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Soils as Carbon Stores and Sinks: Expectations, Patterns, Processes, and Prospects of Transitions

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Abstract

The few percent of soil organic carbon (SOC) among mineral components form the interface of climate, plant growth, soil biological processes, physical transport infrastructure, and chemical transformations. We explore maps, models, myths, motivation, means of implementation, and modalities for transformation. Theories of place relate geographic variation in SOC to climate, soil types, land cover, and profile depth. Process-level theories of biophysical change and socioeconomic theories of induced change explain SOC transitions that follow from land use change when a declining curve is bent and recovery toward SOC saturation starts. While the desirability of recovering from SOC deficits has been mainstreamed into climate policy, the effectiveness of proposed measures taken remains contested. Process-level

requirements for transitions at plot and landscape scales remain uncertain. Expectations of policy-induced SOC transitions have to align with national cross-sectoral C accounting and be managed realistically with land users (farmers) and commodity supply chains (private sector, consumers).

Contents

1. PROCESS-BASED THEORIES OF SOIL CARBON CHANGE: EXPECTATIONS OF INDUCIBLE CHANGE

Global soil organic carbon (SOC) decline and recovery matters, as it involves substantial quantities. Current estimates are that due to human activity, approximately 140 Pg[1] of C have been lost from soils historically (1), while current global C emissions (across all sectors) for the 2010–2019 decade was 9.6 ± 0.5 Pg year^{-1} (2). The state of, and change in, SOC is one of the three indicators used by the United Nations Convention to Combat Desertification and the Sustainable Development Goals (SDGs) reporting to assess the extent of degraded land area, soil health, and restoration effectiveness. SOC is functionally linked to water regulation, crop and pasture production, flood and drought risk mitigation, nutrient cycling, biodiversity habitat, and ecosystem services. The terrestrial C sink in vegetation and soils has over the past decade removed from the atmosphere some 34% of total anthropogenic emissions from industrial activity and land use change, constituting a valuable ecosystem service (3).

[1] 1 Pg = 1 Gt = 10^{15} g.

The 2014 SCOPE assessment of the science, management, and policy associated with the multiple benefits of soil carbon (4, 5) was part of the changes in soil science from a primary focus on classification and mapping, through process-based understanding (6), to relevance for land users and external stakeholders, and to greater attention to policy debates (7), coupled with a clearer role of "legitimacy" and of locally based soil scientists to relate local context to global understanding (8, 9). As part of this increased attention to societal relevance, the desirability of a substantial ("4 per 1000") increase in soil C stocks as part of climate change mitigation has become broadly accepted (10–12), but its feasibility remains contested (13–15), as does the depth to which soil should be considered in the accounting discussed (16). Global uncertainties in the amounts and locations of soil carbon stocks include the extent of wetland, peatland, and permafrost systems and factors that constrain soil depths, such as shallow bedrock (17).

Carbon stocks: any biomass or necromass pool can, at equilibrium, be estimated as inputs per unit time multiplied by mean residence time, suggesting two ways to increase stocks: larger inputs or longer residence times

One of the overarching concepts that emerged from the SCOPE review was that of soil carbon transition curves (18) through time describing initial SOC decline after conversion from natural vegetation, followed by potential recovery of SOC stocks in intensified land use, similar to forest or tree cover transitions (19). SOC transitions occur spatially between degrading and recovering zones of alley-cropping systems or temporally, within a swidden-fallow cycle (20, 21) or the life cycle of a tree crop plantation (22, 23). When expressed as spatially or time-averaged carbon stocks at the land use system level, however, this fine-grained dynamic can be ignored where land use change is described at the between-systems level, as is commonly done in national accounting of change in terrestrial carbon stocks. For such reporting globally, the Intergovernmental Panel on Climate Change (IPCC) has summarized from available evidence default Tier I estimates of the relative change in soil C stocks (with periodic revisions) (24), but countries are inclined to use country-specific data summaries in a similar approach (Tier II) or use more sophisticated gain and loss models validated at the national scale (Tier III). Setting up and maintaining the SOC monitoring system needed at Tier III is not easy, however, and can lead to unwelcome surprises. The historical choice to focus on SOC stocks in the topsoil (0–30-cm depth; typically approximately half of SOC in the upper meter of soil) is challenged by recent data that show that SOC neutrality in the topsoil does not imply SOC neutrality for the soil profile as a whole. Long-term observations at the same site are still the gold standard for quantifying the relatively small and slow changes in soil properties, such as SOC storage. Only a few countries have been able to set up observatories with the number of replications needed to pick up changes in SOC, at a decadal (ten-year) resampling frequency. A recent study in a country that has such a program yielded some unexpected and so far unexplained results that challenge commonly made assumptions (see the sidebar titled Unexplained Loss of Subsoil Carbon in the Netherlands). Until possible explanations for the patterns observed have been checked in follow-up research, any claims of SOC neutrality for the soil profile as a whole based on topsoil results on intensively used agricultural lands, such as in the Netherlands, have to be treated with caution and suspicion.

An ongoing debate on data versus models meanwhile finds a new middle ground (27). Estimates at a national scale, relevant to climate policy agreed upon between nation states, are improving (28, 29), but the policy relevance has also introduced risks of publication bias and selective reporting of the science that fits policy agendas, ignoring what does not (30). A simple observation on all current efforts to increase SOC stocks as part of mitigation measures is that such efforts will not be reflected in national data unless the national accounting system is concurrently refined to include data on the spatial extent of a finer categorization of land use that reflects different phases of a SOC transition curve. Contrary to expectations, a recent review of forest nature-based solutions found no cases that reported positive effects on SOC storage (31). As a quick scan of the literature after

UNEXPLAINED LOSS OF SUBSOIL CARBON IN THE NETHERLANDS

A recent study on 1,152 soil resampling locations for the Netherlands (25) showed unexpected effects: Between 1998 and 2018, SOC concentrations (and by inference, C stocks) in the 0–30-cm depth soil layer did not change (mean decline 1.06 with a standard error of 1.56 g kg^{-1}), but those in the 30–100-cm soil layer decreased (mean decline 17.7 with a standard error of 2.30 g kg^{-1}). This result is surprising, as it is generally assumed that changes in these two layers are correlated; however, the 0–30-cm layer would show a faster response to changes in soil management and, hence, beyond easier measurement, its selection for standardized national C accounting. The statistically significant losses in the 30–100-cm layer show that C neutrality in the topsoil does not imply C neutrality for the soil profile as a whole. Explanations for the observed changes over time are, however, only tentative. The authors note that relatively shallow layers of peat in the subsoil that were classified as mineral soils may contribute to the SOC decline. Beyond that, numerous changes in land use during the 20-year period may have been involved: a continued trend toward deeper drainage in combination with warmer and drier summers, a shift in the rotations on arable lands with less use of deep-rooted grain crops and more tuber and root crops with lower organic inputs into the subsoil, or a continued selection of crop cultivars with a larger resource allocation to harvestable parts and less to roots (26).

2016 showed an overwhelming volume of relevant studies about other aspects of SOC change, we started this review with a set of hypotheses framed within a cross-scale system analysis of policy-relevant models of C dynamics at ped, pedon, plot, land use system, landscape, and global scales (**Figure 1**) and report our findings under the indicated topic headings.

