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Soil carbon sequestration as a climate strategy: what do farmers think?

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Abstract Countries and companies with net-zero emissions targets are considering carbon removal strategies to compensate for remaining greenhouse gas emissions. Soil carbon sequestration is one such carbon removal strategy, and policy and corporate interest is growing in figuring out how to motivate farmers to sequester more carbon. But how do farmers in various cultural and geographic contexts view soil carbon sequestration as a climate mitigation or carbon removal strategy? This article systematically reviews the empirical social science literature on farmer adoption of soil carbon sequestration practices and participation in carbon markets or programs. The article finds thirty-seven studies over the past decade that involve empirical research with soil carbon sequestering practices in a climate context, with just over a quarter of those focusing on the Global South. A central finding is co-benefits are a strong motivator for adoption, especially given minimal carbon policies and low carbon prices. Other themes in the literature include educational and cultural barriers to adoption, the difference between developing and developed world contexts, and policy preferences among farmers for soil carbon sequestration incentives. However, we argue that given the rising profile of technical potentials and carbon credits, this peer-reviewed literature on the social aspects of scaling soil carbon sequestration is quite limited. We discuss why the social science literature is so small, and what this research gap means for efforts to achieve higher levels of soil carbon sequestration. We conclude with a ten-point social science research agenda for social science on soil carbon—and some cautions about centering carbon too strongly in research and policy.

Keywords Soil carbon · Farmers · Adoption · Carbon removal · Negative emissions · Social science

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Introduction

"Soil is the next frontier for storing carbon," declared Joe Biden's campaign plan for rural America (Biden-Harris Democrats 2020). The promise is that farmers could receive an additional revenue source whilst confronting climate change—an attractive idea also centered in the bipartisan Growing Climate Solutions Act, which is under discussion in the US Congress at the time of writing. However, the US is not exceptional in having policy interest in storing carbon in soils. Globally, national strategies for meeting climate goals are also starting to incorporate soil carbon sequestration policies and programs. A review of the first round of Nationally Determined Contributions (NDCs) to the United Nations Framework Convention on Climate Change—the pledges countries make under the Paris Agreement—conducted in 2019 found that 28 countries referred to soil organic carbon in their NDCs; fourteen of those referenced agricultural lands (Wiese et al. 2021). Of course, given that there were 184 countries that submitted NDCs, this means that just 15% of countries had climate pledges that included soil organic carbon, and indicates that many countries don't see soil carbon sequestration as ready for official inclusion, given the challenges to quantifying and monitoring soil organic carbon (Wiese et al. 2021).

Despite the real-world monitoring and verification challenges, policy interest in soil carbon is rising rapidly, due in part to net zero climate goals. Net zero targets mean that some amount of remaining emissions are balanced by removing carbon from the atmosphere. However, the majority of net zero commitments are unclear on how carbon offsets will be used or how removals will be carried out (Hale et al. 2022). Companies are experimenting as they figure out to meet their public commitments to net-zero. For example, Microsoft has an ambitious carbon-negative target; it aims to remove all historical emissions back to its founding. It purchased half a million dollars' worth of soil carbon credits from an Australian grazing operation in 2021. Academics pointed out problems with the methodology and found that some claims made about the carbon sequestered were too optimistic (Simmons et al. 2021), Indeed, at present, soil carbon sequestration is considered a risky investment, given the scientific knowledge base (Oldfield et al. 2021). Yet commercial interest continues to rise. Moreover, the business interest in soil carbon doesn't only stem from companies with emissions they need to negate. Companies that intend to supply markets with soil carbon offsets are also finding venture capital, and platforms looking to connect buyers with sellers are growing in number.

Science underlies both policy and corporate interest. Calculations of the technical potential of soils to take up carbon underpin all the investment. For example, one investigation of the "4 per 1000" initiative, which aims for a growth rate of carbon in soils of 0.4% per year, illustrates how "a small group of French scientists and policy-makers turned a 'back-of-the-envelope' calculation regarding soil, carbon, and climate change into a powerful promise of enhancing the carbon absorptive capacities of soils, which had the effect of fostering new research agendas, organizations, and activities relating to soil carbon monitoring, data, and modeling" (Kon Kam King et al. 2018). This partial reorientation of soil science agendas and activities is part of a wider "strategic climatization," whereby soil scientists have repositioned themselves to access resources and audiences that traditionally have gone to global change sciences (Kon Kam King et al. 2018).

