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OPINION

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Soil carbon sequestration in global working lands as a gateway for negative emission technologies

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Abstract

The ongoing climate crisis merits an urgent need to devise management approaches and new technologies to reduce atmospheric greenhouse gas concentrations (GHG) in the near term. However, each year that GHG concentrations continue to rise, pressure mounts to develop and deploy atmospheric CO_2 removal pathways as a complement to, and not replacement for, emissions reductions. Soil carbon sequestration (SCS) practices in working lands provide a low-tech and cost-effective means for removing CO_2 from the atmosphere while also delivering co-benefits to people and ecosystems. Our model estimates suggest that, assuming additive effects, the technical potential of combined SCS practices can provide 30%–70% of the carbon removal required by the Paris Climate Agreement if applied to 25%–50% of the available global land area, respectively. Atmospheric CO_2 drawdown via SCS has the potential to last decades to centuries, although more research is needed to determine the long-term viability at scale and the durability of the carbon stored. Regardless of these research needs, we argue that SCS can at least serve as a bridging technology, reducing atmospheric CO_2 in the short term while energy and transportation systems adapt to a low-C economy. Soil C sequestration in working lands holds promise as a climate change mitigation tool, but the current rate of implementation remains too slow to make significant progress toward global emissions goals by 2050. Outreach and education, methodology development for C offset registries, improved access to materials and supplies, and improved research networks are needed to accelerate the rate of SCS practice implementation. Herein, we present an argument for the immediate adoption of SCS practices in working lands and recommendations for improved implementation.

KEYWORDS
agroforestry, climate change, cover crops, regenerative agriculture, soil amendments, soil carbon sequestration, no-till

1 | INTRODUCTION

The impacts of climate change are already being felt worldwide and are expected to intensify (IPCC, 2022). While achieving the climate stabilization goals of the Paris Climate Agreement will require the immediate reduction of greenhouse gas (GHG) emissions, this praxis alone is viewed as necessary but insufficient to mitigate the impacts of climate change (IPCC, 2022). Strategies that actively remove GHGs from the atmosphere, known as negative emission technologies (NETs), are critical to stabilizing global climate change. Soil carbon (C) sequestration (SCS) offers one such pathway for atmospheric carbon dioxide (CO_2) removal (Fuss et al., 2018; Griscom et al., 2017). Strategic management of soils in agricultural working lands (croplands and rangelands), which occupy ~40% of Earth's land surface (FAO, 2020), can serve as a critical pathway for both GHG emission reductions and C sequestration (Bossio et al., 2020; Griscom et al., 2017). Practices that promote SCS in working lands hold co-benefits for food production, farmer economics, and environment and can reduce atmospheric CO_2 shortly after implementation (Kutos et al., 2023; Matthews et al., 2022), offering an immediate NET for deployment while other NETs develop, scale, and gain economic feasibility (e.g., direct air capture, decarbonization of energy and transportation sectors, etc.). Meeting this two-pronged agenda of scientific advancement and expedited implementation will require a movement toward innovative, multi-stakeholder research collaboratives or "innovation ecosystems." More research, improved models, and widespread extension are needed to accelerate the efficiency, implementation, and scalability of SCS as a climate change mitigation technique.

Working land NETs, which we define as including soil amendments, agroforestry, and conservation management practices, are a class of natural climate solutions. However, unlike other natural climate solutions that rely on inherently slow, decadal, or longer processes such as peatland restoration or tree growth (Cook-Patton et al., 2021), working lands are generally more intensively managed and offer an opportunity for land managers to drive SCS practice implementation in the near term. Working land NETs are a low-tech, low-cost, low-risk strategy that have been shown to be beneficial for soils and food production, while sequestering C at rates relevant to climate change (Mayer et al., 2018; Roe et al., 2021). Studies have shown that even NETs that are short-lived over decadal time scales can have a significant impact on our long-term climate trajectory (Leifeld & Keel, 2022; Matthews et al., 2022). However, adoption of NETs on working lands remains slow, as uncertainty lingers around where and how to implement these practices, what their soil and crop effects will be, and whether the cost/benefit ratio will be favorable across a variety of geographies. There is a tremendous need for working land NET demonstration projects followed by verification, such that implementation, research, and development can progress in concert. We argue that sufficient data and justification exist to start scaling these practices immediately; implementation can facilitate further adoption as producers, consumers, and legislative bodies experience results. Implementation will thus be key for further advancing the development of these technologies. Here, we summarize some of the existing information on the effects of working land NETs on C sequestration, provide a timeline for working land NET C benefits, and suggest a path forward for more streamlined research/implementation partnerships.

