Soil carbon offset markets are not a just climate solution

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There is growing interest in enhancing soil carbon sequestration (SCS) as a climate mitigation strategy, including neutralizing atmospheric emissions from fossil-fuel combustion through the development of soil carbon offset markets. Several studies have focused on refining estimates of the magnitude of potential SCS or on developing methods for soil carbon quantification in markets. We call on scientists and policy makers to resist assimilating soils into carbon offset markets due to not only fundamental flaws in the logic of these markets to reach climate neutrality but also environmental justice concerns. Here, we first highlight how carbon offset markets rely on an inappropriate substitution of inert fossil carbon with dynamic stocks of soil carbon. We then note the failure of these markets to account for intersecting anthropogenic perturbations to the carbon cycle, including the soil carbon debt and ongoing agricultural emissions. Next, we invite scientists to consider soil functions beyond productivity and profitability. Finally, we describe and support historical opposition to offset markets by environmental justice advocates. We encourage scientists to consider how their research and communications can promote diverse soil functions and just climate-change mitigation.

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Soil carbon is for sale. Shifts in land use can increase soil organic carbon stocks relative to current levels, and these potentials have been commodified in markets (Paustian *et al*. 2016; Fargione *et al*. 2018; Bradford *et al*. 2019; Vermeulen *et al*. 2019; Bossio *et al*. 2020). As global markets adapt to (i) climate change, (ii) potential regulatory pressures, and (iii) consumers' environmental concerns, payments for soil carbon sequestration (SCS) have been proposed by corporations, organizations, and governmental agencies as a strategy to deliver climate-change mitigation. Among a variety of proposed market-based solutions to climate change, soil carbon on agricultural lands can now be purchased as an offset to "neutralize" activities responsible for direct greenhouse-gas (GHG) emissions (Trouwloon *et al*. 2023). These offsets are sometimes used to support net-zero targets in GHG budgets for facilities, supply chains, and regional inventories (Keenor *et al*. 2021; Zelikova *et al*. 2021; Oldfield *et al*. 2022; Gelardi *et al*. 2023; Paul *et al*. 2023; USDA 2023). Here, we posit that this approach is fundamentally flawed and incongruous with environmental justice principles.

In a nutshell:

- Soil carbon offset markets attempt to substitute inert fossil carbon stocks with dynamic soil carbon stocks
- The soil carbon debt must be restored in addition to, rather than instead of, reducing direct emissions
- Soil carbon offset markets account poorly for soil functions beyond carbon storage
- Offset markets can perpetuate environmental injustice, including by exacerbating disparities

Soil carbon offsets are one strategy among several market-based approaches to climate mitigation. There are currently four compliance-based carbon offset markets in the US (USDA 2023). These markets allow regulated facilities to comply with their legal requirements to reduce GHG emissions by purchasing carbon offsets. In the US, these offset markets have generated credits for more than 200 million metric tons of carbon dioxide equivalents (t CO_2e) between 2013 and 2022, primarily issued in the context of compliance-based markets (USDA 2023). In addition, there are more than a dozen voluntary carbon offset markets in the US, which allow users to trade carbon credits outside of regulatory emission reductions requirements, often for the purpose of making climate-related claims in marketing. More broadly, in an analysis of climate neutrality commitments made by 482 large companies across sectors and across countries, nearly half of those companies explicitly intend to rely on offsets to achieve these commitments, with most of the remaining half unclear about the degree to which offsets will be relied upon (Kreibich and Hermwille 2021).

Several recent studies have provided evidence to temper enthusiasm about the climate mitigation potential of SCS. Initial proposals for developing soil carbon offset markets have been critiqued for inflated estimates of SCS potential due to their failure to consider the limited capacity for mineral soils to sorb additional inputs (Abramoff *et al*. 2021), the increasing vulnerability of soil carbon stocks to

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decomposition under climate change (Riggers *et al.* 2021), the impracticability of increasing inputs to the magnitude required to achieve proposed soil carbon targets (Berthelin *et al.* 2022; Bruni *et al.* 2022; Janzen *et al.* 2022; Moinet *et al.* 2023), and other processes regulating carbon storage (Davidson 2022; Schlesinger 2022). Concerns related to soil carbon offset markets extend beyond the need to refine estimates for the magnitude of potential SCS or mere improvements to methods for measuring, monitoring, and verifying changes to soil carbon stocks. While we recognize the importance of improved quantification, we invite scientists to consider fundamental flaws to the logic of climate-change neutralization via soil carbon offset markets and broadly interrogate how their work supports or resists ongoing fossil-fuel extraction, shapes political possibilities, and intersects with climate justice.

