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OVERVIEW

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Global soil organic carbon–climate interactions: Why scales matter

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Abstract

Soil organic carbon (SOC) holds the largest terrestrial carbon stock because of soil conditions and processes that favor soil carbon persistence. Vulnerable to climate change, SOC may cross a tipping point toward liberating carbon-based greenhouse gases, implying massive self-amplifying SOC- climate interactions. Estimates of SOC persistence are challenging as we still lack broad mechanistic insights. Upscaling mechanistic details from small to larger scales is challenging because the driving factors are not available at the needed resolution. Downscaling is problematic as many modeling studies point to the highest uncertainties deriving from the SOC response to climate change, while models themselves have difficulties in replicating contemporary soil properties and dynamics. To bridge the problems of scaling, strict process orientation seems adequate. Holdridge Life Zones (HLZ) classification, as one example, is a climate classification framework at a mesoscale that provides a descriptive approach to facilitate the identification of potential hotspots and coldspots of SOC-climate interaction. Establishing coordinated experiments across all HLZ, but also including multiple global change drivers, has the potential to advance our understanding of general principles regulating SOC-climate interaction and SOC persistence. Therefore, regionally tailored solutions for both experiments and modeling are urgently needed and can lead to better management of soil and the ecosystem services provided. Improving “translations” from the scales relevant for process understanding to the scales of decision-making is key to good management and to predict the fate of our largest terrestrial carbon stock.

This article is categorized under:

Integrated Assessment of Climate Change > Integrated Scenario Development

KEYWORDS

critical mesoscale, ESM, regional perspectives, soil carbon persistence

1 | INTRODUCTION: WHY SOC PERSISTENCE IS IMPORTANT FOR CLIMATE PROTECTION

Soil organic carbon (SOC) is the largest terrestrial carbon stock, harboring more carbon than permafrost, fossil fuels, vegetation, or the atmosphere (Figure 1). In terms of climate change mitigation, if this SOC is destabilized and liberated as carbon-based greenhouse gases (GHG), it would easily induce massive self-amplifying SOC–climate interactions. The huge amount of SOC (1700 Pg $= 10^{15}$ g) is the result of an imbalance of soils receiving more carbon than they return to the atmosphere (Figure 1). The latter is not in a steady-state, but the result of highly dynamic equilibria of interactions mainly between the atmosphere, plants, and soils, which can be directionally tipped by human interventions. The most prominent component of the carbon cycle is photosynthesis, the conversion of atmospheric carbon dioxide (CO_2) to carbohydrates, which are temporarily held as biomass. These carbohydrates eventually return to the atmosphere as CO_2 or methane (CH_4) by autotrophic respiration or decay processes in soils. However, once carbohydrates enter the soil system, and myriads of pathways are possible, the chance that they will persist increases because decay processes in soils can be delayed in multiple ways (Kleber et al., 2011; Schmidt et al., 2011). Therefore, processes that determine SOC persistence (Box 1) contribute to the buildup of global SOC, and consequently are key to understanding and predicting SOC–climate interactions under present and future climate. Actually, SOC persistence has received increased attention (Amundson, 2022; Chen et al., 2021; Heckman et al., 2022; Lehmann et al., 2020), as it controls both carbon sequestration and release, and therefore, human societies have great interests in taking advantage of the resulting ecosystem services.

In the undisturbed global carbon cycle, SOC persistence makes soil systems carbon sinks and helps to regulate global climate. However, SOC is susceptible to climate change, although susceptibility is not homogeneous across the globe because SOC differs in chemical composition, more importantly in the way it is protected from microbial access (Lehmann et al., 2020; Schmidt et al., 2011; Woolf & Lehmann, 2019). Consequently, the heterogeneity of SOC (summarized by Heckman et al., 2022) and the scale at which we interpret this heterogeneity have to be addressed. Both the degree and the relationship to environmental factors of SOC persistence vary across the globe (Heckman et al., 2022), which suggests taking a regional approach to efforts of SOC protection or C sequestration. Soil carbon persistence shows tight relationships to temperature and water balance, which are used as main drivers in Earth system models

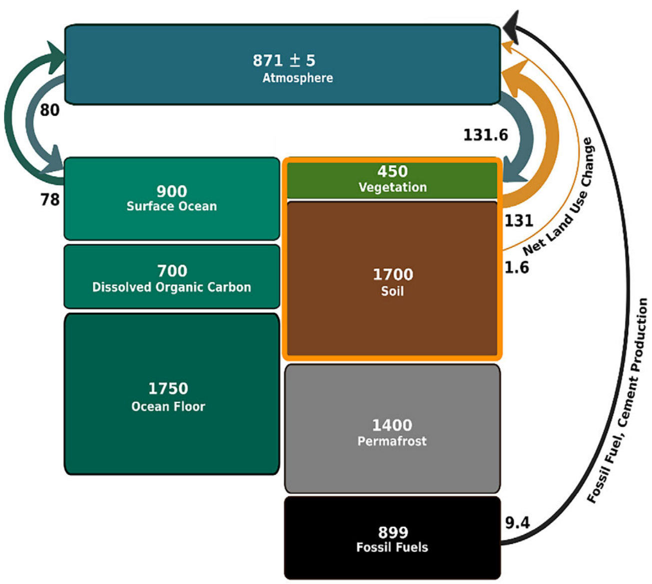

FIGURE 1 The contemporary (2010–2019) global carbon budget—simplified sketch strictly on CO_2 exchanges and based on Canadell et al. (2021). Boxes represent estimated carbon stocks in Pg C, arrows illustrate estimated carbon fluxes in Pg C per year. The orange outline indicates the soil-vegetation-continuum, as the strong interconnection between soil carbon and plant carbon makes a clear distinction hardly possible in both modeling and measurements. The exchange between the soil-vegetation continuum and atmosphere (blue arrow as uptake through photosynthesis and deposition, orange arrow as release through autotrophic and heterotrophic respiration) is still roughly balanced

