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The Realizable Magnitude of Carbon Sequestration in Global Cropland Soils: Socioeconomic Factors

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Natural Climate Solutions

The Realizable Magnitude of Carbon Sequestration in Global Cropland Soils: Socioeconomic factors

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About this report

This report assesses the current scientific understanding of the realizable potential for increasing carbon sequestration in global croplands as influenced by a range of socioeconomic factors. It identifies research needed to better estimate the magnitude and timing of the climate mitigation potential of this natural climate solution (NCS) pathway with consideration of such socioeconomic factors.

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Executive summary

The realizable magnitude, or potential, of carbon sequestration in global croplands is expected to be lower than the estimates of biophysical and technical potential because of varied socioeconomic factors. Here, we review what such factors might be, and how these might result in differential adoption and abandonment of practices expected to increase the total amount of soil organic carbon in croplands.[1] We then lay out four high-priority research areas to help establish the funding and policy priorities around carbon sequestration in croplands as a viable pathway for climate change mitigation globally.

Four key research questions are:

- What are the relevant socioeconomic factors that influence the realizable potential for carbon sequestration in croplands at global and regional scales?
- How do patterns of land tenure, market and other economic drivers, regulatory frameworks and demographics influence the net adoption rates of agricultural practices that affect carbon sequestration in croplands?
- What is the proportion of global croplands that could reasonably be expected to adopt practices that increase carbon sequestration over the next 10–20 years?
- How is conservation practice adoption affected by differential government approaches such as regulation versus voluntary participation?[2]

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[1] While the practices proposed for soil carbon sequestration can also reduce existing loss rates of soil organic carbon, the focus for this report is the capture of CO_2 from the atmosphere and storing it as new soil organic carbon to hold onto it for the long term.

[2] Conservation practices are land management and agricultural activities intended to protect soil, water, air, and related plant and animal resources. As promoted by the Food and Agriculture Organization of the United Nations, “conservation agriculture” is more narrowly defined as a farming system that minimizes soil disturbance, maintains soil cover (mulch or growing plants) and diversifies plant species.

Introduction

Natural soil formation captured carbon in soils over thousands of years. Human activity has dramatically altered global carbon (C) stocks and flows, with significant losses due to agriculture (Sanderman et al. 2017). However, farmers and scientists have found that certain management practices can increase carbon dioxide (CO_2) uptake and/or reduce N_2O emissions, resulting in net greenhouse gas mitigation and increased soil organic carbon (SOC) concentrations in cropland soils. Ways to enhance this cropland soil carbon sequestration include using plant varieties that have deeper roots or greater biomass, adding organic material and changing crop rotations, among others. Implementation of these practices are site-specific, and the results are influenced by the soil type, prior and current land management practices, environmental conditions and other factors. Enhancing SOC can also provide co-benefits, including improved soil health and water quality, higher yields and increased crop yield resilience to drought (IPCC, 2019; Oldfield et al. 2019; Kane et al. 2021). However, there is little direct evidence that demonstrates how and how much specific practices and practice combinations increase SOC and deliver on these outcomes.

Estimates of how much carbon could be sequestered in soils is often referred to as the soil's carbon sequestration (storage) "potential." This potential could be described in terms of what is biophysically achievable (unconstrained by technology or costs, but spatially varied by biome, land cover, soil type); technically achievable given current technology; economically achievable, which adds a cost-effectiveness dimension; and finally, the realizable potential, or the socioeconomically feasible potential, which reflects what is achievable once various political and social factors are considered (see Figure 1). While each of these levels likely further reduces the potential and many factors constrain the potential, some forces may also be enabling. Thus, the funnel concept is a highly simplified model of the system.

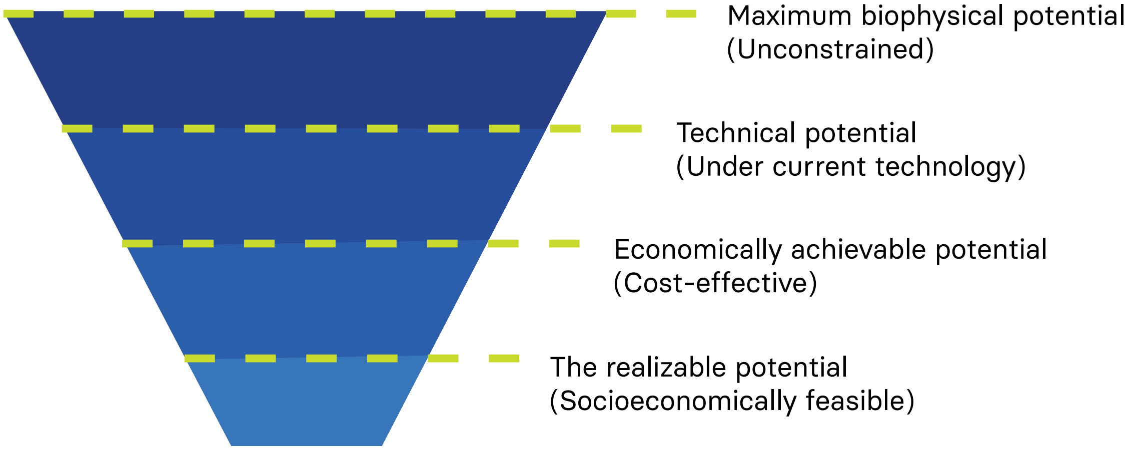

FIGURE 1.
A conceptual overview of the realizable potential of soil carbon sequestration in croplands. Note: This funnel diagram is a modified and expanded version of Figure 2 in Amundson and Biardeau (2018).

Existing scientific estimates associated with each of these potentials vary, reflecting different assumptions and constraints (or lack thereof) included in the analyses. Nonetheless, scientific efforts to assess the biophysical, technical and economic potentials comprise the majority of studies on the topic; research into the realizable potential that also reflects socioeconomic factors — which are often systemic — has been more challenging and is in its infancy. This report summarizes the current state of knowledge on the realizable soil carbon sequestration potential and identifies research priorities for assessing the socioeconomically achievable (or feasible) carbon sequestration potential in cropland soils.

This report is the second of a two-part assessment. The companion report, "The Realizable Magnitude of Carbon Sequestration in Global Cropland Soils: Biophysical Constraints," hereafter the Biophysical report, describes the current understanding of the carbon sequestration potential in croplands, focusing on the maximum biophysical and technical estimates. Here, our objectives are to:

- Assess the state of the science to help establish reasonable expectations for soil carbon sequestration potential in croplands that remain in use as croplands;
- Identify knowledge gaps concerning the role of socioeconomic factors in the adoption of beneficial practices to increase carbon sequestration in croplands; and
- Develop critical research priorities to respond to these knowledge gaps.

In the meantime, warming temperatures and climatic extremes could compromise the ability of soil to absorb carbon (Smith and Dukes, 2013; Frank et al. 2015; IPCC, 2019). Ongoing global land use and land cover change processes — like urbanization, desertification, deforestation and conversion of grasslands — also alter the size and distribution of the pool of available cropland available for carbon sequestration (Foley et al. 2005). Since soils can reach SOC saturation in a matter of decades, these broader trends would compress the timeframe to identify and capitalize on carbon sequestration benefits from existing cropland soils.

Clarifications

- We limit most estimates of sequestration potential to the surface or topsoil, at a depth of 0–30 cm. Topsoil SOC changes more rapidly upon a change in land use, and thus the largest portion of potential new SOC is expected to accrue within surface soils.
- Where annual accrual rates are converted into cumulative total sequestration, we will assume constant rates up to 20 years, with negligible change after that point. This is a simplification of SOC saturation, where a change in management can generate an increase in SOC that then reaches a new equilibrium.
- For soil carbon sequestration to serve as an effective climate mitigation solution, it is essential to consider net greenhouse gas (GHG) fluxes. The overall GHG impact related to soil carbon sequestration is the CO_2 equivalent (CO_2e) of changes in soil carbon net of changes in other GHGs, with nitrous oxide (N_2O) of significant consideration. Because it removes climate pollutants from the atmosphere, this type of mitigation is different from others that focus on reducing existing emissions.
- Much of the discussion and the implications in this review are global although many examples come from North America and other temperate croplands due to the volume of research available.
- Many studies discussing agricultural soil carbon sequestration also consider land-use change (cropland to pasture or natural vegetation) or prevented land-use change (cropland from other cover, most often perennial). While these certainly have mitigation potential, the focus on cropland remaining cropland acknowledges the dual goal of mitigating climate change while also maintaining or increasing production to feed a growing population.

