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Soils and climate change

Pete Smith

Soils contain vast reserves (~1500 Pg C) of carbon, about twice that found as carbon dioxide in the atmosphere. Historically, soils in managed ecosystems have lost a portion of this carbon (40–90 Pg C) through land use change, some of which has remained in the atmosphere. In terms of climate change, most projections suggest that soils carbon changes driven by future climate change will range from small losses to moderate gains, but these global trends show considerable regional variation. The response of soil C in future will be determined by a delicate balance between the impacts of increased temperature and decreased soil moisture on decomposition rates, and the balance between changes in C losses from decomposition and C gains through increased productivity. In terms of using soils to mitigate climate change, soil C sequestration globally has a large, cost-competitive mitigation potential. Nevertheless, limitations of soil C sequestration include time-limitation, non-permanence, displacement and difficulties in verification. Despite these limitations, soil C sequestration can be useful to meet short-term to medium-term targets, and confers a number of co-benefits on soils, making it a viable option for reducing the short term atmospheric CO_2 concentration, thus buying time to develop longer term emission reduction solutions across all sectors of the economy.

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Introduction

Soils contain a stock of carbon to a depth of 1 m that is about twice as large as that in the atmosphere and about three times that in vegetation. Small losses from this large pool could have significant impacts upon future atmospheric carbon dioxide concentrations, so the response of soils to global warming is of critical importance when assessing climate carbon cycle feedbacks [1••]. Models that have coupled climate and carbon cycles show a large divergence in the size of the predicted biospheric feedback to the atmosphere. Central questions which still remain when attempting to reduce this uncertainty in the response of soils to global warming are: first, the temperature sensitivity of soil organic matter, especially the more recalcitrant pools [1••,2•], second, the balance between increased carbon inputs to the soil from increased production and increased losses due to increased rates of decomposition [3], and third, interactions between global warming and other aspects of global change including other climatic effects (e.g. changes in water balance), changes in atmospheric composition (e.g. increasing atmospheric carbon dioxide concentration) and land-use change [4,5]. In addition to responding to climate change, soils could also play an important role in climate mitigation; if carbon can be sequestered in soils, this could be a significant mechanism for reducing atmospheric CO_2 concentrations [6,7]. In this short review, I outline recent evidence of potential responses of soils to climate change, and then outline recent evidence on the possible role of soil C sequestration in climate mitigation, and discuss some limitations associated with this method of climate mitigation. This review is limited to mineral soils, and does not cover peatlands and permafrost soils, since the role of peatlands in climate change has been reviewed recently [8], and space precludes dealing with all soil types in similar depth.

The impact of climate change on soils

Soils in the global carbon cycle

Globally, soils contain about 1500 Pg (1 Pg = 1 Gt = 10^{15} g) of organic carbon [9], about three times the amount of carbon in vegetation and twice the amount in the atmosphere [10]. The annual fluxes of CO_2 from atmosphere to land (global Net Primary Productivity [NPP]) and land to atmosphere (respiration and fire) are each of the order of 60 Pg C y^{-1} [10]. During the 1990s, fossil fuel combustion and cement production emitted 6.3 ± 1.3 Pg C y^{-1} to the atmosphere, while land-use change emitted 1.6 ± 0.8 Pg C y^{-1} [10,11]. Atmospheric C increased at a rate of 3.2 ± 0.1 Pg C y^{-1}, the oceans absorbed 2.3 ± 0.8 Pg C y^{-1} with an estimated terrestrial sink of 2.3 ± 1.3 Pg C y^{-1} [10,11]. Soil carbon pools are smaller now than they were before human intervention. Historically, soils have lost between 40 and 90 Pg C globally through cultivation and disturbance [12–15]. The size of the pool of soil organic carbon (SOC) is large compared to gross and net annual fluxes of carbon to and from the terrestrial biosphere.

