Received: 8 May 2024 | Accepted: 28 May 2024

DOI: 10.1002/sae2.12108

Global Initiative of
Sustainable Agriculture and Environment
Harnessing Natural Resources

REVIEW ARTICLE

A belowground perspective on the nexus between biodiversity change, climate change, and human well-being

Nico Eisenhauer[1,2] | Karin Frank[1,3,4] | Alexandra Weigelt[1,2] | Bartosz Bartkowski[3,5] | Rémy Beugnon[1,6,7] | Katja Liebal[2] | Miguel Mahecha[1,8] | Martin Quaas[1,9] | Djamil Al-Halbouni[8] | Ana Bastos[10] | Friedrich J. Bohn[3] | Mariana Madruga de Brito[3] | Joachim Denzler[11] | Hannes Feilhauer[1,8] | Rico Fischer[12] | Immo Fritsche[13] | Claudia Guimaraes-Steinicke[8] | Martin Hänsel[14,15] | Daniel B. M. Haun[16] | Hartmut Herrmann[17] | Andreas Huth[1,3,4] | Heike Kalesse-Los[6] | Michael Koetter[18,19] | Nina Kolleck[20] | Melanie Krause[9] | Marlene Kretschmer[6] | Pedro J. Leitão[8] | Torsten Masson[13] | Karin Mora[8] | Birgit Müller[1,3,21] | Jian Peng[3,8,22] | Mira L. Pöhlker[6,17] | Leonie Ratzke[23] | Markus Reichstein[1,10] | Solveig Richter[1,24] | Nadja Rüger[1,25,26] | Beatriz Sánchez-Parra[1,2] | Maha Shadaydeh[11] | Sebastian Sippel[6] | Ina Tegen[17] | Daniela Thrän[3,9,27] | Josefine Umlauft[28] | Manfred Wendisch[6] | Kevin Wolf[6] | Christian Wirth[1,2] | Hannes Zacher[13] | Sönke Zaehle[1,10] | Johannes Quaas[1,6]

Correspondence
Nico Eisenhauer, German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany.
Email: nico.eisenhauer@idiv.de

Funding information
Sächsisches Staatsministerium für Wissenschaft und Kunst, Grant/Award Number: 3-7304/35/6-2021/48880; Deutsche Forschungsgemeinschaft, Grant/Award Numbers: Ei 862/29-1, FZT 118, 202548816

Abstract

Soil is central to the complex interplay among biodiversity, climate, and society. This paper examines the interconnectedness of soil biodiversity, climate change, and societal impacts, emphasizing the urgent need for integrated solutions. Human-induced biodiversity loss and climate change intensify environmental degradation, threatening human well-being. Soils, rich in biodiversity and vital for ecosystem function regulation, are highly vulnerable to these pressures, affecting nutrient cycling, soil fertility, and resilience. Soil also crucially regulates climate, influencing energy, water cycles, and carbon storage. Yet, climate change poses significant challenges to soil health and carbon dynamics, amplifying global warming. Integrated approaches are essential, including sustainable land management, policy interventions, technological innovations, and societal engagement. Practices like agroforestry and organic farming improve soil health and mitigate climate impacts. Effective policies and governance are crucial for promoting sustainable practices and soil conservation. Recent technologies aid in

For affiliations refer to page 8.

monitoring soil biodiversity and implementing sustainable land management. Societal engagement, through education and collective action, is vital for environmental stewardship. By prioritizing interdisciplinary research and addressing key frontiers, scientists can advance understanding of the soil biodiversity–climate change–society nexus, informing strategies for environmental sustainability and social equity.

KEYWORDS

biodiversity change, climate change, human well-being, soil biodiversity

1 | BACKGROUND

Biodiversity loss and climate change, which are both driven by human activities like habitat destruction and pollution as well as climate change (IPBES, 2019; Pereira et al., 2024), are closely linked (Mahecha et al., 2022; Pörtner et al., 2021). Climate change worsens biodiversity loss by altering ecosystems, degrading habitats, and intensifying extreme weather events (Mahecha et al., 2022; Pörtner et al., 2021). This loss weakens the ability of ecosystems to provide vital services like clean water and pollination, exacerbating the impact on society. Changes in biodiversity and climate patterns directly affect human well-being, impacting agriculture, food security, health, and livelihoods (Pörtner et al., 2021). To address these challenges, integrated approaches are needed, considering the complex interactions among biodiversity, climate, and society (Pörtner et al., 2021). Here, we highlight that soils play an essential role in this nexus (Figure 1).

2 | THE SOIL BIODIVERSITY—CLIMATE CHANGE—SOCIETY NEXUS

Soil, often referred to as the 'living thin skin of the solid Earth,' has a central role in the intricate interplay between biodiversity, climate, and human society (Pörtner et al., 2021). Its significance results from its function as a reservoir of biodiversity, a carbon sink or source, as well as a regulator of the water cycle, nutrient cycling, and various other ecosystem properties and processes crucial for sustaining life on Earth (Anthony et al., 2024; Bardgett & van der Putten, 2014; Crowther et al., 2019; Porporato et al., 2004; Wall et al., 2015). In the context of ongoing changes in biodiversity and climate, understanding the role of soil becomes increasingly important in addressing environmental challenges and promoting sustainable development (Figure 1).

2.1 | The role of soils in supporting biodiversity

The biodiversity of terrestrial ecosystems, encompassing the variety of life forms at genetic, species, functional, and ecosystem levels, is intimately connected with soil health (Montgomery et al., 2024). Soils harbor a complex diversity of microorganisms, ranging from fungi, bacteria and archaea, to insects and other invertebrates as well as some vertebrates, collectively known as soil biota, which account for ~59% of all species on Earth (Anthony et al., 2024). This rich soil biodiversity contributes to essential ecosystem functions, such as soil fertility, organic matter decomposition, and maintenance of soil structure (Bardgett & van der Putten, 2014). Moreover, soil biodiversity supports aboveground biodiversity by facilitating plant growth and creating biotic niches, influencing plant community composition, and ultimately ecosystem resilience to external stress factors (Van Der Heijden et al., 2008; Wardle et al., 2004).

One of the primary mechanisms through which soil biodiversity influences aboveground biodiversity is through mutualistic interactions with plants (Wardle et al., 2004). Mycorrhizal fungi, for instance, form symbiotic relationships with the roots of most plant species, facilitating nutrient uptake in exchange for carbohydrates (Smith &

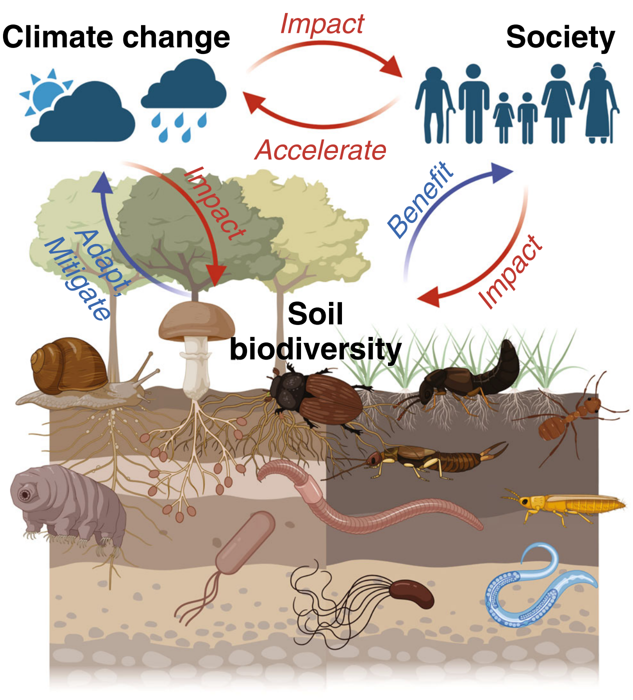

FIGURE 1 The soil biodiversity – climate change – society nexus. Figure redrawn and modified after Korn et al. (2019) and Pörtner et al. (2021). Red arrows represent threats; blue arrows indicate opportunities, according to Pörtner et al. (2021).

Read, 2010; Tedersoo et al., 2020). This mutualism provides protection against pathogens and improves disease resistance (Cameron et al., 2013; Powell et al., 2009), enhances productivity (Powell et al., 2009; Van Der Heijden et al., 2008), and resilience to environmental stressors (Augé et al., 2015), thereby promoting biodiversity at higher trophic levels (Bonfante & Genre, 2010). Soil organisms, such as earthworms, nematodes, and microarthropods, contribute to soil fertility and structure through their activities facilitating plant growth (e.g. of monocultures such as crops), but it also promotes the coexistence of species allowing us to leverage the advantages of polycultures for ecosystem services and stability (Bardgett & van der Putten, 2014).