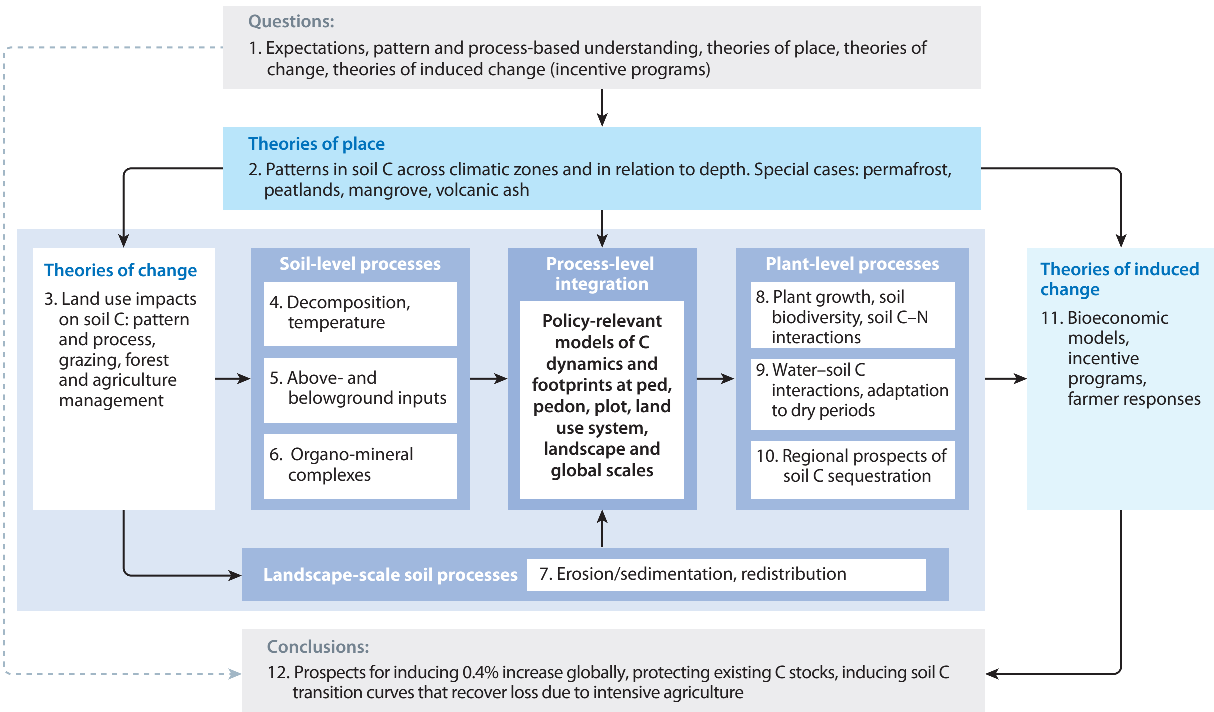

Figure 1

The twelve aspects of policy-relevant models of carbon dynamics at ped, pedon, plot, land use system, landscape, and global scales selected for this review.

This review considers the spatial evidence (theory of place) on existing geographic variation, before reviewing the process-level theory of change of SOC transition curves and their implications, ending with theories of induced change (32), where a policy environment and incentive system is created to induce land users to reduce SOC deficits. Our first tentative conclusion is that high expectations that SOC storage can be increased globally gained policy interest but remain contested, with notable exceptions in conditions with disproportionate SOC change.

2. THEORIES OF PLACE: PATTERNS IN SOIL CARBON ACROSS CLIMATIC ZONES

Just as there remains uncertainty surrounding the total global SOC stock, current maps of the spatial distribution pattern of topsoil SOC vary but share common patterns, in that SOC content generally rises with precipitation and tends to decrease with increasing temperature. SOC values are largest in the boreal and high latitude area, lowest in hot deserts, and intermediate in the humid tropics (33, **Figure 2**).

Soil carbon stocks combine SOC and bulk density (weight per volume) information. Estimates of the C stock of the world's soils, restricted to the top 30-cm soil layer, are estimated to be between 574 and 967 Pg C with a median of 732 Pg C; C stock of the upper meter of soil ranged between 933 and 2,649 Pg C with a median of 1,408 Pg C, or 1.92 times the median for the upper 30 cm (31, 34). There is still much uncertainty about the size of SOC hotspots, including permafrost areas, and landscapes that have not yet been mapped accurately such as peatlands, mangroves, and high-carbon mineral soils:

- The northern permafrost region covers approximately 12% of Earth's land surface and has an SOC density at 320–700 Mg C ha^{-1} with SOC stock estimated at 472 Pg C for 0–1-m depth and 1,035 Pg C for 0–3-m depth (35).

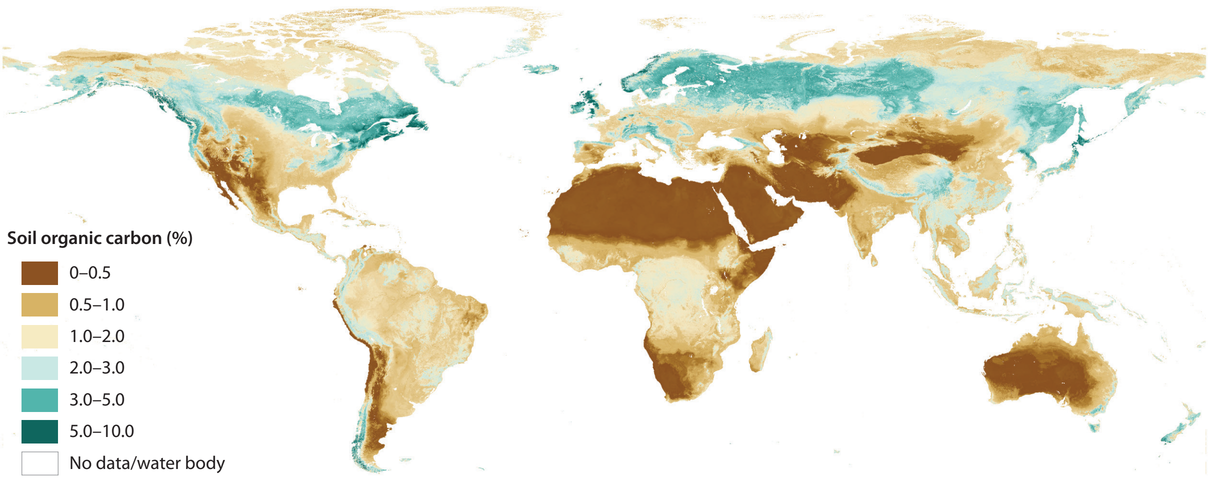

Figure 2

The global distribution of topsoil organic carbon concentrations, predicted for 2001 for the 0–5-cm depth from Reference 33. The map was generated from a global dataset of soil observations coupled with remote sensing images, digital elevation models, and climate and land cover information. A regression tree model linked the observations with the covariates. The soil organic carbon (SOC) distribution shows a pattern that follows the climate, with high SOC in the humid tropics and poles and low contents in dry areas such as the Sahara, Arabian, Gobi, Australian and Atacama deserts; no data available for Greenland outside its coastal zone. SOC content generally rises with precipitation and tends to decrease with increasing temperature

- Peatlands cover 4–6% of the world with C stock of 450–650 Pg C (over the whole depth) (36). Note that due to the low bulk density, the C stock of peatlands in the upper 30 cm of the profile is not very high, but SOC in peatlands does not decline with depth. One of the challenges is that a peat layer of at least 0.5 m is needed before a soil is mapped as peat, while C density in adjacent wet soils can still be high (37; see also the sidebar titled Unexplained Loss of Subsoil Carbon in the Netherlands).
- Mangroves cover approximately 0.1% of Earth's land surface, with C density of 220–350 Mg C ha^{-1} and an estimated stock of 6.4 Pg C (to 1 m) (38).
- Andosols cover approximately 0.8% of Earth's surface and are estimated globally to hold 78 Pg C (39). These soils have a C density (0–1 m) of 163–254 Mg C ha^{-1}. Other high C soils include Chernozems and Kastanozems in high rainfall and low temperature regions of the world, soils with humic layers, topsoil organic carbon content of 5% or more, and a C density of 190–210 t C ha^{-1} (40).

Mapping of SOC stock from the field to the nation and continental extent has progressed rapidly during the past two decades using digital soil mapping. Digital soil mapping follows the *scorpan* spatial prediction function approach (41):

$$C_{x,y,z} = f\,(s, c, o, r, p, a, n) + e, \qquad 1.$$

where SOC at spatial position x, y, and depth z is a function of factors that can be quantified through spatial layers: soil physical and chemical properties (s), climate (c), organisms which include natural vegetation, land use, human effects, and management (o), relief (r), parent materials (p), age or time since cultivation (a), and spatial position such as distance from river (n); e represents the spatially correlated errors. The spatial prediction function *f()* can be a statistical, theory-based, or machine learning model. Recent improvements in machine learning using large spatially explicit data sets can result in improved maps but a lower transparency on how underlying factors interact in the final result (42, 43).

Drivers and indicators of SOC vary with spatial scale (**Figure 3**). At the global scale, climate and vegetation are reported to be the main drivers of SOC stocks, implying that mean annual temperature and precipitation and vegetation type/biome are useful indicators. A meta-analysis of 5,500 global soil profiles suggested that climate and soil acidity are more closely related to soil organic matter stabilization than clay content (44), but in more local studies with less climatic variation soil texture accounts for a larger share of the existing variance in the data set.

Terrain (topography) interacting with land management (**Figure 3**) is an important factor explaining SOC stock in the landscape as it controls water flow, erosion, and depositional processes. The interactions between soils, climate, vegetation, and human land use can lead to surprising outcomes where SOC degrading agriculture is preferentially located in soils with high inherent SOC; if the inherent SOC under natural vegetation is unknown, statistical studies can underrate the impacts of land use on SOC. For example, a recent study (45) found land use was not a major continental-scale control on SOC across sub-Saharan Africa. A study in continental Australia (46) found that soil physicochemical properties (clay and silt content, soil pH, and Fe) have more predictive power for SOC stock than climate, plant productivity, and soil biodiversity. The expected SOC distribution with depth can further assist in reconciling data for various soil layers (47). For example, the pedotransfer function of SOC for humid tropical soils (48) defines SOC as a function of clay, silt, soil pH, elevation (temperature), and soil type (for wetland and volcanic soils). Subsequently, an exponential distribution of SOC with depth was confirmed, allowing the natural vegetation C_{ref} for a layer between any two depths to be calculated (49).

