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Perspective

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A landscape-scale view of soil organic matter dynamics

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Abstract

Soil carbon is an important component of the terrestrial carbon cycle and could be augmented through improved soil management to mitigate climate change. However, data gaps for numerous regions and a lack of understanding of the heterogeneity of biogeochemical processes across diverse soil landscapes hinder the development of large-scale representations of soil organic matter (SOM) dynamics. In this Perspective, we outline how understanding soil formation processes and complexity at the landscape scale can inform predictions of soil organic matter (SOM) cycling and soil carbon sequestration. Long-term alterations of the soil matrix caused by weathering and soil redistribution vary across climate zones and ecosystems, but particularly with the structure of landscapes at the regional scale. Thus, oversimplified generalizations that assume that the drivers of SOM dynamics can be scaled directly from local to global regimes and vice versa leads to large uncertainties in global projections of soil C stocks. Data-driven models with enhanced coverage of underrepresented regions, particularly where soils are physicochemically distinct and environmental change is most rapid, are key to understanding C turnover and stabilization at landscape scales to better predict global soil carbon dynamics.

Sections

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Key points

- Lack of high-resolution soil data for many regions and poor understanding of biogeochemical processes across diverse soil landscapes lead to uncertainties in estimates of soil organic matter (SOM) loss and carbon sequestration potential.
- Plant C input, microbial turnover and organic matter stabilization are influenced by soil heterogeneities that arise from soil formation and degradation processes operating and interacting across various spatial scales, ranging from large-scale controls, such as geology and climate, to localized ones, such as topography and biology.
- Human activities such as agriculture have influenced soil development for millennia. The pace, magnitude and breadth of these impacts has increased throughout the twentieth and twenty-first centuries owing to the growing use of mechanized agriculture and synthetic fertilizers to produce food.
- Approaches to represent and predict SOM dynamics that neglect landscape complexity, and instead scale information from plot-level measurements to regional and global contexts, lead to biased interpretations and uncertainties.
- Accounting for long-term alteration of the soil matrix at the landscape scale is key to improving forecasts of the soil C cycle in regions experiencing rapid environmental changes (such as polar and tropical regions) and regions with soil properties distinct from those assumed by existing Earth system models. Integrating global datasets with data from field and laboratory experiments can support such developments.

Introduction

Throughout the twentieth and twenty-first centuries, global environmental changes have altered, and will continue to alter, soil functions across pedoclimatic regions (areas of relatively homogenous soil type and climate conditions)[1]. Anthropogenic processes such as agricultural intensification and expansion, deforestation and industrialization are affecting soils globally with a pace, magnitude and breadth that is unprecedented in the Holocene, with substantial impacts on biogeochemical cycles such as soil carbon dynamics. Carbon is continually exchanged between land and the atmosphere; this cycle is primarily driven by atmospheric C fixation through plants, decomposition of dead organic matter through microbes[2,3], and lateral fluxes of C along geomorphic cascades to areas of deposition in rivers, lakes and oceans[4]. The soil C pool accounts for approximately 1,500 PgC (in the upper metre) compared with the 750 PgC in the atmosphere. The assimilation of biomass-derived C into soil organic matter (SOM) is counteracted by the release of approximately 33.4–43.6 PgC yr^{-1} globally through microbial SOM respiration[5], contributing to the current terrestrial net C sink of about 3.1 ± 0.6 PgC yr^{-1} (ref. 6).

Soil alterations driven by anthropogenic processes could trigger unanticipated and sometimes counterintuitive biosphere responses across distinct soil landscapes. At the same time, there is growing interest in devising strategies to augment soil C sequestration across various biomes and land-use systems[7]; however, overgeneralized assumptions about soil C storage capacities across different pedoclimatic regions often yield conflicting results between anticipated and actual C gains[8–12]. These inconsistencies largely stem from an inadequate understanding of C stabilization and turnover dynamics in regions with soils with poorly studied physicochemical properties[13]. These gaps in available data and research can cause such regions to be under-represented in current Earth system models (ESMs) and introduce large uncertainties in global-scale predictions of soil C dynamics. Additionally, many soil regions exhibit large spatial heterogeneity in soil landscape features, often related to subsoil characteristics that cannot be inferred from measurements of topsoil properties[14] from remote sensing platforms and are excluded from many assessments. These subsoil features, however, can influence plant C inputs, microbial community composition, C metabolism and mineral-induced C stabilization in sometimes counteractive ways[15–17].

To understand the complexity of soil responses to changes in climate and land use, it will be necessary to consider the coupled nature of the biogeochemical processes that shape soil landscapes. Such interdisciplinary approaches have been used in critical zone research[18,19] to understand how the complex interactions between rock, soil, water, air and living organisms regulate natural habitats and determine the availability of life-sustaining resources such as soil and its functions[20]. Soil formation theory is the description of the change and development of long-term and short-term processes and drivers influencing soil properties at the landscape level. We propose that characterizing soil variability through the lens of this theory could inform predictions of soil C stabilization and turnover patterns across spatial and temporal scales where data are missing but process understanding exists. This knowledge could guide researchers towards refined, location-specific assessments of current and emergent C-cycle dynamics, especially as soils undergo rapid transformations influenced by global change. However, to achieve this transition from overgeneralized and potentially biased interpretations to precise and accurate predictions of future global soil C reservoirs, it will be critical to understand soil dynamics at the landscape scale[21].

In this Perspective, we consider how landscape-scale insights into soil formation can be used to forecast the impacts of evolving soil matrices on C cycling. First, we discuss the variability of soil formation and degradation, and the impacts of human activities on these processes. Next, we outline the challenges involved in representing SOM dynamics at landscape scales. We then consider the spatial and temporal variation in soils and the factors that influence the recovery of a soil's capacity to store SOM following disturbances. Finally, we suggest ways to fill data and knowledge gaps to better understand soil variability at the landscape scale and improve forecasts of SOM dynamics. Outlining specific solutions to address SOM management options for land-use planners is beyond the scope of this Perspective because potential actions vary too widely depending on soil properties, vegetation, climate and land-use history.

The impact of landscape processes on soils

Soil development is driven by factors that operate and interact across multiple spatial scales[21], ranging from overarching controls such as geology and climate (that is, state factors) to localized ones such as topography and biology. Geology, climate and biota establish the foundation for soil biogeochemical cycling and the global differentiation of soil formation across landscapes. Meanwhile, interactions between climate, topography and vegetation can influence water availability and, thus, soil development owing to their impacts on long-term weathering — here defined as the physical and chemical alterations