Small changes in the soil organic carbon pool could have dramatic impacts on the concentration of CO_2 in the atmosphere. The response of soil organic carbon to global warming is, therefore, of critical importance. One of the first examples of the potential impact of increased release of terrestrial C on further climate change was given by Cox *et al.* [16]. Using a climate model with a coupled carbon cycle, this study showed that the release of terrestrial carbon under warming would lead to a positive feedback, resulting in increased global warming. Since then, a number of coupled climate carbon cycle (so-called C4) models have been developed. However, there remains considerable uncertainty concerning the extent of the terrestrial feedback, with the difference between the models amounting to differences in the atmospheric CO_2 concentration of ~250 ppm by 2100 [17•]. This is of the same order as the difference between fossil fuel carbon emissions under the IPCC SRES emission scenarios [18]. It is clear that better quantifying the response of terrestrial carbon, a large proportion of which derives from the soil, is essential for understanding the nature and extent of the earth's response to global warming.

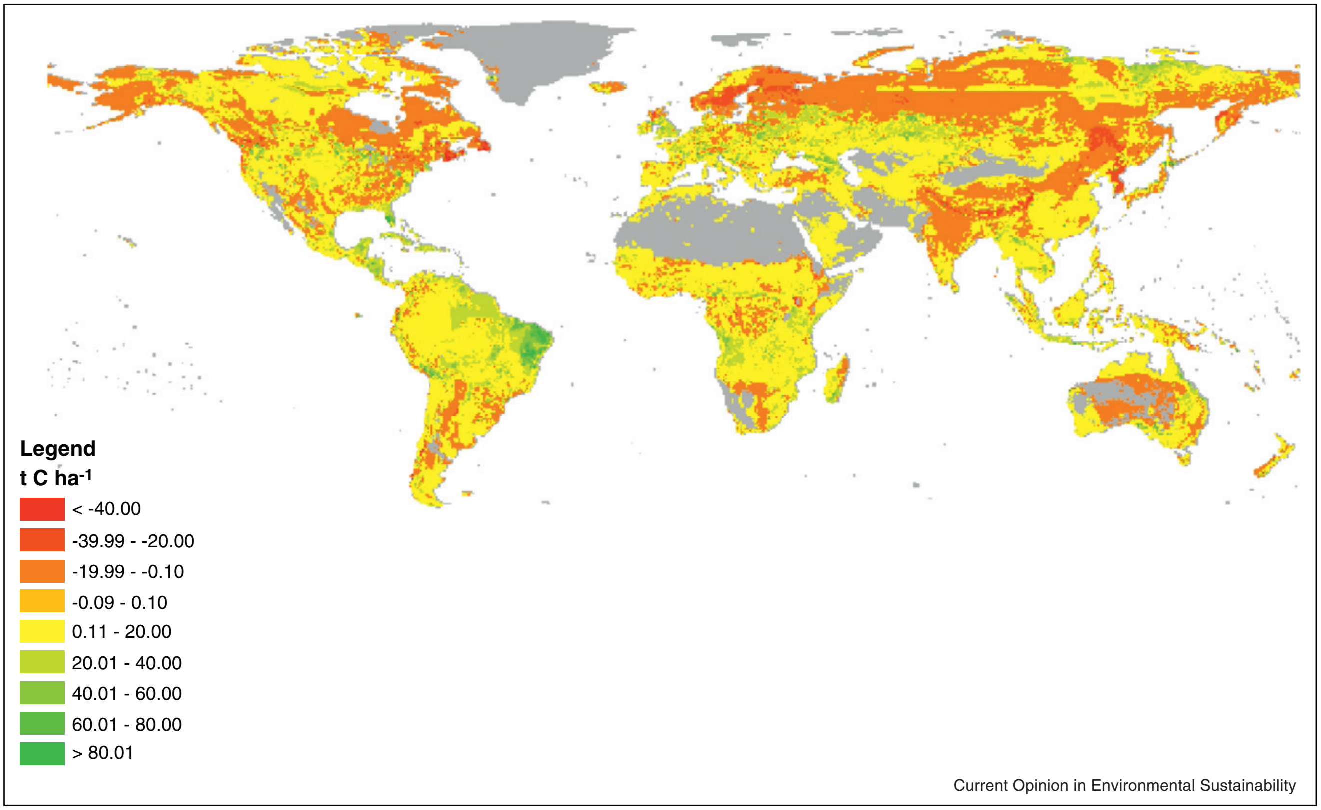
The response of soils to future climate change