This section concludes that the main drivers of SOC stock are above- and belowground organic inputs linked to land cover, soil physical and chemical properties (s) and climate (c). Within

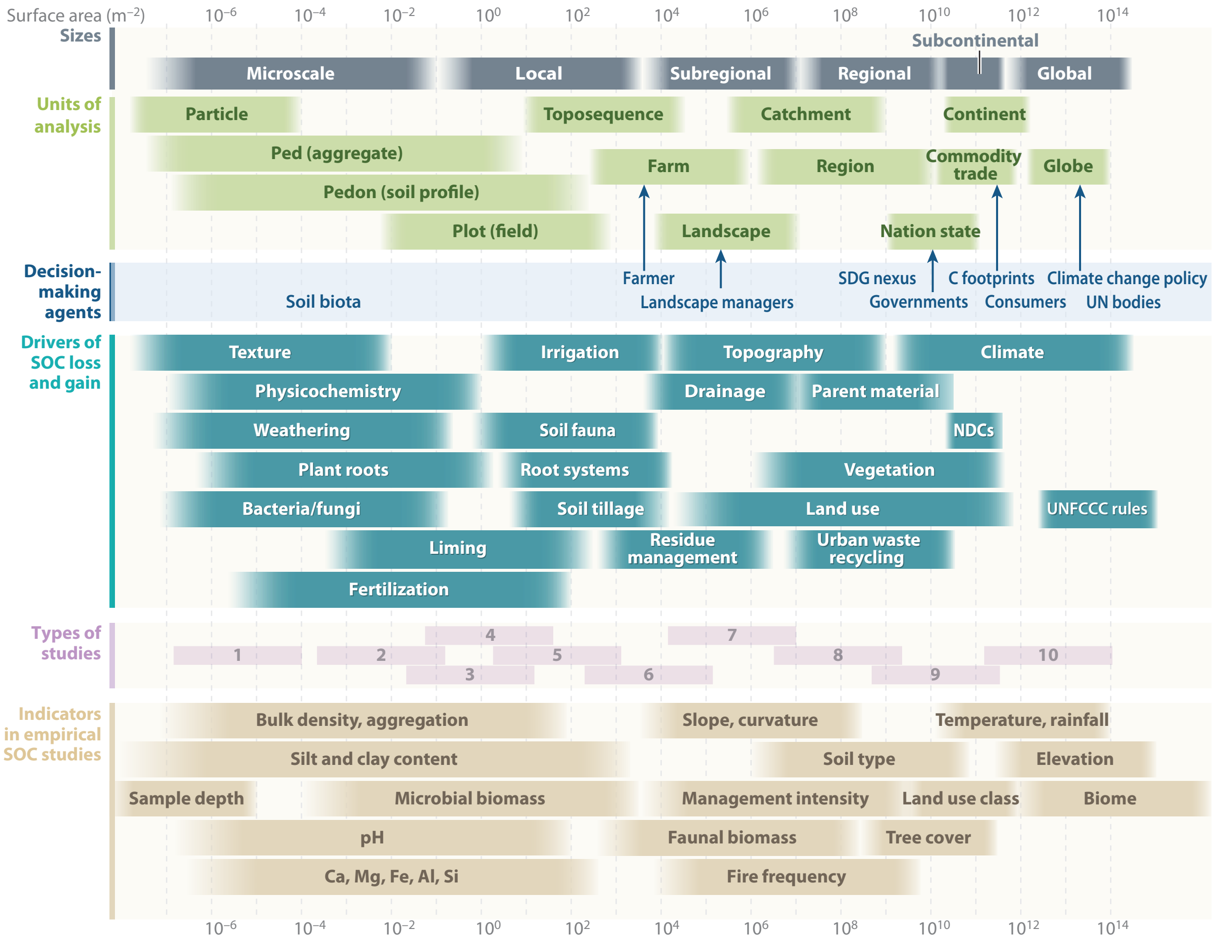

Figure 3

Overview on the scale-dependent units of analysis, hierarchy of drivers and active decision-making agents, and empirical indicators for soil carbon storage; ten types of studies are indicated with numbers: 1. Roots interacting with rhizosphere biota, mycorrhizal hyphae, and soil aggregates; 2. Root systems with fine root turnover linked to water and nutrient supply; 3. Soil tillage and aboveground crop residue management; 4. Irrigation, drainage, and erosion control; 5. Farm-level integration of crops, livestock, and/or trees; 6. Urban and food industry waste recycling; 7. Land use planning based on functional soil maps; 8. NDCs and national C transition policies; 9. Footprints and responsible consumer choices; 10. International climate policy negotiations. Abbreviations: NDCs, Nationally Determined Contributions; SDG, Sustainable Development Goals; SOC, soil organic carbon; UN, United Nations; UNFCCC, United Nations Framework Convention on Climate Change.

the observed ranges, human land use impacts land cover and soil conditions that modify SOC breakdown and buildup. Disproportionately large, relative to the area involved, SOC changes are expected in permafrost, peatland, mangrove, and volcanic ash soils. The focus of the next section is human land use impacts, through a change in vegetation and other aspects of soil degradation.

3. LAND USE IMPACTS ON SOIL CARBON CHANGE

Land use change that modifies tree cover and the presence of perennial grasses can change SOC storage substantially. The current IPCC guidelines for reporting greenhouse gas emissions at the

SOIL CARBON TRANSITION IN CHINA

A recent study in China (50) confirmed a soil organic carbon (SOC) transition curve on arable lands, documenting that topsoil organic carbon increased 15–27% during 1980–2010, while the soil acidified (pH decreased by 0.62–0.71 units). The measured increase in soil nitrogen (N) points to a role of a strong increase in N fertilizer use that links the changes in SOC and soil pH. Across Jiangsu province, with a more neutral soil pH, SOC has increased on average from 8.5 g kg^{-1} to 9.9 g kg^{-1} from 1980 to 2000, with a further increase to 12.6 g kg^{-1} in 2010, accompanied by a decrease in average soil pH from 7.63 to 6.90. In Guangdong, with more weathered and acid soils, the overall increase in average SOC content from 14.2 g kg^{-1} to 16.5 g kg^{-1} and 20.2 g kg^{-1} was associated with a decrease in average soil pH from 5.58 to 4.90 and 4.98, in 1980, 2000, and 2010, respectively. On the one hand, higher cropping intensities may have brought more belowground inputs into the soil; on the other hand, the acidification linked to commonly used N fertilizer may have induced a shift from bacterial- to fungal-dominated soil ecosystems, with greater SOC storage as a consequence. With current knowledge, the induced N_2O emissions due to N fertilizer use may annul the increased carbon storage in terms of net climate forcing (51).

national scale (22) express the effects of land use on SOC stocks as a ratio between current and reference SOC levels, using a prehuman, but ecozone-dependent, natural vegetation as a basis. At the right side of **Figure 3**, land use categories such as forests, grassland, croplands, and urban areas are used for high-level data summaries, but these are too coarse for understanding the decline and potential recovery of SOC within a land use category, described as SOC transitions (for a recent example, see the sidebar titled Soil Carbon Transition in China).

A recent study in the dry forest zone in southern Africa concluded that the response of SOC to agriculture-induced land use changes depends mainly on the presence or absence of trees (52). There are contrasting conclusions in the literature on the effects of grazing intensity (53, 54). Management change within cropping, grazing, or forest management systems can change SOC with soil depth rather than or beyond its impacts on total SOC storage (compare with the sidebar titled Unexplained Loss of Subsoil Carbon in the Netherlands). A closer look at the processes on the left side of **Figure 3** may be needed to clarify the impacts of farm-level management choices within the IPCC land use categories. It is essential that medium- and long-term changes in SOC following land use change are considered in the context of related total ecosystem C losses, which are frequently much larger than any subsequent gains in SOC.

