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Scoping document

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# Preliminary assessment of the knowledge gaps to improve nature conservation of soil biodiversity

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## Introduction

In the past decades, there has been an increasing awareness of the importance of Nature Conservation of Soil Biodiversity. Approximately 59% of all biodiversity on the planet is comprised of soil living organisms (Anthony et al. 2023), ranging from microorganisms to vertebrate species (FAO et al. 2020, Anthony et al. 2023). Soil biodiversity plays a central role in soil health and ecosystem services, as the activities of soil biota support the delivery of various ecosystem services, such as carbon sequestration, nutrient cycling, prevention of soil erosion, pest control, and cleaning of air and water (Banerjee and van der Heijden 2023, Creamer et al. 2022, Pulleman et al. 2012). However, soil biodiversity is currently threatened by intensive agriculture and forestry as well as soil sealing in urban environments. Protecting soil biodiversity and thus its ecosystem functions and services will have positive effects on a number of sustainability development goals (SDGs), including water quality and food security, among others (FAO et al. 2020, Köninger et al. 2022). Nevertheless, recent work did not find positive effects of current conservation practices on soil biodiversity and its ecosystem functions (Zeiss et al. 2022). The authors suggest this is predominantly because the priorities and the decision-making paradigms used for selection of sites for conservation do not take into account soil biodiversity, its associated ecosystem functions, or the value of belowground ecosystems to human well-being and economic development (Bardgett and van der Putten 2014, FAO et al. 2020, Zeiss et al. 2022). While biodiversity-friendly management approaches, such as ecological intensification (Kleijn et al. 2019), regenerative agriculture and agroecology (Barrios et al. 2023, FAO 2023, Grilli et al. 2023) are receiving increasing attention, studies focused on conservation of soil biodiversity and its ecosystem functions are still limited (Bardgett and van der Putten 2014, FAO et al. 2020, Zeiss et al. 2022). Thus, there is a stark need for identifying knowledge gaps and new research and innovation to help protect and conserve soil biodiversity, the ecosystem services they provide, and their impact on human health and economics.

Recently, soil health and biodiversity has also gained increasing attention in European policy. The EU aim is to move well beyond the current status of having only 30-40% of healthy soils. To reach this goal, the EU has put a great effort in setting legal frameworks and strategies that focus on soil health. These frameworks include the soil strategy and the proposal for the Soil monitoring and resilience law. Additionally, the EU biodiversity strategy for 2030 and the upcoming Commission proposal for a Nature Restoration and Resilience Law are aimed to protect and restore aboveground and belowground species and habitats.

The EU Soil Mission “A Soil Deal for Europe” has at its centre the protection and restoration of degraded soils across Europe. Soil biodiversity protection and restoration are integral to many of the Soil Mission’s eight objectives, which are to:

1. reduce desertification
2. conserve soil organic carbon stocks
3. stop soil sealing and increase re-use of urban soils
4. reduce soil pollution and enhance restoration
5. prevent erosion
6. improve soil structure to enhance soil biodiversity
7. reduce the EU global footprint on soils
8. improve soil literacy in society

The Soils for Europe (SOLO) project has identified Nature Conservation of Soil Biodiversity as the overarching theme of the Soil Mission objectives in research and innovation even though it is currently not a stated objective of the Soil Mission. This Think Tank (TT) aims to further the Soil Mission's research and innovation agenda through the TT's collective knowledge of the ecological importance of soil biodiversity to soil health and its economic and societal impact, which also contributes to the soil strategy and the EU biodiversity strategy. The integrative nature of soil biodiversity conservation across the mission objectives is a key feature as soil biodiversity is the basis of soil functions and ecosystem services.

