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Foundations for a national assessment of soil biodiversity

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Abstract

Soils, just like all other ecosystem compartments, change over time and, consequently, conditions for soil-inhabiting organisms are also changing, affecting their composition and diversity. Soil biodiversity is a critical component of ecosystems that supports many essential ecosystem functions and services, such as nutrient cycling, carbon sequestration, water regulation and biomass production for food, fodder, fibre and energy. However, and despite the importance of soil biodiversity for ecosystem health and human well-being, neither current state, drivers, potential consequences for ecosystem services nor options for sustainable governance of soil biodiversity are well understood. Here, we provide a framework for and argue that conducting a national assessment of soil biodiversity, albeit being a complex endeavour, is fundamental to building a baseline to understand the current state and trends of soil biodiversity, but also to identify the main drivers of change, the impacts of soil biodiversity loss and the potential pathways for conservation and sustainable governance of soil biodiversity.

KEYWORDS
belowground biodiversity, biodiversity change, conservation, ecosystem services, governance options, science policy

1 | INTRODUCTION

With the release of the Millennium Ecosystem Assessment in 2005, several international, regional and national assessments have been conducted focusing on the synthesis of available data and literature on state and trends of biodiversity, ecosystems, their functions and services. Although soil biodiversity likely represents roughly 59% of all terrestrial biodiversity and is tightly linked to above-ground biodiversity (Anthony et al., 2023; Bardgett & Wardle, 2010; Decaëns et al., 2006; Scheu, 2001; Wardle et al., 2004), these assessments

For affiliations refer to page 8.

often miss a specific focus on either soil biodiversity, soil functions or soil-related ecosystem services (Cameron et al., 2018; Guerra et al., 2021; Thakur et al., 2020). This is all even more alarming as these services, in particular clean drinking water and nutrition, are essential for human health, well-being and survival (Food and Agriculture Organization [FAO], 2024; Guerra et al., 2021; van der Putten et al., 2023), making soils a critical aspect that requires a more central role in environmental and risk-based assessments.

Soil biodiversity refers to the structural and functional diversity of organisms, species and populations that spend part of or all their life in soil, or whose primary habitat corresponds to the soil surface. Soil organisms cover a substantial range of life forms and size classes, from viruses, bacteria, archaea, protists, algae and fungi to soil-dwelling invertebrates and vertebrates (FAO et al., 2020; NMZB, 2023). This diversity is intrinsically linked to multiple ecosystem functions, merging in ecosystem services (Bardgett & van der Putten, 2014; Haines-Young & Potschin, 2010; Jochum & Eisenhauer, 2022; Wall et al., 2015) (Figure 1). In 2020, the FAO published the first dedicated assessment of the global state of soil biodiversity that highlighted the different global drivers and vulnerabilities of soil biodiversity (FAO et al., 2020). Although monitoring and preserving soil organisms require local to regional data, approaches and solutions, national assessments of soil biodiversity are lacking so far, given the considerable heterogeneity in soil type, land use and climate, even at the national level.

Here, we argue that there is a pressing need for national assessments that focus on the local/regional state, drivers, functions and services and protection of soil biodiversity, and, at the same time, can serve as national baselines for the explicit inclusion of soil ecological features in other environmental and biodiversity assessments and relevant monitoring programmes. Such national assessments can be more targeted and provide actionable knowledge that feeds directly into decision-making processes from a policy and/or land management perspective. In the specific case of soils and soil biodiversity, national assessments provide an opportunity to evaluate local to regional scientific expertise as a prerequisite for reducing biases of global assessments (Monfreda et al., 2004; Schmeller et al., 2017), including nonlinearities, which are often overlooked in large periodic assessments. They can further highlight existing knowledge gaps and highlight priorities considering the need and effort involved (Eisenhauer et al., 2017, 2022; Guerra et al., 2020) (see Box 1), specific examples of impacts and good practices, and have a comprehensive understanding of conservation priorities (both thematic and geographic).

2 | RAISON D'ÊTRE FOR A NATIONAL ASSESSMENT

National boundaries are frequently arbitrary geopolitical delimitations without immediate meaning for natural ecosystems, including soils. However, management and policy decisions are typically under national control, making the country scale highly relevant for soil biodiversity assessments, both in terms of impact and also management options. Soil research has been developed in most countries over the last 150 years (Brevik et al., 2016; Brevik & Sauer, 2015).