4. PROCESS-LEVEL CONTROLS ON DECOMPOSITION AND CARBON TURNOVER

Nearly a century ago, Tenney & Waksman (55, p. 55) identified four distinct controls on "[t]he rapidity of decomposition of different organic substances of either plant or animal origin in soil": (*a*) the chemical composition of the organic material, (*b*) the presence of sufficient nitrogen to enable the microorganisms to bring about the decomposition process in the shortest possible time, (*c*) the nature of the microorganisms active in the decomposition process, and (*d*) the environmental conditions at which the decomposition is carried out, especially aeration, moisture supply, soil reaction, and temperature. These four controls, with slight rewording, connect patch-level processes with macro concepts of vegetation, climate, soil management, and soil biota (**Figure 4**). For example, the microclimate at which decomposition occurs is not standard weather station data and can be up to 2°C cooler due to shading in forests or agroforestry systems (56).

Recent meta-reviews have confirmed temperature (57) and drought (58) impacts on SOC, documenting changes in litterfall rates and decomposition that partially cancel out impacts on C stocks

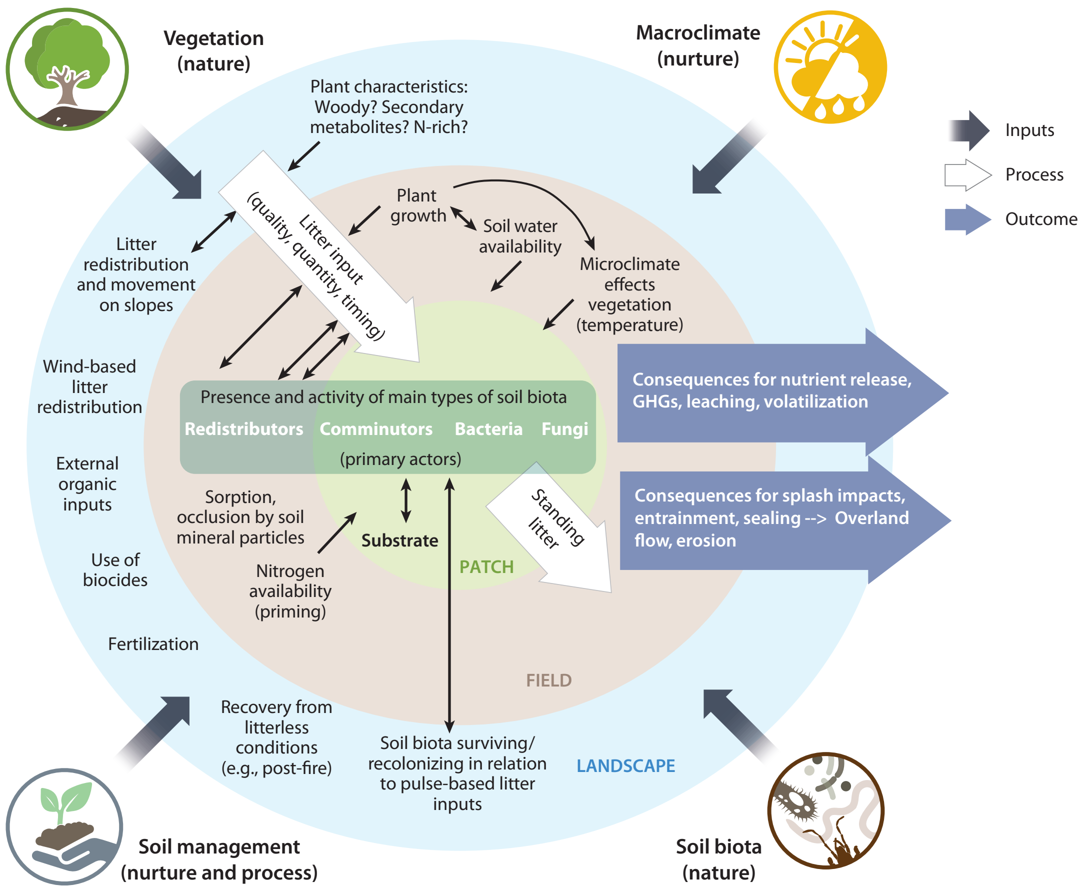

Figure 4

Vegetation (source of above- and belowground organic inputs), macroclimate (modified by vegetation to the prevailing microclimate), soil management (by farmers) and soil biota (as active agents) interact across landscape, field and patch scale (represented by concentric circles) and influence the input of organic inputs to the soil biota, the rates of decomposition and conversion to other soil C pools and thus the residence time of various pools in the surface litter and soil layers. Abbreviation: GHG, greenhouse gas.

in litter or soil. Net reductions in soil C due to drought-rewetting cycles can be expected for soils with C concentrations above 2%, according to another meta-review (59) of stock and flow models. For a first-order Stock-Flow system in equilibrium, the following simple relationship holds (60):

$$Stock = Input \times Mean\ residence\ time. \qquad 2.$$

This means that changes in stock, be it surface litter or SOC pools at any depth in the soil, can be due to a change in either input rates or decomposition rates. *Mean residence time* (MRT) is *1/k* for the standard exponential decay model (assuming that input rates and decomposition are expressed in the same unit of time), where $C/C_0 = exp(-k\ t)$ and C/C_0 is the relative amount remaining after time t with decomposition constant k. As the temperature response of biological mechanisms is generally not linear but follows a power function characterized by a Q_{10} ratio (relative rate increase for a temperature increment of 10°C), the k factor can be corrected to a standard temperature (61).

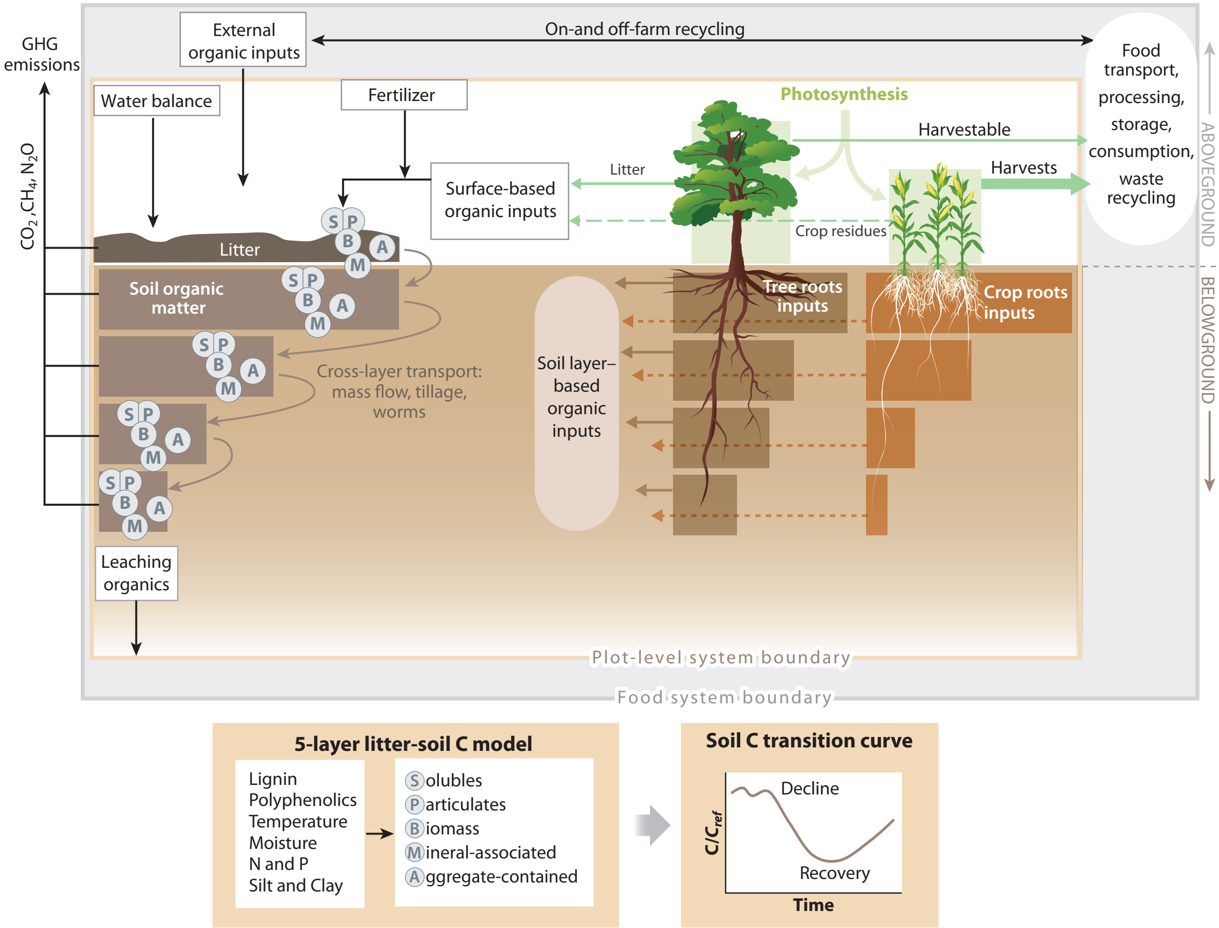

Figure 5

Schematic representation of the above- and belowground inputs to carbon stocks in surface litter and a layered soil, with the five pools used in the Millennium model, for a plot-level system boundary with an indication of how this relates to a food system boundary. Abbreviation: GHG, greenhouse gas. C_{ref} represents the C level expected for the soil type, texture and elevation under natural vegetation.

