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The silent witness: How soil dynamics are influenced by climate change

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ABSTRACT

Climate is one of the five soil forming factors, yet the role of climate change in impacting soils has often been overlooked. Climate change can influence many aspects of soil development and functioning including mineral weathering through to organic matter decomposition. Increased temperatures can initiate feedback loops on soil processes leading to reduced productivity, but these could be ameliorated by considering options to increase soil organic matter and thus improve soil productivity whilst also reducing the rate of carbon dioxide loss from the soil to the atmosphere. There are numerous uncertainties that are important to resolve because understanding the intricate relationships between climate factors and soil systems is crucial for addressing agricultural productivity and environmental sustainability in a rapidly changing world. Against this background, this paper describes how soil dynamics are influenced by climate change. Managing the various impacts of climate change on soil dynamics, through harnessing traditional and current initiatives, is important to maintain soil productivity.

1. The interrelations between climate and soil

Climate change is leading to more extreme and unpredictable weather events, such as hurricanes, droughts, and floods. These events can disrupt ecosystems and human societies alike. Some changes are obvious, like increasingly erratic weather patterns triggering devastating natural disasters more frequently than ever before recorded (Banholzer et al., 2014; Sloggy et al., 2021). Others, however, are fundamentally altering entire biomes while going relatively unnoticed. Climate change is, for example, influencing soil dynamics right under our feet. Soil plays a pivotal role in nearly every aspect of the human experience, from food production to clothing to infrastructure and even air quality (Bardgett, 2016). Yet, this silent witness is easy to ignore as the effects of climate change on soil are difficult to identify and quantify (Cornu et al., 2023).

While climate change has myriad impacts, most stem from increases in temperature and precipitation variability, both of which impact soil dynamics. Indeed, climate has long been recognized as one of the five soil-forming factors (Jenny, 1941). Soil formation occurs when small particles erode from rocks and are combined with organic material. Precipitation and temperature impact the physical and chemical erosion of rocks in multiple and interacting ways, accelerating the process at extremes. For example, high precipitation combined with low temperatures lead to the erosion of rock through freeze/thaw cycles that physically weaken the rock structure (Murton et al., 2006). Water is a key driver of the chemical erosion of rocks due to its ability to dissolve

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soluble minerals, and elevated temperatures enhance chemical reactions (Boggs, 2006).

Precipitation and temperature not only fundamentally affect the formation of soil but also the characteristics of the soil once formed. High precipitation and temperatures support vegetation growth, which results in soils generally with greater soil organic matter (SOM) stocks. This SOM enriches the soil, but warmer temperatures also increase the rate at which micro-organisms break down SOM in the soil (Crowther et al., 2016). Furthermore, high precipitation increases the rate of nutrient leaching from the soil that can contribute to its acidification. Soil organic matter decreases with decreased vegetation cover thereby reducing the strength of the soil and increasing the likelihood of soil erosion (Beillouin et al., 2023). Overall, warm and wet regions tend to have acidic soils with high SOM content (Paré et al., 2022). Conversely, dry regions tend to have neutral soils with low SOM content but plentiful nutrients due to low rates of leaching (Fetzer et al., 2022; Liu et al., 2025).

Depending on location, climate change is expected to lead to increased temperatures and either increased or decreased precipitation, which will not only impact the formation of soil but also their dynamics. Crucially, some of these impacts will lead to negative feedback loops, which intensifies the impacts of global warming. Rising temperatures increase the rate of the biologically driven conversion of soil carbon (C) to carbon dioxide (CO_2) (Bradford et al., 2016), and wildfires remove further C from the soil, increasing concentrations of CO_2 in the atmosphere (Ribeiro-Kumara et al., 2020). In addition, as temperatures rise and permafrost melts, C and methane (CH_4) that were previously trapped in the soil are released to the atmosphere and have the potential to amplify global climate change (Schuur et al., 2015; Biskaborn et al., 2019). Leal Filho et al. (2023a) identified that the current permafrost thaw will likely intensify under this century's projected global warming, releasing substantial amounts of greenhouse gases (GHGs) and exacerbating the problem. Elevated atmospheric CO_2 does not simply trap more heat, it also affects nutrient cycling and biological fluxes in soil. Due to this soil-climate feedback, managing the various impacts of climate change on soil dynamics could play a key role in mitigating the longer-term effects of climate change.