The TT on Nature Conservation of Soil Biodiversity is led by researchers from Lund University and University of Leipzig. TT members represent the areas of research and policy from a range of universities, NGOs, industry and policy bodies. Through literature reviews and transdisciplinary work with stakeholders and researchers, this TT is assessing knowledge gaps and developing possibilities for research and innovation in future roadmaps, as needed for improving knowledge on conservation of soil biodiversity. The TT has identified current knowledge and knowledge gaps with an initial four-pronged approach:

- A literature review of the most recent research into gaps of knowledge regarding nature conservation of soil biodiversity (September 2023)
- Online workshop with TT members (November 2023)
- In-person workshop (December 2023)
- Future reassessment of knowledge gaps after public review (January 2024)

From an initial TT online workshop in November 2023, preliminary gaps in knowledge, based on expert knowledge and input from TT members, are presented here in summary. Together with comments from public review, this document will serve as the basis for recommendations and further work of the TT.

## State-of-the-Art for Conservation of Soil Biodiversity

Soil biodiversity is defined by FAO et al. (2020) “as the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes”. To paraphrase Orgiazzi (2022), this, ideally, includes all organisms whose interface with soils is key to their life histories. This large abundance and diversity of taxa is a challenge in researching the importance and roles of soil biodiversity as is the fact that most soil biota are very small and require specialized expertise to identify.

### Nature conservation approaches for biodiversity

In conservation theory and practice, biodiversity can be maintained and protected through two general conservation approaches; 1) protec ting areas and species and 2) integrating conservation in use and management of land (Hummel et al. 2019, Niesenbaum 2019). Methods employed may differ among different land-use perspectives.

## Protected areas

The Convention on Biological Diversity (CBD) definition of protected area is: “A geographically defined area, which is designated or regulated and managed to achieve specific conservation objectives”. These areas are chosen for conservation for varying desired outcomes, both ecological and cultural. The IUCN categorises protected areas depending on the level of protection (Table 1).

Table 1.

The IUCN categories of protected areas (Lausche 2011).

| Category No. | Description |
|---|---|
| Category Ia | Strict nature reserves function to preserve the biodiversity and sometimes geomorphological features of an area and allow only light human traffic |
| Category Ib | Wilderness areas are generally larger than nature reserves and have less stringent regulations |
| Category II | National Parks - areas protected for the preservation of ecosystem functions but with more allowance for human visitation |
| Category III | Protection of national monuments or features, either natural or influenced by humans |
| Category IV | Area managed for continuous protection of a species or habitat |
| Category V | Protected landscape or seascape with the allowance of for-profit activities |
| Category VI | Areas protected but with the sustainable use of natural resources |

This current system of categorising protected areas continues to be utilised even though these focus on management practices rather than monitoring biodiversity outcomes (Boitani et al. 2008), particularly soil biodiversity conservation (Guerra et al. 2022, Zeiss et al. 2022). Cameron et al. (2019) found a considerable mismatch between aboveground and belowground biodiversity, so if only areas with the highest aboveground diversity are protected a large portion of soil biodiversity rich areas are at risk for degradation. Zeiss et al. (2022) examined soil biodiversity and ecosystem services across nature conservation areas and non-conserved areas across Germany and found that, while conserved areas are assumed to have positive effects on non-target ecosystems, there was no evidence of these conservation measures having positive influence on soil biodiversity or benefits regarding associated ecosystem functions. In evaluating the aims in selecting these sites, multiple reasons were found for the lack of observed effects. Firstly, there is a lack of emphasis on site selection for conservation based on the value of soil biodiversity and associated ecosystem services as evidenced by language used in selection justifications. Secondly, Zeiss et al. (2022) found an emphasis on threats to chemical and physical properties of soil in the selection language instead of emphasis on the value of the belowground ecosystems and the functions that influence abiotic factors.

## Protected species

Species of soil organisms that are protected for being rare are atypical because knowledge of specific species' abundances and distributions are, for the most part, lacking (Phillips et al. 2017, Karam-Gemael et al. 2020) . Lists of endangered soil organisms are generally comprised of rare fungal species (Mueller et al. 2022) or earthworms (Stojanović et al. 2008) , although the IUCN is beginning to establish a working group to guide the identification of threatened soil species, and here knowledge of taxa and their distributions and threats are crucial.