Research traditions in the decomposition of surface litter (by vegetation scientists and soil biologists) have developed partly independently of studies of the dynamics of SOC pools, but litter and SOC are closely linked and a systems approach needs to connect the two, recognizing the complementarity in functions. Standing litter protects the soil surface from runoff and erosion (62). Transfer of litter (products) to SOC in deeper soil layers can occur by tillage, mass flow of soluble components (leaching), or bioturbation (**Figure 5**). Recovery of a permanent litter layer is an important step in ecological restoration, achievable before statistically significant changes in SOC can be expected. Surface litter is easily observed in terms of input (litter traps) as well as standing necromass stock and decomposition rates (litterbags) (63–65), while SOC studies have had to rely on laboratory analysis of samples taken in the field (where a classically trained soil scientist would first remove surface litter and then start sampling “real soil”).

More specific biological interactions can be involved, such as synergistic effects in mixed-species litter decomposition (66) and the adaptation of decomposers to the specific litter sources that they are used to ("home-field advantage"), which may in practice be hard to distinguish from microclimatic differences between habitats involved in the comparisons (67). Earthworms may destabilize SOC through aggregate destruction but may also create new aggregates and redistribute litter-layer C into the mineral horizons (68), as can roots with their exudates and mobile root tips when growing into macropore spaces and leading to reorientation of soil particles as observed on soil thin sections (69). By stabilizing soil aggregates ectomycorrhiza can slow C cycling (70).

Biochar: partially scorched organic materials produced by pyrolysis ex situ and applied to soils; can have a range of properties, and reported effects on soil processes tend to be site-specific

The SOC transition in China has been associated with a decrease in soil pH (see the sidebar titled Soil Carbon Transition in China). A curvilinear relationship between soil pH and C storage implies an association of agronomically optimum soil pH (5–6) with low SOC storage has been noted and was found to remain consistent between the 1930s and 1980s in Sumatra (Indonesia) (55). Part of the positive yield effects of lime application in past experiments may have been due to induced N mineralization in the transition phase rather than to crop responses to soil acidity as such, offering scope for using N fertilizer to increase SOC storage.

Global warming will reduce SOC storage, with strongest effects in subarctic zones. Global warming can enhance carbon fluxes both to and from the soil, with the net global balance between these responses uncertain (71, 72). Net global effects will probably be dominated by the strong responses of increased SOC emissions in tundra (73) and arctic (74) zones. A meta-review of freeze-thaw impacts in the field and laboratory found evidence for physical disturbance of aggregates, opening up soil organic material to microbial activity, but also impacts through increased root turnover (75). Microbial responses to climate warming are often short-lived and unpredictable (76), with both microbial acclimation and substrate depletion probably interacting.

In wet agroforests adjacent to tropical peatlands, as an important component of peatland rewetting efforts, the relatively slow litter decomposition still stayed short of the threshold for tropical peat formation. Based on current understanding, this is due to a prevalence of anoxic conditions together with low nutrient availability that can jointly offset the high temperatures of the lowland humid tropics (77).

An analysis (78) of 48 sites in savanna grasslands, broadleaf forests, and needleleaf forests spanning up to 65 years, during which time the frequency of fires was altered at each site, found that frequently burned plots experienced a decline in surface SOC and nitrogen that was nonsaturating through time, having 36% (±13%) less carbon and 38% (±16%) less nitrogen after 64 years than plots that were protected from fire. Yet, a randomized experiment of controlled burning and grazing could not confirm such results, possibly due to increased fine root turnover caused by the aboveground disturbance of plants that may have compensated for reduced aboveground litter inputs (79). Further interactions may be involved, as external biochar applications, which may be similar to the parched root-based biochar formed in field-level burns, were found to stabilize rhizodeposits (80). Many of these studies point to the special roles of belowground inputs, relative to aboveground litter, in soil organic matter formation, especially in the absence of soil tillage, as the next section explores.

5. BELOW- VERSUS ABOVEGROUND ORGANIC MATTER INPUTS

The modification of SOC inputs from aboveground (leaf litter and woody tissue) and belowground C inputs (roots and C allocated belowground by plants to root-associated organisms) and decomposition rate (MRT) lead to differences in SOC stocks. However, the relative contribution of these two carbon input pathways and the difference in MRT to the SOC stocks are much debated.

Root-based inputs to SOC stocks dominate in many soils over aboveground inputs but remain poorly quantified. A long-term crop experiment in Sweden showed that root-derived SOC was approximately 2.3 times higher than SOC from aboveground crop residues (81). Meanwhile, a review of agronomic studies suggests that root inputs in arable cropping systems are approximately five times more likely to be retained in soil organic matter than an equivalent mass of aboveground litter after one year, with an average and median retention of 46% and 39% for belowground inputs and 8.3% and 6.6% for aboveground residues of the same crop (15). Fractal relationships between fine and coarse woody roots can be used to quantify tree root systems (82). A $\delta^{13}C$ study in a bioenergy plantation of poplar (*Populus* spp.) in Belgium found that belowground C input's conversion efficiency to SOC was 76% compared to only 9% from the aboveground source (83). Meanwhile, a modeling study showed that 50–70% of SOC in a Boreal forest in Sweden was derived from root and root-associated microorganisms (84).

A recent review of the knowledge gaps in understanding how climate change will impact soil carbon cycling by the soil microbiome includes aspects of stability, resistance, resilience, and functional redundancy (85). Negative impacts of climate change on plant-microbe interactions can affect the soil microbiome and its role in soil carbon cycling.

Arbuscular mycorrhizal fungi (AMF) can make large, direct contributions to soil organic matter via glomalin (a glycoprotein) (86). A study in a dry Afromontane forest in northern Ethiopia found that AMF spore density and root colonization was significantly lower in disturbed forest and associated with lower SOC stocks (87). The extraradical hyphae along with glomalin-related soil protein significantly influence soil carbon dynamics through their large extent and turnover. AMF hyphae and their production of glycoprotein are important for the formation of soil aggregates (88).

The combination of X-ray microtomography and microscale enzyme mapping revealed that the development of 30–150-μm pores (plant root-stimulated soil pores) was associated with higher microorganism activities (as part of the belowground pathway) and larger SOC storage capacity (89). The entombing effect provided by microorganisms' activity and growth in the rhizosphere could also provide carbon stabilization through physical protection and/or lack of activation energy due to chemical composition that translates into greater SOC stocks (90). The presence of ectomycorrhizal fungi in the soil could also modify soil organic matter dynamics. However, the net effect of ectomycorrhiza on the SOC stock increment varies with the range of ectomycorrhiza communities across regions, soil properties, fertility gradients, and land use systems (91–93). Additionally, belowground root-related pathways resulted in greater efficiency in forming mineral-stabilized SOC than surface litter inputs mixed with bulk soil through tillage. However, the relative contributions of aboveground versus belowground carbon inputs pathways in the soil profile depend on the ratio of rhizosphere to bulk soil (94).

6. ORGANO-MINERAL INTERACTIONS IN SOIL CARBON STABILIZATION

SOC persistence is mostly controlled by physical protection of carbon through soil aggregation and by accessibility of reactive mineral surfaces (95). There is a notion that to be effectively aggregated, carbon inputs from plants need to be processed by microbes into simpler compounds and microbial necromass and extracellular products. The extent of plant- versus microbial-derived soil carbon is still being debated (96). Known especially from tropical grasses such as rice and bamboo, phytoliths or organic-silicate concretions can have a long residence time in soils, making them useful as archaeological and paleobotanical markers (97).

