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Nature conservation of soil biodiversity

Scoping document

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# Outlook on the knowledge gaps to improve nature conservation of soil biodiversity

Monica A. Farfan[‡], Carlos A. Guerra[§], Maria Ingimarsdottir[|], Katarina Hedlund[|], Edmundo Barrios[¶], Neil Cox[#], Anders Dahlberg[¤], Francisco de Assis Sanchez Crespo[«], Franciska de Vries[»], Manuel Delgado-Baquerizo[˄], Nico Eisenhauer[‡,˅], Maria Lundesjö[¦], Alberto Martin[ˀ], Alberto Orgiazzi[ˁ], J. Jacob Parnell[¶], Anton Potapov[₵], Kelly S. Ramirez[ℓ], Natália Raschmanová[₰], David Russell[₵], Vincent Kolia Tchedry[₱], Maria Tsiafouli[₳], Lia Uhde[˅], Andrey Zaytsev[₵]

‡ German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Leipzig, Germany
§ University of Coimbra, Coimbra, Portugal
| Lund University, Lund, Sweden
¶ UN Food and Agriculture Organization (FAO), Rome, Italy
# Conservation International's Center for Applied Biodiversity Science, Washington DC, Washington, United States of America
¤ Swedish University of Agricultural Sciences, Uppsala, Sweden
« European Comission DG ENV, Brussels, Belgium
» University of Amsterdam, Amsterdam, Netherlands
˄ Instituto de Recursos Naturales y Agrobiología de Sevilla, Sevilla, Spain
˅ University of Leipzig, Leipzig, Germany
¦ Axfoundation, Stockholm, Sweden
ˀ IUCN Centre for Mediterranean Cooperation, Málaga, Spain
ˁ EC Joint Research Centre (JRC), Ispra, Lombardia, Italy
₵ Senckenberg Museum of Natural Sciences, Görlitz, Germany
ℓ University of Texas, El Paso, United States of America
₰ P.J. Safarik University, Kosice, Slovakia
₱ European Commission, Brussels, Belgium
₳ Aristotle University of Thessaloniki, Thessaloniki, Greece

Corresponding author: Monica A. Farfan (monica.farfan@idiv.de), Maria Ingimarsdottir (maria.ingimarsdottir@biol.lu.se)

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## 1. Introduction

There has been an increasing awareness of the importance of soil biodiversity and the ecosystem services it provides (Mikola et al. 2002, Eisenhauer et al. 2024). Approximately 59% of all biodiversity on the planet comprises belowground-dwelling organisms (Anthony et al. 2023), ranging from microorganisms to vertebrate species (FAO et al. 2021, Anthony et al. 2023). The activities of soil biodiversity (soil biota) support the delivery of various ecosystem services, such as, for example, carbon sequestration, nutrient cycling, prevention of soil erosion, pest control, and cleaning of air and water (Pulleman et al. 2012, Creamer et al. 2022, Banerjee and van der Heijden 2023). However, soil biodiversity is currently threatened by changing climate extremes, intensive agriculture and forestry, as well as pollution and soil sealing in urban environments (Tsiafouli et al. 2015, FAO et al. 2021, Beaumelle et al. 2023, Phillips et al. 2024). Protecting soil biodiversity, and thus its ecosystem functions and services, through conservation will have positive effects in achieving the Sustainability Development Goals (SDGs) (Bach et al. 2020), including increasing water quality and food security, among others (FAO et al. 2021, Köninger et al. 2022).

Soil life is key to the survival and health of life and ecosystems on Earth (Banerjee and van der Heijden 2023, Singh et al. 2023) but it is under-protected (Guerra et al. 2022), leaving its associated ecosystem functions and services under-protected as well. Soil biodiversity is defined by FAO et al. (2021) “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”.

There is little research on the efficacy of current conservation methods and frameworks specifically for soil biodiversity protection (Guerra et al. 2022). Recent work did not find positive effects of current conservation practices on nematode diversity (Ciobanu et al. 2019) and soil biodiversity and its ecosystem functions (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. 2021, 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.

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 impacts, which also contributes to the EU Soil Strategy and the EU biodiversity strategy. The integrative nature of soil biodiversity conservation across the Mission objectives is a key feature because soil biodiversity is the basis of soil functions, processes, and ecosystem services. Led by researchers from Lund University with support from University of Leipzig, TT members represent the areas of research and policy from universities, NGOs, 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 for future roadmaps to improve knowledge on the nature conservation of soil biodiversity. The TT has identified current knowledge and knowledge gaps with the following steps:

- A literature review of the most recent research into gaps of knowledge regarding Nature Conservation of Soil Biodiversity (September 2023)
- Online workshop with TT stakeholders (November 2023)
- Joint TT meeting, Barcelona, Spain (December 2023)
- Reassessment of knowledge gaps after public review (January 2024)
- Joint TT meeting, Sofia, Bulgaria (November 2024)
- Literature analysis on soil ecology and conservation biology (Summer 2024)
- Online meeting with Nature Conservation TT stakeholders (January 2025)

# 2. State-of-the-Art on Nature Conservation of Soil Biodiversity

## 2.1 Current State of Knowledge on nature conservation of soil biodiversity

"*Soil, at any scale, is complex: opaque, composed of a myriad of organo-minerals, roots, large and small organisms, and exhibiting truly impressive gradients in its biology, chemistry and physics over large and small spatial ranges." – Young and Bengough 2018*

### Soil biodiversity, ecosystem functions, and ecosystem services

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. Eisenhauer et al. 2022). However, linking the diversity of soil organisms to ecosystem functions at different spatial and temporal scales in real ecosystems is a difficult process due to the sheer number of individuals and interactions, therefore studies produce mixed results in the types and magnitude of effects (de Vries et al. 2013, Nielsen et al. 2011, Schuldt et al. 2018, Veen et al. 2019, Delgado-Baquerizo et al. 2020, FAO et al. 2021).

The importance of soil biodiversity for ecosystem functioning has been investigated in experimental systems, with support found for the importance of the soil food web to ecosystem functions (de Vries et al. 2013, Wagg et al. 2014). Soil ecosystem research developed from soil food web ecology, where it is understood that both direct and indirect interactions among soil organisms 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, Jochum and Eisenhauer 2021). The research in the 1970s and -80s, such as the Man and the Biosphere (MAB) programme of UNESCO, created knowledge on the significance of soil organisms in ecosystem functioning globally (Persson and Lohm 1977). Of note are the Tropical Soil Biology and Fertility Programme (TSBF), 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 this last 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).