### Integration of conservation into sustainable use

Protected areas have long been the most important tools in conservation. However, with increased focus on ecosystem services and human well-being the focus is changing from protection of (threatened) species towards sustainable use (Hummel et al. 2019), and thus ecosystem functions and services. Sustainable use is defined as “The use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations” (EC 1993). This approach is widely used, especially in agriculture and forestry. Examples of integration of conservation are e.g. agro-ecological intensification, agroforestry and extensive forest technical management. The EU Common Agricultural Policy (CAP) provides several suggestions on how to protect soil biodiversity, e.g. moving from conventional to reduced tillage, banning burning of organic material, and maintenance of grasslands. However, discussions and data concerning soils and their sustainable use have long focused on either their vulnerability to physical impacts (e.g., soil erosion, mining) or improvements to their food production potential (e.g., through fertilisation). These narrow perspectives, often missing indicators and being disconnected from environmental monitoring, limit a wider discussion on the ecological importance of soil biodiversity and its role in maintaining ecosystem functioning beyond food production systems (Guerra et al. 2021). This prevailing emphasis has also prevented soils from becoming a more mainstream “nature conservation priority” (Guerra et al. 2021). In 2018, no indicators of soil biodiversity could be provided to monitor the environmental performance of the post-2020 CAP, due to lack of data (Köninger et al. 2022).

## Research on soil biodiversity and conservation

### Soil biodiversity, ecosystem functions and services

Soils contain diverse communities and these can be found at very small scales, which is a challenge in research on soil biodiversity. The evolvement of molecular techniques has in the last decades led to accumulation of scientific papers on soil biota, especially on soil microorganisms, and thus our knowledge of soil biodiversity is increasing rapidly (Mishra et al. 2022).

In the past decades, there has been a growing body of knowledge and awareness on the importance of soil biodiversity to ecosystem functioning and processes (Bardgett and van der Putten 2014, Barrios 2007, Creamer et al. 2022, Delgado-Baquerizo et al. 2020, FAO et al. 2020, Giller et al. 1997) though this is relatively small compared to what we do not yet understand. The research in the 1970s and -80s, such as the *Man and the Biosphere*

*(MAB)* programme of UNESCO programme, created knowledge on the significance of soil organisms in ecosystem functioning globally (Persson and Lohm 1977) . The scientific scope of ecosystems ecology today emphasises functions and the role that soil biodiversity plays in understanding decomposition, energy fluxes or resilience aspects (e.g. de Ruiter et al. 2002) . Notably, the Tropical Soil Biology and Fertility Programme (TSBF) was established in 1984 under the patronage of the MAB programme of UNESCO and the Decade of the Tropics initiative of the International Union of Biological Sciences (IUBS). The objective of the programme was to develop appropriate and innovative approaches for sustaining tropical soil fertility through the management of biological processes and organic resources (Woomer and Swift 1994) .

Ecosystem research has been developed over the years through the concept of soil food webs and the direct and indirect interactions among soil organisms in order to determine how the diversity of species and functional groups influence the energy and nutrients fluxes in soil (de Ruiter et al. 1993, de Ruiter et al. 1998). The importance of soil biodiversity to ecosystem functions has been investigated in experimental systems, with much support found for the importance of the soil food web to ecosystem functions (Wagg et al. 2014). However, linking the diversity of soil organisms to ecosystem functions at different spatial and temporal scales in real ecosystems is a difficult process within the array of interacting soil organisms, and studies produce mixed results (de Vries et al. 2013, FAO et al. 2020, Nielsen et al. 2010, Schuldt et al. 2018, Veen et al. 2019).

