The role of soil carbon in natural climate solutions

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Summary

Mitigating climate change requires clean energy and removing atmospheric carbon. Building soil carbon is an appealing way to increase carbon sinks and reduce emissions due to the associated benefits to agriculture. However, practical implementation of soil carbon climate strategies lag 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 (NCS), and review some of the project design mechanisms available to tap into the potential. We show that soil carbon represents 25% of the 23.8 $GtCO_2eyr^{-1}$ NCS potential 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 as a natural climate solution (NCS) thus has a role both through 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 climate benefits can be achieved through strategies that both conserve existing soil organic carbon stocks (avoid loss), and restore stocks in carbon-depleted soils[6]. There are important additional benefits. Protecting and increasing soil carbon storage can (i) protect or increase soil fertility, (ii) maintain or increase resilience to climate change, (iii) reduce soil erosion, and where implemented through conservation of natural ecosystems iv) reduce habitat conversion, all in line with the United Nations Sustainable Development Goals (SDG’s)[7], the goals of the United Nationals Framework Convention on Climate Change (UNFCCC) and the United Nations Convention on Combating Desertification (UNCCD). As such, soil carbon is promoted as a common denominator amongst 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 soil carbon projects, to aid prioritization and decision making.

Status of soil carbon as a climate solution

Despite scientific consensus around its potential and multiple benefits, deployment of soil carbon storage and sequestration for climate mitigation remains limited in practice. There is growing interest in soil in international climate mitigation conversations, with the recognition of 'wetland drainage and rewetting' (WDR) as an accounting option under the Kyoto Protocol (formalized in 2011), the launch of the '4 per 1000' Initiative in Paris in 2015 and formal recognition of soil carbon sequestration in the UNFCCC process in 2017 (COP23 decision 4/CP.23). To date there are only a few dozen projects that address soil organic carbon in registered compliance or voluntary carbon markets. Fewer than 60 projects (half of them in Australia) provided under 50 thousand tonnes of CO_2-equivalent 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 (CDM) which limited potential soil carbon 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, as well as peatlands and coastal wetlands. While still occupying no more than a niche in the toolbox for international climate action, there is experience on soil carbon projects to provide confidence and to support 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] soil carbon, 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 United Nations Sustainable Development Goals (SDGs). Beyond governments, a growing number of companies are including soil organic carbon within their set of options to build the resilience and long-term profitability of agricultural value chains[9]. The enthusiasm arises because, in general, soil carbon enhancement practices are considered to have positive co-benefits, do not require additional land area, have minimal water footprint, and are readily deployable considering that they do not require changes in land use[11,14].

The science supporting the global technical potential of soil carbon mitigation is relatively well established, even though measuring changes in soil carbon is more difficult than for plant biomass. Recent estimates of global soil carbon sequestration technical potential, i.e. 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 Gt CO_2 per year[11, 14-18] albeit many of these estimates rely on the same underlying data. Counter to this relative certainty, recent scholarly debates focused primarily on debunking claims that soil carbon sequestration could fully offset current increases in atmospheric CO_2[19-21] have created confusion for practitioners. Yet, even these debates do not call into question the significance of the global potential, and the multiple benefits of increasing global soil carbon stocks.

Caveats surrounding soil carbon sequestration such as sink saturation and non-permanence risk (reversibility) have also been well explored in the soil science literature. Soil carbon saturation refers to a maximum capacity of the soil to retain organic carbon[15], meaning that soil organic carbon does not increase indefinitely with the exception of 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 period 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 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 soil carbon management practices), even after a new steady-state is reached and no further mitigation benefits accrue[14]. In other cases, i.e. when there is protection of existing soil carbon 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 soil carbon, 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 in particular which are challenges for the entire Agriculture, Forestry and Land Use (AFOLU) sector. Soil does not differ substantially from forestry in this regard, and because this has been a topic for decades, significant experience exists in managing these risks as part of project and policy design[24]. Some methods to account for and resolve these issues in soil carbon project design are reviewed by[25]. The CDM issues temporary credits that are continuously renewed as long as the removal benefit persists. If a reversal event occurs, renewal of the temporary credit concerned is no longer possible (Decision 5/CMP.1; Decision 14/CMP.1).