Economic values of soil ecosystem services associated with soil biodiversity lack optimised and standardised models. There are general frameworks of valuation of soil biodiversity (Pascual et al. 2015, Plaas et al. 2019, Bartkowski et al. 2020, Han et al. 2023, Johnson et al. 2024), but this has not become an important focus in awareness raising nor in policy or land management decision making as of yet (Phillips et al. 2020). Thorough assessments of the contributions of soil organisms to ecosystem services are urgently needed to guide decisions regarding tradeoffs in choosing areas to conserve and conservation methods. Fig. 1 details the overall linkage of soil biodiversity to ecosystem functions, services to humans, and the feedback of land management and conservation practices by human society on soil biodiversity. Changes to agriculture, land management, environmental regulations, and stewardship can be made to protect soil biodiversity, its ecosystem functions, and services to humans and support the Sustainability Development Goals of the UN (Bach et al. 2020; Fig. 2)

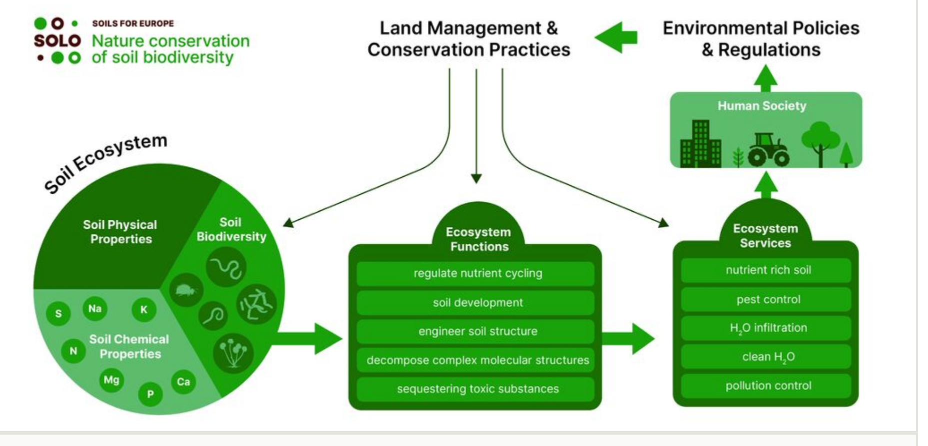


Figure 1. doi

Soil biodiversity is integral to ecosystem functions and benefits human society through its associated ecosystem services. In turn, conservation and land-management policy and decision making directly impact soils biodiversity and, indirectly, ecosystem functions and services. Credit: Pensoft Publishers.

## Conservation

Because we have incomplete, yet useful, information on the taxonomic and functional diversity in soils, this leads to challenges in understanding how to effectively protect and preserve functions through conservation and restoration practices. 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 they provide (Table 1, Lausche 2011).

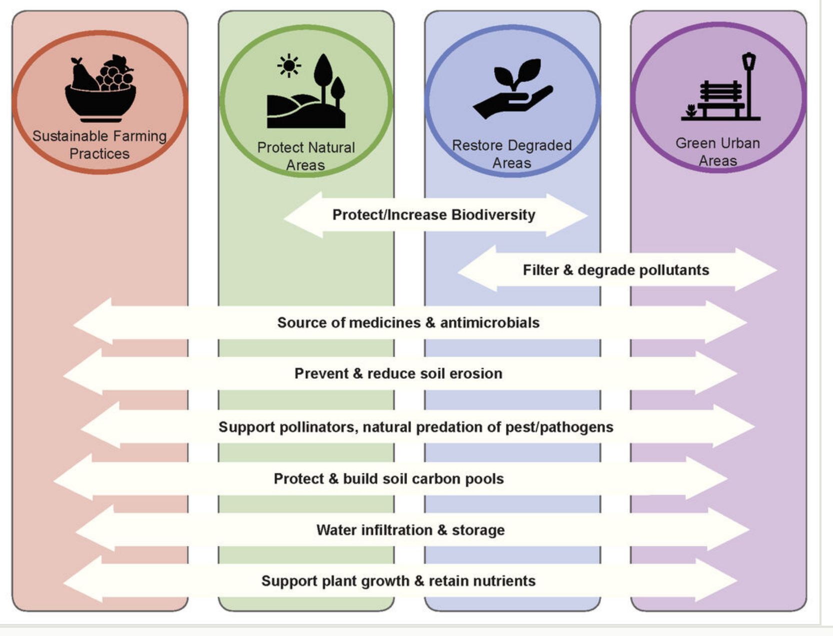


Figure 2. doi

Areas where action can be taken that support soil biodiversity and its associated ecosystem services. From Bach et al. 2020. Image credit: K.S. Ramirez, E.M. Bach.

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 system of categorising continues to be utilised even though it focuses on management practices rather than monitoring biodiversity outcomes (Boitani et al. 2008), particularly soil biodiversity conservation (Guerra et al. 2022, Zeiss et al. 2022). Most conservation areas were designated to protect specific plants and animals, with soil ecosystems not being directly considered while developing such protected environments. Cameron et al. (2018) found a considerable mismatch between aboveground and belowground biodiversity at the global scale. This means, if only areas with the highest aboveground diversity are protected, a large portion of soil biodiversity-rich areas may be at risk for degradation. Zeiss et al. (2022) examined soil biodiversity and ecosystem services across nature conservation areas and non-conserved areas across Europe 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 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 protected area selection language instead of an emphasis on the value of the belowground ecosystems and the functions that influence abiotic factors.

## Integration of conservation into sustainable use

Protected areas have long been the most important tools in biodiversity 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” (European Commission 1993). This approach is widely used, especially in agriculture and forestry. Examples of integration of conservation are e.g. agroecological intensification, agroforestry, and extensive forest technical management.

The EU Common Agricultural Policy (CAP) provides several suggestions on how to protect soil biodiversity through soil health, e.g. enhanced crop rotations, reduced tillage, cover crops and fertiliser regulations. 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). Narrow perspectives, often missing indicators and disconnectedness 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. 2021b). This prevailing emphasis has also prevented soils from becoming a more mainstream nature conservation priority (Guerra et al. 2021b).

