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The Realizable Magnitude of Carbon Sequestration in Global Cropland Soils: Biophysical constraints

Natural Climate Solutions

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About this report

This report assesses the current scientific understanding of cropland soil carbon (C) and the potential for increasing sequestration with management change. It discusses the implications for overall greenhouse gas (GHG) emission reductions and global climate change mitigation, with emphasis on North America, especially the U.S. corn belt. Identify the research needed to improve assessment of the real potential for C storage in cropland soils.

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Executive summary

Global agricultural soils are estimated to contain 406 Pg C in the upper 30 cm, with a loss of 22 Pg C over 12,000 years incurred by land conversion and agricultural management (Sanderman et al., 2017). Grasslands and savannas comprise at least two-thirds of this total, and cropland contains up to 130 Pg C in this soil horizon, having lost almost 10 Pg C through human activity. Urgency for climate change mitigation, combined with agricultural-sector interest in ecosystem services as marketable products, has led to a significant increase in the number of companies and other organizations working to engage with farmers in soil carbon sequestration.[1] This voluntary market has new companies and initiatives announced monthly, some of them already paying farmers for practice changes with money invested by market giants like Microsoft and Shopify.[2]

The estimated potential for net GHG mitigation through soil carbon sequestration on cropland varies widely — from replacing some or all the organic carbon that has been lost (Mayer et al., 2018; Stockmann et al., 2013) to exceeding that amount by almost four-fold (Zomer et al., 2017). Published potential soil C sequestration estimates for 20 years of improved practices range from 2.3–37 Pg C for cropland surface (0–30 cm) soils only (Griscom et al., 2017; Zomer et al., 2017) to upwards of 68–76 Pg C for all land uses and greater soil depths (Lal, 2010; Soussana et al., 2019). These differences reflect the substantial sources of variation in methods as well as in the combinations of soils, climates, geographies, crops, agricultural practices, depths and scales. Refining our understanding of the role of soil carbon sequestration in mitigating climate change is critical for achieving global goals to avert this threat.

This report describes the current state of the science in quantifying the biophysical potential for cropland soil C sequestration. Even though scientists have studied the topic in increasingly greater detail over the past decades, significant gaps remain in understanding the mechanisms and variation of carbon dynamics in agricultural soils. As socioeconomic factors will further constrain realizable carbon sequestration, the biophysical potential will overestimate the actual potential (see companion report "The Realizable Magnitude of Carbon Sequestration in Global Cropland Soils: Socioeconomic Constraints", hereafter called the Socioeconomic report).

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[1] Similar enthusiasm surrounded agricultural GHG mitigation in 2009 when the voluntary carbon market was buoyed by expectations of U.S. federal cap-and-trade policy. The failure of that national market to emerge along with the 2008 financial crisis put much of this activity on hold until more recent private commitments combined with international urgency about climate change revitalized efforts.

[2] Publicly available documentation on Microsoft activity includes an article about their purchase of credits from an Australian cattle company (farmonline.com.au/story/7105542/microsoft-buys-carbon-credits-from-nsw- cattle-operation/); their published criteria for high-quality credits (query.prod.cms.rt.microsoft.com/cms/api/am/binary/RWGG6f); and the lessons learned from their first purchase of carbon credits (query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4MDlc). In October 2020, Shopify announced plans to purchase 25,000 Mg CO_2e of credits at ~$12/Mg (or metric ton) from an Iowa farmer using no-till and specialized nutrient formulations to qualify for soil C credit generation via Nori (agriculture.com/news/crops/shopify-is-first-high-volume-corporate-buyer-of-carbon-credits, www.bloomberg.com/news/articles/2020-10-28/iowa-farmer-finds-fortune-in-selling-carbon-credits-to-shopify)

High priority research needs for improving the estimates of potential net carbon sequestration in global croplands after agricultural practice changes include[3]:

- Better understanding of the capacity for different cropland soils to store more soil organic carbon (SOC) and hold onto it over the long-term. This includes overall sink potential as well as timing or rate.
- Quantification of the realistic impacts of on-farm management practices (e.g., episodic tillage versus no-till, varied biomass production for cover crops) at scale over time in different geographies.
- Nitrogen (N) implications of storing additional SOC. This includes quantifying the N fertilizer or other additions that may be needed to support higher biomass production, as well as impact on direct and indirect nitrous oxide (N_2O) losses.
- Role of climate (temperature and precipitation), soil texture and depth on the stock of SOC at the points of equilibrium (new steady state) and saturation (cannot store more).[4]

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[3] In this context we use the term "net carbon sequestration" instead of "net GHG mitigation" to draw attention to the anticipated CO_2 drawdown, for which the impact is reduced by any other GHGs emitted in the process. Because it removes climate pollutants from the atmosphere, this type of mitigation is different from others that focus on reducing existing emissions. "Net C sequestration" is thus the overall GHG impact related to soil C sequestration (i.e., the CO_2 equivalent of changes in soil C net of changes in other GHGs like N_2O).