The trouble with the enthusiasm about high technical potentials of soils to remove carbon is that these potentials are going to be constrained by social factors, including whether farmers want to change what they do day-to-day to offer a sink for the world's emissions. In tracking much of the buzz about soil carbon sequestration, it's striking how often producers are left out of the conversation, including in research. Indeed, a previous review of the wider soil carbon literature found that farmer participation in soil carbon research was low, with only 10% of articles gathering information directly from farmers or using information provided through use of farmer fields. Moreover, 68% of articles in that review did not consider farmers' capacity needs (resources, knowledge and skills) when examining soil carbon management (Amin et al. 2020).

What kind of policies would best serve farmers, and what are the challenges they identify to benefit from the existing and emerging opportunities? In the real world, what burdens do they face by engaging in soil carbon markets? How do farmers navigate the standards on the voluntary carbon markets, and how do they view the safeguards in those standards, in terms of data privacy or landowner protections? These are questions that policymakers, investors, and developers looking to create or expand incentives for soil carbon sequestration would want to answer. This paper looks at whether the peer reviewed social science literature could be a guide.

Studies of the adoption of soil carbon sequestering practices fit into a few different wider literatures. One is farmer beliefs regarding climate change, including willingness to mitigate or adapt to climate change, including using "climate-smart" practices, many of which overlap with soil carbon sequestering practices (Gosnell et al. 2020). "Climate-smart agriculture" emerged as a concept about a decade ago, and deals with both reducing greenhouse gas emissions from agriculture and increasing adaptive capacity (Chitakira and Ngcobo 2021).

There is also a much wider literature on farmer adoption of practices, including willingness to accept payment for ecosystem services, adoption of conservation agriculture, or adoption of soil conservation practices. A notable review of the latter, which looked at 69 studies reported in 38 papers since 1980, found that the results were disappointing for policy, since there were not universal patterns in adoption to discover, and variables that for decades were regarded as classic were actually insignificant (Wauters and Mathijs 2014). The literature on adoption theory is decades old, and adoption studies that use correlational techniques to explain adoption behavior have been conducted since the 1970s. There are several paradigms within this field, as it comes from varying disciplines such as marketing, economics, sociology, and psychology. For example, from marketing, there are conceptual models focusing on contagion, where innovation spreads like epidemics. From sociology, there's a focus on social norms and adopting what other people adopt. From economics, there's a social learning paradigm, where people adopt techniques when they have enough evidence to do so (Montes de Oca Munguia, Pannell, and Llewellyn 2021). A meta-analysis that used 367 regression models from 204 adoption studies found that education, land size, access to credit, land tenure, contact with extension agents, and membership in farmers' organizations all positively influence adoption of most agricultural technologies (Ruzzante et al. 2021).

It might seem that we know enough about farmer adoption of new behaviors and technologies, given decades of general research. But in fact, all this research has failed to converge on a stable explanation for why farmers adopt new technologies and practices (Oca Munguia and Llewellyn 2020). We can also ask whether soil carbon sequestration would be any different from more general adoption behavior. Do policymakers really need guidance from studies on soil carbon sequestration specifically? However, there may be aspects that are distinct with soil carbon, because of the context of climate change, which is an emotional and political issue. We need to also distinguish between *adoption of practices that sequester carbon* and *participation in carbon schemes or markets*, which are two different things (Kragt et al. 2017). The existing literature on adoption is less suited to tell us about the latter.