## Soil biodiversity conservation and policy

The importance of soil biodiversity to ecosystem functioning and human well-being are often lacking in nature conservation literature and policy instruments. The conservation status of most soil organisms is almost completely unknown, but there is evidence that protected/conservation areas do not necessarily protect soil biodiversity (Cameron et al. 2019, Ciobanu et al. 2019, Guerra et al. 2021, Zeiss et al. 2022). While chemical and physical properties are relatively well known, we now have access to the high-resolution and molecular tools needed to study biodiversity and function in soil (Guerra et al. 2021). As part of the 2018 LUCAS survey, 885 locations throughout the EU were sampled to study taxonomical and functional diversity in soil by metabarcoding. This may allow us to develop a suite of biodiversity indicators that may be considered for official inclusion in assessments and reviews of EU policies (Orgiazzi et al. 2022, Köninger et al. 2023, Labouyrie et al. 2023). The identification of indicator organisms of e.g. biodiversity or deteriorated communities is still an unanswered research question that currently is receiving a lot of focus (e.g. the EU Horizon project SOB4ES: https://sob4es.eu/).

Köninger et al. (2022) analysed how EU legislation and directives address conservation of soil biodiversity. Most of the legislations and strategies only address the threat to soil biodiversity indirectly, e.g. the Biodiversity Strategy for 2030 and the Farm to Fork strategy. The same goes for the 17 EU directives that Köninger et al. (2022) identified. All of them address issues, e.g. soil pollution, that could benefit soil biodiversity, but they do not explicitly address soil biodiversity per se. Soil biodiversity monitoring schemes in the EU member states often only focus on chemical and physical properties, but rarely on soil biology (Köninger et al. 2022), and out of the 196 parties of the CBD only a few had national targets (for 2011 – 2022) considering conservation of soil and soil biodiversity (Guerra et al. 2021).

## Drivers of soil biodiversity change

Both spatial and temporal environmental variations play an important role in determining the distribution and coexistence of species. Thus, natural and anthropogenic processes drive the change of species distribution in soil. In ecological terms, the distribution of species are often caused by trade-offs in life history, but changing environmental conditions instigates extremes in these trade-offs (Jousset et al. 2017). For example, species with a highly specialised niche space may be abundant in a small number of locations but rare overall and would be adversely affected by increasing homogeneity of soil habitats due to human activities.

To identify the main drivers of soil biodiversity change, Work Package 3 (WP3) of the SOLO Project has identified **D**riving forces, **P**ressures, **S**tate, **I**mpact, and **R**esponse measures (DPSIR) as fundamental components of soil health. Knowledge from previous research across the four land-use types of agriculture, forest, urban and industrial areas, and natural areas has contributed to a creation of an inventory of drivers of changes, with a focus on their potential to motivate the future change. This work is ongoing and will be integrated in the SOLO project roadmap during 2024.

## Soil biodiversity conservation awareness and information sharing

To contribute to conservation and sustainable management of soil biodiversity, a few initiatives and research networks have been established over the years. Agreements and definitions of the conservation of soil biodiversity were brought to the international agenda by FAO in cooperation with the Convention on Biological Diversity (CBD) with the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, established in 2002. In 2012, the FAO set up the Global Soil Partnership (GSP) to further increase attention and work on soils, due to their vital importance for food and agriculture. Another important initiative is the Global Soil Biodiversity Initiative (GSBI), a network of scientists, policy and public, that was established in 2011 and has given an international platform for assessing and synthesising knowledge on soil biodiversity.

The collection of data on soil biodiversity is a challenge that is also raised by e.g. the GBIF (Global Biodiversity Information Facility), an international network and data infrastructure funded by the world's governments and aimed at providing open access to data about all types of life on Earth. In addition, the European Cost Action Edaphobase will create the structures, capacities and procedures necessary for expanding the existing data platform on soil fauna ("Edaphobase") into an open, publicly available data warehouse for Europe-wide soil biodiversity data as well as for developing tools that use and evaluate this data. Additionally, efforts such as the Soil Biodiversity Observation Network (SoilBON) https://

www.globalsoilbiodiversity.org/soilbon are aimed toward systematically collecting observational data on soil biotic and abiotic factors worldwide to assess the condition of soil biodiversity and functions with a focus on the effects of protection/conserved status of the land area (Guerra et al. 2021).