Despite suggestions during the 1990s that climate change could lead to massive losses of carbon from the world's soils, more recent studies have suggested that climate change impacts on soil carbon could be less significant [4,5,19,20•]. The level of SOC in a particular soil is determined by many factors including climatic factors (e.g. temperature and moisture regimes) and edaphic factors (e.g. soil parent material, clay content, cation exchange capacity [21]). For a given soil type, however, SOC stock can also vary, the stock being determined by the balance of net carbon inputs to the soil (as organic matter) and net losses of carbon from the soil (as carbon dioxide, dissolved organic carbon and losses through erosion).

Examining climate impacts on cropland and grassland soils in Europe, Smith *et al.* [4] showed that SOC stocks were projected to change little between 1990 and 2080, since increased productivity, feeding more carbon into the soil, balanced the increased losses of SOC from faster decomposition under climate change. Further, in some European regions, the future climate is projected to dry so much that decomposition rate is slowed, despite large increases in soil temperature [4]. Ciais *et al.* [19] reviewed a number of European studies and showed that other modelling studies confirm this finding, with cropland soil C stocks projected to change little during 1990–1999 (ranging from a small sink of 15 $gCm^{-2}\,yr^{-1}$ to a source of over the 1.3–7.6 $gCm^{-2}\,yr^{-1}$, from the ORCHIDEE-STICS, LPJmL and RothC models, respectively). Future changes in cropland SOC were found to be highly dependent on management and land use change assumptions, but the direct impact of combined climate drivers was not found to be large [19].

Globally, there is some uncertainty about the impact of climate change on mineral soils, related to the complexity of the factors determining the C balance of soils [3], and uncertainties in the ways models deal with interactions among the climate drivers. Despite this uncertainty, projections are similar. Cramer *et al.* [22] used the IS92a anthropogenic emission scenario (which is comparable to the later IPCC A1b scenario) in conjunction with the HadCM2-SUL version of the Hadley Centre climate model. Their simulations show a ca. 10% increase (mean of six Dynamic Global Vegetation Models; DGVMs) between 2000 and 2100. Gottschalk *et al.* [20•], using the RothC model, driven by a range of climate scenarios and scaled NPP changes from the IMAGE 2.2 model, found a similar impact with a comparable scenario of ~8% increase in SOC stocks. Ito [23] reported projected global SOC changes for the 21st century using seven climate model realisations of the IPCC A2 scenario, which shows lower climate forcing than the scenarios used by Cramer *et al.* [22] and Gottschalk *et al.* [20•]. Unsurprisingly, Ito [23] projected smaller changes in SOC, in some cases showing a small loss of SOC, where similar scenarios in the studies of Cramer *et al.* [22] and Gottschalk *et al.* [20•] showed small increase. Lucht *et al.* [24] used the LPJ model to simulate SOC stock changes from 2000 to 2100, and found similar percentage increases in SOC (~5–6%) to the 3.5% increase projected by Gottschalk *et al.* [20•] for similar climate forcing scenarios. The bulk of the evidence from models suggests that, at the global scale, projected changes in SOC in mineral soils are relatively small, and that SOC stocks may well increase under future climate change. This global finding, however, masks a complex pattern of regional responses [20•,25,26]. Whereas SOC stocks increase in most regions, because the increase in NPP offsets the effects of higher temperatures, there is little change or some loss in high latitude parts of Canada and eastern Europe (Siberia) and parts of east Asia, where the effects of higher temperatures outweigh changes in rainfall and NPP. The complex regional patterns of change in SOC are demonstrated in Figure 1, which shows average trend in SOC stock change 1971–2100 across 10 climate scenarios from Gottschalk *et al.* [20•]. The spatial heterogeneity in the response of SOC to changing climate shows how delicately balanced the competing gain and loss processes are, with subtle changes in temperature, moisture, soil type and land use interacting to determine whether SOC will increase or decrease in the future. Given this delicate balance, we should stop asking the general question of whether soils will increase or decrease in SOC under future climate as there appears to be no single answer. Instead, we should focus on our research efforts on improving our prediction

Figure 1



Average trend in SOC stock change 1971–2100 across 10 climate scenarios (after Gottschalk *et al.*, 2012).

of factors that determine the size and direction of change, and the land management practices that can be implemented to protect and enhance SOC stocks as discussed in Smith *et al.* [27].

