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ANALYSIS

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The role of soil carbon in natural climate solutions

D. A. Bossio[1]✉, S. C. Cook-Patton[1], P. W. Ellis[1], J. Fargione[1], J. Sanderman[2], P. Smith[3], S. Wood[1,4], R. J. Zomer[5], M. von Unger[6], I. M. Emmer[6] and B. W. Griscom[7]

Mitigating climate change requires clean energy and the removal of atmospheric carbon. Building soil carbon is an appealing way to increase carbon sinks and reduce emissions owing to the associated benefits to agriculture. However, the practical implementation of soil carbon climate strategies lags behind the potential, partly because we lack clarity around the magnitude of opportunity and how to capitalize on it. Here we quantify the role of soil carbon in natural (land-based) climate solutions and review some of the project design mechanisms available to tap into the potential. We show that soil carbon represents 25% of the potential of natural climate solutions (total potential, 23.8 Gt of CO_2-equivalent per year), of which 40% is protection of existing soil carbon and 60% is rebuilding depleted stocks. Soil carbon comprises 9% of the mitigation potential of forests, 72% for wetlands and 47% for agriculture and grasslands. Soil carbon is important to land-based efforts to prevent carbon emissions, remove atmospheric carbon dioxide and deliver ecosystem services in addition to climate mitigation.

Protecting and restoring soil organic matter delivers many benefits to people and nature[1,2]. Globally, soils hold three times more carbon than the atmosphere[3], and the role of soil organic matter as a regulator of climate has been recognized by scientists for decades[4]. Recent work has highlighted the historical loss of carbon from this pool[3] and the threat of future accelerated loss under warming scenarios[4,5]. Soil organic carbon (SOC) as a natural climate solution (NCS) thus has a role through both restoring a carbon sink and protecting against further CO_2 emissions in response to predicted land-use change and climate change.

This dual role for soil in the global carbon budget suggests that climate benefits can be achieved through strategies that both conserve existing SOC stocks (avoid loss) and restore stocks in carbon-depleted soils[6]. There are important additional benefits. Protecting and increasing SOC storage can (1) protect or increase soil fertility, (2) maintain or increase resilience to climate change, (3) reduce soil erosion and (4) reduce habitat conversion (where implemented through the conservation of natural ecosystems), all in line with the United Nations Sustainable Development Goals (SDGs)[7], the goals of the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention on Combating Desertification (UNCCD). As such, SOC is promoted as a common denominator among a variety of global and national initiatives[7]. Although recent academic comment and perspective pieces point the way towards accelerated action on soils[8,9], there remains much uncertainty around actionable pathways for achieving the global opportunity. Here we examine the scientific and policy context surrounding SOC projects, to aid prioritization and decision-making.

Status of SOC as a climate solution

Despite the scientific consensus around its potential and multiple benefits, the deployment of SOC storage and sequestration for climate mitigation remains limited in practice. There is a growing interest in soil in international climate mitigation conversations, with the recognition of wetland drainage and rewetting as an accounting option under the Kyoto Protocol (formalized in 2011), the launch of the 4 per 1000 Initiative in Paris in 2015 and the formal recognition of SOC sequestration in the UNFCCC process in 2017 (COP23 decision 4/CP.23). To date there are only a few dozen projects that address SOC in registered compliance or voluntary carbon markets. Fewer than 60 projects (half of them in Australia) provided under 50 kt of CO_2-equivalent (CO_2e) removals by soil in agriculture and grassland projects per year[10]. This is less than 0.0001% of the estimated mitigation potential[11]. As a comparison, there are 1,500 carbon projects covering 12 Mha of land in the forest sector[12]. The small soil-carbon numbers are due in part to the sector's near exclusion from early carbon market mechanisms, notably the Kyoto Protocol's Clean Development Mechanism, which limited potential SOC mitigation to afforestation and reforestation projects. Nevertheless, the past two decades have witnessed the emergence of a variety of robust methodological approaches for the calculation of mitigation benefits and the issuance of carbon credits in a wide range of project categories covering croplands, grasslands, savannahs, peatlands and coastal wetlands. While still occupying no more than a niche in the toolbox for international climate action, there is experience on SOC projects to provide confidence and to support the development of mitigation plans at larger scales[10].

Experience with implementation has not yet caught up with aspirations in the political arena. While soil targets for mitigation are included in only eight nationally determined contributions (NDCs) to the UNFCCC[9], the UNFCCC is now exploring agriculture and soils—including with respect to "[improved] SOC, soil health and soil fertility under grassland and cropland as well as integrated systems, including water management" as a more explicit part of their agenda[13]. At the same time, nations are moving forward to invest in solutions and set targets that address the food security and land-use commitments of the SDGs. Beyond governments, a growing number of companies are including SOC in their set of options to build the resilience and long-term profitability of agricultural value chains[9]. This enthusiasm arises because, in general, SOC enhancement practices are considered to have positive cobenefits, do not require additional land area, have minimal water footprints and are readily deployable considering that they do not require changes in land use[11,14].