Estimates of carbon sequestration potential in cropland soils

Even before considering how other GHGs might affect the net GHG impact of practice changes, estimates of the global biophysical potential for soil carbon sequestration in cropland and other land uses vary dramatically (see Table 1) and are associated with a large degree of uncertainty even within studies (Minasny et al. 2017; Sanderman et al. 2017; Bossio et al. 2020). These estimates most often take current technology into account, and thus would more precisely be called technical potential. In the short term, however, the two categories (biophysical and technical) are very close, so could be considered mostly interchangeable for the remainder of this discussion.

TABLE 1.

Scientific estimates of global soil carbon sequestration potential for land that includes cropland. Items are listed starting with those limited to cropland surface soils, then expanding to estimates that include other land use types and other soil depths.

Reference	Practices, as reported	Timeframe, as reported	Depth	Estimates			Study Scope[a]
				As reported	Annual, Pg CO_2e/yr	Total over 20 yrs, Pg C	
Roe et al. (2021)	soil organic C in croplands	2020–2050	0–30 cm	1024 Mt CO_2/yr	1.0	5.6	CR
Roe et al. (2019)[b]	soil C sequestration in cropland	varied	surface	0.3–6.8 Gt CO_2/yr	0.3–6.8	1.6–37	CR
Griscom et al. (2017)	conservation agriculture (cropland)	in 2030	0–30 cm	413 Tg CO_2e/yr	0.4	2.3	CR
Zomer et al. (2017)	cropland soil SOC sequestration, pessimistic and optimistic scenarios	current +20 yrs	0–30 cm	0.90–1.85 Pg C/yr	3.3–6.8	18–37	CR
Paustian et al. (2019)	managed cropland and grasslands	2–3 decades	not spec'd	4–5 Gt CO_2/yr	4–5	22–27	CR, GR
Sanderman et al. (2017)	max biophysical potential cropping and grazing land	20 years	0–30 cm	8–28 Pg C	1.5–5.1	8–28	CR, GR
Sommer and Bossio (2014)	SOC sequestration on agricultural land	in 2036	0–25 cm	0.74–1.37 Gt C/yr	2.7–5.0	15–27	CR, GR
Smith et al. (2008)	cropland management no-till, cover crops, agroforestry,	not specified	not spec'd	1.3 Gt C/yr	4.8	26	CR, SA
Lal (2004)	grazing, energy crops, woodland regeneration	not specified	not spec'd	0.4–1.2 Gt C/yr	1.5–4.4	8–24	CR, SA, GR
NASEM (2019)	ag practices to enhance soil C storage	20-40 yrs	0–30 cm	3 Gt CO_2e/yr	3.0	16	CR, SA, GR, AG

[a] Scope of practices and systems included in the reported numbers: AC (avoided conversion), CR (cropland), SA (set-aside from cropland), GR (grassland or pasture), FS (forest soils), B30 (below 30 cm depth), UN (unconventional technologies), AG (above-ground C)

[b] Note that Roe et al. (2019) is a meta-analysis that includes data from other studies also listed in this table.

TABLE 1. CONTINUED

Scientific estimates of global soil carbon sequestration potential for land that includes cropland. Items are listed starting with those limited to cropland surface soils, then expanding to estimates that include other land use types and other soil depths.

Reference	Practices, as reported	Timeframe, as reported	Depth	Estimates As reported	Estimates Annual, Pg CO_2e/yr	Estimates Total over 20 yrs, Pg C	Study Scope[a]
Soussana et al. (2019)	aspirational, all land-use types	30 years	0–30 cm	2.8 Gt C/yr	10.3	56	CR, SA, GR, FS
Griscom et al. (2017)	conservation agriculture, plus biochar, agroforestry, avoided grassland conversion and improved grazing	in 2030	0–30 cm	3.0 Pg (Gt) CO_2e/yr	3.0	16	CR, AC, SA, GR, UN, AG
NASEM (2019)	agricultural practices (practically achievable PLUS frontier tech)	20-40 yrs	0–30 cm	8 Gt CO_2/yr	8.0	44	CR, SA, GR, AG, UN
Lal (2010)	afforestation, degraded soil restoration, agricultural mgmt	not specified	0–100 cm	3.8 Pg C/yr	13.9	76	CR, SA, GR, FS, B30
Soussana et al. (2019)	aspirational, all land-use types	30 years	0–40 cm	3.4 Gt C/yr	12.5	68	CR, SA, GR, FS, B30
Minasny et al. (2017)	increase SOC stocks, all soils	first 20 yrs	0–100 cm	2–3 Gt C/yr	7.3–11.1	40–60	CR, SA, GR, FS, B30
Fuss et al. (2018)	crop and grassland mgmt change	for 2050	not specified	2.28–5.34 Gt CO_2e/yr	2.3–5.3	12–29	CR, AC, SA, GR

Proposed annual estimates for global cropland SOC sequestration (see Table 1) range from 0.25 to 6.78 petagrams (Pg) CO_2 per year (IPCC, 2019; Roe et al. 2019), with the highest values greater than the total annual GHG emissions of the United States, which were 5.8 Pg CO_2 in 2019 (EPA, 2021).[3] Potential for SOC sequestration in grazing lands is somewhat lower overall, estimated at 0.15–2.56 Pg CO_2 per year (IPCC, 2019). Some research suggests that, over time, cropland soil has the capacity to recover some (or even most) of the average 7.1% of the historical SOC stocks lost as a result of agricultural activity over millennia (Mayer et al. 2018). Cropland topsoil (0–30 cm) lost an estimated 5.6 Pg C over the past 12,000 years (Sanderman et al. 2017). This provides a useful benchmark for physically achievable carbon sequestration in soils.

Other approaches use experimental or modeled values for different practices and then multiply by total cropland area and a chosen timeframe. The published values of maximum GHG mitigation potential from SOC in global cropland soils over 20 years vary by more than an order of magnitude from 2 (Griscom et al. 2017) to 37 (Zomer et al. 2017) Pg C in the top 30 cm of soils. In addition to land area and timing, this range reflects scientific uncertainty and a lack of consensus concerning the effectiveness of different practices to sequester carbon in croplands and demonstrably mitigate climate change (VandenBygaart, 2016; Schlesinger and Amundson, 2019; Bradford et al. 2019). The bottom-up estimates of Zomer et al. (2017) are three to seven times the estimated cropland SOC loss in Sanderman et al. (2017). In contrast, Griscom et al. (2017) include a more limited number of practices and applicable cropland area, ending up with a much lower estimate. Other studies with higher overall values for SOC sequestration bundle forest and grassland soils along with agriculture (Lal, 2010; Minasny et al. 2017; Soussana et al. 2019), while still other estimates aggregate set-aside or restored area with cropland management (Smith et al. 2008; Griscom et al. 2017).

Biophysical potential for annual increases in cropland soil carbon can vary across space and time and is influenced by factors such as current and past land management approaches, local resource availability, soil type and soil microbial communities, and other environmental factors (Lal, 2013). The range of values in these estimates also depends on the methods used to determine the areal values (e.g., tonnes of C per ha per year). For more details, see the Biophysical report. Extrapolation of those values over space and time requires knowing the amount of relevant land area for SOC management and then the anticipated adoption rates after a policy or other incentive.

Most scaled-up estimates of cropland carbon sequestration potential assume that a given practice change (e.g., implementing cover cropping) will not only be fully implemented over the entire available land area, but also that such implementation will take place immediately (i.e., in year zero or year one) and will be sustained. These assumptions associated with available land area and timing of sequestration are simplistic and result in inflated estimates of the mitigation potential of carbon sequestration in croplands, as we discuss below.

Available land area

Total GHG mitigation from a practice or a system of practices is often calculated by multiplying the areal impact by the total area available for that practice (Griscom et al. 2017; Roe et al. 2019). Existing estimates tend to use coarsely defined cropland areas available for conservation practices and are also limited in their consideration of the socioeconomic dimensions of land-use decisions. Additionally, some practices can be combined to achieve the best possible outcome; others may be mutually exclusive. It is often challenging for modelers to prioritize different pathways or practices while avoiding double-counting of the underlying land base for individual practices or combinations. For example, reforestation or riparian buffers cannot take place on the same field location as cover crop adoption, but the mitigation potential calculated for each of these separately might have considered some of the same cropland area.

