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Future projections of modelled soil EBVs for ecosystem restoration and climate scenarios

Irene Calderon Sanou, Carlos Guerra, Graciela Rusch, Sergei Põlme, Joachim Maes, Néstor Fernández

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EUROPABON

Future projections of modelled soil EBVs for ecosystem restoration and climate scenarios

31/10/2023

Lead beneficiary:

Martin Luther University

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Project ref. no.	**101003553**
Project title	**EUROPA BIODIVERSITY OBSERVATION NETWORK: INTEGRATING DATA STREAMS TO SUPPORT POLICY**

Deliverable title	**Future projections of modelled soil EBVs for ecosystem restoration and climate scenarios**
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Author(s)	**Irene Calderon-Sanou, Carlos Guerra, Graciela Rusch, Sergei Põlme, Joachim Maes, Nestor Fernandez**
EC project officer	**Laura Palomo-Rios**

Deliverable description	This Deliverable describes the modular procedure to estimate four essential biodiversity variables important to monitor soils and support their ecological restoration. These four essential biodiversity variables include taxonomic diversity, functional diversity, soil basal respiration and microbial biomass. At the end, we also propose a synthesis indicator that can be used to support the identification of the ecological status of European soils.
Keywords	soil restoration, taxonomic diversity of soils, functional diversity, soil basal respiration, microbial biomass, soil ecological status

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Contents

Executive summary 6
1. Introduction 7
2. Showcase participatory design 11
3. Policy targets 12
4. Essential Biodiversity Variables design 14
5. Discussion 30
6. References 30

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Executive summary

The Deliverable discusses the critical role of soil in supporting terrestrial ecosystems, agriculture, and global climate regulation. It highlights that a significant portion of European soils are currently unhealthy, which has far-reaching consequences, including risks to human health, the environment, and the economy. Soil degradation affects food security, water quality, climate change, and biodiversity. It also emphasizes the importance of soil monitoring in Europe to ensure sustainable land management, preserve biodiversity, and mitigate environmental challenges. Healthy soils are essential for agriculture, food security, and climate resilience. The European Union (EU) recognizes the importance of soil health in addressing the food needs of a growing global population increasing the need for improved soil monitoring. It also discusses the role of advanced remote sensing technologies in soil monitoring and mentions initiatives and projects focused on soil biodiversity and ecosystem functioning.

This Deliverable highlights the showcase in soil restoration and climate change mitigation that is aimed at developing soil essential biodiversity variables to test the capacity of current datasets and monitoring frameworks to provide relevant information on the distribution and future trends of key soil biodiversity variables. The development process also stakeholder engagement in the context of selecting essential biodiversity variables (EBVs). Two main approaches were used: a working group involving researchers and targeted meetings with institutional stakeholders. Key meetings were held with stakeholders from organizations such as the European Environmental Agency, the Joint Research Center, and German soil and biodiversity monitoring agencies. These meetings aimed to gather input and insights on the selection of EBVs. The stakeholder engagement process revealed three key points: i) the importance of using readily available and open data to ensure data continuity and promote transparency and accessibility (his includes data from sources like the European Soil Data Centre (ESDAC) and GBIF, as well as point data from the LUCAS sampling framework); ii) the need for diversity in modeling approaches, incorporating multiple data sources and levels of expertise (the goal is to showcase the potential use of existing information and allow various stakeholders to identify their roles in producing soil-based EBVs for different functions or ecosystem services); and iii) the importance of including climate and land use prediction data in modeling frameworks when possible. Overall, the stakeholder engagement process emphasized the significance of data accessibility, diverse modeling approaches, and the incorporation of relevant future data in the selection and development of essential biodiversity variables.

Furthermore, the Deliverable discusses the existing gap in the EU's legal framework concerning soil management and highlights the proposed Soil Monitoring Law as a comprehensive framework to address this gap. The outcomes of this Deliverable align with several EU environmental policy initiatives, such as the EU Biodiversity Strategy for 2030, the Zero Pollution Action Plan, the Circular Economy Action Plan, and the Chemicals Strategy for Sustainability. Finally, it proceeds with the selection of essential biodiversity variables (EBVs) for soil-related monitoring within the EuropaBON initiative. Three primary soil-related EBVs have been chosen: 'Functional Composition of soil biota' and 'Community Biomass of soil microbes' and ‘Taxonomic diversity’. These EBVs belong to the 'Community Composition' class within the 'Terrestrial' realm category.