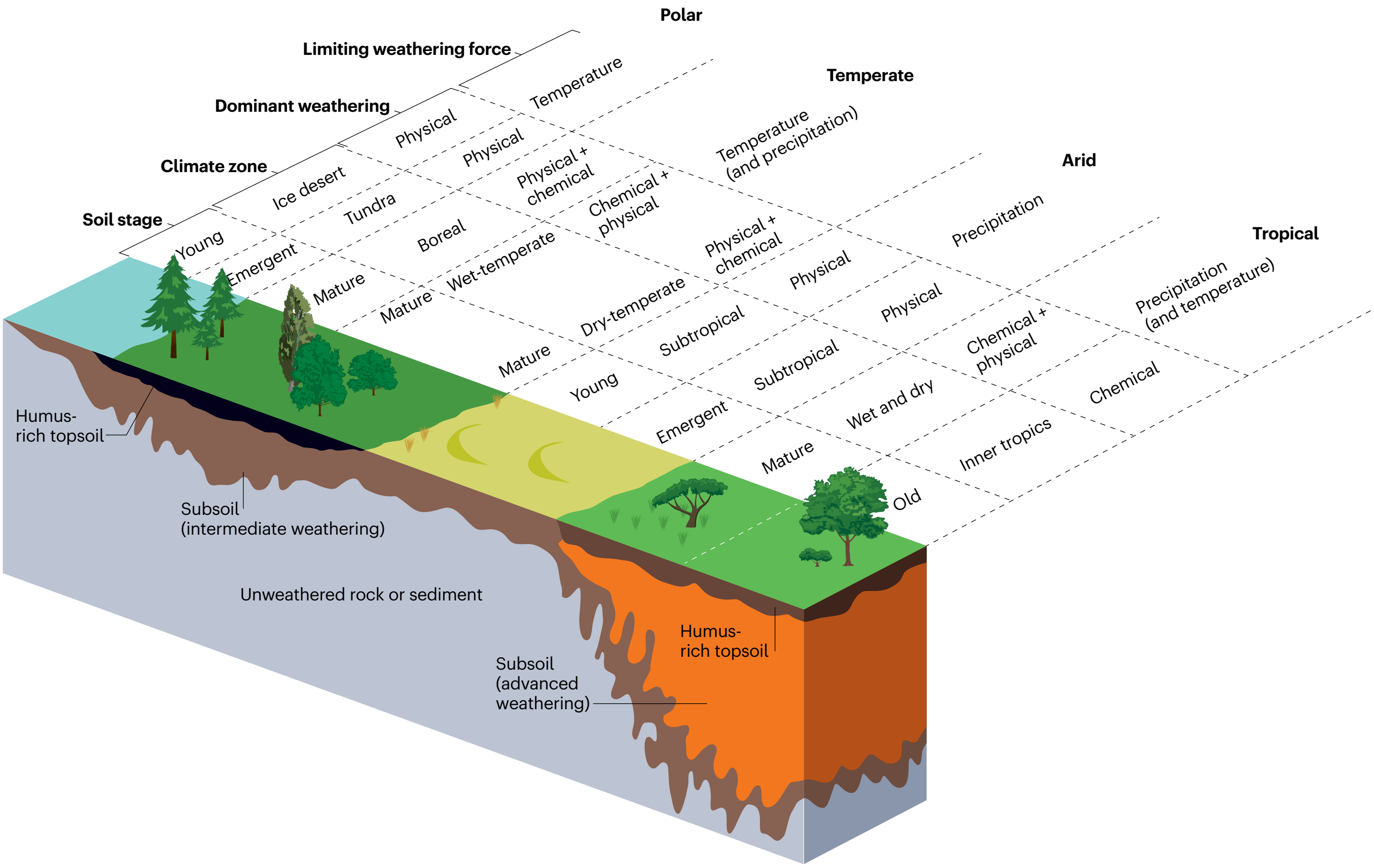


Fig. 1 | Global-scale patterns of soil formation and limiting weathering force. Variation in soil profile, soil stage (young, less weathered, to mature, heavily weathered soils), weathering type and limiting weathering force across different climate zones and ecosystems[40,220–222]. Different soil types present distinct environments for biogeochemical cycling in which the biosphere and geosphere react to changes on different timescales. Figure adapted with permission from ref. 223, BD science publishing.

that rocks and minerals undergo during soil development — or the equilibrium between soil erosion and production. In this section, we discuss spatial and temporal variations in the processes that drive soil formation and degradation, their impacts on the C cycle and how they are influenced by human activities.

Weathering and soil formation

Rocks weather differently across climate zones and geologies, releasing varying quantities of diverse nutrient types into the soil solution. These spatial variations in weathering create distinct patterns of secondary mineral accumulation, changing the geochemical composition of soil and enabling SOM to be stabilized by minerals to aid long-term C storage[22,23]. The longer that soil development continues, the fewer weatherable minerals remain, while the existing or newly formed weathering products generally become more resistant to further change. Thus, soil biogeochemistry reflects many pedogenic developments across regional, local and even microscales[24–26].

Soil spatial heterogeneity has developed from past differences in processes occurring over extensive timescales. Climate-related weathering forces and the sensitivity of soils and their parent material to weathering all vary across the globe (Fig. 1), resulting in enduring differences that affect soil biogeochemical cycling. However, in many areas, soils have also historically been heavily modified by ancient or medieval agricultural practices, which have affected soil landscapes and C storage[27–30]. Although modern-day anthropogenic disturbances appear to have a faster impact on SOM cycling than these historical activities, it is important to recognize the contribution of past soil genesis and disruption because it dictates soil functions that regulate SOM dynamics in the future.

Variations in soil formation in return influence biogeochemical cycles, affecting the direction and magnitude of C stocks and matter fluxes. For example, variations in the water flux through soils caused by changes in soil structure, mineralogy and water holding capacity lead to differential patterns of mineral weathering and secondary mineral accumulation, with subsequent impacts on the translocation and retention of C in subsoils[23]. The changing thickness of the developing soil and its distinct layers also affects the water available to plants[31] because thick soils, which often also have large amounts of clay-sized secondary, reactive minerals and complex pore structures, can store more water than coarse-grained, less developed soils.

Variation in soil mineralogy with space and time

The ability of minerals to slow down SOM decomposition varies across geologies and soil weathering stages. For instance, the interaction of

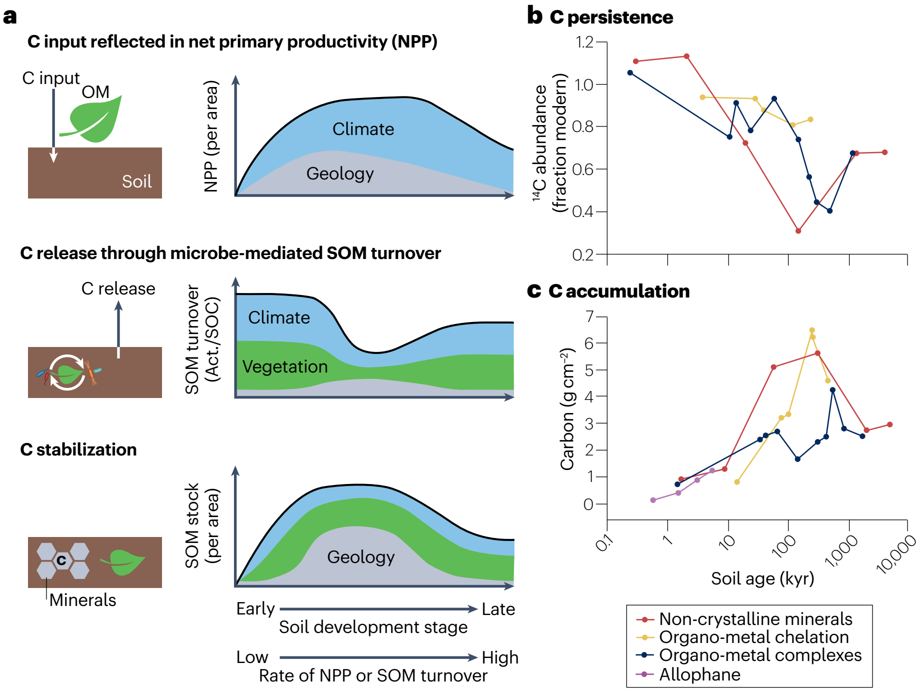


Fig. 2 | Carbon dynamics and controls during soil development. **a**, Relative influence of climate (blue), vegetation (green) and geology (grey) on net primary productivity (NPP) and thus organic matter (OM) and carbon (C) inputs (top); soil organic matter (SOM) turnover (activity/soil organic carbon, Act./SOC) and thus C release (middle); and SOM stock and C stabilization (bottom). **b**, Measured variation in soil C persistence (^{14}C abundance as a fraction of modern values) with soil age for bulk soils with distinct mineralogical features. Data from ref. 47 (red), ref. 49 (yellow), ref. 39 (blue) and ref. 164 (purple). **c**, As in **b**, but for soil C accumulation. As pedogenesis progresses, the importance of different large-scale controls changes for specific elements of the C cycle regarding input (low to high), turnover or C flux (slow to fast) and stock (low to high). Parts **b** and **c** reprinted with permission from ref. 224, Elsevier.