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[1]The Nature Conservancy, Arlington, VA, USA. [2]Woods Hole Research Center, Falmouth, MA, USA. [3]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, UK. [4]Yale School of Forestry and Environmental Studies, New Haven, CT, USA. [5]Center for Mountain Futures, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming, China. [6]Silvestrum Climate Associates LLC, San Francisco, CA, USA. [7]Conservation International, Arlington, VA, USA. ✉e-mail: deborah.bossio@tnc.org

The science supporting the global technical potential of SOC mitigation is relatively well established, even though measuring changes in SOC is more difficult than for plant biomass. Recent estimates of the global technical potential for SOC sequestration (that is, the level of mitigation that could be achieved when accounting only for biophysical constraints, if there were no economic, social, institutional or other barriers to implementation) align around 2–5 $GtCO_2$ per year[11,14–18], although many of these estimates rely on the same underlying data. Counter to this relative certainty, recent scholarly debates focused primarily on debunking claims that SOC sequestration could fully offset current increases in atmospheric CO_2 (ref. [19–21]) have created confusion for practitioners. Yet, even these debates do not call into question the significance of the global potential or the multiple benefits of increasing global SOC stocks.

Caveats surrounding SOC sequestration such as sink saturation and non-permanence risk (reversibility) have also been well explored in the soil science literature. SOC saturation refers to a maximum capacity of the soil to retain organic carbon[15], meaning that SOC does not increase indefinitely (except in some wetland systems)[16]. For most improved carbon management practices, the rate at which soils will store additional carbon therefore begins to decline after some decades, and eventually will reach a new steady state when a higher carbon stock is achieved. The time before a new steady state is reached will vary greatly depending on soil type, management intervention, climate regime and pre-existing SOC depletion[15], but is generally on the order of decades[22]. This timing aligns with the need to reduce peak atmospheric CO_2 levels and mitigate peak warming. With respect to non-permanence, maintaining high SOC stocks (such as with cover cropping and manuring in croplands) requires some form of maintenance (continuation of improved SOC management practices), even after a new steady state is reached and no further mitigation benefits accrue[14]. In other cases (that is, when there is protection of existing SOC stocks, such as avoided grassland conversion), it is likely that SOC levels are at steady state, and the management activity (in this case, protection) also needs to be maintained to maintain those SOC stocks[23]. Nevertheless, SOC may be more resilient to fire, pests and wind than carbon in aboveground biomass in many environments[17], and some forms of SOC, such as biochar, can persist for millennia[18].

Meanwhile, outside of soil science, carbon project design approaches have moved forward to deal with heterogeneity, uncertainty, additionality and non-permanence, which are challenges for the entire Agriculture, Forestry and Other Land Use sector. Soil does not differ substantially from forestry in this regard, and because this has been a topic for decades, substantial experience exists in managing these risks as part of project and policy design[24]. Some methods to account for and resolve these issues in SOC project design are reviewed in ref. [25]. The Clean Development Mechanism issues temporary credits that are continuously renewed as long as the removal benefit persists. If a reversal event occurs, the renewal of the temporary credit concerned is no longer possible (decision 5/CMP.1 and decision 14/CMP.1).

An alternative approach to the non-permanence of SOC sequestration is based on the installation of portfolio-wide buffer reserves (each project contributes with a share of the credits achieved) that works as an insurance scheme. For any event, either intentional (subsequent land degradation or land conversion) or unintentional (usually force majeure events such as extreme weather, storms, flooding, fire and so on), that causes sink reversals or carbon stock losses, credits held in the buffer account will be released (in an amount equivalent to the reversal) and permanently cancelled[26]. Most voluntary carbon market standards operate with buffer reserves[27]. In Australia, carbon farming associated with the government's land-based strategies for climate mitigation follows a mixed approach that combines buffer reserves with discount elements: farmers that would receive a certain amount of credits in a 100-year permanence scenario (with maintenance obligations being transferred to subsequent landowners within the 100-year window) will receive 20% less credits if they commit to 25-year stable conditions only[10]; the discount comes on top of the general 5% buffer amount. No case is known in which a buffer reserve was ever depleted, which suggests that, while important, permanence is a manageable issue. As a caveat, this experience arises primarily from the forest sector, and given that most SOC projects in the agriculture sector are relatively new, there has been little time for permanence issues to arise. SOC sequestration ambitions can benefit from this experience in the markets and the accepted protocols that now exist for most types of SOC sequestration project, including for grasslands, peatlands and croplands[10].

Practical solutions aside, the relevance of the non-permanence issue is also fading[28]. While of great importance in the context of project-level offsetting, the non-permanence risk of mitigation actions within wider jurisdictional or national schemes is less a concern of environmental integrity than of legal responsibility (liability). In the Paris Agreement, in particular, nations are expected "to include all categories of anthropogenic emissions or removals in their nationally determined contributions and, once a source, sink or activity is included, continue to include it" (decision 1/CP.21, paragraph 31.c). Once SOC emissions are thus covered under a target, the non-permanence issue in specific measures is solved in the higher-level accounting framework: any reversal events will translate into a fresh obligation (a priori for the government) to reduce or avoid emissions. As with permanence, issues of additionality and leakage require strong safeguards and binding agreements. Australia's direct action subsidy approach may fund non-additional projects and therefore deliver less abatement than expected[29].

There are several other challenges to the implementation of soil as a climate mitigation strategy. Historically, there have been limited finance and policy options. The Kyoto mechanisms failed to address SOC interventions. Carbon prices (the price paid per tCO_2e) then collapsed after the 2008 global economic recession, and the Copenhagen summit in 2009[10] failed to generate a new agreement. Further, carbon pricing currently covers only about 20% of global emissions. However, there are some signs that the viability of climate financing for soil is improving. There is increased action on agriculture under the Paris Agreement. The Green Climate Fund has established a funding window targeting land use and agriculture. There are a range of fresh private-sector initiatives on SOC that promise sufficient funding and transformational change[30,31], and impact investors focusing on landscapes, soil resources and payments for ecosystem services schemes[10].