## Soil biodiversity conservation, policy, and indicators

The conservation status of most soil organisms is almost completely unknown, with most soil taxa yet to be described. Among 17 EU directives, a review determined that 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 (Köninger et al. 2022). These address issues, e.g. soil pollution, that could benefit soil biodiversity, but they do not explicitly address soil biodiversity per se. Soil monitoring schemes in the EU member states often only focus on chemical and physical properties, but rarely on soil biology (Köninger et al. 2022). Out of the 196 parties to the CBD, only a few had national targets in years 2011 – 2022 that consider conservation of soil and soil biodiversity (Guerra et al. 2021b). Therefore, monitoring and the careful choice of indicators to monitor soil biodiversity are of key importance. Though with the coming EU soil monitoring and resilience directive, further data sets of soil biodiversity across all land use will secure data on soil biodiversity (COM/2023/416 final 2023).

The Land Use and Land Cover Survey (LUCAS) action from the European Commission (2025) enables EU wide sampling of soils and land use. Eight hundred and eighty-five locations were sampled in 2018 and 2021/2022 to study taxonomical and functional soil biodiversity by metabarcoding. This may allow data and development of a suite of biodiversity indicators that may be considered for official inclusion in assessments and reviews of EU policies (Köninger et al. 2023, Labouyrie et al. 2023). The identification of indicator organisms of 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/).

## Soil biodiversity conservation awareness and information sharing

At regional and local levels, awareness raising targeted to stakeholders, general public and in education is needed for understanding of the importance of soil biodiversity and to support for regional and EU-wide policies and regulations on soil biodiversity conservation. To contribute to conservation and sustainable management of soil biodiversity, several initiatives and research networks have been established over the years. Agreements on 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 effort is the Global Soil Biodiversity Initiative (GSBI), an independent, third-party network of scientists, policymakers, and citizens. Established in 2011, the GSBI provides a platform for assessing and synthesising knowledge on soil biodiversity and was called upon by the CBD to support post-2020 soil biodiversity monitoring and target development, among others.

# 3. Roadmap for nature conservation of soil biodiversity

## 3.1 Key knowledge gaps

Key knowledge gaps, as judged through a combined Think Tank prioritization process, are shown in Table 2.

Table 2.

Ranking of the top 10 knowledge gaps identified (a full list of all identified knowledge gaps is given in section 3.3)

| Rank | Knowledge gap | Type of knowledge gap |
|---|---|---|
| 1 | Standardisation of soil biodiversity monitoring methods | Knowledge Development Gap |
| 2 | Economic valuation of soil biodiversity | Knowledge Development Gap |
| 3 | Effective conservation and restoration methods | Knowledge Development Gap |
| 4 | Effective conservation frameworks | Knowledge Development Gap |
| 5 | Public awareness of soil biodiversity | Knowledge Application Gap |
| 6 | Effective soil biodiversity conservation strategies | Knowledge Application Gap |
| 7 | Minimum dataset to index soil biodiversity | Knowledge Development Gap |
| 8 | Threats to soil biodiversity | Knowledge Development Gap |
| 9 | Species taxonomic identity and ecology | Knowledge Development Gap |
| 10 | Spatial & temporal distribution of soil biodiversity | Knowledge Development Gap |

### 3.1.1 Standardisation of soil biodiversity monitoring methods

One of the major barriers in the capacity to develop effective soil biodiversity conservation practices and policies is the lack of standardised methods of field data collection. Identifying a set of soil indicators to track soil conservation is critical to provide a set of standard tools and a public repository to monitor trends in the biomass, abundance and diversity of soil biota and its functions. The level of methodological standardisation largely depends on the aspect and type of soil organism to be measured. For instance, the characterization of microbial biomass is largely lacking a widely accepted and standardised method in the literature, with multiple coexisting methods. The standardisation of methods for both fully monitoring and conserving soil biodiversity have been raised as concerns multiple times, and many alternatives have been put forth (Gardi et al. 2009, de Bello et al. 2010, Cluzeau et al. 2012, Pulleman et al. 2012, Griffiths et al. 2016).

For effective, standardised monitoring, there is a need for the combination and integration of indicators to adequately interpret the state of soil biodiversity and trends in the functions of soil organisms. There are registered ISO standards for a number of the soil organisms and suggestions for methodological approaches to measure structural and functional diversity of soil organisms, and to identify gaps and methodological improvements so as to cross data sets generated worldwide (Römbke et al. 2018). Thus, for key aspects of soil microbes such as taxonomic and functional diversity, next generation sequencing "omics" have imposed a relative level of standardisation over the last two decades with many researchers using the same technology (e.g., Miseq and Hiseq Illumina) and similar primer sets (e.g., 16s, V3-V5 regions). Such standardisation has been further supported by significant initiatives such as the Earth Microbiome Project (earthmicrobiome) which already suggested standardised protocols more than a decade ago. This knowledge is key to providing standardised information for supporting soil conservation worldwide.

Soil biodiversity indicators need to be easy to standardize and widely available to researchers worldwide (Guerra et al. 2021b). For instance, previous studies have proposed combinations of indicators such as the evaluation of abundance and diversity of earthworms and Collembola, along with determination of microbial respiration (Bispo et al. 2009, Pulleman et al. 2012). Nematode communities have also been used successfully to evaluate the functional and ecological conditions of soils (e.g. Ferris 2010 ). Cluzeau et al. (2012), found that soil fauna and microbial biomass were adequate as bioindicators for land-use types and their managements, showing that, depending on the depth of the functional aspects that are examined, the dataset need not be large to discern differences in how the land is used and managed.

Table 3 summarises the indicators by biodiversity and functional categories that are examples of indicators to adequately represent the state of soil biodiversity in general and the method used to rank these indicators. The problem is that many of these indicators are not easy to measure and researchers have not yet agreed on a golden standard to measure such parameters.

Table 3.