An alternative approach to non-permanence of soil carbon 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 of intentional (subsequent land degradation, land conversion) or unintentional (usually force majeure events such as extreme weather events, storms, flooding, fire, and so on) that causes sink reversals or carbon stock losses reversal risks, credits held in the buffer account will be released (in an amount equivalent to the reversal or stock loss amount) and permanently canceled[26]. Most voluntary carbon market standards operate with a buffer reserve[27] based on some standardized or project-specific risk assessment. In Australian carbon farming associated with the government’s land based strategies for climate mitigation follow 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 soil carbon projects in the agriculture sector are relatively new, there has been little time for permanence issues to appear. Soil carbon sequestration ambitions can benefit from this experience in the markets and the accepted protocols that now exist for most types of soil carbon sequestration project types 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 action within wider jurisdictional or national schemes is less a concern of environmental integrity but of legal responsibility (liability). Within 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 soil carbon emissions are thus covered under a target, the non-permanence issue in specific measures is solved at 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 implementation of soil as a climate mitigation strategy. Historically, there have been limited finance and policy options. The Kyoto mechanisms failed to address soil carbon interventions. Then, carbon prices (the price paid per tCO_2e) collapsed following 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 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 soil carbon that promise sufficient funding and transformational change[30,31], and impact investors focusing on landscape, soil resources, and payments for ecosystem services schemes[10].

Soil contribution to Natural Climate Solution Pathways

Experience and trends in the AFOLU market sector, emerging finance opportunities for climate positive agriculture, and earlier global potential analyses provide the framework for actions on soil carbon. Here we extend the analysis of Griscom et al. [32] to offer improved guidance on the set of actions available for realizing the soil carbon 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 "natural climate solutions" (NCS). 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 emissions across global forests, wetlands, grasslands, and agricultural lands was determined to be 23.8 Gt CO_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, policy makers and practitioners can prioritize across various sectors 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 co-benefit in 16 of the 20 pathways, the specific contribution of soil carbon 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 (see methods). Table 1 describes the soil carbon protection and sequestration pathways, the annual mitigation potential and benefits for sustainability.

Our results (Figure 1) show the global additional mitigation potential of protecting and rebuilding soil carbon to be 5.5 Gt CO_2e yr^{-1}, representing 25% of the total mitigation potential of the 20 NCS pathways. Of this, 4.3 Gt CO_2e yr^{-1} comes from non-forest pathways, thus soil carbon represents more than half of the 7.6 Gt CO_2e yr^{-1} NCS potential of non-forested lands, with safeguards for food security, fiber security and biodiversity conservation. Avoidable losses represent 2.2 Gt CO_2e yr^{-1}, or 40%, of the total soil carbon mitigation potential of all NCS pathways. Protection is important not only because the potential is large, but also because soil carbon is lost more quickly than it can be gained[33], and in many cases it is not possible to restore to soil organic carbon to 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 (i.e. N_2O and CH_4) without protecting or enhancing soil carbon sinks, for example improved rice, nutrient and livestock management strategies, which together constitute an additional 1.85 Gt CO_2e yr^{-1} [32].

The predominance of SOC protection and sequestration within the overall contribution of NCS differs among different biomes (Figure 2). Across forest pathways, the SOC mitigation potential of 1.2 Gt CO_2e 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 Gt CO_2e yr^{-1}) arises from soil carbon protection and sequestration, while 20% involves other greenhouse gases involved with improved soil management practices. In wetland pathways soil carbon is estimated to comprise 2.0 Gt CO_2e yr^{-1}, 72% of the total mitigation potential of wetland pathways. For forest pathways, soil carbon can bring an additional component to mitigation accounting which is largely dominated by the above ground tree biomass, while in wetland pathways soil carbon is the main vehicle through which climate mitigation can be achieved (Table 1). In agriculture and grassland pathways overall, soil carbon is approximately half of the abatement potential, and importantly accounting for soil carbon can bring large areas of grasslands and croplands under the Paris Agreement.

About half of the soil carbon mitigation potential, 2.8 Gt CO_2e yr^{-1}, is considered cost-effective at \$100/tCO_2 (based on Griscom et al. [32]methodology) 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 Gt CO_2e yr^{-1}, is considered to be low cost at \$10/tCO_2. Low-cost and cost-effective removal is, therefore, equivalent to about 3% and 7%, respectively, of recent annual anthropogenic emissions of carbon dioxide to the atmosphere. In other studies, negative costs have been estimated for soil carbon sequestration, based on the co-benefits such as increased productivity and resilience of soils[36], and have suggested that many soil-based NCS are cost-effective even without supportive climate policy. The IPCC recently concluded that the cost for soil carbon mitigation is below \$100/tCO_2[37]. Despite the relatively low or negative costs, soil carbon actions are not yet implemented due to other economic, social, institutional or other barriers as noted and highlighted above.