Navigating carbon offset markets may be relatively new to soil scientists; however, we can learn from the expertise of environmental justice advocates who have organized around issues of environmental degradation and developed positions on offset market-based mitigation strategies for decades. Many environmental justice advocates and frontline communities have a long history of opposition to market-based solutions to climate change (Cushing *et al.* 2018; CJA 2020; CorpWatch 2002; IEN 2023). We propose that scientists and policy makers learn from these lessons and join us to advocate for keeping offset markets out of soil.

Here, we outline four reasons to be wary of soil carbon offset markets for climate neutrality, ranging from biophysical limitations to environmental justice concerns. We focus our discussion on offset markets, which are a subset of market-based strategies to incentivize SCS, specifically relating to trading enhancements in SCS in one location to neutralize emissions elsewhere. This commentary is not a critique of soil stewardship, restoration, conservation, or preservation efforts. Rather, we invite scientists and policy makers to reframe the role of soils in climate-change mitigation beyond the commodification of soil as GHG offsets, especially where regulatory or otherwise mandatory direct emissions reductions are possible, and to critically consider environmental justice in the development of climate solutions.

Dynamic soil organic carbon is not a substitute for fossil carbon

Soil organic matter is part of the dynamic carbon cycle. Carbon in soil can accumulate, saturate, disperse, and decompose through a diversity of biogeochemical interactions, including inputs from leaf litter, plant roots, and microbial necromass, and outputs from decomposition by bacteria, archaea, and fungi (Jackson *et al.* 2017; Berhe *et al.* 2018). Microbial community dynamics, mineral interactions, climate, and other factors impact whether soil organic carbon persists for days, decades, or centuries (Sierra *et al.* 2018; Bailey *et al.* 2019; Cotrufo *et al.* 2019; Wiesmeier *et al.* 2019; Shi *et al.* 2020). However, even the oldest soil organic carbon is hundreds of millions of years younger than fossil carbon stored deep underground (and a greater disparity would exist in the absence of anthropogenic fossil-fuel emissions; Sierra *et al.* 2018). Due to rapid mineralization by soil microorganisms, less than 10% of organic matter inputs are likely to remain in soil a decade after their addition (Berthelin *et al.* 2022). In contrast, in the absence of industrial extraction, fossil carbon is largely inert and is not closely linked with seasonal to decadal biological fluxes of carbon. Thus, inert stocks of fossil carbon inherently differ from even the most persistent stocks of soil organic carbon in terms of the timescales at which this carbon is likely to cycle through the atmosphere.

Soil carbon offset markets often obfuscate these distinctions. Actors within offset markets may frame the dynamic nature of soil carbon as a limitation circumventable through advancements in technology and land-use management. For example, many offset market participants claiming neutrality treat these fundamental differences in permanence as uncertainties that may be refined through improvements in biogeochemical and economic modeling or by framing permanence as an issue primarily shaped by land management decisions potentially addressed through contractual language and buffers (Demenois *et al.* 2022). Certainly, it will be critical to develop a better understanding of factors impacting persistence, including the ways in which sociopolitical drivers shape land-use practices (Gosnell *et al.* 2019, 2020; Silva 2022). However, efforts to characterize the effects of soil management will not change the fact that fundamental differences exist between inert fossil carbon stocks and dynamic, biogenic soil carbon stocks.

The impermanence, volatility, and transitory nature of some forms of soil carbon are not necessarily flaws in need of correction. The dynamism of soil organic matter is a critical ecosystem function, as decomposition makes nutrients available for re-uptake by organisms, enabling plant and microbial growth (for further discussion, see the section "Soils are more than carbon sinks" below). For example, direct releases of carbon from soils through microbial respiration are a function of decomposer activities, and this biological activity is even included in assessments of soil health (Allen *et al.* 2011). In this way, active cycling of carbon can be a critical component of soil function that is overlooked by offset markets that exclusively seek to increase belowground stores of carbon to make carbon neutrality claims.

Restoring prior losses of soil carbon cannot neutralize ongoing direct emissions, including those from land-based sectors

Anthropogenic activities have multiple, intersecting impacts on the carbon cycle and climate. First, fossil-fuel combustion has removed 445 ± 20 petagrams of carbon