[4] While "saturation" is used here to denote the point at which a soil is unable to store more SOC even with increasing inputs, the term has been used slightly differently in different contexts (e.g., mineral-associated organic matter MAOM saturation versus saturation with increasing inputs).

Introduction

Soil in managed and natural landscapes contains large amounts of carbon captured by plants from carbon dioxide (CO_2) in air over millennial timeframes. Plant compounds then enter the soil and go on to form soil organic matter (SOM) through both microbial decomposition or directly with little or no microbial transformation. Much of this organic matter continues to cycle actively through soil microbes and other organisms, releasing nutrients for plants along with CO_2 as it decomposes further, and pulling in new SOM from new plant and animal matter deposits. Note that SOM is approximately 50% soil organic carbon (SOC) by mass (Pribyl, 2010).

Over time, soils reach a point where there is a balance between inputs and outputs, meaning that new SOM enters the system at approximately the same rate as which existing SOM decomposes to release CO_2 and plant-available nutrients (e.g., nitrogen, phosphorus). Conversion from one land use to another can upset this relationship. For example, agricultural activity that disturbed the soil and converted perennial grasslands, forests and wetlands to annual cropland is estimated to have released 116 Pg C (or 3.5% of the total stock) from the upper 2 m of soil globally (Sanderman et al., 2017). Because the topsoil is where biological activity is concentrated and contains the highest SOC concentrations, the top 30 cm also comprised a greater proportion of losses (31 Pg C, or 27% of total SOC losses in only 15% of the soil depth considered). Improved management practices can reverse that trend and capture new SOC, particularly within the surface soil horizons. However, for most soils and practices, gains in SOC might level off despite increased inputs in about 30 years (West et al., 2004). Note that a warming climate may add further disruption if SOM decomposition exceeds the formation of SOM (Bradford, 2017).

Whether these agricultural practices can actually provide the benefits promised depends on the answers to two big questions that continue to cause much uncertainty for cropland soil carbon as a climate mitigation pathway.[5] First, what is the total potential for net carbon sequestration, how does it vary from place to place and how does that potential change with time? While biophysical estimates exist (Paustian et al., 2019), they extrapolate global potential from a limited number of studies that address only some combinations of crop, soil, environment and management practices. Here, we address sources of uncertainty in estimates of biophysical potential. Another report addresses how socioeconomic factors also modify the biophysical potential for carbon storage (see Socioeconomic report). The second question involves how changes in the soil carbon pool can be measured and verified in order to provide sufficient certainty for a market, for country-level emission reduction commitments, and above all, for achieving climate benefits. This second question is addressed in more detail in an accompanying report that focuses on measurement, reporting and verification (Oldfield et al., 2021).[6] Another report addresses how socioeconomic factors also modify the biophysical potential for carbon storage (see Socioeconomic report).

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[5] While policies and incentives are necessary to prompt conservation of existing SOC stock, this report focuses on the latter i.e., the potential for drawdown of atmospheric CO_2 that would increase the total amount of carbon stored in cropland soils.

[6] https://www.edf.org/ZB7h

Little consensus exists in the literature on the feasibility of managing agricultural soils to sequester sufficient atmospheric carbon to have an appreciable impact in mitigating climate change (Bradford et al., 2019; Schlesinger and Amundson, 2019; VandenBygaart, 2016). Even without considering net GHG impact, estimates of the global potential for soil carbon sequestration vary dramatically and are associated with a large degree of uncertainty (Bossio et al., 2020; Minasny et al., 2017; Sanderman et al., 2017). Table 1 in the Socioeconomic report lists estimates from peer-reviewed scientific literature. Although research is underway in several institutions, efforts to better understand the realistic potential and feasibility for increasing cropland SOC are uncoordinated and involve varied methods and scales (Paustian et al., 2019). Technical collaboration and coordination among soil scientists can provide a more accurate estimation of the sink and the associated uncertainty (Bradford et al., 2019), all of which are necessary for "right-sizing" policy, funding and market mechanisms. We present the scientific evidence of the technical potential to store new SOC, including how those estimates differ by management practice as well as by soil and climate characteristics. While our focus is on SOC sequestration, we also appreciate the fact that many agricultural practices touted for carbon accrual likewise have clear value in improving soil quality (soil health), which improves productivity, water filtration and resilience to drought (Kane et al., 2021; Oldfield et al., 2019; Renwick et al., 2021).

Much of the discussion and the implications in this review are global in scale, even though many examples come from North America and other temperate cropland, due to the volume of research available. Active cropland has captured much of the market focus — as well as the discussions of scientific uncertainty. As a result, this assessment will exclude activities related to avoided conversion, converting from annual to perennial crops including pasture, and removing land from production (e.g., planting to trees, restoring wetlands). While these activities do have soil carbon sequestration potential, our focus is on annual cropland that does not shift to another system.