Method

We systematically searched for empirical social science peer-reviewed articles related to farmers and soil carbon sequestration as a climate strategy from 2012–2022 using Web of Science Complete. We also ran similar searches on Google Scholar as a check to ensure that Web of Science was representative of the wider literature. Several search strings were utilized: "soil carbon" + adoption (303 articles) or "soil organic carbon" + adoption (373), "soil carbon" + perception (46) or "soil organic carbon" + perception (36); "soil carbon" + interview (36) or "soil organic carbon + interview" (27); "soil carbon" or "soil organic carbon" + farmers + "climate change" (187 / 188); "soil carbon" + "climate change" + social (136); "no till" + "climate change" + adoption or perception or interview (87 / 4/ 2); "cover cropping" + "climate change" + adoption or perception or interview (25 / 4 / 2); soil + "carbon market" or "carbon credit" or "carbon offset" + soil (52 / 59 / 55); "carbon farming" (259); and "regenerative agriculture" (137).

Selection criteria for inclusion were: (1) study used *empirical social science* data from *farmers or producers*—e.g. data was gathered using surveys, workshops, interviews, etc., including secondary analysis of such datasets. Empirical studies only focusing on experts or lay publics were not analyzed. (2) The analysis focused on *agricultural soil carbon*, rather than carbon sequestered in forests. (3) The analysis at least mentioned soil carbon as a *climate change strategy* at some point, even if the focus of the article was largely on conservation agriculture more broadly, or other benefits from soil health. In some cases the articles could be ruled out by title and abstract; in other cases it required reading the article to exclude. The remaining articles were reviewed to identify themes, first by writing short summaries of each article to look at what research questions and themes the article was examining. The articles were then coded using an Excel spreadsheet to document the geography of the research, research methods used, number of respondents, opportunities identified in soil carbon sequestration, barriers to adoption, major conclusions, and recommendations for future action.

Findings

State of the literature

Thirty-seven studies met the criteria. The literature is highly skewed towards studies in North America (27%), Europe (24%), and Australia (24%), with just 27% of studies taking place in the Global South. Of the studies in the Global South, nearly all took place in Africa, with one study in Asia and none in Latin America. Slightly more than half the studies (n = 20) employed surveys or questionnaires; nearly half employed interviews (n = 16), and seven studies involved workshops or focus groups. Some articles employed mixed methods. Just five involved on-farm participatory research with farmers, or integration with soil carbon research that measured whether practices were in fact sequestering carbon.

While most studies mentioned that soil carbon sequestration could contribute to climate change goals, given the inclusion criteria for the review, few mentioned soil carbon sequestration explicitly in the context of net zero goals or carbon credits/carbon markets. Most of those that did were from Australia, where the soil carbon credits under the Carbon Farming Initiative have been a longer policy discussion. Many studies treated soil carbon sequestration as a subset of sustainable land management, in the context of adaptation or food security, and were not designed to address issues of participation in carbon markets. Notably, the majority of papers reviewed here did not deeply engage with or seek to develop theory. Few studies focused on the development of research methods. In general, the literature reviewed took more of an applied focus on reporting study results.

Themes

Co-benefits drive adoption

The most coherent of the findings across the studies was that co-benefits, such as soil fertility, reduced erosion risk, or water holding capacity, were often more important than compensation; financial incentives may be a low driver (Cook and Ma 2014; Mattila et al. 2022; Kragt et al. 2017; Dumbrell et al. 2016; Gosnell et al. 2020; Fleming et al. 2019; Andrews et al. 2013; Page and Bellotti 2015). It is possible that financial incentives could be a driver of adoption under a stronger policy environment (e.g. with measures allowing farmers to participate more easily in voluntary carbon markets, such as government-funded fundamental research and demonstration trials, standards for monitoring, reporting and verification, and technical assistance for farmers—or with new or strengthened compliance markets that include soil carbon credits). Still, at present, financial incentives do not seem to be a key driver in many areas. One survey in the US found that ecological benefits were perceived as most important, with ¾ of respondents finding them moderately or very important; 61% of respondents considered tax benefits "moderately important" or "very important"; while 43% valued receiving income/monetary payments from carbon sequestration. Notably, just half of respondents "considered reducing human contribution to climate change an important benefit of participating in a carbon sequestration program" (Cook and Ma 2014). A survey in Australia similarly found improved soil quality and productivity benefits to be major drivers of adoption, with the opportunity to earn Australian carbon credits regarded as one of the least important reasons to undertake carbon farming (Kragt et al. 2017).