Summary of research and proposals for indicators for continental-scale monitoring of soil biodiversity, assessment methodology, and proposed context for application suggested by the source authors.

| **Biodiversity indicators (assessment method)** | **Ecosystem function indicators** | **Context** | **Source** |
|---|---|---|---|
| Microbial biomass;<br>16S rRNA; pcaH;<br>Nematode (abundance);<br>Nematode (richness);<br>Acari (abundance);<br>Collembola (abundance);<br>Collembola (richness);<br>Earthworm (abundance); Earthworm (richness);<br>Total macrofauna | | Association of biological indicators to land use and management | Cluzeau et al. 2012 |

| Biodiversity indicators (assessment method) | Ecosystem function indicators | Context | Source |
|---|---|---|---|
| Nematode (molecular);<br>Earthworm (morphological);<br>Collembola (morphological);<br>Enchytraeids (morphological);<br>Mites (morphological);<br>Functional genes;<br>Fungi: ergosterol;<br>Microbial T-RFLP;<br>PLFA | Nematode (molecular);<br>Earthworm (morphological);<br>Collembola (morphological);<br>Enchytraeids (morphological);<br>Mites (morphological);<br>Functional genes;<br>Nitrification;<br>Potentially mineralisable N;<br>Hot-water extractable C;<br>Bait lamina;<br>Extra-cellular enzyme activity;<br>Microbial respiration;<br>Water infiltration;<br>DNA abundance;<br>Resilience | Policy-relevant; ecologically-relevant | Griffiths et al. 2016 |
| Tier 1: Earthworm species; Collembola species<br>Tier 2: Macrofauna; Mites; Nematode functional diversity; Bacterial and fungal diversity by DNA or PLFA | Tier 1: soil respiration<br>Tier 2: Bacterial and fungal activity | European-scale monitoring | Römbke et al. 2006, Bispo et al. 2009 |
| Bacteria & Archaea (molecular);<br>Fungi (molecular);<br>Fungi (morphological);<br>Mites (molecular);<br>Pyrosequencing of soil DNA;<br>Molecular microbial biomass | Functional genes (targeting antibiotic producers);<br>Pyrosequencing of soil DNA;<br>Chip Technology (gene regulation);<br>Multiple enzyme assay;<br>Multiple substrate induced respiration | European-scale monitoring | Stone et al. 2016 |

Modern statistical analyses such as Species Distribution Modelling, General Dissimilarity Modelling and Niche-Space Modelling can estimate values of biodiversity, but will require (1) more trans-European observational soil-biodiversity data collation, including open-access data sharing (e.g., Michener 2015, Tedersoo et al. 2021), (2) improved thematic precision of the association between observational soil-biodiversity data and environmental and climate metadata (e.g. Bhusal et al. 2015), as well as (3) capacity building in the form of training expertise, time-consuming tasks of data collation, running the models species by species for the large range of extant soil species, and the human resources necessary to do accurate assessments.

**Actions to fill knowledge gaps in standardising soil biodiversity monitoring methods**

- Harmonisation and standardisation of methods and data management
  - Cooperation and discussions between soil ecologists and other disciplines
  - Methods standardisation should inform plans for current and future monitoring and 'assessments', such as the Soil Biodiversity Observation Network (Soil BON) and the Global Soil Biodiversity Observatory (GLOSOB) (Nielsen et al. 2011, Eisenhauer et al. 2021, Guerra et al. 2022)
  - The use of sequencing technology to track soil microbial diversity
  - In the case of larger organisms and soil processes, there are also critical limitations when it comes to data standardisation and comparison across databases
- Develop and enhance soil biodiversity indicators
- Identify examples of standard and easy to measure biodiversity indicators
- Develop a comprehensive information system of soil biodiversity

**Bottlenecks to filling knowledge gaps in standardising soil biodiversity monitoring methods**

The barriers to standardising methods for monitoring and conserving biodiversity are relatively few, though a transformation towards open access and agreements on standardisation is needed. There is a wide range of methodologies for measuring soil biodiversity and functions, including ISO standards, as mentioned above, but although many suggestions have been made for suites of parameters, there is still a lack of common agreement on one suite that is valid across science and end users of the assessment. However, not all methods work for all climatic conditions or soil types (van der Putten et al. 2012).

### 3.1.2 The valuation of soil biodiversity

The value of soil biodiversity and ecosystem services to environmental and human well-being can be a powerful tool to 1) educate and influence public understanding of the costs and the benefits of protecting diverse soil life, 2) incentivise farmers/growers to protect soil biodiversity-based ecosystem services for public as well as private reasons, and 3) provide a context for the benefits and tradeoffs associated with soil biodiversity conservation and land management decision-making and policy development as their efficacy is evaluated over time (Daily et al. 2009, Fig. 3; Brady et al. 2019).

There are several approaches to valuing soil biodiversity as a bundle of ecosystem services, but a common, comprehensive framework is needed (Jónsson and Davíðsdóttir 2016). An economic value depends on the agent of the valuation so it can be one value to the land manager and another to the value of public goods (Scherzinger et al. 2024). The Total Economic Value (TEV) method values not only the flow of the services but also the insurance values, or the values associated with certain-world and uncertain-world values in the future demand or supply buffering against external environmental disturbance (Pascual et al. 2015, Bartkowski 2017, Johnson et al. 2024). The most common tools to determine use values here are market pricing, net factor method, cost-based methods, travel cost method, and hedonic pricing (Jousset et al. 2017). In agriculture the value of soil biodiversity has been used in a general way of how biodiversity enhances production and through that its value (Brady et al. 2015, Brady et al. 2019).

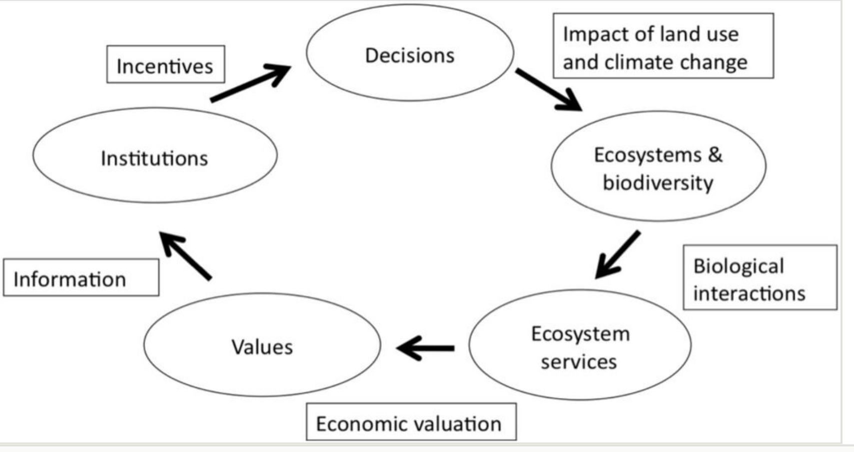


Figure 3. doi

A decision loop which can be used for policy development accounting for soil biodiversity and the resulting ecosystem services and their values when taking actions and decision on natural capital (modified from Daily et al. 2009)

To date, scattered knowledge exists on the valuation of soil-based and biodiversity-based ecosystem services, but there are *no studies on full evaluations of soil-biodiversity-based ecosystem services*. A combination of multiple methods may be fruitful, though further development of valuation methodologies is needed. The concept of different Soil-mediated Contributions to People (SmCPs) have been used to value ecosystem services and drivers of change e.g. land use (Johnson et al. 2024). Soil-biodiversity-based ecosystem services valuations could follow the example by Bartkowski et al. (2020) who define soil-based ecosystem services as “the outcomes of soil processes that economic valuation focuses on in order to make visible the benefits of soils for human well-being and inform sustainable soil management and policy.” In defining it this way, Bartkowski et al. (2020) could associate soil-based ecosystem services to the Common International Classification of Ecosystem Services tool (CICES V5.1) (Haines-Young and Potschin 2018). Since this is a framework for all types of ecosystem service valuation, Bartkowski et al. (2020) used a subset of biotic ecosystem service categories for evaluation.