Background: Soil C market and policy activity

Depiction of the potential for cropland soil carbon gains has included much optimism in the media and environmental organizations (see Table 1). Some of the stories introducing these opportunities include only the highest numbers from what was a range of values in a scientific report, double count practices within categories, or otherwise provide inflated visions of the potential. In response to claims of very high rates, extension experts, researchers and others have provided reality checks.[7] One extension article showed how rather than increasing SOM by 1% per year — as suggested by some — a highly productive corn crop with rye cover crop could more realistically achieve 0.1% gains (e.g., going from 2% to 2.1%), or up to 0.17% if also applying high rates of manure (which may only move carbon [via manure] from one location to another, without net climate benefits).[8]

Many of the same practices that have the potential to increase SOC have significant value for soil health, agricultural productivity and resilience to drought and other stresses. Given these benefits, farmers need support for implementing these practices regardless of their carbon sequestration value. In some cases, these other benefits have reduced the requirements for projects to provide the certainty required by carbon markets including the need to address additionality, leakage and potential reversals. As a result, by focusing on soil health rather than assured GHG impact, initiatives like California's Healthy Soils Program have been able to address some of the challenges and critiques that plagued early cropland soil C programs such as the Alberta program that incentivized no-till (which tended to exclude small farms due to costs, and for which a large portion of payments went to early adopters).[9, 10] In addition, since no-till is not a guaranteed net GHG-reducing practice, a focus on soil health that does not pay for soil C sequestration avoids a miscalculation of net GHG impact.

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[7] insideclimatenews.org/news/16042021/politicians-are-considering-paying-farmers-to-store-carbon-but-some-environmental-and-agriculture-groups-say-its-greenwashing/

[8] extension.psu.edu/can-i-increase-soil-organic-matter-by-1-this-year

[9] cdfa.ca.gov/healthysoils/

[10] alberta.ca/agricultural-carbon-offsets-conservation-cropping-protocol.aspx

TABLE 1.
Examples of cropland soil carbon sequestration potential claims from news articles, websites or other popular press

Organization	Claim(s)
Locus Agricultural Solutions[a]	Rhizolizer® soil "probiotics" sequester up to additional 9 metric tons CO_2e/ac/yr
World Economic Forum & McKinsey[b]	Natural climate solutions (NCS) (agriculture and forest) 6.7 Gt CO_2 "practical" annual GHG mitigation potential by 2030
The Land Institute[c]	Perennial grains are significant part of the SOC storage potential, citing IPCC (2019), "better management of soils can offset 5–20% of current anthropogenic emissions"
Foundation for Food & Agriculture Research[d]	"Soil and farmlands already sequester one hundred more times carbon than is emitted in a year."
Gentle Farming[e]	"2.5 = Average number of CO_2e offset tonnes produced per year per hectare. Typical range: 2–3. Some fields seeing 4+."
Rodale Institute[f]	"Shifting both crop and pasture management globally to regenerative systems is a powerful combination that could drawdown more than 100% of annual CO_2 emissions, pulling carbon from the atmosphere and storing it in the soil."

[a] January 20, 2020, locusag.com/news-releases/partnership-between-locus-ag-and-nori-sets-the-stage-for-monetizing-carbon-farming/

[b] January 1, 2021, http://www3.weforum.org/docs/WEF_Consultation_Nature_and_Net_Zero_2021.pdf

[c] March 19, 2021, https://landinstitute.org/philanthropic-funding-ignites-promising-carbon-sequestration-modeling/

[d] April 13, 2021, https://foundationfar.org/news/initiative-to-reduce-greenhouse-gas-emissions-in-agriculture-marks-one- year-anniversary-welcomes-first-partner/

[e] gentle-farming.co.uk/

[f] October 27, 2021, rodaleinstitute.org/education/resources/regenerative-organic-agriculture-and-climate-change/

Approaches for estimating biophysical sequestration potential

Potential by agricultural practice

A significant challenge for researchers and policymakers has been determining how to extrapolate from small-plot evidence of SOC increases to derive national or global estimates of sequestration potential. Field research measuring long-term changes in cropland SOC has monitored the impacts of reduced tillage (including no-till), eliminating fallow seasons, growing winter cover crops and diversifying crop rotations (Eagle and Olander, 2012; Sperow, 2016).

Average gains of about 0.3 t C/ha/yr can be achieved with practices such as cover crops in temperate cropland systems (Eagle and Olander, 2012; Poeplau and Don, 2015). Many national or global estimates of overall potential have multiplied practice-specific SOC stock or concentration changes from research syntheses or model predictions by the available land area, and then added together the values for different practices (Sperow, 2016).

