as usual • There is a reasonable expectation for carbon dioxide drawdown from project activity • Credits issued for carbon stored after the initiation of soil testing • Credits issued for "look back" periods of 5 to 10 years
Reversals	• A percentage of credits are held in a buffer pool to mitigate reversal • The risk of reversal determines whether credits can be sold
Permanence	• Depending on the protocol, practices have to be maintained for 10, 20, 25 or 100 years (with buffers held for reversal)
Net carbon addressed	• Nitrous oxide and other emissions are addressed through models/emissions factors • Emissions are only included if they are greater than 5% of baseline/business as usual • Only soil carbon sequestered is credited
Acceptable uncertainty	• Depending on the protocol, uncertainty cannot be above 10, 15, 20 or variable • The probability of exceedance = 60%

Information synthesized from 10 published and publicly available protocols including CAR Soil Enrichment Protocol (CAR SEP); Verra Methodology for Improved Agricultural Land (VM0042); Verra Soil Carbon Quantification Methodology (VM0021); Verra Adoption of Sustainable Land Management (VM0017); Gold Standard Soil Organic Carbon Framework Methodology (GS-SOC); Australian Carbon Credits (Carbon Farming Initiative-Measurement of Soil Carbon Sequestration in Agricultural Systems) Methodology Determination (AUS-SM); Australian Carbon Credits (Carbon Farming Initiative-Estimating Sequestration of Carbon Using Default Values) Methodology Determination (AUS-DV); Food and Agriculture Organization GSOC MRV Protocol (FAO GSOC); Alberta Quantification Protocol for Conservation Cropping (Alberta CC); Regen Network Methodology for GHG and Co-Benefits in Grazing Systems; and BCarbon Soil Carbon Credit Systems.

Related to this, some reviewers felt that the summary may conflate uncertainty and variability in terms of our understanding of the efficacy of agricultural practices in sequestering carbon. These reviewers agreed that substantial variability exists in the impacts of practices on soil carbon sequestration due to different climate and soil types, however, there is a good degree of certainty on the impact of specific practices within certain systems, as well as robust estimates for expected mean outcomes at regional and national scales. All reviewers agreed that there is a large degree of uncertainty about the "practical" and "realistic" potential of using agricultural soils for climate mitigation.

Where reviewers identified important information as missing, we have incorporated key points into the summary. For instance, several reviewers felt that the co-benefits of building soil carbon on soil health and agricultural resilience, and the question of how agricultural practices impact soil carbon stocks at depth, should be addressed in greater detail.

[29] Adapted from Oldfield et al., 2021.

Conclusions

Cropland soil management has the potential to sequester significant amounts of soil carbon. Multiple environmental and agronomic benefits result from improvements in soil health, such as increased yields and yield resilience, enhanced water quality, and reduced soil loss and erosion.[30] Increased resources enabling producers to adopt practices that improve soil health is a public good.

Despite the appeal of carbon markets to generate funding to support practice adoption at the farm scale — resulting in a burgeoning voluntary carbon market supported by multiple registries and project developers in the U.S. — sequestering soil carbon remains an uncertain approach to climate change mitigation. To support a robust carbon marketplace, we need an accounting framework that 1) accurately estimates net sequestration (accounting for carbon and other GHGs), 2) includes safeguards against reversals, and 3) operates at a regionally appropriate scale that can improve accuracy and enhance efficiency.

Additionally, better integration of socioeconomic constraints on the biophysical potential is necessary in order to manage expectations for funding and policy that incorporates the realizable net soil carbon sequestration as a climate solution.

[30] Kane et al., 2021; Lehmann et al., 2020; Oldfield et al., 2019.

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