1.1 | Soil carbon sequestration practices in working lands as a near-term climate solution

The global SCS capacity is limited by questions of permanence and saturation of C in soils (Schlesinger and Amundson, 2019), yet SCS is likely to promote lasting C drawdown on timescales relevant to climate change mitigation (Matthews et al., 2022). Indeed, no C sink is truly permanent (e.g., Berner, 2003). On timescales relevant for anthropogenic climate change, however, C stocks with residence times from decades to millennia (Table 1) offer mitigation opportunities that can contribute to climate stabilization if coupled to deep emissions reductions (Leifeld & Keel, 2022). Approaches that can rapidly store large C stocks over years to decades, such as many SCS strategies (Figure 1), can be deployed immediately while additional NETs are developed and scaled up. Many working land NET practices generate detectable increases in SCS within 3–5 years (Figure 1; Tables S1 and S2) and their capacity to continue net C sequestration is estimated to last for decades or longer (Mayer & Silver, 2022; Poeplau et al., 2011; Ryals et al., 2015). Some of the most common practices in the United States today, like cover cropping and no-till, may provide short-lived C benefits by reducing the rate that soil C is converted to CO_2 and increasing the annual production of organic C in above- and belowground biomass (Mutegi et al., 2013). Soil amendments like compost and biochar stimulate above- and belowground biomass production, but also provide exogenous C to the soil, which can provide longer-term C benefits that can last decades or more (Ukalska-Jaruga et al., 2020). Increasing biological C inputs deeper in the soil, agroforestry could allow C storage on century to millennial timescales (Fuss et al., 2018). The SCS practices discussed here can be implemented in concert (i.e., surface application of multiple or mixed soil amendments to a cropland with cover crops) and are assumed to have additive effects. However, further field research will be necessary to elucidate synergistic, antagonistic, or neutral effects of combined implementation.

Soil C sequestration practices contribute to climate change mitigation only if they provide additional C removal above and beyond business-as-usual scenarios (see Data S1 for details). Conventional agricultural practices have resulted in high emissions from soils and a large loss of soil C (Sanderman et al., 2017). Conventional agriculture typically uses tillage, leaves soil bare in the absence of cover crops, and currently does not use the types of soil amendments described here. Thus, these practices, as well as agroforestry on abandoned cropland, are considered to provide an additional C benefit beyond business-as-usual. While current and projected rates of SCS practice implementation are poorly understood in most cases, we estimated the extent of working lands that currently implement said practices and removed them from our projections. In all cases, SCS practices can only serve as a NET if the C accrual is greater than it would have been prior to implementation. While these practices were modeled in a fashion as to not compete with food production, there could be instances where they could compete for land with other NETs. Together, these SCS practices can provide an effective pathway for lasting

TABLE 1 Soil carbon sequestration technologies. Estimated turnover times (or the amount of time carbon remains in soils) from literature values for soil carbon following a range of SCS technologies.

Management practice	Definition	Carbon sequestration pathway	Turnover time
Agroforestry	The planting of trees and shrubs among or adjacent to farmlands	Trees increase above- and belowground C	Decades to centuries[a]
Biochar	Pyrolysis of organic material	Increases C inputs into soil and increases C stabilization through organo-mineral associations	100–1300 years[b]
Compost	Composted organic material	Stimulates above- and belowground plant growth and subsequently contributes additional C to the soil	22 years[c]
Cover crops	Species planted with or between crop plantings	Additional plant materials contribute photosynthetic-derived C to the soil	No more than 20 years[d]
Enhanced weathering	Finely ground silicate rock particles that accelerate the weathering process	Chemical weathering consumes atmospheric CO_2 and turns it into turns it into inorganic carbonates in soil or pore water	10^6 years or more[a]
No-till	Foregoing traditional soil tillage practices	No-till practices promote soil aggregation and reduce disturbance-related CO_2 emissions	N/A[e]

[a]Fuss et al. (2018).
[b]Singh et al. (2010).
[c]Fortuna et al. (2003).
[d]Mutegi et al. (2013).
[e]No till is a common practice now, though it is more so an emissions reduction strategy than a carbon sequestration strategy.