Organo-mineral complexes stabilize SOC. By simply shaking an aggregated soil, part of the SOC will become accessible as substrate for microbial activity and will respire in subsequent weeks. Measurements based on this concept have allowed the study of an aggregate-contained,

CONTROLS IN PROCESS-BASED SOIL CARBON MODELS

Models used in understanding the dynamics of soil organic carbon (SOC) typically distinguish between pools of different MRTs, as, for example, in Century (101) and RothC (102) models, or treat it as a continuum (103). A direct link between the pools inferred in the models and direct measurements has long been elusive, but some progress has now been claimed (104). The recently proposed Millennial model (105), conceptually built on the Century model, has five SOC pools. With increasing residence times these are Pool 1, low molecular weight C (i.e., root exudates and the by-products of exoenzyme activity); Poll 2, microbial biomass; Pool 3, particulate organic matter (i.e., free fragments of plant detritus); Pool 4, aggregate C; and Pool 5, mineral-associated organic matter. In contrast to Century pools, these have operational measurement protocols. Responses to single-parameter changes in key variables are similar between Century and Millennial models, but in interactions, differences become more pronounced. Another approach moves away from the pool but defines monomer- and polymer-carbon substrate groups reacting with bacteria and fungi within physical, chemical, and biological processes (106).

physically protected SOC pool, distinguishable from the mineral-associated, chemically protected pool (compare with the sidebar titled Controls in Process-Based Soil Carbon Models and with **Figure 5**). A review of 41 published studies on the effect of aggregate disruption through diverse management techniques on SOC physical protection revealed that the reduction of macroaggregate turnover promotes SOC accumulation via a more significant C concentration of macroaggregate-occluded fractions (98), providing the notion that macroaggregates offer a beneficial setting for the short-term persistence of particulate organic matter in soils. Analysis of a European-wide database on SOC physical stabilization in different ecosystems revealed that grassland and arbuscular mycorrhizal forests stored more SOC in persistent but finite mineral-associated organic C. In contrast, ectomycorrhizal forests store more SOC in labile but indefinite particulate organic matter (99). The temperature response of arctic permafrost soils was attenuated by mineral protection, suggesting part of the substrate remains unavailable to microbes (100).

The C saturation deficit ($C_{sat\text{-}def}$)—the relative difference between the maximum and the current amount of C that can be or is associated with its fine (<20 μm) fraction—is essential as a basis to estimate the ability of a soil to store additional organic C (107). A meta-analysis of 1,144 globally distributed soil profiles suggested that the current organic C amount of the surface and deeper layer (up to 1 m) was only at 42% and 21%, respectively, of its mineralogical capacity to store and protect C (108). Areas under agriculture and deeper layers show the largest undersaturation yet have the fastest sequestration rates, providing the opportunity to boost SOC stocks through proper organic matter management practices such as increasing the presence of deep-rooted plants as part of diversity (89), biochar addition (109), and compost application. The $C_{sat\text{-}def}$ concept suggests greater opportunities for additional C storage than the C_{org}/C_{ref} concept that uses a natural vegetation point of reference and forms the basis for the current IPCC C stock accounting procedure. However, opinions vary about the practical feasibility of exceeding C_{ref} values, as exceeding the above- and belowground organic matter inputs on a sustained basis may not allow substantial harvests to be removed from a plot (110, 111).

As a result of their particular characteristics, the coarse-sized particles of volcanic ash (tephra) provide SOC protection through organo-metallic complexes; when volcanic ash of zero C content ultimately turns into an Andosol of approximately 10% SOC, atmospheric CO_2 is sequestered (112, 113). For example, during the early years after the eruption, volcanic ash-derived soils in Indonesia could accumulate SOC from 0.2–1.4% year^{-1}, depending on the land use systems (114) that influence whether or not the ash stays on-site or is transported to rivers and wetlands.

7. EROSION AND SEDIMENTATION PROCESSES AT PLOT AND LANDSCAPE SCALES

Erosion, the net loss of soil particles from a system, depends strongly on the scale under consideration. Where erosion is often measured at relatively small plots, scale-dependent sediment delivery ratios are needed to adjust results for coarser scales. Uncertainty on these sediment delivery ratios may often constrain the overall results at policy-relevant scales beyond where erosion results are quantified.

While there is no doubt that erosion of C-rich topsoil is a major cause of reduced C stocks at the plot or field level, the net effect on terrestrial C stocks may well depend on the spatial and temporal scales of consideration. Much depends on where the soil particles "on the move" end up: trapped in vegetation downhill or riparian zones (115), deposited in lakes or reservoirs, forming fertile floodplains (or even countries formed in the river delta, such as the Netherlands), or supporting mangrove development along coasts (116). Erosion currently results in the lateral movement of approximately 0.5 Pg of SOC annually, but an erosion-induced carbon sink may have offset 37% of the cumulative carbon emissions due to anthropogenic land cover change over the past 8,000 years, according to some estimates (117).

The timescale of evaluation matters, as some authors have argued that after erosion of topsoil, new C stocks may form that, in combination with the persistence of SOC from eroded soil trapped in riparian sediments, can lead to a net increase over time (118–121). Yet, for the policy-relevant timeframe of current land use, erosion is likely to be a net loss factor for SOC and its control is relevant, even though there may be "positive leakage" and net effects at the landscape scale may be smaller than what plot-level measurements suggest (122). In synthesis, the net impacts of erosion/sedimentation on landscape-level C storage depend on context, while reducing plot-level losses remains a major target for land management.

8. PLANT GROWTH, CROP DIVERSITY, AND NUTRIENT AVAILABILITY

Plant species control over long-term SOC sequestration depends on the species' traits (123). Fertile grassland ecosystems dominated by fast-growing species would support fast decomposition resulting in low net accumulation of C, whereas infertile ecosystems dominated by slow-growing species would be associated with slow decomposition promoting high SOC sequestration (124). A recent global meta-analysis found that plant diversity led to higher soil carbon across forest, grassland, and cropland systems (125). Diversified rotations of crops could increase SOC content by mitigating crop water stress (126). However, crop rotations on cultivated land that include non-mycorrhizal species (such as rapeseed) can reduce the level of glomalin-related soil proteins and thus reduce SOC sequestration (127).

Compared to simple agroforestry and cocoa monoculture, complex agroforestry has shown greater root length and weight in the topsoil, even though it attained only half the soil carbon values found in degraded forests. Higher root density was positively correlated with SOC. In upper soil layers, complex agroforestry had slightly higher soil aggregate stability compared to other agricultural systems (21). High plant diversity may greatly increase carbon capture and storage rates on degraded and abandoned agricultural lands (128) by elevating belowground biomass, increasing soil microbial activities, and minimizing the decomposition of existing soil carbon. If accompanied by a reduction in crop diversity, agricultural intensification may reduce SOC stocks. At the same time, agricultural intensification often comes with higher nutrient application rates, that may increase aboveground, while reducing root biomass (26). It is well-known that soil organic matter provides a buffering function for nutrient supply to crops in the growing season (129). Simultaneously, recent research has revealed that nutrient application can support SOC sequestration via four different pathways (123–125, 127, 128): (*a*) increased crop yields and related above- and belowground C inputs; (*b*) removing nutrient limitations for soil organic matter formation; (*c*) a reduction in lignin-modifying enzymes; and (*d*) soil acidification.

Transfers of plant biomass to SOC can be constrained by nutrient availability (130). In a field experiment in Australia (131), similar amounts of crop residues led to either an increase or a decrease in SOC, depending on the accompanying nutrient (nitrogen, phosphorous, or sulfur) application rates. Besides the required stoichiometric relations between C and N in soil organic matter (132), a reduction of lignin-modifying enzymes can also play a role in the increased SOC sequestration when N application rates are increased (133). Interactions might be more complex, as N-induced soil acidification can strongly affect mineral-associated C (134). In more intensively managed systems, higher crop yields can increase SOC. As the maximum root development tends to occur at lower soil fertility levels than the maximum agricultural yield (135), responses are not linear and depend on the fertility range investigated (136). Shifts in the types of crops cultivated (e.g., from cultivars with large to smaller root systems or with a larger harvest index) can reverse the trend. This may be one explanation for the decline in SOC in Dutch subsoils over the past three decades (23; see also the sidebar titled Unexplained Loss of Subsoil Carbon in the Netherlands). We conclude in this section that loss of plant and belowground diversity induces a loss of SOC, but agricultural intensification can induce recovery in SOC transitions where belowground inputs are increased.

9. BUFFERED WATER AVAILABILITY AS ADAPTATION TO CLIMATE CHANGE

Increasing SOC often leads to improved soil structure, faster infiltration, and higher water storage. Nonetheless, benefits for crop productivity often remain modest (compare with the sidebar titled Urgency and Expected Effectiveness of Land Restoration). A study on cacao-based agroforestry in Sulawesi, Indonesia, found that a 1% increase in SOC added 5.7 mm in available water capacity per 1 m of the rooted soil profile (137), which equals approximately a week of evapotranspiration without rain in the case study area. The effort needed to increase SOC by 1% is substantial. These modest positive impacts of SOC on available water capacity are in agreement with an extensive databases analysis of >50,000 global measurements (138).