BOX 1 Revised understanding of SOC persistence

Our understanding of organic matter in soil was dominated by the idea that carbon entering the soil forms products with "recalcitrant" characteristics. This "humification" process was presumed to transform biomass carbon into persistent SOC and has been the basis for our understanding of stable SOC for more than 200 years. More recently, organic matter in soil was described as a "continuous flow of C-atoms" (Agren & Bosatta, 1996; Janzen, 2006; Lehmann & Kleber, 2015), emphasizing the spatial and temporal dynamics of SOC, rather than describing it as a distinct chemical category. Subsequently, a new consolidated view of stabilized SOC was developed, integrating the adsorption and desorption to and from mineral surfaces to form mineral associated organic matter (MAOM) and the formation and destruction of aggregates as a continuous process of organic matter formation and stabilization (Kleber et al., 2015, 2021; Lavallee et al., 2020). Next to mineral associations, the concept of priming (Kuzyakov et al., 2000; Siles et al., 2022), the impact of roots (Dijkstra et al., 2021; Rasse et al., 2005), better integration of the soil structure (Fatichi et al., 2020; Guhra et al., 2022; Vogel et al., 2022) and variations in soil moisture forming gradients of oxygen availability (Huang et al., 2021; Keiluweit et al., 2017) advanced our understanding of SOC persistence. The new, consolidated view considers knowledge gains regarding soil functional complexity like "molecular diversity, spatial heterogeneity, and temporal variability" from small to large scales as fundamental in protecting vital soils for ecosystem functioning, predicting SOC persistence under climate change, and recommending management practices sustaining soil fertility (Dungait et al., 2012; Kleber et al., 2011; Lehmann et al., 2020; Schmidt et al., 2011). Yet, science-based definitions of persistent SOC and political interest of SOC permanence do not align, and resolving definitions used to describe the lifespan of SOC and carbon sequestration activities requires a common language in scientific and policy sectors (Baveye et al., 2020; Dynarski et al., 2020; Smith, 2005).

BOX 2 Earth system models

Mechanistic models incorporate mathematical process understanding and are used to calculate possible reactions of a system to changes in the driving conditions. In climate change science, earth system models (ESMs) are applied to assess the reactions of the whole earth system as well as its respective subsystems to potential climate changes (GHG concentrations, temperature, precipitation). Commonly, ESMs are composed of multiple submodels, of which some can be regarded as individual models if they can operate independently. For estimating the SOC changes, the latest developments of ESM use advanced soil biogeochemical sub-models, where soil C formation and decomposition rates are influenced by clay content, pH, differing turnover times of carbon pools, and SOC pool size. Other ESMs are less well prepared to reduce the high uncertainties associated with estimating the feedback of SOC to climate change. Haaf et al. (2021) and Song et al. (2019) noted the limitations of transferability between experimental and mechanistic knowledge on soil processes across geo-climatic zones. ESMs will most likely have to be regionally tailored to each geo-climatic zone in order to improve the global picture supported by modeling of SOC–climate interactions. One other major source of uncertainty is the appropriate spatial resolution of needed input variables of certain soil properties, which are not detectable with remote-sensing techniques. Provided that these data gaps can be filled, we will need to broaden our process understanding from areas outside China, Europe, and North America when forecasting future terrestrial carbon-climate feedback (Song et al., 2019).

(Box 2) to estimate the global budget (Figure 1) but disaggregated into regions. Relevant details of processes determining SOC persistence are yet to be understood, and therefore are among the greatest challenges in climate change science (Lal et al., 2007; Lehmann et al., 2020; Schmidt et al., 2011; Trumbore, 1997). Time to fully understand earth system complexities, however, is not on our side if we want to manage human influence on the earth's climate system. If we remain on our present course, we risk degrading soil carbon persistence and creating a self-amplification of global warming due to SOC-climate interactions.

Global SOC-climate interactions are driven by planetary-atmospheric processes and governed by SOC persistence at very detailed scales down to soil aggregates and molecules. Hence, we face an intrinsic scaling challenge to unveiling the mechanisms of SOC–climate interactions. It is of utmost importance to understand if, when, and how climate change will alter SOC retention and foresee when soils will release more carbon to the atmosphere than they receive. It is this potential self-amplification between soil and atmosphere that poses a Pandora's Box scenario (Amundson, 2022) because not only the soils but also the whole earth system would then cross a tipping point toward a new stage (Lenton et al., 2019; Steffen et al., 2018). Recent ESMs, designed to simulate process complexity and spatial heterogeneity, predict that soils will maintain their function as carbon sinks at the global scale at least until 2100 (IPCC, 2019; Ito et al., 2020; Todd-Brown et al., 2013), giving hope like in the Pandora's Box mythology. These data, however, point to a high uncertainty related to SOC persistence. Therefore, the tremendous importance of SOC persistence is widely identified and accepted as the key knowledge gap to improving our scientific understanding (Dynarski et al., 2020; Lehmann et al., 2020; Lehmann & Kleber, 2015; Schmidt et al., 2011). So, it all boils down to improving our understanding of SOC persistence under varying climatic conditions across different scales.

Preventing the earth system from crossing this tipping point requires human actions. The most straightforward way, albeit difficult in practice, remains reducing carbon emissions (Schlesinger & Amundson, 2019). As important as protecting the existing SOC stocks is, it is tempting to overly promote the atmospheric CO_2 sequestration potential of agricultural soils by improved soil management in order to regain its preindustrial values. Carbon sequestration is often used to describe human activities aimed at the removal of atmospheric carbon. However, it may be more appropriate to think of it as a longer-termed transfer of atmospheric CO_2 to soils, or other parts of the global carbon budget (Friedlingstein et al., 2019; Lal, 2008). Since the onset of agriculture, an estimated 115–154 Pg of SOC (Lal et al., 2018; Sanderman et al., 2017) has been lost through land-use change, but it is estimated that the sink capacity of agricultural and degraded soils might be only 50%–66% of the historic-C loss (Lal, 2004; Stockmann et al., 2013). Still, parts of society have focused on implementing management practices, such as the 4p1000 initiative that aims at atmospheric C sequestrations in agricultural soils at rates of 4‰ (0.4%) per year (Chenu et al., 2019; Minasny et al., 2017; Rumpel et al., 2020). It will have positive effects and could stem the expected additional losses of SOC by agriculture, but it appears naive to consider it the only option. Evidence is pending that agricultural soils can store carbon at a rate that is comparable to the current emissions. Furthermore, despite good intentions, we run the risk of releasing more carbon from the soil if we enact misguided conservation programs without understanding the large global scale variation of underlying processes. SOC sequestration potentials vary regionally and, for example, have higher "costs" in water-limited and hot areas compared with cool, moist zones (Chenu et al., 2019). The underlying processes that explain the spatial distribution of SOC stocks and SOC persistence need to be accounted for to develop regionally tailored soil management optimization. Consequently, we need concepts and models that account for regionally specific soil carbon persistence. Here we run into the scale dilemma. Processes that govern soil persistence are much finer than those scales of decision-making, which is taking place at scales finer than the processes in the climate system. To best support decision-making, translations are needed that meet in a critical mesoscale.