Soil contribution to NCS pathways

Experience and trends in the Agriculture, Forestry and Other Land Use market sector, emerging finance opportunities for climate-positive agriculture, and earlier global potential analyses provide the framework for actions on SOC. Here we extend the analysis of Griscom et al.[32] to offer improved guidance on the set of actions available for realizing the SOC climate mitigation opportunity. The recent study by Griscom et al.[32] provides a framework for an integrated assessment of the overall global mitigation potential of NCSs. In the Griscom et al.[32] study, the potential of 20 conservation, restoration and improved land-management actions (including reforestation, planting trees in croplands, grazing land management, peatland protection and others) to increase carbon storage and/or avoid greenhouse gas (GHG) emissions across global forests, wetlands, grasslands and agricultural lands was determined to be 23.8 $GtCO_2e\,yr^{-1}$. This analysis estimated mitigation potentials constrained by a requirement for additionality and by food security and biodiversity safeguards. A benefit of this analysis is that researchers, policymakers and practitioners can prioritize across various sectors

Table 1 | Summary of SOC elements of NCSs showing the role of soil and cobenefits for sustainable development

NCS pathway	Contribution of SOC	Cobenefits for sustainable development
Avoided forest conversion[a]	1.2 GtCO$_2$e yr^{-1} for soil protection and carbon sequestration is about 9% of the mitigation benefit from these two forest pathways.[a]	Water retention and flow regulation. Biodiversity benefits. Maintains soil biological and physical properties, ensuring the health and productivity of forests.[a]
Reforestation[a]		Measured increase in soil fauna in reforested sites. Drought resilience. Water retention and flow regulation.[a]
Biochar[b]	1.1 GtCO$_2$e yr^{-1} biochar direct mitigation potential.[b]	Soil quality and fertility enhancement in temperate regions.[b]
Cover cropping[b]	0.41 GtCO$_2$e yr^{-1} is entirely SOC.[b]	Soil quality and fertility enhancement. Reduced agricultural water demands with appropriate cover crops. Reduced soil erosion and redistribution, maintaining soil depth and water retention.[b]
Trees in croplands[b]	0.28 GtCO$_2$e yr^{-1} in SOC is 40% of the total mitigation potential.[b]	Biodiversity, habitat connectivity, erosion control, water recharge and reduced soil erosion. Tree planting helps capture airborne particles and pollutant gasses.[b]
Avoided grassland conversion[b]	0.23 GtCO$_2$e yr^{-1} is entirely SOC.[b]	Permanent grasslands provide biological flood control and maintain the ecosystem water balance, assuring adequate water resources. Important habitat for nesting and foraging birds.[b]
Grazing—optimal intensity[b]	0.15 GtCO$_2$e yr^{-1} is entirely SOC.[b]	Reduces disturbance to plant–insect interactions. Reduces water use on managed pastures and increases the soil's ability to trap contaminants.[b]
Grazing—legumes in pastures[b]	0.15 GtCO$_2$e yr^{-1} is entirely SOC.[b]	Higher insect diversity, biological nitrogen fixation, improved soil structure, erosion protection and greater biological diversity.[b]
Peatland restoration[c]	0.65 GtCO$_2$e yr^{-1} in SOC is 80% of the total mitigation potential.[c]	Restoration re-establishes diverse communities and increases faunal species that help develop soil structure and fertility. Waste water treatment and storm water remediation. Flood attenuation. Reduced fire risk, lessening exposure to pollutants associated with lung and pulmonary disorders.[c]
Avoided peatland impacts[c]	0.54 GtCO$_2$e yr^{-1} in SOC is 72% of the total mitigation potential.[c]	
Coastal wetland restoration[c]	0.52 GtCO$_2$e yr^{-1} in SOC is 62% of the total mitigation potential.[c]	Maintains the provision of structure, nutrients, primary productivity and nurseries for commercially important fish and shrimp. High economic value for water treatment. Benefits of cross-system nutrient transfer to coral reefs, coastal protection and water-quality regulation.[c]
Avoided coastal wetland impacts[c]	0.24 GtCO$_2$e yr^{-1} in SOC is 79% of the total mitigation potential.[c]	

[a]Forest pathway. [b]Grassland/agricultural pathway. [c]Wetland pathway. Table adapted with permission from tables S2 and S5 in Griscom et al.[32], PNAS.

of potential activity. An additional benefit is that by using a common framework, the analysis avoids double-counting across the various mitigation options, referred to as pathways—an important consideration for national accounting with NDC commitments. While soil-related ecosystem services are identified as a cobenefit in 16 of the 20 pathways, the specific contribution of SOC storage (avoided losses and enhanced sinks) to each of these pathways, and overall, was accounted for but not reported as a component distinct from biomass carbon. Here we elaborate on Griscom et al.[32] by incorporating findings from a few key papers published since 2017 and by separating out the contribution of soils to each pathway (Methods). Table 1 describes the SOC protection and sequestration pathways, the annual mitigation potential and benefits for sustainability.