Would this change with stronger, more certain policy that placed a higher value on carbon credits? We do not know, but the literature cautions against ignoring intrinsic, nonmonetary motivation and values. A study that looked at framing effects found no effect on willingness to adopt no-till from frames that mentioned payments for carbon offsets, and pointed to existing literature suggesting that small economic incentives can crowd out intrinsic motivations for providing social goods such as soil carbon sequestration (Andrews et al. 2013). Another study noted that non-financial motivations can be important drivers, including personal and family well-being, stewardship ethics, passing the land in better condition, pride of ownership, and so on can strongly correlate with participating in conservation programs (Page and Bellotti 2015).

Barriers to adopting soil carbon sequestering practices

Educational barriers, such as lack of knowledge or training, were a widely cited barrier to adoption (10 studies). In theory, this could be remedied by more technical assistance; however, in some contexts, having to employ private advisors can be a barrier (McRobert and Rickards 2010). Some studies also found that while lack of education is a barrier, this does not necessarily mean that more information will mean greater adoption of soil carbon sequestering practices. One study actually found that the most knowledgeable farmers were the most skeptical about carbon sequestration, suggesting that providing more technical information could backfire (Ma and Coppock 2012).

Other frequently mentioned barriers included policy barriers, such as policy uncertainty, bureaucracy, influence of agrochemical industry, and land tenure issues (8 studies). Uncertain effectiveness or biophysical barriers (6 studies), such as low biomass availability or removal of crop residues (Boakye-Danquah et al. 2014), were also mentioned. Economic barriers (5 studies) and cultural barriers (5 studies) were common as well.

All of these barriers are interrelated—for example, the economic issue of uncertainty over whether carbon offsets are priced at a level that is worth it to farmers (Rochecouste et al. 2017) is also a policy issue. Contract terms are both a policy issue and a cultural issue. One study in Australia found that just under half of farmers contacted were not at all interested in carbon farming due to the potential loss of control of what they could do on their land, and a need for freedom to operate (Rochecouste et al. 2017). Another cultural factor involves norms—for example, the idea that "good farming" involves a tidy landscape and the absence of weeds (Gosnell 2021).

A cultural lens can help identify barriers, but also opportunities. Transitioning to regenerative agriculture isn't just about climate-smart practices that are adopted via education, innovation, and policy support. Rather, "it involves subjective, nonmaterial factors associated with culture, values, ethics, identity, and emotion that operate at individual, household, and community scales and interact with regional, national and global processes" (Gosnell et al. 2019). Another study identified a "soil stewardship ethic" to explain soil conservation, and pointed to an emergent aspect of a conservationist identity (Roesch-McNally, Arbuckle, and Tyndall 2018). Social networks are an important part of developing this identity and new norms; observing practices on neighboring farms can inspire adoption of new practices (Roesch-McNally, Arbuckle, and Tyndall 2018).

Smallholder and developing country contexts

The ten studies focusing on developing world farming contexts identified additional considerations. When it comes to setting up carbon market initiatives in particular, a paper studying sub-Saharan Africa identified challenges around raising finance for project development and limitations in the technical capacity in potential applicant institutions, carbon market documents only available in English (and complex legalistic English difficult for even native speakers), and bureaucratic obstacles (Siedenburg et al. 2016). Land tenure is also a consideration, with many market opportunities requiring formal tenure documents (Siedenburg et al. 2016). The cost of labor may also be a consideration, with one study in Senegal finding that cheap labor increases the probability of adopting soil carbon enhancing opportunities (Demenois et al. 2020).

"Carbon revenues represent a potentially pivotal opportunity for small-scale farmers," write Siedenburg and colleagues, given that revenues provide a needed service to the global community and could catalyze rural transformation (Siedenburg et al. 2016). But they ask: are reforms to carbon markets adequate to make it possible for the world's two billion small-scale farmers to access the carbon market at scale? If markets are to be the main way of coordinating the action of smallholders, the dilemma is that the amount of carbon stored on an individual farm may not justify payments for the effort, e.g. if the effort and cost in monitoring, reporting, and verification outweighs the payment for the carbon stored.