## Knowledge Gaps for Nature Conservatioon of Soil Biodiversity

The knowledge gaps for nature conservation of soil biodiversity and their related bottlenecks are detailed here. Table 2 represents a "quick reference" to these.

Table 2.

**Table 2.** Knowledge gaps and bottlenecks to closing knowledge gaps related to the nature conservation of soil biodiversity. Time frames to fill or accomplish are defined as Short – 1-5 years; Med – 5-10 years; Long – 10-20 years. SB – Soil biodiversity

| No. | Knowledge Gap | Time frame to fill/accomplish | | | Dependent on filling the gap or bottleneck |
|---|---|---|---|---|---|
| | | Short | Med | Long | |
| Data and method standardisations | | | | | |
| 1 | Standard SB indicators | X | X | | |
| 2 | Standard methods | X | | | |
| 3 | Model improvement | X | X | | |
| Conservation | | | | | |
| 4 | Conservation methods | | X | X | 6;7;8 |
| 5 | Characteristics of SB to focus conservation | | X | | 7;8 |
| **Bottlenecks** | | | | | |
| Taxonomy, ecology and distributions | | | | | |
| 6 | Unknown taxa & distributions | | | X | |
| 7 | Unknown species' ecologies | | X | X | |
| 8 | Drivers of distributions | | X | X | 7 |
| Threats to soil biodiversity | | | | | |
| 9 | Unknown threats | | X | X | 7;8 |
| 10 | Unknown extinction risks | | X | X | 7;8 |
| 11 | Invasive species as risks | | X | | 6;7;8 |

## Need for Indicators, Methods, Modeling and Expertise for Conserving and Monitoring Soil Biodiversity (Table 2. Gaps 1,2,3)

One of the major barriers in the capacity to develop effective soil conservation practices and policies is the *lack of standardised indicators and methods to collect data* to provide baselines and trends in monitoring conservation of soil biodiversity (from now on SB).

Different methods used by different research groups to measure the same taxonomic groups and their functions, although acceptable for local conservation purposes, result in incomparable datasets across different regions and temporal scales. Additionally, it remains unknown if, and to what degree, the spatial and temporal resolution of the measurements of environmental parameters are adequate to the actual resolution of SB presence and abundance data thus far (Eisenhauer et al. 2021, Gábor et al. 2022). The question remains, what standard indicators and methods provide substantial information on the levels of soil biodiversity and associated ecosystem functions? (Guerra et al. 2021).

Predictive modeling. Modern statistical analyses such as Scenario Modelling, Species Distribution Modelling (Salako et al. 2023), General Dissimilarity Modelling, and Niche-Space Modelling can be effective ways to predict adequate habitat and select areas for conservation of SB. These can also overcome some sampling bias but cannot be a "silver bullet" due to the small-scale heterogeneity of communities in soil. Success of these techniques will require (1) further collation and harmonisation of observational soil-biodiversity data at an international level (including a paradigm change among researchers and funding agencies regarding open-access data sharing (e.g. Michener 2015, Tedersoo et al. 2021), (2) improved precision in the association between observational SB data and environmental and climate metadata, as well as (3) a strategy to increase capacity-building efforts in these efforts as well as training new taxonomic experts and local stakeholders/ practitioners to conduct accurate assessments and use models. How can experts, methods, and models be further developed and honed to provide an effective portfolio of best practices?