Our results (Fig. 1) show the global additional mitigation potential of protecting and rebuilding SOC to be 5.5 GtCO$_2$e yr^{-1}, representing 25% of the total mitigation potential of the 20 NCS pathways. Of this, 4.3 GtCO$_2$e yr^{-1} comes from non-forest pathways; thus, SOC represents more than half of the 7.6 GtCO$_2$e yr^{-1} NCS potential of non-forested lands, with safeguards for food security, fibre security and biodiversity conservation. Avoidable losses represent 2.2 GtCO$_2$e yr^{-1}, or 40%, of the total SOC mitigation potential of all NCS pathways. Protection is important not only because the potential is large but also because SOC is lost more quickly than it can be gained[33], and in many cases it is not possible to restore SOC to the original levels on climate-relevant timescales[3,34]. These estimates do not include land or agricultural management practices that reduce non-CO$_2$ GHG emissions (that is, N$_2$O and CH$_4$) without protecting or enhancing SOC sinks—for example, improved rice, nutrient and livestock management strategies, which together constitute an additional 1.85 GtCO$_2$e yr^{-1} (ref. [32]).

The predominance of SOC protection and sequestration in the overall contribution of NCSs differs among biomes (Fig. 2). Across forest pathways, the SOC mitigation potential of 1.2 GtCO$_2$e yr^{-1} is a small portion (9%) of the total and is split almost equally between increased sequestration from reforestation and avoidable emissions through prevented conversion. In grasslands and agriculture, 47% of the total potential mitigation (2.3 GtCO$_2$e yr^{-1}) arises from SOC protection and sequestration, while 20% involves other GHGs involved with improved soil management practices. In wetland pathways, SOC is estimated to comprise 2.0 GtCO$_2$e yr^{-1}, 72% of the total mitigation potential of wetland pathways. In forest pathways, SOC can bring an additional component to mitigation accounting, which is largely dominated by the aboveground tree biomass, while in wetland pathways SOC is the main vehicle through which climate mitigation can be achieved (Table 1). In agriculture and grassland pathways overall, SOC is approximately half of the abatement potential, and accounting for SOC can bring large areas of grasslands and croplands under the Paris Agreement.

About half of the SOC mitigation potential, 2.8 GtCO$_2$e yr^{-1}, is considered cost-effective at US\$100 (tCO$_2$)$^{-1}$ (on the basis of the methodology of Griscom et al. [32]), which is one estimate of the amount that society is expected to have to pay to mitigate climate change[35]. About one-quarter, 1.2 GtCO$_2$e yr^{-1}, is considered to be low cost at US\$10 (tCO$_2$)$^{-1}$. Low-cost removal and cost-effective removal are therefore equivalent to about 3% and 7%, respectively, of recent annual anthropogenic emissions of CO$_2$ to the atmosphere.

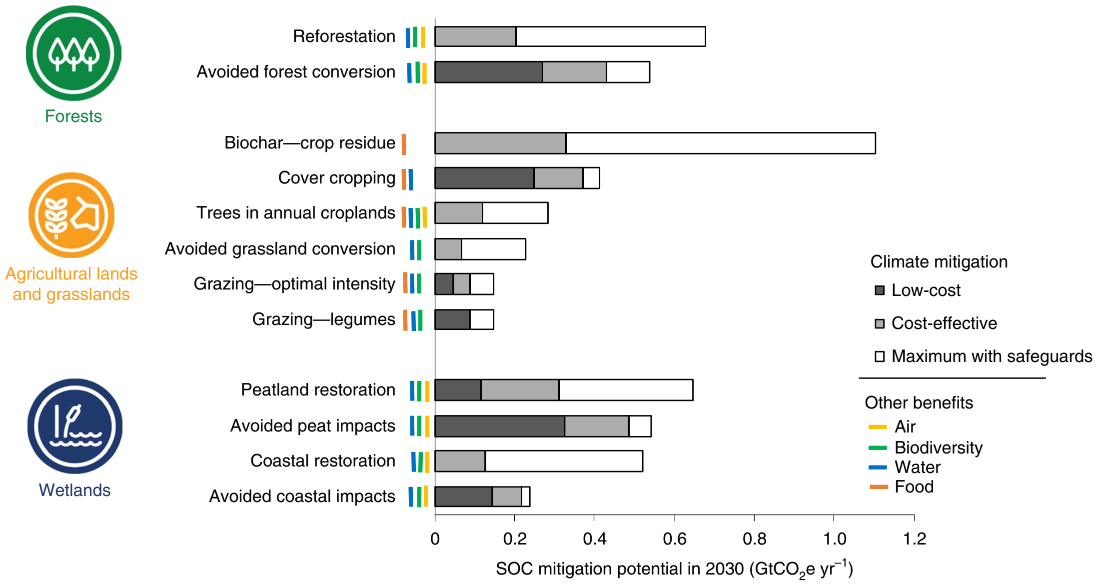

Fig. 1 | Additional SOC storage potential for 12 natural pathways to climate mitigation. We estimate the annual maximum potential of climate mitigation with safeguards for the reference year 2030. The light-grey portions of the bars represent cost-effective mitigation levels assuming a global ambition to hold warming below 2 °C (<US\$100 (MgCO$_2$e)$^{-1}$ yr^{-1}). The dark-grey portions of the bars indicate low-cost mitigation levels (<US\$10 (MgCO$_2$e)$^{-1}$ yr^{-1}). Ecosystem service benefits linked with each pathway are indicated by coloured bars for biodiversity, water (filtration and flood control), food and air filtration. Most pathways also contribute biomass carbon (see Fig. 2), with the exception of pathways that are entirely SOC: biochar, cover cropping, both grazing options and avoided grassland conversion. More than half of the pathways (reforestation, cover cropping, biochar, trees in croplands, grazing, improved pasture options and coastal wetland restoration) represent enhanced SOC sinks, while the others are avoided SOC losses. The remaining 8 of the 20 pathways from Griscom et al.[32] are not expected to have an impact on SOC and therefore have not been included in this figure. Icon credit: The Nature Conservancy.