organic matter with the soil mineral matrix can influence soil weathering[32] and limit microbial decomposer accessibility, enhancing the stabilization and storage of SOM[15,33–35]. The dominance of specific SOM stabilization mechanisms is primarily determined by the soil mineral properties, which can differ across climate zones, geochemical regions and soil developmental stages[36–42]. Moreover, many biogeochemical processes that shape the soil landscape occur on the microscales at which alterations in soil microorganisms, plant roots and soil geochemistry occur[43]. Plants and microorganisms adapt as soils gain and lose rock-derived nutrients through weathering and leaching, leading to distinct patterns of organic matter input and SOM persistence[44,45]. Thus, understanding the wider temporal dimension is vital for comprehending biological processes that affect the C cycle and the soil-forming factors that influence the matrix hosting these processes (Fig. 2). Moreover, the natural variation in biogeochemical factors shape soil properties and SOM cycling unevenly along the soil column[46]. Alterations of physicochemical properties are usually more pronounced at the surface than in deeper layers near the bedrock or the modern-day weathering front because the surface is the first place to experience weathering and is exposed to more intense weathering and for longer periods.

Variation in SOM storage across latitudes

Mid-latitude regions in which direct human intervention on soils is among the oldest and strongest show a wide range of SOM storage capacities, owing to changes in minerals induced by weathering processes over millennia[23,39,40,47–50]. For example, in temperate humid regions of mid-latitudes, soils at intermediate weathering levels and ages (up to 12,000 years) can have substantial variations in their developmental stages and capabilities to efficiently sequester and store soil organic carbon (SOC) in the long term[51,52]. The range of SOC density for the upper metre of soil in temperate regions is almost as wide (6.4–14.5 PgC 10^6 km^{-2}) as the global range (5.2–18.7 PgC 10^6 km^{-2} (ref. 21)).

Aeolian, glacial and fluvial deposits formed during the Pleistocene have an important role in the formation of fertile soil in mid-latitudes. For example, agricultural regions with periglacial deposits that have loess (a late-Pleistocene aeolian deposit) as the parent material for soil formation are among the most productive croplands in temperate climates (across North America, Europe and Asia). However, loess, which is primarily a product of late-Pleistocene geomorphic processes, is not actively formed in those highly productive areas under the current climate. Regions that are actively producing loess are limited to cold and dry (sub)Arctic environments such as northern Canada and Alaska, Siberia and the Gobi Desert[53]. In most cultivated regions, deposits of loess are generally limited to a maximum of a few metres in thickness[54], with the exception of the Chinese loess plateau, which has an average loess thickness of ~106 m (ref. 55). Loess regions worldwide face severe degradation under increased erosion from historic and modern agriculture, leading to the loss of this important resource that is not renewable on human timescales, and in many cases to soils that have reduced capacity to support biomass production and the efficient long-term storage of SOM.

The capacity of high-latitude soils of boreal and subpolar pedoclimatic zones to store SOM is, on average, larger than in mid-latitudes, but could change under anthropogenic warming. In these regions, the primary controls on C cycling are plant growth limitations, which curtail C input, and limited decomposition of SOM owing to the climatic and environmental constraints on microbial activity. Rising global temperatures are expected to increase the decomposition rates of SOM[56,57] and thus increase the release of greenhouse gas from soils in almost all polar and high alpine ecosystems[58]. Such changes could lower the net C sink capacity of many Arctic soils, accelerating global warming[59,60]. However, heightened soil reactivity through accelerated weathering as a result of increased chemical reaction rates under warmer climate could increase the soil C storage capacity of minerals[61–63] and increase biomass production[64,65]. These changes could alter the trajectory of net soil greenhouse gas emissions of the geochemically 'young', less altered (in comparison with their respective parent material) soils in Arctic regions. Therefore, the timescales of changes in SOM storage capacity will be an important control on the evolution of greenhouse gas emissions from high-latitude soils, with initial changes in decomposition driving increased greenhouse gas emissions and C losses from soil, whereas longer-term changes in weathering, although not likely to compensate for prior SOM losses, can potentially increase the soil C sink again.

In contrast to soils from high and mid-latitudes, many soils in tropical climate regions are products of very prolonged weathering over tens or hundreds of thousands of years. Deep weathering in tropical areas results in soils with a reduced abundance of reactive minerals, leading to increased SOM turnover and reduced capacity to store SOM efficiently compared with the less weathered temperate soils and, thus, a decrease in SOM stocks[47,66] that is independent from the C inputs. The efficient cycling of remaining nutrients between plants and soils by an intact tropical biosphere[67,68] is important for the stability of tropical C cycles. However, disruptions such as soil erosion[69,70] or biomass and nutrient extraction through logging and agricultural harvest cause prolonged degradation of the tropical biosphere, further diminishing the ability of these soils to store C efficiently in the future[71,72]. Despite their relevance, tropical soils and ecosystems remain among the world's least studied, with socio-ecological interactions and developments in distinct soil landscapes frequently being ignored when creating strategies for climate change mitigation. It will be important to better understand the trajectories, drivers and impacts of land-use change for the C cycle, particularly for understudied regions such as sub-Saharan Africa where much of the agriculture is still pursued by subsistence farmers who depend on wood fuel resources from forests for energy[73–75].

Erosion and soil redistribution

In many biomes, lateral soil fluxes caused by wind, water and mechanical deterioration of the soil surface are incremental constraints to the natural equilibrium between soil formation and degradation. Depending on the local environmental and topographic settings, specific forms of soil redistribution can prevail, showing typical patterns across topographic soil gradients that are more affected or less affected by soil redistribution. For example, natural soil loss through erosion is most evident in regions with limited soil cover, such as arid zones, high-altitude areas, or locations exposed to high winds or torrential rain combined with steep terrain[76]. In these regions, soils are much shallower and, in most cases, less weathered than in regions where dense vegetation cover protects soils from erosion and allows soil formation to continue without major soil disturbance.

Erosion disrupts biogeochemical cycles within the plant–soil–atmosphere nexus, with contradictory consequences for soil C cycling across different landscape elements[77]. Soil redistribution at sites of soil loss often leads to continuous degradation[78], which manifests as the loss of fertile topsoil through erosion, nutrient depletion or soil compaction. These changes can influence soil C cycling by reducing plant organic matter inputs[79], enhancing microbial SOM decomposition[80], and altering the C storage potential of the soil[81–84]. However, there are cases where erosion-driven soil loss might locally enhance SOM stabilization through mineral rejuvenation processes[85,86]. For example, in terrain with deeply weathered soils or those arising from nutrient-rich substrates, soil loss can lead to the incorporation of less weathered deeper subsoil, which is often rich in primary minerals and rock-derived nutrients, into near-surface soil layers where it releases nutrients through weathering into the soil solution.