2. Impacts of climate change on soil dynamics

The drastic changes in global climate expected during the 21st century are anticipated to affect soil integrity, here defined as: "the ability of soil to maintain its structure, function, and ecosystem services over time, despite external disturbances … ensuring that the soil remains productive and viable for plants and other organisms" (Haines and Smith, 2017). It also influences the dynamics of soil and its biodiversity (Leal Filho et al., 2023b), thus impacting the ecosystem services that they provide (Fig. 1; Table 1). This is attributed to elevated concentrations of CO_2 caused by natural and anthropogenic activity resulting in an

Table 1
Climate change related stressors and their effects on soils.

Stressor	Effect	Reference
Heatwaves	Altered soil moisture content and pH	Materia et al. (2022) Siebert et al. (2019)
Drought and reduced moisture	Decreases soil water content, thus affecting biological activity which prevents soil aggregation	Materia et al. (2022) Siebert et al. (2019)
Increased precipitation	Increases soil organic matter, nutrient leaching and erosion	Liu et al. (2018) Sun et al. (2020) Van Oost et al. (2009)
Elevated CO_2	Affects nutrient cycling and biological fluxes	Kuzyakov et al. (2019)
Rise in sea levels	Introduces contaminants to coastal soil and increases salinity via salt water intrusion	Corwin (2021) Mondal (2021) Várallyay (2010)
Permafrost melting	Releases stored carbon and methane from the soil	Schuur et al. (2015)
Wildfires	Alters pH in soil and thus affects growth of organisms	Jansson and Hofmockel (2020)

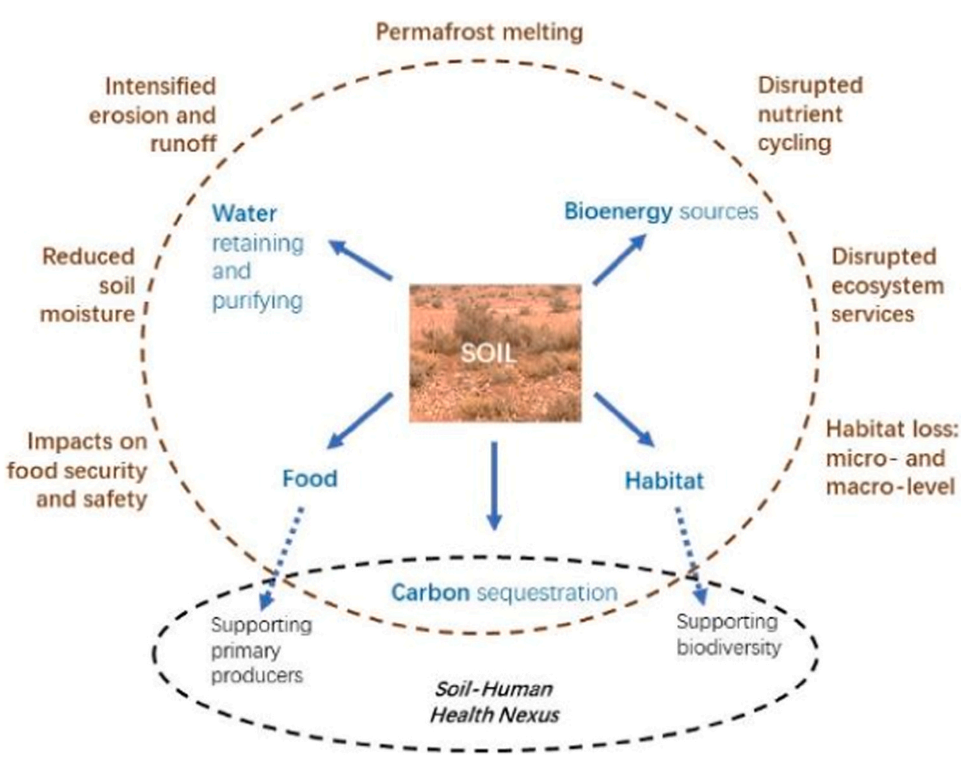

Fig. 1. Soil roles and associated ecosystems services that are disrupted by climate change.

increase in the global average temperatures that have risen by about 0.06 °C per decade over the last 150 years (Lindsey and Dahlman, 2024).