It is possible that smallholders could coordinate to earn carbon credits together. This was done, for example, in the Kenya Agricultural Carbon Project, which was coordinated by the World Bank and a Swedish development organization, Vi Agroforestry. A few studies have addressed this issue of coordinating smallholders and this model of soil carbon through development projects. For example, a study of this project by Lee and colleagues examined equity in access, decision-making, and outcomes (Lee et al. 2015). It found that international requirements in the project and top-down program design created difficulties for communities, and that gendered division making within households has consequences for both adoption of soil carbon sequestering practices and the flow of benefits (Lee et al. 2015). This was the sole study reviewed that addressed equity or gender to any degree—aspects which would be central to soil carbon sequestration at scale. The study also cautioned about assuming livelihood benefits, noting that there were project delays, small carbon payments, and uncertainty, which led to farmers only deeming adoption of sustainable land management practices to be a fair deal based on cobenefits (Lee et al. 2015).

Climate change perceptions as a factor in adoption

A number of studies examined the climate change perceptions of farmers, though some of them did not seek to correlate this with adoption of carbon sequestering practices. The results are mixed. A study in Australia found that likelihood of adopting carbon farming was affected by experience with negative impacts of climate change, but also found that less than 35% of respondents agreed that carbon farming is an appropriate way to reduce Australia's greenhouse gas emissions, and that the opportunity to generate carbon credits was not an important driver of adoption (Dumbrell et al. 2016). Another study, focused on adoption of climate-mitigative practices in Alberta, found that climate change beliefs had no bearing on adoption decisions, and noted that a sizeable proportion of farmers had already adopted these practices because of co-benefits, not because of agreement with climate science (D. J. Davidson et al. 2019). Granted, this population has some skepticism of anthropogenic global warming, but the authors caution that attempts to garner support for political mandates linked to climate change may trigger cognitive dissonance and lead to rejection of these mandates (D. J. Davidson et al. 2019). Other studies, however, have linked willingness to adopt conservation agriculture behaviors to concern about climate change (Roesch-McNally et al. 2017).

Policy preferences

Few studies have examined what policies farmers would prefer. One study found that respondents preferred education programs over incentive programs; about 40% of respondents found government payments for meeting voluntary carbon sequestration goals and a voluntary carbon offset not appealing at all. Seventy percent found the compliance market approach (cap-and-trade) not appealing at all; among all program options, 41% of respondents did not want to be the first few to participate (Cook and Ma 2014). Another study found that farmers opinions on a market-based structure (like from cap-and-trade) were not any more or less favorable than opinions on government conservation payment for adopting practices (Gramig and Widmar 2018). This is definitely worthy of further study—and should be treated as a distinct question from adoption of carbon sequestering practices. Even if farmers adopt carbon farming, it might not increase program participation and generate verifiable credits.

A few studies underscored the need for policy to present both simple methodologies and flexibility (Aslam et al. 2017), including easy-to-follow rules and administrative processes, with one suggesting that projects that impose legal constraints that may affect the viability of the farm and the earning potential of future farmers would be unlikely to be taken up (Rochecouste et al. 2017).

Recommendations in the studies

Here, we will highlight three recommendations that were made multiple times. First, some studies recommended emphasizing co-benefits in both communication and policy, aligning with this finding that co-benefits were in many cases the driver of adoption (Ma and Coppock 2012; Gosnell et al. 2020). Important co-benefits include nutrient building in soils, reduced erosion risk, and increased water holding capacity. These co-benefits can help with climate adaptation, in terms of making farms more resilient against both heavy rainfall events and drought. However, focusing on and incorporating co-benefits may be in tension with new platforms and policies for monitoring carbon, which need rigorous and cheap quantification of carbon storage to succeed. The case for recognizing co-benefits include social consequences (improved farmer livelihoods, new markets that tap into consumer values), financial consequences, environmental outcomes, and the potential to revitalize carbon trading and benefit farmers by driving a premium price for credits that demonstrate environmental and social co-benefits (Fleming et al. 2019).