Mobilized soil material can be transported by water over a long geomorphic cascade to deposition sites, building up alluvial valleys and riparian sediments while moving toward oceans over years, decades and millennia[4]. In these locations, former topsoil and the associated SOM is buried in deep, often water-logged layers, protecting it from microbial decomposition because local soil conditions with limited gas exchange in deeper soil layers can slow down microbial SOM turnover[81,87,88] (Fig. 3). However, it is not yet known what specific conditions are required for prolonged soil development to offset erosional losses in this way. It is also unclear how stable this mobilized C remains over decades or centuries and whether the properties of minerals, organic matter, or site characteristics are the main drivers for determining the prolonged stability of the redistributed C (refs. 34,89,90).

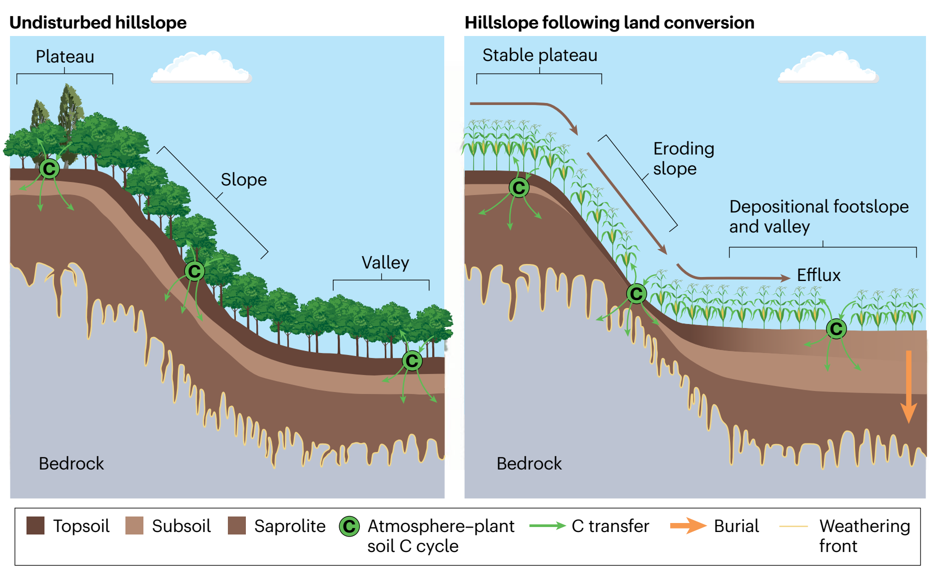


Fig. 3 | Impact of land conversion on hillslope sink carbon cycling. Schematic depicts atmosphere–plant–soil carbon cycling (green circles and green arrows) and burial (orange arrow), erosional transport (brown arrow) and bedrock weathering front (yellow line) in an undisturbed hillslope (left) and a hillslope following conversion to arable land (right). Processes such as the change in input after land conversion, the depletion of soil organic matter (SOM) on slopes, and the burial of SOM in valleys severely affect soil properties not only in topsoil but also in subsoil. Adapted from ref. 40, Springer Nature Ltd.

Wind erosion, particularly in dryland settings, can also lead to the transport of soil material over hundreds and sometimes thousands of kilometres across larger scales[91], where it can contribute to soil formation. This redistribution might have a key role in providing rock-derived nutrients in otherwise nutrient-poor environments[92]. Although soil C density in semi-arid landscapes is often low, the large spatial extent of drylands means that these regions make an important contribution to the global C cycle. Drylands, including semi-arid grasslands, are estimated to account for roughly one-third of global SOM storage to a depth of 2 m (refs. 93,94). At the same time, wind erosion and water erosion are heavily influenced by recurring natural and anthropogenic fires[95], which are affected by climate change; therefore, it is challenging to assess what contribution drylands will make to future C cycling.

Impact of anthropogenic processes on soil C fluxes

The impact of human activities on soils through accelerated erosion is longstanding, pre-dating contemporary climate shifts[96]. Human activities have intensified erosion, often introducing it to regions that were previously unaffected by heavy erosion. These activities have exacerbated water and wind erosion and introduced new erosion types, such as those caused by tilling[97] and harvesting[98] with increasing agricultural machinery power[94] and the shift from traditional to mechanized farming. In many regions, the C storage of soil reflects its historical land use more than its current climate conditions or vegetation. Many landscapes in regions across the world (in particular in temperate and subtropical climate zones) have been heavily modified by human intervention[99–103] through intensive agricultural activities over millennia. Even some seemingly natural forested landscapes show signs of historical agricultural use in soil properties[104] or are late-medieval or modern plantations previously used for grazing or farming[105–107].

Soil changes driven by human activities have increased notably since the middle of the nineteenth century owing to rising populations, mechanized agriculture and surging application rates of synthetic fertilizers[108]. Agriculture and land-cover alterations have reconfigured almost all landscapes and soil regions where highly productive cropland and pastures can be established[96,109]. Currently, croplands (16×10^6 km^2) and pastures (30×10^6 km^2) cover over 40% of the Earth's terrestrial surface, equivalent to the combined land area of Africa and South America[87,110,111]. Most agricultural systems now show erosion rates that are 1–10 times faster than soil formation rates[108,112–114]. Concerningly, about one-third of all sediments displaced through agricultural erosion originated since the onset of mechanized agriculture alone (1860 onwards), which will affect the functionality of soils for millennia[96,109]. Modern-day global estimates of the impact of soil erosion on SOM cycling accelerated by human activity are much debated and suggest outcomes ranging from being a net C source of 1 PgSOC yr^{-1} to a net C sink of equal magnitude[3,82,85,115,116].

As described above, humans have transformed the mobilization, transport and sequestration of sediments (and C associated with sediments) such that human activities now dominate these fluxes at the global scale. Erosion induced by human activity now displaces tenfold more soil and sediment than all natural processes combined[82,117]. Human activities have increased fluvial sediment delivery by 215%, while dams and river course alterations have decreased the amount of fluvial sediment reaching the ocean by 49%[118]. It is estimated that 31,000 ± 9,000 Pg soil has been relocated in this way across croplands and pastures since the start of the Neolithic Revolution[4]. This restructuring has mobilized approximately 783 ± 243 PgC throughout agricultural history, with an estimated 116–150 PgC released into the atmosphere over the past 12,000 years due to agricultural practices[88,96]. Such altered landscapes, marked by intense erosion and subsequent soil degradation, now have physicochemical soil features that are distinctly different from their natural counterparts. Therefore, human-driven soil erosion, which greatly surpasses most soil formation rates, is one of the most persistent and geographically widespread threats to soil functionality and health.

Representing SOM dynamics at landscape scales

Most effects of physicochemical soil properties on C inputs, stabilization and turnover are nonlinear; therefore, it is difficult to accurately predict soil C cycling at the landscape scale. Furthermore, the challenges in representing SOM dynamics in stable landscapes differ from those in more geomorphologically dynamic landscapes. Similarly, the relevant scale for landscape effects on SOM dynamics – from regions to hillslopes – largely depends on the questions posed. Thus, the strategies and generalizations needed to improve the representation of subgrid soil processes in global land-surface models will be different from those needed by land-use planners aiming to minimize SOM loss and enhance C sequestration across specific landscape units. We propose that for the ecosystem-modelling and land-surface-modelling communities, as well as stakeholders on the ground, achieving a robust depiction of SOM dynamics over extended periods will require an understanding of how landscape attributes form and influence contemporary soil characteristics and biogeochemical cycles. In this section, we discuss the challenges associated with this from the point of view of data assessment, modelling and process understanding in dynamic landscapes.