Temperature plays a key role in determining the physicochemical properties of soil. Soil temperature alters the decomposition rates of SOM and affects the mineralization of key nutrients. Furthermore, it directly affects soil water content with resulting availability to plants and other organisms. Therefore, increases in heatwaves and droughts are expected to unfavorably affect soil dynamics (Miralles et al., 2019).

Increased temperatures can also increase enzymatic reactions in soil, however, they are very likely to reduce the soil moisture content. This, in turn, results in decreased water availability for biological processes. An example is decreased soil water resulting in stomatal closure and thus CO_2 limitation of plant photosynthesis. Such effects may result in decreased vegetation cover in affected regions, which in turn leads to increased soil degradation, erosion and desertification (Reich et al., 2018).

Aside from these, changes in temperature and precipitation due to climate change affect soil formation, with more rapid rock weathering and soil development in warmer and more humid conditions. Furthermore, climate stressors result in the simplification of mineral matrices in the soil through the weathering of soil minerals. This, in turn, will reduce fertility in some soils and create a greater dependence on fertilizers (Olsson et al., 2019).

Climate change can reduce soil organic carbon (SOC) content, with warming implying more or less C released than in colder conditions depending on the soil water content, which is also a climate-dependent variable (Zhao et al., 2021). This, in turn, can have different implications. For example, recent research reveals that SOC has a strong role to play in enhancing human health through supporting nutritional needs and supplying antibiotics via soil micro-organisms, among others (Rumpel et al., 2022; Kopittke et al., 2024).

Elevated CO_2 has also been shown to have indirect impacts on soil integrity. For instance, elevated CO_2 results in the accelerated biogeochemical cycling of C within the soil. Additionally, depending on the concentrations, it causes increased fluxes of biological activity in soil (Kuzyakov et al., 2019). Increases in wildfire through climate change have been noted to increase the pH of soil (Köster et al., 2021). This, in turn, is responsible for favouring soil microbial diversity through the promotion of growth of certain organisms (Jansson and Hofmockel, 2020).

However, we have to be aware of the diversity of different soil types brought about highly contrasting soil forming processes in different locations. Cornu et al. (2023) suggested that highly weathered soils such as Ferralsols may be little affected by climate change if not subjected to land-use change and/or soil erosion. Similarly, clay-rich or SOM-rich soils will have some buffering capacity against climate change. In contrast, soils that have little clay or SOM (e.g., Cambisols or Luvisols) will rapidly reach their buffering capacity and have limited resilience, i.e., the capacity to withstand and recover from disturbance, to climate change. For example, the interrelationship between climate and soil C sequestration is challenging in drylands because these regions have experienced loss of topsoil due to increased animal grazing and erosion, which has degraded soil structure and dynamics. Additionally, limited precipitation in these regions restricts vegetation development and inhibits enzymatic activities (Szejgis et al., 2024), both of which will negatively affect organic matter decomposition and thus soil development. Soil resilience is shaped by a combination of biological diversity, historical management, and structural integrity, not just passive buffering capacity. However, unsustainable practices can initiate destructive feedback loops that push soils beyond recovery thresholds. Recognizing these mechanisms is important for designing land-use systems that enhance rather than undermine long-term soil health.

3. Unresolved debates and model uncertainties in climate change and soil research

Climate change and soil structure and biodiversity are deeply interconnected. Yet several unresolved debates and model uncertainties persist, limiting our ability to predict future impacts on soil properties accurately. One major debate revolves around the role of soils as C sinks or sources. While soils store vast amounts of C - more than the atmosphere and vegetation combined - their capacity to sequester additional C under climate change remains uncertain. Many studies (e.g., Bradford et al., 2016; Crowther et al., 2016) suggest that warming could enhance microbial decomposition, releasing stored C as CO_2 (a positive feedback loop). Others (e.g., Jastrow et al., 2005) argue that increased plant growth from CO_2 fertilization could offset these losses by adding more organic matter to soils, although this effect is not consistent (Carrillo et al., 2018).

Another key uncertainty lies in the response of soil microbial communities to climate change. Micro-organisms drive critical processes like decomposition and nutrient cycling, but their diversity and functional resilience under changing temperatures and moisture regimes are poorly understood. Models often simplify microbial dynamics, leading to projections of soil C feedbacks that lack the role of this key player. This is important because resilient soils often contain diverse microbial communities with metabolic redundancy, allowing them to maintain nutrient cycling even when some species are compromised (Chen et al., 2022).