(Pg C) from belowground fossil carbon stocks, transferring previously inert carbon into the biosphere (Friedlingstein *et al*. 2020). Second, agricultural activities and other land-use conversions can lead to removals of organic carbon from surface soils. The cumulative loss of 116 Pg C from the upper 2 m of soil globally over the past 12,000 years of land use has been termed the soil carbon debt (Sanderman *et al*. 2017). Third, agricultural land use incurs a carbon opportunity cost, or a reduction in sequestration relative to that which would occur over time in the absence of agriculture (Hayek *et al*. 2021). As a specific example, the cumulative carbon opportunity cost of land use for livestock production globally is comparable in order of magnitude to the past decade of fossil-fuel emissions, in the hundreds of petagrams of carbon (Hayek *et al*. 2021). Fourth, agricultural activities result in additional direct emissions, including carbon dioxide (CO_2) emissions from farm equipment, methane from livestock and manure, and nitrous oxide from fertilizer use. Offset markets fail to account for these overlapping impacts to the carbon cycle and climate, or in some cases, obscure ongoing emissions and prior losses from within the agricultural sector (Paul *et al*. 2023). While increases in soil carbon may most directly address the soil carbon debt, offset markets propose that instead we credit efforts to restore soil carbon as an excuse for ongoing direct emissions.

Estimates of prior losses of soil organic carbon, like the soil carbon debt, have been used to calculate the potential for restoring soil carbon stocks on agricultural lands relative to current levels. These studies have formed the basis for a wide range of global and regional targets for increasing soil carbon, as well as revisions to previous estimates (Fargione *et al*. 2018; Amelung *et al*. 2020; Bossio *et al*. 2020; Berthelin *et al*. 2022; Bruni *et al*. 2022; Moinet *et al*. 2023). Rather than viewing the potential for SCS as an opportunity to neutralize fossil-fuel emissions via offset markets, these quantifications of prior soil carbon losses should be understood as their own distinct debt to be restored through shifts in soil management.

Distinguishing between the soil carbon debt, fossil carbon emissions, and changes in carbon sequestration is particularly important in the development of counterfactuals used to determine *additionality* within carbon offset markets. Additionality is the point at which increased carbon storage in one location is attributed to have occurred as a result of a given market intervention and therefore used to excuse emissions elsewhere. To determine which gains in soil carbon are deemed additional and eligible for compensation, offset markets compare soil carbon quantities under alternative scenarios or timepoints. The development of these counterfactuals is not simply a scientific question, but rather one representing sociopolitical and market visions of what concentrations should and can exist in a certain location under alternative land-use choices.

For instance, one may arrive at different determinations of additionality depending on the following counterfactuals: (i) soil carbon concentration prior to major historical land-use changes (eg before deforestation for croplands), (ii) soil carbon concentration prior to the market intervention (eg before payments for adoption of cover crops), or (iii) soil carbon concentration accounting for carbon opportunity costs (eg predicted concentration with ecosystem restoration). Offset markets often accept additionality to mean an increase in soil carbon using counterfactual (ii). Although this type of counterfactual has informed many global and regional targets (Berthelin *et al*. 2022; Bruni *et al*. 2022), it fails to account for the major impact of prior agricultural land-use conversion or to treat alternative land-use scenarios outside of current modes of agricultural production as serious possibilities.

Continued agricultural production on existing acres, even when practiced with building soil carbon in mind, cannot pay back the soil carbon debt alone. Although shifts in land-use strategies can increase soil carbon stocks relative to current levels (Lal 2001; Smith *et al*. 2005, 2008; Paustian *et al*. 2016; Bossio *et al*. 2020), estimates generated by Sanderman *et al*. (2017) suggested that adoption of these management practices could at most only repay up to 30% of the soil carbon debt. Furthermore, the agricultural sector is not merely a sink for emissions but is also a source. In the US, agricultural activities are responsible for 36% of methane emissions and 75% of nitrous oxide emissions (EPA 2023). Recent analyses indicate that offsetting the warming effect of methane and nitrous oxide emissions from the ruminant sector worldwide would require nearly doubling the current global carbon stock stored in managed grasslands (Wang *et al*. 2023). While shifts toward practices that build soil carbon and reduce losses may help restore a portion of the soil carbon debt and offer other ecological co-benefits, these transitions should not be considered additional until the soil carbon debt has been repaid and agricultural direct emissions have been properly accounted for. Given the limited size of the soil carbon sink and considerable ongoing and hard-to-abate agricultural emissions, it is unlikely that SCS can support both net-zero emissions targets within and beyond this land-based sector.

Scientists and policy makers may also heed the warnings imparted by several concerning projects focused on natural climate mitigation aboveground, in which biogenic stocks of carbon were offered as offsets to excuse fossil-fuel emissions without meaningfully increasing carbon sequestration (Anderegg *et al*. 2020; Haya *et al*. 2020; Coffield *et al*. 2022; Jones and Lewis 2023; West *et al*. 2023). For example, studies of aboveground forest carbon offset markets have repeatedly found that additionality has been exaggerated through misleading counterfactual constructions and the reversibility of sequestered carbon. Badgley *et al*. (2022) found evidence for systematic over-crediting of 30.0 million t CO_2e in California's forest carbon offsets program alone. In an analysis of voluntary carbon offset market projects in six countries, West *et al.* (2023) reported that most projects failed to reduce deforestation substantially, and a subset of analyzed projects were used to offset nearly three times the amount of carbon emissions relative to their actual contribution to climate-change mitigation. Often such land-based projects may even incur additional emissions rather than remove atmospheric carbon (Paul *et al.* 2023). These cautionary signs are especially concerning as markets shift belowground, where assessment and verification of carbon stocks are even harder to confirm and as climate change makes soil carbon stocks increasingly vulnerable to decomposition (Crowther *et al.* 2016; Soong *et al.* 2021; Wang *et al.* 2022).