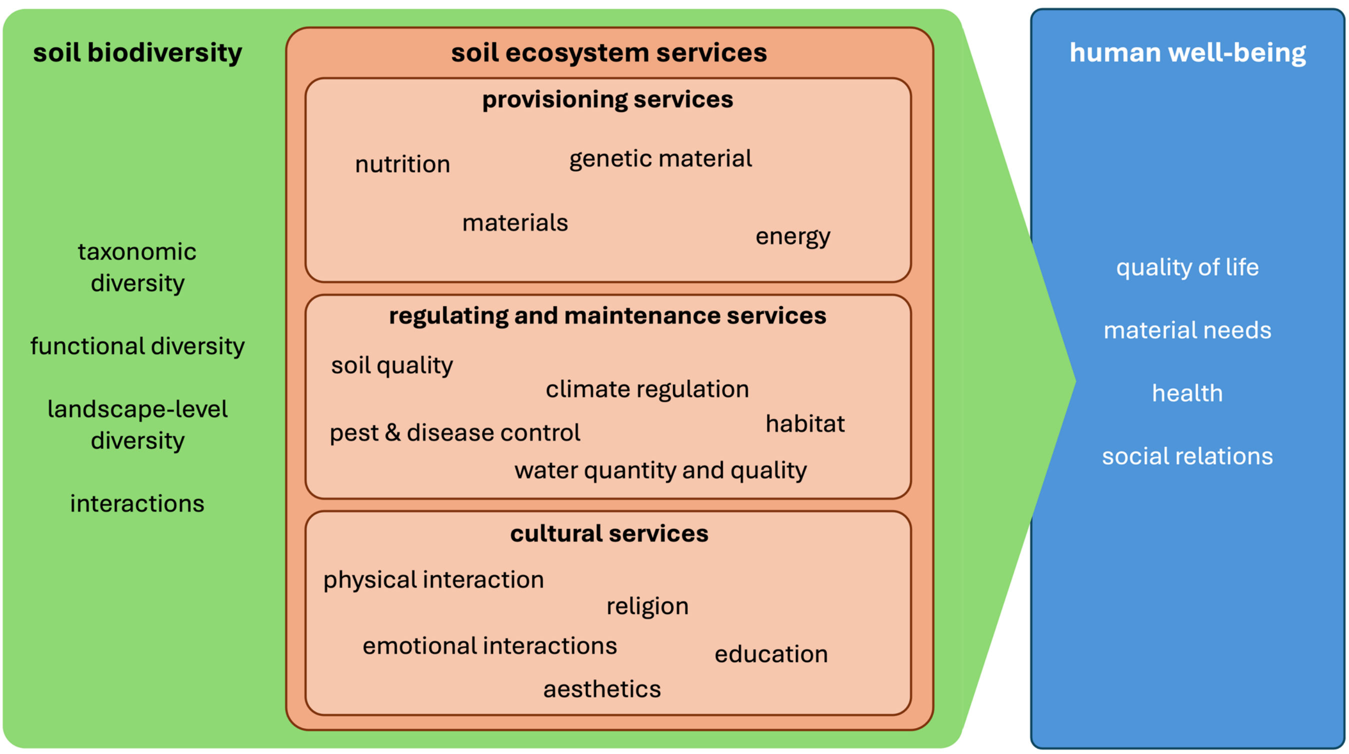


FIGURE 1 Linkages between soil biodiversity, ecosystem services and human well-being.

BOX 1: Knowledge gaps, open questions and challenges

- For many groups of soil organisms, only a minor fraction of the expected number of species has been described
- We have very limited information on the occurrence of soil-dwelling species, viruses in soil and endemism in soil at national levels
- We have very limited knowledge about invasive species in soil and their effects on ecosystems
- There are very few temporal analyses (trends) of soil biodiversity at the regional, national and global scale
- We have very patchy and inconsistent data on soil biodiversity in space and time, with often inadequate reference conditions to assess changes in soil biodiversity, functioning and health
- Many drivers of soil biodiversity have only been tested in isolation, and we lack information on the interacting effects of co-occurring drivers
- Information on the threats to soil biodiversity is very biased towards few taxa that have been used as bioindicators in ecotoxicological studies (e.g., some earthworm species)
- There is a paucity of data and concepts on cultural ecosystem services of soil biodiversity
- The intrinsic value of soil biodiversity has rarely been considered
- There is a lack of research on causal relationships between direct and indirect drivers that change soil biodiversity and consequences for ecosystem services
- We have limited knowledge about the effects of non-native or future climate-adapted crops and other plant species on soil organisms and functions
- We are losing taxonomic expertise in soil biodiversity to link molecular to morphological data
- The scientific community has to invest in broad capacity building including school and university education but also citizen science
- Consideration of soil biodiversity in land-use decisions and policy is highly limited and understudied, in particular with respect to the impact of dramatically changing climatic conditions
- Knowledge of the effectiveness of existing and opportunities for further advancing governance options for soil biodiversity is limited

However, this research was mainly driven by forestry and agriculture and focused on soil chemistry, physics and plant nutrition. Despite early interest in soil biodiversity research (Agrell, 1941; Moore, 1904), the majority of ecological concepts (D'Hondt et al., 2021; Thakur et al., 2020) that are unveiling complex networks and ecological relationships have only recently emerged. Especially, the advances in methods allowed to capture a wider range of soil biodiversity but this also gave rise to the problem of insufficient standardization. In soil ecology, the lack of standardization across measurements is particularly relevant due to two aspects: (i) the lack of large-scale (e.g., national-level) coordinated surveys that are replicated through time to assess soil biodiversity trends and to identify underlying drivers; and (ii) the abundance of methods and application contexts (e.g., multiple soil depths) that coexist across the literature. The first aspect is still a point for improvement in future assessments and a pivotal point to highlight when addressing thematic, spatial and temporal gaps. The second aspect relates back to the lack of methodological standardization, for example, with ISO standards for the sampling of soil invertebrates not covering all groups. This can translate to a substantial problem, mainly when the pool of available data and literature is small, incoherent or thematically and taxonomically biased.

To overcome these issues, national assessments should use the findings of all available and relevant data and literature from local to international scale. This would allow to compare local trends and drivers against regional ones, but also national assessments to their counterparts by using regional data sets as baselines for comparison. For example, at the European level, the Land Use/Cover Area frame statistical Survey (LUCAS), which has been running since 2009, included a component dedicated to assessing soil biodiversity from 2018 (Orgiazzi et al., 2018). Similarly, the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forest), which launched in 1985, has monitored soil chemistry and atmospheric deposition since 1994 (Forest Condition in Europe, 2023). Given the cross-boundary aspect of LUCAS and ICP and their high level of standardization, both constitute valuable resources for European countries when performing their national soil biodiversity assessments, particularly when making comparisons across borders. While any given European country may not have enough information specific to their borders on the effects of pesticides on diverse soil taxa, complementing this information with information gathered at the European level can provide a better understanding of the main effects of specific pesticides on specific taxa and communities that may be relevant for that particular country (Orgiazzi et al., 2022). For instance, the data warehouse on soil biodiversity, Edaphobase (Burkhardt et al., 2014), constitutes a source of valuable information for national and regional global assessments of soil biodiversity. It connects European soil biodiversity data with all available environmental and climate data, allows to determine species' niche spaces, to identify potential drivers and provides data for projections (Phillips et al., 2019; Potapov et al., 2023; Salako et al., 2023; Thakur et al., 2020). Combining results from multiple national and international networks and experimental facilities (Sünnemann et al., 2021) can also provide insights into the causal mechanisms behind direct and indirect drivers of change.