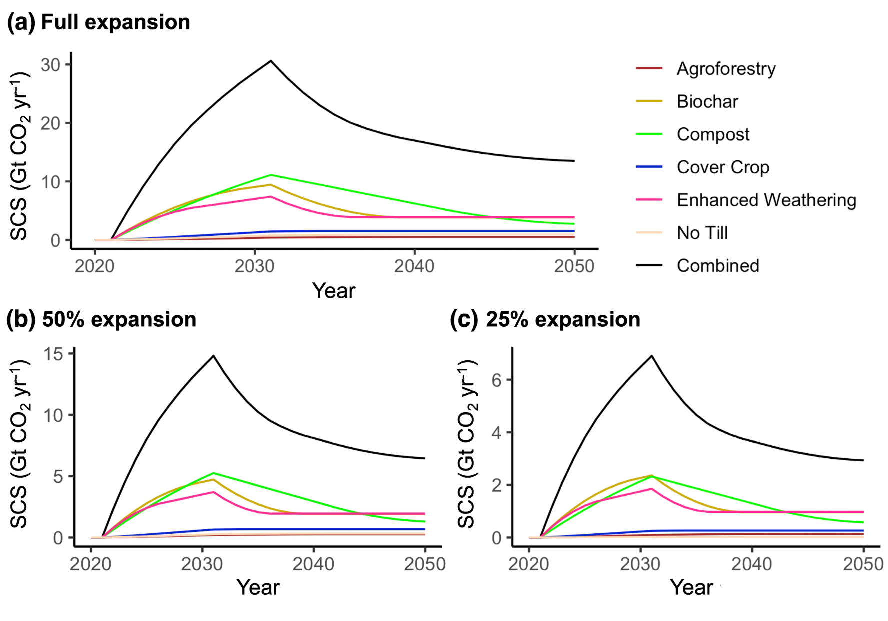

FIGURE 1 Additional soil carbon sequestration (SCS) potential for various and combined soil management practices from 2020 to 2050, based on (a) expansion of SCS practices over 100% of available land, (b) expansion of SCS practices over 50% of available land, and (c) expansion of SCS practices over 25% of available land. *Y*-axis scales differ between panels.

and additional C drawdown that can begin immediately and assist in wider adoption of NETs outside of the working land sector.

1.2 | Estimating the benefits of soil carbon sequestration practices in working lands

One of the primary constraints on widespread SCS is the lack of necessary technical knowledge required to facilitate adoption of practices across broad regions. This in turn slows the rate of full-scale implementation and consequently increases the time required before SCS benefits are detected and final SCS intensity is achieved. To estimate the technical potential (not considering socioeconomic, political, and other environmental limitations) for SCS at the global scale, we modified a model originally developed by Qin et al. (2021). The model estimates the integrated impacts of timeframes for implementation (extent; T_e) and C sequestration rate (intensity; T_i) of NET practices (Table S1). The model output provides scenarios of when maximum technical capacity of NET practices can be reached based on delays in the extent and/or intensity. We tested the global CO_2 drawdown potential of six important and scalable working land NETs including soil amendments (compost, biochar, enhanced weathering), agroforestry, no-till, and cover cropping (Table 1). We used published values of changes in SCS rates due to each management practice relative to a business-as-usual control to parameterize the model (Table S2). We explored the near-term (through 2050) technical potential CO_2-equivalent benefits of SCS strategies in working lands given variation in their current extent and their annual per-hectare benefit over time (see model details and assumptions in Section 2 and Data S1). We assumed a 10-year delay to reach full implementation area (sensu Qin et al., 2021's *delayed extent* scenario; also Fuss et al., 2018, Gasser et al., 2015) and used NET-specific literature data on the initial SCS rate, final sequestration rate, lag time for detecting SCS benefits, and time to reach final SCS rates (Tables S1 and S2). The SCS rates in the initial adoption areas (areas where the practice has been deployed previously) are unknown due to the lack of information regarding when and for how long these lands have been managed, and thus the focus here is on quantifying the benefits of area expansion. Three different expansion scenarios represent the full extent of available working lands to estimate the technical potential (i.e., achievable SCS capacity with available technology, regardless of socioeconomic constraints; Roe et al., 2021), or a proportion of the full extent (or of the expansion in the case of agroforestry) as comparative benchmarks (25% or 50%; Figure 1). One area of uncertainty is how each SCS technology will perform across a range of soil, bioclimatic, and management conditions. For example, biochar and compost applications have been studied across a wide range of environments (Martínez-Blanco et al., 2013; Schmidt et al., 2021), while enhanced weathering is not well studied in the field across broad spatial scales or intermixed with other management practices (Almaraz et al., 2022). The effects of climate change and atmospheric CO_2 are not considered here, but present additional areas of uncertainty for future research directions. Our analysis is limited to field-scale SCS and does not include addition or avoidance of CO_2, nitrous oxide, or methane emissions, or other lifecycle emissions associated with the practices (e.g., production, transportation, commodity impacts, etc.) which represent important areas for future research.

Our model-based results showed that the maximum technical potential of combined working land NETs, if deployed to their fullest spatial extent, have the capacity to remove 13.5 gigatons (Gt) CO_2/year by 2050 (final rate in the year 2050; Figure 1a). This magnitude of C sequestration is similar to current food system emissions (~10–19 Gt CO_{2eq}/year; Crippa et al., 2021; Rosenzweig et al., 2020). Deployed at 25 to 50% of the globally available land area (Figure 1b,c), the combined SCS practices could remove 2.9–6.5 Gt CO_2/year by 2050, respectively. In addition to the uncertainties discussed in detail below, socioeconomic, and political realities could impact the realization of this potential. Regardless, our analysis demonstrates that SCS approaches have sufficient potential to be considered as part of a portfolio of NETs for climate change mitigation. We compared our estimates with those published in the literature, which were similar in magnitude (Beerling et al., 2018; Griscom et al., 2017; Lessmann et al., 2022; Roe et al., 2021). For example, Roe et al. (2021) estimated a global technical mitigation potential for NETs in working lands of ~9 Gt CO_{2eq}/year; however, that analysis did not include technologies such as enhanced weathering or compost applications.