For example, while no-till and other conservation tillage practices have been consistently included in lists of SOC sequestration opportunities (e.g., Eagle and Olander, 2012; West and Post, 2002), more recent studies note that tillage reductions can only contribute significantly if combined with increased addition of organic matter (Minasny et al., 2017; Powlson et al., 2014). Deeper soil sample cores from tillage and even from cover crop studies suggest that these conservation practices shift organic matter upward in the soil profile, so that sampling only the top 10–30 cm does not capture the full picture and can bias results upward (Cai et al., 2022; Meurer et al., 2018). The high uncertainty and minimal benefit mean that more recent estimates of SOC sequestration potential exclude no-till as an opportunity and focus only on practices or suites of practices known to add new organic carbon to the system when including the whole soil profile (Fargione et al., 2018; Griscom et al., 2017). However, the voluntary carbon marketplace for U.S. croplands generally credits both cover crops and no-till (Oldfield et al., 2021). This may be largely due to the fact that the existing protocols rely heavily on process models that have not yet incorporated newer research findings and are limited in their modeling to the top 30 cm or so of the soil (Oldfield et al., 2021). Many of the models and protocols also do not separately consider how new practices change soil water and aggregates and how these factors affect N_2O emissions, instead using Tier I methods to estimate the non-C GHGs (Oldfield et al., 2021).

Potential related to soil and climate

The long-term and annual-rate biophysical potential for SOC accrual certainly depends on the degree of improved management that is possible in comparison with historic and current practice, but it also depends on climate, soil type and other environmental conditions (Bradford et al., 2019). Considering only one practice at a time with its given estimate of SOC accrual can create computational challenges for land areas that might be suitable for more than one practice. Data are limited for the combined SOC response of multiple co-located practices (e.g., cover crops and reduced tillage and extended crop rotations).

Sykes et al., (2020) provide a crosswalk of sorts between assessing the potential of individual practices and the desired or intended outcome of groups of those practices. Using a framework that considers interim outcome metrics that are tied to SOC sequestration (i.e., increased primary production, reduced soil disturbance, minimizing C removal) rather than checking off a list of practices helps to direct focus toward the end goal and encourages local adaptation in favor of what could be seen as the equivalent of rote learning.

Such principles can then be used to consider the SOC sequestration potential in a practice- agnostic manner, that then estimates the ability of the soil to store new carbon under whatever combination of management practices would work best (Wiesmeier et al., 2019). Usually this includes setting some boundary conditions like keeping the same land use (e.g., same crop[s] at similar production capacity) or at least maintaining overall agricultural productivity within a given region. The annual accrual rate and the maximum potential are then limited largely by mineral surface area (i.e., the fine mineral fraction) and refined by climatic, topographic (including soil depth) and management factors (Sykes et al., 2020). Application of this method in France revealed that some high carbon soils are already saturated (e.g., 59% of French grasslands), with little opportunity for additional sequestration (Martin et al., 2021).

Most SOC is associated with fine textured fractions of the soil; in temperate studies, between 56% and 96% of all SOC was in 0–63 μm size fractions (Chen et al., 2018). Chen et al., (2018) used the Hassink (1997) equation to estimate total soil carbon saturation deficit as a function of the soil texture (fine fraction) and current soil carbon concentration for soils across France. While this suggests that French soils have capacity to add 1008 Tg C to topsoil (0–30 cm depth) and even more to the subsoil, it does not address the timeframe for this sequestration to move from current levels to saturation.

Other researchers use a top-down approach and posit that biophysical C sequestration potential is equivalent to the amount that has been lost due to human disturbance such as agriculture (Mayer et al., 2018) or that at least a portion of the lost C can be recovered. The majority of SOC changes over millennia (mostly losses) have been attributed to agriculture, largely since 1850 (Smith et al., 2016). Broad generalizations and assumptions from bottom-up processes described above may generate predictions of SOC sequestration potential that sometimes exceed the estimated losses (Soussana et al., 2019; Zomer et al., 2017). Losses over time can then provide a useful benchmark for physically achievable C sequestration in soils — perhaps a reality check. Globally, the approximately 3.5% of SOC stocks estimated to have been lost from topsoil over 12,000 years, or 31 Pg C in the top 30 cm, represents 26% of the total 116 Pg C estimated to have been lost from the first 2 m depth of soil (Sanderman et al., 2017). The U.S. accounts for approximately 10% of each of these global values. Regional differences are somewhat dependent on whether non-agricultural land was converted to cropland (Scharlemann et al., 2014) or kept as grassland and used for large-scale grazing (Sanderman et al., 2017).[11] In fact, cropland topsoil losses of 5.6 Pg C represent the highest rate (7.1%) in proportion to historical SOC stocks in any land use category (see Figure 1). Also, while croplands hold about 8% of the contemporary SOC stock, the SOC losses from cropland represent 18% of total losses worldwide.