With this review, we aim to provide a summary of the current challenges in translating insights into SOC–climate interaction obtained from different scales. The scales most relevant for decision-making lie between the fine scales relevant for process understanding of SOC cycling and the coarse scales relevant to understand climate change. We highlight the advantages that intermediate mesoscales provide by taking advantage of the benefits of each scale without adopting too many of the individual drawbacks. These "sweet spots" differ with the questions raised and have yet to be precisely identified. Process orientation should guide us to finding the best individual mesoscale, which includes regional variations that may provide outcomes deviating from global gradients (Doetterl et al., 2015; González-Domínguez et al., 2019; Sanderman et al., 2017). Yet, dominant factors of SOC turnover and SOC persistence are related to temperature and water (oxygen) availability (Conant et al., 2011; Davidson & Janssens, 2006; Doetterl et al., 2015; Keiluweit et al., 2017), producing strong relationships between SOC stocks and climate zones (Batjes, 2014; Beillouin et al., 2022; Ciais et al., 2014; Heckman et al., 2022; Kramer & Chadwick, 2018; Rasmussen et al., 2018). Therefore, disaggregating the global scale into mesoscalic climate zones was the best first step toward finding the sweet spot for "translating" SOC–climate interaction. Beyond climate, SOC persistence is determined by the interplay of organic matter and soil minerals forming mineral-associated organic matter (MAOM) (Grant et al., 2022; Hemingway et al., 2019; Kleber et al., 2021; Mikutta et al., 2006). Therefore, the next step of disaggregating the global scale, or aggregating from detailed- to meso-scale, most likely seems to be applying soil properties like clay content or pH values, but the availability of these at reasonable resolution will always be limited. Additionally, recent literature indicates systematic variations in the importance of individual mineral or microbial relations with climate (Chen et al., 2021; Haaf et al., 2021; Hall et al., 2020; Heckman et al., 2022; Kramer & Chadwick, 2018; Rasmussen et al., 2018). Therefore, it seems very timely to identify overarching soil proxies for fine-tuning individual climatic zone, which justifies sticking to a climate-driven disaggregation. Incorporating both climatic and soil factors will be necessary to enable regionally tailored approaches, where separate trajectories must be identified to improve understanding and implementation of SOC–climate interactions across the entire range of scales. By adopting a regionalization approach to better understand climate change impacts on SOC persistence, we bridge the gap between process understanding and potential management actions, as well as tie in global modeling approaches.

2 | WHICH SCALE TO CHOOSE TO BEST ADDRESS GLOBAL SOC-CLIMATE INTERACTIONS?

According to O'Rourke et al. (2015), top-down approaches (from global to local) are necessary to isolate effects of climate change on SOC, while bottom-up approaches (from local to global) are necessary to integrate the smallest-scaled SOC–climate dynamics. Concepts are needed that bring the large- and the small-scale processes together. Experimentally, SOC persistence is determined at the molecular, mineral, or aggregate scale to gain a bottom-up understanding of processes. Consequently, the key challenge to gaining a global overview of SOC–climate interactions is to identify the scale that best reflects the underlying processes without getting lost in details less relevant at the transnational, global, or earth system scales. Tradeoffs always exist when deciding which scale is best suited for understanding a given system (Levin, 1992). We need to account for these tradeoffs and find the best individual scale, where the components of variability and complexity that affect the processes of interest are highest compared with those that are just noise (Burt & Pinay, 2005). However, interests usually differ when it comes to interdisciplinarity and transdisciplinarity. The overlapping areas of interest then have to be defined by developing common questions, which also requires a common language. Burt and Pinay (2005) originally coined the term "problematic" mesoscales to describe this overlap. We will call this overlapping area of interest the critical mesoscale or the sweet spot. This scale reflects the level of interests, and therefore scales, that are most relevant for people acting on the science as well as primary stakeholders and political decision-makers (Figure 2).

The reason for the high scientific interest in safeguarding SOC is that it is considered the most important knowledge gap in global SOC–climate interactions (Lehmann et al., 2020). The scales at which SOC persistence is experimentally

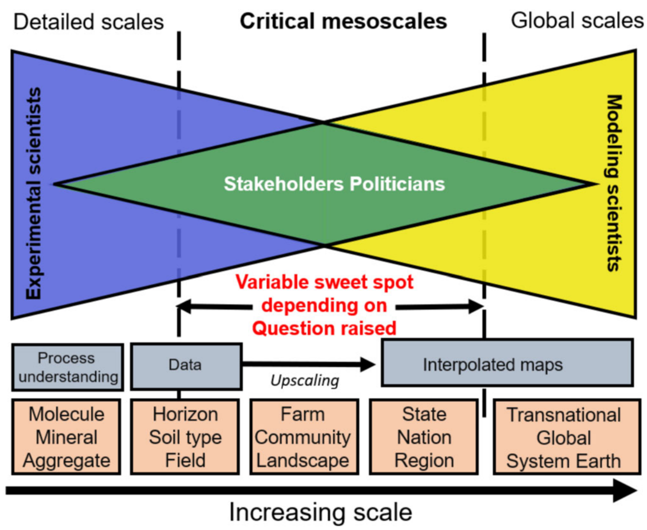

FIGURE 2 Categorical scales used to describe SOC–climate interaction ranging from detailed scales at the molecular, mineral, or aggregate level of soils to the transnational, global scales to the earth system level. Data produced at specific scales serve different purposes, for example, data from the detailed scale is obtained from scientists that work experimentally to gain process understanding. These data can be used to produce interpolated maps from modeling scientists. Stakeholders and politicians work at the critical scale in between as they (1) require the knowledge of small-scaled data and (2) base the decision-making on projected model outputs. As we still lack the theoretical framework to bridge the gap between the detailed scales and the global scales, we call the intermediate scales the critical mesoscales that—depending on the addressed need—are variable

determined are smaller (processes between molecules and up to soil horizons) than the scales of interest of most decision-makers. For example, a farmer would be mainly interested in spatial scales from field to farm, whereas a politician may be more interested in the scale from community to state/nation. Therefore, various authors highlight the need to improve our "translations" from the scales relevant for process understanding to the scales of interest and decision-making (Amelung et al., 2020; Lehmann et al., 2020; O'Rourke et al., 2015). This goal is best achieved by developing mutual hypotheses that, when addressed, help to define the critical mesoscale and the sweet spot that in turn results in the best possible individual governance–science symbiosis. In contrast, scales of continental to planetary size have low resolution, containing few details, and most interpolations are beyond the scales relevant for most decision-making. However, to understand climate change and the processes driving the climate system, continental to global scales require consideration because they predict climate change and therefore affect all other scales by, for example, influencing political decisions and directions of established experiments to study SOC–climate interactions.