The role of soils in mitigating climate change

Increasing soil C stocks to combat climate change (soil carbon sequestration)

Carbon stocks in the soil can be increased in managed ecosystems by optimising 'best management practices'. There have been numerous reviews of management to increase soil carbon stocks [28,29•,30], so a full review is not presented here. Increased carbon stocks in the soil increase soil fertility, workability, water holding capacity, and reduce erosion risk [29•]. Increasing soil carbon stocks can thus reduce the vulnerability of managed soils to future global warming [27,31]. Management practices effective in increasing SOC stocks include improved plant productivity (through nutrient management, rotations, improved agronomy), reduced/conservation tillage and residue management, more effective use of organic amendments, land-use change (crops to grass/trees), set-aside, agroforestry, optimal livestock densities, and legumes/improved species mix [27]. While these measures have the technical potential to increase SOC stocks by about 1–1.3 Pg yr^{-1} [27,29•], the economic potentials for SOC sequestration were estimated to be 0.4, 0.6 and 0.7 Pg C y^{-1} at carbon prices of 0–20, 0–50 and 0–100 USD t CO_2-equivalent^{-1}, respectively [27]. A small loss of C from permafrost or peatlands could offset this potential sequestration [8], but the increase in SOC engendered by improved management is expected to also reduce vulnerability of the soils to future SOC loss under global warming. As such, soil carbon sequestration can, in many respects, be regarded as a 'win-win' and a 'no regrets' option [32–34].

Drawbacks associated with soil carbon sequestration as a climate mitigation measure

While there are many advantages to increasing soil C stocks, and 'win-win' and 'no regrets' options can be identified, there are a number of issues associated with soil C sequestration which make it a risky climate mitigation option [35,36]. These issues are: first, saturation of the carbon sink (the carbon is only removed from the atmosphere until the soil reaches a new equilibrium soil carbon level [35]), second, non-permanence (carbon sinks can be reversed at any stage by poor soil management [35]), third, leakage/displacement (e.g. increasing soil C stocks in one area leads to soil C losses in another; IPCC, 2000), fourth, verification issues (can the sinks be measured?; [37]) and fifth, total effectiveness relative to emission reduction targets (only a fraction of the reduction can be achieved through sinks [38]). These issues are discussed briefly below.

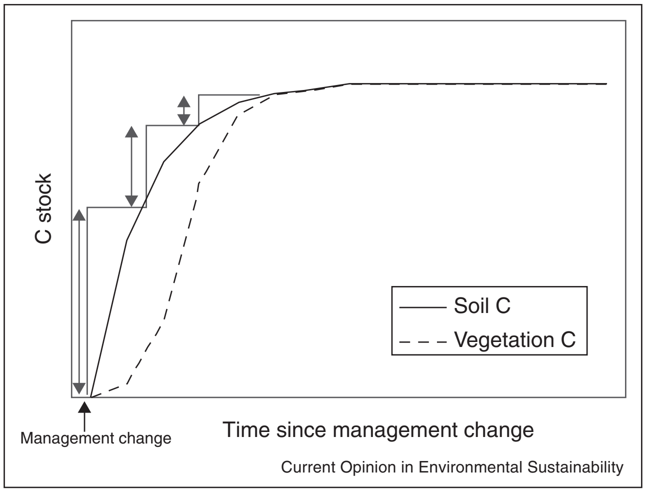
Saturation of the carbon sink

The carbon sink can be defined as the annual removal of carbon from the atmosphere into soil. When a carbon sequestration measure is first implemented, the change in soil carbon is large to begin with, but slows over time as the soil approaches a new equilibrium (see Figure 2 [35]). Sink strength, therefore, decreases over time until the soil reaches a new equilibrium. This phenomenon is termed sink saturation. Compared to reduced emissions of other greenhouse gases, which can continue indefinitely, carbon sequestration in soils (and indeed in vegetation) is therefore time-limited and finite [35]. Improved management needs to be maintained indefinitely to maintain the higher soil carbon stocks, but with no additional sink benefit.