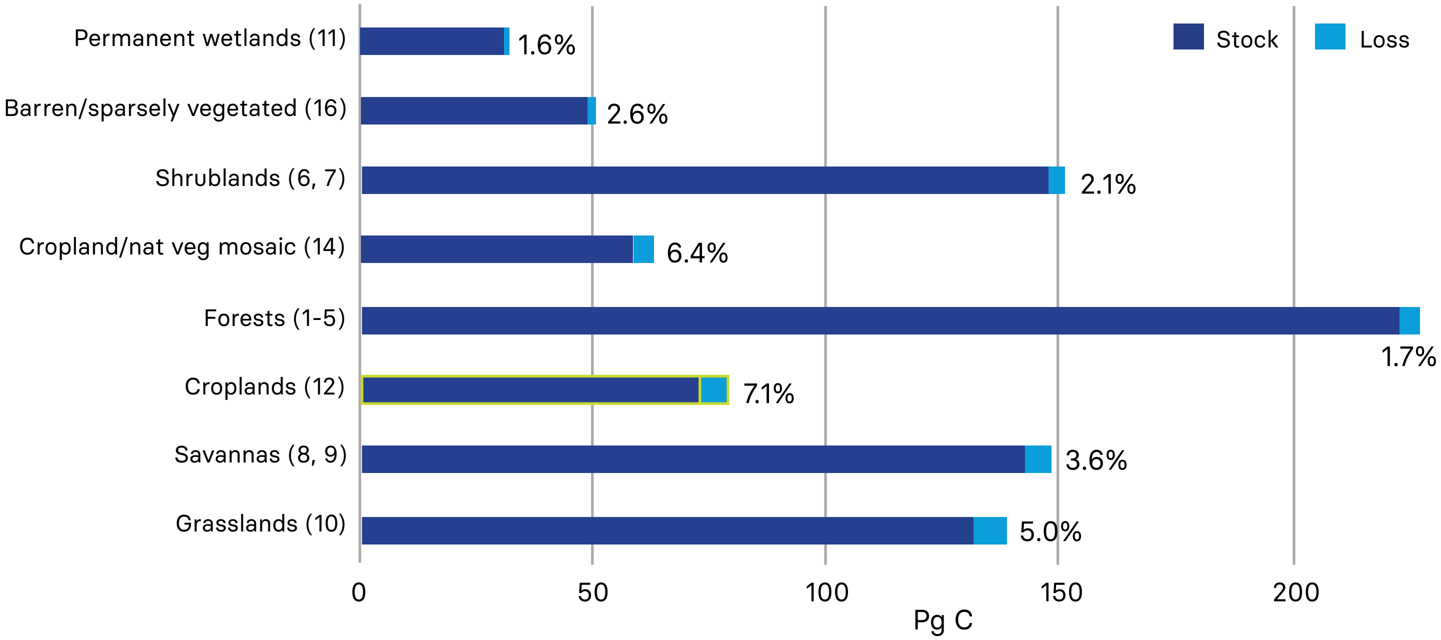

FIGURE 1.
Estimated global soil organic carbon (SOC, in petagrams of Carbon, Pg C) stocks for the contemporary period (2010) and historical SOC losses (from no land use case) at 0–30 cm depth, presented by aggregated MODIS-IGBP land classification categories (IGBP codes in parentheses). Bars are ordered by total SOC loss where the bottom bar is the land use type that has experienced the largest amount of SOC losses (i.e., grasslands). Percentage labels at the end of each bar indicate the proportion of SOC loss with respect to historical SOC stocks (e.g., SOC Loss / (2010 SOC stock plus SOC Loss)). Bar chart constructed using data from Table S3 in Sanderman et al., (2017).

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[11] Taking into account climatic, topographic, geologic, and land-use characteristics (as well as distribution across the globe), these modeled soil C losses of ~7% from cropland at 0-30 cm depth are likely conservative; a paired-plot meta-analysis by the same authors found median “loss” estimates for 0-30 cm depth of 32% for forest-to-cropland and 31% for grassland-to-cropland (Sanderman et al., 2017).

The Soils Revealed website (soilsrevealed.org/) uses the World Soil Information System (WoSIS; Appendix A) data to map out soil carbon at 0–30 cm depth across the globe (with historic data to 100 cm and 200 cm depth). The data are presented in units of t C/ha. Current SOC storage ranges from 0 to ≥120 t C/ha, and overall modelled changes between 2000 and 2018 range from losses of ~10 t C/ha to gains of the same amount. These SOC stock data are then combined with statistical space-time modeling data on historic losses as estimated by Sanderman et al. (2017), to predict potential SOC storage. For example, the Soils Revealed tool shows that improved cropland management (low disturbance and high organic inputs) is expected to generate SOC gains in some locations across the world of up to ~20 t C/ha over a 20-year period (and 1.4–9.4 t C/ha for the U.S. Corn Belt).

These practice-agnostic approaches that rely on soil characteristics and historical soil C changes shift attention from specific practices to the physical potential of a soil or field to accumulate carbon. On the other hand, practices remain important as a way to understand the pathway along which this potential can be achieved. For example, as has been identified for the United States, other temperate agricultural systems are also likely to find the best opportunities in cover crops and agroforestry (Wiesmeier et al., 2020). Furthermore, most estimates do not account for social and economic realities (e.g., land ownership, land use changes, and practice adoption and reversal rates) that further constrain realizable sequestration.