However, habitat destruction, increasing urbanization (Castells-Quintana et al., 2021), intensive land use and exploitation, pollution (Zacher et al., 2023), and climate change impacts, pose significant threats to soil biodiversity and ecosystem stability (Castells-Quintana et al., 2021; FAO et al., 2020; Phillips et al., 2023). A decline in soil biodiversity can potentially lead to reduced nutrient cycling, decreased carbon-use efficiency, decreased soil fertility, and increased susceptibility to pests and diseases, compromising the productivity and resilience of agricultural and natural ecosystems (FAO et al., 2020; Fonte et al., 2023). Moreover, disruptions to soil biodiversity can have cascading effects on aboveground biodiversity (Wardle et al., 2004), potentially triggering further biodiversity loss and ecosystem degradation.

2.2 | The role of soils for climate regulation

Soils are crucial for the intricate interplay between the biosphere and the atmosphere. They influence and modulate the partitioning of energy, mass, and momentum fluxes; thus, they play an important part in all major climate cycles. For example, soil moisture regulates the water cycle through the evapotranspiration flux to the atmosphere. Biodiverse soils are characterized by functional diversity (Wall et al., 2015), which includes the capability to retain rainwater. The capacity to hold water has several positive effects. Two of them are reduced runoff and reduced degradation of the soil (Zhang et al., 2019), as well as the ability to reduce heat waves by evaporative cooling (Lapidot et al., 2019; Moss et al., 2019; Paschalis et al., 2021). Both effects help to moderate extreme events, such as floods or drought and even effects of heatwaves, where soils have been shown to be even more affected than air (García-García et al., 2023), which can lead to feedbacks with increased hydrophobicity (Goebel et al., 2011). In the energy cycle, soil moisture and soil temperature determine the fluxes of latent and sensible heat, respectively. Soil albedo regulates the amount of solar radiation that is absorbed by the land surface. While moist and nutrient-rich soils have a low albedo and absorb the majority of radiation, dry and nutrient-deficient soils are more reflective (Lohila et al., 2010). While this leads to a potential warming by absorbing more radiation compared to nutrient-deficient soils, nutrient-rich and biodiverse soils promote vegetation growth (Fonte et al., 2023), which, in the long term, acts as a carbon sink but also enhances the broadband solar albedo and reduces solar warming.

Soil plays a crucial role in the global carbon cycle, greenhouse gas emissions, and climate regulation (Bossio et al., 2020; Paustian et al., 2016; Tian et al., 2020). Moreover, they represent the largest terrestrial carbon pool, storing more carbon than the atmosphere and vegetation combined (Crowther et al., 2019; Friedlingstein et al., 2023). This organic carbon is derived from plant residues, microbial biomass, and organic matter inputs, which are decomposed and transformed by soil organisms into stable forms of soil organic carbon (SOC; Schmidt et al., 2011). SOC not only contributes to the long-term biospheric carbon storage, mitigating the accumulation of carbon dioxide (CO_2) in the atmosphere, but also regulates soil fertility, water retention, and nutrient availability. Microbially-mediated mechanisms of soil carbon sequestration include soil aggregation, transfer of carbon from labile to recalcitrant fractions, and improving plant growth and thus carbon input to the soil (Mason et al., 2023). Furthermore, natural and agricultural soils emit N_2O and other greenhouse gasses to the atmosphere, thereby further contributing to changes in the Earth's radiative budget (Tian et al., 2020).

Under strong wind speed conditions, open soil surfaces can serve as significant sources of atmospheric dust aerosols (e.g. Tegen & Schepanski, 2009). These dust aerosols play crucial roles in climate dynamics, atmospheric chemistry, and biogeochemical cycling on regional and global scales (Kok et al., 2021). Dust aerosols are a crucial element in clouds by facilitating ice formation at comparatively warm temperatures (up to 10°C warmer; Villanueva et al., 2021), with consequences for rain formation (e.g., Mülmenstädt et al., 2015). Dust can also inhibit leaf processes, such as photosynthesis, respiration, and transpiration (Farmer, 1993), but also aid nutritional uptake through leaves as an alternative to roots (Gross et al., 2021). Agricultural activities can contribute significantly to generating aeolian dust through the disturbance of soil surfaces and intensive land-use practices (Bartkowski et al., 2023; Chen et al., 2023). Moreover, about 25% of soil surfaces in drylands are covered by biological crusts, corresponding to approximately 12% of land surfaces. These crusts can consist of various amounts of algae, lichens, mosses, fungi, and bacteria, which live in the top part of the soil (Bowker et al., 2018). Such crusts are thus key to soil stability and erosion control, inhibiting the emission of mineral dust in areas that would otherwise be strong dust emission sources and reducing carbon loss through erosion. It has been estimated that this effect reduces the atmospheric dust burden by up to 60% (Rodriguez-Caballero et al., 2022), which is why alterations in factors that change the stability of these crusts may have significant consequences for biodiversity-climate feedback effects.

However, climate change poses significant challenges to soil carbon dynamics and climate regulation (Beillouin et al., 2023). Rising temperatures, altered precipitation patterns, and extreme weather events can accelerate soil carbon losses (Fan et al., 2022; Nottingham et al., 2020; Patoine et al., 2022) through increased microbial activity, decomposition rates, and soil hot extremes (García-García et al., 2023;

Mahecha et al., 2010) and erosion (Guerra et al., 2020). Moreover, changes in land use and management practices, such as deforestation, intensive agriculture, and urbanization, can lead to the depletion of soil carbon stocks, the release of stored carbon into the atmosphere or through erosion and lateral transport (Lauerwald et al., 2023; Van Vliet, 2019; Wang et al., 2023). These mechanisms may further contribute to climate change and exacerbate its impacts on soil health and ecosystem functioning.

Furthermore, changes in soil carbon dynamics can influence climate-carbon feedback loops, with the potential to exacerbate the rate and magnitude of climate change (Heimann & Reichstein, 2008; Paustian et al., 2016). For example, the thawing of permafrost soils in high-latitude regions can release large amounts of greenhouse gasses, including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) into the atmosphere, further accelerating global warming and permafrost degradation (Gasser et al., 2018; Ramage et al., 2024; Schuur et al., 2015; Voigt et al., 2020). Similarly, the loss of soil carbon, nutrients, and fertility in tropical forests due to deforestation and land degradation can reduce the resilience of these ecosystems to climate change and increase the risk of significant ecosystem change (Dlamini et al., 2014; Labrière et al., 2015; Mitchard, 2018; Veldkamp et al., 2020).

Moreover, climate extreme events like drought can alter soil-plant-atmosphere interactions and compromise the soil's role as a sink for volatiles (Insam & Seewald, 2010; Werner et al., 2021), which may have significant positive feedback effects and accelerate climate change (Eisenhauer & Weigelt, 2021; Mahecha et al., 2022, 2024). Targeted soil management has the potential to influence the exchange rates between ecosystems and the atmosphere, and "climate-smart soils" can thus reduce climate feedbacks mediated by greenhouse gasses (Figure 2; Paustian et al., 2016).

3 | CONNECTING THE DOTS: LINKAGES BETWEEN SOIL BIODIVERSITY LOSS AND CLIMATE CHANGE

Climate change and the loss of soil biodiversity are intricately linked through complex feedback loops and interdependencies, requiring a holistic approach that addresses both issues simultaneously (Figure 1). Based on the review of current knowledge above, there are several key reasons why these two challenges should be addressed together:

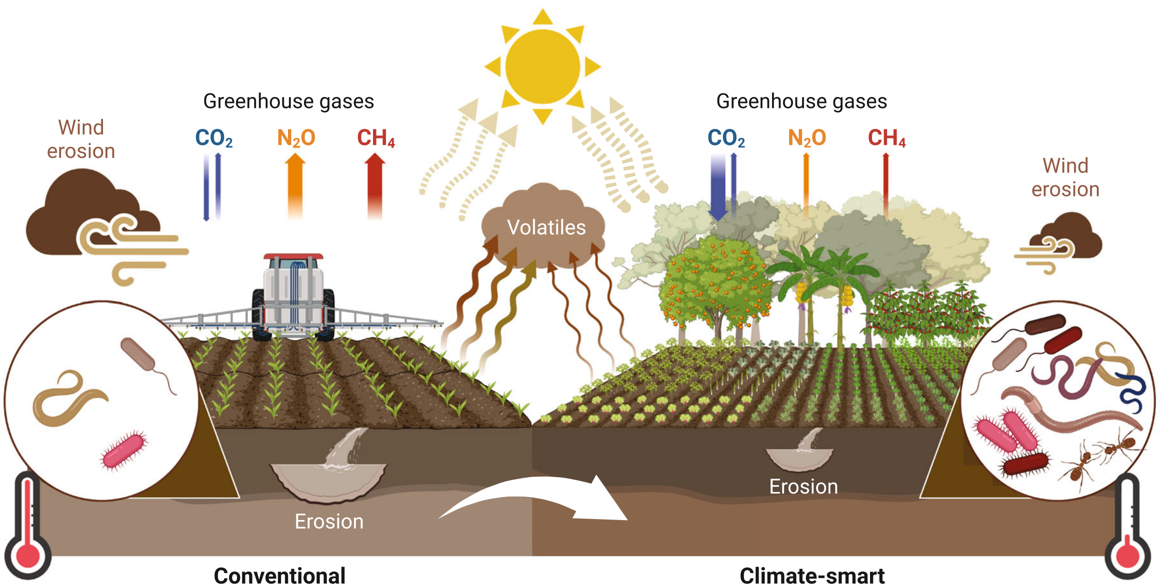

FIGURE 2 Climate-smart soils (redrawn and revised after Paustian et al. 2016). Fundamental research into soil processes, the expansion of measurement and monitoring networks, and the continued development of global geospatial soil data can enhance predictive models and decrease uncertainties. Ongoing advancements in information technology and the integration of complex systems and 'Big Data' present opportunities to involve a wide range of stakeholders, including land managers, in contributing local agricultural management insights through web-based computer and mobile applications. This collaboration can drive the development of advanced model-based greenhouse gas (GHG) metrics. Such efforts will facilitate the adoption of climate-smart soil management policies, including cap-and-trade systems, product supply-chain initiatives for 'low-carbon' consumer goods, and national and international GHG mitigation strategies, while also fostering more sustainable and climate-resilient agricultural systems worldwide. As a consequence, climate-smart soils are likely to experience lower soil erosion rates, will reduce GHG emissions and alter the amount and composition of volatiles taken up by and released from soils, and change albedo (see main text for more details on these mechanisms). According to Paustian et al. (2016) promising science and technology advancements include basic research on plant-soil processes, research measurement networks, soil monitoring networks, advanced greenhouse gas networks, and remote sensing, spatial databases and model integration. Practices for climate-smart soils include reduced tillage, biochar management, land restoration, improved crop rotations, organic amendments, nutrient management, cover crops, and agroforestry. Implementation requires national and international greenhouse gas mitigation programs, greenhouse gas offset and ecosystem service markets, agricultural product supply chain management, decision-support systems, and land-user engagement.

1. **Feedback loops:** Soil biodiversity loss and climate change may be related to and even exacerbate each other through feedback loops that amplify their respective impacts. However, empirical evidence is scarce thus far and more research on potential reciprocal effects is needed. For example, as climate change alters temperature and precipitation patterns, it can directly affect soil biodiversity by threatening soil communities and processes (Phillips et al., 2023; Sünnemann et al., 2023). In turn, changes in soil biodiversity can influence soil moisture, soil temperatures, carbon sequestration rates, soil fertility, and ecosystem resilience (Bardgett & van der Putten, 2014; Delgado-Baquerizo et al., 2020), thereby altering the climate regulation capacity of soils (Eisenhauer & Weigelt, 2021; Paustian et al., 2016). Climate change can disrupt these processes by altering temperature and moisture regimes, leading to increased rates of soil carbon loss and reduced carbon sequestration capacity as well as changes in greenhouse gas and volatile emissions.
2. **Ecosystem resilience:** Soil biodiversity is critical in enhancing ecosystem resilience to climate change by supporting ecosystem functions. Healthy soils with diverse microbial and animal communities are better able to withstand environmental stressors, such as drought, flooding, and extreme temperatures, as well as plant, animal, and human pathogens (Wall et al., 2015), thereby maintaining ecosystem stability and productivity (Scherzinger et al., 2023). Conversely, soil biodiversity loss can weaken ecosystem resilience, making ecosystems more vulnerable to the impacts of climate change and reducing their capacity to provide essential services to society (Bardgett & Caruso, 2020; Yang et al., 2018).
3. **Land degradation:** Soil biodiversity loss and climate change are major drivers of land degradation, which encompasses processes, such as soil erosion, desertification, and salinization (FAO et al., 2020). Land degradation reduces soil fertility, impairs ecosystem functioning, increases dust emissions, and threatens food security, water resources, and biodiversity. By addressing soil biodiversity loss and climate change together, synergistic solutions can be developed to restore degraded lands, improve soil health, and enhance ecosystem resilience. This approach can thereby promote sustainable land-management practices and mitigate the impacts of environmental degradation (Figure 2; Wall et al., 2015).

4 | THE ROLE OF SOCIETY IN MITIGATING SOIL BIODIVERSITY LOSS AND CLIMATE CHANGE

Society's pivotal role in mitigating soil biodiversity loss and climate change hinges on comprehensive engagement across all levels, from grassroots initiatives to global governance structures (van der Putten et al., 2023) as well as from individuals, groups, and businesses, thus state and non-state actors alike (Fritsche et al., 2018; Zacher et al., 2023). These interconnected challenges can be addressed only through concerted efforts encompassing collective action, policy advocacy, inclusive practices, and individual behavioral change (Hoppe et al., 2023; IPBES, 2019). Several key roles emerge for society in this endeavor:

1. **Sustainable land management practices:** Adopting sustainable land management practices is critical for preserving soil biodiversity, enhancing ecosystem resilience to disturbances, and mitigating climate change (Sünnemann et al., 2023). Practices and approaches, such as intercropping, soil inoculation, agroforestry, organic farming, conservation agriculture, reforestation, and ecological restoration, can promote soil health, reduce soil erosion, and enhance carbon sequestration in soil and vegetation (Figure 2; Paustian et al., 2016). By supporting farmers, landowners, and land managers in implementing these practices (Gütschow et al., 2021; Zacher et al., 2023), society can contribute to the restoration of degraded lands, the conservation of biodiversity, and the mitigation of greenhouse gas emissions (Paustian et al., 2016). Support can, for example, come in the form of payments for the public-good ecosystem services that healthy soils provide. At the same time, strengthening a sense of social identity, collective ecological responsibility, soil stewardship norms, and collective efficacy (Fritsche & Masson, 2021) in agricultural communities should support the emergence of joint collective action intentions to protect soils (Rabinovich et al., 2020). While many of these actions have a local focus, sustainable soil management requires a global perspective to not 'relocate' pressures on soil biodiversity to other regions of the globe (van der Putten et al., 2023).
2. **Policy and governance:** Climate and biodiversity policy constitute an intricate web of international, transnational, national, and local dynamics. Across diverse studies, researchers have delved into this intricate web, scrutinizing its layers across various levels while pinpointing avenues for policy intervention and identifying key stakeholders and influences (Amador-Jimenez et al., 2024; Kolleck et al., 2017; Tindall et al., 2023). Essential for addressing soil biodiversity loss and climate change are effective policies and governance mechanisms spanning local, national, and international spheres. Relatedly, effective policies require tractable economic mechanisms in general (e.g., Brock & Xepapadeas, 2003; Metrick & Weitzman, 1998; Weitzman, 1992) and financial markets to value biodiversity losses in particular (Karolyi & Tobin-de La Puente, 2023). Importantly, as people get richer and ecosystems become scarcer due to climate change and environmental degradation, the economic valuation of climate and biodiversity benefits to people should increase over time (Drupp & Hänsel, 2021; Drupp et al., 2024). Governments, regulatory bodies, and international entities have the power to enact legislation, regulations, publication requirements, and incentives that bolster sustainable land use, safeguard natural habitats, and mitigate greenhouse gas emissions (Christensen et al., 2021; McDonald et al., 2023). These governance regimes need to be well-designed and inclusive to be effective (Bartkowski et al., 2021;

Paul et al., 2023), also taking into account connections across different actors (Williams et al., 2023) and their behavioral heterogeneity (Huber et al., 2024; Swart et al., 2023). Perceived fairness and effectiveness of such policy measures and trust in implementing institutions will determine their acceptance by citizens (Bergquist et al., 2022). Businesses and industries can also contribute to addressing soil biodiversity loss and climate change by implementing corporate sustainability policies. By advocating for enhanced environmental safeguards, endorsing sustainable development goals, and backing multilateral agreements, such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD), society can wield significant influence over policy-making processes.