Furthermore, the adoption and use of essential soil biodiversity variables (Guerra et al., 2021) can facilitate the consistent reporting of soil biodiversity and ecosystem function patterns and trends. This is particularly relevant if we consider that soils represent complex and heterogeneous habitats formed by the combined effects of parent material, local topography, specific local abiotic conditions, the activity of living organisms and human activity, especially in terms of climate change, land-use intensity and land-use change (Totsche et al., 2010). An assessment focusing on soil biodiversity can be sectorial (i.e., per land use or soil type) or integrated (i.e., across ecosystems and land-use types), depending on the assessment's purpose and the depth of the available literature and other data. Likewise, it is important to define the temporal scope of each assessment. In countries where previous assessments exist, it is plausible to update them regularly, focusing on additional information (e.g., following the example of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES, 2019], the EU-wide ecosystem assessments [Maes et al., 2020] or the UN System of Environmental-Economic Accounting—Ecosystem Accounting SEEA EA [Hamilton, 2016]). However, for situations in which no previous assessments exist, stakeholders should make an effort to do an in-depth search of all available data (e.g., remote sensing data; Wellmann et al., 2020) and literature, including national scientific and technical reports that may shed light on the particular aspects being assessed according to their temporal and spatial scope.

However, an important caveat is that, in countries where scientific priorities do not (or did not in the past) sufficiently consider soils and soil biodiversity, it might be challenging to identify the necessary local scientific evidence needed for such an assessment. Even in countries where relevant local evidence exists, the information is often scattered, due to complex and sectorial institutional frameworks that make it challenging to acquire data, share knowledge and conduct integrated assessments. Therefore, to succeed, national assessments of soil biodiversity require (i) an adequate definition of the specific stakeholders to be involved in the process; (ii) an overview of the prerequisites regarding standardization, accessibility and availability of soil biodiversity data sources as well as of the opportunities for their integration; and (iii) a clear definition of soil indicators, thematic and spatial scope and the ecological and temporal baseline for such an assessment. Furthermore, (iv) they are ideally supported by a monitoring and sampling design that aims to cover local/national soil heterogeneity, a wide range of relevant taxa and multiple land-use, land cover and land-use intensity types. Lastly, (v) such assessments require dedicated transdisciplinary research including social sciences to understand relevant drivers, societal interests, individual preferences and possible governance options and institutional remedies.

The interdisciplinary integration of soil biodiversity should include ecological and biological knowledge about species and habitats, but also consider the information coming from diverse disciplines like geography, geology, soil sciences, agronomy, biogeochemistry, chemistry, ecotoxicology, global change biology, environmental engineering, land-use technology, urban and landscape planning, climatology, molecular ecology, bioinformatics and social sciences. Therefore, integrating information and knowledge across disciplines is a critical requirement for an adequate assessment of soil biodiversity. Given that, soil biodiversity is an integral component of a larger ecosystem, national assessments require an understanding of the observed state and trends, their relationships and drivers. A national assessment of soil biodiversity thus needs information about the local context (e.g., soil pH, carbon content, parent material, vegetation coverage and composition) and information about past and present drivers (e.g., land use practices and history, climate, social, institutional and economic factors). Integrating many disciplines also opens the discussion to, and acceptance by, a wide range of stakeholders. These include representatives from research, governmental (e.g., environmental, agriculture, forestry, nature protection or planning agencies at municipal, city and regional or national levels) and nongovernmental organizations (e.g., for nature conservation, farmers, land owners and foresters), as well as private companies, political decision-makers and the wider public (Baum & Bartkowski, 2020). These multiple stakeholders can define and expand the scope of a national assessment by contributing knowledge to the pool of scientific data and literature that stands as the basis for an assessment of soil biodiversity and the development of evidence-based policy and management options. While an assessment should not be prescriptive nor cater to the needs of any specific stakeholder group, to be effective, the expectations of stakeholders should also be met by highlighting the evidence that supports sustainable land management options. Taken together, a systematic involvement of stakeholders and experts from diverse disciplines is essential in the definition of key questions and the design of the assessment process to increase the chances that the assessment process and its outputs are considered scientifically credible, practically salient and politically legitimate by the respective audiences (Cash et al., 2003).

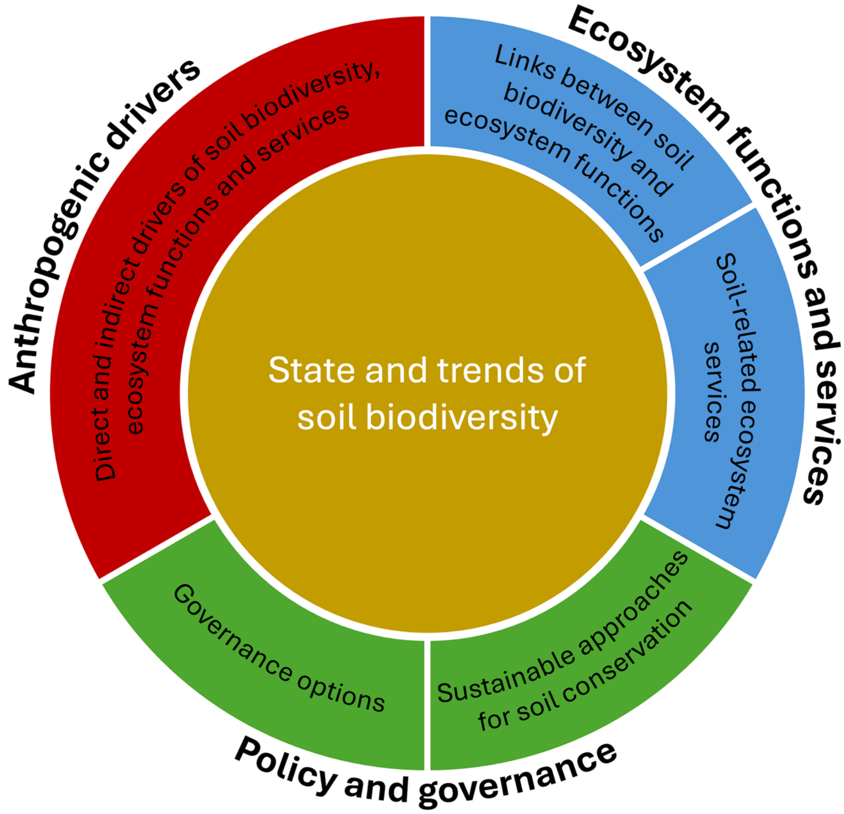
Given the complexity of soil systems and their cross-cutting nature in terms of ecosystem and land-use types, we propose that national assessments of soil biodiversity include four components (Figure 2): (i) the state and trends of soil biodiversity; (ii) anthropogenic drivers (i.e., direct and indirect drivers related to soil biodiversity, ecosystem functions and services); (iii) ecosystem functions and services, including the assessment of the links between soil biodiversity and ecosystem functions and the supply of soil-related ecosystem services that are relevant for human health; and (iv) policy and governance options, including sustainable approaches for land management, soil biodiversity conservation and governance options. While other elements can be added or further specified, we argue that these four elements are fundamental to encompass and describe the condition of soil biodiversity and to provide meaningful pathways to preserve and restore soil's ecological health.