Dealing with data gaps

The principal mechanisms through which mineral association protects organic compounds have been characterized by extensive research. Measurements of organic molecule structures, stabilization mechanisms, and C and N isotopy of SOM have characterized these mechanisms at microscales to plot scales; however, these measurements have only been performed extensively for a relatively narrow range of soil types[9,119,120]. A universal concept of the importance of specific protective mechanisms within and across climate zones has not been identified, owing to the sensitivity of mineral composition and reactivity to soil environmental conditions[13,121]. Many soil types and ecosystems remain under-researched, with unique processes pertinent to specific geoclimatic soil settings omitted from global models[9]. This knowledge gap is especially concerning for Arctic, tropical, semi-arid, arid and mountainous regions, which are all understudied but heavily affected by global climatic, demographic and land-cover transformations. Understanding the net impact of global change on soil C dynamics will require expanded data collection from understudied and often remote regions, together with continued development of remote sensing techniques.

Similarly, advances in the coverage and quality of high-resolution remote sensing data have refined estimates of plant C input[122,123]. However, global soil C reserves and their turnovers remain elusive because central soil attributes that dictate C dynamics, such as subsoil properties or SOM persistence, cannot be directly detected with remote sensing. To discern the implications of changes in the cycling of C, nutrients and water across spatially varied landscape units[124–126] and the soil column induced by global climate change, it will also be necessary for multiple disciplines to recognize the importance of sampling subsoils rather than just topsoils. For example, many biogeochemical drivers of C cycling are distinct between topsoil and subsoil and can only be directly derived from physicochemical parent material and subsoil properties, which change depending on the stages of soil development, which in turn are distinct across pedoclimatic soil regions[8,127,128].

Pedotransfer functions and proxy indicators[129] are promising approaches to leverage known mechanistic relationships to predict soil properties at the global scale[130]. Pedotransfer functions use easy-to-measure soil variables to predict harder-to-measure soil and environmental properties[131–133] and offer reasonable estimates by extrapolating subsoil features from topsoil data. For example, proxies such as the chemical index of alteration and pedotransfer functions that are sensitive to variation in soil-forming factors that shape soils could be used to connect soil development with SOM[128]. To obtain such functions, it is important to determine whether identified mechanisms governing soil C cycling are universally applicable or specific to soil types. Tools such as mid-infrared spectroscopy[134–138], chemometrics (relating measurements of a chemical system to the property of interest) and machine learning[139–142] for rapid (and cheaper) sample analysis and data generation for diverse soil properties could help to develop pedotransfer functions. However, data to calibrate SOM properties and dynamics remain sparse in most regions except for temperate climate zones. Thus, pedotransfer functions can only provide a fragmented understanding of global C cycling and soil C stabilization at present[9,143,144].

Soil formation theory could help to develop sampling strategies to ensure that spatial variability is represented in the sampling of targeted soil attributes across spatial scales. Statistical methods, such as conditioned Latin hypercubes[145–148] (an algorithm for stratified random sampling that leverages prior information on the heterogeneity of environmental variables in an area), could be used in study designs to provide sampling strategies that optimize the distribution of soil variables across the area or timescale of interest. A broad understanding of soil formation theory — including insights into the primary soil-forming factors shaping the soils and their functions — could guide sampling campaigns aiming to obtain representative assessments that can be scaled to larger areas. Despite preliminary efforts to connect soil development and SOM turnover at the point scale[149,150], a comprehensive representation linking C stabilization to soil evolution at the landscape scale has not yet been achieved. Similarly, heterotrophic soil respiration, which has an important role in global C cycling, has not been properly linked to soil C stabilization mechanisms at a global scale[8,151,152]. The development of effective sampling strategies will require knowledge of land cover, key soil types or statistical prerequisites that depend on the questions asked and guide the sampling.

Integrating data and models at the landscape scale

Global datasets could provide quantitative insight into the role of landscape attributes in regulating SOC storage across different spatial extents and help to identify key processes. Several (growing) compilations of global soil data are already available, such as the World Soil Information Service (WoSIS[153]), works done by the USGS Powell Center[50,129], the soil radiocarbon dataset (ISRaD[154]), the soil respiration dataset (SRDB[155]) or the mid-infrared spectral library for SOC[134]. Although these are global datasets, the datapoints are not evenly distributed, leading to uncertainties in predictions and a limited capacity to estimate global SOM patterns and C dynamics[144]. Large-scale datasets can have spatial bias (for example sampling biased towards flat terrain, certain types of land use and land covers) and/or temporal bias (for example sampling during classic field seasons or specific times of the plant growth cycle). High-resolution techniques to measure the (bio)chemical properties of soil are needed to close data gaps at the pedon scale. However, improving understanding of SOM processes[156] at the landscape scale will also require measurements of the physical soil structure (for example X-ray computed tomography measurements of pore structures and hydrological measurements of water infiltration) connected with high-resolution topographic data (for example by lidar[157]).

Existing models of SOM dynamics do not yet fully incorporate the long-term evolution of SOM stabilization mechanisms resulting from soil development. However, changes in SOM stabilization can have a large impact on C dynamics, especially in subsoils that become exposed to surface conditions or less matured soils that undergo rapid mineralogical alterations[47,51,158,159]. In such cases, changes in patterns of soil weathering and soil formation can yield short-term changes in SOM stabilization. Consequently, controls on SOM stability, distribution and redistribution from the regional to global level are underrepresented in land-surface models, leading to high uncertainties[160]. Using soil formation theory, which can predict the short-term to long-term development of the soil matrix, could help to improve SOM models in regions that lack soil data but are undergoing rapid transformations owing to human-induced climatic and land-cover shifts. However, soil formation theory is largely underused for predicting current and future soil C cycling, owing to the perceived process complexity and often complex role of specific but interacting soil-forming factors.

Although land-surface models of SOM turnover incorporate the influence of mineral stabilization on the fate of SOM, most models do not perform well when the soil mineral matrix changes. Soil chronosequences suggest that changes in the soil matrix as it adapts to evolving environmental conditions can have a substantial impact on the biogeochemical cycling of nutrients[161–163] and the capacity of soils to sorb and bind C at decadal to millennial timescales[23,39,47,49,164]. Thus, an interdisciplinary approach is needed to improve process-based SOM models[156] to address such divergences in the effect of soil development on C cycling and its representation in advanced land-surface models. ESM models in particular will benefit from representing current soil landscapes as foundational to contemporary C cycling and accounting for changes in soil properties that are currently considered static, such as changes in the soil matrix.

New modelling frameworks are being developed for data–model integration at the landscape scale, using data assimilation and machine-learning approaches to take advantage of globally distributed soil information. For example, the process-guided deep learning and data-driven modelling (PRODA) approach integrates soil and environmental data with Bayesian data assimilation and deep learning to predict SOC storage across diverse landscapes[165]. These approaches require that landscapes are treated as units to transfer information from the microscale to the global scale in which the weight and influence of state factors can vary across space and time. The primary challenge with such frameworks is sourcing state factors effectively across various spatial and temporal dimensions, because their importance and the best proxies to represent them change (Fig. 2).

As the scale of the region being investigated increases, the relationship between a soil function of interest and its proximal (or primary) factors becomes increasingly obscured because, at large spatial or temporal scales, the proximal factors are themselves a function of distal controls[166]. For example, relief, as a standalone factor, does not affect soil microbes, but its associative factors such as nutrient fluxes, water retention and availability do[167]. Analogously, mean annual air temperature (MAT) and mean annual precipitation (MAP), which are long-term climate markers, might not directly influence short-lived soil microbes but serve as indicators for varying temperature and water conditions, respectively. Through their direct impacts on soil moisture excess, steering soil transport, weathering dynamics and organic matter inputs over extended timescales, MAT and MAP govern factors that influence the C cycling environment. The cumulative short-term microbial processes that link C cycling to the environment can in turn shape soil development and at times lead to irreversible shifts or pedogenic thresholds[23,168–170].