Soil science knowledge gaps

Given the availability of project design mechanisms to realize the potential for soil carbon mitigation actions (see Table 2 for example actions for each pathway), soil management planning and prioritization at various scales would benefit from increasingly more 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 co-benefits. Tillage, cover cropping, enhanced crop rotations and grazing management are in fact broad sets of activities, each with potentially very different impacts on soil organic carbon[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 soil organic carbon is restored in wetland environments, and improving estimates of the potential and existing carbon storage in peatland soils.

Our estimates are lower overall than Fuss et al. [11] for the sequestration pathways, and lower for agriculture than 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, silvo-pasture, climate smart agriculture, agroforestry, and permaculture are all complex and not mutually exclusive agricultural systems that can have significant positive impacts on soil organic carbon 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], that 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/biosolids applied[48], but may pose a risk to native plant biodiversity[49] and more research is needed (and is underway) to understand how universal these findings are. Early research from row-crop systems suggests endogenous vs. exogenous organic matter have similar effects[50].

Soil carbon 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 soil carbon sequestration is substantial (Fig 1). Conversion of forests to permanent croplands and pastures often generates soil carbon emissions and forest restoration is expected to increase soil carbon[34]. Recent estimates for the extent of potential reforestation vary widely[51,52], and our estimate is based on an intermediate spatial extent of potential reforestation (6.8 M km^2), and includes food security and biodiversity safeguards [32]. However, the potential for additional soil carbon storage from improved management practices on natural and plantation forests are much more complex and more research is needed to include the potential soil carbon 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, soil carbon can be an important way to increase carbon sinks and reduce emissions. Soil carbon sequestration is not an alternative to emission reductions in other sectors, but rather an additional opportunity for increasing currently insufficient ambition in existing nationally determined contributions (NDCs) to the Paris Agreement. This opportunity should neither be 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 sub-national programs.

A strong benefit of soil carbon 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 soil carbon 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, soil carbon aligns targets across different international conventions (SDG, UNFCCC, UNCCD) and agendas by providing measurable benefits towards diverse goals with a common metric. Prospects for soil carbon sequestration action are promising because project design tools are sufficient to address accounting challenges, and climate financing seems to be growing for the sector; notably, because enhancing soil carbon 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 significant, cost effective soil carbon protection and enhancement to meet climate targets and improve resilience.

Methods

Estimating soil carbon mitigation potential in NCS pathways

Griscom et al. [32] identified 20 pathways by which natural systems could contribute to mitigation of greenhouse gases. 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”) and time until a new steady-state, and the amount of total mitigation attainable at different costs informed by marginal abatement curves. For complete sources see Griscom et al. [32] supplementary information. Pathways were constructed carefully to estimate additional annual mitigation potential above a business-as-usual baseline, to avoid double counting and to safeguard biodiversity and human needs for food, fiber and fuel. The analysis also included estimates of uncertainty around extent, flux and mitigation for each pathway, and propagated across all pathways. In this current work, we have separated out the soil contribution of each pathway as briefly described below; full details of pathway methods are found in Griscom et al. [32]:

- Avoided conversion of forested ecosystems (>25% tree cover) where they are threatened by agriculture preventing the loss of soil carbon. Don et al[55] estimated that 17.4 Mg C ha^{-1} are lost when forests are converted to various commercial agricultural uses. Powers et al. [56] further found that conversion of forests for shifting cultivation results in a slightly lower impact to soil carbon stocks (14.5 Mg C 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 excluded due to lack of spatial data and/or albedo considerations. Forested wetlands excluded to avoid double-counting with wetland pathways.

- Soil carbon 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 afforestation of grass-dominated ecosystems to avoid negative biodiversity impacts on grassland ecosystem[57,58] and croplands for food security reasons. The pathway does allow for reforestation of potentially forested grazing lands based on 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 soil carbon accumulation rate of 0.4 Mg C ha^{-1} yr^{-1} for tropical and subtropical reforestation from Powers et al[56], which we disaggregated here. We then further quantified the soil carbon accumulation for temperate forests using a more recent study by Nave et al[34]. This analysis estimated that reforesting stands accumulated between 0.11 to 0.34 Mg C ha^{-1} yr^{-1} in the topsoil. We therefore used the midpoint of this range (0.23 Mg C ha^{-1} yr^{-1}) to estimate potential soil accumulation in temperate biomes.