3 | FRAMEWORK FOR A NATIONAL ASSESSMENT OF SOIL BIODIVERSITY

3.1 | State and trends of soil biodiversity

Describing the state and trends of soil biodiversity within a national assessment of soil biodiversity is an important step to provide a comprehensive picture of the current state of soil biodiversity, its spatial distribution and changes over time, which in turn can provide

FIGURE 2 Components of a national assessment of soil biodiversity.



a basis for developing policy and governance strategies to conserve and sustainably manage soil biodiversity. While this spatial and temporal characterization may be easier for some groups (e.g., for earthworms), others (e.g., bacteria) may require special consideration of the relevant scale and characteristics to be represented. It would also help to identify the critical gaps in local knowledge and understanding of soil biodiversity, such as the role of microbial communities and the interactions between above- and below-ground biodiversity, but also support the establishment of national distribution maps of soil organisms and monitoring systems that target specific areas or are closing important knowledge gaps. While such information may be seen as a mere mapping of current knowledge, it is crucial for researchers, policy-makers, land managers and other stakeholders that aim to improve the knowledge base on soil biodiversity and functions in their country or region. Therefore, national assessments should consider (i) presenting the distribution of soil biodiversity groups as well as the main ecosystem functions and services associated with them; (ii) highlighting the trends in distribution, abundance and community composition of particularly threatened groups; and (iii) identifying vulnerable areas of strong soil biodiversity loss and gaps in research, including taxonomic experts.

3.2 | Direct drivers of soil biodiversity, ecosystem functions and services

Drivers of biodiversity change can be differentiated based on their characteristics (biological, chemical and physical), their direction of effect (positive or negative), their mode of function (e.g., toxicity vs. change in resource availability or energy requirements; Baas et al., 2010) or their specificity (i.e., whether they are specific to one taxon, have consistent effects across taxa or if they induce cascades across soil taxa and functional groups) (Rillig et al., 2021). Given that driver attribution and general ranking (i.e., in terms of importance) may substantially vary across countries and environmental conditions, as well as given that different groups of organisms vary in their responses to environmental change, detailed information on multiple taxa and traits at the national level is urgently needed to better understand and predict threats to the different facets of soil biodiversity (FAO et al., 2020). Therefore, a national assessment should provide evidence of their impacts and an outlook of potential or effective ecological, social and economic consequences. Special attention may be given to co-occurring drivers of soil biodiversity that can have synergistic effects (Beaumelle et al., 2021; Krause et al., 2023; Rillig et al., 2019), where the consequences of multiple stressors can intensify each other and thus have more pronounced effects than one would expect to find based on single-driver studies (Rillig et al., 2019; Thakur et al., 2020). For example, the effects of increasing temperature were shown to be minor under ambient water conditions, but detrimental to soil biological activity under drought (Thakur et al., 2018). Therefore, when assessing the drivers of changes in soil biodiversity, ecosystem functions and services it is important to (i) describe the distribution of specific drivers, including their intensity and frequency (when relevant); (ii) identify areas where these drivers accumulate, including their nature; and (iii) their potential trends based on socioeconomic development pathways.

3.3 | Indirect drivers of soil biodiversity, ecosystem functions and services

How soils are managed is driven by higher-level factors related to economic forces, policies, consumption patterns, land use, culture and tradition. Given the multiplicity of factors that affect soil biodiversity in an indirect way as well as the scarcity of policies directly focusing on the protection of soils (Bartkowski et al., 2021), let alone soil biodiversity (Köninger et al., 2022), it is essential that national assessments of soil biodiversity adopt a broad view and include as broad a set of factors as possible. This may be challenging due to the scarcity of dedicated research on indirect drivers of soil (biodiversity) change in social and political sciences, especially beyond agriculture. Because of that, it may be necessary for soil biodiversity assessments to rely on indirect evidence, for example, related to the drivers of changes in land use or management that are known to have effects on soil biodiversity (e.g., consequences of the common agricultural policy on tillage or pesticide application). Furthermore, it is essential that assessments consider indirect drivers of soil biodiversity change across sectors, including land-use sectors (e.g., agriculture, food production and forestry), relevant policies (agricultural policy, energy policy, settlement policies and regional planning, etc.) and relevant value chains (e.g., food from farm through retail to consumption) (Bartkowski & Bartke, 2018; Gütschow et al., 2021). An increasingly important role can be expected by the impact of education and social media (e.g., the recent rise in veganism may substantially impact animal husbandry and any associated land use practice).