Estimates of cropland carbon sequestration to date incorporate both differences in potential across regions and in baseline management. Climatic constraints on primary productivity (e.g., shorter growing seasons or lack of water limiting suitability of winter cover crops or other cropping intensification) mean that not all cropland is suitable for all management improvements. Differences in baseline management and SOC will mean that some fields or regions will have less potential for carbon sequestration than others (e.g., well-managed grasslands will be able to sequester less than degraded grasslands; regions with high rates of no-till adoption will have less potential than those that have not yet adopted that practice). Some estimation efforts have worked to

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[3] Note that 1 Petagram (Pg) is equal to 1 Gigatonne (Gt). Both units are common in the scientific literature, but this report will use Pg, the SI units.

incorporate this variation: Roe et al. (2021) constrained the area available for no-till and for cover crops by removing certain regions from consideration, incorporating current adoption rates of these practices, and including only degraded grassland for new storage opportunity. Such differences result in a mosaic of carbon sequestration potential as displayed, for example, in the publicly available Soils Revealed tool.[4]

Timing: Non-permanence and sink saturation

In reality, the processes that capture soil carbon may not function fully or consistently until a few years after starting to grow cover crops or changing tillage or other crop management, since soil properties change gradually. In addition, growers may realize better success in a new activity after some practice and experience, as they tailor practices to their farming system and region. As a result, it may take time for carbon sequestration rates to reach the anticipated levels (e.g., McLauchlan et al. 2006). Related to this learning process and to risk management, many farmers will try out a new practice on limited field area while assessing how to fit it into their whole operation. Then it takes a number of years before the practice — if successful — becomes standard for most or all applicable fields. Thus, even though a large proportion of farmers may use a certain conservation practice, it is most likely implemented on a smaller total area than the sum of all those operations and implementation intensity can vary. In addition, farmers may determine that a practice is only suitable for fields of given characteristics, further restricting the total area.

Another source of uncertainty for the biophysical and technical potentials concerns how long the carbon sequestration rates (per year) can be sustained, as the rates of gain tend to level off as soils become saturated (see, for example, West and Six, 2007). Some assessments assume sequestration rates remain constant for the first 20 years after practice change and are minimal after that (Minasny et al. 2017; Sanderman et al. 2017; Zomer et al. 2017); others suggest increases can occur for 30 years or more (Poulton et al. 2018; National Academies of Sciences, Engineering, and Medicine, 2019; Soussana et al. 2019).

Practices impacting carbon sequestration in cropland soils

Practices such as reduced tillage, cover crops, crop diversity and enhanced crop rotations, agroforestry, integrated disease and pest management, and precision agriculture technologies to tailor input use could increase carbon sequestration in cropland soils (Stockmann et al. 2013; Schulte et al. 2014; Poeplau and Don, 2015; Agus et al. 2015). It is increasingly understood, however, the adoption of, and carbon sequestration benefits from, these practices are highly context-specific. Thus, the suitability of practices needs to be evaluated regionally and with consideration of existing land uses and management practices. Moreover, a suite of practices, rather than a single practice, could be more successful in delivering optimal carbon sequestration outcomes in croplands.

Conservation agriculture involves minimal topsoil disturbance with no tillage or minimum tillage, and together with crop rotations or use of mulch that keep a near-permanent or permanent soil cover (Hobbs et al. 2008). Evidence for long-term carbon sequestration benefits from conservation agriculture is mixed. Some studies like Powlson et al. (2016) report promising outcomes, while others (e.g., Palm et al. 2014) are more circumspect. With respect to individual practices, a pair of recent systematic reviews (Haddaway et al. 2017; Meurer et al. 2018) report positive carbon sequestration benefits mainly in the topsoil from modifying tilling practices, which disappear when deeper soil layers are included. These studies caution against overly optimistic earlier assessments of no-till for climate change mitigation.[5] There is more agreement concerning the adoption of cover crops to help sequester carbon in cropland soils (Mazzoncini et al. 2011; Eagle and Olander, 2012; Poeplau and Don, 2015). However, SOC sequestration with cover crops is not guaranteed, and is mainly observed in where the soil starts off with low C levels and with sufficient cover crop biomass (Blanco-Canqui, 2022). Rotations that integrate crop varieties with deeper roots (e.g., short-rotation woody crops) or agroforestry (e.g., alley cropping) can also provide carbon sequestration benefits (Nair et al. 2009; Schoeneberger, 2009; Schoeneberger et al. 2012; Fargione et al. 2018).

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[4] https://soilsrevealed.org/

[5] Reduced or no-tillage has clear value for soil conservation (erosion control) in many cropping systems, and evidence suggests that it is more likely to reduce SOC losses than to store new carbon (Nicoloso and Rice, 2021). In addition, while no-till tends to cause SOC losses at depth, these can be mitigated with long-term no-till (Cai et al. 2022).

An important consideration is the relationship between practices that influence SOC in croplands and their impact on N_2O emissions (Paustian et al. 2016). Winter cover crops can reduce N_2O emissions (Tonitto et al. 2006; Kaye and Quemada, 2017), especially if nitrogen (N) application rates are adjusted downward to account for avoided N losses and legume-fixed N. Other practices, like reduced tillage, can increase N_2O emissions to the point of counteracting or even negating carbon sequestered (Li et al. 2005). Maximizing net GHG mitigation with these practices may be best combined with precision agriculture technologies to improve N use efficiency (Zhang et al. 2015).

Soils depleted of SOC have lower productivity and low use-efficiency of added inputs. As a result, these soils may sequester less carbon on an annual basis (Lal, 2011), but they may have larger capacity for storage in the long run. Practices targeted towards carbon sequestration in croplands can also improve soil productivity (Oldfield et al. 2019), drought resilience (Oldfield et al. 2019; Kane et al. 2021) and deliver numerous other co-benefits (Griscom et al. 2017).

What is realizable? Considering socioeconomic factors

The realizable potential for soil carbon sequestration is expected to be smaller than the biophysical potential, based on what is technically, economically and socioeconomically achievable (Figure 1). Smith et al. (2008) concluded that realistic potential is only about half of biophysical-technical potential, although they noted that previous studies had estimated price and non-price barriers limited implementation to only 30% of the biophysical potential for agricultural GHG mitigation. Thus, there is uncertainty as to the relative reduction in potential from these different levels of constraint — or even how some may include enabling conditions. Cumulative uncertainty around the “realizable potential” estimates might be increasing as we move from one layer/slice to the next. However, it is also possible that as uncertainty is resolved in the upper layers (e.g., we have high consensus on the biophysical potential), this knowledge would permeate and reduce downstream uncertainty.

Different physical, economic and social factors constrain the potential for carbon sequestration to mitigate climate change at various scales (see Table 2). Sykes et al. (2020) categorize these as private barriers and incentives (financial as well as non-financial) and as externalized impacts (both environmental and socio-economic). So far, few, if any, of these factors have been used to refine the carbon sequestration potential from cropland soils, as efforts to date have generally focused on qualifying the biophysical potential in terms of purely technical and economic constraints, as discussed above.

TABLE 2.
Select socioeconomic factors known or expected to constrain soil C sequestration potential estimates across different scales of influence and intervention, with examples from the literature.

Constraint	Level of influence or scale	Description / Examples
New practices may require capital investments (e.g., equipment) with uncertain outcomes	Farm	Arbuckle and Ferrell (2012) found that 40% of Iowa farmers lacked the equipment necessary for cover cropping. More diverse rotations may also require different equipment (planters, storage) for small grains (Carlisle, 2016).
Lack of experience with new or different practices imposes hurdles	Farm to regional	Arbuckle and Roesch-McNally (2015) found increased cover crop adoption rates when neighbors or other facilitators demonstrated practices.
Market demand for main commodities drives management choices	Farm to global	Demand for small grains and forage crops associated with diverse cropping systems and cover cropping lag demand for global commodities like corn and soy.
Farm finance oriented toward near-term profit; lenders may not encourage soil health practices	Regional to national	Lacking information about long-term benefits of conservation practices and discouraged by perceived short-term risks to farm revenues from transitioning to such practices, private lenders may be reluctant to provide financing or accommodations in loan terms for conservation practices (Monast, 2020).
Outreach and adoption take time	Regional to global	Sommer and Bossio (2014) assumed adoption on 5% of arable land in year 1, increasing to 60% after 20 years.
Government programs encourage business-as-usual	National	In the United States, crop insurance programs are oriented to main commodity crops, with 80% of claims paid to corn, soybeans, wheat and cotton from 2000-2016 (Rosa, 2018). Yield records and planting timeframe requirements for taking part in such programs may hamper farmer adaptation efforts.
Scale of the change necessary to impact SOC	Global	Would need to change practices over 570 M farms (Lowder et al. 2016) and almost 5 billion ha (cropland plus rangeland) to realize the estimated benefits.