## The Multifunctionality of and Conservation Practices that Protect Soil Biodiversity (Table 2. Gaps 4 & 5)

Richness vs. Function. What about soil biodiversity needs protecting? In contrast to aboveground life, which is more easily observed and vastly more investigated, the richness and ecosystem functions of soil invertebrate and microbial taxa are still in need of clarification. This leads to the question, what aspect(s) of SB should be the target of conservation? While the overall diversity (species richness) of taxa in soil is important in and of itself (Phillips et al. 2020), the functional aspects of soil faunal and microbial life cannot be lost in the process of protecting taxonomic diversity (Phillips et al. 2020). Active restoration and conservation require attention to this complexity of species diversity and other biodiversity facets (e.g. size variation, life history traits) (Eisenhauer et al. 2021, Guerra et al. 2022Eisenhauer et al. 2021, Guerra et al. 2022) as well as a diversity of functions (Nielsen et al. 2010Nielsen et al. 2010).Maintenance of species richness, community composition, and ecosystem functions are not often synonymous, and investigations into a trait-based approach to SB conservation and restoration are largely lacking (Guerra et al. 2022). Auclerc et al. (2022) summarised the importance of functional-trait approaches to restoration with soil invertebrates, but also detailed critical knowledge gaps. These include:

1. the lack of use of trait-based techniques for restoration and, therefore, a dearth of evidence of its benefits,

2. general lack of knowledge of the roles invertebrates play in ecosystems,

3. a lack of representation of these data in current trait-based databases, and

4. the complex relationships of function to traits (Auclerc et al. 2022)

What conservation methods protect soil biodiversity? Since conservation management and site selection have typically not considered SB and its ecosystem functions, it is still unclear how current conservation affects SB and how to adjust current conservation and restoration practices to positively impact soil biodiversity across the EU and regionally. We know that current site selections and management practices do not generally benefit SB ( Zeiss et al. 2022), but potential biodiversity-friendly management options exist that could be "scaled-up" (Barrios et al. 2023). However, regions across Europe must be evaluated for what specific SB communities and associated functions they are capable of supporting. Guerra et al. (2022) showed that, globally, areas that may rank highly in one ecological dimension, such as species richness, may not rank highly in another. This suggests that potential sites for conservation are not equal, nor can they be treated similarly, when considering what areas to conserve and what restoration/conservation practices are effective when targeting SB.

## Bottlenecks Filling Gaps in Knowledge of Soil Biodiversity Conservation

A number of challenges and bottlenecks to filling these gaps in knowledge to conserve SB require an expansion of toolsets and innovative approaches to tackle. Developing a fundamental understanding of the following will lead to knowledge of the great majority of taxa inhabiting soils, habitat suitability and, therefore, distributions, which are critical to conserving SB and furthering goals of the Soil Mission. In brief, we explain these bottlenecksand the importance of advancing the science of soil-dwelling taxa to inform how to effectively conserve and restore soil life. We discuss 1) the barriers to discovering and describing the numerous and diverse, yet unknown, taxa in soils, 2) the lack of understanding of ecologies and functions of these microbes and invertebrates and how this drives their distributions, and 3) the threats to SB, such as invasive species, and extinction risks.

### Problem of Unknown Taxa (Table 2. Bottleneck 6)

Many soil taxa are simply unknown to science and awaiting description (Orgiazzi et al. 2016) because:

A. soil fauna and microbes are often cryptic and difficult to observe without disturbing their functioning and habitat, and the variance in the diversity of these communities is significant over just millimetres (Rillig et al. 2015);

B. microbial taxa are difficult, sometimes impossible, to isolate and culture with our current methodologies. This is compounded by the differences in methods necessary to detect and quantify different soil organisms due to heterogeneity in their ecologies (ranging from water-related to truly terrestrial species), size classes (ranging from microbes to megafauna), and distribution patterns (White et al. 2020, Decaens 2010, Eisenhauer et al. 2021);

C. for invertebrate taxa, specialised taxonomic expertise is often needed to identify species within groups of soil animals. Expertise in many soil fauna groups is rare, leading to a perpetual cycle of infrequent opportunities for knowledge transfer and a dwindling body of experts;

D. and, lastly, we lack a unified definition of soil biodiversity to use as a basis for policy development and regulatory measures (Rillig et al. 2019, FAO et al. 2020, Orgiazzi 2022).