3.4 | Links between soil biodiversity and ecosystem functions

The interactions of different coexisting soil organisms with their abiotic and biotic environment drive a multitude of different ecosystem functions and affect their ecological state (Bardgett & van der Putten, 2014; Bender et al., 2014; Geisen et al., 2019; Wagg et al., 2014). Experiments have shown that the diversity of soil organisms is critical for ecosystem functions like soil formation, organic matter decomposition (Bradford et al., 2002, 2014; Hättenschwiler et al., 2005; Heemsbergen et al., 2004), carbon cycling (Nielsen et al., 2011), nutrient dynamics (Sheehan et al., 2006), soil water dynamics, soil aggregation and aeration (Lehmann et al., 2017), plant growth (Eisenhauer et al., 2018; van Groenigen et al., 2014) and plant community succession (De Deyn et al., 2003). However, the composition and roles of biological soil communities vary across environmental contexts, requiring assessments of context-dependent relationships between biodiversity and ecosystem functioning. This nuanced view of the effects of soil biodiversity on multiple ecosystem functions in different contexts is essential for a national assessment as it provides local evidence on the context-dependency of such relations. It can also serve to highlight the positive or negative effects of local land use and/or management practices and support the identification of regional best practices. In a larger context, with the future global availability of national soil biodiversity assessments, these contextual examples can also be used to support an international framework of good practices to support ecosystem multifunctionality in soils from different land-use types. In fact, when establishing these links between soil biodiversity and ecosystem functions in such an assessment, several considerations should be taken to capture different local land use and soil types and the national environmental gradient. For instance, linking experimental results to observational studies and/or remote sensing generated data (Wellmann et al., 2020) allows to better understand these causal relationships. When local relationships are missing it is important to highlight such gaps (e.g., geographical, environmental or land-use type) to give room for the next assessment to fill them and also to give clear directions to new research topics that may need to be developed.

3.5 | Soil-related ecosystem services

Although soils are a central component of ecosystems, and soil-related ecosystem services are essential for human well-being, there is a plethora of soil-related ecosystem services with almost no standardization or specific classification (Paul et al., 2021). Soil biodiversity influences numerous soil-related ecosystem services, but most of the regulatory influences of soil biodiversity on soil-related ecosystem services are only theoretically known. More importantly, the lack of scientific evidence is obvious for the links between soil and soil biodiversity and human health (Banerjee & van der Heijden, 2023; Brevik & Sauer, 2015). National assessments of soil biodiversity may thus highlight that the analysis of causal relations between soil biodiversity and ecosystem services is complex, given the national combination of biotic and abiotic characteristics (e.g., pore volume, humus and other C content and nutrient content) as well as land management measures (Bethwell et al., 2021) that shape ecosystems and, therefore, the supply of ecosystem services. Especially cultural ecosystem services related to the perceptions, values, indirect effects and benefits, for example, the contribution of soil biodiversity to landscape aesthetics, are more difficult to assess. Considering these aspects, a national assessment of soil biodiversity should focus on first identifying the relevant ecosystem services provided by soils using available data and literature (Paul et al., 2021), and second on identifying the distribution, frequency (e.g., ecosystem services supply is known for having temporal and spatial variability) and amount of the supply of the identified services. Together, these aspects will allow for a better identification of the most important benefits and values from ecosystem services. Furthermore, the supply of soil-related ecosystem services within one country might depend on or come from areas beyond national administrative borders (interregional flows), for example, flood regulation/flood risk management (Kleemann et al., 2020), and, therefore, requires monitoring systems across national borders (Koellner et al., 2019; Schröter et al., 2016) including the use of remote sensing techniques (Wellmann et al., 2020).

3.6 | Sustainable approaches for soil nature conservation

Given the enormous biological diversity in the soil, it is important to note that conservation policies at multiple scales (e.g., regional, national or global), and more importantly nature conservation actions, have rarely considered soil biodiversity (Cameron et al., 2019; Eisenhauer & Guerra, 2019; Zeiss et al., 2022). This becomes even more apparent in comparison to marine or aboveground terrestrial biodiversity that were frequently and prominently used to underpin the establishment of nature conservation policies (Guerra et al., 2021; Jung et al., 2021). These facts are all the more alarming as the majority of publications on insect decline do not point out that a huge share of aboveground insect species (in particular Diptera, Hymenoptera and Coleoptera) spend most of their life as larvae in soils. Recently, at the global level, countries engaged in the Convention of Biological Diversity have agreed to consider the assessment and sustainable use of soil biodiversity in their national legislation. While this is an important step, it is now essential that national assessments of soil biodiversity provide clear guidelines that highlight the nature conservation potential as well as the vulnerability of local soil communities. As a direct contribution to this aspect, a national assessment should evaluate nature conservation management practices and existing nature protection areas, to assess the existence and feasibility of targeted actions to protect and sustainably manage soil biodiversity and ecosystem functions (Zeiss et al., 2022). This approach allows for the identification of positive and/or potentially negative consequences for soil biodiversity and can aid future research and policy-makers in assessing the effectiveness of different nature management, conservation and restoration practices. As this approach targets nature conservation management plans and their included actions, it also serves as an important mechanism to improve awareness among conservation managers of the importance of local, context-dependent actions to improve soil condition and protect soil biodiversity.

Another aspect to consider is the existence of Red List species within national borders. This requires two parallel approaches: (i) the identification of currently classified Red List species within the country's borders (including their distribution), and (ii) if not existing, the elaboration or support of the identification and assessment of national Red List species. While Red List species are significantly biased (Phillips et al., 2017), recent efforts (e.g., focusing on fungi [Põlme et al., 2020] or myriapods [Karam-Gemael et al., 2020]) show that, when targeted approaches are implemented, a significant amount of information on soil communities can be gathered, and the understanding of their vulnerabilities improved. In addition, since most conservation management practices and nature protection areas are related to a given ecosystem, such as agricultural sites, forests or urban landscapes, we advise that interdisciplinary teams should be formed to aid in the evaluation of such management practices. Ultimately, such an approach can guide future management practices and the establishment of nature protection areas, as well as identify ecosystems, areas or soil organisms that are in need of sustainable management or active conservation and protection.