Efforts to qualify the biophysical mitigation potential with economic constraints have used practice-specific cost curves and expert opinion to estimate the proportion of the total that could be feasible under carbon-market (or other pricing and incentive) mechanisms. For example, using a series of marginal cost curves to characterize the anticipated costs of different practice changes, Smith et al. (2008) estimated economic potential of all agricultural GHG mitigation practices to be between 28% and 73% of the technical potential depending on the expected payment price per unit of CO_2e (see Table 3). This range is somewhat higher than that estimated by Griscom et al. (2017) for all agricultural and grassland activities at similar price ranges. However, the subset of cropland practices is among the least costly (compared to restoring cultivated organic soils, agroforestry, and livestock or manure management), leading to a lower expected economic hurdle (Griscom et al. 2017; Roe et al. 2021).

TABLE 3.

Examples of maximum biophysical GHG mitigation potential estimates for global agriculture, refined to account for different economic constraints (carbon market prices).

Reference	Activity(ies)	Biophysical, Tg CO_2e/yr	Constraint	Constrained, Tg CO_2e/yr	% of original
Roe et al. (2021)	Cropland soil carbon	1487	<\$100 t CO_2e	922	90%
Griscom et al. (2017)	All agriculture and grasslands activities	4817	<\$10 t CO_2e	1095	23%
		4817	<\$100 t CO_2e	2456	51%
Griscom et al. (2017)	Conservation agriculture	413	<\$10 t CO_2e	248	60%
		413	<\$100 t CO_2e	372	90%
Smith et al. (2008)	All agricultural GHG mitigation activities	5480–5950	<\$20 t CO_2e	1540–1640	28%
		5480–5950	<\$50 t CO_2e	2530–2690	46%
		5480–5950	<\$100 t CO_2e	4030–4340	73%

While these marginal cost curves assess opportunity costs for land use and the relevant activities, they may underestimate the full range of, or the heterogeneity in, economic costs associated with adopting some beneficial practices (e.g., access to finance and training). Some practices may require continued support (financial or otherwise), while others may only require support during the initial stages of the transition or until the farmer has experienced sufficient benefit from the practice. As overall adoption rates for improved practices increase, it also remains unclear how much continued support farmers will need to maintain the practices.

Moreover, economic constraints might need to reflect possible barriers to obtaining insurance and financing, as well as market access and input availability, as applicable to the new practices. In addition, non-economic social and political constraints can slow or prevent adoption.[6] These systemic barriers are likely better addressed

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[6] Note that certain systemic social and political factors may also serve to encourage adoption, but here we focus on barriers since they are more common (and more likely in need of intervention).

by directing resources or efforts to a community or social network or to regulatory structures, rather than to individuals. Further, while studies may attempt to quantify the costs associated with changing management practices, they often fail to account for the time it may take to fully transition to an improved practice, especially at a large scale.

Researchers use economic research surveys, revealed preference studies and other methods to estimate farmers' willingness to accept a given practice change (i.e., how much farmers say they would need to be paid) and — preferably — to retrieve true adoption rates. Such measures attempt to bring all social, fiscal, labor and other barriers into a common economic framework (e.g., Nyongesa et al. 2016) since the actual costs are difficult to quantify. On-the-ground experience and studies using bio-economic models find lower farmer adoption rates than would be expected at an economic optimum signifying that information barriers, risk preferences and market imperfections can have serious limiting influence (Berazneva et al. 2019).

The full breadth of forces that affect current practices and the potential for change will vary by cropping system and region and can be complex. Regardless, some data do exist that can be used to assess trends and patterns, evaluating the impact of individual- and societal-level factors on adoption (see Table A-1). These factors include farmer demographics (e.g., education, gender, age), farmer objectives (e.g., cash crop versus subsistence), traditions and values, risk perception, land tenure and other farm characteristics, as well as centralized investment in research, technology and infrastructure (Kuehne et al. 2017; Godde et al. 2018).

Even though change on the ground must take place in individual fields and on individual farms, which are managed by many individual producers, the choices available to individuals can be constrained and influenced by an overarching system. Such constraints might manifest themselves as farmers having access to a limited set of inputs (e.g., only GMO seeds), only a single bank or insurance company to work with, or only one place to sell (or store) their crop.

Studies often fail to acknowledge or incorporate such a systems viewpoint, which would better capture the broader social-ecological context of conservation behavior (Yoder et al. 2019). Indeed, the existing literature, which has generally focused on explaining conservation practice adoption through individual factors, finds that none of these individual-level factors are powerful or consistent predictors (Prokopy et al. 2019).

Access to inputs and markets

Even with sufficient capital and insurance, the success of new practices depends on reliable and available equipment, seeds and technical support, as well as markets for any new products. Consolidation along the agricultural value chain from the farm to the consumer reduces opportunities for diversification and flexibility for all market participants. For example, regional specialization across the globe for grains — and indeed also for fruit and vegetable production — affect market access and farmers' relationships with land and local communities (Hendrickson et al. 2020). Labor availability, with shortages highlighted during the COVID-19 pandemic, also affects rates of practice change, especially if improved practices alter timing of labor inputs (seeding, harvest, etc.) or require additional planning and management.

Technological change

Advances in field monitoring technology and equipment may facilitate and encourage changes to management practices, as long as these advances are affordable or provide benefits for the farmer to justify the cost (e.g., Michler et al. 2019). For example, the use of a smartphone can increase the ability of a producer to use on-farm data to customize nutrient management, irrigation and pest control on a sub-field basis, while also being of low cost to the producer (Gallardo et al. 2020). However, because specialized equipment facilitates and might be needed for the adoption of certain conservation practices, it can be prohibitively expensive for many farmers. Consequently, equipment can be a significant barrier to adopting some conservation practices, particularly cover cropping, in the United States (Carlisle, 2016). Achieving more widespread adoption of conservation practices will likely require increased access to financing for specialized equipment necessary for their implementation.

Land tenure

Farmland that is owner-occupied and farmed could look quite different from land leased from an absentee landlord for short-term crop production. International investors have been increasingly purchasing agricultural land in Africa, Asia and Latin America (Tscharntke et al. 2012), largely for the promise of return on investment, but also perhaps with an eye toward sustainability.[7] Between 2001 and 2012, over 200 million ha in 60 countries had been purchased or leased by numerous companies and governments.[8] The impact of this trend on actual conservation activity and cropland SOC will likely vary by jurisdiction and the nature of operator-landlord relationships.

On average, 46% of U.S. cropland is owner-operated, a proportion that has remained relatively constant for the last 50 years despite land ownership turnover (Bigelow et al. 2016).[9] This means that more than half of the cropland is rented, with about 80% of the land rented from non-operator landlords (see Figure 2). Farm operations that focus on cash grains (e.g., corn, soybeans), peanuts and cotton tend to have a greater proportion of rented land area than those with livestock, fruit or diversified non-grain crops (Bigelow et al. 2016). In Illinois, for example, more than 80% of the cash-grain producing cropland area is rented (Schnitkey et al. 2021b). As of 2014, the majority of rented cropland acres (81%) in the U.S. have been leased or rented to the same farmer for at least three years, while a smaller proportion (38%) have stayed with the same farmer for over 10 years.[10] However, even with high renewal rates, this seeming stability may be undermined by the reality that 70% of leases are single-year contracts (Petrzelka et al. 2020; Masuda et al. 2021). In the U.S., non-operator landlords (absentee landowners who do not actively participate in any farming operation) seem to be associated with greater adoption of conservation tillage between 2012 and 2017 but also lower cover crop incidence (Bawa and Callahan, 2021). For tillage, this may be related to the fact that farmers who invest in equipment for conservation tillage or no-till tend to operate larger farms, including rented land that is used to