3 | LIMITATIONS OF SCALING: FROM SMALL TO LARGE AND FROM LARGE TO SMALL

Both up- and downscaling have associated shortcomings (Anderson et al., 2003). Therefore, it is important to know how and at what scale data were gathered to get an idea of the associated uncertainty. For example, global soil maps appear very detailed and complete (Figure 4a). However, all information gathered about soils that feeds into models derives from the detailed scales of pits and augurs. These represent an extremely small area because they are usually limited to a few cm^2 to m^2 multiplied by the number of samples taken per site. Independent of the scale, this localized datum of SOC information always has to be extrapolated and extended to the spatial area of interest. Given that the sampling points are not evenly distributed globally, for example, lacking data in Northern Africa, Greenland, and large parts of the Asian continent (Figure 4b), the global SOC map mirrors an accuracy that may not be realistic. Therefore, important regions for SOC–climate interactions like Siberia are not well represented compared with North America and Europe, and even these are not displayed at a grid size that the ESM uses. SOC content and stocks vary largely at any scale, which introduces inherent uncertainties (Chen et al., 2021; Smith et al., 2020). According to Smith et al. (2020), these difficulties in measuring content and changes of SOC create fundamental problems for SOC sequestration programs, which happen within the critical mesoscale.

Data gaps will always need to be filled because of the uneven distribution of soil data (see, e.g., Doetterl et al. (2021)) Both interpolation and gap-filling procedures are done with expert knowledge and transfer functions and carry random error. The most common way to interpolate is to select a regular grid size, that is, resolution (pixel) of the image chosen to show the landscape, state, nation, or globe. Usually, the grid size is not chosen randomly but rather determined by the resolution at which models use that information or are validated by it. Hence, the area of interest for the interpolation of the soil data is defined by the grid (pixel) size chosen and not by the underlying process knowledge. For example, for the world map of SOC stocks (Fischer et al., 2008), a resolution of about 1 km^2 (30 arc seconds by 30 arc seconds) is selected to fit many global modeling approaches. Therefore, a map depicting the global SOC distribution conveys a rather fine resolution, even scaled up to the resolution of Community Land Model (CLM) grid cells (0.05 degrees by 0.05 degrees) (Wieder, 2014), which is used in the Community Earth System Model (CESM) (Figure 4a). The distribution of data sources (harmonized soil parameters as of 2020) demonstrates the uneven distribution of information (Figure 4b) (Batjes et al., 2017), which highlights the geographic bias. Another layer of complexity relates to the depth for which SOC stocks are considered. Since deeper soil is increasingly recognized to be important in SOC–climate interactions (Rumpel & Kögel-Knabner, 2011), considering SOC to a depth of 1 m instead of 30 cm has been proposed (Lal, 2018; Rumpel & Kögel-Knabner, 2011).

An alternative to using regular grid sizes for interpolation is to apply irregularly sized polygons, whose boundaries are set by well-defined ranges of the main factors that drive the processes of interest. An example would be Hydrological Response Units that are mainly defined by topography and used successfully in Soil and Water Assessment Tool Models (e.g., Kalcic et al. (2015)). The range and the number of driving factors are adjustable to the scale of interest. Based on the strong dependence of SOC distribution on temperature and precipitation, they should be primarily used to define the boundaries of the polygons in which SOC is scaled up. Climate zones (polygons) of climate classification systems are defined by differences in temperature and simplified water budgets (precipitation as input and potential evapotranspiration as output). Consequently, climate zone polygons of various sizes should be used for regionalizing the SOC distribution. Including soil properties (Rasmussen et al., 2018) or pedogenetic soil group classification (Kögel-

Knabner & Amelung, 2021) in SOC descriptions is a great step forward, and integration of these could improve the definition of the shape of polygons tremendously. Since global soil data are not yet available in a density needed to justify fine resolution, regional patterns rely on fairly coarse resolutions. In addition, process knowledge required for classification is not yet fully unraveled. To guide real management options within the critical mesoscale, finer and climate-independent polygons referring to soil properties, like clay content and beyond (Rasmussen et al., 2018) are needed. Similarly, the required global soil type data are not available—we are thus left to rely on interpolated information, which portends to give higher resolution in the data than actually exists.

In a nutshell, process-oriented polygons could provide scientific-based interpolation in contrast to regular homogenized grids. In a first hierarchical step, we suggest these boundaries to be strictly set by temperature and water balance as primary drivers of SOC (Chen et al., 2021; Davidson & Janssens, 2006; Shi et al., 2020). However, integrating pedogenic controls, like mineral-associated organic matter content (Kleber et al., 2021; Kramer & Chadwick, 2018; Lavallee et al., 2020), could greatly improve predictions of SOC persistence, which is well summarized by Rasmussen et al. (2018). Several studies present that SOC and mineral interactions vary with climate (Hall et al., 2020; Kramer & Chadwick, 2018; Rasmussen et al., 2018). Crowther et al. (2019) additionally emphasize that it is not only the abiotic environment but also organisms that drive the persistence of SOC, suggesting the inclusion of the functional diversity of soil organisms to identify general global patterns. Recently it has been shown that pedogenic controls vary systematically with climate (temperature and water balance) (Heckman et al., 2022; Kramer & Chadwick, 2018). Accordingly, it is of utmost importance to identify the climate classification that best fits the polygons to the drivers of SOC distribution. It is clear that these polygons (climate classes) should be fine rather than coarse, and strictly defined by temperature and water balance.