The classic concept that more soil organic matter means more water retention does not always hold, as recent research shows that organic matter exhibits significant water repellency, directly impacting water ingress in soil (even sands) and water distribution (139–141). In contrast, some studies concluded that water repellency on soils could positively affect soil moisture conservation against evaporative loss and facilitate groundwater recharge and replenish deep moisture storage (142–144). In wet climates, this repellency might even have a positive impact on crop yield. A study showed that the additional yield effect of using organic matter inputs was more pronounced in wetter than drier areas in a temperate region (145). Even without including these benefits for wet climates, modeling studies show the positive effect of improving water holding capacity on buffering maize yields against variable weather by providing sufficient water for crop demand in the US rainfed maize system (146). In the context of climate change mitigation and adaptation, SOC may thus play a role in its buffering capacity with increased extreme weather events (in either very wet or dry climates). The role of SOC will, however, depend on nature (climate regions) and nurture (land use management) (147).

Reduced tillage: soil tillage operations differ in the depth of soil involved, the degree of mixing of soil within that depth, and the degree of disturbance to existing soil biota and aggregates; reduced tillage may increase soil C in the top layers but, depending on modified rooting patterns of crops, have opposite effects at depth, with net results depending on an agreed sampling depth

Soils with depleted organic content have a vulnerable structure that is unable to absorb and transmit water effectively during rain events, causing runoff and erosion. Good soil management could create drought-proof soils; for example, reduced tillage decreases soil evaporation and increases a greater ability to store moisture. Retaining crop residue reduces soil temperature and evaporation. Belowground, drought-tolerant plants generate larger-diameter roots with greater and a more porous rhizosheath masses. These conditions allow the plants to have better water uptake capacity (148). Collectively, these produce more resilient soil that can help crops through short-term drought and avoid the detrimental moisture stresses in the plant.

An analysis of global crop data indicated that soils with organic carbon content greater than 40 Mg C ha^{-1} on drylands had increased drought tolerance (149). Globally, increasing soils with lower organic carbon to 40–90 Mg C ha^{-1} would result in an increase in farmers' economic output in drought years by 16%. This SOC increase also has a co-benefit of reducing global decadal mean temperature warming by 0.011°C. In China, soils with higher SOC are more buffered against climate variability, resulting in both higher mean crop yield ($10 \pm 7\%$) and higher yield stability (decreasing variability by $15 \pm 14\%$) (150). We conclude that positive effects of SOC recovery on water buffering are modest but relevant for climate change adaptation.

10. REGIONAL PROSPECTS OF ENHANCED SOIL CARBON SEQUESTRATION

SOC transitions, where past losses are partially recovered by changing soil management, have previously occurred without specific SOC incentives (16; see also the sidebar titled Soil Carbon Transition in China). Increased SOC levels can arise as co-benefits of efforts to increase land productivity (see the sidebar titled Urgency and Expected Effectiveness of Land Restoration), halt and revert soil degradation, avoid hydrological disturbances that lead to floods when it rains and droughts when it does not. Awareness of the social and environmental (including soil health) conditions on the production side can lead to individually determined responsibility of consumers of globally traded commodities (151).

URGENCY AND EXPECTED EFFECTIVENESS OF LAND RESTORATION

A recent global scenario study of the potential for land restoration (152) tried to incorporate numerous societal and economic feedbacks, such as negative effects elsewhere, as land use change is connected through global markets. In the underlying model, it is assumed that as a consequence of SOC improvements, soil water-holding capacity would increase by more than 4%, a modest amount, which is relevant especially for rain-fed agriculture in arid areas where it can help plants to bridge dry spells. Model calculations suggest that restoration boosts agricultural yields globally by 2% and by up to 10% in some regions, compared to the baseline scenario. Approximately five billion hectares could be restored before 2050 through agroforestry, conservation agriculture, silvopasture, grazing management, grassland improvement, forest plantations, assisted natural regeneration, and cross-slope barriers. Compared to a business-as-usual baseline, a net gain of 17 Pg C could be achieved between 2015 and 2050. As the conversion of natural land to agriculture will be reduced, biodiversity loss could be 11% less in 2050 compared to the baseline. In a restoration-and-protection scenario, restoration measures would be combined with effective protection of important areas to maintain ecosystem functions, preventing one-third of the global biodiversity loss in the baseline scenario. However, food prices would increase and agriculture might intensify faster due to limited available land. The net effect would still be positive, with 83 Pg of carbon stored in soils and vegetation, equivalent to more than seven years of current global emissions.

11. BIOECONOMIC MODELS, INCENTIVE PROGRAMS, AND FARMER RESPONSES

Changes in SOC resulting from land management are difficult to measure especially at scale due to the heterogeneous nature of soils and the slow rate of SOC change. Models can offer a means of scaling up measurements and simulating changes over time. There are at least 250 soil carbon models (153), nearly all representing SOC in compartments with different turnover and residence times. In addition to the heterogeneity of soils, a recent review (154) lists the following issues that have yet to be fully overcome when modeling SOC change: (*a*) insufficient understanding of how SOC is affected by land use, management, climate, and edaphic factors; (*b*) the large stocks against which small changes in SOC need to be detected; and (*c*) the nonpermanent nature of SOC change. However, political and socioeconomic constraints could put this potential on hold. Thus, modeling platforms need to combine a suite of tools to capture socioeconomic and biophysical constraints to soil carbon sequestration (155, 156). Bioeconomic models that capture multiple economic and biophysical drivers have also been developed (157), but these tend to be site-specific.

While increasing SOC is generally accepted to improve soil fertility from the perspective of crop production, SOC sequestration does not always lead to higher crop yields (158) or long-term economic returns (159, 160). This implies that farmers may need financial incentives or co-investment to overcome existing investment hurdles. Despite the critique of expectations that "correct" prices will nudge a market-based economy to avoid points of no return in global climate change (161), the use of carbon credit schemes to enhance SOC across agricultural landscapes remains popular. There is evidence that under specific circumstances, payment for ecosystem services (PES) can provide effective incentives for changing farmers' practices (162), with successes relying on benefits for all involved that exceed the cost of implementation, secure property rights, and sufficient administrative, monitoring, and enforcement capacity. Four basic manifestations of PES are compensation for mandated ecosystem services enhancement; market-based commodification of pollution rights (carbon credits); consumer-driven preferences for low C footprint commodities (163) or co-investment in environmental stewardship (164), representing increasing levels of internalization of externalities (165); and a balancing act between efficiency and fairness (166).

Soil fertility and ecosystem services benefits of increased SOC also vary across soil types and climates, with more pronounced benefits for soils with low SOC content in tropical climate zones (167). Given that smallholder farms still dominate in the tropics, with relatively little capital available, the relevance of C finance as a form of co-investment may be attractive. However, lack of clarity on land or land use rights and of rights to "trade" carbon across national borders currently restrict the use of PES instruments.

PES schemes can use either results-based payments or management-based payments (168). For SOC sequestration, this would mean either high-resolution SOC monitoring or paying for observed changes in management. The latter still requires SOC models to accurately relate changes in management with changes in SOC. A major hurdle for the use of performance-based financial instruments is that SOC monitoring remains difficult, with current remote sensing tools only providing information on the soil surface. Recent improvements in laboratory procedures for monitoring soil C still require field sampling of soils. For example, infrared spectroscopy promises a rapid, reliable, and cost-effective measurement of SOC. However, this may have a limited effect on the total cost of soil carbon measurement, because staff time and transport for soil sampling could be two to three times more costly than the laboratory part of the chain.

SOC change at national scale is reported internationally in the IPCC mandated national communications and to the UNFCCC as part of the Nationally Determined Contributions (NDCs). Countries can use management-based incentives domestically and report empirically

Nationally Determined Contributions (NDCs): commitment by national governments to the climate change convention to reduce emissions relative to a specified baseline; typically combine changes in fossil energy use, land use change, and waste management verified results as part of their NDCs (169). As current incentive programs for increased soil C storage rely on proxies that remain to be calibrated, rather than plot-level C monitoring due to costs of high-resolution monitoring, it is important that national SOC accounting is refined. Refined (Tier II and Tier III) National Communications are an essential step in getting SOC programs accepted as a verifiable part of NDCs at the relevant scale. A recent review concluded that region-specific approaches are required for the implementation and monitoring of SOC sequestering practices (170).

12. PROSPECTS FOR INDUCING A GLOBAL 0.4% SOIL CARBON INCREASE THROUGH SOIL CARBON TRANSITIONS

At the 21st session of the Conference of the Parties in Paris in December 2015, the 4 per 1000 international program was launched with a vision to increase soil carbon in the world to support food security and mitigate climate change (9, 171). The 4 per 1000 program has an aspirational target of increasing the SOC stock of the world 4‰ per year by adopting balanced practices. As many countries aim to be C-neutral by 2030, it became more apparent that SOC sequestration must be part of the solution in agriculture.