- Biochar amendment to increase the soil carbon pool of agricultural soils is a soil-only pathway in Griscom et al. [32] and remains unchanged in this analysis. Increased soil carbon pool results from conversion of non-recalcitrant carbon (crop residue biomass) to recalcitrant carbon (charcoal) through pyrolysis. Biochar carbon mitigation was estimated using a mid-range estimate of available crop residues and multiplying this value by the amount of persistent biochar assuming 79% is recalcitrant, 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 Mg C ha^{-1} yr^{-1} [62]. 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 expansion of farmer-managed natural regeneration across dry croplands in Africa (150 Mha), windbreaks over 50% of non-African croplands (318 Mha), and alley cropping across 22% of non-African croplands (140 Mha). Note that windbreaks and alley cropping were applied to non-African croplands to avoid double counting with farmer-managed natural regeneration. Estimates of soil carbon accumulation derive from a literature review around the soil benefits of windbreaks, or shelterbelts based[63-65] and alley cropping[66-68]. We estimate that windbreaks capture an additional 0.69 Mg C ha^{-1} yr^{-1}, whereas alley cropping capture an additional 0.59 Mg C ha^{-1} yr^{-1}. Because we could not

find independent estimates of soil carbon accumulation for farmer managed natural regeneration, we assumed 25% of the mitigation potential was attributable to soil accumulation, averaging together the proportion of mitigation potential for alley cropping and windbreaks. Silvopastoral systems were not included here to avoid double counting with the reforestation pathway.

- Avoided grassland conversion refers to avoided soil carbon 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 soil carbon to be lost down to 1 m in the soil based upon the findings of Sanderman et al[3]; and the new soil carbon modeling for temperate and tropical grasslands based on ISRIC database[3]. Thus, we applied this soil carbon 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 soil carbon on both rangeland and planted pasture. We assumed 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, therefore the mitigation potential of this pathway was subtracted from Reforestation mitigation potential to avoid double-counting. Accounting with Grazing – Legumes is additive, so no double-counting concerns.
- Grazing – legumes, sowing leguminous crops on planted pastures to increase soil carbon, is a soil only pathway in Griscom et al. [32], and remains unchanged in this analysis. The

pathway quantifies the net increase in soil carbon (after accounting for increases in N_2O emissions) in planted pastures due to the fertilizing effect of increased nitrogen fixation. We estimate an additional sequestration potential of 0.56 MgC ha^{-1} yr^{-1} over 72Mha of land. This was restricted to global planted pastures. Spatial overlap with Reforestation and Grazing – Optimal Intensity. 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 concerns.

- Peatland restoration includes 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 soil carbon 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 soil carbon[70-72] occurring over a 20-year period. Due to the strong likelihood of near-term increased CH_4 emissions arising from increased soil organic carbon in peatlands[73], we do not include increased soil carbon sinks in freshwater peatlands upon 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].
- Avoided peat impacts refers to avoided soil carbon 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 M ha yr^{-1} [72]. Avoidable soil carbon 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 Avoided Forest Conversion pathway to avoid double-counting.

- Restoration of coastal blue carbon ecosystems (mangroves, salt marshes and seagrass meadows) typically leads to significant soil carbon 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 soil carbon and enhanced sequestration are included, and were estimated based on addition sequestration at an average rate of 1.7 tC ha^{-1} yr^{-1} [75,76], and avoided fluxes averaging 3.4 tC ha^{-1} yr^{-1}estimated by assuming a potential 50% loss of the original soil carbon[77,78] occurring over a 20-year period.
- Avoided coastal impacts refer to the avoided soil carbon 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 based on estimates of soil carbon stocks to 1m 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 Avoided Forest Conversion pathway to avoid double-counting.

Uncertainty estimates

Uncertainty for maximum mitigation estimates of each pathway can be found 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 were combined.