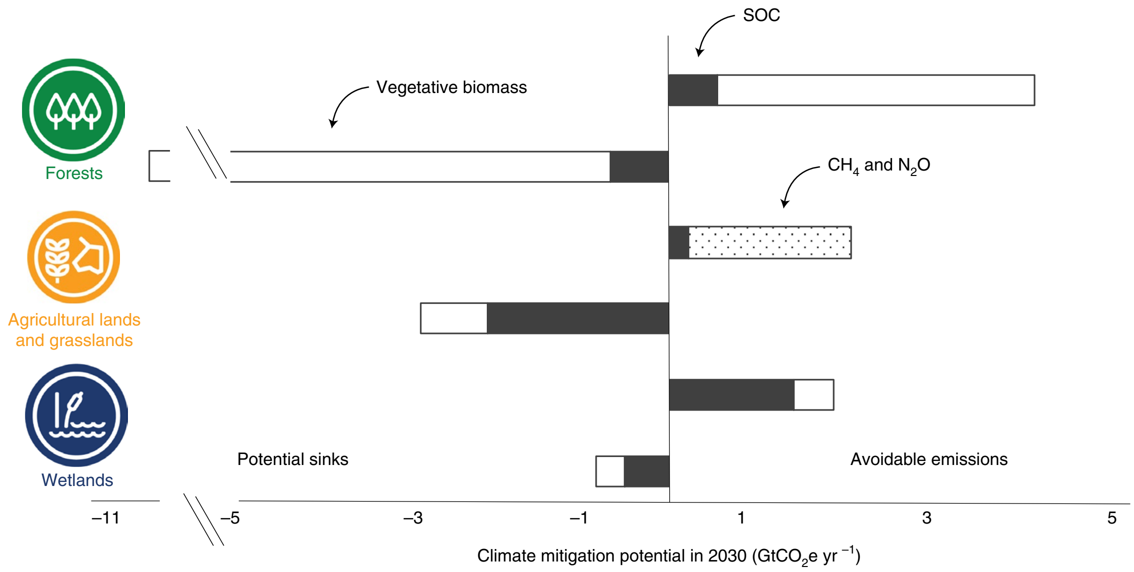

Fig. 2 | Maximum climate mitigation potential of soil in 2030 across forest, agriculture and grassland, and wetland biome pathways with safeguards. The bars to the left indicate the magnitudes of potential sinks, whereas the bars to the right indicate the magnitudes of avoided emissions. The dark portions of the bars represent SOC; the white portions represent vegetative biomass; and the dotted portion represents avoided CH$_4$ and N$_2$O through improved nutrient, rice and animal management. Note that owing to the strong likelihood of near-term increased CH$_4$ emissions arising from increased SOC in peatlands[73], we do not include increased SOC sinks in freshwater peatlands on rewetting for restoration. Icon credit: The Nature Conservancy.

In other studies, negative costs have been estimated for SOC sequestration, on the basis of the cobenefits such as increased productivity and resilience of soils[36], and these studies have suggested that many soil-based NCSs are cost-effective even without supportive climate policy. The Intergovernmental Panel on Climate Change (IPCC) recently concluded that the cost for SOC mitigation is below US\$100 (tCO$_2$)$^{-1}$ (ref. [37]). Despite the relatively low or negative costs, SOC actions are not yet implemented owing to other economic, social, institutional or other barriers as noted and highlighted above.

Table 2 | Example activities to achieve the mitigation potentials of SOC sequestration pathways

NCS pathway	General activities	Specific activities
Avoided forest conversion[a]	Protection Establishment and improved enforcement of protected areas, improved land tenure, indigenous community management	Improved citing of non-forest land use; forest certification; zero-deforestation commitments; sustainable intensification of agriculture; diet shifts; avoided loss of high-carbon forests.[a]
Avoided grassland conversion[b]		Prevented conversion of grasslands to tilled croplands; intensification of existing croplands.[b]
Avoided peatland impacts[c]		No-net-loss mitigation regulations; resiting of oil palm plantation permits to non-peat locations.[c]
Avoided coastal wetland impacts[c]		No-net-loss mitigation regulations; avoided harvest of mangroves for charcoal; avoided consumption of food products with acute impacts on coastal wetlands (for example, mangrove replacing shrimp farms).[c]
Biochar[b]	Management Realignment of agriculture support programmes, ecosystem services payments, certification schemes, improved land tenure, mitigation programmes and markets	Extension programmes to build capacity on biochar management.[b]
Cover cropping[b]		Cultivation of additional cover crops in fallow periods; shift to reduced-tillage or zero-tillage systems and other conservation agriculture practices may enhance SOC benefits of cover crops.[b]
Trees in croplands[b]		Regulations and certification programmes that promote wind-breaks (shelter-belts), alley cropping, agroforestry systems and farmer-managed natural regeneration.[b]
Grazing—optimal intensity[b]		Maintaining forage consumption rates that enable maximum forage production.[b]
Grazing—legumes in pastures[b]		Sowing legumes in existing planted pastures.[b]
Reforestation[a]	Restoration Certification and mitigation programmes, indigenous community management	Regulations that advance minimum forest cover requirements; integration of trees into grazing lands (that is, silvopastoral systems); diet shifts.[a]
Peatland restoration[c]		Rewetting and replanting with native freshwater wetland species.[c]
Coastal wetland restoration[c]		Rewetting and replanting with native saltwater wetland species.[c]

[a]Forest pathway. [b]Grassland/agricultural pathway. [c]Wetland pathway. Table adapted with permission from table S7 in Griscom et al.[32], PNAS and Griscom et al.[81], John Wiley & Sons.