Hydrological feedbacks further complicate predictions. Changes in precipitation affect soil moisture, influencing both C storage and GHG emissions (e.g., CH_4 from waterlogged soils). However, models disagree on the magnitude of these effects, particularly in permafrost regions, where thawing could release vast amounts of C but at uncertain rates (Biskaborn et al., 2019).

Finally, the integration of soil processes into Earth system models remains a challenge. Many models lack detailed representations of soil structure, organic matter chemistry, and plant-microbe interactions, leading to wide-ranging climate projections. Improving these models requires better empirical data, particularly from understudied regions like tropical and Arctic soils.

Addressing these uncertainties is important for refining climate predictions and guiding mitigation strategies. Future research should prioritize interdisciplinary approaches, combining long-term field experiments, advanced modeling, and incorporating emerging technologies like machine learning to reduce these knowledge gaps.

4. The way ahead: towards a greater resilience of soil to climate change

Climate change severely affects agricultural production because of increased temperatures and changes in the frequency of precipitation, along with more frequent and severe droughts and flooding. The capacity of soil to provide both water and nutrients is the main factor that determines the growth and productivity of crops (Altieri et al., 2015; Qiao et al., 2022), and therefore solutions to increasing soil resilience relate to appropriate soil management practices. Improving soil quality could clearly reduce the potential declines in crop production caused by climate change (Timpane-Padgham et al., 2017; Qiao et al., 2022). We now highlight some of the measures which may be used to increase soil resilience to climate change, some of which are described in Box 1.

Soil organic matter plays a critical role in improving soil water holding capacity, fertility, infiltration capacity, microbial activities, and temperature (Stockmann et al., 2013; Cotrufo and Lavallee, 2022). Therefore, utilizing various forms of SOM effectively is one of the keys towards improving soil's biological, chemical and physical properties. Many smallholder farmers enrich and enhance soil quality by adding animal manures and mulches, and grow cover crops and rotation crops. This leads to agricultural crops having an increased tolerance to drought

Box 1
Examples of traditional soil management techniques used by smallholder farmers in Ghana.

Characterized by smallholdings, many Ghanaian farmers cultivate on marginal lands known to be poor in structure and fertility. However, these soils have always been managed by traditional farmers to ensure productivity season after season. Indigenous techniques are applied by local people in two ways: to improve soil structure i.e., aeration, percolation, and retention of soil water for crop use, and to improve soil fertility to ensure sufficient nutrients for adequate crop production. As in most indigenous communities, small-scale farmers have been using their experience and traditional knowledges to manage their soil during farming activities and adapt to climatic variations (Fig. 2).

and reduced run-off. Application of such organic amendments could increase nitrous oxide (N_2O) emissions, but N_2O emissions from organic fertilization are generally less than when inorganic fertilizers are applied (Tang et al., 2024). Soil organic matter also enhances well-developed soil aggregates, formed through fungal hyphae and root exudates, which keep soil particles bound more tightly during potentially erosive events such as heavy precipitation or windstorms, as well as enhancing water retention (Magdoff and Weil, 2004; Iqbal et al., 2025). Since 2016, a new global scientific concept called the "4 per 1000 Initiative" has been established to promote C storage in agricultural soils. This concept assumes that an annual growth rate of 0.4 % of the global SOC stocks can counterbalance the current increases in atmospheric CO_2 (Rumpel et al., 2020, 2022). As a multi-disciplinary and multi-stakeholder entity, the platform aims to integrate scientific findings and convert them into field-based and policy actions.

Water harvesting, where excess water is collected, stored, and redistributed during dry seasons through irrigation, is important for regulating the temporal and spatial distribution of water needed for plant growth in areas with low precipitation. Water harvesting practices have been shown to increase crop productivity in different parts of sub-Saharan Africa (Dile et al., 2013; Tefera et al., 2024). Conservation tillage is also important in increasing SOM because of the presence of crop residues on the soil, increasing the activity of soil micro-organisms, and reducing soil erosion in erosion-prone cropland as it involves full coverage of the soil surface using other crops (Agus et al., 2015). This soil management practice also increases soil moisture by minimizing water evaporation, especially during long dry seasons, and because soil aggregation is promoted by the reduced soil disturbance (Iqbal et al., 2025). No-till systems and perennial vegetation preserve soil aggregates, whereas conventional tillage disrupts them, increasing vulnerability to compaction and runoff. Moreover, soils with a history of organic amendments (e.g., compost, manure) retain greater microbial activity and carbon sequestration capacity (Wu et al., 2024). These legacy effects create a "biological memory" that helps soils rebound after disturbances (Borisov et al., 2021).