Second, some studies suggested further research and policy focus on grassroots mobilization and peer-to-peer learning in order to achieve scalability (Mattila et al. 2022; Mills et al. 2020; Gosnell et al. 2020; Kragt et al. 2017). In particular, research has looked at social media in farmer-to-farmer knowledge transfer, and allows new people to learn about regenerative agriculture (Cusworth et al. 2021). While most do not spell out how policymakers can facilitate or support communities and practice and peer-to-peer learning, they recognize this as important for scalability (Gosnell et al. 2020). A top-down approach to incentivizing change—e.g. programs to allot payments for enhanced soil carbon sequestration—may be less successful than a bottom-up approach which studies what shifts the thinking, purpose, and worldviews of farmers, from which climate-smart practices will logically follow (Gosnell et al. 2019). One study recommends looking at regenerative agriculture as a "grassroots emergent phenomenon, in which food systems are being reshaped from the bottom up by increasingly aware ranchers and consumers," (Gosnell et al. 2020) and researchers should do on-site co-production of knowledge with farmers in order to understand this in order to understand how changes can be not just implemented, but sustained over time.

These questions about grassroots mobilization and learning are directly related to choice of research methods. Indeed, a third set of recommendations centered on using a wider variety of research methods. Ethnographic methods can help with accessing tacit knowledge which can be missed in less in-depth methods; walking interviews can examine farmer knowledge as embodied in the farm landscape (Brockett et al. 2019). Participatory research with farmers can generate management options from beyond current research and extension recommendations (Mattila et al. 2022). Furthermore, farmer attitudes and motivations are not fixed and can change over time; identifying how this happens depends on the methods used (Brockett et al. 2019).

Discussion

What, then, can this literature tell policymakers and others about how to proceed with designing programs for soil carbon? We should be wary about drawing conclusions from a body of literature this small, geographically uneven, and in many cases, not designed to answer that question. We can conclude that in a context with limited soil carbon policy, co-benefits are driving adoption of soil carbon sequestering processes, and in this current context, lack of knowledge or training is a strong barrier, as well as cost, cultural factors, the uncertain policy environment, and in some cases, uncertain efficacy of soil carbon sequestering practices or biophysical limitations. But it will take more research to learn what will drive adoption if the policy context changes.

Another important question is: Why is this literature so limited, given all the interest in soil carbon? We can offer four hypotheses.

First: There is research being done, but it is being conducted in non-peer-reviewed domains, such as white papers by NGOs and private sector market research. This begs the question, do we really need peer-reviewed social science on these questions? Might it be enough for the private sector to implement soil carbon sequestration credits and learning by doing? However, there is a strong case for asking people about their preference and the barriers they face in a systematic, openly accessible way, free from market pressures, especially if significant public funding will be spent supporting soil carbon sequestration endeavors.

Second: There is academic research being done, but the timeframes of academic research can't keep pace with developments in policy and technology. There may be four or five years from an idea for a grant to publication, and the widespread circulation of regenerative agriculture or soil carbon sequestration as a strategy are just a few years old.

A third possibility is that some may be assuming that farmer adoption is not a "problem" worth studying, with the idea that it will naturally be solved by introducing proper financial incentives. However, previous research on participation in payment for conservation schemes or adoption behaviors of other practices would certainly indicate it is more complicated than this. But perhaps the right experts are simply not always in the room to share that research.

Fourth, the enthusiasm about soil carbon may be driven more by developments in technology—both in software, in monitoring techniques, and in the value of gathering on-farm data—rather than a desire to actually implement soil carbon sequestration. Adoption may be secondary to developing the monitoring platform. This could make sense if a company's initial valuation is based on technology and data rather than outcomes.

The reason for the small number of studies may be a mix of these factors, or something else. In any case, the gap indicates a lack of seriousness about scaling up soil carbon sequestration. It is also not unique. The wider research landscape for carbon removal technologies also faces a lack of integration of social considerations that could impact the scalability of these approaches.

Conclusion: The future of social science research on soil carbon sequestration

If society is serious about scaling up soil carbon sequestration as a carbon removal strategy, there are several things that would be worth doing. In what follows, we outline ten items to focus on in terms of research.