4 | CLIMATE CLASSIFICATION AS CRITICAL MESOSCALE TO IDENTIFY GLOBAL SOC–CLIMATE INTERACTIONS

Holdridge Life Zones (HLZ) (Holdridge, 1947; Holdridge, 1964) proved to be a highly suitable polygon-based system for demonstrating process-oriented regional SOC distribution across the globe (Jungkunst et al., 2021; Post et al., 1982) (Figure 3). Already 40 years ago, Post et al. (1982) argued it to be "important to establish the relationships between the geographical distribution of SOC and climate as a basis for assessing the influence of changes." Following studies have recognized the importance of understanding the SOC dynamics and being able to link these with larger global-scale modeling approaches, and have also taken a regionalization approach, but this means generally looking at smaller, landscape, or even national scales (Anderson et al., 2003; Doetterl et al., 2015; Slessarev et al., 2022). Elmore and Asner (2006) demonstrate a relationship between remotely sensed surface litter and field SOC measurements, allowing for regionalization of SOC estimations using remote sensing data. Nave et al. (2018) propose a method and consequently quantify SOC stocks based on 15,000 national-level observations combined with remote sensing information on land use and land cover, and later, Nave et al. (2021) demonstrate the applicability of this method in another effort of ecoregional SOC assessment. However, they do not present a methodology for upscaling the "regional" information to broader-scale uses (possibly with the exception of going from regional to global in one step). In this context, Paustian et al. (2019) propose a quantification system consisting of several methods (integrated model frameworks, expanded measurement and monitoring networks, remote sensing and crowd-sourcing of relevant management activity data) to inform global-scale soil science. Still, to the next step of upscaling from regional to global-scale SOC estimates seems missing. Authors using climate zonation in relation to SOC stocks chose almost exclusively, to our knowledge, classifications based on HLZ above all other possible climate zonation systems or at least a system that similarly uses polygons defined by climate variables (Kramer & Chadwick, 2018; Lin et al., 2020; Rasmussen et al., 2018).

Jungkunst et al. (2021) showed that the approach of Post et al. (1982) even improved when updated data points on SOC stocks were added. A possible reason why the SOC stock for each of the 38 zones of the HLZ is so distinguishable is the fact that (a) there are 38 polygons (more than others) that are (b) strictly defined by annual values, and which (c) exclusively use temperature and water balance rather than plant-related parameters. For example, other climate-classification systems like Köppen–Geiger use specified climate data controlling plant growth in individual-specific zones, which may be less influential for SOC persistence than the uniformly and strictly annual biotemperature and water balance classes used in HLZ. Therefore, HLZ may provide a good critical mesoscale for showing regionalized global SOC stocks and SOC persistence without mimicking greater details than exist in the data.

In detail, HLZ include 38 zones that are distributed across seven latitudinal/altitudinal regions and up to eight humidity provinces (Figure 3). The latitudinal/altitudinal regions are defined according to biotemperature (which focuses on the effective temperature for plant growth and is the mean of unit-period temperatures with substitution of zero for all temperature values below 0°C and above 30°C (0°C < T < 30°C)) and named from cold to hot polar, subpolar, boreal, cool temperate, warm temperate, subtropical, and tropical. The number of humidity provinces increases with biotemperature. The humidity provinces are defined by mean annual precipitation (MAP) and potential evapotranspiration (PET). When MAP exceeds PET, this ratio is <1, and the zone is considered as humid; when this ratio is >1, the zone is considered as dry. All eight are defined as super-arid, per-arid, arid, semi-arid, humid, per-humid, and super-humid.

The global map using HLZ to display SOC stocks (Figure 4c) has certain similarities with the regular grid-based map (Figure 4a). These similarities beg the question of which is closer to reality. From our perspective, HLZ enable linking process knowledge and global modeling approaches and aligns better with the expected latitudinal patterns for the processes, which make them ideal sweet spots improving "translations" from the scales relevant for process understanding to the scales of decision-making.

5 | PREDICTIONS OF SOC–CLIMATE INTERACTIONS BY USING CLIMATE CLASSIFICATION

The response of SOC to climate change is one of, if not the greatest uncertainty in climate change projections (Varney et al., 2020; Veldman et al., 2019). More energy (temperature) available for microbial decomposer communities leads to higher decomposition rates, as long as other resources are not limited. Consequently, elevated respiratory CO_2 releases from the soil are to be expected with continuing climate change. Understanding the global heterogeneity of both SOC stocks and climate change is key for an improved and regionally diversified understanding of the processes governing SOC–climate interactions. Similarly, as regions with higher SOC stocks and regions with very low SOC stocks exist (Figures 4 and 5), climate change will not happen uniformly. In general, the HLZ classification provides a descriptive approach to facilitate the identification of potential hotspots and coldspots of SOC–climate interaction (Figure 5). If zones with high SOC stocks spatially overlap with zones where above-average temperature increases are predicted, potential hotspots of SOC–climate interactions emerge. In contrast, coldspots will form in areas with low SOC and below-average temperature increases. For example, the highest temperature changes are predicted for the boreal, cool, and warm temperate temperature zones by 2050 (Figure 5). Regarding the humidity provinces, the arid zones will be affected by temperature increases, whereas the predicted temperature in humid zones will be lower (Figure 5). Accordingly, hotspots of potential SOC susceptibility form in the boreal and cool temperate humid regions where 36.9% SOC is stored globally and which is affected by large rises in mean temperature. Interestingly, the humid subtropical zone bares 10.7% of the global SOC and has the potential to turn into a hotspot after 2050. The strongest reductions in precipitation are expected in the rather dry warm temperate zones and strongest increases in precipitation in the tropic dry areas. While studies investigating SOC persistence across global climate classes may be suitable to show the long-term response of SOC to a given climate, they may fail to present the shorter-term dynamics of non-adapted systems. Understanding ecosystem threats imposed by interspersed climate extremes or climate change in a specific area, requiring manipulated experiments.

We know from field experiments that the response of SOC to warming alone is inconsistent with reported increases and decreases in SOC stocks (Crowther et al., 2016; Sulman et al., 2018; van Gestel et al., 2018). Measuring respiratory CO_2 fluxes to the atmosphere provides limited insights to resolve SOC responses to climate change (Conant et al., 2011). Apparently, soil ecosystem reactions are complex even to the manipulation of only a single climate variable like heating. For example, SOC has recently been shown to respond contrary to plant behavior under elevated atmospheric CO_2 concentrations implying a revision of future SOC projections (Terrer et al., 2021). According to Duffy et al. (2021), the thermal maximum for photosynthesis has already been reached globally, which is predicted to result in a nearly 50% reduction in the land-sink strength of atmospheric carbon by as early as 2040. In total, the complexity extends to multiple reactions and dynamics like input, transport, sorption, (co-)precipitation, and aggregation that occur even in highly heterogeneous patterns. Consequently, Haaf et al. (2021) propose that more process knowledge from spatial diverse soil types is needed to advance predictions of SOC–climate interactions under climate change. We are convinced that climate classification provides a way forward for improved predictions as it allows for separating contrasting processes. In line with that, Haaf et al. (2021) interpret their results separately for the colder, temperate,