SOM cycling in dynamic landscapes

Most land-surface models or pedotransfer functions do not consider lateral soil and water fluxes despite their important contribution to soil development and movement in many regions. A large number of small-scale to medium-scale measurements in temperate climate zones[171–173] have provided insight into the implications of lateral fluxes caused by agricultural land use for soil C cycling. However, the implications of modern-day cropland expansion and intensification in (sub) tropical soil regions, which is creating hotspots of human-induced changes in land cover and soil redistribution dynamics, are largely unknown. For example, in some landscapes, SOM and nutrient recycling are driven by organisms specific to (sub)tropical ecosystems (such as termites), which are known to be heavily disturbed by industrialized farming[174–176] but are not represented in SOM or land-surface models. This lack of understanding is concerning, as mechanized agriculture is increasingly placed in such landscapes.

Furthermore, the temporal and spatial variability of soil erosion makes it difficult to include in models. Soil and SOM redistribution largely coincide with episodic or extreme events at localized scales[174]; thus, it is challenging to upscale these processes to broader regional or global scales[175]. Furthermore, there is a need for more spatially extensive data on the evolution of land use and management spanning centuries. Such data would help to decode the long-term influence of soil movement on SOM between geomorphic units in landscapes that are heavily influenced by anthropogenic activities.

There are two methods that are currently used to estimate the global ramifications of soil redistribution on SOM cycling: soil-centred approaches and sediment-centred approaches. Soil-centred approaches use simplistic modelling strategies to scale results from measurements ranging from plot to minor catchment scales up to the global scale[27,82,87,176,177]. These approaches excel in pinpointing internal erosion and deposition within catchments and its subsequent effects on SOM fluxes. However, owing to their point-scale nature and the growing variability of soil features as scale increases, the power and precision of most soil assessment methods is often limited to smaller, well-defined catchments. Sediment-centred approaches focus on deducing the role of soil movements on SOM dynamics based on sediments present in river systems and sites of soil deposition[175,178–180]. These methods offer a holistic integration of erosion, deposition and mineralization processes on land and within inland waters; however, they sometimes neglect intricate internal dynamics within catchments.

Although regional or local impacts of soil movements on SOM can be delineated, further work is needed to clarify the global impacts. For example, erosional losses of SOM from cultivated land in Australia are often misattributed to losses from soil respiration, leading to the net C flux from cropland being overestimated by up to 40% and the potential (100-year) C sink being overestimated by up to 17%[173]. This example illustrates that to better assess the global impact of soil redistribution on SOM dynamics, there is a need to develop connected soil-centred and sediment-centred approaches that integrate erosion, deposition, transport and mineralization across a range of depositional settings, including colluvial hillslopes, alluvial floodplains, fluvial networks and inland waters.

Innovative methods are emerging for discerning the movement and stability of SOM across landscapes. For example, fallout radionuclide tracers[181,182] complemented by emergent biomarkers for SOM fingerprinting have been used to track sediment sources and rates of deposition over decadal timescales[183]. However, the use of these methodologies remains scarce owing to high costs, intensive fieldwork requirements, and the need for extensive knowledge of local geomorphic and hydrological conditions. Implementing these methods in remote or financially restricted research settings poses additional challenges, underscoring a need for more resources and funds to train researchers for spatially explicit soil sampling and analyses using these techniques to assess C dynamics in understudied landscapes.

Landscape variability of soils and C recovery

Overlooking spatial heterogeneity and temporal variation in soils when identifying viable regions for soil C sequestration can impede progress in devising nature-based climate solutions. For instance, numerous tropical afforestation initiatives that advocate the introduction of new forests to augment the terrestrial C reservoir[144,184,185] assume that tropical soils can naturally sequester large amounts of plant C inputs. Additionally, an inadequate understanding of the degradation of fertile soils leads to a low seedling establishment success rate in many tropical afforestation and reforestation ventures[186]. For example, plants acclimated to deep soil layers with fertile topsoil for root expansion struggle to thrive on shallow, degraded soils, reducing the likelihood of tropical forest biome recovery. The success of new forest establishment can be further curtailed by a failure to acknowledge natural variability in soil characteristics, which is influenced by geology or topography within regions, when selecting target regions for afforestation[187]. Thus, research into the discrepancies of tropical plant–soil systems is urgently needed to avert further ecosystem degradation. Such research should be steered by researchers from the global south to ensure that findings are applied for maximal efficacy and application[188] and to improve the global coverage of high-resolution soil data and reduce the uncertainty on estimates of C losses or sequestration potentials[189].

The ability of soils to store C in the future will be determined by the recovery trajectory of SOM after disturbances. The complexities of SOM dynamics mean that it is unrealistic to assume that the impacts of past human activities on soils can be fully reversed in years or even decades. However, even partial recoveries of the C lost through degradation can serve as a temporary respite, providing time for industrialized nations to transition to C neutrality[190]. Many degraded soils might never be able to promote the rapid SOM sequestration or increased plant growth needed to act as a rapid C sink. In some cases, crossing a pedogenic threshold might permanently prevent soil from returning to a prior state. We propose that recovery trajectories might result instead in alternative quasistable states[191], leading to future soils with distinct biophysical properties and ecological functions (Fig. 4).

The future recovery of SOM after disturbances could depend on three main factors: the type of soil and stage of soil development before the disturbance; type, severity and duration of a disturbance; and the recovery potential of soil, which depends on climate, geology or landscape, and on C inputs. For example, soils formed from fertile parent material (for example loess and tephra such as volcanic ashes)

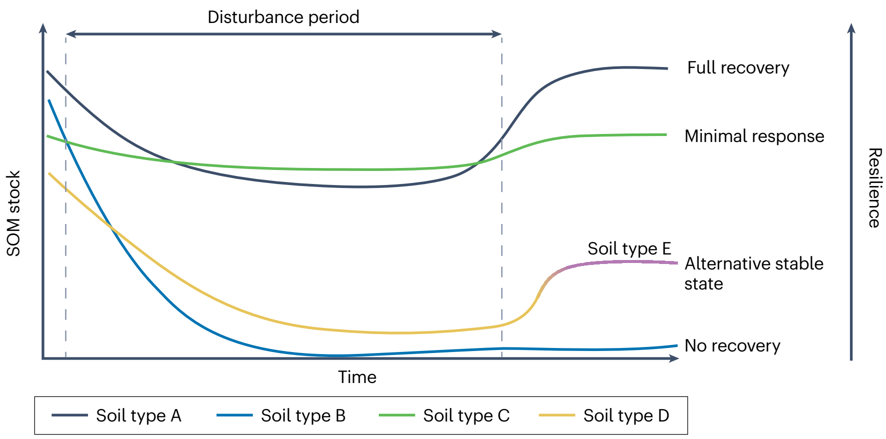


Fig. 4 | Soil organic matter recovery after disturbance. Change in soil organic matter (SOM) stock over time for hypothetical soil types A–D during and after a period of disturbance. SOM stock recovery and soil resilience are indicated on the right, and soil type E (pink) represents a new alternative quasistable state for soil type D. The recovery of SOM depends on the type, severity and duration of a disturbance; the stage of soil development before the disturbance; and the recovery potential of soil, which is determined by the climate, geology and carbon inputs.

might show a faster and more holistic recovery from degradation than soils from less fertile parent material (for example granite). Additionally, regions where long-lasting weathering has depleted deeper subsoil and saprolite from rock-derived nutrients and minerals (such as in tropical lowland) might also be slow to recover. Given the diverse history and formation processes of soils, worldwide generalizations about soil degradation and recovery (such as the assumption that all soils can sequester an additional percentage of their current SOM stocks over a comparable set amount of time) are likely to be incorrect. Therefore, we advocate the use of a more dynamic approach that simulates the changes in the C sorption capacity of soils as a result of its development as well as potential saturation effects to forecast the responses of SOM after disturbances.