Soil science knowledge gaps

Given the availability of project design mechanisms to realize the potential for SOC mitigation actions (see Table 2 for example actions for each pathway), soil management planning and prioritization at various scales would benefit from increasingly accurate system and practice-specific estimates of climate impacts. For agriculture and grassland pathways, future work should disaggregate mitigation accounting to specific activities each with their own mitigation estimates, trade-offs and cobenefits. Tillage, cover cropping, enhanced crop rotations and grazing management are in fact broad sets of activities, each with potentially very different impacts on SOC[8], different N_2O emissions, and different feasibilities. An activity that builds organic carbon on one soil type might be ineffective on a different soil[38]. In wetland pathways, more research should focus on accurately predicting the magnitude of increasing CH_4 emissions when SOC is restored in wetland environments, and improving estimates of the potential and existing carbon storage in peatland soils.

Our estimates are lower overall than those of Fuss et al.[11] for the sequestration pathways, and lower for agriculture than those of Zomer et al.[39], which used unconstrained cropland area availability. We provide conservative estimates because we exclude interventions for which there is less consensus on the impact, such as no-till[40], and we use conservative estimates for pathways with a large range in published numbers, such as biochar[41,42] and optimal grazing[43]. Thus, agricultural pathways in our analysis encompass only the best-understood options for incremental change to existing farming practices. Opportunities for greater innovation may result in higher per-hectare mitigation rates than those reflected here, but data are lacking to make robust global estimates of their potential. Regenerative agriculture, organic farming, agroecology, silvopasture, climate smart agriculture, agroforestry and permaculture are all complex and not mutually exclusive agricultural systems that can have substantial positive impacts on SOC in specific geographies, according to a recent literature review by Toensmeier[44]. Other, less well-established opportunities for SOC management take advantage of the potential to build organic matter into deeper soil layers through deep-rooted grasses and new crop varieties[45], and deep inversion techniques[46]. Organic biosolids from cities are a large pool of organic material that are often a pollution and waste-disposal problem[47], but could provide substrate to build soil health and sequester carbon in soils. Exogenous organic matter additions can stimulate rangeland productivity and sequester endogenous organic matter beyond the actual tonnage of compost or biosolids applied[48], but may pose a risk to native plant biodiversity[49]. More research is needed (and is underway) to understand how universal these findings are. Early research from row-crop systems suggests that endogenous and exogenous organic matter have similar effects[50].

SOC fluxes associated with forest pathways are often ignored, given the more obvious changes observed in woody biomass, even though the contribution from forest pathways to SOC sequestration is substantial (Fig. 1). The conversion of forests to permanent croplands and pastures often generates SOC emissions, and forest restoration is expected to increase SOC[34]. Recent estimates for the extent of potential reforestation vary widely[51,52]; our estimate is based on an intermediate spatial extent of potential reforestation (6.8 $\mathrm{Mkm^2}$), and includes food security and biodiversity safeguards[32]. However, the potential for additional SOC storage from improved management practices on natural and plantation forests is much more complex, and more research is needed to include the potential SOC benefits in this NCS framework.

Looking forward

As the urgency to harness all available opportunities to mitigate catastrophic climate change grows[53,54], we emphasize that if we are to limit warming well below 2 °C as called for by the Paris Agreement, SOC can be an important way to increase carbon sinks and reduce emissions. SOC sequestration is not an alternative to emission reductions in other sectors, but rather an additional opportunity for increasing currently insufficient ambition in existing NDCs to the Paris Agreement. This opportunity should be neither dismissed nor exaggerated. Our analysis disaggregates this opportunity across all land sectors in a way that is relevant to target setting and prioritization efforts at scales from NDCs to subnational programmes.

An important benefit of SOC mitigation action is that it can positively engage rural landowners and the agricultural sector as beneficiaries of mitigation incentives that are likely to be produced by successful climate negotiations. Further, the majority of SOC pathways are no-regrets opportunities for climate mitigation, by delivering improved soil fertility, climate resilience and other ecosystem services in addition to climate mitigation. As such, SOC aligns targets across different international conventions (SDGs, UNFCCC and UNCCD) and agendas by providing measurable benefits towards diverse goals with a common metric. The prospects for SOC sequestration action are promising because project design tools are sufficient to address accounting challenges, and climate financing seems to be growing for the sector. Because enhancing SOC brings multiple benefits, there are opportunities to incentivize action beyond formal carbon markets. Policies in both the climate sector (with a focus on mitigation) and the agriculture sector (with a focus on soil health) are needed to achieve substantial, cost-effective SOC protection and enhancement to meet climate targets and improve resilience.