3. **Innovation and technology:** Harnessing innovation and technology can accelerate efforts to mitigate soil biodiversity loss and climate change by developing sustainable solutions, enhancing monitoring and assessment capabilities, and facilitating knowledge sharing and collaboration. Advances across scientific disciplines and technologies, including soil science, remote sensing, digital and vertical as well as hydroponic agriculture (Kabir et al., 2023; Kannan et al., 2022), robotics and artificial intelligence, next-generation harvesters able to deal with mixed crops, and renewable energy monitoring, can provide new tools and approaches for sustainable land management, climate mitigation, and adaptation. Technologies for future carbon cycles are necessary to reach net zero targets but may come along with manifold risks (Borchers et al., 2024). By investing into research and development, supporting entrepreneurship, and fostering inter- and transdisciplinary collaboration, society can drive technological innovation and promote the adoption of sustainable practices and technologies.
4. **Consumer choices and lifestyles:** Individual consumers and groups of consumers also play a role in mitigating soil biodiversity loss and climate change through their everyday choices and lifestyles. Individual diets influence future land-use intensity (Chan et al., 2022), and they have important consequences for the economic feasibility of diversification options in agricultural production (Gütschow et al., 2021). By making sustainable choices in food, energy, transportation, and consumption behaviors, individuals and certain groups of people can reduce their environmental footprint, and support businesses and products that prioritize environmental sustainability. By advocating for sustainable practices, demanding transparency and accountability from companies, and participating in community initiatives, individuals can contribute to collective efforts to address soil biodiversity loss and climate change (Bamberg et al., 2015; Zacher et al., 2023).
5. **Awareness, education, and collective intention building:** Increasing public awareness and understanding of the importance of soil biodiversity and climate change, and their potential effects on human health (Liebal et al., 2024) is essential for fostering a culture of environmental stewardship and sustainability (Bach et al., 2020). By fostering climate education and education for sustainable development, we can enhance people's awareness and understanding of the interconnectedness between soil biodiversity loss, climate change, and sustainable land-management practices. Through education, individuals are equipped with the knowledge and skills needed to actively address these pressing environmental challenges, fostering a culture of environmental stewardship and sustainability for present and future generations (e.g., Kolleck & Yemini, 2020; Kolleck, 2019). However, increasing problem awareness and knowledge is only a first step, given the gaps between individual attitudes and behavior (Bamberg & Möser, 2007) as well as individuals' social interdependencies when aiming at protecting nature (Fritsche et al., 2018). As a second step, it is thus crucial to support individual action and the acceptance of soil protection policies to foster and encourage people's sense of collective environmental agency (e.g., pro-environmental social norms and collective efficacy; Fritsche & Masson, 2021) in their self-relevant social groups, such as local and large-scale communities or professional groups (e.g., farmers; Hoppe et al., 2023; Marder et al., 2023).
6. **Inclusion and participation**: More often than not, there is a missing link between community strategies of biodiversity protection and (inter)national stakeholders, researchers, and decision-makers, specifically when it comes to governance and protection schemes in countries of the Global South with both highest levels of biodiversity and effects of climate change (Ide et al., 2023). Yet, social systems and ecosystems form a mutually dependent yet interwoven and complex relationship at the local level. Still, both research and policy rely solely on improved communication but largely ignore local knowledge, experiences, and cultural practices of local groups, e.g. indigenous communities (Amador-Jimenez et al., 2024). Systematic inclusion and participation of these often marginalized groups are key to overcoming the nature-culture divide that often undermines effective biodiversity protection, especially when it comes to the protection of soil biodiversity (Phillips et al., 2020).

5 | THE TOP 10 RESEARCH FRONTIERS RELATED TO THE SOIL BIODIVERSITY–CLIMATE CHANGE–SOCIETY NEXUS

1. **Soil carbon dynamics:** Investigate the drivers of soil carbon dynamics in response to climate change and soil biodiversity loss, including changes in soil biological activity, decomposition rates, and soil erosion, to improve predictions of future soil carbon storage and greenhouse gas emissions. A promising step forward would be to establish or extend standardized soil monitoring initiates (Guerra et al., 2021; Orgiazzi et al., 2018) to understand the spatial and temporal dynamics of soil carbon dynamics and combine those with experimental work on potential main drivers

Global Initiative of Sustainable Agriculture and Environment
Harnessing Natural Resources

(Delgado-Baquerizo et al., 2020; Sünnemann et al., 2023) and their combined effects on soils (Rillig et al., 2019, 2023).

2. **Ecosystem resilience:** Explore the role of soil biodiversity in enhancing ecosystem resilience to climate change, including its effects on nutrient cycling, water retention, and carbon sequestration, to inform strategies for ecosystem management and adaptation. Again, combining information from observational and experimental sources will be key to understanding ecosystem responses to climate change (Sáez-Sandino et al., 2023) and model the future vulnerability as well as buffering capacities of soils. Moreover, biodiverse soils may enhance ecosystem resilience by providing natural protection against plant. animal, and human pathogens (Wall et al., 2015).
3. **Sustainable land management:** Evaluate the effectiveness of land management practices proposed as more sustainable, such as intercropping, soil inoculation, agroforestry, organic farming, and conservation agriculture, in mitigating soil biodiversity loss, enhancing soil carbon sequestration and soil fertility, regulating greenhouse gas emissions, and promoting ecosystem resilience and multifunctionality (Scherzinger et al., 2023). Here, the development of large-scale trials and continuous monitoring may be crucial to shed light on potential joint environmental and social benefits of sustainable land management. For instance, a recent meta-study across 2,655 farms worldwide showed that applying multiple diversification strategies creates more positive outcomes than individual management strategies alone (Rasmussen et al., 2024).
4. **Feedback mechanisms:** Investigate feedback mechanisms between soil biodiversity loss and climate change, such as the impacts of climate change on soil biodiversity and the subsequent effects on soil moisture, carbon sequestration, soil fertility, and ecosystem multifunctionality. Addressing such feedback mechanisms would require the development of adequate observational and modeling capabilities and include multiple potential mechanisms, such as greenhouse gas (Paustian et al., 2016) and volatile (Eisenhauer & Weigelt, 2021; Werner et al., 2021) emissions as well as erosion processes (Tegen & Schepanski, 2009).
5. **Integrating the role of soil biodiversity in different modeling schemes:** Develop integrated modeling schemes that incorporate system-relevant aspects of soil biodiversity dynamics, climate change impacts and feedback, and societal responses—for example consumer behavior and land user's decision making—to better understand the complex interactions between these factors and their implications for sustainability. Agent-based models are a promising avenue to describe these complex relations.
6. **Technological innovations:** Explore technological innovations, such as remote sensing, digital and vertical agriculture, and precision farming, for monitoring soil biodiversity, assessing soil carbon stocks, and implementing sustainable land-management practices at large scales. Modern information technologies can also help consumers to make more informed choices.
7. **Community engagement:** Investigate the formation and role of community engagement and participatory approaches in promoting soil conservation, biodiversity protection, and climate resilience, including the effectiveness of education campaigns, outreach programs, community-supported agriculture, and citizen science initiatives. Ultimately, such work could target land managers, practitioners, and consumers.
8. **Consumer behavior:** Examine the influence of consumer behavior and lifestyle choices on soil biodiversity loss and climate change, including adopting sustainable consumption patterns, support for environmentally friendly products, and demand for ethically sourced food and goods. Technological innovations (point 6) may play a role here. Also, investigate the personal and collective conditions under which people change their individual behavior and accept pro-ecological policies.
9. **Policy and governance:** Evaluate the acceptance and impact of policy and governance mechanisms on mitigating soil biodiversity loss and climate change. This encompasses governance and the creation of collective agency at various levels: locally, where initiatives such as community-supported agriculture provide incentives for sustainable land management; regionally and nationally, where social movements and networks play a crucial role, alongside the development of regulations and economic incentives; and internationally, through agreements aimed at promoting sustainable land use and biodiversity conservation.
10. **Interdisciplinary and transdisciplinary research:** Foster interdisciplinary research collaborations among scientists as well as between scientists, policymakers, practitioners, local communities, and stakeholders to address the complex challenges of soil biodiversity loss, climate change, and societal responses, integrating insights from ecology, agriculture, climate research, economics, sociology, meteorology, psychology, conflict studies, and other disciplines (Amador-Jimenez et al., 2024; Bartkowski et al., 2023; Kelly et al., 2019). Promising approaches may be the development of real-world labs in the context of transformation research (Horcea-Milcu, 2022).