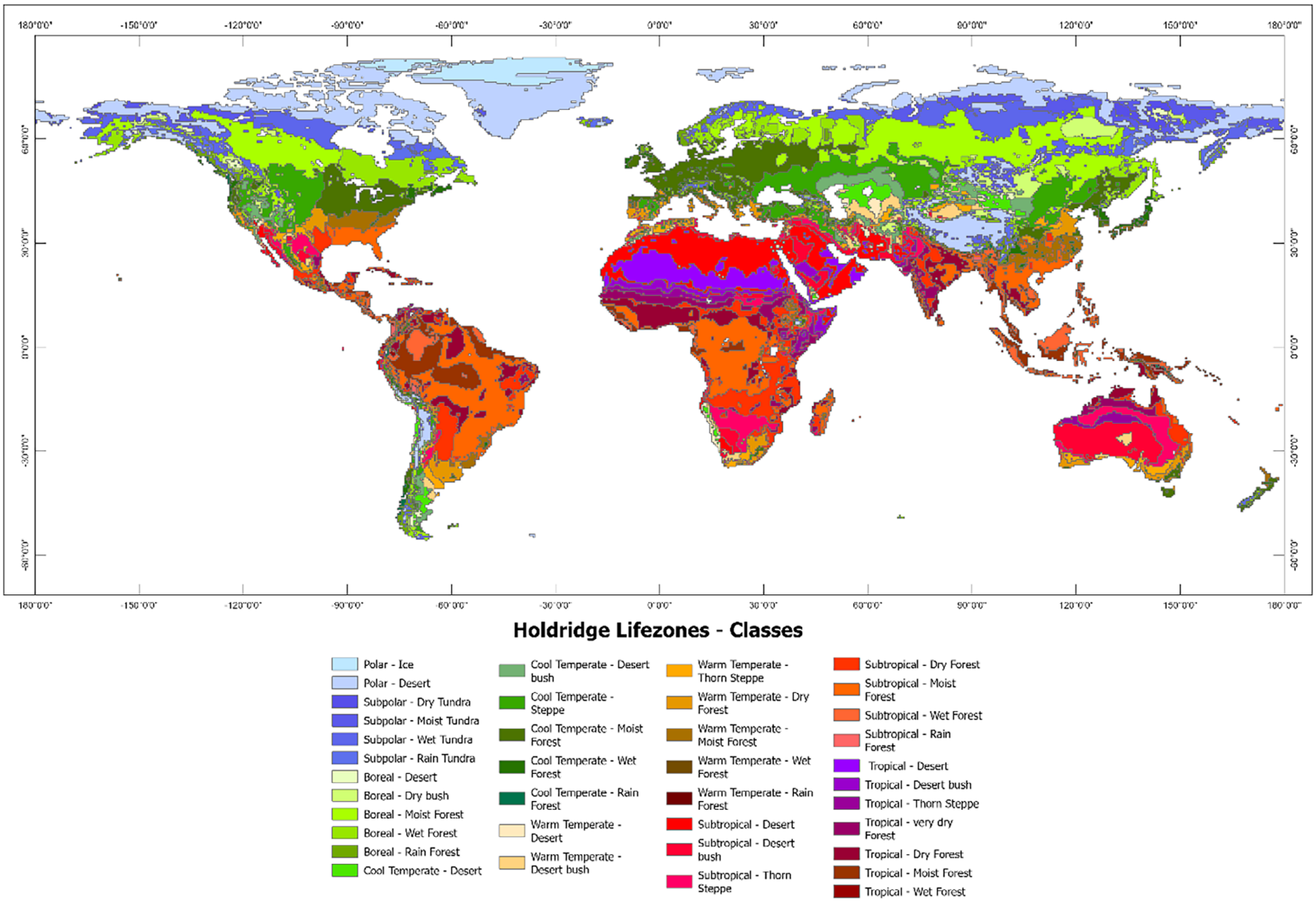

FIGURE 3 The global map of the Holdridge Life Zones (HLZ). The HLZ dataset (Leemans, 1990) is supplied by the International Institute for Applied Systems Analyses (IIASA) in Laxenburg, Austria, and was retrieved from the FAO GeoNetwork (last update FAO, 2008)

and tropical climate zones and justify it by different mineral ages and complexity between these zones. In colder climate zones, SOC is hardly being stabilized by minerals as there is less mixture of organic and mineral material, which explains a quicker response to warming compared with warmer zones (Doetterl et al., 2015). At least between cold and warm climates, repeatable patterns of differences emerge (Crowther et al., 2019; Koven et al., 2017). There seems to be a consensus that climate class and difference in temperature sensitivity of SOC are key to precisely predicting the SOC dynamics under global warming (Wang et al., 2019). Otherwise, it is impossible to unravel the cause of the spatial patterns in SOC changes under warming that need to be understood to improve climate change projections (Crowther et al., 2018).

Other predictive variables accounting for heterogeneously distributed soil carbon persistence are necessary to explain large-scale patterns (Bradford et al., 2016; Bradford et al., 2017). Thus, more observational studies across diverse soils are needed to accurately predict the response of SOC to warming at the global scale (Haaf et al., 2021). Moreover, when forecasting future terrestrial SOC–climate interactions, there is an urgent need to explore the interactions among multiple global change drivers (Song et al., 2019) like elevated atmospheric CO_2 concentrations, atmospheric N depositions, and varying precipitation. To gain fine-scaled process understanding, manipulative experiments with multiple factors are required which push observational studies beyond what is feasible, particularly as these observations would need to be evenly distributed across the globe within relevant geo-climatic zones. As coordinated globally distributed experiments are designed to compare ecosystem sensitivity to global-change drivers, their performance depends on whether they cover a significant proportion of the global range of environmental variables (Fraser et al., 2013; Yahdjian et al., 2021). Establishing coordinated experiments across all HLZ, but also including multiple global change drivers, has the potential to advance our understanding of general principles of SOC–climate interaction, and SOC persistence.