1. Participatory research with farmers Many studies reviewed treated farmers as subjects of the research rather than active participants or used methods like surveys rather than on-farm research. Participatory research is often undertaken with an emphasis on empowering farmers, and it also brings insights into decision-making in complex systems. Participatory research with farmers on soil carbon sequestration would allow a deeper understanding of farmers' choices, how farmers build knowledge about different techniques, how they conduct monitoring, and more. Participatory on-farm studies could also incorporate soil sampling to see if there are relationships between social factors and soil carbon outcomes.

2. A greater geographic diversity of studies A global initiative requires understanding adoption in a variety of contexts. Research in Latin America and Asia is particularly lacking.

3. Access, participation, and justice This is relevant in both developing and developed world contexts. How can smallholders access the benefits of soil carbon sequestration policy? This is not simply a "developing world" issue. In the United States, structural racism, such as discrimination in the processing of Black farm loan applications, has harmed farmers of color (Oldfield et al. 2021). What policies could make the benefits of carbon programs available to historically marginalized people who may face barriers to participation? One report advises that crediting programs explicitly address environmental justice concerns, and describes a crediting program that includes strategies for diversity, equity, and inclusion in outreach, internships, and partnerships (Oldfield et al. 2021). Co-produced social science research can help determine under what conditions these are successful.

4. Co-benefits, motivators and barriers These are being explored, as this review shows, but unevenly. Co-benefits need to be further understood in regards to soil carbon, but also within the wider context of carbon markets that are trying to figure out how to measure and reward co-benefits. Researchers can work on identifying underexplored motivations, like the infrastructure of the soil health movement, including alternative sources of information through videos, conferences, and communication (Rosenzweig et al. 2020), and underexplored barriers (like insecure land tenure).

5. Labor Virtually no studies address the labor dimensions of soil carbon sequestering practices, including who does the work, how it changes their relationship to their work, and what sort of new jobs are created by a soil carbon sequestration regime.

6. Maintenance of soil carbon How do farmers approach maintenance of soil carbon, and in what instances can losing soil carbon pose additional financial risks to farmers? Soil carbon sequestration can be reversed by repeated tillage after no-till, or from climate events like droughts, floods, or fires (Oldfield et al. 2021). There is a social dimension to all of these that has not been studied; most research has focused on the choice to implement new practices, not how to maintain existing ones. Many conceptual models of adoption seem to use a "transactional" viewpoint, observe Montes de Oca Munguia et al. (2021), which look at adoption as a one-off exercise. Others recommend using a "relational" viewpoint, which involve a relationship between farmers and the practice as well as farmers and companies and institutions (Montes de Oca Munguia, Pannell, and Llewellyn 2021). Scholars also identify different stages of adoption (the recognition of a problem, the decision to adopt, the decision of how much to do, trial and implementation, and so on); there is no binary decision variable (Wauters and Mathijs 2014). Research on soil carbon sequestration should consider these frameworks, since permanence is so important to climate goals.

7. Farmer relationships to data and platforms for carbon monitoring Enrollment in on-farm sustainability platforms can be far more difficult than expected. One study of the Fieldprint Platform, which uses sustainability metrics for agriculture found recruitment at 5% of the goal, identifying challenges with non-user friendly interfaces that made farmers reliant upon agents to collect data; confusion and suspicion about data collection if data fell into the hands of regulators or adversarial NGOs; and discussions of whether farmers should be compensated for their data (Freidberg 2020). Some of these challenges will be in play with soil carbon platforms too. There is a lot of discussion on monitoring, reporting, and verification of soil carbon, but much of it does not center farmers.

8. Farmer relationships to other actors, including consumers Consumers are expected to play some role in demand for products grown with regenerative agriculture, or which sequester carbon, but few studies have addressed consumers nor the wider landscape of actors (farmers, consumers, policymakers, researchers, extension, agrochemical companies, and so on). The political economy of adoption, and how it relates to farmer decisions, is underexplored.

9. Policy preferences Only a few studies thus far have looked at what policy options farmers prefer. This is critical since policies in many countries and subnational jurisdictions are under construction.