6 | CONCLUDING REMARKS

In conclusion, soil is deeply involved in the interplay between biodiversity, climate change, and human society. As a major reservoir of biodiversity, soil supports essential ecosystem functions and services that sustain life on Earth. Moreover, soil is a critical carbon sink and regulator of the global carbon cycle and greenhouse gas emissions, influencing climate regulation and feedback mechanisms. However, ongoing changes in biodiversity and climate pose significant threats to soil health and ecosystem functioning, with profound implications for human well-being and sustainability. Addressing these challenges requires concerted efforts to conserve soil biodiversity, promote sustainable land management practices, and mitigate climate change, thereby safeguarding the vital role of soil in supporting biodiversity, climate regulation, and human society. By adopting integrated approaches that prioritize soil conservation, sustainable land management, and climate change mitigation and adaptation strategies, we can enhance ecosystem resilience, safeguard essential ecosystem services, and build a more resilient and sustainable future for generations to come. Society is vital in mitigating soil biodiversity loss and climate change through awareness raising, sustainable land management, policy advocacy, innovation, and individual action. By prioritizing interdisciplinary research in these areas based on the top 10 research frontiers outlined in this paper, scientists can advance our understanding of the soil biodiversity–climate change–society nexus and inform evidence-based strategies for promoting environmental sustainability, resilience, and social equity.

AUTHOR CONTRIBUTIONS

Conceptualization: Nico Eisenhauer, Karin Frank, Alexandra Weigelt, Bartosz Bartkowski, Rémy Beugnon, Katja Liebal, Miguel Mahecha, Martin Quaas, and Johannes Quaas. *Funding acquisition*: Nico Eisenhauer and Johannes Quaas. Investigation: All co-authors. *Project administration*: Johannes Quaas. *Software*: Nico Eisenhauer. *Supervision*: Nico Eisenhauer, Johannes Quaas, Alexandra Weigelt, and Karin Frank. *Visualization*: Nico Eisenhauer. *Writing—original draft preparation*: Nico Eisenhauer. *Writing—review & editing*: All co-authors.

AFFILIATIONS

[1]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany

[2]Leipzig University, Institute of Biology, Leipzig, Germany

[3]Department of Bioenergy, Helmholtz Centre for Environmental Research GmbH (UFZ), Leipzig, Germany

[4]Institute of Environmental Systems Research, University of Osnabrück, Osnabrück, Germany

[5]Department of Economics, Martin Luther University Halle-Wittenberg, Halle, Germany

[6]Leipzig Institute of Meteorology, Leipzig University, Leipzig, Germany

[7]CEFE, Univ Montpellier, CNRS, EPHE, IRD, Montpellier, France

[8]Institute for Earth System Science and Remote Sensing, Leipzig University, Leipzig, Germany

[9]Department of Economics, Leipzig University, Leipzig, Germany

[10]Max Planck Institute for Biogeochemistry, Jena, Germany

[11]Department of Mathematics and Computer Science, Computer Vision Group, Friedrich Schiller University Jena, Jena, Germany

[12]Julius Kühn-Institute (JKI) - Federal Research Center for Cultivated Plants, Institute for Forest Protection, Quedlinburg, Germany

[13]Wilhelm Wundt Institute for Psychology, Leipzig University, Leipzig, Germany

[14]Faculty of Economics and Management Science, Leipzig University, Leipzig, Germany

[15]Potsdam Institute for Climate Impact Research (PIK), Leibniz Association, Potsdam, Germany

[16]Department for Comparative Cultural Psychology, Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany

[17]Leibniz-Institute for Tropospheric Research (TROPOS), Leipzig, Germany

[18]Halle Institute for Economic Research (IWH), Halle, Germany

[19]Otto-von-Guericke University Magdeburg, Magdeburg, Germany

[20]Chair of Education and Socialization Theory, Potsdam University, Potsdam, Germany

[21]Chair of Modelling of Human-Environment-Systems, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus, Germany

[22]Remote Sensing Centre for Earth System Research, Leipzig University, Leipzig, Germany

[23]Faculty of Economics and Management Sciences, Leipzig University, Leipzig, Germany

[24]Institute of Political Science, Leipzig University, Leipzig, Germany

[25]Institute for Infrastructure and Resource Management, Leipzig University, Leipzig, Germany

[26]Smithsonian Tropical Research Institute, Ancón, Panama

[27]DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig, Germany

[28]ScaDS.AI Dresden/Leipzig- Center for Scalable Data Analytics and Artificial Intelligence, Leipzig University, Leipzig, Germany

ACKNOWLEDGEMENTS

We acknowledge funding by the Saxon State Ministry for Science, Culture and Tourism (SMWK) – [3-7304/35/6-2021/48880] in the context of the Breathing Nature initiative at Leipzig University. Moreover, we acknowledge additional support from the German Centre for Integrative Biodiversity Research Halle–Jena–Leipzig, funded by the German Research Foundation (DFG; FZT 118 – FZT 118, 202548816), as well as by the DFG (Ei 862/29-1). Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

This is a review paper and does not contain any primary data.

ETHICS STATEMENT

We comply with all aspects of the Wiley's Best Practice Guidelines on Research Integrity and Publishing Ethics and the Committee on Publication Ethics' guidance.

ORCID

Nico Eisenhauer http://orcid.org/0000-0002-0371-6720
Rémy Beugnon http://orcid.org/0000-0003-2457-5688
Djamil Al-Halbouni https://orcid.org/0000-0003-2254-3914
Karin Mora https://orcid.org/0000-0002-3323-4490
Hannes Zacher http://orcid.org/0000-0001-6336-2947

REFERENCES

Amador-Jimenez M, Ramos Baron PA, Richter S. Complementary ways of seeing “the nature”: integrating varieties of knowledge practices in the management of local environmental conflicts in Colombia. Environ Secur. 2024;2(1):47–74. https://doi.org/10.1177/27538796241232031

Anthony MA, Tedersoo L, De Vos B, Croisé L, Meesenburg H, Wagner M, et al. Fungal community composition predicts forest carbon storage