Even without pushing observational studies to their limits, simulations of possible climate change impacts on SOC should employ calculation exercises with mechanistic models (Box 2). Powerful ESMs are already capable of

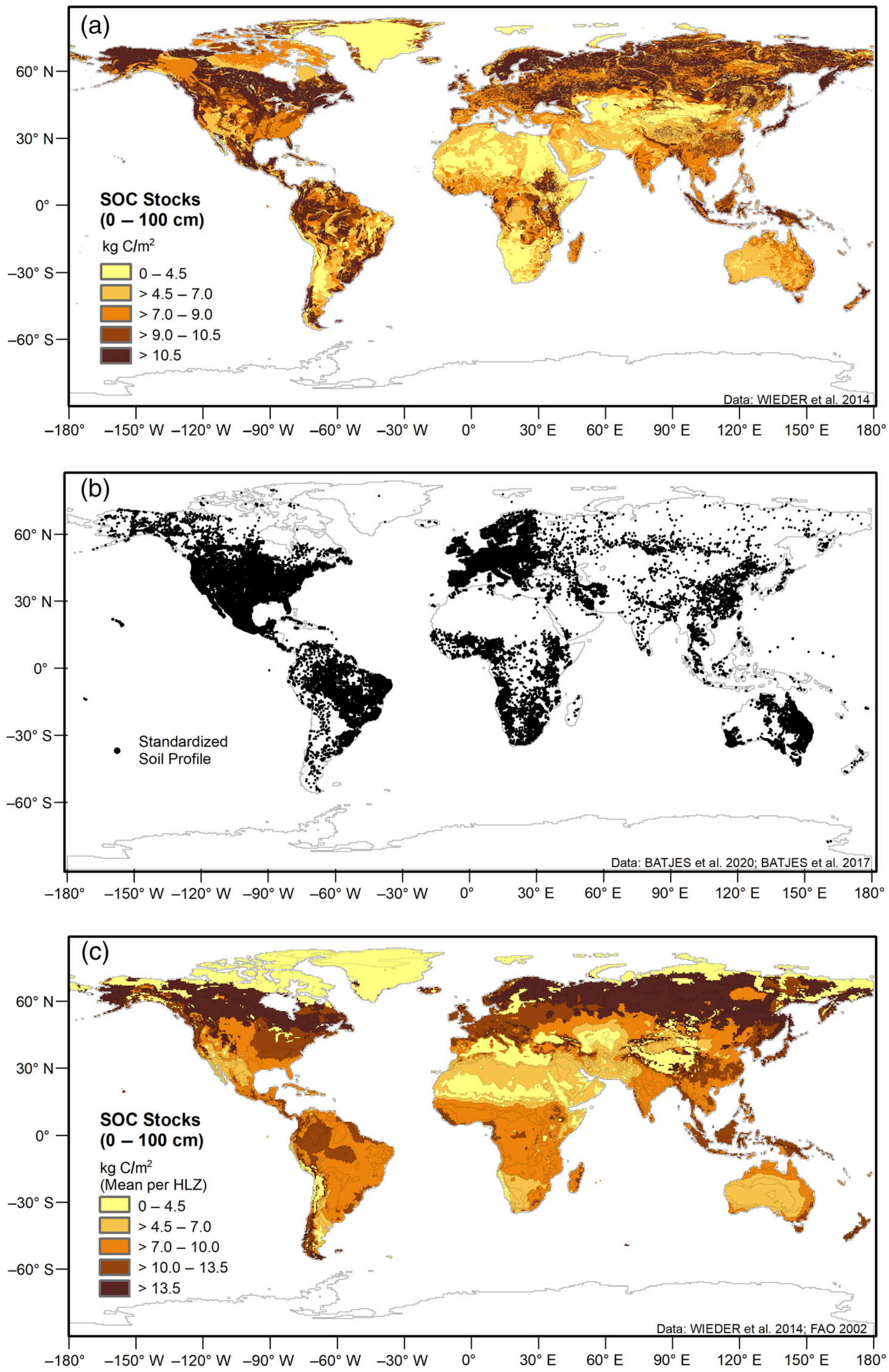

FIGURE 4 (a) Global map of soil organic carbon (SOC) stocks representing the regular grid-based map, (b) the numbers and location of underlying soil profiles (Batjes et al., 2017; Wieder, 2014), and (c) the calculated mean SOC stocks separated with HLZ classification. Sources of data sets are provided under further reading. As part of the World Soil Information Service (WoSIS) workflow, soil profile data are being populated from different kinds of studies with varying focus, and therefore termed standardized soil profile to ensure completeness and quality criteria like observation date, level of trust including soil expert knowledge and accuracy (Batjes et al., 2017; Ribeiro et al., 2020). Since the data are submitted in multiple formats, the data were converted into a digital standard format and units standardized to make data usable (Batjes et al., 2017; Ribeiro et al., 2020)

realistically simulating possible feedback reactions of soils to climate change scenarios (Ito et al., 2020; Todd-Brown et al., 2013), and most of them tell us that global SOC stocks will increase until 2100. Todd-Brown et al. (2013) simulated the global SOC response to range from a carbon loss of 72 Pg to a carbon gain of 253 Pg and a multimodel mean