What is realistic? Biophysical and technical constraints

While most of the research on soil carbon sequestration has focused on biophysical potential, many questions remain unresolved and unincorporated in national to global estimates. Table 2 lists biophysical and technical factors that constrain the estimated contribution of SOC sequestration to net GHG mitigation, with examples from the scientific literature. Few, if any, of these factors have been used to actually generate revised expectations for net carbon sequestration values and for estimated rates of change.

While this report focuses on attempts to draw down atmospheric CO_2 by increasing SOC stocks, other climate change benefits (i.e., net GHG emission reductions) related to soil carbon can be realized when an ongoing loss is slowed or halted. Such losses still occur in some regions (e.g., recently tile-drained fields in the Midwest) and could also be exacerbated by warming temperatures (Lal, 2010). However, given that these losses are less common in long-term cropland that has experienced consistent management over time, we note that the practices used to increase SOC would also help mitigate ongoing losses within cropland, and that GHG accounting tools can take such factors into consideration.

Choosing appropriate data

Reports of soil C sequestration potential depend on the choice of data used for syntheses and meta-analyses. Soil carbon research advances that accounted for changes in bulk density (equivalent soil mass), collected deeper samples and measured increased emissions of other GHGs have changed the expectations for net climate mitigation from a number of SOC sequestration practices. Data used to draw conclusions about causality need to be carefully chosen to ensure that trends over time as well as differences between treatments are distinguished. When full-factorial experiments or full time series data are not available, some researchers have suggested that a change in SOC was related to management when in fact a portion of the change would have happened regardless of a management change.

TABLE 2.
Quantification challenges impacting biophysical estimates of SOC sequestration potential and factors known or expected to constrain technical potential across different scales of influence and intervention, with examples from the scientific literature.

Quantification challenges impacting biophysical estimates of SOC sequestration potential

Challenge	Scale of influence	Examples
Soil sampling to greater depth finds some practices that enhance surface SOC actually reduce SOC at lower horizons	Sub-field	No-till redistributes SOC to surface, in comparison to full- or partial-inversion tillage (Du et al., 2017; Powlson et al., 2014)
Since bulk density is difficult to measure, estimates often based on concentration differences	Sub-field	SOC increases from conservation agriculture tend to be overestimated if not correcting for changes in bulk density (Powlson et al., 2016)
Publication bias and lack of long-term data results in higher estimates	N/A	Poeplau and Don (2015) found that excluding the four longest-running experiments (out of 37 total) increased the average annual SOC sequestration rate for cover crops by 9% Extreme values (all high) came from experiments with the shortest time frame, thus pointing toward likely publication bias (since experiments without statistically significant results are less likely to be published)

Biophysical constraints to soil carbon sequestration potential

Constraint	Scale of influence	Examples
Water limitations or short growing season (cold regions) constrain varieties and species can be used	Sub-field to regional	Poeplau and Don (2015) estimate that cover crops could be used on only 25% of total global cropland — others assume more feasible cropland area
Little potential to increase soil C in unmanaged grasslands	Region	Smith et al. (2008) note that available grassland area for C sequestration is limited
Peak SOC sequestration rate 3– 7 years after practice change; then rate slows to zero over time (steady-state at 10–30 years, some suggestions of up to 100 years)	Field	Sommer and Bossio (2014) assume initial increase in rate, then gradual decline toward new equilibrium level; Fuss et al., (2018) account for this new equilibrium by assuming that a practice implemented in 2020 will no longer store new carbon after 2040

Land-use and management considerations at the nexus of biophysical and socioeconomic factors

Land-use competition for practices exclusive of one another (e.g., cannot both plant trees and adopt winter cover crops on same field)	Farm to national	Eagle and Olander (2012) report the total maximum area available for each practice but do not calculate overall total because a separate economic analysis would be needed to determine allocation between practices
Prior adoption of improved practices in some regions (assuming that reduced tillage can store SOC)	Field	Conservation tillage (including no-till) already in place reduces eligible cropland area for some programs, limiting potential for additional SOC

Net GHG emissions

The net GHG emission impact related to SOC accrual can be affected by other GHGs, with N_2O of especial importance in highly fertilized field crops (McLellan et al., 2018). While no-till is promoted as increasing soil C, it can also generate increased N_2O emissions, especially during the initial years after conversion from conventional tillage (van Kessel et al., 2013). Where no-till is not continuous (e.g., biennial), this effect could lead to higher N_2O emissions that do not stabilize in the way that they do in long-term no-till systems (van Kessel et al., 2013). Farmers that fertilize cover crops in order to get a well-established stand also risk increased N_2O emissions. Thus, it is important to avoid increased N fertilizer applications for cover crops, especially when a key purpose is retention of nutrients within the field.