Engineering soil conservation techniques are important in reducing slope length and gradient and thus giving precipitation more time to infiltrate the soil (Xiong et al., 2018). This technique also helps in reducing the volume and velocity of water run-off and, as a result, reduces soil erosion. Some of the engineering soil conservation practices include the construction of bench terraces, run-off or sedimentation pits, contour hedgerow systems, mulching, and strip cropping. Also, following Xiong et al. (2018), these engineering soil conservation techniques increase the soil water content, regulate soil temperature and reduce erosion.

Soil amelioration and soil biological management are also important in improving soil resilience to different stresses caused by climate change. Soil ameliorants like dolomite, limestone, silica, gypsum and organic matter restore soil's chemical, biological and physical properties by regulating soil elemental composition, improving soil structure, altering soil pH, and increasing nutrient retention (Agus et al., 2015).

Soils, with all their functions necessary for life, are an incredibly

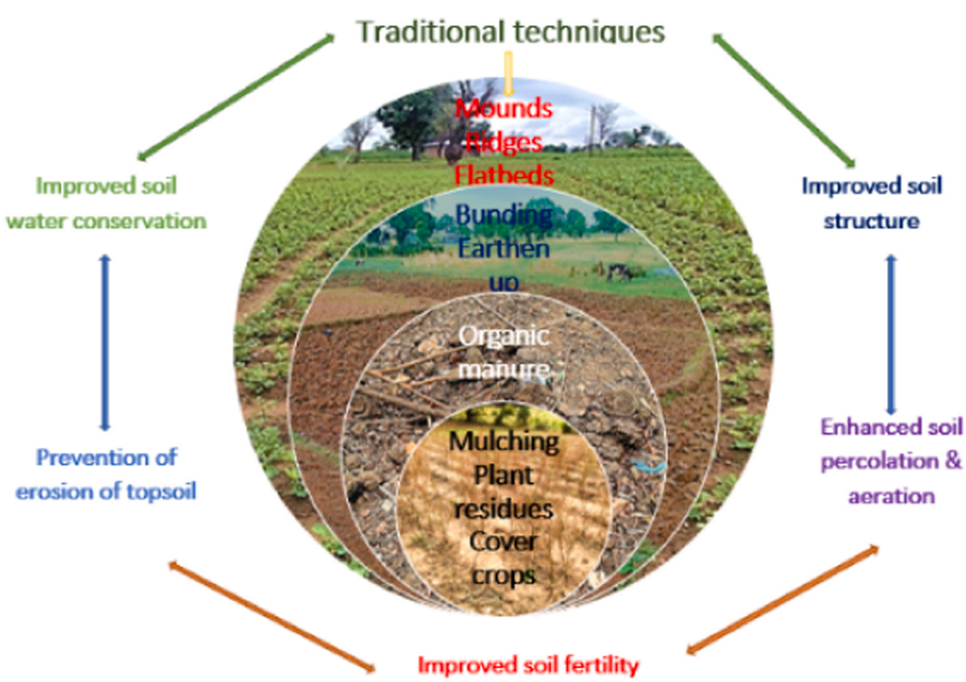

Fig. 2. Some examples of traditional soil conservation methods from Ghana.

important non-renewable resource and, as a CO_2 store ("carbon sink"), an indispensable component for climate protection efforts. Overall, the state of knowledge on how climate change impacts soil integrity should be used in future efforts to address the problem. Adaptation measures must be geared towards protecting soils from erosion, SOM loss and other climate change-related risks.

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Walter Leal Filho: Writing – review & editing, Writing – original draft, Visualization, Project administration, Conceptualization. **Jessica A. Eisma:** Writing – review & editing, Writing – original draft. **Farshad Amiraslani:** Writing – review & editing, Writing – original draft. **Anastasia Ago Baidoo:** Writing – review & editing, Writing – original draft, Visualization. **Natalia Limones:** Writing – review & editing, Writing – original draft. **Francis Q. Brearley:** Writing – review & editing, Writing – original draft, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

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