Soils are more than carbon sinks

Offset markets narrowly focus on soils as sinks for carbon, which can often come at the exclusion of considering impacts on nutrients, water cycling, nitrous oxide and methane emissions, and other ecosystem processes. Soil organic carbon exists in a heterogenous matrix of organic matter with different stoichiometric ratios of carbon, nitrogen, phosphorus, and other nutrients. Thus, changes to soil carbon storage both rely on and impact soil nutrient availability, which in turn impacts plant productivity and microbial activity. Critically, interventions focused solely on building soil carbon can even result in increases of other soil-based GHG emissions (Lugato *et al.* 2018; Quemada *et al.* 2020).

Failing to account for these interconnections results in gross overestimations of SCS potential and unrealistic targets (Berthelin *et al.* 2022; Bruni *et al.* 2022; Schlesinger 2022). For example, on farm soils with crop biomass removed, the amount of nitrogen required to achieve a previously proposed soil carbon concentration target of "4 per 1000" (0.4% per year) is greater than global natural and anthropogenic nitrogen fixation combined, and the amount of phosphorus required is a substantial proportion of global phosphate rock mined each year (Abramoff *et al.* 2021). Accounting for factors such as soil carbon saturation (Moinet *et al.* 2023), the priming effect of new soil carbon inputs on soil microbial activities (Guenet *et al.* 2018), the dependency of soil carbon stocks on photosynthetic inputs and nutrient uptake (Janzen *et al.* 2022), or the net GHG balance of soils (Lugato *et al.* 2018; Quemada *et al.* 2020) also dampens estimates of SCS potential. Wider systematic thinking needs to be implemented when discussing the potential of rebuilding soil organic carbon, including trade-offs of soil and plant carbon sequestration with elevated CO_2 (Terrer *et al.* 2021). Given the multifunctionality of soil carbon in organic matter, there are many reasons to both build soil carbon and reduce additional losses (Minasny *et al.* 2023) while bearing ecosystem-specific aspects in mind.

Soil organic carbon stocks also impact soil biodiversity, as microbes, plants, and other organisms are adapted to particular soil conditions (He *et al.* 2012; Yu and Chen 2019). Thus, changes to soil organic carbon may affect soil microbial community composition, with poorly understood impacts. Especially in low organic matter soils that support specialized species and high beta-diversity across regional scales (Fernandez-Going *et al.* 2013), adding organic carbon could change belowground and aboveground communities, resulting in biodiversity loss. Exclusively focusing on potential carbon storage has unknown consequences for the diversity of interconnected organisms living in and with soil. The dangerous consequences to biodiversity resulting from a singular focus on carbon have been obvious in the context of offset programs centered on aboveground stocks. For example, some existing afforestation programs have targeted large swaths of savanna for tree planting based on their designation as "deforested" or "degraded", thereby undermining grassland biodiversity (Veldman *et al.* 2015; Bond *et al.* 2019).

Furthermore, the exclusive focus on carbon storage reflects a narrow and new teleology of soil health and function, in which low carbon storage is equated with poor soil health. This perspective can at times conflict with a prior focus on maximizing the availability of soil nutrients for crop production or, more broadly, alternative relations to soil and soil health beyond maximizing capital (Krzywoszynska 2020). Historically, many scientific developments in the understanding of soil function have shaped and been shaped by their implications for agricultural productivity and profitability (Foster and Magdoff 1998; Mauro 2014; Puig de la Bellacasa 2015). For example, equations and models describing the kinetics of soil nutrient limitation for crop productivity drive particular modes of land management and mold conceptions of optimal soil function, which can also influence future research foci, priorities, and related policies (Foster and Magdoff 1998; Mauro 2014; Puig de la Bellacasa 2015; Krzywoszynska and Marchesi 2020; Lyons 2020; Nightingale *et al.* 2019). Recognizing the ways in which these factors have influenced the history and framing of soil science is critical as scientists are increasingly called upon to inform climate mitigation policies in agriculture. How might our work support a diversity of soil functions, soil organisms, and human–soil relations beyond those deemed economically profitable?