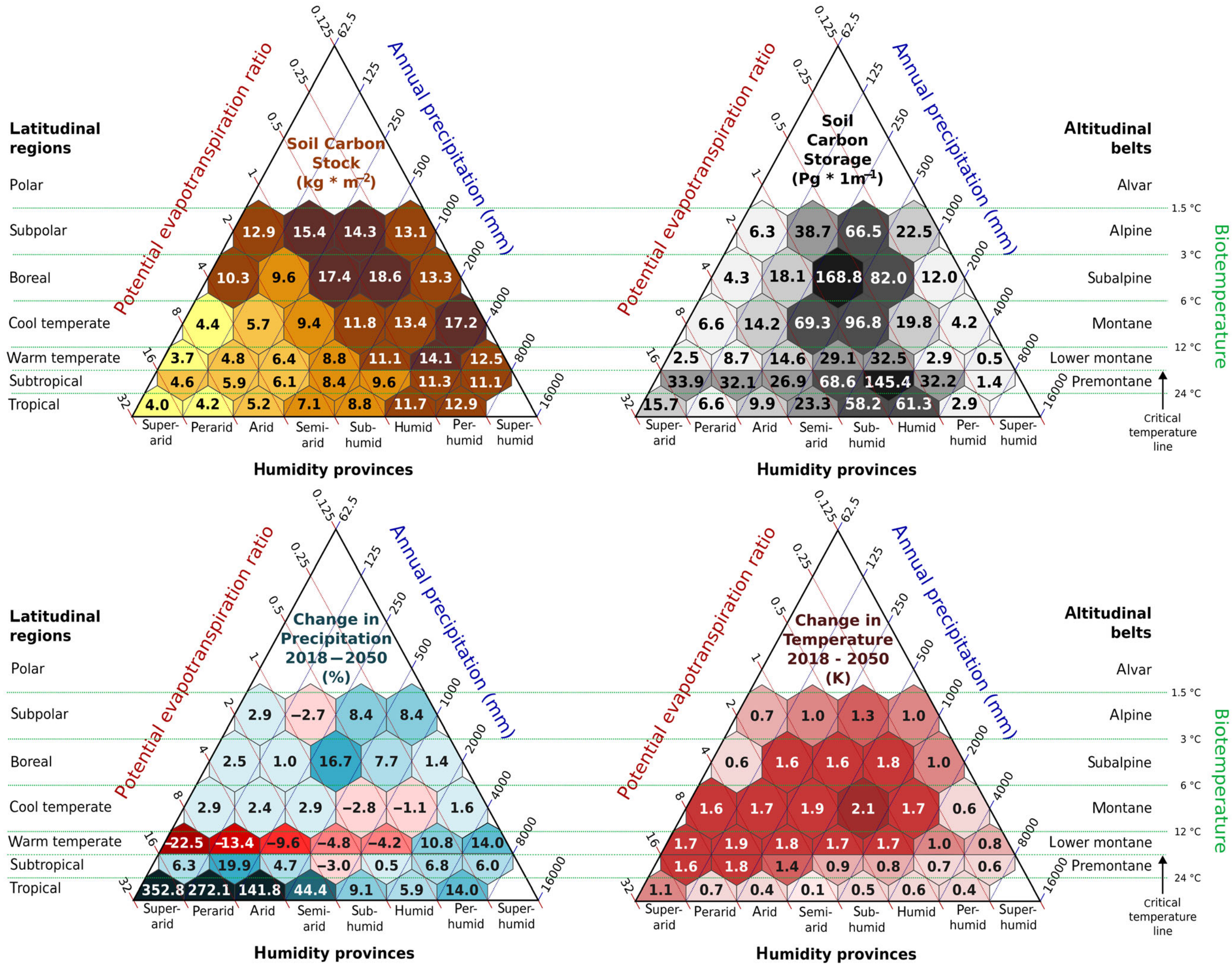

FIGURE 5 Mean soil organic carbon (SOC) stocks (0–100 cm) and SOC storage (total per zone) plotted across the Holdridge scheme for world life-zone classification (upper triangles). Zones are sorted by biotemperature region (from top subpolar to bottom tropical) and humidity provinces (from super arid on the left to super humid on the right) (Cramer & Leemans, 1993; Harris, 1973; Lugo et al., 1999). Lower triangles present predicted changes in precipitation and temperature within the HLZ classes. Climate change predictions refer to the projected change from 2018 to 2050 assuming the CMIP6 SSP3 RCP7.0 climate scenario which lies right in the middle of the range of baseline outcomes produced by energy system models (Tebaldi et al., 2021) and addresses a timescale relevant to decision making

gain of 65 Pg carbon. Todd-Brown et al. (2013) point out that ESMs have not fully incorporated fine-scale mechanisms like priming effects, nutrient availability, mineral surface stabilization, and aggregate formation. However, according to Ito et al. (2020), model uncertainty has not been markedly diminished since 2013 and they report future (2015–2100) global SOC stock increases of 48 ± 32 Pg and 49 ± 58 Pg. But literally, all modeling studies point to the highest uncertainties deriving from the reaction of SOC to climate change. ESMs also have difficulties in replicating contemporary soil properties and dynamics (Luo et al., 2017; Todd-Brown et al., 2013). It will be interesting if present model calculations hold in predicting a global rise of SOC—this will give us hope. Some improvements in ESM soil calculations are reported that capture this emergent behavior (Koven et al., 2017). However, ESMs most likely have to be regionally tailored to represent diverse mechanistic understanding to the diverse soil regions. How can we approach this – potentially by scaling the HLZ further down to soil properties like pH and clay, since the key to improvement lies within explaining SOC persistence. However, this will end up in fine scales that may be beyond the critical mesoscales for a global overview, so more aggregate soil information like soil types may be more appropriate.

6 | CONCLUSION

One of humanity's greatest challenges will be managing the impacts of global climate change. As the mythical story goes, Pandora opened the "box" and unleashed evils on humanity. Analogously, this can happen if the SOC stocks were to enter the atmosphere in a self-amplifying mechanism. But, as in the myth, there is hope. We propose that this hope lies in the soils themselves. Their ability to continue providing the ecosystem service of protecting the global climate and preventing a tipping point is supported by current models. Assessing any solutions on global scales will require better data from a wider variety of soil types and regions, as well as deeper process knowledge of soils. Our revelation from this review convinces us that if soil processes (from the fine-scale) can be better integrated into models (more global scale, better proxy variables, and ability to incorporate multiple variables), we may yet have fine-tuned tools to inform management interventions working in the critical mesoscale. One possible way forward is to reconsider the approach of relying solely on regular grids, which have inherent resolution and upscaling issues, and explore irregular grids (i.e., polygons) that can better represent the process knowledge gains in soil science. Results from applying HLZ are encouraging and may help connect approaches at the extreme scales with the critical mesoscale. Given that the largest stocks of carbon are stored in soils, the scientific community must help inform management practices and ultimately allow the hope rather than the calamity of Pandora's box to prevail.

AUTHOR CONTRIBUTIONS

Hermann F. Jungkunst: Conceptualization (lead); methodology (supporting); writing – original draft (equal); writing – review and editing (equal). **Jan Göpel:** Conceptualization (supporting); data curation (lead); methodology (supporting); writing – review and editing (supporting). **Thomas Horvath:** Conceptualization (supporting); writing – original draft (supporting); writing – review and editing (lead). **Simone Ott:** Conceptualization (supporting); data curation (lead); writing – original draft (supporting); writing – review and editing (supporting). **Melanie Brunn:** Conceptualization (equal); data curation (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The SOC stocks are available from the Regridded Harmonized World Soil Database v1.2 (RHWSD) (Wieder, 2014) and provided by Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee. Profile data, the basis of the RHWSD is available online as the database WISE3 (Batjes, 2008) on ISRIC—World Soil Information Wageningen University & Research in Wageningen, the Netherlands. The latest state of standardized Profile Data with harmonized soil parameters (last update 2020) is available as the database WoSIS on ISRIC as well (Batjes et al., 2017). The HLZ dataset (Leemans, 1990) is supplied by the International Institute for Applied Systems Analyses (IIASA) in Laxenburg, Austria, and was retrieved from the FAO GeoNetwork (last update FAO, 2008). For more information of HLZ usage refer to Jungkunst et al. (2021) and http://www.fao.org/geonetwork/?uuid=c6f35470-88fd-11da-a88f-000d939bc5d8.

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