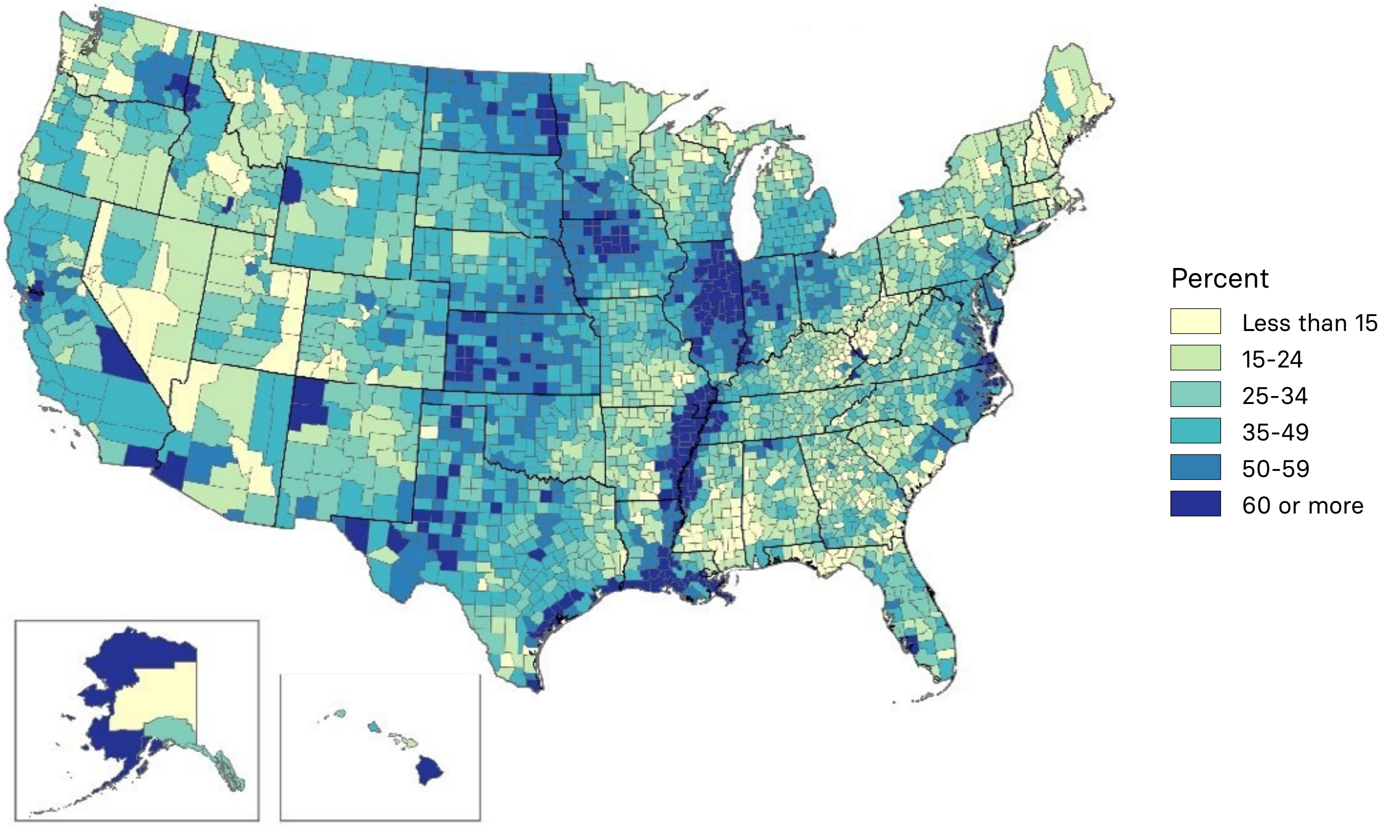

FIGURE 2.
Percent of farmland area rented or leased in the United States, by county, 2017. Figure from Petrzelka et al. (2020), American Farmland Trust report on non-operator landowners. Data source: USDA NASS Agricultural Census, 2017.

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[7] worth.com/farmland-investing-impact-beyond-returns/

[8] viacampesina.org/en/wp-content/uploads/sites/2/2012/05/mali-report-2012-en1.pdf

[9] Schnitkey et al. (2021b) attributed constancy in proportion of rental farmland to very slow ownership turnover.

[10] Author calculations based on data from Bigelow et al. (2016): 70%/84% operator/non-operator landlord acres with same tenant for 3+ yrs; 28%/41% operator/non-operator landlord acres for 10+ yrs.

expand their operations. Cover crops, having greater initial investment and risk may be less attractive to renters who have less certainty of farming that same land over the long-term.

The high proportion of rental cropland in the U.S., especially that in annual crops, has implications for conservation practices that have up-front costs with longer-term benefits. As for the well-known cases of housing and automobiles, renters have less incentive than owners to invest in the property (Schnitkey et al. 2021a). Farmers in Ontario and Manitoba reported that they were more likely to invest in management with longer-term soil health and carbon sequestration benefits on cropland that they owned rather than rented (Nadella, 2013; Deaton et al. 2018). Owned land was more likely to receive manure applications (53% versus 31%) and to be planted to cover crops (26% versus 15%), although conservation tillage practice did not differ by land tenure. These patterns suggest that for farmers operating on both owned and rented land, the equipment costs are more "fixed" and investments like cover crops are easier to adjust on a field-by-field basis. These more flexible conservation practices could also be more likely under longer-term landowner-renter relationships or when the landlord has a farming background.

Even when interested in and motivated by opportunities to implement practices that improve soil health and SOC, rental land operators can face additional obstacles, regardless of whether government or private incentive programs are available. These include the difficulty if multiple landlords need to separately approve or otherwise participate in the process and uncertainty about production outcomes (i.e., income) when faced with set rental and other operational costs (Masuda et al. 2021). Increasing trends in cash rent over time in Illinois — as opposed to share rent — mean that the operators rather than landlords bear a greater proportion of the costs for cover crops and similar up-front investments (Schnitkey et al. 2021a).

Farm and farmer characteristics

Decisions about cropland management with SOC implications are also affected by the type of farm and crops produced and by individual characteristics of the farmers themselves. Farmers raising cash crops (e.g., commodities or market vegetables) will have different pressures and goals than those mainly producing food for their families. Gender, age, values and traditions may affect resources available and farmer objectives (Druschke and Secchi, 2014) with implications for conservation and practice change.

Type of crop and cropping system. The needs and objectives of farmers growing cash crops are different than those of subsistence farmers. Near-term needs of small-scale farmers in Africa, India and other regions of the world may hamper efforts for long-term investments. For example, if crop residue provides significant livestock forage, keeping these materials on the land in order to build soil carbon may not be an option (Sykes et al. 2020).

Farm size. Globally, a large proportion of the world's more than 608 million individual farms (Lowder et al. 2021) may need to change agricultural practices to achieve sufficient carbon sequestration to influence net GHG mitigation. This means changes to agricultural systems in nearly every country, and to smallholder farms that are key to food security in developing countries (see Figure 3). On the other hand, most farmers have very small land holdings — over 80% of farmers across the globe cultivate crops on less than 2 ha of land (Tscharntke et al. 2012; Lowder et al. 2021), but the top 1% of farms operate 70% of the farmland worldwide (Lowder et al. 2021). The corollary is that it may be possible to achieve significant results while focusing on the largest farms, or on smallholder farms concentrated in one country or region.[11]

Farmer demographics. Gender, age and education level affect rates of agricultural conservation and technology adoption across the globe. According to the FAO, fewer women than men have either ownership or secure tenure rights over agricultural land, especially in the developing world.[12] In some cases, this is because of a lack of legal frameworks that guarantee equal rights to women in land ownership or control over land. In addition, women and minority or low-caste farmers face educational obstacles as well as disparities in obtaining credit, accessing markets, and receiving extension advice and other information (Tanellari et al. 2014). On the other hand, researchers in industrialized countries (e.g., Europe, Australia and North America) regularly report that gender and age do not affect adoption of precision farming (Paustian and Theuvsen, 2017) or expressed interest in payments for ecosystem services (Page and Bellotti, 2015).

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[11] For example, China alone has an estimated 209 million individual farms (Lowder et al. 2021) operating 11% of total world agricultural area (525 million hectares).