Data Deposition

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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Figure Legends

Figure 1. Additional soil carbon storage potential for 12 natural pathways to climate mitigation. We estimate annual maximum climate mitigation potential with safeguards for the reference year 2030. Light gray portions of bars represent cost-effective mitigation levels assuming a global ambition to hold warming below 2°C (<100 USD $MgCO_2e^{-1}$ y^{-1}). Dark grey portions of bars indicate low cost (<10 USD $MgCO_2e^{-1}$ y^{-1}) portions. Ecosystem service benefits linked with each pathway are indicated by colored bars for biodiversity, water (filtration and flood control), food and air filtration. Most pathways also contribute biomass carbon, (see Figure 2), with the exception of pathways that are entirely soil carbon: 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 soil carbon sinks, while the others are avoided soil carbon losses. The remaining 8 of the 20 pathways from Griscom et al. [32] are not expected to have an impact on soil organic carbon, and therefore have not been included in this figure.

Figure 2. Maximum climate mitigation potential of soil in 2030 across forest, agriculture and grassland, and wetland biome pathways with safeguards. Bars to the left indicate the magnitude of potential sinks, whereas the bars to the right indicate magnitude of avoided emissions. Dark portions of bars represent soil carbon; white portions of bars represent vegetative biomass; and dotted portion of bar is avoided CH_4 and N_2O through improved nutrient, rice, and animal management. Note that due to the strong likelihood of near-term increased CH_4 emissions arising from increased soil organic carbon in peatlands[73], we do not included increased soil carbon sinks in freshwater peatlands upon rewetting for restoration.

Tables

Table 1. Summary of soil carbon elements of natural climate solutions (NCS): the role of soil and co-benefits for sustainable development. Cells in green indicate Forest pathways, in yellow indicate grassland/agricultural pathways, and in blue indicate wetland pathways. Adapted from Table S2 and S5 in Griscom et al. [32].

NCS Pathway	Contribution of soil carbon	Co-benefits for Sustainable development
Avoided Forest Conversion	1.2 Gt CO_2e yr^{-1} for soil protection and carbon sequestration is about 9% of the mitigation benefit from these two forest pathways.	Water retention and flow regulation. Biodiversity benefits. Maintains soil biological and physical properties ensuring health and productivity of forests.
Reforestation		Measured increase in soil fauna in reforested sites. Drought resilience. Water retention and flow regulation.
Biochar	1.1 Gt CO_2e yr^{-1} biochar direct mitigation potential.	Soil quality and fertility enhancement in temperate regions.
Cover cropping	0.41 Gt CO_2e yr^{-1} is entirely soil carbon.	Soil quality and fertility enhancement. Reduced agricultural water demands with appropriate cover crops. Reduced soil erosion and redistribution maintaining soil depth and water retention.
Trees in Croplands	0.28 Gt CO_2e yr^{-1} in soil carbon is 40% of the total mitigation potential.	Biodiversity, habitat connectivity, erosion control, water recharge, and reduced soil erosion. Tree planting helps capture airborne particles and pollutant gasses.
Avoided Grassland Conversion	0.23 Gt CO_2e yr^{-1} is entirely soil carbon.	Permanent grasslands provide "biological flood control" and maintain ecosystem water balance assuring adequate water resources. Important habitat for nesting and foraging birds.
Grazing - Optimal Intensity	0.15 Gt CO_2e yr^{-1} is entirely soil carbon.	Reduces disturbance to plant-insect interactions. Reduce water use on managed pastures, increase the soils ability to trap contaminants.
Grazing - Legumes in Pastures	0.15 Gt CO_2e yr^{-1} is entirely soil carbon.	Higher insect diversity, biological nitrogen fixation, improved soil structure, erosion protection and greater biological diversity.
Peatland Restoration	0.65 Gt CO_2e yr^{-1} in soil carbon is 80% of the total mitigation potential.	Restoring reestablishes 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.
Avoided Peatland Impacts	0.54 Gt CO_2e yr^{-1} in soil carbon is 72% of the total mitigation potential.	
Coastal Wetland Restoration	0.52 Gt CO_2e yr^{-1} in soil carbon is 62% of the total mitigation potential.	Maintains the provision of structure, nutrients and 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.
Avoided Coastal Wetland Impacts	0.24 Gt CO_2e yr^{-1} in soil carbon is 79% of the total mitigation potential.	

Table 2. Example activities to achieve mitigation potentials of soil carbon sequestration pathways. Cells in green indicate Forest pathways, in yellow indicate grassland/agricultural pathways, and in blue indicate wetland pathways. Adapted from Table S7 in Griscom et al. [32] and Griscom et al. [81].