The model also highlighted variance in the technical potential of SCS practices and extent of global implementation. The model incorporates mitigation potential in working lands as well as temporal aspects related to the amount of time SCS practices take to start detecting C sequestration, reach full sequestration intensity, reach full extent of adoption area, as well as temporal variation in initial vs. final C sequestration intensity. When deployed at 100% capacity (Figure 1a), biochar and enhanced weathering maintained the highest SCS rate, sequestering 3.9 Gt CO_2/year by 2050, each. The high impact of biochar and enhanced weathering occurred because these practices were implemented on more area than other practices. It is notable that enhanced weathering is currently limited in its geographical extent, but in the model the potential area for implementation was much larger, assuming available substrate (Beerling et al., 2020). Therefore, enhanced weathering may have lower SCS if substrate is unavailable. Compost had the highest peak sequestration rate of 11.1 Gt CO_2/year in 2031, which declined to 2.8 Gt CO_2/year by 2050. This is due to its longer period for reaching final intensity, effectively maintaining a higher SCS rate for a longer period and accumulating the most C of all the practices by 2050 (Table S3). Variation in SCS rate over time was the result of transitions between initial and final intensity, which varies in relative magnitude and timing between SCS practices and was derived from field-based observations (Tables S1 and S2). Biochar, compost, and enhanced weathering have been observed to show fast rates of SCS initially, followed by reductions in efficacy (Aydin et al., 2020; Kelland et al., 2020; Madari et al., 2017; Powlson et al., 2012). Cover crops and no-till had relatively low climate mitigation potential with rates of 1.5 and 0.95 Gt CO_2/year by 2050, respectively, also with relatively low implementation area. Agroforestry had the lowest final potential intensity and the lowest expansion and max area, resulting in the lowest annual SCS rate by 2050 (0.53 Gt CO_2/year). We assumed that agroforestry could only be adopted on 20% of abandoned croplands to avoid competition with the production of other food commodities, and that SCS is just 30% of agroforestry's overall C benefit, with additional C gains possible in aboveground biomass (Kim et al., 2016). Thus, agroforestry may have greater overall potential than estimated here. To address potential socioeconomic constraints, we generated a range of estimates based on deployment rates that varied from 25%–100% adoption (Figure 1a–c). At 50% adoption, the mitigation potential of biochar and enhanced weathering was 1.9 Gt CO_2/year by 2050. Compost was in between at 1.3 Gt CO_2/year while cover crops, no-till, and agroforestry were < 1 Gt CO_2/year by 2050 (Figure 1b). At 25% adoption, the mitigation potential of biochar and enhanced weathering was ~1 Gt CO_2/year by 2050. Compost was 0.57 Gt CO_2/year whereas cover crops, no-till, and agroforestry were <0.3 Gt CO_2/year by 2050 (Figure 1c).

Cumulative SCS of combined practices over the 30-year time period of our analysis ranged from 118 to 531 Gt CO_2 based on adoption rates that varied from 25 to 100% of working land extent (Table S3). It is estimated that if NET implementation were delayed to 2030, 450–800 Gt CO_2 removal will be required by 2100 to stabilize our climate to just 2°C of warming (Gasser et al., 2015), making working land SCS practices a potentially important tool to reaching those goals. Our estimates are in line with others that suggest NET deployment results in gross cumulative removal of 290–760 Gt CO_2 between 2030 and 2050 (assuming delayed action until 2030) and that total NET deployment results in cumulative removal of 150–1180 Gt CO_2 in the 21st century (including non-agricultural NETs; Fuss et al., 2018). Given limited evidence, we do not consider C saturation (sensu Qin et al., 2021). Modeling data estimated considerable potential to lower global temperatures even within a 50-year time horizon (Mayer et al., 2018). Sanderman et al. (2017) suggested that a global soil C deficit of 133 Gt exists as a result of historical agricultural land use, thus we consider our lowest (25% adoption) estimate of 118 Gt cumulative SCS to be conservative with respect to potential C saturation, particularly given the short duration of the time horizon considered.

Our findings show significant C benefit of working land NETs, and that the benefit varies by practice. However, work is needed for all practices to achieve the scale required to realize the maximum SCS potential. Cover crops and no-till are some of the most widely adopted SCS practices in developed nations (Porwollik et al., 2019; USDA, 2017) and while these have lower soil SCS potential than other practices, they are widely implemented. Soil amendments show high degrees of technical potential but are less well studied at mechanistic, field, or regional scales. Deployment of field demonstrations of soil amendments, both singly and in combinations, could help researchers study their C benefits across a variety of biophysical contexts (e.g., soil types, crop types, climates, etc.), the mechanisms that drive effective C sequestration and parameterize more spatially sophisticated models of their climate impact at large scales. Agroforestry was one of the least impactful SCS strategies as a result of limiting expansion area to abandoned croplands. However, on farm agroforestry practices such as hedgerows or intercropping area widely studied and practiced, predominately on small holder farms in developing nations and holds additional SCS potential. While extensive data sets on agroforestry as an NET exist, the practice is often not compatible with mechanization in industrial agriculture and quantification issues remain when assessing the C benefit of agroforestry (Cardinael et al., 2018; Chapman et al., 2020). Research demonstrations on how to incorporate agroforestry into industrialized agricultural landscapes or remote sensing methodology that better characterize agroforestry from other land use types might help enhance the extent of this practice.