[12] fao.org/sustainable-development-goals/indicators/5a1/en/; fao.org/sustainable-development-goals/indicators/5a2/en

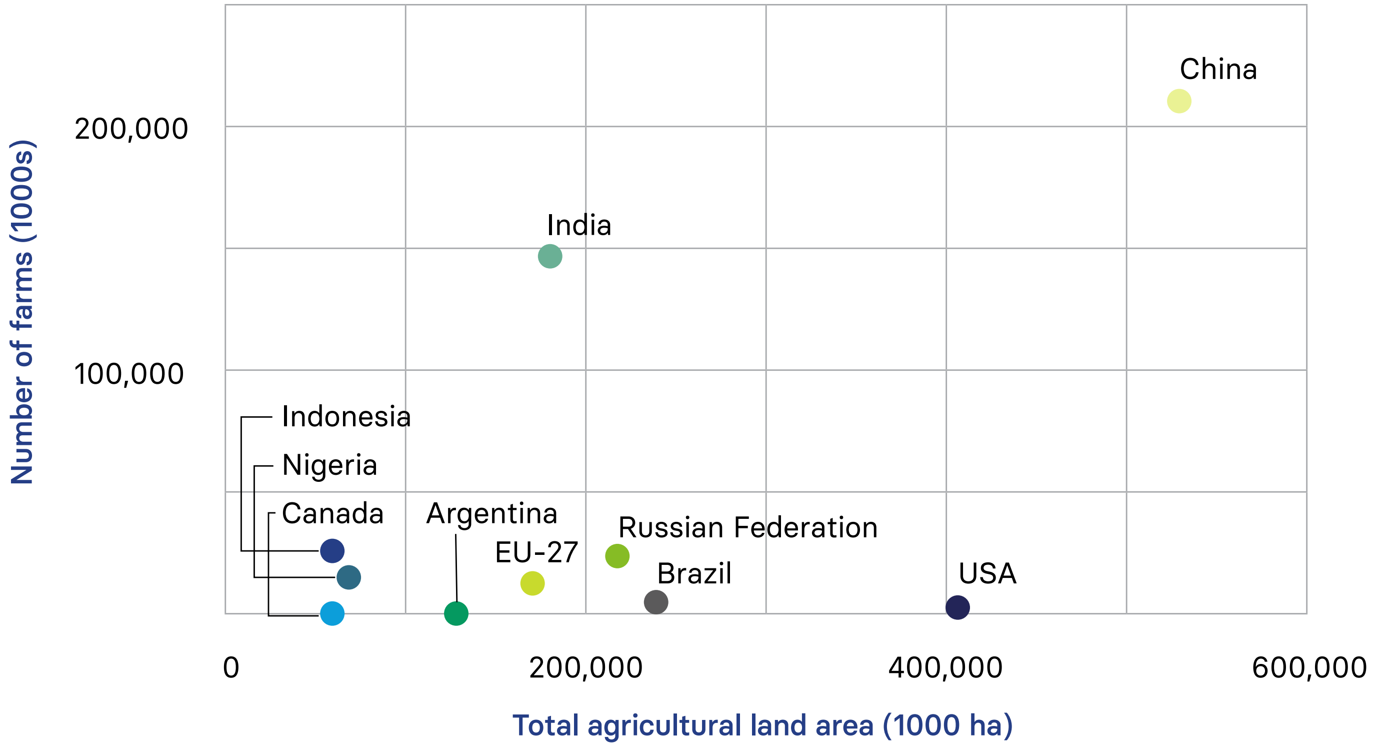

FIGURE 3.
Number of farms and total agricultural land area (cropland plus pasture) for the top 10 countries with the largest cropland area. Sources and notes: Number of farms data from Lowder et al. (2021). Here we use data for a subset of countries (N=148) that reported farm size data in censuses conducted on or after year 2000. Total agricultural land area data is from FAOStat. We use agricultural land area rather than cropland area since Lowder et al. (2021) does not provide a breakdown of farms operating on croplands versus others, and in their analysis, they too relate number of farms data to agricultural land area. Given the single market system and common agricultural policy of the EU-27, we sum the cropland area for the 27 EU countries and represent them as a single country/jurisdiction.

Practice characteristics

The type and costs of management change can also influence initial adoption and the persistence of that change. To date, research on adoption of conservation practices has focused more on the characteristics of the farmers and the farming context and has overlooked the role practice characteristics might play in successful adoption (Pannell and Zilberman, 2020). These practice characteristics can be categorized in terms of the timing and level of economic costs and benefits associated with a practice; its environmental advantage; its potential for risk reduction (including yields); its convenience or similarity to existing practices being used; its ease of adoption; its "trialability" and complexity; and the observability of the practice change by other potential adopters (de Oca Munguia and Llewellyn, 2020).

Practices that require regular investment (like seed purchase for cover crops) or additional time and labor may be more susceptible to reversals than those with a one time or less frequent investment (such as buying a no-till seeder). On the other hand, an easily divisible investment (e.g., seed for each field could be purchased separately) allows for experimentation on a smaller part of the farm (Carlisle, 2016). Thus, while a single large investment (like a seeder) makes it more likely for a whole farm to shift practices at once, the ability to trial at low-risk may lead to more adoption of unfamiliar practices in the long-run. These factors then interact with land tenure as well, so that easily divisible practices requiring regular investment are less common on rented land with short lease periods (Deaton et al. 2018).

Perceived risk of new practices may also influence adoption rates for farmers that anticipate lower crop yields or crop quality issues. Unknown practices, especially ones that could risk short-term profit, may also be less likely to receive approval banks that provide operating capital to farmers.

Social norms and farmer experience

The community within which a farmer operates also has a potentially significant impact on rates of new conservation adoption. Certain individuals are keystones in their community and have an outsized influence on others in their community. Social pressure to maintain tidy crop fields or stay within traditional production practices can deter a farmer from experimenting with a new practice. On the other hand, collective approaches — where farmers work with their neighbors to address local pollution or water availability problems — can provide social incentives for change beyond financial payments (Yoder, 2019). Untested and new practices are also more likely to be adopted as they gain visibility (Arbuckle and Roesch-McNally, 2015). This relationship may explain what has been observed with cover crops in the U.S., which, while not new, are used on a relatively small portion of cropland, and promotion efforts from government and others have recently increased. The rate of cover crop adoption in 2017 was positively correlated to the percent of corn and soy cropland in cover crops between 2012 and 2017 (Wallander et al. 2021).

Conservation practices may also work well together. Once farmers have a positive experience with one conservation practice, they may be more inclined to adopt additional conservation practices. Evidence from USDA ARMS data suggests that cover crops are more likely to be adopted in fields also using no-till, at least for certain crops. For example, in the U.S. cover crops were used more than twice as frequently (8% versus 3%) in no-till and strip-till corn fields than in conventionally tilled ones in 2016, and were used more than four times as frequently (27% versus 6%) for the same tillage comparison in cotton farming in 2015 (Claassen et al. 2018).

Government policies and programs

It is important to consider whether and how policy design, program eligibility and associated incentives (and their levels) affect adoption of practices and their abandonment.

In the United States, federal and state government programs over the past years have directed significant resources to encourage conservation practices in field crop and other agriculture.

Extension outreach, increasing focus among commodity groups, and growing interest in carbon markets have also increased interest in practice adoption. Two of the U.S. Department of Agriculture's (USDA) largest conservation programs are Environmental Quality Incentives Program (EQIP) and the Conservation Technical Assistance Program (CTA). Total payments for cover crops under EQIP increased by about 20 times between 2005 and 2018, with $155 million allocated in 2018 and annual payments of up to $90 per acre across a variety of federal and state programs (Wallander et al. 2021). The cost per acre of the support provided under the CTA program range from about $30/acre in 2010 to over $50/acre in 2021.[13] There is evidence of increased adoption of cover crops connected with this incentivization, but in all, less than 5% of cropland in the U.S. Corn Belt had winter cover crops in 2017 (Wallander et al. 2021), and Biardeu et al. (2016) report a similarly low proportion of croplands receiving funds to implement soil health practices under EQIP and CTA.

In a recent study focusing on the EU, Kathage et al. (2022) report policy to be the "by far strongest" determinant of cover crop adoption and the key lever to increase it, well ahead of any agronomic benefits the practice might provide and unrelated to any environmental considerations of farmers.[14]

Practices taken up solely due to incentive payments might be abandoned once those payments cease. For example, funding under government cost-share programs generally decline and eventually stop after a certain number of years. This assumes adoption costs decline with experience, at which point farmers can finance these practices without support, though this may not always be the case (Sawadgo and Plastina, 2022).