An alternative to this method is to use the multiple studies proposing methodologies to support the use of a valuation framework that goes beyond the strictly ecosystem services model to a use of multiple methods in combination or more holistic, integrated models combining monetary and non-monetary benefits (Pascual et al. 2015, Bartkowski et al. 2020, Han et al. 2023, Johnson et al. 2024). Non-monetary methods, which include preference-based and cultural valuation methods, have the advantage of being more inclusive of multiple value systems and of diverse stakeholders. Preference-based valuation methods are more accurate in acknowledging the public good value of soil biodiversity and soil health (Bartkowski et al. 2020).

Fixed monetary estimates of biodiversity have been estimated, but this is without an agent for the valuation and instead compared to values for e.g. food production (Pimentel et al. 1997, Jónsson and Davíðsdóttir 2016, van der Putten et al. 2012). They suggest that maintaining a diversity of functions to sustain ecosystem services may be more important than certain species' presence, *but they caution that this is an area where further research is needed.* Indeed, recent work provides empirical evidence for the significance of soil biodiversity for valuing ecosystem multifunctionality (Scherzinger et al. 2024).

**Actions to fill gaps in the economic valuation of soil biodiversity**

- Identify impacts on soil biodiversity that will have economic value, either from the natural capital value of the resilience and insurance values to future disturbances
- Identify socio-economic drivers of soil biodiversity in planning activities
- Foster interdisciplinary actions between economist and soil biodiversity research communities
- Increase research on how values can be used in conservation and management of land use

**Bottlenecks to filling knowledge gaps in the economic valuation of soil biodiversity**

The barriers to efficient economic valuation of soil biodiversity in response to management or conservation actions lies mainly in the gap between economic sciences and the soil biodiversity science. It is the lack of knowledge of the community of soil organisms ("who is there") and functions of these ("what are they doing") and how this connects to the valuation of the soils to different agents, e.g. land owners, society, and thus each depends on the user (Jónsson and Davíðsdóttir 2016) and their objective(s) (van der Putten et al. 2012, Pascual et al. 2015). Valuations that are not done with a clear objective and/or known recipient of the valuation will arrive at values of estimated ecosystem services that does not provide the necessary information to change a management or a policy (Bartkowski et al. 2020)

Identifying the costs of losing soil biodiversity and its services is difficult because service levels are realized over different spatial and temporal scales (Pascual et al. 2015, Jónsson and Davíðsdóttir 2016, Bartkowski et al. 2020) due to climatic gradients, soil organismal ecologies, and the change in weather and climatic condition (Scherzinger et al. 2024).

### 3.1.3 Conservation and restoration methods

What conservation methods protect soil biodiversity? Since conservation management and site selection have typically not considered soil biodiversity and its ecosystem functions, it is still unclear how current conservation affects soil biodiversity and how to adjust current conservation and restoration practices to positively impact soil biodiversity across the EU and regionally. The means of protection (e.g. creating protected areas, use of integrated management) can be applied to conserve soil biodiversity as mentioned above, protected areas are chosen based on varying desired outcomes, both ecological and cultural (Boitani et al. 2008, IUCN Standards and Petitions Committee 2024), and typically not for soil biodiversity conservation (Ciobanu et al. 2019, Zeiss et al. 2022). Rare species protection of soil organisms is atypical because knowledge of specific species' abundances and distributions are, for the most part, lacking (Phillips et al. 2017, Karam-Gemael et al. 2020). Though examples exist on Earthworm species diversity and their conservation status (Stojanović et al. 2008), the distribution of species is often caused by trade-offs in life history; with changing environmental conditions the risks of extinctions increase (Jousset et al. 2017). Thus, we can expect both natural and anthropogenic processes driving the change of species spatial and temporal distribution in soil (Phillips et al. 2020, Patoine et al. 2022).

Regions across Europe must be evaluated for the objectives of conservation and what specific soil communities and associated functions they can support. Globally, areas that may rank highly in one ecological dimension, such as species richness, do not always have the highest functionality (Guerra et al. 2022). This suggests that potential sites for conservation are not equal, nor can they be treated similarly, when evaluating potential areas to conserve and what restoration/conservation practices are effective when targeting soil biodiversity. Abiotic conditions known to affect biodiversity have a large potential to host and conserve a diverse community of biota as shown for certain regions across Europe, such as Ireland, Slovenia, and Sweden (Aksoy et al. 2017).

Effective evaluation of current conservation and restoration practices requires knowledge of biotic/abiotic relationship complexities, including effects of land-use and human pressure to interpret the evaluation of current practices but what we know is that with sustainable land use, soil biodiversity can be supported (Phillips et al. 2024). General management options could be "scaled-up" (Barrios et al. 2023) as considering ecosystem functions during assessment of site-scale measures to management efficacy can vastly improve conservation of soil biodiversity at broader, social scales i.e. landscape scale (Ciobanu et al. 2019, Zeiss et al. 2022). Improvement and use of long-term studies and experiments that focus on specific techniques needs further research, such as dead wood management in forests and encouraging heterogeneous soil habitats through diversifying plant species (Eisenhauer et al. 2013, Eisenhauer 2016, Scherber et al. 2010). In addition, there is increasing evidence that suggests that landscape diversification benefits soil biodiversity (e.g. Vahter et al. 2022).