We present preliminary estimates of technical potentials based on an uneven complication of average rates of field and modeling studies across practices and generalized spatial extents. However, rates that varied by biophysical characteristics and land management could better identify where these practices could be most effective. For example, the SCS benefit of enhanced weathering varies based on emissions associated with rock transport (i.e., life cycle emissions; Beerling et al., 2020), chemical composition of the rock, soil characteristics (like pH or texture), management practices (like irrigation or crop type), the form in which CO_2 is sequestered (with bicarbonate sequestering 2 moles and calcium carbonate sequestering 1 mole of CO_2), and whether CO_2 is released back into the atmosphere along surface water flow paths. Greater climate benefit may be available for composted amendments depending upon feedstock used and avoided emissions from diverting waste from high-emitting waste streams. More field data are needed to better quantify SCS and associated emissions. Soil C sequestration practices have also shown evidence of climate change mitigation for gases not considered in this analysis, such as CH_4 or N_2O, both at the field scale and beyond. For instance, compost may reduce CH_4 emissions associated with food waste disposal in landfills, replace inorganic nitrogen fertilizer inputs and subsequent N_2O emissions, increase aboveground biomass C, and decrease soil N_2O emissions, thus increasing it is over all mitigation potential (DeLonge et al., 2013; Guenet et al., 2021; Ryals et al., 2014). The boundaries between emission reductions and SCS can be difficult to disentangle because the agricultural emissions and climate change mitigation sectors are so closely related (e.g., avoided food waste or manure emissions through composting co-occurring with increases in compost facilities and transport). While addressing emission reductions is outside of the scope of this paper (which focuses on SCS) future analyses should take into consideration emission reductions and links between working lands and peri-urban environments. We show that NETs in working lands hold tremendous near-future potential based on available data; however, the effectiveness of these SCS practices will likely vary based on available substate, embedded emissions, and the durability of the C.

1.3 | Strategies to scale soil carbon sequestration practices in working lands

Soil C sequestration practices produce co-benefits for farmers and ranchers, are relatively simple to implement, and generally have widespread public support (Lo et al., 2021). Co-benefits that provide services to land managers can help enable the adoption of practices that promote SCS, for example, increased crop yield and improved soil health indicators such as decreased erosion, improved water retention (Flint et al., 2018) and enhanced nutrient inventories (Almaraz et al., 2021). Such benefits can reduce input costs and improve profits. Additionally, SCS practices can promote broader ecosystem services. For example, compost applications can improve drought resilience (Flint et al., 2018) and agroforestry can increase wildlife habitat (Daryanto et al., 2018; Delgado et al., 2011; Paustian et al., 2016). Most SCS practices can be implemented in working lands using existing technology. Cover cropping and agroforestry use resources like seeds, germplasm, and planters that many farmers have access to; soil amendment applications are similar to that of spreading other inputs like manure, fertilizer, or lime; and no-till equipment is available to many farm operations. A survey of US adults found support for SCS practices beyond that of direct air capture or biomass with C capture and storage (Sweet et al., 2021). Still, barriers do remain, particularly with respect to cost-effectiveness, issues of scale, and knowledge gaps (Dumbrell et al., 2016).

Co-benefits to soil health that have the potential to cut operating costs (i.e., water or fertilize use) and increase profitability (i.e., yields) can incentivize the adoption of SCS practices. The direct payment for implementation is another powerful mechanism to increase adoption. The C offset market creates such financial incentives and is developing quickly, which may increase SCS practice adoption. Still, many of the SCS practices discussed here are not incorporated into C offset registries or similar state programs. Advancing a broader category of SCS methodologies into C offset registries may help facilitate adoption of such practices. Issues remain with regard to verification, permanence, standardization, and perverse incentives that come from self-regulation of a private industry (Badgley et al., 2022; Oldfield et al., 2022). To avoid payment programs that exacerbate climate change through the sale of low-quality offset credits, it will be important to either develop regulatory agencies that set and enforce high crediting standards across the industry or to develop novel incentivization programs. Carbon offsets can benefit SCS as an effective bridging technology by providing a vehicle to increase the adoption of improved management practices in the short term; however, we caution readers that they do not provide longer-term benefits and thus may be counterproductive to climate change mitigation should outstanding issues remain unaddressed.