3.7 | Governance options

National assessments of soil biodiversity should not only study the drivers, state and trends as well as potential consequences for human well-being but also critically review the effectiveness of management practices to halt biodiversity loss and propose governance options for biodiversity conservation and sustainable use. We suggest that such a portfolio of governance options should be evidence-based, ecologically effective, economically feasible, target group-oriented, considered legitimate and relevant by societal actors and take into account local and regional as well as national (and international) constraints (Bartkowski et al., 2021). Given that many stakeholders, such as land owners/users, consumers and policy-makers, can indirectly and directly influence soil biodiversity and quality, the development of options for action should not happen in isolation but in close collaboration with stakeholders and with the support and at best a mandate from political decision-makers (Albert et al., 2017). In that context, it is important that the development of options for decision-makers, including land managers, considers the context specificity of its recommendations, which reflects the ecological and societal heterogeneity, and associated trade-offs. For instance, local trade-offs may arise with above-ground processes and related management or nature protection actions. Considering societal heterogeneity and these trade-offs or synergies can improve the effectiveness and acceptance of sustainable options for actions. Citizen science can be a helpful tool in that endeavour. Although a specific list of options for action will vary from country to country as well as over time, we suggest some key options for action that may be discussed in each national assessment of soil biodiversity. Such options include (i) the establishment or long-term support of a nationwide, coordinated and regular soil biodiversity monitoring (including accompanying pedological data); (ii) incentives for site-specific and environmentally friendly soil management, for the diversification of landscape structures (Lausch et al., 2015), and the reduction of land take (including unsealing of sealed soils); (iii) the designation of more protected areas focusing on specific soil organisms and their sustainable management; and (iv) the transfer of knowledge into society to raise awareness for the importance of soil biodiversity. Ultimately, such a target-oriented, integrative and societally inclusive approach can initiate the necessary processes to protect soil biodiversity and sustainably manage soils at the local, regional and national levels.

4 | CONCLUSIONS AND OUTLOOK

In summary, we laid out the need and motivation for national assessments of soil biodiversity as well as key topics to cover and steps for implementation. Our framework will allow for assessments to present the best available and relevant knowledge on soil biodiversity and its changes, its drivers and consequences for soil-related ecosystem services—thus forming the centrepiece for long-term soil biodiversity reporting and a main source of information for evidence-based governance and decision-making. We further propose that through the integration of relevant stakeholders in the process of implementing a national assessment of soil biodiversity it becomes legitimized by societal actors, thus enhancing its chances for effectively informing policy and decision-making. This can build national capacity, unravel synergies that may not have existed in the past (e.g., crossing discipline boundaries) and identify knowledge gaps both in the scientific basis of the assessment and in societal needs. In a time of rapid overall terrestrial biodiversity change, global assessments of biodiversity cannot, due to their nature, identify local needs and solutions. Therefore, national assessments of soil biodiversity are key for the development of adaptive changes that support governance for the conservation and sustainable management of soil biodiversity for people and nature.

AUTHOR CONTRIBUTIONS

Carlos A. Guerra, Nico Eisenhauer, Christoph Tebbe, Willi Xylander and Christian Ristok conceptualized the work. Carlos Guerra, Nico Eisenhauer, Christoph Tebbe, Willi Xylander, Doreen Babin, Bartosz Bartkowski, Janina Kleemann, Christina Lachmann, Stefan Scheu and Christian Ristok provided investigation resources and wrote the original draft. All authors substantially revised and edited the final work.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no data sets were generated or analysed during the current study.

ETHICS STATEMENT

Not applicable.

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REFERENCES

Agrell I. Zur Ökologie der Collembolen. Untersuchungen im schwedischen Lappland. Opusc Entomo Suppl. 1941;3:236.

Albert C, Neßhöver C, Schröter M, Wittmer H, Bonn A, Burkhard B, et al. Towards a National Ecosystem Assessment in Germany: a plea for a comprehensive approach. GAIA—Ecol Perspect Sci Soc. 2017;26: 27–33.

Anthony MA, Bender SF, van der Heijden MGA. Enumerating soil biodiversity. Proc Natl Acad Sci USA. 2023;120:e2304663120.

Baas J, Jager T, Kooijman B. A review of DEB theory in assessing toxic effects of mixtures. Sci Total Environ. 2010;408:3740–5.

Banerjee S, van der Heijden MGA. Soil microbiomes and one health. Nat Rev Microbiol. 2023;21:6–20.

Bardgett RD, van der Putten WH. Belowground biodiversity and ecosystem functioning. Nature. 2014;515:505–11.

Bardgett RD, Wardle DA. Aboveground–belowground linkages: biotic interactions, ecosystem processes, and global change. Oxford, UK: Oxford University Press; 2010.

Bartkowski B, Bartke S. Leverage points for governing agricultural soils: a review of empirical studies of European farmers' decision-making. Sustainability. 2018;10:3179.

Bartkowski B, Bartke S, Hagemann N, Hansjürgens B, Schröter-Schlaack C. Application of the governance disruptions framework to German agricultural soil policy. Soil. 2021;7:495–509.

Baum CM, Bartkowski B. It's not all about funding: fostering interdisciplinary collaborations in sustainability research from a European perspective. Energy Res Soc Sci. 2020;70:101723.

Beaumelle L, Thouvenot L, Hines J, Jochum M, Eisenhauer N, Phillips HRP. Soil fauna diversity and chemical stressors: a review of knowledge gaps and roadmap for future research. Ecography. 2021;44:845–59.

Bender SF, Plantenga F, Neftel A, Jocher M, Oberholzer HR, Köhl L, et al. Symbiotic relationships between soil fungi and plants reduce N_2O emissions from soil. ISME J. 2014;8:1336–45.

Bethwell C, Burkhard B, Daedlow K, Sattler C, Reckling M, Zander P. Towards an enhanced indication of provisioning ecosystem services in agro-ecosystems. Environ Monit Assess. 2021;193:269.

Bradford MA, Jones TH, Bardgett RD, Black HIJ, Boag B, Bonkowski M, et al. Impacts of soil faunal community composition on model grassland ecosystems. Science. 2002;298:615–8.

Bradford MA, Wood SA, Bardgett RD, Black HIJ, Bonkowski M, Eggers T, et al. Discontinuity in the responses of ecosystem processes and multifunctionality to altered soil community composition. Proc Natl Acad Sci USA. 2014;111:14478–83.

Brevik EC, Fenton TE, Homburg, J. A. Historical highlights in American soil science—prehistory to the 1970s. CATENA. 2016;146:111–27.

Brevik EC, Sauer TJ. The past, present, and future of soils and human health studies. Soil. 2015;1:35–46.