This lack of understanding of what soil-dwelling taxa exist leads to a fundamental roadblock in pursuit of other information vital to SB conservation, such as their distributions and understanding the ecosystem functions and services they provide to humans and other life on Earth.

## Problem of Unknown Ecologies, Distributions, & Drivers (Table 2. Bottlenecks 7 & 8)

We lack critical information on the ecologies of most soil taxa, the habitats in which they dwell, and what drives their distributions (Cameron et al. 2018) to be able to understand how and where conservation can be achieved for different taxonomic groups. In the same wheelhouse as function, ecology includes “how and what” biota interact, procreate, and consume in their environment to drive ecosystem functions and services for human well-being. Studies in the ecology and life histories of soil-dwelling species are time-consuming and detail-oriented undertakings necessary to understand their ecosystem functions and effects on other life, yet they are often considered not innovative enough to be funded. Current knowledge in invertebrate ecology is based on manipulative landscape experiments and some direct observation and mesocosm experiments, the latter two of which are rare research approaches in ecology, but common in biological control. In microbial research, the current methods include molecular methods for identification (i.e. metabarcoding, “shotgun” approaches), which many fewer studies on the functional genes that reveal what different microbes digest and release.

Current understanding of distributional patterns is based on expert knowledge, observational data from landscape gradient studies, and/or available records in museum collections, but these vary in utility. One common issue if the lack necessary environmental and climate metadata to associate taxa to habitat characteristics is missing from publications and essentially non-existent in museum records (Gotelli et al. 2023). While large-scale efforts are underway to coalesce observational data on species' occurrences in international databases, again the required environmental and climate metadata is often missing in uploaded datasets. Experimental research on the response of soil taxa presence and diversity to environmental predictors is patchy (Phillips et al. 2023), biased towards unrealistic levels of edaphic parameters change and unrepresentative for the tropics (Cameron et al. 2018, Guerra et al. 2020), and not directly comparable across ecosystems.

Drivers. Data and theory on the influence of drivers on small- and broad-scale distributions are widely lacking (Thakur et al. 2020, Eisenhauer et al. 2021), rendering conservation assessments and priorities difficult (Decaens et al. 2006). This includes the drivers of community dissimilarity in soil taxa across ecosystems, along with their uniqueness (e.g., endemic species, specialisation for given habitats). For instance, while disturbed habitats can show high species richness and total densities, these are often caused by generalist species, leading to a homogenization of SB and loss of diversity at the landscape scale in a region or country (Gossner et al. 2016, Delgado-Baquerizo et al. 2021, Guerra et al. 2021, Banerjee et al. 2024). Recent work revealed the ubiquity of complex interactions between multiple co-occurring environmental drivers that could affect distributions or evolutionary tactics (Rillig et al. 2019), yet these are poorly studied. These complexities, including effects of land-use and human pressures, are needed in an integrated evaluation of current practices. Extrapolation of conclusions from agricultural research investigating increasing SB for increased ecosystem function can be a starting point for developing best practices. Long-term studies and experiments focusing on specific techniques, such as dead wood management in forests, recognition of trees as "hot spots" of soil biological activity and encouraging heterogeneous soil habitat through diversification of plant species (Eisenhauer et al. 2018) are needed to understand their direct and indirect effects on SB.

Considering qualitative (functional) attributes of soil life during assessment of site-scale measures will vastly improve conservation of SB at broader scales i.e. landscape scale (Ciobanu et al. 2019, Zeiss et al. 2022). These would inform, specifically, the proportion of species within a local community specifically adapted or specialised to the site/habitat as a first approximation in assessing "intact" habitats for soil health as well as land-use measures and conservation.