There is also evidence, however, that suggests farmers adopt practices in the absence of incentives or maintain them after discontinuation of incentives. For example, only about one-third of all U.S. croplands planted with a cover crop in 2018 received financial assistance (Wallander et al. 2021). In the case of reduced tillage and no-till adoption across much of North America and beyond, we see that farmers can start and maintain conservation practices in the absence of payments. In some cases, however, existing government policies and programs

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[13] Source: authors' calculation using data from nrcs.usda.gov/resources/data-and-reports/rca-data-viewer

[14] Policies in the EU that have shaped cover crop adoption include the Nitrates Directive and greening requirements under the Common Agricultural Policy.

might become barriers to conservation practice adoption. The crop insurance program in the United States is one example. This program represents the largest proportion of U.S. government assistance to agriculture comes in the form of business risk management programs, primarily crop insurance (in the form of subsidized premiums). This type of government support to agriculture is also significant in some other countries (e.g., Canada, European Union), where evidence suggests that chemical and fertilizer inputs are higher than they would be in the absence of these programs (Eagle et al. 2016; Möhring et al. 2020). Crop insurance coverage in the U.S. and in Canada is focused on major commodity crops. Payment structures in these programs are based on historic yield and eligibility is contingent on defined seeding dates and other requirements (Rosa, 2018). Farmers may be hesitant to test or adopt new practices because of this inflexibility, although Fleckenstein et al. (2020) tested these ideas with a farmer survey and interviews and concluded that crop insurance requirements are not a barrier to cover crop adoption in the U.S. Midwest. In addition, the availability of external risk management may reduce the incentive to "self-insure" with long-term conservation practices (Hatfield et al. 2018; Luken, 2020; Connor et al.).

Extent and rate of adoption

Unless a farm or field is already at a saturation point for soil carbon, creating an environmental benefit will require a certain amount of change, or adoption of a new activity. Researchers and extension advisors have worked for decades with farmers around the world to encourage adoption of improved management practices, with both productivity and environmental goals. The relevant adoption and abandonment rates can serve as proxies for adoption of practices for carbon sequestration in croplands. Intervention design can then incorporate the key factors that affect both adoption and reversal.

Practice change does not happen instantaneously, and in fact it can take many years to reach all (or even most) farmers and the land area that they manage (Kuehne et al. 2017). Social factors such as community values, tradition and education all play a role in adoption rates. For example, Sommer and Bossio (2014) assume that pasture areas will be more difficult to reach for implementing carbon sequestration schemes across the globe, suggesting that about 60% of arable land and 40% of pasture might see practice change after 20 years of outreach effort. Based on this factor alone, the range of carbon sequestration potential would decrease from 0.3–6.8 Pg CO_2e/yr (Roe et al. 2019; Table 1) to 0.2–4.1 Pg CO_2e/yr.

Social and economic factors that influence adoption of practices that can sequester carbon in croplands are generally exemplified by studies on cover crop adoption in North America or, more broadly, on conservation agriculture adoption in the global context (Kassam et al. 2019; Sun et al. 2020). While the system of practices most likely to store new carbon will likely be more complex than simply adopting cover crops or no-till (the central practices in most conservation agriculture literature), programs and incentives encouraging these practices provide an opportunity to explore factors associated with successful long-term implementation.

Kassam et al. (2019) estimated global conservation agriculture adoption in 2015/2016 at about 180 million hectares, a 69% increase from 2008/2009 and making up 12.5% of all cropland. Their definition of conservation agriculture includes a combination of no-till or minimum till and at least 30% soil mulch cover after seeding (from cover crops or other biomass mulch cover). For some countries, these practices are already in place on a majority of their cropland area (e.g., on more than 70% of cropland in Argentina, Brazil, Paraguay and Uruguay). If this is true, the additional amount of practice change (and thus additional soil carbon sequestration) may be minimal in such regions. On the other hand, this same analysis suggests that 28% of cropland in North America is under conservation agriculture. While reduced tillage frequency is reported to be in practice on 51% of U.S. cropland (Claassen et al. 2018), only about 5% was planted to cover crops as of 2017 (Wallander et al. 2021), with lower proportions in the Corn Belt (Hagen et al. 2020; Wallander et al. 2021). Thus, while a significant portion of cropland may be managed with conservation tillage, there is still room for additional change within existing practices. The extent to which global estimates of carbon sequestration potential incorporate only the percentage of cropland without the conservation practices in place, or the percentages with partial practice adoption versus no practice adoption is unclear in the numbers in Table 1.

Climate change mitigation benefits from carbon sequestration are contingent on this incremental sequestration becoming "permanent" storage in soils. Practice abandonment (or disadoption) that re-releases the carbon sequestered via conservation practices might reduce or even eliminate any climate benefit. Moreover, SOC is lost quicker than accumulated: one tillage pass for weed control could release multiple years of carbon sequestered back into the atmosphere (Wade and Claassen, 2017). Reasons for practice abandonment can be multiple and varied. For example, reversal of conservation agriculture in Africa is related to labor demand for weeding, lack of access to external inputs, and competition for crop residues between livestock and mulch (Giller et al. 2009). These factors effectively reduce the anticipated "adoption rate" for such a region (see Figure 3 in Soussana et al. 2019). Gains in organic matter and associated soil health improvements under these practices are unlikely to be permanent or significant if producers use these practices intermittently. In an analysis of the USDA ARMS survey data, Claassen et al. (2018) report that 51% of farmers producing corn, cotton, soybean and wheat returned to full tillage from no-till or strip-till at least once every four years. As discussed above, policy design may also play a role in the abandonment of practices.

Therefore, it is important to track and uncover the factors that influence full versus partial adoption (within a given farm); the extent of adoption (number of farmers adopting in a given area); opportunistic ("as needed") adoption; and alternating versus sustained adoption, for a variety of practices (Pannell and Claassen, 2020).

Research priorities to serve a long-term vision

Quantification of the realizable carbon sequestration potential within cropland soils is a prerequisite for developing agricultural carbon markets, policy and effective funding of mitigation efforts. This involves both identifying and measuring the socio-economic factors influencing the sequestration potential and the mechanisms that modify these factors.

Climate change mitigation from croplands will only be effective if the management practices implemented have longevity. Education and extension can fill much of the gap, especially where new practices will eventually show significant return on investment and warrant ready and long- term incorporation into the agricultural system. However, some benefits from adopting practices that build soil carbon may not be immediately experienced or realized by the farmers themselves. Internalizing these externalities might require incentive schemes or other policy interventions. Carbon markets, either voluntary or regulatory, may provide a source of the necessary funds.

We identify the following as high priority research areas needed to develop robust, global estimates of the realizable potential of carbon sequestration in cropland soils:

- What are the socioeconomic factors that influence the realizable carbon sequestration potential in croplands at different scales?
- How do patterns of land tenure, market and other economic drivers, regulatory frameworks and demographics influence the net adoption of agricultural practices that affect cropland carbon sequestration?
  - Which of these factors vary by type of practice and cropping system, country and region, and which are more universal?
  - How have such factors affected the adoption of new agricultural practices more generally, including those that might not have an impact on carbon sequestration in croplands, but could have other environmental, social or productivity benefits?
  - How is the adoption of conservation practices affected by commodity markets?
- What is the proportion of global croplands that could reasonably be expected to adopt practices that increase carbon sequestration over the next 20 years?
  - What would, if any, be the yield (i.e., output) impact of such expansion?
- How is conservation practice adoption affected by differential government approaches such as regulation versus voluntary participation?
  - For example, do farmers in countries with regulations that dictate agricultural practices adopt new practices more rapidly or consistently and experience lower reversal rates?

Filling these key gaps in research and understanding will help prioritize the role of cropland soil C sequestration in climate change mitigation efforts. To that end, EDF will focus identification of the realizable potential starting with the U.S., China, India and EU. These are among the top five countries with the greatest total cropland area — and thus likely possess the most potential for cropland soil carbon sequestration (see Figure 4).

This research will allow development of broad sequestration adjustment factors and quantify the realizable potential of carbon sequestration in croplands. The frameworks developed would allow for subsequent refinement of these adjustment factors as more or better data become available for different countries or regions.

FIGURE 4.

Top 10 countries with the largest cropland areas globally. They are diverse geographically and in terms of cropping systems. Data source: FAOStat. Notes: EU-27 sums the cropland area for the 27 EU countries and represents them as a single country/jurisdiction. A crop is included as a top 5 crop if it is in the top 5 by harvested area in any of the years during 2010-2019. The percentages indicate share of harvested area by crop as a proportion of total cropland area. Due to double or multiple cropping systems, which FAO data does not adjust for, some of the area shares might be overestimates.

The top 10 countires account for 60% of world's croplands. Maize is the crop cultivated consistently across the top 10 countries.