Protecting soil biodiversity in a nature conservation framework has the potential to not only preserve the biotic community, but also the ecosystem functions provided. Active restoration and conservation require attention to the complexity of species diversity and other biodiversity facets (e.g. size variation, life history traits) (Eisenhauer et al. 2021, Guerra et al. 2022, Guerra et al. 2024) as well as a diversity of functions (Nielsen et al. 2011). Maintenance of species richness, community composition, and ecosystem functions are not often synonymous, and investigations into a trait-based approach to soil biodiversity conservation and restoration are largely lacking (Guerra et al. 2022). Assessments of soil biodiversity and its associated functions are known from only 0.3% of sampled sites (Guerra et al. 2020) and this lack of data results in an incomplete picture of how identified taxonomic units are functioning in soils and how to affect them through management. Auclerc et al. (2022) summarised the importance of functional trait approaches to restoration with soil invertebrates but also detailed critical knowledge gaps. These include a lack of knowledge of:

- trait-based techniques for restoration of soil biodiversity
- the functions invertebrates play in the ecosystems
- representation of functional data in current trait-based databases
- relationships of ecosystem function to traits

**Actions to fill gaps in soil biodiversity conservation and restoration methods**

- Explore and promote land management strategies improving soil biodiversity.
- Evaluate current and future policy instruments and develop decision frameworks and guidelines for conservation of soil species biodiversity
- Address data gaps and enhance soil biodiversity indicators
- Support stakeholders' networks and engagement in soil policy and land use management.

**Bottlenecks to filling knowledge gaps in soil biodiversity conservation and restoration methods**

Challenges and bottlenecks to filling these gaps in knowledge to conserve soil biota require an expansion of toolsets and innovative approaches to tackle the predictions of diversity at sites. In brief, the bottlenecks and the importance of advancing the science of soil-dwelling taxa need information on how to effectively conserve and restore soil life. These include:

1. the barriers to discovering and describing the numerous and diverse, yet unknown, taxa in soils,
2. the lack of understanding of life histories and functions of a large part of the soil organisms and how this drives their distributions,
3. the threats to soil biodiversity, such as invasive species and extinction risks.

## 3.2 Prioritized knowledge gaps

### 3.2.1 Harmonised conservation frameworks

Conservation frameworks are employed for different purposes and include not only species richness but also cultural, aesthetic, ecological aspects, as well as ecosystem services. 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 (Eisenhauer et al. 2019). This leads to the question, what species/taxa are in need for conservation, and what frameworks could be used to secure the efficient conservation of soil biodiversity? While the overall diversity (species richness) of taxa in soil is huge, largely unknown, and important in and of itself, the functional aspects of soil faunal and microbial life cannot be lost in the process of protecting taxonomic diversity (Phillips et al. 2020). It is not clear for example, whether aspects of soil biodiversity can be related to aboveground ecosystems' conservation status and conservation frameworks (Cameron et al. 2018, Zeiss et al. 2022). Thus, new research is needed to investigate if current (aboveground) conservation frameworks can be used for soil biodiversity or specific frameworks for soil biodiversity conservation are needed. As with other conservation frameworks, clear goals and objectives should be set, which should focus on both diversity of taxa and diversity of functions/services provided. Policies and legal foundations are needed for the efficient implementation of the conservation framework. These should be implemented at several scales, from the local to the national, regional or global scale, and complement each other.

Stakeholder identification and engagement is also a significant step towards conservation efficiency at any level. Additionally, there is a 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. 2021). Finally, the conservation framework should encompass monitoring requirements and selection of soil indicators, thus the previous knowledge gaps on monitoring and standardisation methods needs to be aligned to the frameworks that are used in actions to conserve soil biodiversity.

### 3.2.2 Need for public awareness of soil biodiversity

Education and awareness-raising of the importance of soil biodiversity to the provision of ecosystem functions and services is important to adjust perceptions regarding the protection of soil life. Many of the challenges of communicating the importance and need for the protection of soil biodiversity are similar to other issues in global environmental science education. Thus, this knowledge gap will be linked to the Think Tank on Soil Literacy, which addresses knowledge gaps regarding public awareness. The knowledge gap is here to see the transformation of change and when to make use of public awareness of soil biodiversity. A thorough understanding of the problem, and solution is needed, to translate understanding to a change in behavior in order to gain public support for protection of soil life and its functions.

How can communication of soil biodiversity be enhanced? One way to do this is to focus on the local context of soil conservation to a particular audience (i.e. urban, agricultural, land manager/steward) – the "why-YOU-should-care" approach (Moscatelli and Marinari 2024). Another is to use methods in media communications rather than soil science to reach the public since scientific jargon can cause a feeling of disaffectedness. Through artistic means we can also engage the wider public in a way to evoke caring about soil and soil life (Toland and Wessolek 2010).

In 2009, the JRC, with support from the European Soil Bureau Network, established a Working Group on "Soil Awareness and Education" to establish an action plan for development of initiatives to raise awareness of the importance of soil and soil biodiversity across the European society. Subsequently, the JRC initiated a Working Group that now has been broadened to support European Soil Partnership (ESP) Pillar 2, which targets soil awareness and education.

### 3.2.3 Need for implementation of effective soil biodiversity conservation strategies

Conservation strategies involve the planning and implementation of protection of a species or area as well as specific methods. While we have a lack of knowledge of what an effective nature conservation strategy looks like, there are inter- and transdisciplinary ways of implementing the integration of soil biodiversity into the decision-making process of conservation professionals (Fig. 4,Parker 2010). This requires the interactions and cooperation between conservation planners and soil ecologists.

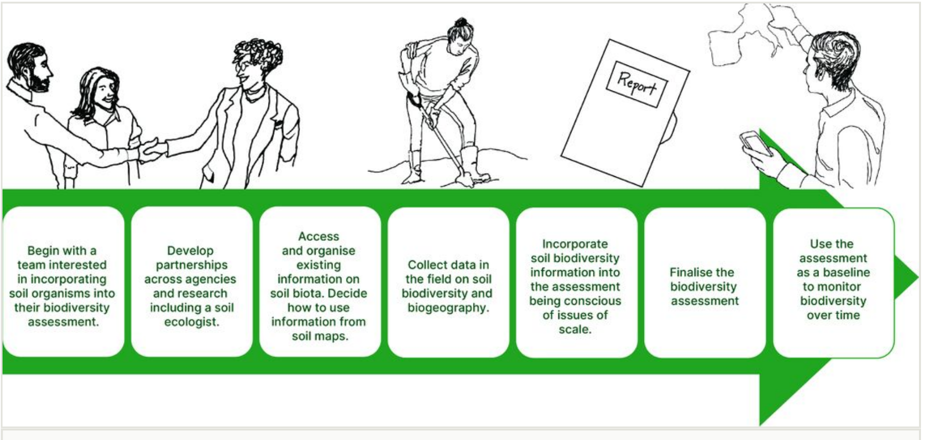


Figure 4. doi

Suggested steps to incorporate soil biodiversity into overall biodiversity assessments for the purposes of conservation strategies. Redrawn from Parker (2010).