## Threats to Soil Biodiversity and Understanding Risks of Species' Extinction (Table 2. Bottlenecks 9 & 10)

The current knowledge on threats and, especially, extinction risks for soil-dwelling biota is little and inconsistent, but vital to knowing where and how to start conserving this diverse biotic group. We have more questions than answers: Which potential aboveground biodiversity threats are also threats to SB? What known threats need redefined thresholds to inform conservation decisions? How do we define threats to SB that may be overlooked in conventional conservation thinking (e.g. intentional foreign microbial inocula)?

Unknow extinction risks. The vulnerability of soil invertebrate and microbial organisms, including rare species, is almost entirely unknown and little progress has been made (the best being Decaens et al. 2008). Bottlenecks to conservation of SB include *identifying very rare/threatened, endemic, and vulnerable species and their habitats for protection* (Veresoglou et al. 2015).

Currently, abundance and distribution baselines and thresholds for soil organisms comparable to those for above-ground organisms do not exist though they are urgently called for by policy (EEA 2023). “Red Listing” of soil invertebrate organisms is rare (Phillips et al. 2017, Mueller et al. 2022), for one reason, because typical criterion for listing, such as “population size” in a region or country, are inappropriate for organisms in substrate such as soil. Few studies have incorporated IUCN criteria (i.e. IUCN 2022) for identifying threatened or endangered soil species (Marchán and Domínguez 2022, Salako et al. 2023 ). However, this necessitates answers to some fundamental, yet wholly uninvestigated, questions: What defines rarity for soil taxa? How appropriate for the myriad of soil taxa are local abundance, habitat specificity, and/or geographical distribution in determining rarity? How do we determine susceptibility to extinction for soil biota?

To identify and have threatened species recognized, this requires knowledge of the species and its detailed functional criteria, especially in the case of species that are highly sensitive to climate shift, invasion of exotic species, etc. Moreover, standardised assessment criterion for rare or threatened taxa across the EU as is necessary for European and EU regional efforts of conservation (van der Putten et al. 2023). With these standards, we can identify the taxa at risk, create a preliminary list of what species/OTUs are threatened, and identify conservation practices, concrete management options, and potential sites for conservation. This is critical to predict the fate of soil organisms under global change and ensure their conservation.

## Invasive Species’ Knowledge and Risks (Table 2. Bottleneck 11)

A corollary to the identification of rare, threatened, and endemic species *is, what are the criteria to designate something as invasive with regards to SB*? This has not been taken into consideration, primarily, because the directionality of invasions in soils is difficult to determine, and we are unaware of the identity of most local and invasive soil taxa. It is also unknown what environmental or economic damage 'invasive' organisms can cause to soils and ecosystems, unlike similar studies in, for example, agricultural settings. The two barriers to finding out this information are that:

1. there is little way to track invasion or origin of a present microbial OTU and

2. specifically for microbes, there is no conceptual models to think about what a species is in the way other species are conceptualized.

Increasing the taxonomic information of soil biota communities, starting with that in already vulnerable ecosystems, such as those susceptible to the increasing oscillations in heat and temperature regimes, will be critical to provide the foundation to monitor the influence of soil invasive species on the functioning and stability of our ecosystems.

## Conclusion

Conservation of soil biodiversity is a multifaceted process involving, what we expect will be, a multitude of approaches that will benefit the large-scale diversity of soil life across Europe as well as the needs and environments of the regions within Europe. Developing effective ways to conserve and monitor the trends in soil biodiversity across the complex functions of these communities is as important as the communities themselves and should be taken into account in considering their protection. To do this, increasing cooperation between soil ecologists and other disciplines for, as examples, chemical analyses and molecular and morphological identification, continue to be integral to developing a full understanding of the soil biodiversity community. In this regard, one of our responsibilities for the future of soil health and should be plans for current and future monitoring and 'assessments' i.e. Soil Biodiversity Observation Network (SoilBON), Global Soil Biodiversity Observatory (GLOSOB) (Eisenhauer et al. 2021, Guerra et al. 2022, Nielsen et al. 2010).

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