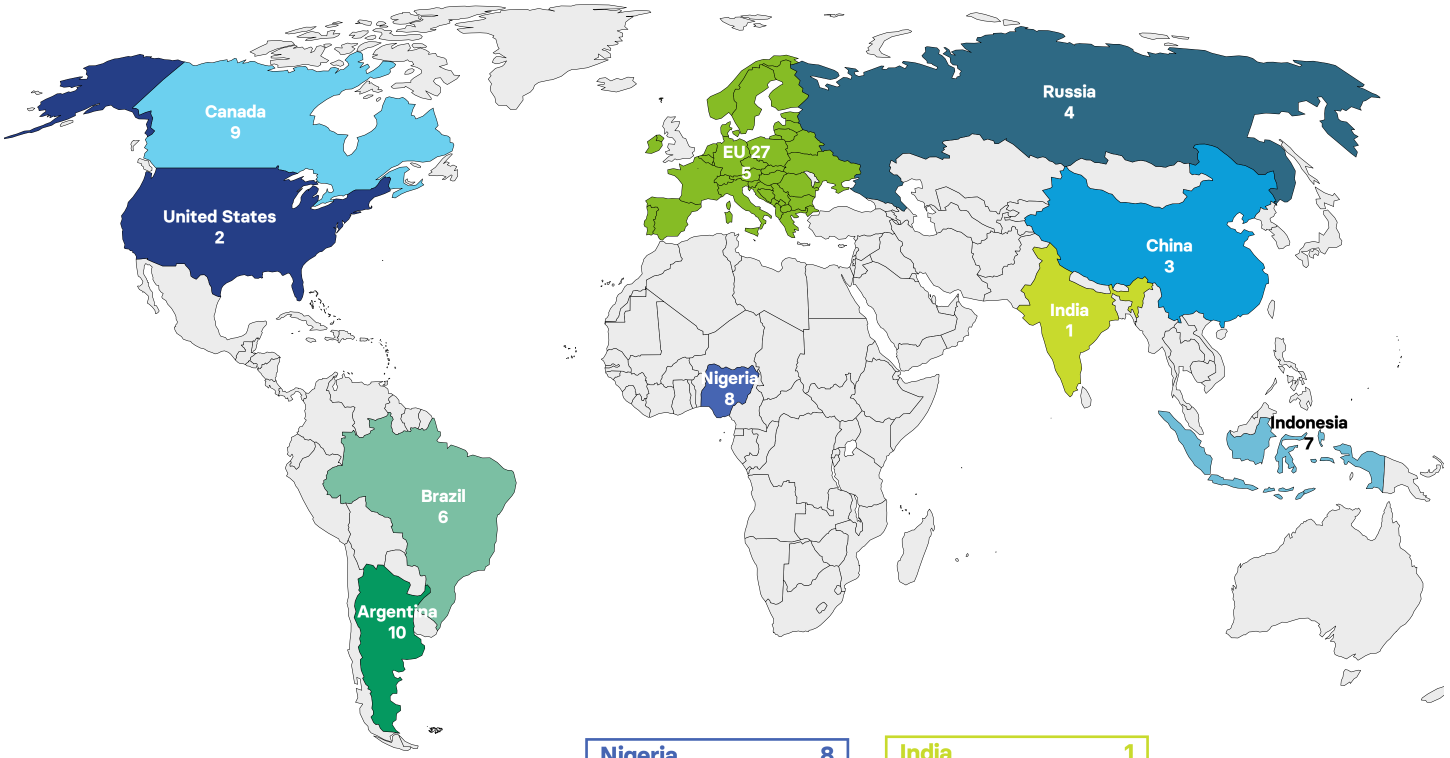
USA	**2**
Maize	21%
Soybeans	20%
Wheat	11%
Seed cotton	2%
Sorghum	1%

Canada	**9**
Wheat	24%
Rapeseed	22%
Barley	6%
Soybeans	6%
Peas, dry	4%
Lentils	5%
Maize	4%

EU 27	**5**
Wheat	22%
Barley	10%
Maize	8%
Rapeseed	5%
Olives	4%

Russia	**4**
Wheat	20%
Barley	6%
Sunflower seed	6%
Soybeans	2%
Oats	2%
Maize	2%
Potatoes	2%

China	**3**
Maize	29%
Rice, paddy	22%
Wheat	18%
Vegetables, fresh	8%
Soybeans	6%
Rapeseed	5%



Argentina	**10**
Soybeans	49%
Maize	14%
Wheat	12%
Sunflowers	4%
Sorghum	2%
Barley	3%

Brazil	**6**
Soybeans	48%
Maize	24%
Sugar cane	16%
Beans, dry	5%
Rice, paddy	4%
Wheat	4%

Nigeria	**8**
Maize	15%
Milet	11%
Cassava	15%
Sorghum	13%
Yams	14%
Rice, paddy	13%
Oil palm fruit	8%
Cow peas, dry	9%

India	**1**
Rice, paddy	26%
Wheat	18%
Seed cotton	7%
Beans, dry	7%
Soybeans	7%
Millet	7%
Maize	6%
Chick peas	6%

Indonesia	**7**
Rice, paddy	24%
Oil palm fruit	24%
Maize	9%
Rubber, natural	8%
Coconuts	6%

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Appendix

Useful datasets for estimation of realizable cropland soil carbon sequestration.

TABLE A-1.
Geopolitical or geospatial datasets that may help with constraining soil C sequestration estimates, globally or for U.S.

Dataset or Tool	Date	Scale(s)	Select Variables Available	Access Details
AFT survey of NOLs	2019 and 2020	USA: state-level (13 states)	For non-operating landlords: demographics, terms of agreements, etc.	State-level summaries and methodology can be found here: farmlandinfo.org/collections/?special_collections=197
FAO Gender and Land Rights database	Varies by country	Global: country-level	Gender and land-related statistics such as share of women engaged in agriculture.	fao.org/gender-landrights-database/background/en/
FAOSTAT	1969 to current	Global: country-level	Land use, land cover, inputs, agricultural employment, conservation tillage adoption; food price indices; SDG indicators	http://www.fao.org/faostat/en/#data Many different indicators related to land use and agriculture
OpTIS (Operational Tillage Information System)	2005 through 2019	U.S. Corn Belt and surrounding states; aggregated to regional and watershed scale	% winter cover crops, tillage practices	ctic.org/optis, available because of partnership with Regrow and TNC. Latest dataset released June 2021. See Hagen et al. (2020) for links to datasets within OpTIS.
Persistence of practice dataset	2021	USA	Persistence of CRP, CREP & other NRCS conservation practices	Compiled from literature by Adam Chambers (USDA-NRCS); contact him for more details
SoilsRevealed.org	2018	Global: 250 m to 15 arc seconds	Population, land use, erosion risk	SoilsRevealed.org/
USDA Census of Agriculture	Every five yrs, including 2012, 2017	County to national	Crop level land use, production, and yields. Farm expenditures and input use. Farm characteristics and farmer demographics.	nass.usda.gov/Publications/AgCensus/2017/ (most recent) agcensus.library.cornell.edu/ (archive for earlier)

TABLE A-1. CONTINUED

Dataset or Tool	Date	Scale(s)	Select Variables Available	Access Details
USDA ARMS (Agricultural Resource Management Survey)	Periodically for different crops, 1996 to current	USA: county, LRR	% of land rented, land cover (incl. crops grown), cover crop adoption, tillage, crops planted, nutrient management	ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/
USDA ERS Commodity Costs and Returns	Annual, 1975 to current	USA: six regions	Average costs and returns, $ per acre, broken down to different categories (e.g., hired labor, seed, fertilizer, primary product income)	usda.gov/data-products/commodity-costs-and-returns/
USDA Cropscape – Cropland Data Layer	Annual, 1997 to current	Contiguous USA: gridded (60m to 30m)	Crop-specific land cover	data.nal.usda.gov/dataset/cropscape-cropland-data-layer
USDA NASS TOTAL survey	2014	USA	Economics of land ownership, demographics, land uses	Tenure, Ownership, and Transition of Agricultural Land (TOTAL) Survey; see: ers.usda.gov/publications/pub-details/?pubid=74675
World Census of Agriculture	2006 through 2015 (the 2010 WCA)	Global: country-level	Land tenure, number of holdings, area per holding, landowner legal status, landowner demographics, farm labor source, area irrigated	fao.org/world-census-agriculture

TABLE A-2.
Tools designed to predict or otherwise help understand agricultural practice adoption.

Tool	Description	Access Details
ADOPT (Adoption and Diffusion Outcome Prediction Tool)	Assuming consistent institutional structures, ADOPT evaluates individual practices and their characteristics making quantitative predictions about adoption outcomes of new farming practices, estimating the level and rate of adoption	Described by Kuehne et al. (2017)
PROMIS (PRactice-Oriented Multi-level perspective on Innovation and Scaling) framework	Systematically defines a theory of scaling for agronomic innovation by looking beyond individual behavior to include systemic forces from social networks to political structures	Described by Wigboldus et al. (2016)