Burkhardt U, Russell DJ, Decker P, Döhler M, Höfer H, Lesch S, et al. The Edaphobase project of GBIF-Germany—a new online soil-zoological data warehouse. Appl Soil Ecol. 2014;83:3–12.

Cameron EK, Martins IS, Lavelle P, Mathieu J, Tedersoo L, Bahram M, et al. Global mismatches in aboveground and belowground biodiversity. Conserv Biol. 2019;33:1187–92.

Cameron EK, Martins IS, Lavelle P, Mathieu J, Tedersoo L, Gottschall F, et al. Global gaps in soil biodiversity data. Nat Ecol Evol. 2018;2:1042–3.

Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, et al. Knowledge systems for sustainable development. Proc Natl Acad Sci USA. 2003;100:8086–91.

Decaëns T, Jiménez JJ, Gioia C, Measey GJ, Lavelle P. The values of soil animals for conservation biology. Eur J Soil Biol. 2006;42:S23–38.

De Deyn GB, Raaijmakers CE, Zoomer HR, Berg MP, de Ruiter PC, Verhoef HA, et al. Soil invertebrate fauna enhances grassland succession and diversity. Nature. 2003;422:711–3.

D'Hondt K, Kostic T, McDowell R, Eudes F, Singh BK, Sarkar S, et al. Microbiome innovations for a sustainable future. Nat Microbiol. 2021;6:138–42.

Eisenhauer N, Antunes PM, Bennett AE, Birkhofer K, Bissett A, Bowker MA, et al. Priorities for research in soil ecology. Pedobiologia. 2017;63:1–7.

Eisenhauer N, Bender SF, Calderón-Sanou I, de Vries FT, Lembrechts JJ, Thuiller W, et al. Frontiers in soil ecology—insights from the World Biodiversity Forum. J Sustain Agric Environ. 2022;1:245–61.

Eisenhauer N, Guerra CA. Global maps of soil-dwelling nematode worms. Nature. 2019;572:187–8.

Eisenhauer N, Hines J, Isbell F, van der Plas F, Hobbie SE, Kazanski CE, et al. Plant diversity maintains multiple soil functions in future environments. eLife. 2018;7:e41228.

FAO. Soil biodiversity, soil conservation and agriculture. Rome, Italy: FAO; 2024. https://www.fao.org/soils-portal/soil-biodiversity/soil-conservation-and-agriculture/en/

FAO, ITPS, GSBI, CBD & EC. State of knowledge of soil biodiversity—status, challenges and potentialities, report 2020. Rome, Italy: FAO; 2020. https://doi.org/10.4060/cb1928en

Forest Condition in Europe. The assessment; ICP Forests Technical Report under the UNECE Convention on long-range transboundary air pollution (air convention). Eberswalde, Germany: Thünen Institute; 2023. https://doi.org/10.3220/ICPTR1697801881000

Geisen S, Wall DH, van der Putten WH. Challenges and opportunities for soil biodiversity in the anthropocene. Curr Biol. 2019;29:R1036–44.

van Groenigen JW, Lubbers IM, Vos HMJ, Brown GG, De Deyn GB, van Groenigen KJ. Earthworms increase plant production: a meta-analysis. Sci Rep. 2014;4:6365.

Guerra CA, Bardgett RD, Caon L, Crowther TW, Delgado-Baquerizo M, Montanarella L, et al. Tracking, targeting, and conserving soil biodiversity. Science. 2021;371:239–41.

Guerra CA, Heintz-Buschart A, Sikorski J, Chatzinotas A, Guerrero-Ramírez N, Cesarz S, et al. Blind spots in global soil biodiversity and ecosystem function research. Nat Commun. 2020;11:3870.

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;21:103.

Haines-Young R, Potschin M. The links between biodiversity, ecosystem services and human well-being. In: Raffaelli DG, Frid CLJ, editors. Ecosystem ecology. Cambridge, UK: Cambridge University Press; 2010. p. 110–39. https://doi.org/10.1017/CBO9780511750458.007

Hamilton K. Measuring sustainability in the UN system of environmental-economic accounting. Environ Resour Econ. 2016;64:25–36.

Hättenschwiler S, Tiunov AV, Scheu S. Biodiversity and litter decomposition in terrestrial ecosystems. Annu Rev Ecol Evol Syst. 2005;36: 191–218.

Heemsbergen DA, Berg MP, Loreau M, van Hal JR, Faber JH, Verhoef HA. Biodiversity effects on soil processes explained by interspecific functional dissimilarity. Science. 2004;306:1019–20.

IPBES. Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn, Germany: IPBES Secretariat; 2019.

Jochum M, Eisenhauer N. Out of the dark: using energy flux to connect above- and belowground communities and ecosystem functioning. Eur J Soil Sci. 2022;73:e13154.

Jung M, Arnell A, de Lamo X, García-Rangel S, Lewis M, Mark J, et al. Areas of global importance for conserving terrestrial biodiversity, carbon and water. Nat Ecol Evol. 2021;5:1499–509.

Karam-Gemael M, Decker P, Stoev P, Marques MI, Chagas Jr. A. Conservation of terrestrial invertebrates: a review of IUCN and regional Red Lists for myriapoda. Zookeys. 2020;930:221–9.

Kleemann J, Schröter M, Bagstad KJ, Kuhlicke C, Kastner T, Fridman D, et al. Quantifying interregional flows of multiple ecosystem services—a case study for Germany. Glob Environ Change. 2020;61:102051.

Koellner T, Bonn A, Arnhold S, Bagstad KJ, Fridman D, Guerra CA, et al. Guidance for assessing interregional ecosystem service flows. Ecol Indic. 2019;105:92–106.

Köninger J, Panagos P, Jones A, Briones MJI, Orgiazzi A. In defence of soil biodiversity: towards an inclusive protection in the European Union. Biol Cons. 2022;268:109475.

Krause SMB, Szoboszlay M, Dier M, Erbs M, Manderscheid R, Weigel HJ, et al. Impact of elevated atmospheric CO_2 on the wheat rhizomicrobiome under the additional influence of warming, drought, and nitrogen fertilization. Eur J Soil Biol. 2023;117:103515.