To understand the processes regulating SOM dynamics, it is important to account for differences across spatial and temporal scales[29,192] (Fig. 5). At the local level, environmental factors that influence SOM dynamics are intimately connected to the effects of localized biogeochemical processes that can be experimentally manipulated and researched, such as the influence of fine roots, soil aggregates, preferential flow and microorganisms[193,194]. At this level, fine-scale processes in space (for example microbial diversity[195]) and time (for example rewetting and thawing[196]) have high spatial and temporal dependency. The landscape complexity intensifies at regional extents with ecosystem-to-landscape interactions exemplifying the impact of gradients in topography, vegetation and soil types, along with their unique disturbance and management histories[197,198]. At such scales, local and global processes intertwine to regulate SOM dynamics, which are ultimately influenced by mesoscale processes in space (such as topography gradients[199]) and time. Only parts of the regional-scale environmental interactions that affect SOM dynamics can be explored experimentally. At the global scale, large-scale processes in space (such as global biogeochemical cycles driven by geology, climate and vegetation) and time (such as global-scale teleconnections[200,201]) regulate the spatial and temporal dependency of SOM dynamics. Across all considered spatial scales, it is often not possible to disentangle these interactions. Instead, a multitude of causes must be considered when assessing the drivers of SOM changes[202].

Most approaches used to predict the future of C dynamics have focused on global scales; however, such approaches fail to give precise estimates at regional and local scales. To reduce uncertainties in predictions of the future global SOM cycle, it will be necessary to integrate fine-scale processes that vary at these smaller scales into global models[203]. Generally, factors that influence SOM cycling at the global scale such as long-term climate change cannot be directly manipulated experimentally; therefore, global processes must be inferred from processes observed at local scales or larger. But such approaches assume that the same local processes occur across vast regions[204]; thus, predictions of SOM dynamics from generalizations derived from global observations are not necessarily applicable at the local level. Filling data and knowledge gaps across spatial and temporal scales will help to address these limitations[205–207].

Cumulative effects of different biogeochemical processes and interactions lead to emergent properties that determine SOM dynamics and change with scale and geomorphological complexity[208] (Fig. 5). For example, at the local scale, the metabolic interplay between microbial communities, mineral-related C stabilization, and local plant productivity and C allocation dictate SOM dynamics through synergistic relationships that are not apparent when considering individual components[34]. At the regional extent, landscape connectivity becomes a prominent emergent property[209], where the interlinking of various ecosystems influences nutrient and water flows, altering SOM characteristics and distribution[119] in a way that cannot be predicted from the isolated segments of the landscape (that is, local level). At the global scale, C feedback mechanisms, such as thawing permafrost, demonstrate emergent properties by revealing intricate feedback loops between climate change and SOM dynamics[201]. These emergent properties underscore the complexity of SOM cycling and the need to integrate multiscale processes to accurately understand, model, manage and forecast the SOM pool.

There have been great efforts to improve the representation of soil processes in many ESMs[210]. For example, better representations of soil C dynamics in ESMs have improved predictions of C-cycle–climate feedbacks[211,212]. Additionally, incorporating soil structure in ESMs has improved the estimation of hydraulic parameters[213], which influence predictions of terrestrial primary production and climate scenario projections[214]. It is possible that including microbial processes[215] or organo–mineral interactions could lead to more accurate predictions of feedback between C and the climate[216]. However, the coarse spatial resolution at which many ESMs operate, their high computational costs and existing data gaps currently still prevent accurate landscape-scale representations of soil C dynamics for many regions of the world.

Summary and future perspectives

In this Perspective, we assert the need to use a landscape approach to understand SOM dynamics. Soil landscapes across different climate zones and geologies are shaped by regional and local factors such as weathering and erosion, which drive pedogenesis and produce heterogeneity in soil conditions. The progressive nature of this soil development means that soils are not static over long timescales but are constantly evolving in response to environmental changes. Following disturbances, soils transition along a malleable trajectory towards a state in which the sensitivity of the soil to different types of disturbance is altered. This altered state can differ across soil types, regions and landforms. Past and present global land-cover change and climate change have long-term effects on SOM cycling and sequestration; the impacts of these changes cannot be fully understood without accounting for soil variation at the landscape scale. To achieve this landscape-scale understanding, there are many knowledge gaps that must be filled, ranging from point-scale process understanding of C fluxes to the landscape-scale effects of biogeochemical differences across soil types and landforms on the global C balance.

Management strategies that account for soil formation processes at the level of landscapes (Box 1) can enable sustainable food production while also aiding additional SOM sequestration in regions with growing population and land-use intensification[10,13,217,218]. Such approaches are crucial for maintaining C cycling, especially in soil regions with a long agricultural history. To develop such strategies, it will be necessary to account for the spatial and temporal variability of soil structure and functionality, which can influence organic matter input, microbial turnover and organic matter stabilization in soils. In addition to developing sustainable farming strategies, it is also important to safeguard former topsoil C buried in valley soils — for