Soil C sequestration on working lands is a high-value climate change mitigation strategy with a favorable return on investment given the low cost of implementation relative to more technologically complex solutions. The current cost of SCS practices described here (Table 1) range from \$7–119/t CO_2 sequestered (or as much as \$300/t CO_2 in the case of biochar; Smith et al., 2008; McLaren, 2012), making them relatively affordable compared to other NETs like direct air capture (US\$600–1000/t CO_2; Fuss et al., 2018). Growing economic incentives for farmers storing C in soils can promote adoption of these practices, and future returns from agronomic co-benefits can make these practices more economically viable (Marland et al., 2001; Thangata & Hildebrand, 2012; Zaher et al., 2013). A recent analysis found that other NETs, such as direct air capture, pose significant challenges to implementation with regard to cost and resource use, while SCS enhances the land, air, and water resources on which working lands depend, leading to improvements in environmental quality, food security, and rural economies (Field & Mach, 2017). In general, more technologically intensive NETs have higher capital and energy costs, require new infrastructure, and need further research and development before being brought to scale (Field & Mach, 2017; Fuss et al., 2018; Hanna et al., 2021). While decarbonization and improved efficiency of energy and transportation is a critical aspect of any climate change mitigation portfolio (Stokes & Breetz, 2018), the necessary policy, economic, and infrastructural change will take time to implement (Breetz et al., 2018). Soil C sequestration in working lands represents a high-value gateway to wider NET adoption with the potential to sequester C in the near term that may be long lived.

While SCS practices in working lands hold promise for climate, food security, and the environment, widespread adoption remains a principal challenge. Greater attention to the quantification of agronomic outcomes of SCS practices across diverse agroecological systems, and the dissemination of this information to farmers and ranchers will help to facilitate widespread adoption. Potential barriers to adoption can be overcome by leveraging existing research and extension frameworks that demonstrate practice efficacy and provide technical knowledge while promoting social learning (Hoffman et al., 2015), identifying limiting factors (Niles et al., 2015), and fostering innovation and cooperation within social networks (Levy & Lubell, 2018). For example, farmers may be hesitant to adopt certain SCS practices given uncertainties around sourcing, costs, and application methods, as well as their variable efficiencies across different soil types, climates, crop types, and other farming practices. By more effectively collaborating with agricultural stakeholders such as farmers, ranchers, Tribes, researchers, state agencies, private industry initiatives (e.g., C offset registries, C credit producers, amendment suppliers, etc.), and the entities that develop and manage the standards and protocols eligible for obtaining C offsets, academic, and public projects can produce scientific frameworks of SCS practices that have current market applicability for land owners (e.g., Marin Carbon Project, USDA SARE program, NRCS EQIP, COMET-Planner for the CDFA Healthy Soils Program, etc.). Such collaborative frameworks will help to build trust in SCS practice utility within farming communities, businesses seeking voluntary C offsets, and policymakers.

Future soil C research will benefit from an "innovation ecosystem" approach (Figure 2) that is based on the principle of community input to rapidly scale research into policy and practice, considering the full array of stakeholder input and tailoring promotion of SCS practices to the site-specific conditions (Knowler & Bradshaw, 2007). Scientific advancements aimed at rapid and scalable application in working lands will benefit from collaborative networks that involve multi-sector actors in the areas of: (1) knowledge and technology (e.g., earth and life scientists, private industry, etc.), (2) economics and infrastructure (e.g., economists, government agencies, suppliers and distributors, etc.), and (3) agronomy and adaption (e.g., farmers and ranchers, social scientists, technical advisors, etc.). Building such partnerships that involve players who are integral to all aspects of implementation at the research and development stage can help overcome barriers to adoption early on, disseminate information regarding new climate change mitigation practices, and potentially kick start the development of infrastructure and supply chains that will support scalable implementation. These networks will improve scientific research by incorporating bi-directional learning between researchers and agricultural practitioners, as well as provide the necessary metrics, monitoring strategies, and evaluation capabilities needed for effective implementation.