Offset markets perpetuate environmental injustice

Coalitions of environmental justice advocates and frontline communities have a history of opposing carbon offset markets, which can allow industries to evade accountability or delay reductions in direct emissions based on promised benefits elsewhere (ActionAid 2011; CJA and IEN 2017; NAACP 2021). For example, the Bali Principles of Climate Justice, which was endorsed by a broad coalition of organizations during the 2002 Johannesburg Earth Summit, identify "market-based mechanisms" as "false solutions" (CorpWatch 2002), and the Indigenous Environmental

Network's Principles of Just Transition specifically call for the rejection of carbon offset markets (IEN 2023). These objections are grounded in part by the experiences of communities located in proximity to polluting facilities. Offset sales within compliance markets have led to distributive injustices by enabling emissions—including both GHG emissions and harmful air pollutants—to persist or increase around vulnerable communities, based on presumed sequestration or reductions in emissions elsewhere (Cushing *et al.* 2018; Lejano *et al.* 2020; Declet-Barreto and Rosenberg 2022).

Historically, communities that are most burdened by environmental pollution have not benefited from offset market-based policies. For instance, in an analysis of the first 2 years of California's Cap and Trade program, Cushing *et al.* (2018) found that (i) regulated facilities were disproportionately sited in economically disadvantaged neighborhoods with higher proportions of residents of color; (ii) most of the regulated facilities increased emissions of both GHGs and co-pollutants, such as nitrous oxide, particulate matter, and sulfur dioxide, while participating in the program; and (iii) neighborhoods that experienced increases in both annual average GHGs and co-pollutants had higher proportions of people of color or other demographic factors indicating environmental justice concerns. Thus, the use of carbon offsets can allow regulated facilities to keep polluting and degrading local air quality by funding projects located far away from the source of direct emissions without directly benefiting frontline communities.

Enlisting agricultural soils as distant and opaque carbon sinks within carbon offset schemes has the potential to exacerbate environmental concerns for historically marginalized communities impacted directly by sites of extraction and emissions. Many social considerations exist around participation in aggregated offset markets (Barbato and Strong 2023), including issues of self-determination, procedural justice, and land rights. Prescribing particular land-use strategies based on global budgets and estimates of biogeochemical potential has direct implications to Indigenous and rural land rights (Bond *et al.* 2019; Nightingale *et al.* 2019; Newell 2022). These concerns extend across both compliance-based and voluntary markets. For example, tree-planting programs have targeted land in the Global South for afforestation efforts with poor consultation of local communities and harmful consequences to Indigenous land rights, food security, rural livelihoods, and biodiversity (Bond *et al.* 2019; Fleischman *et al.* 2020, 2022; Fischer *et al.* 2023). Regardless of improvements in methodologies for measuring soil carbon or reductions in uncertainty around the magnitude of potential sequestration in soils, scientists and policy makers must seriously consider concerns raised by environmental justice advocates and frontline communities and recognize that nearly all policies related to soil carbon management have implications for land rights.

Conclusions

Soil scientists are increasingly invited to engage in climate policy and market spaces. Often, these engagements are focused on providing quantitative estimates for the climate mitigation potential of SCS or developing methods to quantify carbon stocks for use within offset markets. We must recognize that these efforts are deeply intertwined with a wide range of issues, including biodiversity, land rights, food production, and environmental justice. Scientific findings operationalize particular framings of soil health and function, build the underlying protocols shaping carbon market structures, and are used to inform land-use policies. As soil scientists continue their critical research, we invite them to oppose the inclusion of soil carbon in offset markets and to further explore how the use of their work upholds or resists systems of fossil-fuel extraction and intersects with climate justice.

Strategies to restore the soil carbon debt must not be used as an opportunity to greenwash direct emissions. To shape climate policy, we urge soil scientists to ensure that any efforts to restore soil organic carbon are placed in appropriate context to distinguish between fossil carbon and soil organic carbon, and to distinguish between sources of often overlapping anthropogenic perturbations to the carbon cycle. Soil carbon simply cannot offset fossil-fuel emissions due to differences in permanence, existing agricultural climate impacts, and the interconnectedness of soil with multiple ecosystem functions.

Critically, offset markets raise several environmental justice concerns and have been opposed for several decades by frontline communities. Rather than developing methods to include SCS in climate neutrality claims, we invite scientists to draw from a long history of advocacy in opposition to offset markets to explore opportunities for climate mitigation that seriously consider environmental justice. Corporations, organizations, and governments must be held accountable to realize absolute emissions reductions, and this accountability is not the work of environmental justice advocates alone. Soil scientists can advocate for shifting efforts from developing offset markets toward promoting action on direct emissions reductions, including those from land-based sectors. Finally, soil scientists can support transitions to systems that support a broader diversity of soil functions and honor soil relations beyond commodification.