For conservation and environmental planners, the scale of conservation strategies is typically the landscape level, but, for the majority of soil-dwelling species, interactions happen at the scale of micrometer to over hundreds of meters (Hedlund et al. 2004). The challenges of scaling-up monitoring and conservation schemes that are representative of the heterogeneity and scale of interaction of soil biodiversity remains a main frontier for both conservation strategy development and soil ecology and is a relevant knowledge gap. Knowledge from previous assessment and strategies for conservation show that there has been a bias towards large soil taxa and a lack of soil microbes in previous assessments and strategies (Klironomos 2002). In the last 10 years, one can argue that this bias has reversed with the relative ease of modern molecular techniques intended to investigate microorganisms in water and soil substrates.

This knowledge gap is highly integrated into the already mentioned knowledge gap on conservation frameworks (see 3.1.1) and research is needed to work out how both frameworks and strategies can be further developed into conservation of biodiversity.

### 3.2.4 Lack of minimum dataset to index soil biodiversity

While chemical and physical parameters can be measured easily in routine procedures, biological parameters are more difficult to measure, more costly and require special expertise. Time and financial limitations are significant barriers for the analysis of numerous parameters in each soil sample (O'Sullivan et al. 2017). The choice of relevant soil parameters and interpretation of measurements are not straightforward and often several parameters show collinearity, thus some are redundant (Lima et al. 2013). Hence, it is not anticipated that all possible biological parameters would be measured in a soil sample (especially at large scales), nor is it self-evident that the ones selected for measurement would also be the most informative ones.

The concept of a Minimum Data Set (MDS) for soil quality assessment, which would be a set of selected key physical, chemical, and biological indicators, was propsed in work with human health by Doran and Parkin (2015). The concept of MDS has also been used successfully in the assessment of water quality (Ingvertsen et al. 2011). But is it possible to monitor soil for the conservation of soil biodiversity with an MDS? The typical biological parameters measured are those for which the researcher has interest and expertise (e.g. focusing on one group of organisms, such as earthworms, microbes etc.). Molecular tools have provided new opportunities for the possible inclusion of biological aspects into MDS selection, but their informativeness has boundaries and additional conventional or morphological methods are needed to complete the necessary input.

The MDS selection should cover criteria such as integrating soil processes, consistency and comparability across different studies and management systems, sensitivity to management and climatic changes (Doran and Parkin 2015). For soil biodiversity other aspects, like the soil as a habitat, have to be considered as well (Baveye et al. 2016). Methodological transparency and simplicity would be essential for enabling the broad adoption and application of the MDS selection. Among soil parameters/indicators, biological ones are considered more informative but are not always included in MDS selections (Bünemann et al. 2018). In systematic, large scale soil monitoring projects, the MDS of parameters typically include chemical and physical parameters, and, lately, some biological ones (e.g. LUCAS inventories from 2018 and 2021). Several biological indicators have been proposed in literature as being efficient in denoting a wider biodiversity range (e.g. in Ritz et al. 2009). Using a subset of those for an MDS would provide merit in large-scale monitoring projects for soil biodiversity conservation, as this would reduce cost and labor. However, standard operating procedures (SOPs) are essential for this work at a large scale. This, in turn, requires collaboration among different experts and setting common scopes.

### 3.2.5 Lack in knowledge of specific threats to soil biodiversity

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 conserve this diverse biotic group. However, the vulnerability of soil invertebrate and microbial organisms, including rare species, is almost entirely unknown and little progress has been made (Decaëns et al. 2008). Bottlenecks to the conservation of soil organisms include knowledge of identifying very rare/threatened, endemic, and vulnerable species and their habitats for protection (Veresoglou et al. 2015).

To protect vulnerable species or groups, there is a need to identify and have threatened species recognized, requiring knowledge of the species (or group) and its functional role, 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 is necessary for European and regional EU conservation efforts (van der Putten et al. 2023). With these standards, we could potentially 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.

A corollary to the identification of rare, threatened, and endemic species is, what are the criteria to designate something as invasive with regards to soil organisms? 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 organism, and (2) there are no conceptual models to think about what a species is in the way plant or animal species are conceptualized, especially for microbes.

### 3.2.6 Lack in knowledge of species taxonomic identity and ecology

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

1. 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).
2. 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 (Decaëns 2010, White et al. 2020, Eisenhauer et al. 2021).

3. Specialised taxonomic expertise is needed to identify invertebrate 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.

Filling gaps in the taxonomic, as well as functional, information of soil biota communities, starting with those in already vulnerable ecosystems is of key importance. Knowledge is partly lacking on impact of extreme oscillations in precipitation and temperature. It is also critical to provide the foundation to monitor the influence of soil invasive species, both for conservation of diversity but also for the functioning and stability of our ecosystems.

Studies of ecology and life histories of soil-dwelling species are time-consuming and detail-oriented undertakings are 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), with substantially fewer studies on the functional genes that reveal what different microbes digest and release.

### 3.2.7 Lack in knowledge of spatial and temporal distribution of soil biodiversity

We lack critical information on most soil taxa, their habitats and what drives their distributions to be able to understand how and where conservation can be achieved for different taxonomic groups (Cameron et al. 2019). 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 soil biodiversity 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. 2021a, 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. Extrapolating conclusions from agricultural research that investigated increasing soil biodiversity for increased ecosystem function can be a starting point for developing knowledge of distribution patterns. 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 soil biodiversity.

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 is thatnecessary 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). Experimental research on the response of soil taxa presence and diversity to environmental predictors is patchy (Phillips et al. 2024), biased towards unrealistic levels of edaphic parameters change, unrepresentative for some climates, such as the tropics (Cameron et al. 2018, Guerra et al. 2020), and not directly comparable across ecosystems.

The overall lack of abundance and distribution baselines and possible thresholds for soil organisms comparable to those for above-ground organisms do not exist though they are urgently called for by policy (European Environment Agency 2023). “Red Listing” of soil invertebrate organisms is rare (Phillips et al. 2017, Mueller et al. 2022) because, for one reason, typical criteria 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 Standards and Petitions Committee 2024) 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?

### 3.3 Overview of knowledge gaps

Table 4 provides an overview of knowledge gaps (KGs) for effective nature conservation of soil biodiversity, their types, actions by which these KGs may be filled, and barriers (bottlenecks) to previous attempts to fill these gaps.

## 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 considered in developing plans for their protection.

Table 4.