Lausch A, Blaschke T, Haase D, Herzog F, Syrbe RU, Tischendorf L, et al. Understanding and quantifying landscape structure—a review on relevant process characteristics, data models and landscape metrics. Ecol Model. 2015;295:31–41.

Lehmann A, Zheng W, Rillig MC. Soil biota contributions to soil aggregation. Nat Ecol Evol. 2017;1:1828–35.

Maes J, Teller A, Erhard M, Conde S, Vallecillo Rodriguez S, Barredo Cano JI, et al. Mapping and assessment of ecosystems and their services: an EU ecosystem assessment. Ispra: JRC Publications Repository; 2020. https://publications.jrc.ec.europa.eu/repository/handle/JRC120383

Monfreda C, Wackernagel M, Deumling D. Establishing national natural capital accounts based on detailed ecological footprint and biological capacity assessments. Land Use Policy. 2004;21:231–46.

Moore JP. Description of a new species of earthworm (*Diplocardia longa*) from Georgia. Proc Acad Natl Sci Phila. 1904;56:803–8.

Nielsen UN, Ayres E, Wall DH, Bardgett RD. Soil biodiversity and carbon cycling: a review and synthesis of studies examining diversity–function relationships. Eur J Soil Sci. 2011;62:105–16.

NMZB. Expert Committee 'Monitoring of soil biodiversity and its functions' [Internet]. BfN, Berlin, Germany: Monitoringzentrum NMZB. 2023. Available from: https://www.monitoringzentrum.de/en/expert-committee-monitoring-soil-biodiversity-and-its-functions

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;69:140–53.

Orgiazzi A, Panagos P, Fernández-Ugalde O, Wojda P, Labouyrie M, Ballabio C, et al. LUCAS soil biodiversity and LUCAS soil pesticides, new tools for research and policy development. Eur J Soil Sci. 2022;73:e13299.

Paul C, Kuhn K, Steinhoff-Knopp B, Weißhuhn P, Helming K. Towards a standardization of soil-related ecosystem service assessments. Eur J Soil Sci. 2021;72:1543–58.

Phillips HRP, Cameron EK, Ferlian O, Türke M, Winter M, Eisenhauer N. Red list of a black box. Nat Ecol Evol. 2017;1:0103.

Phillips HRP, Guerra CA, Bartz MLC, Briones MJI, Brown G, Crowther TW, et al. Global distribution of earthworm diversity. Science. 2019;366:480–5.

Põlme S, Abarenkov K, Henrik Nilsson R, Lindahl BD, Clemmensen KE, Kauserud H, et al. FungalTraits: a user-friendly traits database of fungi and fungus-like stramenopiles. Fungal Divers. 2020;105:1–16.

Potapov AM, Guerra CA, van den Hoogen J, Babenko A, Bellini BC, Berg MP, et al. Globally invariant metabolism but density-diversity mismatch in springtails. Nat Commun. 2023;14:674.

van der Putten WH, Bardgett RD, Farfan M, Montanarella L, Six J, Wall DH. Soil biodiversity needs policy without borders. Science. 2023;379:32–4.

Rillig MC, Ryo M, Lehmann A. Classifying human influences on terrestrial ecosystems. Glob Change Biol. 2021;27:2273–8.

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;366:886–90.

Salako G, Russell DJ, Stucke A, Eberhardt E. Assessment of multiple model algorithms to predict earthworm geographic distribution range and biodiversity in Germany: implications for soil-monitoring and species-conservation needs. Biodivers Conserv. 2023;32:2365–94.

Scheu S. Plants and generalist predators as links between the below-ground and above-ground system. Basic Appl Ecol. 2001;2:3–13.

Schmeller DS, Böhm M, Arvanitidis C, Barber-Meyer S, Brummitt N, Chandler M, et al. Building capacity in biodiversity monitoring at the global scale. Biodivers Conserv. 2017;26:2765–90.

Schröter M, Albert C, Marques A, Tobon W, Lavorel S, Maes J, et al. National ecosystem assessments in Europe: a review. Bioscience. 2016;66:813–28.

Sheehan C, Kirwan L, Connolly J, Bolger T. The effects of earthworm functional group diversity on nitrogen dynamics in soils. Soil Biol Biochem. 2006;38:2629–36.

Sünnemann M, Siebert J, Reitz T, Schädler M, Yin R, Eisenhauer N. Combined effects of land-use type and climate change on soil microbial activity and invertebrate decomposer activity. Agric Ecosyst Environ. 2021;318:107490.

Thakur MP, Phillips HRP, Brose U, De Vries FT, Lavelle P, Loreau M, et al. Towards an integrative understanding of soil biodiversity. Biol Rev. 2020;95:350–64.

Thakur MP, Reich PB, Hobbie SE, Stefanski A, Rich R, Rice KE, et al. Reduced feeding activity of soil detritivores under warmer and drier conditions. Nat Clim Change. 2018;8:75–8.

Totsche KU, Rennert T, Gerzabek MH, Kögel-Knabner I, Smalla K, Spiteller M, et al. Biogeochemical interfaces in soil: the interdisciplinary challenge for soil science. J Plant Nutr Soil Sci. 2010;173:88–99.

Wagg C, Bender SF, Widmer F, van der Heijden MGA. Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proc Natl Acad Sci USA. 2014;111:5266–70.

Wall DH, Nielsen UN, Six J. Soil biodiversity and human health. Nature. 2015;528:69–76.

Wardle DA, Bardgett RD, Klironomos JN, Setälä H, van der Putten WH, Wall DH. Ecological linkages between aboveground and belowground biota. Science. 2004;304:1629–33.

Wellmann T, Lausch A, Andersson E, Knapp S, Cortinovis C, Jache J, et al. Remote sensing in urban planning: contributions towards ecologically sound policies? Landsc Urban Plan. 2020;204:103921.

Zeiss R, Eisenhauer N, Orgiazzi A, Rillig M, Buscot F, Jones A, et al. Challenges of and opportunities for protecting European soil biodiversity. Conserv Biol. 2022;36:e13930.

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