at a continental scale. Nat Commun. 2024;15(1):2385. https://doi.org/10.1038/s41467-024-46792-w
Augé RM, Toler HD, Saxton AM. Arbuscular mycorrhizal symbiosis alters stomatal conductance of host plants more under drought than under amply watered conditions: a meta-analysis. Mycorrhiza. 2015;25(1):13–24. https://doi.org/10.1007/s00572-014-0585-4
Bach EM, Ramirez KS, Fraser TD, Wall DH. Soil biodiversity integrates solutions for a sustainable future. Sustainability. 2020;12(7):2662. https://doi.org/10.3390/su12072662
Bamberg S, Möser G. Twenty years after hines, hungerford, and tomera: a new meta-analysis of psycho-social determinants of pro-environmental behaviour. J Environ Psychol. 2007;27(1):14–25. https://doi.org/10.1016/j.jenvp.2006.12.002
Bamberg S, Rees J, Seebauer S. Collective climate action: determinants of participation intention in community-based pro-environmental initiatives. J Environ Psychol. 2015;43:155–65. https://doi.org/10.1016/j.jenvp.2015.06.006
Bardgett RD, Caruso T. Soil microbial community responses to climate extremes: resistance, resilience and transitions to alternative states. Philos Trans R Soc, B. 2020;375(1794):20190112. https://doi.org/10.1098/rstb.2019.0112
Bardgett RD, van der Putten WH. Belowground biodiversity and ecosystem functioning. Nature. 2014;515(7528):505–11. https://doi.org/10.1038/nature13855
Bartkowski B, Bartke S, Hagemann N, Hansjürgens B, Schröter-Schlaack C. Application of the governance disruptions framework to German agricultural soil policy. Soil. 2021;7(2):495–509. https://doi.org/10.5194/soil-7-495-2021
Bartkowski B, Schepanski K, Bredenbeck S, Müller B. Wind erosion in European agricultural landscapes: more than physics. People Nat. 2023;5(1):34–44. https://doi.org/10.1002/pan3.10418
Beillouin D, Corbeels M, Demenois J, Berre D, Boyer A, Fallot A, Feder F, Cardinael R. A global meta-analysis of soil organic carbon in the anthropocene. Nat Commun. 2023;14(1):3700. https://doi.org/10.1038/s41467-023-39338-z
Bergquist M, Nilsson A, Harring N, Jagers SC. Meta-analyses of fifteen determinants of public opinion about climate change taxes and laws. Nat Clim Change. 2022;12(3):235–40. https://doi.org/10.1038/s41558-022-01297-6
Bonfante P, Genre A. Mechanisms underlying beneficial plant–fungus interactions in mycorrhizal symbiosis. Nat Commun. 2010;1(1):48. https://doi.org/10.1038/ncomms1046
Borchers M, Förster J, Thrän D, Beck S, Thoni T, Korte T, et al. A comprehensive assessment of carbon dioxide removal options for Germany. Earth Future. 2024;12(5):e2023EF003986. https://doi.org/10.1029/2023ef003986
Bossio DA, Cook-Patton SC, Ellis PW, Fargione J, Sanderman J, Smith P, et al. The role of soil carbon in natural climate solutions. Nat Sustain. 2020;3(5):391–8. https://doi.org/10.1038/s41893-020-0491-z
Bowker MA, Reed SC, Maestre FT, Eldridge DJ. Biocrusts: the living skin of the earth. Plant Soil. 2018;429(1–2):1–7. https://doi.org/10.1007/s11104-018-3735-1
Brock WA, Xepapadeas A. Valuing biodiversity from an economic perspective: a unified economic, ecological, and genetic approach. Am Econ Rev. 2003;93(5):1597–614. https://doi.org/10.1257/000282803322655464
Cameron DD, Neal AL, Van Wees SCM, Ton J. Mycorrhiza-induced resistance: more than the sum of its parts. Trends Plant Sci. 2013;18(10):539–45. https://doi.org/10.1016/j.tplants.2013.06.004
Castells-Quintana D, Krause M, McDermott TKJ. The urbanising force of global warming: the role of climate change in the spatial distribution of population. J Econ Geogr. 2021;21(4):531–56. https://doi.org/10.1093/jeg/lbaa030
Chan K, Millinger M, Schneider UA, Thrän D. How diet portfolio shifts combined with land-based climate change mitigation strategies could reduce climate burdens in Germany. J Clean Prod. 2022;376:134200. https://doi.org/10.1016/j.jclepro.2022.134200
Chen S, Chen J, Zhang Y, Lin J, Bi H, Song H, Chen Y, Lian L, Liu C, Zhang R. Anthropogenic dust: sources, characteristics and emissions. Environ Res Lett. 2023;18(10):103002. https://doi.org/10.1088/1748-9326/acf479
Christensen HB, Hail L, Leuz C. Mandatory CSR and sustainability reporting: economic analysis and literature review. Rev Account Stud. 2021;26(3):1176–248. https://doi.org/10.1007/s11142-021-09609-5
Crowther TW, van den Hoogen J, Wan J, Mayes MA, Keiser AD, Mo L, et al. The global soil community and its influence on biogeochemistry. Science. 2019;365(6455):eaav0550. https://doi.org/10.1126/science.aav0550
Delgado-Baquerizo M, Reich PB, Trivedi C, Eldridge DJ, Abades S, Alfaro FD, et al. Multiple elements of soil biodiversity drive ecosystem functions across biomes. Nat Ecol Evol. 2020;4(2):210–20. https://doi.org/10.1038/s41559-019-1084-y
Dlamini P, Chivenge P, Manson A, Chaplot V. Land degradation impact on soil organic carbon and nitrogen stocks of sub-tropical humid grasslands in South Africa. Geoderma. 2014;235–236:372–81. https://doi.org/10.1016/j.geoderma.2014.07.016
Drupp MA, Hänsel MC. Relative prices and climate policy: how the scarcity of nonmarket goods drives policy evaluation. Am J Econ Pol. 2021;13(1):168–201. https://doi.org/10.1257/pol.20180760
Drupp MA, Hänsel MC, Fenichel EP, Freeman M, Gollier C, Groom B, et al. Accounting for the increasing benefits from scarce ecosystems. Science. 2024;383(6687):1062–4. https://doi.org/10.1126/science.adk2086
Eisenhauer N, Weigelt A. Ecosystem effects of environmental extremes. Science. 2021;374(6574):1442–3. https://doi.org/10.1126/science.abn1406
Fan N, Reichstein M, Koirala S, Ahrens B, Mahecha MD, Carvalhais N. Global apparent temperature sensitivity of terrestrial carbon turnover modulated by hydrometeorological factors. Nat Geosci. 2022;15(12):989–94. https://doi.org/10.1038/s41561-022-01074-2
FAO, ITPS, GSBI, SCBD, & EC. State of knowledge of soil biodiversity—Status, challenges and potentialities. Report 2020. Rome, FAO; 2020. p. 616. https://doi.org/10.4060/cb1928en
Farmer AM. The effects of dust on vegetation—a review. Environ Pollut. 1993;79(1):63–75. https://doi.org/10.1016/0269-7491(93)90179-R
Fonte SJ, Hsieh M, Mueller ND. Earthworms contribute significantly to global food production. Nat Commun. 2023;14(1):5713. https://doi.org/10.1038/s41467-023-41286-7
Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Bakker DCE, Hauck J. et al. Global carbon budget 2023. Earth Syst Sci Data. 2023;15(12):5301–69. https://doi.org/10.5194/essd-15-5301-2023
Fritsche I, Barth M, Jugert P, Masson T, Reese G. A social identity model of Pro-Environmental action (SIMPEA). Psychol Rev. 2018;125(2):245–69. https://doi.org/10.1037/rev0000090
Fritsche I, Masson T. Collective climate action: when do people turn into collective environmental agents? Current Opinion in Psychology. 2021;42:114–9. https://doi.org/10.1016/j.copsyc.2021.05.001
García-García A, Cuesta-Valero FJ, Miralles DG, Mahecha MD, Quaas J, Reichstein M, Zscheischler J, Peng J. Soil heat extremes can outpace air temperature extremes. Nat Clim Change. 2023;13(11):Article 1237–41. https://doi.org/10.1038/s41558-023-01812-3
Gasser T, Kechiar M, Ciais P, Burke EJ, Kleinen T, Zhu D, Huang Y, Ekici A, Obersteiner M. Path-dependent reductions in CO_2 emission budgets

caused by permafrost carbon release. Nat Geosci. 2018;11(11):830–5. https://doi.org/10.1038/s41561-018-0227-0

Goebel M-O, Bachmann J, Reichstein M, Janssens IA, Guggenberger G. Soil water repellency and its implications for organic matter decomposition—is there a link to extreme climatic events?: EXTREME EVENTS AND SOIL WATER REPELLENCY. Global Change Biol. 2011;17(8):2640–56. https://doi.org/10.1111/j.1365-2486.2011.02414.x

Gross A, Tiwari S, Shtein I, Erel R. Direct foliar uptake of phosphorus from desert dust. New Phytol. 2021;230(6):2213–25. https://doi.org/10.1111/nph.17344

Guerra CA, Bardgett RD, Caon L, Crowther TW, Delgado-Baquerizo M, Montanarella L, et al. Tracking, targeting, and conserving soil biodiversity. Science. 2021;371(6526):239–41. https://doi.org/10.1126/science.abd7926

Guerra CA, Rosa IMD, Valentini E, Wolf F, Filipponi F, Karger DN, et al. Global vulnerability of soil ecosystems to erosion. Landsc Ecol. 2020;35(4):823–42. https://doi.org/10.1007/s10980-020-00984-z

Gütschow M, Bartkowski B, Felipe-Lucia MR. Farmers' action space to adopt sustainable practices: a study of arable farming in saxony. Reg Environ Change. 2021;21(4):103. https://doi.org/10.1007/s10113-021-01848-1

Van Der Heijden MGA, Bardgett RD, Van Straalen NM. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett. 2008;11(3):296–310. https://doi.org/10.1111/j.1461-0248.2007.01139.x

Heimann M, Reichstein M. Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature. 2008;451(7176):289–92. https://doi.org/10.1038/nature06591

Hoppe A, Fritsche I, Chokrai P. The "I" and the "we" in nature conservation—investigating personal and collective motives to protect one's regional and global nature. Sustainability. 2023;15(5):4694. https://doi.org/10.3390/su15054694

Horcea-Milcu A-I. Values as leverage points for sustainability transformation: two pathways for transformation research. Curr Opin Environ Sustain. 2022;57:101205. https://doi.org/10.1016/j.cosust.2022.101205

Huber R, Bartkowski B, Brown C, El Benni N, Feil J-H, Grohmann P, et al. Farm typologies for understanding farm systems and improving agricultural policy. Agricult Sys. 2024;213:103800. https://doi.org/10.1016/j.agsy.2023.103800

Ide T, Johnson MF, Barnett J, Krampe F, Le Billon P, Maertens L, Von Uexkull N, Vélez-Torres I. The future of environmental peace and conflict research. Env Polit. 2023;32(6):1077–103. https://doi.org/10.1080/09644016.2022.2156174

Insam H, Seewald MSA. Volatile organic compounds (VOCs) in soils. Biol Fertil Soils. 2010;46(3):199–213. https://doi.org/10.1007/s00374-010-0442-3