Non-permanence

As well as declining over time, soil carbon sinks are also reversible. A soil carbon stock that has been increased by improved soil management will rapidly lose carbon unless the improved management is maintained. The rate of C loss is more rapid than the rate of gain [35]. Compared to reduced emissions of other greenhouse gases, where an emission reduction is permanent, carbon sequestered in the soil (and in vegetation) is non-permanent, presenting a risk of future release [35].

Figure 2



Current Opinion in Environmental Sustainability

Decline in sink strength over time. Change in soil and vegetation carbon sequestration showing large atmospheric carbon removals (sink strength) soon after management change (large vertical arrow on left hand side of the figure), but over the subsequent equivalent time periods, removals become smaller as the soils approach a new equilibrium (smaller arrows as soils gain in carbon).

Leakage/displacement

Increasing soil carbon stocks do not necessarily lead to a decrease in atmospheric CO_2 concentrations [39••]. It is possible, for example, to enhance soil carbon stocks in one area by applying large inputs of organic matter. If, however, the organic matter applied to the area gaining in carbon would otherwise have been applied in another area, the other area would lose carbon (i.e. the emissions are displaced; also termed 'leakage' where emissions occur outside the greenhouse gas accounting boundary [40]). In this example, the impact across the two areas would be neutral, leading to no net atmospheric carbon removal. An increase in soil carbon stocks in this case does not constitute a genuine decrease in atmospheric CO_2 concentrations [35]. Displacement/leakage also occurs where land use change to increase carbon stocks in one area leads to land use change that causes carbon release in another area in a process termed indirect land use change [41].

Verification issues

Changes in soil carbon are small compared to the large stocks of carbon present in the soil, meaning that the change in carbon stock can be difficult to measure, presenting problems for monitoring, reporting and verification (MRV [37]). If the value of the carbon removed from the atmosphere is less than the cost of measuring the change, MRV costs can make soil carbon less cost competitive with greenhouse gas reduction measures that are less expensive to demonstrate [37].

Total effectiveness relative to emission reduction targets

Soil carbon sequestration is an important climate mitigation strategy, but it is not a panacea for greenhouse gas emission reduction. Only a fraction of the reduction can be achieved through sinks [38]. Soil carbon sequestration, therefore, needs to be considered alongside many other greenhouse gas emission reduction strategies across all sectors.

The problem of attempting to use soil and vegetation to sequester carbon as a climate mitigation measure has been succinctly summarised by W.H. Schlesinger as 'trying to sequester the geosphere in the biosphere'. The carbon that humans are currently releasing through fossil fuel use has been locked up in the geosphere for hundreds of millions of years, and was accumulated over many millions of years. Using the biosphere to capture this geospheric carbon does not add up — the geospheric carbon released is too large for the biosphere to effectively store. Given this knowledge, reducing carbon emissions is obviously more important than attempting to sequester the carbon after it has been released.

Conclusions

There is still some uncertainty over future responses of soils to climate change, but most projections suggest that, globally, soils either lose only small quantities of soil carbon or soil carbon stocks may in fact increase. The global picture, however, is underpinned by considerable regional variation in response, with the response determined by a combination of factors including opposite impacts of increased temperature and decreased soil moisture on decomposition rates, and the balance between changes in C losses from decomposition and C gains through increased productivity.

In terms of using soils to mitigate climate change, soil C sequestration globally has a large, cost-competitive mitigation potential. Soil C sequestration can be useful to meet short term to medium term targets, especially if these targets are large. In addition to the mitigation potential, increasing soil C stocks provides many co-benefits in terms of soil fertility, workability, water-holding capacity, nutrient cycling, reduced emission risk and a range of other positive soil attributes [29•]. These arguments for using carbon sequestration for climate mitigation need to be weighed against the limitations discussed above, for example, time-limitation, non-permanence, displacement and difficulties in verification. Despite these limitations, soil C sequestration may have a role in reducing the short term atmospheric CO_2 concentration, thus buying time to develop longer term emission reduction solutions across all sectors of the economy.

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- •• of outstanding interest

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