Methods

Estimating SOC mitigation potential in NCS pathways. Griscom et al.[32] identified 20 pathways by which natural systems could contribute to the mitigation of GHGs. For these pathways, an analysis of over 300 publications was conducted in concert with expert elicitation to define the maximum areal extent, the amount of avoided emissions or sequestration rate (flux), the time until a new steady state, and the amount of total mitigation attainable at different costs informed by marginal abatement curves. For the complete sources, see the supplementary information of Griscom et al.[32]. The pathways were constructed carefully to estimate the additional annual mitigation potential above a business-as-usual baseline, to avoid double-counting and to safeguard biodiversity and human needs for food, fibre and fuel. The analysis also included estimates of uncertainty around extent, flux and mitigation for each pathway and propagated across all pathways. In this study, we have separated out the soil contribution of each pathway, as briefly described below; the full details of the pathway methods are in Griscom et al.[32].

- Avoided conversion of forested ecosystems (>25% tree cover) where they are threatened by agriculture, preventing the loss of SOC. Don et al.[55] estimated that 17.4 MgC ha^{-1} are lost when forests are converted to various commercial agricultural uses. Powers et al.[56] further found that the conversion of forests for shifting cultivation results in a slightly lower impact on SOC stocks (14.5 MgC ha^{-1}). These avoided emission values were then applied to the 5.93 Mha of tropical forest that are lost annually with the assumption that 54% of the loss goes to commercial agriculture and the remainder to shifting cultivation. Most temperate and all boreal regions are excluded owing to the lack of spatial data and/or albedo considerations. Forested wetlands are excluded to avoid double-counting with wetland pathways.
- SOC sequestration arising through reforestation, including silvopastoral practices. The reforestation pathway quantifies potential conversion from non-forest (<25% tree cover) to forest (>25% tree cover) in areas that historically supported forests. This pathway excludes the afforestation of grass-dominated ecosystems to avoid negative biodiversity impacts on grassland ecosystems[57,58] and croplands for food security reasons. The pathway does allow for reforestation of potentially forested grazing lands on the basis of recent analyses that show the potential to shrink the footprint of livestock production through improved efficiencies in production and/or shifts towards a more plant-based diet[59,60], but to avoid double-counting, the mitigation potential from grazing pathways was deducted from the mitigation potential for reforestation. To further avoid double-counting, the area of reforestation opportunity excluded wetland areas. Finally, the reforestation pathway did not include opportunity assessments in boreal zones (since changes in albedo can offset the climate benefits of carbon capture[61]) and excluded opportunity within denser human settlements where widespread tree-cover expansion is constrained. The original NCS assessment included an average SOC accumulation rate of 0.4 MgC ha^{-1} yr^{-1} for tropical and subtropical reforestation from Powers et al.[56], which we disaggregated here. We then further quantified the SOC accumulation for temperate forests using a more recent study by Nave et al.[34]. This analysis estimated that reforesting stands accumulated between 0.11 and 0.34 MgC ha^{-1} yr^{-1} in the topsoil. We therefore used the midpoint of this range (0.23 MgC ha^{-1} yr^{-1}) to estimate potential soil accumulation in temperate biomes.
- Biochar amendment to increase the SOC pool of agricultural soils is a soil-only pathway in Griscom et al.[32] and remains unchanged in this analysis. An increased SOC pool results from the conversion of non-recalcitrant carbon (crop residue biomass) to recalcitrant carbon (charcoal) through pyrolysis. Biochar carbon mitigation was estimated using a midrange estimate of available crop residues and multiplying this value by the amount of persistent biochar assuming that 79% is recalcitrant and that there is a 50% conversion efficiency during pyrolysis and a carbon content of crop residues of 45% of available crop residues.
- Cover cropping is a soil-only pathway in Griscom et al.[32] and remains unchanged in this analysis. We assumed that 50% of the 800 Mha of cropped land were amenable to cover cropping. To this area we applied a mean sequestration rate of 0.32 MgC ha^{-1} yr^{-1} (ref. [62]). The effects of no-till and other potential conservation agriculture practices were not included to avoid double-counting with cover crops and unresolved questions about long-term efficacy.
- The trees in annual croplands pathway entails the expansion of three agroforestry practices into annual croplands that currently have low (<10%) tree cover. These include the expansion of farmer-managed natural regeneration across dry croplands in Africa (150 Mha), wind-breaks over 50% of non-African croplands (318 Mha) and alley cropping across 22% of non-African croplands (140 Mha). Note that wind-breaks and alley cropping were applied to non-African croplands to avoid double-counting with farmer-managed natural regeneration. The estimates of SOC accumulation derive from a literature review around the soil benefits of wind-breaks, or shelter-belts-based[63–65] and alley cropping[66–68]. We estimate that wind-breaks capture an additional 0.69 MgC ha^{-1} yr^{-1}, whereas alley cropping captures an additional 0.59 MgC ha^{-1} yr^{-1}. Because we could not find independent estimates of SOC accumulation for farmer-managed natural regeneration, we assumed that 25% of the mitigation potential was attributable to soil accumulation, averaging together the proportion of the mitigation potential for alley cropping and wind-breaks. Silvopastoral systems were not included here to avoid double-counting with the reforestation pathway.
- Avoided grassland conversion refers to avoided SOC loss by protecting grasslands from conversion to croplands in areas where grasslands are threatened. For this pathway, we updated the initial NCS analysis of Griscom et al.[32] by allowing 28% of SOC to be lost down to 1 m in the soil on the basis of the findings of Sanderman et al[3]; and the new SOC modelling for temperate and tropical grasslands on the basis of the ISRIC database[3]. We thus applied this SOC loss to the estimated 155 tC ha^{-1} in temperate grasslands and 122 tC ha^{-1} in tropical grasslands over 0.7 Mha and 1.0 Mha, respectively, for temperate and tropical grasslands converted annually[69].
- Grazing—optimal intensity is a soil-only pathway in Griscom et al.[32] and remains unchanged in this analysis, representing changes in grazing intensity that optimize forage removal and increase SOC on both rangeland and planted pasture. We assumed an additional sequestration potential of 0.06 MgC ha^{-1} yr^{-1} over 712 Mha of land. This includes global rangelands and planted pastures. There is some spatial overlap with reforestation and grazing—legumes; the mitigation potential of this pathway was therefore subtracted from reforestation mitigation potential to avoid double-counting. Accounting with grazing—legumes is additive, so no double-counting occurs.
- Grazing—legumes, sowing leguminous crops on planted pastures to increase SOC, is a soil-only pathway in Griscom et al.[32] and remains unchanged in this analysis. The pathway quantifies the net increase in SOC (after accounting for increases in N_2O emissions) in planted pastures owing to the fertilizing effect of increased nitrogen fixation. We estimate an additional sequestration potential of 0.56 MgC ha^{-1} yr^{-1} over 72 Mha of land. This was restricted to global planted pastures. There is spatial overlap with reforestation and grazing—optimal Intensity. The mitigation potential of this pathway was subtracted from reforestation mitigation potential to avoid double-counting. Accounting with grazing—optimal intensity is additive, so no double-counting occurs.
- Peatland restoration includes the restoration of global non-tidal freshwater forested and non-forested wetlands. The restoration opportunity across tropical, temperate and boreal peatlands, estimated at 46 Mha, was not changed[32]. Avoidable SOC losses of 5.44 tC ha^{-1} yr^{-1} for tropical peatlands, 3.55 tC ha^{-1} yr^{-1} for temperate peatlands and 1.42 tC ha^{-1} yr^{-1} for boreal peatlands were estimated by assuming an avoided loss of 50% of the original SOC[70–72] occurring over a 20-yr period. Owing to the strong likelihood of near-term increased CH_4 emissions arising from increased SOC in peatlands[73], we do not include increased SOC sinks in freshwater peatlands on rewetting for restoration. In other words, we assumed that any possible enhanced carbon sink was at risk of being offset by increased CH_4 emissions[32]. Recent work shows that this problem may be greater than expected also in coastal wetlands[74].
- The avoided peat impacts pathway refers to avoided SOC loss by protecting threatened tropical, temperate and boreal peatlands. It includes all threatened non-tidal freshwater forested and non-forested wetlands estimated to cover 0.78 Mha yr^{-1} (ref. [72]). Avoidable SOC fluxes were estimated to be 217 tC ha^{-1} for tropical peatlands[70,72], 142 tC ha^{-1} for temperate peatlands[71,72] and 57 tC ha^{-1}