Data Availability Statement

No data were collected for this study.

References

Abramoff RZ, Georgiou K, Guenet B, *et al.* 2021. How much carbon can be added to soil by sorption? *Biogeochemistry* **152**: 127–42.

ActionAid. 2011. Say no to soil carbon markets! Six reasons why soil carbon markets won't work for smallholders. Johannesburg, South Africa: ActionAid.

Allen DE, Singh BP, and Dalal RC. 2011. Soil health indicators under climate change: a review of current knowledge. In: Singh B, Cowie A, and Chan K (Eds). Soil health and climate change. Berlin, Germany: Springer.

Amelung W, Bossio D, de Vries W, *et al.* 2020. Towards a global-scale soil climate mitigation strategy. *Nat Commun* **11**: 5427.

Anderegg WRL, Trugman AT, Badgley G, *et al.* 2020. Climate-driven risks to the climate mitigation potential of forests. *Science* **368**: 1327.

Badgley G, Freeman J, Hamman JJ, *et al.* 2022. Systematic over-crediting in California's forest carbon offsets program. *Global Change Biol* **28**: 1433–45.

Bailey VL, Pries CH, and Lajtha K. 2019. What do we know about soil carbon destabilization? *Environ Res Lett* **14**: 083004.

Barbato CT and Strong AL. 2023. Farmer perspectives on carbon markets incentivizing agricultural soil carbon sequestration. *npj Climate Action* **2**: 26.

Berhe AA, Barnes RT, Six J, and Marín-Spiotta E. 2018. Role of soil erosion in biogeochemical cycling of essential elements: carbon, nitrogen, and phosphorus. *Annu Rev Earth Pl Sc* **46**: 521–48.

Berthelin J, Laba M, Lemaire G, *et al.* 2022. Soil carbon sequestration for climate change mitigation: mineralization kinetics of organic inputs as an overlooked limitation. *Eur J Soil Sci* **73**: e13221.

Bond WJ, Stevens N, Midgley GF, and Lehmann CER. 2019. The trouble with trees: afforestation plans for Africa. *Trends Ecol Evol* **34**: 963–65.

Bossio DA, Cook-Patton SC, Ellis PW, *et al.* 2020. The role of soil carbon in natural climate solutions. *Nat Sustain* **3**: 391–98.

Bradford MA, Carey CJ, Atwood L, *et al.* 2019. Soil carbon science for policy and practice. *Nat Sustain* **2**: 1070–72.

Bruni E, Chenu C, Abramoff RZ, *et al.* 2022. Multi-modelling predictions show high uncertainty of required carbon input changes to reach a 4‰ target. *Eur J Soil Sci* **73**: e13330.

CJA (Climate Justice Alliance). 2020. Carbon capture and storage: a clear and present danger. Berkeley, CA: CJA.

CJA and IEN (Climate Justice Alliance and Indigenous Environmental Network). 2017. Carbon pricing: a critical perspective for community resistance. Bemidji, MN: IEN.

Coffield SR, Vo CD, Wang JA, *et al.* 2022. Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects. *Global Change Biol* **28**: 6789–806.

CorpWatch. 2002. Bali principles of climate justice. Berkeley, CA: CorpWatch.

Cotrufo MF, Ranalli MG, Haddix ML, *et al.* 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. *Nat Geosci* **12**: 989–94.

Crowther TW, Todd-Brown KEO, Rowe CW, *et al.* 2016. Quantifying global soil carbon losses in response to warming. *Nature* **540**: 104–8.

Cushing L, Blaustein-Rejto D, Wander M, *et al.* 2018. Carbon trading, co-pollutants, and environmental equity: evidence from California's cap-and-trade program (2011–2015). *PLoS Med* **15**: e1002604.

Davidson EA. 2022. Is the transactional carbon credit tail wagging the virtuous soil organic matter dog? *Biogeochemistry* **161**: 1–8.

Declet-Barreto J and Rosenberg AA. 2022. Environmental justice and power plant emissions in the Regional Greenhouse Gas Initiative states. *PLoS ONE* **17**: e0271026.

Demenois J, Dayet A, and Karsenty A. 2022. Surviving the jungle of soil organic carbon certification standards: an analytic and critical review. *Mitig Adapt Strat Gl* **27**: 1.

EPA (US Environmental Protection Agency). 2023. Inventory of US greenhouse gas emissions and sinks: 1990–2021. Washington, DC: EPA.

Fargione JE, Bassett S, Boucher T, *et al.* 2018. Natural climate solutions for the United States. *Sci Adv* **4**: eaat1869.