Boosting primary productivity — with more overall biomass — likely requires increased nutrient availability as well, which might require additional inputs. Where nitrogen is added to the system to support growth, increased losses of the potent GHG N_2O are likely. In addition, soils with greater SOC levels tend to experience higher N_2O emissions (Eagle et al., 2017). Any such trade-offs must be incorporated into calculations of net carbon sequestration.

Careful nutrient management is therefore essential to keep added N within the system and avoid the unintended negative consequences of N losses, including in the form of N_2O. Research finds that economically optimal N fertilizer rates for field crops tend to be in the same range as the rates that keep N balance at safe levels, and thus minimize environmental losses (Hao et al., 2001; McLellan et al., 2018). Crop root biomass is also maximized at economically optimal N rates, declining by up to 33% when N is deficient or excessive (Ordóñez et al., 2021). Thus, keeping N balance in check to minimize N_2O losses also provides potential for SOC maintenance and possible accrual with higher below-ground inputs. The 4 per mille estimate of soil carbon sequestration potential (Soussana et al., 2019) has been criticized for not considering this tradeoff between soil carbon gain and N_2O loss. Furthermore, critiques of 4 per mille point out that the total amount of N needed to accompany that level of SOC sequestration would be approximately 75% of current global N fertilizer production assuming a C:N ratio of 12:1 for stabilized soil organic matter (van Groenigen et al., 2017).

For programs that promote soil carbon enhancing practices to reduce overall GHG emissions, it is also essential to address additionality, leakage and reversals. Ensuring that the practice change is new or “additional” to business-as-usual validates the claim that the program or project was indeed the cause of the emission reductions (Oldfield et al., 2021). If the new practices reduce crop yield — and no-till does reduce crop yield in some regions (Sun et al., 2020) — this risks leakage, or increased emissions in another location where production increases make up for the lost yield. While the food security threat of yield loss may be challenge enough, the production increases elsewhere likely entail land-use conversion from native forest or grassland, incurring loss of both carbon and other values. To guard against such losses and take leakage into account, SOC credits may be discounted in quantification mechanisms. Reversals can result from changing practices or from unforeseen climate impacts (e.g., drought, fire, flood), which risks losing much or all of the new carbon captured — discussed in more detail in the Socioeconomic report.

From research plot to on-farm impact and beyond

While these factors affect quantification on a per acre or hectare basis, climate change mitigation from conservation agriculture depends on large-scale implementation. If expectations are to be met, results from plot-scale research studies must reflect outcomes when applied at the field and farm scales. Accurate predictions also depend on accurate assessment of total land area available for the practice change, and some understanding of the realistic implementation or adoption timing across that area.

Biophysical or technical potentials in the scientific literature are generally based on observations from small-plot research trials, which benefit from careful management and possibly greater resources than available for typical farms. This means that some research outcomes may not be fully realizable and may not reflect the real variability of the field scale. Practices on the farm are also not always accurately mimicked on research farms. For example, while research trials tend not to apply fertilizer N to winter cover crops, fertilizer application to cover crops or to the following main crop is somewhat common in practice (UCANR, 2021). As a result, real increases in N_2O emissions that reduce the net GHG mitigation benefits may not be captured in reports from experimental tests. Therefore, it is important that any GHG mitigation counted from cover crop ensure that fertilizer N use increases have been discouraged and properly quantified. The unintended consequence of elevated N_2O emissions can be limited by better accounting for N in soil and cover crops or by using grass cover crops instead of legumes (Quemada et al., 2020).

Additionally, the baseline management practices may also differ between research trials and farms in a region. Therefore, it is important to determine where the region fits with respect to the continuum between assumed conventional practice (e.g., full-inversion tillage and bare fallow, monocrop) and ideal practice (i.e., best possible primary productivity, minimal disturbance). Realistic baselines will affect the per hectare SOC sequestration potential that can be assigned to a new system of practices.

Conservation practices like no-till and cover crops may also cycle between different fields, which means that soil carbon outcomes also may not match up with research trials where practices are maintained over the longer term. While no-till before corn and chisel plow before soybean has been a fairly common on-farm practice, only a small number of research studies have explored the carbon implications of this system compared to continuous no-till (Cook and Trlica, 2016; Venterea et al., 2006). Some recent studies of on-farm cover crop adoption also suggest that cover crops are not planted year-over-year on the same fields.

Timing and land area

Total GHG mitigation from a practice or a system of practices is often calculated by multiplying the areal impact (e.g., tonnes CO_2 per hectare) by the total area available for that practice and then by an estimated timeframe during which the practice is implemented (Griscom et al., 2017; Roe et al., 2019). The available estimates generally simplify calculations by assuming that practices change immediately over the entire applicable area. But adoption curves are more complex than that, and overall adoption rates are unlikely to reach 100%. Further, it is important to avoid double counting for two or more practices that could be applied to the same land area but are mutually exclusive. The extent to which realizable potential is reduced by decisions about area available and time is closely related to other socioeconomic factors and is discussed in more detail in the Socioeconomic report.