Overview of knowledge gaps (KGs) for effective nature conservation of soil biodiversity (SB), their types, actions by which these KGs may be filled, and barriers (bottlenecks) to previous attempts to fill these gaps. Type of KG: KDG - Knowledge Development Gap; KAG - Knowledge Application Gap. Action: (R) - Research; (I) - Innovation. All knowledge gaps apply across multiple sectors (i.e. agriculture, forest, urban and industrial and/or nature).

| Knowledge gap | Short description | Type of KG | Action | Bottlenecks | Time-frame |
|---|---|---|---|---|---|
| Standardisation of SB and ecosystem function monitoring methods | Standardised methods of field data collection are needed to provide baselines and monitor trends in the abundance and diversity of soil biota and its functions. | KDG | - Harmonisation and standardisation of methods and data management (R, I)<br>- Develop and enhance soil biodiversity indicators (R, I)<br>- Identify examples of standard and easy to measure biodiversity indicators (R)<br>- Develop a comprehensive information system of soil biodiversity (R, I) | - Lack of unified network of sharing methods hinders standardisation of monitoring methods<br>- Complicated to develop SB indicators that work for all climatic conditions or soil types | Short-term |
| Economic valuation of SB | A common, comprehensive framework is lacking for economic valuation of SB. Studies on evaluations of SB are lacking | KDG | - Identify impact on soil properties that will have economic value (R)<br>- Identify socio-economic drivers of soil functions and services in planning activities (R)<br>- Foster interdisciplinary actions between economist and SB research communities (I)<br>- Increase research on how values can be used conservation and management (R) | - Disconnection between economic sciences and SB sciences hinders efficient valuation of SB in response to management or conservation actions | Short-term toMid-term |
| Conservation and restoration methods | Current conservation and restoration methods' impact on SB is unclear and it is also unclear how to adjust them so that they positively affect soil biodiversity | KDG | - Explore and promote sustainable land management strategies (R,I)<br>- Evaluate current and future policy instruments and develop decision frameworks and guidelines for conservation of soil species (R)<br>- Address data gaps in soil health, improvement measures and enhance SB indicators (R,I)<br>- Support stakeholders' networks and engagement in soil policy and land use management (I) | - Unknown species and taxa in soil hinders conservation actions and strategies<br>- Lack of understanding of life histories and functions of many soil organisms and how this drives their distribution hinders conservation actions and strategies<br>- Knowledge on threats to SB, and extinction risks, is lacking, which hinders conservation actions and strategies | Short-term |

| Knowledge gap | Short description | Type of KG | Action | Bottlenecks | Time-frame |
|---|---|---|---|---|---|
| Harmonised conservation frameworks | How can frameworks be used to secure efficient conservation of SB. Can we use existing framework or do we need a new framework? | KDG | - Establish framework for conservation of soil biodiversity and functions (R,I)<br>- Evaluate current and future policy instruments, advocate regional knowledge adoption strategies and integrate SB into planning activities (R,I) | - Lack of policy targets for conservation and restoration hinders conservation | Short-term |
| Need for public awareness of SB | Effective ways of communicating about conservation of SB are lacking. It is necessary to gain public support for protection of soil life and its functions | KAG, KDG | - Stakeholders' learning networks, collaboration and early engagement in soil policy and management development (R,I)<br>- Social research on the best communication methods for SB awareness (R) | - Disconnection between social sciences and SB sciences hinders social research on the best communication methods for SB awareness | Short-term |
| Need for implementation of effective SB conservation strategies | Knowledge of effective nature conservation strategies for SB is lacking. Inter- and transdisciplinary ways of implementing the integration of SB into decision making process of conservation professionals is needed | KAG | - Stakeholders' learning networks and engagement in soil policy and management development (R,I)<br>- Develop guidelines for conservation of soil species and integrate SB conservation into planning activities (R,I) | - The scale of conservation strategies focuses on landscape level, but most soil organism interactions occur at very small scales causes discrepancies in actions | Mid-term |
| Lack of minimum dataset to index SB | A minimum dataset to index SB is lacking. Would it be possible to monitor soil for the conservation of SB with the concept of Minimum Dataset? | KDG | - Methods development/ improvement (R)<br>- Develop understanding of relevant biological soil parameters and interpretation of measurements for conservation of SB (R)<br>- Collaboration network for different experts (I) | - Difficulty and cost of measuring biological parameters causes uncertain predictions due to low replication | Mid-term |
| Lack in knowledge of specific threats to SB | Current knowledge on threats and extinction risks for soil organisms is little and inconsistent. Vulnerability of most soil organisms, including rare species, is almost entirely unknown | KDG | - Red list development (R)<br>- Develop criteria for invasive species designation (R)<br>- Identification and monitoring of threats impacts (R)<br>- Standardised assessment and risk analysis for policy guidance (R,I) | - Difficulty of tracking origin of a present soil organism causes uncertainties regarding invasive species<br>- Unclear species concept hinders concervation actions to mitigate threats to SB | Short-term |

| Knowledge gap | Short description | Type of KG | Action | Bottlenecks | Time-frame |
| --- | --- | --- | --- | --- | --- |
| Lack in knowledge of species taxonomic identity and ecology | Filling gaps in taxonomic and functional information on soil biota communities is needed to provide the foundation for monitoring and conserving soil biodiversity | KDG | - Capacity building (training in taxonomy)<br>- Methods development/ improvement (R)<br>- Develop a unified definition of SB for policy development (R)<br>- High resolution sampling and monitoring (R) | - Lack of taxonomic expertise hinders identification of species<br>- Unclear species concept hinders identification of species | Short-term |
| Lack in knowledge of spatial and temporal distribution of SB | Information on the spatial and temporal distribution of most soil taxa and what drives the distribution is lacking. This is needed for understanding of how and where conservation can be achieved for different taxonomic groups | KDG | - High resolution sampling and monitoring (R)<br>- Develop a comprehensive understanding of what drivers affect distribution of soil organisms (R)<br>- Red list development (R)<br>- Develop a definition for rarity for soil taxa (R) | - Unclear species concept hinders identification of species<br>- Lack of taxonomic expertise hinders identification of species | Short-term |
| Data storage & Digitalisation needs | Data is generally stored with IPR regulations and not available for open access | KAG | - Develop a comprehensive information system of soil biodiversity (I) | - Lack of binding policy | |
| Improved predictive modelling | Predictive modelling needs improvement due to the small-scale heterogeneity of soil communities | KDG | - Methods development/ improvement (R) | | |

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