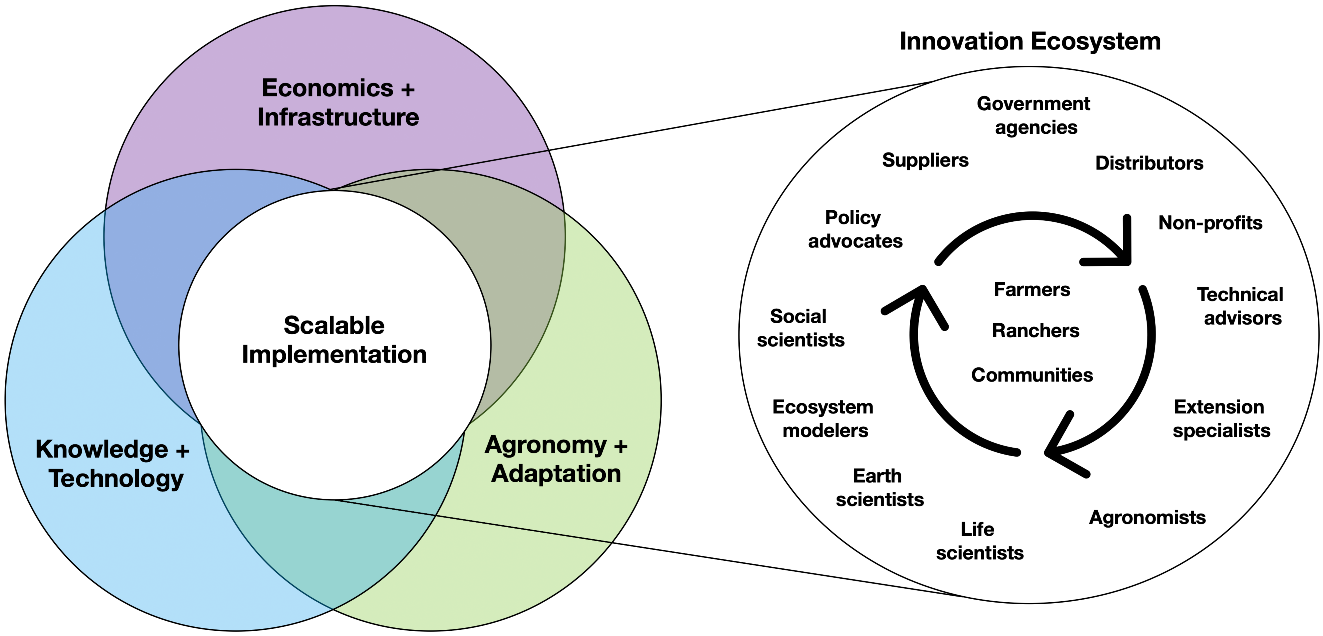

FIGURE 2 Venn diagram representing economic, infrastructure, knowledge, technology, and agronomy and adaptation attributes to support scalable implementation of soil carbon sequestration (SCS) practices and the innovation ecosystem network in support of farmers, ranchers, and rural communities to execute net emissions technologies (NET) on working lands.

2 | METHODS

We followed the modeling approach used by Qin et al. (2021) and parameterized the model using a combination of published values of soil C fluxes and agricultural land cover areas, assumptions about the length of time to achieve final annual C sequestration rates, and potential extents of implementation areas for each NET. To better determine the impact of SCS on CO_2 removal, we used only estimates of soil C sinks, and not addition or avoidance of CO_2, N_2O, or CH_4 emissions due to management. This analysis is limited to field scale belowground C sequestration and includes neither aboveground C sequestration nor broader life cycle emissions. The model is implemented in an algorithm that we built in R version 3.6.3 that simulates soil C dynamics in agricultural lands, treated with a NET, on an annual timestep (see "Data Availability" for code).

The model assesses the impact of implementation patterns in time and space by incorporating both a temporal component of implementation (T_e, how long it takes to reach maximum potential implementation area) and spatial intensity (T_i, how long it takes to reach final potential SCS rate). Specifically, the model is comprised of three sub-routines that simulate the following *for each NET*:

1. *Annual per area net soil C flux* (t CO_2e ha^{-1} year^{-1}) starting the first year of the NET treatment: the "initial_intensity" and "ti_delay" input values dictate the initial net soil C flux (baseline) and the number of years before the effect of the NET is detectable, respectively; and the "max_intensity" and "ti" input values dictate the final net soil C flux for the NET and the number of years to max_intensity following the ti_delay, respectively. A linear increase in the intensity is assumed starting in the year following the delay (Qin et al., 2021) at a rate equivalent to: (max_intensity—initial_intensity)/ti
2. *Annual extent of implementation area* (Mha) the "initial_area" had been managed previously, but the current rates of SCS are unknown on these lands due to lack of information on timing and persistence of management, so we focus on quantifying the benefits of expanding from the initial_area to the "max_area" by setting the SCS rates for the initial_area to zero. The "te" input value dictates the number of years it takes to reach max_area. A linear increase in the area extent is assumed (Qin et al., 2021) at a rate (rate_expand) equivalent to: (max_area—initial_area)/te. This expansion is implemented such that the start year represents only the initial_area and the first expansion is completed by the beginning of the second year.
3. *Total annual global net soil C flux* (t CO_2e year^{-1}) starting the first year of the NET treatment: the annual per area net soil C flux trajectory calculated in sub-routine #1 is applied to each new amount of treatment area ("parcel") calculated in sub-routine #2 (equivalent to rate_expand) to calculate the total annual soil C flux for each of these parcels for the simulation period. The parcels are subsequently summed for each year to get the total annual soil C flux for the NET.