Moving Baselines

Climate change has implications for SOC; warming can increase microbial activity, respiration and other processes that would decrease SOC stocks. While such a decrease can be mitigated under high soil water content conditions, with positive plant productivity responses to higher temperatures (Quan et al., 2019; Reich et al., 2018), the outcome is also dependent on soil type and other environmental conditions (Zhao et al., 2021). These relationships will complicate estimation of the realizable soil carbon sequestration potential for net GHG mitigation over the next several decades.

A path forward

The challenges with bringing together sufficient long-term, high-quality, practice-by-practice SOC change data for even the most relevant regions and cropping systems for calibrating empirical and process-based models contribute to significant uncertainty. The online tool at AgEvidence.org provides an updated literature review of the evidence for carbon sequestration and other benefits of cover crops, nutrient management, pest management and tillage practices applied in the midwestern U.S.[12] They document significant net soil carbon sequestration benefits only from no-till. This deviation from the conclusions mentioned above may be largely related to the volume of shallow-sampled no-till studies that did not correct for yield decline, bulk density changes and increased N_2O emissions. This means that soil sampling, with assessment of SOC stock and concentration as well as potential interim indicators (e.g., particulate organic matter (POM), mineralizable C), is increasing in relevance. Such sampling may become even more important if crediting or other incentive programs move away from practice specification to the more agnostic “do whatever works best in your field” approach, allowing for more creative problem solving on the part of farmers.

While SOC stock change is affected by both addition of organic carbon and losses from the system, recent research generally finds that significant increases in SOC are only possible with higher input rates, most often from enhanced primary productivity (i.e., more total plant biomass). In fact, while limited SOC gains can come from external amendments like manure, compost or biochar (Poulton et al., 2018; Powlson et al., 2014; Sykes

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[12] agevidence.org/

et al., 2020), a significant portion may not originate from the amendments themselves but results from their promotion of greater plant productivity (Ryals et al., 2016).

Any mechanism for potential SOC sequestration from reduced disturbance is therefore most likely related to reduced rates of loss rather than actual addition of new carbon from the atmosphere. While reduced losses (and avoided losses) can provide climate mitigation, quantification and accounting requires identifying the appropriate baseline, which can lead to uncertainty. In fact, reduced rates of loss may only be relevant for soils converted to agriculture relatively recently, such that they are still on a downward SOC stock trajectory. Recent research finds that, on their own, no-till and conservation till are unlikely to provide a significant climate benefit (Cai et al., 2022), and high-quality carbon credit mechanisms may require actual drawdown of atmospheric CO_2.

While SOC stocks include soils to depths of at least 2 m, most studies limit assessment of sequestration potential to the upper 30 cm, which is the most active root zone (and also the easiest to sample). Following the nature of available data, tools (e.g., Soils Revealed and SoilGrids) and models (e.g., COMET-Farm and DNDC) also focus on the surface soil (usually 0–30 cm) when assessing stocks as well as new storage potential. However, it is important to consider impact at deeper soil horizons, since some studies finding SOC gains in surface soils have noted associated declines below 30 cm (Du et al., 2017; Powlson et al., 2014).

Conclusion: A long-term vision

Understanding the carbon sequestration potential of global croplands is a prerequisite for understanding how natural climate solutions (NCS) from this sector can offset GHG emissions as the technology is developed to allow other sectors to realize their decarbonization potential. Improved understanding of the biophysical potential is critical for then integrating socioeconomic factors to estimate the realizable magnitude of soil carbon sequestration.[13] Current over-estimates in the potential for SOC increase and the speed at which this increase can be implemented will threaten our ability to maintain the global temperature increase below 1.5°C. Further, understanding the real sequestration potential will ensure that we effectively scale agricultural markets, policy and funding to achieve net GHG mitigation.

Recent advances have helped us better understand the soil carbon implications of human activity over millennia (Deng et al., 2016; Gottschalk et al., 2012; Guo and Gifford, 2002; McLauchlan, 2006; Sanderman et al., 2017), mechanisms of soil carbon stabilization (Castellano et al., 2015; Chen et al., 2019; Cotrufo et al., 2019) and barriers to practice change on the farm (Church et al., 2019; Fleckenstein et al., 2020), along with other issues. However, the quantification tools used to estimate field-level outcomes and the existing policy and program interventions to promote change do not adequately integrate and apply these lessons. Process-based models for soil carbon continue to assign greater net GHG emission reductions to individual practices than accorded by recent science (e.g., no-till in COMET-Planner).

Standardized data collection, compilation and maintenance in accessible repositories can help fill gaps in understanding relationships and processes, and also provide calibration and validation for predictive models at sub-field to global scales (Malhotra et al., 2019). The International Soil Carbon Network has identified soil datasets currently available and highlighted priority research areas (Malhotra et al., 2019). Such efforts are essential if carbon markets or government and supply-chain programs are to effectively quantify the environmental outcomes from investments.

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[13] See Socioeconomic report.

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