Fernandez-Going BM, Harrison SP, Anacker BL, and Safford HD. 2013. Climate interacts with soil to produce beta diversity in Californian plant communities. *Ecology* **94**: 2007–18.

Fischer HW, Chhatre A, Duddu A, *et al.* 2023. Community forest governance and synergies among carbon, biodiversity and livelihoods. *Nat Clim Change* **13**: 1340–47.

Fleischman F, Basant S, Chhatre A, *et al.* 2020. Pitfalls of tree planting show why we need people-centered natural climate solutions. *BioScience* **70**: 947–50.

Fleischman F, Coleman E, Fischer H, *et al.* 2022. Restoration prioritization must be informed by marginalized people. *Nature* **607**: E5–6.

Foster JB and Magdoff F. 1998. Liebig, Marx and the depletion of soil fertility: relevance for today's agriculture. *Mon Rev* **50**: 32.

Friedlingstein P, O'Sullivan M, Jones MW, *et al.* 2020. Global carbon budget 2020. *Earth Syst Sci Data* **12**: 3269–340.

Gelardi DL, Rath D, and Kruger CE. 2023. Grounding United States policies and programs in soil carbon science: strengths, limitations, and opportunities. *Front Sustain Food Syst* **7**: 1188133.

Gosnell H, Gill N, and Voyer M. 2019. Transformational adaptation on the farm: processes of change and persistence in transitions to "climate-smart" regenerative agriculture. *Global Environ Chang* **59**: 101965.

Gosnell H, Grimm K, and Goldstein BE. 2020. A half century of holistic management: what does the evidence reveal? *Agric Human Values* **37**: 849–67.

Guenet B, Camino-Serrano M, Ciais P, *et al.* 2018. Impact of priming on global soil carbon stocks. *Global Change Biol* **24**: 1873–83.

Haya B, Cullenward D, Strong AL, *et al.* 2020. Managing uncertainty in carbon offsets: insights from California's standardized approach. *Clim Policy* **20**: 1112–26.

Hayek MN, Harwatt H, Ripple WJ, and Mueller ND. 2021. The carbon opportunity cost of animal-sourced food production on land. *Nat Sustain* **4**: 21–24.

He Z, Piceno Y, Deng Y, *et al.* 2012. The phylogenetic composition and structure of soil microbial communities shifts in response to elevated carbon dioxide. *ISME J* **6**: 259–72.

IEN (Indigenous Environmental Network). 2023. Indigenous principles of just transition. Bemidji, MN: IEN.

Jackson RB, Lajtha K, Crow SE, *et al.* 2017. The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. *Annu Rev Ecol Evol S* **48**: 419–45.

Janzen HH, van Groenigen KJ, Powlson DS, *et al.* 2022. Photosynthetic limits on carbon sequestration in croplands. *Geoderma* **416**: 115810.

Jones JPG and Lewis SL. 2023. Forest carbon offsets are failing. *Science* **381**: 830–31.

Keenor SG, Rodrigues AF, Mao L, *et al*. 2021. Capturing a soil carbon economy. *Roy Soc Open Sci* **8**: 202305.

Kreibich N and Hermwille L. 2021. Caught in between: credibility and feasibility of the voluntary carbon market post-2020. *Clim Policy* **21**: 939–57.

Krzywoszynska A. 2020. Nonhuman labor and the making of resources. *Environ Hum* **12**: 227–49.

Krzywoszynska A and Marchesi G. 2020. Toward a relational materiality of soils. *Environ Hum* **12**: 190–204.

Lal R. 2001. World cropland soils as a source or sink for atmospheric carbon. *Ad Agron* **71**: 145–91.

Lejano RP, Kan WS, and Chau CC. 2020. The hidden disequities of carbon trading: carbon emissions, air toxics, and environmental justice. *Front Environ Sci* **8**: 593014.

Lugato E, Leip A, and Jones A. 2018. Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. *Nat Clim Change* **8**: 219–23.

Lyons KM. 2020. Vital decomposition: soil practitioners and life politics. Durham, NC: Duke University Press.

Mauro SED. 2014. Ecology, soils, and the Left. New York, NY: Palgrave Macmillan.

Minasny B, McBratney AB, Arrouays D, *et al*. 2023. Soil carbon sequestration: much more than a climate solution. *Environ Sci Technol* **57**: 19094–98.

Moinet GYK, Hijbeek R, van Vuuren DP, and Giller KE. 2023. Carbon for soils, not soils for carbon. *Global Change Biol* **29**: 2384–98.

NAACP (National Association for the Advancement of Colored People). 2021. Nuts, bolts, and pitfalls of carbon pricing: an equity based primer on paying to pollute. Baltimore, MD: NAACP.