for boreal peatlands[71,72]. Forested wetlands were excluded from the avoided forest conversion pathway to avoid double-counting.

- The restoration of coastal blue carbon ecosystems (mangroves, salt marshes and seagrass meadows) typically leads to substantial SOC accumulation. Mean literature estimates of carbon sequestration rates during ecosystem restoration were applied to the historic area lost of each of these ecosystems (11 Mha, 2 Mha and 17 Mha respectively for mangrove, salt marsh and seagrass) and was not changed from Griscom et al.[32]. Here both avoided losses of SOC and enhanced sequestration are included, and were estimated on the basis of added sequestration at an average rate of 1.7 tC ha^{-1} yr^{-1} (ref. [75,76]), and avoided fluxes averaging 3.4 tC ha^{-1} yr^{-1} estimated by assuming a potential 50% loss of the original SOC[77,78] occurring over a 20-yr period.
- The avoided coastal impacts pathway refers to the avoided SOC emissions by protecting threatened blue carbon ecosystems (mangroves, salt marshes and seagrass meadows). This pathway was updated from Griscom et al.[32] by using more recent lower estimates of ongoing mangrove loss rates[79,80]. The soil portion was calculated on the basis of estimates of SOC stocks to 1 m and expected losses resulting in avoidable fluxes of 197.47 tC ha^{-1}, 133.78 tC ha^{-1} and 77.43 tC ha^{-1} respectively over 0.05 Mha yr^{-1} of mangroves, 0.08 Mha yr^{-1} of salt marshes and 0.45 Mha yr^{-1} of seagrass meadows[77,78,80]. Mangroves were excluded from the avoided forest conversion pathway to avoid double-counting.

Uncertainty estimates. The uncertainty for the maximum mitigation estimates of each pathway are in Griscom et al.[32]. In brief, methods consistent with IPCC good practice guidance were used when empirical uncertainty estimation was possible. For other pathways, the Delphi method of expert elicitation involving two rounds of explicit questions about expert opinion on the potential extent and intensity of flux was used.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

A global spatial dataset of reforestation opportunities is available on Zenodo (https://zenodo.org/record/883444). Figures 1 and 2 have associated raw data that can be made available upon request.

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Author contributions

D.A.B. and B.W.G. designed the study. D.A.B., B.W.G., S.C.C.-P., P.W.E., J.F. and J.S. provided the data analysis. D.A.B., B.W.G., S.C.C.-P., P.W.E., J.F., J.S., P.S., S.W., R.J.Z., M.v.U. and I.M.E. interpreted the data and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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