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. (Version 1). Zenodo. 2019. p. 1148. https://doi.org/10.5281/ZENODO.3831673

Kabir MSN, Reza MN, Chowdhury M, Ali M, Samsuzzaman K, Ali MR, et al. Technological trends and engineering issues on vertical farms: a review. Horticulturae. 2023;9(11):1229. https://doi.org/10.3390/horticulturae9111229

Kannan M, Elavarasan G, Balamurugan A, Dhanusiya B, Freedon D. Hydroponic farming—a state of art for the future agriculture. Mater Today: Proc. 2022;68:2163–6. https://doi.org/10.1016/j.matpr.2022.08.416

Karolyi GA, Tobin-de La Puente J. Biodiversity finance: a call for research into financing nature. Financ Manag. 2023;52(2):231–51. https://doi.org/10.1111/fima.12417

Kelly R, Mackay M, Nash KL, Cvitanovic C, Allison EH, Armitage D, et al. Ten tips for developing interdisciplinary socio-ecological researchers. Socio-Ecological Pract Res. 2019;1(2):149–61. https://doi.org/10.1007/s42532-019-00018-2

Kok JF, Adebiyi AA, Albani S, Balkanski Y, Checa-Garcia R, Chin M, et al. Contribution of the world's main dust source regions to the global cycle of desert dust. Atmos Chem Phys. 2021;21(10):8169–93. https://doi.org/10.5194/acp-21-8169-2021

Kolleck N. The emergence of a global innovation in education: diffusing education for sustainable development through social networks. Environ Educ Res. 2019;25(11):1635–53. https://doi.org/10.1080/13504622.2019.1675593

Kolleck N, Well M, Sperzel S, Jörgens H. The power of social networks: how the UNFCCC secretariat creates momentum for climate education. Global Environ Polit. 2017;17(4):106–26. https://doi.org/10.1162/GLEP_a_00428

Kolleck N, Yemini M. Environment-related education topics within global citizenship education scholarship focused on teachers: a natural language processing analysis. J Environ Educ. 2020;51(4):317–31. https://doi.org/10.1080/00958964.2020.1724853

Korn H, Stadler J, Bonn A. Global developments: policy support for linking biodiversity, health and climate changeIn: Marselle MR, Stadler J, Korn H, Irvine KN, Bonn A, editors. Biodiversity and health in the face of climate change. Springer International Publishing; 2019. p. 315–28. https://doi.org/10.1007/978-3-030-02318-8_14

Labrière N, Locatelli B, Laumonier Y, Freycon V, Bernoux M. Soil erosion in the humid tropics: a systematic quantitative review. Agric Ecosyst Environ. 2015;203:127–39. https://doi.org/10.1016/j.agee.2015.01.027

Lapidot O, Ignat T, Rud R, Rog I, Alchanatis V, Klein T. Use of thermal imaging to detect evaporative cooling in coniferous and broadleaved tree species of the Mediterranean maquis. Agricult Forest Meterol. 2019;271:285–94. https://doi.org/10.1016/j.agrformet.2019.02.014

Lauerwald R, Allen GH, Deemer BR, Liu S, Maavara T, Raymond P, et al. Inland water greenhouse gas budgets for RECCAP2: 1. State-Of-The-Art of global scale assessments. Global Biogeochem Cycles. 2023;37(5):e2022GB007657. https://doi.org/10.1029/2022GB007657

Liebal K, Denzer V, Eisenhauer N, Fritsche I, Kunzmann U, Oña L, et al. Biodiversity, mental health and well-being: psychological mechanisms and moderators of a complex relationship (BIOWELL). Res Ideas Outcomes. 2024;10:e116333. https://doi.org/10.3897/rio.10.e116333

Lohila A, Minkkinen K, Laine J, Savolainen I, Tuovinen JP, Korhonen L, et al. Forestation of boreal peatlands: impacts of changing albedo and greenhouse gas fluxes on radiative forcing. J Geophys Res Biogeosci. 2010;115(G4):2010JG001327. https://doi.org/10.1029/2010JG001327

Mahecha MD, Bastos A, Bohn FJ, Eisenhauer N, Feilhauer H, Hartmann H, et al. Biodiversity loss and climate extremes—study the feedbacks. Nature. 2022;612(7938):30–2. https://doi.org/10.1038/d41586-022-04152-y

Mahecha MD, Bastos A, Bohn FJ, Eisenhauer N, Feilhauer H, Hickler T, et al. Biodiversity and Climate Extremes: Known Interactions and Research Gaps. Earth's Future. 2024;12:e2023EF003963. https://doi.org/10.1029/2023EF003963

Mahecha MD, Reichstein M, Carvalhais N, Lasslop G, Lange H, Seneviratne SI, et al. Global convergence in the temperature sensitivity of respiration at ecosystem level. Science. 2010;329(5993):838–40. https://doi.org/10.1126/science.1189587

Marder F, Masson T, Sagebiel J, Martini C, Quaas M, Fritsche I. Discounting the future: the effect of collective motivation on investment decisions and acceptance of policies for renewable energy. PLOS Climate. 2023;2(6):e0000173. https://doi.org/10.1371/journal.pclm.0000173

Mason ARG, Salomon MJ, Lowe AJ, Cavagnaro TR. Microbial solutions to soil carbon sequestration. J Clean Prod. 2023;417:137993. https://doi.org/10.1016/j.jclepro.2023.137993

McDonald RI, Aronson MFJ, Beatley T, Beller E, Bazo M, Grossinger R, et al. Denser and greener cities: green interventions to achieve both urban density and nature. People Nat. 2023;5(1):84–102. https://doi.org/10.1002/pan3.10423

Metrick A, Weitzman ML. Conflicts and choices in biodiversity preservation. Journal Econ Perspect. 1998;12(3):21–34. https://doi.org/10.1257/jep.12.3.21

Mitchard ETA. The tropical forest carbon cycle and climate change. Nature. 2018;559(7715):527–34. https://doi.org/10.1038/s41586-018-0300-2

Montgomery DR, Rabinowitz P, Sipos Y, Wheat EE. Soil health: a common focus for one health and planetary health interventions. One Health. 2024;18:100673. https://doi.org/10.1016/j.onehlt.2023.100673

Moss JL, Doick KJ, Smith S, Shahrestani M. Influence of evaporative cooling by urban forests on cooling demand in cities. Urban For Urban Green. 2019;37:65–73. https://doi.org/10.1016/j.ufug.2018.07.023

Mülmenstädt J, Sourdeval O, Delanoë J, Quaas J. Frequency of occurrence of rain from liquid-, mixed-, and ice-phase clouds derived from A-Train satellite retrievals. Geophys Res Lett. 2015;42(15):6502–9. https://doi.org/10.1002/2015GL064604

Nottingham AT, Meir P, Velasquez E, Turner BL. Soil carbon loss by experimental warming in a tropical forest. Nature. 2020;584(7820):234–7. https://doi.org/10.1038/s41586-020-2566-4

Orgiazzi A, Ballabio C, Panagos P, Jones A, Fernández-Ugalde O. LUCAS soil, the largest expandable soil dataset for Europe: a review. Eur J Soil Sci. 2018;69(1):140–53. https://doi.org/10.1111/ejss.12499

Paschalis A, Chakraborty T, Fatichi S, Meili N, Manoli G. Urban forests as main regulator of the evaporative cooling effect in cities. AGU Advances. 2021;2(2):e2020AV000303. https://doi.org/10.1029/2020AV000303

Patoine G, Eisenhauer N, Cesarz S, Phillips HRP, Xu X, Zhang L, Guerra CA. Drivers and trends of global soil microbial carbon over two decades. Nat Commun. 2022;13(1):4195. https://doi.org/10.1038/s41467-022-31833-z

Paul C, Bartkowski B, Dönmez C, Don A, Mayer S, Steffens M, Weigl S, Wiesmeier M, Wolf A, Helming K. Carbon farming: are soil carbon certificates a suitable tool for climate change mitigation. J Environ Manage. 2023;330:117142. https://doi.org/10.1016/j.jenvman.2022.117142

Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. Nature. 2016;532(7597):49–57. https://doi.org/10.1038/nature17174

Pereira HM, Martins IS, Rosa IMD, Kim H, Leadley P, Popp A, et al. Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. Science. 2024;384(6694):458–65. https://doi.org/10.1126/science.adn3441

Phillips H, Beaumelle L, Eisenhauer N, Hines J, Smith LC. Lessons from the WBF2020: extrinsic and intrinsic value of soil organisms. Soil Org. 2020;92(2):121–7. https://doi.org/10.25674/so92iss2pp121