Newell P. 2022. Climate justice. *J Peasant Stud* **49**: 915–23.

Nightingale AJ, Eriksen S, Taylor M, *et al*. 2019. Beyond technical fixes: climate solutions and the great derangement. *Clim Dev* **12**: 343–52.

Oldfield EE, Eagle AJ, Rubin RL, *et al*. 2022. Crediting agricultural soil carbon sequestration. *Science* **375**: 1222–25.

Paul C, Bartkowski B, Dönmez C, *et al*. 2023. Carbon farming: are soil carbon certificates a suitable tool for climate change mitigation? *J Environ Manage* **330**: 117142.

Paustian K, Lehmann J, Ogle S, *et al*. 2016. Climate-smart soils. *Nature* **532**: 49–57.

Puig de la Bellacasa M. 2015. Making time for soil: technoscientific futurity and the pace of care. *Soc Stud Sci* **45**: 691–716.

Quemada M, Lassaletta L, Leip A, *et al*. 2020. Integrated management for sustainable cropping systems: looking beyond the greenhouse balance at the field scale. *Global Change Biol* **26**: 2584–98.

Riggers C, Poeplau C, Don A, *et al*. 2021. How much carbon input is required to preserve or increase projected soil organic carbon stocks in German croplands under climate change? *Plant Soil* **460**: 417–33.

Sanderman J, Hengl T, and Fiske GJ. 2017. Soil carbon debt of 12,000 years of human land use. *P Natl Acad Sci USA* **114**: 9575–80.

Schlesinger WH. 2022. Biogeochemical constraints on climate change mitigation through regenerative farming. *Biogeochemistry* **161**: 9–17.

Shi Z, Allison SD, He Y, *et al*. 2020. The age distribution of global soil carbon inferred from radiocarbon measurements. *Nat Geosci* **13**: 555–59.

Sierra CA, Hoyt AM, He Y, and Trumbore SE. 2018. Soil organic matter persistence as a stochastic process: age and transit time distributions of carbon in soils. *Global Biogeochem Cy* **32**: 1574–88.

Silva LCR. 2022. Expanding the scope of biogeochemical research to accelerate atmospheric carbon capture. *Biogeochemistry* **161**: 19–40.

Smith P, Andrén O, Karlsson T, *et al*. 2005. Carbon sequestration potential in European croplands has been overestimated. *Global Change Biol* **11**: 2153–63.

Smith P, Martino D, Cai Z, *et al*. 2008. Greenhouse gas mitigation in agriculture. *Philos T Roy Soc B* **363**: 789–813.

Soong JL, Castanha C, Hicks Pries CE, *et al*. 2021. Five years of whole-soil warming led to loss of subsoil carbon stocks and increased CO_2 efflux. *Sci Adv* **7**: eabd1343.

Terrer C, Phillips RP, Hungate BA, *et al*. 2021. A trade-off between plant and soil carbon storage under elevated CO_2. *Nature* **591**: 599–603.

Trouwloon D, Streck C, Chagas T, and Martinus G. 2023. Understanding the use of carbon credits by companies: a review of the defining elements of corporate climate claims. *Global Challenges* **7**: 2200158.

USDA (US Department of Agriculture). 2023. Report to Congress: a general assessment of the role of agriculture and forestry in US carbon markets. Washington, DC: USDA.

Veldman JW, Overbeck GE, Negreiros D, *et al*. 2015. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience* **65**: 1011–18.

Vermeulen S, Bossio D, Lehmann J, *et al*. 2019. A global agenda for collective action on soil carbon. *Nat Sustain* **2**: 2–4.

Wang M, Guo X, Zhang S, *et al*. 2022. Global soil profiles indicate depth-dependent soil carbon losses under a warmer climate. *Nat Commun* **13**: 5514.

Wang Y, de Boer IJM, Persson UM, *et al*. 2023. Risk to rely on soil carbon sequestration to offset global ruminant emissions. *Nat Commun* **14**: 7625.

West TAP, Wunder S, Sills EO, *et al*. 2023. Action needed to make carbon offsets from forest conservation work for climate change mitigation. *Science* **381**: 873–77.

Wiesmeier M, Urbanski L, Hobley E, *et al*. 2019. Soil organic carbon storage as a key function of soils – a review of drivers and indicators at various scales. *Geoderma* **333**: 149–62.

Yu T and Chen Y. 2019. Effects of elevated carbon dioxide on environmental microbes and its mechanisms: a review. *Sci Total Environ* **655**: 865–79.

Zelikova J, Chay F, Freeman J, and Cullenward D. 2021. A buyer's guide to soil carbon offsets. CarbonPlan. https://carbonplan.org/research/soil-protocols-explainer. Viewed 24 Jan 2024.