10. Relationship of soil carbon to wider decarbonization goals, and how farmers see this and are affected by it In many long-term strategies for decarbonization, "residual" or leftover emissions in the later part of this century come from agriculture. It is one of the hardest sectors to decarbonize, though carbon removals can in theory negate emissions of nitrous oxides. Will there be policy that takes a sectoral approach, requiring agriculture to compensate for the emissions in agriculture? If so, how does that impact farmers? No one knows.

This is the sort of research we should be vigorously pursuing if we wanted to see initiatives like 4 per 1000 realized. However, we should also take a step back and ask whether this is the right approach to researching soil health and to climate policy (E. A. Davidson 2021; Sanderman et al. 2021) The answer hinges upon several things, including (a) what the biophysical science says about how well soil carbon sequestration actually works, and (b) how well other carbon removal strategies work, and what their profile of benefits and risks is. We can also imagine a scenario in which soil health is viewed primarily as a climate adaptation or an ecosystem-benefitting strategy, which would imply a somewhat different research enterprise oriented towards different questions.

Much of the writing on carbon removal centers on what's been termed moral hazard, mitigation deterrence, or phaseout deterrence: the idea that by pursuing carbon removal, there will be less motivation and resources for mitigation (Markusson et al. 2018; McLaren 2020). The mitigation deterrence risks of soil carbon take many forms. First, a lack of standardized reporting protocols could create credits that overstate what is happening in the real world. Relatedly, field trials may introduce unrealistic management practices like large amounts of inputs that could not be accessible to farmers, or could shift carbon from one location to another; benefits might look better in trials than in commercial fields (Oldfield et al. 2021). These overstatements could be risky for producers: a review of twelve soil carbon protocols by the Environmental Defense Fund noted that these protocols use process-based models, soil sampling or both to estimate SOC sequestration, and soil samples taken in the fifth year of a program could potentially demonstrate that modeled estimates exceeded measured rates of SOC accrual (Oldfield et al. 2021) which bring financial risks for farmers who were expecting higher incomes. Second, there's also the possibility that agricultural practices that build SOC could result in increased nitrous oxide emissions, though this trade-off is difficult to quantify (Oldfield et al. 2021). Third, a focus on soil carbon could lessen resources for mitigation opportunities like reducing nitrous oxide emissions from soil, reducing on-farm fuel consumption, or reducing methane emissions from livestock. If resources go into carbon outcomes at the expense of other inquiries into climate change mitigation and adaptation, or even other ecological and social outcomes, that could be a loss. Conversely, emphasizing adaptation and ecosystem resilience might end up storing some soil carbon as a side benefit, and might even store more soil carbon than a soil carbon sequestration perceived narrowly as a regulatory or government-pressured climate change strategy, if the adaptation-focused program had greater adoption.

Prominent efforts to scale up soil carbon sequestration to a gigaton scale removal strategy, such as 4 per 1000, are bolstered by modeling estimates of technical potential (Minasny et al. 2017). Some scientists have questioned the feasibility of such efforts (Amundson and Biardeau 2018), while others have supported the effort as it can also help soil health and adaptation efforts (Loisel et al. 2019). What is interesting about goals like 4 per 1000 is that its promise relies on a restrictive version of soil as a global stock of carbon that can be monitored, modeled, managed, and enhanced, as Kon Kam King et al. observe (2018). This rather reductive way of approaching the world is in contrast to how some studies describe the mindset of regenerative agriculture. Regenerative agriculture has been characterized as having a systems mindset, where instead of thinking about the end product the focus is placed on nurturing the conditions—grass and soil—that make the end product possible. In other words, "carbon is a means to an end and not an end in itself" (Gosnell et al. 2020). Gosnell et al. quote a farmer: "Everyone talks about carbon, but to increase carbon you've got to fix the other problems first"—soil structure, plants, microbial health—"it comes well after all that, the increase in carbon" (Gosnell et al. 2020). That is to say, farmers may be approaching all the other aspects first, and carbon last. In the quest to stand up vigorous monitoring that will underly carbon markets and gigaton-scale visions like 4 per 1000, we risk losing sight of the bigger picture, and might miss some of the co-benefits that could drive adoption of soil carbon sequestration and make it actually work as a carbon removal strategy.

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Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

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