Phillips HRP, Cameron EK, Eisenhauer N, Burton V, Ferlian O, Jin Y, et al. Global change and their environmental stressors have a significant impact on soil biodiversity—a meta-analysis. 2023. https://doi.org/10.22541/au.167655684.49855023/v1

Porporato A, Daly E, Rodriguez-Iturbe I. Soil water balance and ecosystem response to climate change. Am Nat. 2004;164(5):625–32. https://doi.org/10.1086/424970

Pörtner H-O, Scholes RJ, Agard J, Archer E, Arneth A, Bai X, et al. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. (Version 5). *Zenodo*. 2021. p. 256. https://doi.org/10.5281/ZENODO.4659158

Powell JR, Parrent JL, Hart MM, Klironomos JN, Rillig MC, Maherali H. Phylogenetic trait conservatism and the evolution of functional trade-offs in arbuscular mycorrhizal fungi. Proc R Soc B. 2009;276(1676):4237–45. https://doi.org/10.1098/rspb.2009.1015

van der Putten WH, Bardgett RD, Farfan M, Montanarella L, Six J, Wall DH. Soil biodiversity needs policy without borders. Science. 2023;379(6627):32–4. https://doi.org/10.1126/science.abn7248

Rabinovich A, Heath SC, Zhischenko V, Mkilema F, Patrick A, Nasseri M, et al. Protecting the commons: predictors of willingness to mitigate communal land degradation among Maasai pastoralists. J Environ Psychol. 2020;72:101504. https://doi.org/10.1016/j.jenvp.2020.101504

Ramage J, Kuhn M, Virkkala AM, Voigt C, Marushchak ME, Bastos A, et al. The net GHG balance and budget of the permafrost region (2000–2020) from ecosystem flux upscaling. Global Biogeochem Cycles. 2024;38(4):e2023GB007953. https://doi.org/10.1029/2023GB007953

Rasmussen LV, Grass I, Mehrabi Z, Smith OM, Bezner-Kerr R, Blesh J, et al. Joint environmental and social benefits from diversified agriculture. Science. 2024;384(6691):87–93. https://doi.org/10.1126/science.adj1914

Rillig MC, van der Heijden MGA, Berdugo M, Liu Y-R, Riedo J, Sanz-Lazaro C, et al. Increasing the number of stressors reduces soil ecosystem services worldwide. Nat Clim Change. 2023;13(5):478–83. https://doi.org/10.1038/s41558-023-01627-2

Rillig MC, Ryo M, Lehmann A, Aguilar-Trigueros CA, Buchert S, Wulf A, et al. The role of multiple global change factors in driving soil functions and microbial biodiversity. Science. 2019;366(6467):886–90. https://doi.org/10.1126/science.aay2832

Rodriguez-Caballero E, Stanelle T, Egerer S, Cheng Y, Su H, Canton Y, et al. Global cycling and climate effects of aeolian dust controlled by biological soil crusts. Nat Geosci. 2022;15(6):458–63. https://doi.org/10.1038/s41561-022-00942-1

Sáez-Sandino T, García-Palacios P, Maestre FT, Plaza C, Guirado E, Singh BK, et al. The soil microbiome governs the response of microbial respiration to warming across the globe. Nat Clim Change. 2023;13(12):1382–7. https://doi.org/10.1038/s41558-023-01868-1

Scherzinger F, Schädler M, Reitz T, Yin R, Auge H, Merbach I, et al2023. Sustainable land management enhances ecological and economic multifunctionality under ambient and future climate (2023.01.30.525902). bioRxiv. https://doi.org/10.1101/2023.01.30.525902

Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, et al. Persistence of soil organic matter as an ecosystem property. Nature. 2011;478(7367):49–56. https://doi.org/10.1038/nature10386

Schuur EAG, McGuire AD, Schädel C, Grosse G, Harden JW, Hayes DJ, et al. Climate change and the permafrost carbon feedback. Nature. 2015;520(7546):171–9. https://doi.org/10.1038/nature14338

Smith SE, Read DJ. Mycorrhizal Symbiosis. Academic Press; 2010 p. 787. https://doi.org/10.1016/B978-0-12-370526-6.X5001-6

Sünnemann M, Beugnon R, Breitkreuz C, Buscot F, Cesarz S, Jones A, et al. Climate change and cropland management compromise soil integrity and multifunctionality. Commun Earth Environ. 2023;4(1):1. https://doi.org/10.1038/s43247-023-01047-2

Swart R, Levers C, Davis JTM, Verburg PH. Meta-analyses reveal the importance of socio-psychological factors for farmers' adoption of sustainable agricultural practices. One Earth. 2023;6(12):1771–83. https://doi.org/10.1016/j.oneear.2023.10.028

Tedersoo L, Bahram M, Zobel M. How mycorrhizal associations drive plant population and community biology. Science. 2020;367(6480):eaba1223. https://doi.org/10.1126/science.aba1223

Tegen I, Schepanski K. The global distribution of mineral dust. IOP Conf Ser Earth Environ Sci. 2009;7:012001. https://doi.org/10.1088/1755-1307/7/1/012001

Tian H, Xu R, Canadell JG, Thompson RL, Winiwarter W, Suntharalingam P, et al. A comprehensive quantification of global nitrous oxide sources and sinks. Nature. 2020;586(7828):248–56. https://doi.org/10.1038/s41586-020-2780-0

Tindall D, Kolleck N, McLevey J. Social networks and anthropogenic climate change. Soc Networks. 2023;75:1–3. https://doi.org/10.1016/j.socnet.2023.03.002

Veldkamp E, Schmidt M, Powers JS, Corre MD. Deforestation and reforestation impacts on soils in the tropics. Nat Rev Earth Environ. 2020;1(11):590–605. https://doi.org/10.1038/s43017-020-0091-5

Villanueva D, Neubauer D, Gasparini B, Ickes L, Tegen I. Constraining the impact of dust-driven droplet freezing on climate using cloud-top-phase observations. Geophys Res Lett. 2021;48(11):e2021GL092687. https://doi.org/10.1029/2021GL092687

Van Vliet J. Direct and indirect loss of natural area from urban expansion. Nat Sustain. 2019;2(8):755–63. https://doi.org/10.1038/s41893-019-0340-0

Voigt C, Marushchak ME, Abbott BW, Biasi C, Elberling B, Siciliano SD, et al. Nitrous oxide emissions from permafrost-affected soils. Nat Rev Earth Environ. 2020;1(8):420–34. https://doi.org/10.1038/s43017-020-0063-9

Wall DH, Nielsen UN, Six J. Soil biodiversity and human health. Nature. 2015;528(7580):69–76. https://doi.org/10.1038/nature15744

Wang Z, Zhang Y, Govers G, Tang G, Quine TA, Qiu J, et al. Temperature effect on erosion-induced disturbances to soil organic carbon cycling. Nat Clim Change. 2023;13:174–81. https://doi.org/10.1038/s41558-022-01562-8

Wardle DA, Bardgett RD, Klironomos JN, Setälä H, van der Putten WH, Wall DH. Ecological linkages between aboveground and belowground biota. Science. 2004;304(5677):1629–33. https://doi.org/10.1126/science.1094875

Weitzman ML. On diversity. Q J Econ. 1992;107(2):363–405. https://doi.org/10.2307/2118476

Werner C, Meredith LK, Ladd SN, Ingrisch J, Kübert A, Van Haren J, et al. Ecosystem fluxes during drought and recovery in an experimental forest. Science. 2021;374(6574):1514–8. https://doi.org/10.1126/science.abj6789

Yang G, Wagg C, Veresoglou SD, Hempel S, Rillig MC. How soil biota drive ecosystem stability. Trends Plant Sci. 2018;23(12):1057–67. https://doi.org/10.1016/j.tplants.2018.09.007

Zacher H, Rudolph CW, Katz IM. Employee Green behavior as the core of environmentally sustainable organizations. Annu Rev Organ Psychol Organ Behav. 2023;10(1):465–94. https://doi.org/10.1146/annurev-orgpsych-120920-050421

Zhang J, Zhou L, Ma R, Jia Y, Yang F, Zhou H, Cao X. Influence of soil moisture content and soil and water conservation measures on time to runoff initiation under different rainfall intensities. CATENA. 2019;182:104172. https://doi.org/10.1016/j.catena.2019.104172

How to cite this article: Eisenhauer N, Frank K, Weigelt A, Bartkowski B, Beugnon R, Liebal K, et al. A belowground perspective on the nexus between biodiversity change, climate change, and human well-being. J Sustain Agric Environ. 2024;3:e212108. https://doi.org/10.1002/sae2.12108