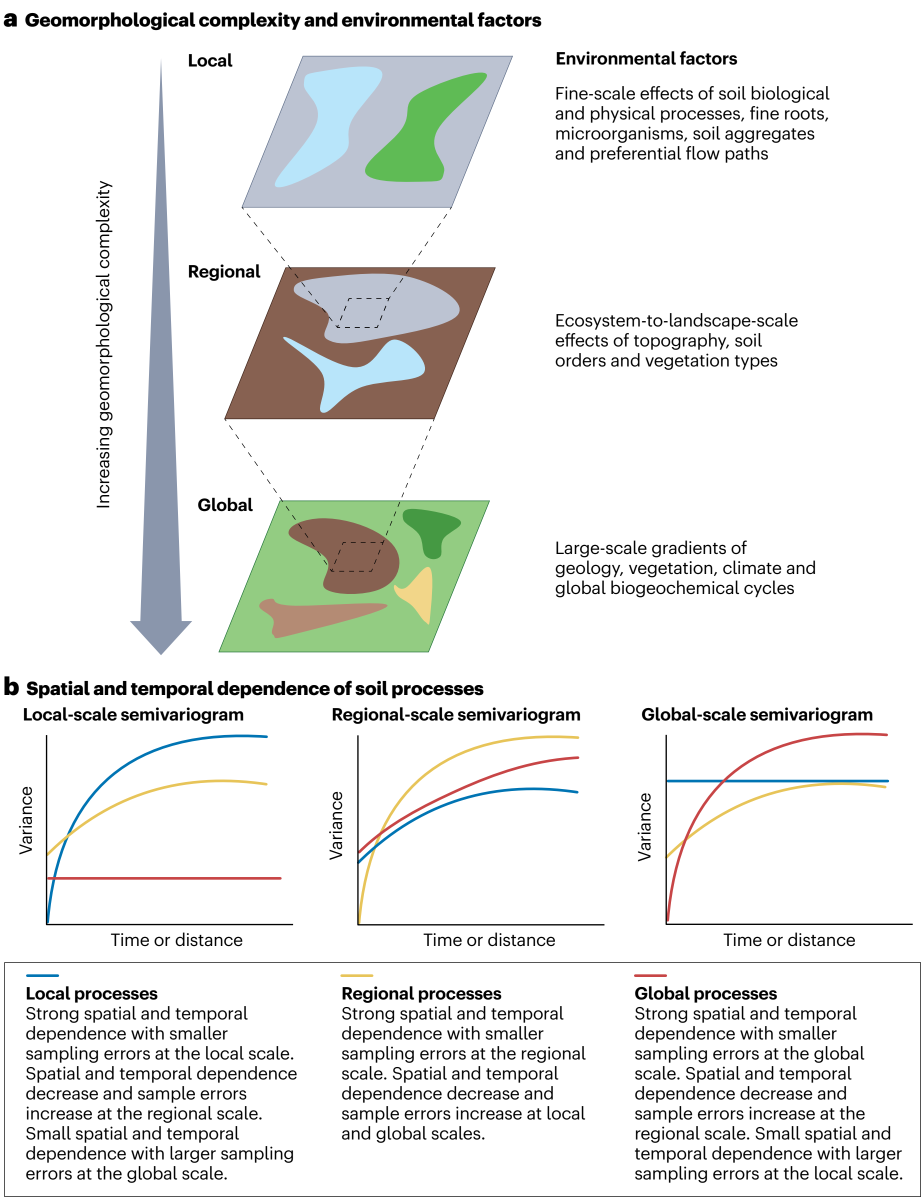
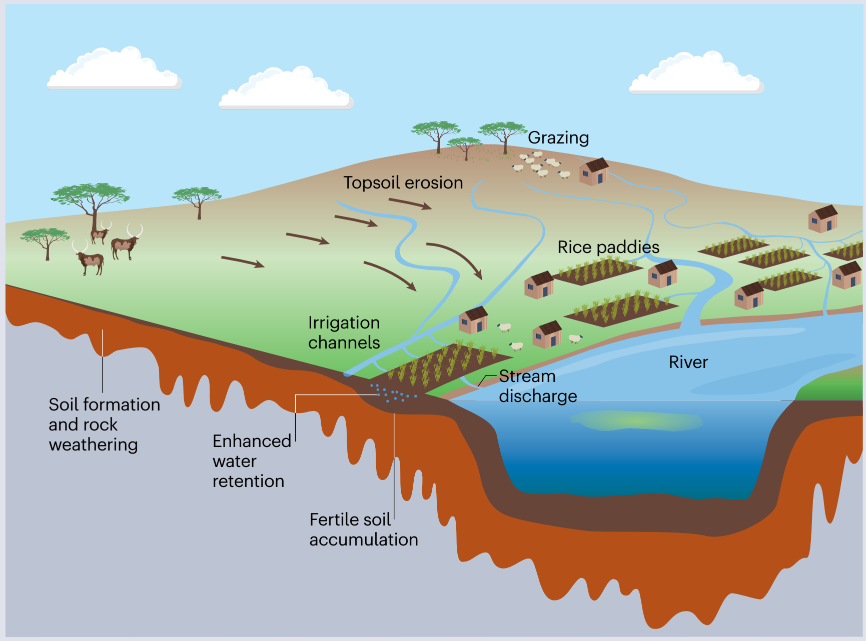


Fig. 5 | Soil organic matter dynamics across spatial and temporal scales. a, The effect of increasing geomorphological complexity in relation to environmental factors relevant to soil organic matter (SOM) dynamics. **b**, Hypothetical semivariograms of the spatial or temporal dependence of local, regional and global processes across spatial scales. As increasing spatial scales are considered, the overall geomorphological complexity increases; the environmental factors that best explain this variability shift from those varying at small spatial extents to those that vary over large extents; processes can show less spatial and temporal dependence and larger sampling errors, or vice versa, depending on the scale of observation and the occurrence of the observed processes.

Box 1 | Taking advantage of soil formation and fluxes with sustainable cultivation systems



Civilizations that emerged in (sub)tropical lowland landscapes are good examples of how agricultural practices developed by the earliest farming civilizations based on knowledge of specific soil formation and biogeochemical processes are still used today. First, erosion of topsoil from surrounding uplands in a watershed leads to the accumulation of nutrient-rich, finer-texture soil and sediment at lower landscape positions. Second, plant nutrient availability increases owing to high levels of soil organic matter and nutrients from these soil inputs and nutrient-rich water influx from uplands, including rock-derived cations and anions. This increased nutrient availability increases the fixation of N_2 by algae and pH neutralization, further increasing the availability of micronutrients. Third, the accumulated soil-derived sediments increase the retention of water, reducing the risk of crop water stress while allowing groundwater recharge. Such approaches have been practised for thousands of years in Asia using a minimum set of interventions to the land (for example, field levelling, bunding and canal construction).

Many African inland valleys and floodplains are more impoverished in nutrients than other lowlands near major river systems because the soils are much older and more strongly weathered[215]. Thus, in such regions it is especially important to capture nutrient-rich soil particles and water from wider, geochemically less weathered upland areas. Rice production systems in inland valleys and lowlands in Africa are a good example of the application of soil formation theory and an understanding of soil, nutrient and water fluxes through different landscape compartments to achieve sustainable agricultural intensification and meet increasing food demands by increasing yields (see figure)[215,225,226]. Compared with upland rice production (yield average of approximately 1 t ha^{-1}), lowland systems that profit from these processes can produce 2.5 t ha^{-1} of rice without fertilizer and up to 8 t ha^{-1} with standard fertilizer application and high-yield rice cultivars[227].

example through wetland restoration or by increasing water tables in valleys – to avoid additional emissions from SOM decomposition of deposited soil. Ensuring the future potential of soils for farming, sustaining ecosystem health and storing C to mitigate climate change will require also a better understanding of SOM stabilization and release in understudied yet rapidly changing regions of the globe, such as (sub)tropical and (sub)Arctic regions.

Obtaining global model predictions of soil C loss or sequestration potential requires data that accurately represent the heterogeneity of soil processes at landscape scales. Future research must consider regional and local differences in soil formation and variability across landscapes rather than trying to find superficial, universal, global-scale relationships. Additionally, work is needed to understand how past processes and disturbances have altered the developmental trajectory of a soil. Soils change and develop at fundamentally different timescales than can be assessed experimentally in laboratories and field trials. To overcome this challenge, analyses of regional to global soil data sets should be combined with (multiyear or decadal) long-term field and laboratory measurements of SOM storage, sequestration and losses in different regions of the world. Such approaches have already led to an improved understanding of the Earth system in many other fields of critical zone research.

Finally, with continued data collection and research on SOM dynamics, it will be increasingly important that knowledge is shared and analysed synergistically: for example through meta-analyses using the rapidly evolving AI tools. Research institutes must emphasize the importance of storing and sharing data in open-access repositories and create infrastructures to enable this. Such data sharing should follow the FAIR principles (Findable, Accessible, Interoperable, Reusable)[219] to promote open science and decrease the barriers to knowledge transfer between fields to stimulate interdisciplinary and transdisciplinary systems research. Additionally, adequate and fair funding must be provided particularly for research in and researchers from the global south to address the scientific gaps in these often data-poor regions, which at the same time face increasing ecological and socio-economic challenges.

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Author contributions

S.D., K.H., C.L., R.V. and R.W. researched data for the article. All authors contributed substantially to discussion of the content. S.D., K.H., C.L., R.V. and R.W. wrote the article. All authors reviewed and/or edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Additional information

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