NCS Pathway	General Activities	Specific Activities
Avoided Forest Conversion	PROTECTION Protected areas establishment and improved enforcement, 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.
Avoided Grassland Conversion		Prevent conversion of grasslands to tilled croplands; intensification of existing croplands.
Avoided Peatland Impacts		No-net-loss mitigation regulations; re- siting of oil palm plantation permits to non-peat locations.
Avoided Coastal Wetland Impacts		No-net-loss mitigation regulations; avoided harvest of mangroves for charcoal; avoided consumption of food products with acute impacts on coastal wetlands (e.g. mangrove replacing shrimp farms).
Biochar	MANAGEMENT Realignment of agriculture support programs, ecosystem services payments, certification schemes, improved land tenure, mitigation programs and markets	Extension programs to build capacity on biochar management.
Cover cropping		Cultivation of additional cover crops in fallow periods; shift to reduced-tillage or zero-tillage systems and other conservation agriculture practices may enhance soil carbon benefits of cover crops.
Trees in Croplands		Regulations and certification programs that promote windbreaks (shelterbelts), alley cropping, agroforestry systems and farmer managed natural regeneration (FMNR).
Grazing - Optimal Intensity		Maintaining forage consumption rates that enable maximum forage production.
Grazing - Legumes in Pastures		Sowing legumes in existing planted pastures.
Reforestation	RESTORATION Certification and mitigation programs, indigenous community management	Regulations that advance minimum forest cover requirements; integration of trees into grazing lands (i.e. silvopastoral systems); diet shifts.
Peatland Restoration		Re-wetting and re-planting with native freshwater wetlands species.
Coastal Wetland Restoration		Re-wetting and re-planting with native salt-water wetlands.

Figure 1

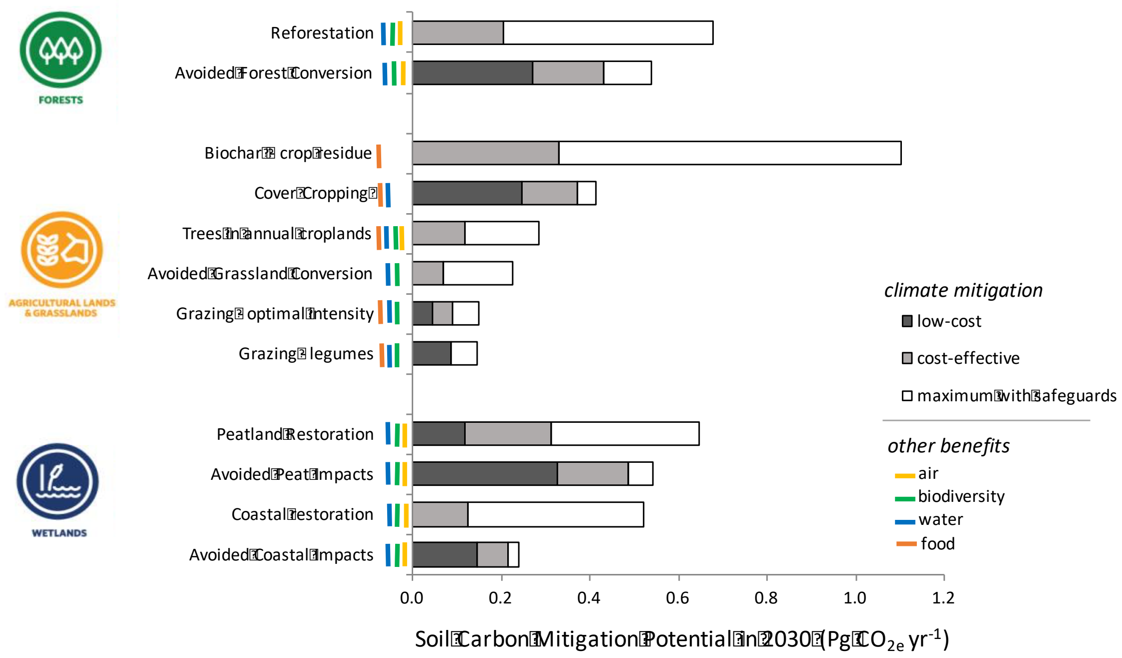

Figure 2