An initial review (9) surveyed the sequestration potentials from 20 regions in the world. High SOC sequestration rates (up to 10 per 1,000) can be achieved for soils with low initial C stock (topsoil less than 30 t C ha^{-1}) and in the first 20 years after the implementation of best management practices. A study on European-scale simulation found that to achieve a 4‰ target, annual C inputs into soil need to be increased by 43 ± 5% or 0.66 ± 0.23 Mg C ha^{-1} $year^{-1}$ (172). Areas with high C stock that have reached equilibrium will not be able to increase their sequestration further, such as in Bavaria (173). A similar conclusion was found in France, where a 30–40% increase in C inputs to the soil is needed to reach the 4‰ SOC target (146). Croplands in mainland France were unsaturated in mineral-associated SOC but had low net primary production (NPP) inputs. Conversely, most of the unimproved grasslands in France had adequate NPP, but half of the area was C-saturated. A meta-analysis shows that agroforestry and conservation agriculture in sub-Saharan Africa could achieve SOC sequestration rates higher than 4‰ (174). In the Mediterranean, the application of organic amendments shows the largest potential, followed by fertilizer application and cover crops (175).

The potential of SOC sequestration for climate change mitigation is being debated. For example, a review estimated the SOC sequestration potential through improved land management on cropping land, grassland, woodland, and wetlands ranging from 1.7–4.6 Pg C per year with a total potential of 114–241 Pg C (176). Another review suggested a more conservative potential between 20.1 and 46.2 Pg C (177). Recent studies indicate that topsoil organic carbon sequestration potential on global cropping land (excluding grassland) ranges from 18 to 65 Pg C (178, 179), equivalent to 2 to 7 years of annual anthropogenic CO_2 emissions. Critics of global SOC sequestration as a building block of global climate policies argued its unfeasibility due to nutrient limitation and biogeochemical constraints (120), nonaccounting for other greenhouse gas (N_2O and CH_4) emissions (180), and political, cultural, and economic barriers (181).

It has been stated that the 4 per 1,000 target should not be taken literally but, rather, as an aspirational target (182). While the potential for SOC sequestration is small, we still rely on soil for food production, which means a continued release of C from soil. The loss of SOC in agricultural production is significant. Each year in the tropical region, approximately 11 million hectares fall below the 1.1% SOC critical limit (31), which may have an impact on crop production. Annual SOC loss in the world's cropping topsoil was estimated at a rate of 2.4‰ $year^{-1}$ (31), while in European croplands the rate was 5‰ $year^{-1}$ (183). Thus, increasing SOC at a rate of 4‰ $year^{-1}$

would be required to compensate for such historical loss rates, after a soil C transition curve has bottomed out.

SOC sequestration is not a blanket approach, but identifying region-specific opportunities, especially those with large yield gaps and large historic SOC losses, would be promising (184). The standard approaches for increasing SOC include (98) the following:

- reduced tillage and conservation agriculture, including crop rotation and stubble retention;
- establishing cover crops beyond the main cropping season;
- increasing belowground inputs or roots through deep and dense rooting crop varieties, perennial crops, and trees in agroforestry;
- organic or biochar amendments, where easily degraded organic matter can contribute to more resistant soil carbon; a meta-analysis suggests that an addition of 10 ton of biochar resulted in a sequestration of 2.5 ton of soil C in the long term (185);
- managing soil nitrogen and other nutrients, to balance the plant productivity, decomposition, and greenhouse gas emissions; and
- adding irrigation where possible, which has a trade-off with water security.

There are also speculative approaches that need further research and are applicable in region-specific settings. Managing plant and soil biodiversity, as part of ecological restoration, may lead to further interactions on SOC formation. Manipulating microbial physiology to select microorganisms that have a higher carbon use efficiency may have uncertain knock-on effects on the interactive SOC pools. Full inversion tillage to bring organic inputs deeper into the soil may increase SOC. Adding mineral amendments, such as volcanic ash, may draw down atmospheric CO_2.

Since the publication of the SCOPE study (3), numerous topics, apart from progress in linking process-based models to observed patterns, have emerged at the science-policy interface:

- Besides the climate, biodiversity, and hydrological roles of SOC, it became one of the three indicators of Land Degradation Neutrality (SDG15.3).
- Regenerative agriculture, where increasing SOC is central, has gained public interest and policy support.
- SOC is now mentioned in 28 (out of 184 assessed) NDCs (186). In a database updated until September 2022, 107 out of 164 countries (65%) referred to soil carbon explicitly (36 countries) or soil carbon–related practices (71 countries) in the new and updated NDCs (**https://ndcpartnership.org/toolbox/agricultural-sectors-nationally-determined-contributions-ndcs**).
- Many NDCs specify practices known to have the potential to achieve SOC sequestration or protection without explicitly mentioning SOC. The SOC-related mitigation potential of these practices can be quantified in future NDCs.
- Soil C markets have started to operate in some countries; in Australia, it is formally recognized as a carbon unit, with operational measurement protocols. Market demand is strong, as polluting companies are now seeking ways to offset emissions and improve their public image. In the United States, the developing market focuses on developing insetting mechanisms for food and fiber branding.
- Remote sensing methods have progressed and are demonstrated to be somewhat operational; monitoring of soil C from space has progressed (31).
- Increased attention is being paid to reducing emissions from agriculturally used peatlands by controlling water tables as a priority in reducing greenhouse gas.
- There is an increased focus on legal aspects of soil-oriented policies (187, 188).
- More attention is being paid to C footprints in global commodity trade (163).

A recent analysis (161) discussed why, despite three decades of political efforts and a wealth of research on the causes and catastrophic impacts of climate change, global carbon dioxide emissions have continued to rise and are 60% higher today than they were in 1990. In this analysis, soils are only mentioned as a substrate in which metaphorical ostriches denying and ignoring unwelcome information, bury their heads, not as part of a globally desired solution. Denial-phase ostriches have to transform into self-renewing phoenixes before the relevance of soil C for containing climate change is appreciated.

SUMMARY POINTS

1. High expectations that soil organic carbon (SOC) storage can be increased globally have gained policy interest but have remained contested, with notable exceptions in conditions with disproportionate SOC change.
2. Disproportionately large, relative to the area involved, SOC changes are expected in permafrost, peatland, mangrove, and volcanic ash soils.
3. Land use change that modifies tree cover and the presence of perennial grasses can change SOC storage substantially; management change within cropping, grazing, or forest management systems can change SOC with depth rather than total SOC storage.
4. Global warming will reduce SOC storage, with the strongest effects in subarctic zones.
5. Root-based inputs (including mycorrhizal hyphae) to SOC dominate in many soils over aboveground inputs, but remain poorly quantified.
6. Organo-mineral complexes stabilize SOC and are the basis for SOC saturation deficit estimates.
7. Net impacts of erosion/sedimentation on landscape-level C storage depend on context, while reducing plot-level losses remains a major target for land management.
8. Loss of plant and belowground diversity induces a loss of SOC, but agricultural intensification can induce recovery in SOC transitions where belowground inputs are increased.
9. Positive effects of SOC recovery on water buffering are modest, but relevant for climate change adaptation. Agriculture in a climate with more drought and extreme rainfall needs soils with high SOC that maintains aggregate stability and structure to improve water cycling.
10. SOC transitions, where past losses are partially recovered by changing soil management, have occurred without specific SOC incentives.

FUTURE ISSUES

1. Incentive programs for increased SOC storage currently rely on proxies that remain to be calibrated, rather than plot-level C monitoring due to the cost of high-resolution monitoring.
2. Refined (Tier II and Tier III) National Communications are an essential step in getting SOC programs accepted as verifiable parts of Nationally Determined Contributions at the relevant scale.

3. The interface of area-based national accounting and product-based footprint consumer decisions deserves further analysis to clarify overlaps and gaps in policy change.
4. There need to be continued efforts to clarify the dynamics of subsoil SOC and its dependence on root turnover as the missing link between vegetation and soil and the response to land management interventions.
5. SOC needs to be looked at beyond food and fiber production and climate change mitigation and adaptation. As SOC affects the water cycle, the nutrient cycle, biodiversity, climate, and human livelihoods, all underpinning human survival, it warrants a multifunctional assessment.

DISCLOSURE STATEMENT

B.M. declares that he is a holder of a patent for auditing of soil carbon (Australia and USA) and is a member of the Scientific and Technical Committee of the 4per1000 initiative. The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. Through the diversity of disciplinary backgrounds of the authors, their geographical origin and experience, and current position on the science–policy continuum, we have tried to control for potential bias in this review.

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