We assumed the time to reach full implementation area (T_e) to be 10 years for all SCS practices, with model estimates beginning in 2020 and ending in 2050. Current implementation extent (initial_area), time to start detecting benefits (T_i_delay), time to reach full intensity (T_i), and time to reach maximum SCS benefit (T_i_adjusted) varied between practices according to the literature (Table S2). The actual mitigation each year is proportional to its annual potential, which depends on the time to reach full extent (T_e) and the maximum mitigation intensity (T_i). Te is largely influenced by the speed of implementation and potential area of deployment while T_i depends more so on biophysical controls on SCS rates as observed with field studies. The rate of expansion was determined by calculating the difference between initial implementation extent at onset of the analysis (initial_area) and the potential implementation extent (max_area), both of which were sourced from the literature, over the time it takes to reach full extent of potential adoption area (T_e). Agroforestry was scaled to abandoned cropland only (613 Mha), and its max_area was scaled based on the difference between initial_area and max_area because otherwise the max_area would have been less than the initial_area. No-till and cover crops were scaled exclusively to croplands (1132 Mha), whereas soil amendments (biochar, compost, and enhanced weathering) were additionally scaled to managed pastures (2800 Mha) as opposed to the entirety of rangelands due to limitations on source materials (e.g., feedstock for compost). The 50% and 25% adoption scenarios use a fraction of this land area. Expansion extent over time is depicted in Figure S1. No-till is already widely practiced in areas like the United States and Australia (Powlson et al., 2014), thus additional SCS will vary regionally. Since our analysis is not spatially explicit, we instead account for this by using an initial area of 265 Mha considered to be "less intensively tilled" (used in place of "no-till") and apply our analysis to areas considered to be "intensively tilled" (Porwollik et al., 2019). Biochar and compost can be generated from organic matter, such as crop residues, timber, logging residues, grasses, food waste or animal, and human fecal matter (Berendes et al., 2018; FAO 2011; Griscom et al., 2017; Matovic, 2011). Others have estimated feedstock available for conversion at 10% of the net primary production, or 60.6 Gt/year (Matovic, 2011). At an application rate of 10 metric tons/ha for biochar and 3.6 metric tons/ha for compost (Gravuer & Gunasekara, 2016), feedstock requirements across 1132 million ha of global cropland and 2800 million ha of global pasture equate to 39 Gt and 14 Gt, respectively. Others have determined adequate substrate availability for enhanced weathering in global croplands, thus this was not a consideration (Beerling et al., 2020). The intensity slope was determined as a function of the "max_intensity" (which represents final intensity) minus the "initial_intensity" over the time it takes to reach full intensity (T_i), once accounting for the time delay it takes to start detecting benefits (T_i_delay). For compost, biochar, and enhanced weathering the max_intensity is less than the initial_intensity because we assume a single soil amendment with these practices on each new parcel and decreasing intensity over time. For no-till, cover crop, and agroforestry the intensity increases over T_i as the effects of annual management mature. We assume additive effects given multiple strategies on the same area. Detailed parameterization values of SCS, land area, time to detect benefits, literature sources, and assumptions/justifications can be found in Tables S1 and S2.

3 | CONCLUSION

There is an urgent need to develop and deploy tools to reduce atmospheric greenhouse gas concentrations if we are to minimize the devastating impacts of climate change. Soil C sequestration practices are low risk, low-tech approaches that offer multiple agronomic co-benefits and promise within the portfolio of climate change solutions, as well as support the adaptation of working lands to the local effects of climate change. Scientists can help facilitate SCS by focusing resources on demonstration, application, and implementation of individual and portfolios of SCS practices and by tailoring results and information to practitioners and communities. To solve the climate crisis and ensure that working lands adapt to supplying the future demand of the global population, we need better incentives and rewards for SCS practices from the private sector, support from our policymakers for both organizational infrastructure for communication and knowledge sharing across an innovation ecosystem, including those existing (e.g., Cooperative Extension) and improved incentives for farmers, ranchers, and technical advisors (Eanes et al., 2019). The road to SCS can be short if adequate support is provided to promote the widespread adoption of NETs in working lands. Collaborative, solution-based science grounded in innovation networks can help actualize the benefits of SCS when it is needed; now.

AUTHOR CONTRIBUTIONS

Maya Almaraz and F. Garrett Boudinot collected model parametrization data. Maegen Simmonds developed the modeling algorithm. Alan V. Di Vittorio revised the model and some model inputs and produced model outputs and figures. Maya Almaraz created tables and conceptual figures. All authors helped formulate concepts around the immediacy of soil C action. Sat Darshan S. Khalsa and Steven Ostoja contributed to concepts around network science. Whendee L. Silver and Maya Almaraz conceptualized the manuscript, and Whendee L. Silver provided guidance and feedback on the writing and framing. Maya Almaraz drafted the first version of the manuscript with input from Nina Bingham. All authors commented on the draft and improved the manuscript substantially.

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CONFLICT OF INTEREST STATEMENT

The authors have no competing interests to declare.

DATA AVAILABILITY STATEMENT

Analyses were conducted using R, code for which can be found at: https://www.dropbox.com/s/5glzjslnoe1n7gb/Call_To_Arms_Model_20230501.R. The input data that support the findings of this study were compiled from the literature and are openly available on Zenodo at https://doi.org/10.5281/zenodo.8121937. The output data for this study are openly available on Zenodo at https://doi.org/10.5281/zenodo.8125193. Model parameterization data can also be found in Tables S1 and S2. Any additional data can be made available by the authors upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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