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1. Introduction

1.1. State of the art in soil biodiversity and ecosystem function monitoring in Europe

Soil plays a crucial role in supporting terrestrial ecosystems, agriculture, and even global climate regulation (Bardgett and van der Putten 2014). Soils provide a habitat for countless organisms and serve as the primary medium for plant growth (Beck et al. 2005). Healthy soils support food production, climate resilience, and overall well-being (H. R. P. Phillips et al. 2019; de Graaff et al. 2015). However, in the European Union (EU), scientific evidence suggests that 60-70% of soils are currently unhealthy, leading to degradation issues across member states. Soil degradation has far-reaching consequences, including risks to human health, the environment, climate, economy, and society. These risks encompass food security, water quality, flooding, drought impacts, biomass production, carbon emissions, and biodiversity loss (H. Phillips et al. 2023). In Europe, where diverse landscapes and ecosystems abound, soil monitoring is of paramount importance to ensure sustainable land management, preserve biodiversity, and mitigate environmental challenges such as climate change and land degradation. This is particularly relevant for the development of four key axes of current European policy, namely assessing the outcomes of sustainable agriculture, ensuring that climate mitigation measures are successful, informing land-use planning and regulation, and conserving and restoring biodiversity. As an example, agriculture is a cornerstone of European economies, and soil health directly influences crop productivity and food security (Foley et al. 2011) with multiple large food distribution companies investing in their own soil monitoring systems to control and monitor the capacity of producers to meet their market goals. Healthy soils are strategically crucial for securing access to sufficient, nutritious, and affordable food. As the EU plays a significant role in global food markets, it recognizes the importance of soils in good ecological condition in addressing the food needs of a growing global population, expected to reach 9-10 billion by 2050. Since 95% of food is linked to soil, soil degradation directly impacts food security and cross-border food markets. Globally, the pressure on soil and land is increasing, with 4.2% of EU territory already affected by land take and soil sealing, primarily at the expense of agricultural land. Additionally, soil degradation poses a threat to the long-term fertility of agricultural soils, with erosion, organic carbon loss, nutrient exceedances, compaction, and secondary salinisation affecting 61-73% of EU agricultural soils. Without sustainable soil management and regeneration efforts, deteriorating soil health could become a central factor in future food security crises.

Healthy soils are crucial for agriculture and the overall agro-ecosystem (Alberto Orgiazzi et al. 2022). They contribute to stable or increased crop yields, biomass production for non-food sectors, and long-term production security for farmers. Healthy soils also play a vital role in the transition to a sustainable bioeconomy, preserving land value, and reducing operational costs for farmers. Financial support for soil-enhancing practices is available under the Common Agricultural Policy (CAP) (Pe'er et al. 2019) and proposed EU carbon removal certification framework and the recent proposal of a European Soil Monitoring Law. Soil degradation has adverse effects on human health, including respiratory and cardiovascular diseases due to airborne particulate matter from wind erosion. Sealed soils exacerbate heatwaves and reduce pollutant absorption capacity. Contaminated soils can compromise food safety. Healthy soils support environmental and recreational value, benefiting both rural and urban areas by supporting the establishment of green spaces, improving air quality, and reducing heat islands. Improving soil health enhances the EU's resilience to climate change by increasing organic matter, water retention, filtering capacity, and erosion resistance. Carbon farming practices help mitigate climate change by storing CO2 in the soil (Freibauer et al. 2004). Enhanced soil water retention reduces flood intensity and mitigates drought effects. Certain soil bacteria and symbiotic fungi assist crop plants in tolerating drought. As climate-related hazards, including wildfires, intensify in Europe, healthy soils with water retention capacity support resilient forest ecosystems. However, wildfires can lead to soil degradation and increased erosion, landslides, and floods. Strengthening soil knowledge aids

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disaster risk assessments, recognizing the diverse roles soils play in disaster mitigation. While EU and national policies have made positive strides in improving soil health, significant gaps remain in addressing soil degradation drivers. Soils form slowly, but their health can be maintained or improved with the right measures and practices.

The past decade has witnessed significant progress in soil monitoring sensors, technologies, and applications allowing for more precise and efficient data collection. In Europe, the adoption of advanced remote sensing techniques has revolutionized soil monitoring. These technologies enable researchers to gather real-time data on soil moisture (Ruosteenoja et al. 2018; Almendra-Martín et al. 2022), temperature (e.g., (Haesen et al. 2021); https://www.soiltempproject.com), pH (Ballabio, Panagos, and Monatanarella 2016), nutrient content, and microbial activity (Smith et al. 2021) across various spatial scales. A prime example is the deployment of satellite-based remote sensing, which provides comprehensive coverage of soil properties at regional and continental scales. The European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission and the European Space Agency's Copernicus program have played pivotal roles in this regard. These platforms allow for monitoring soil moisture dynamics, aiding in drought prediction, flood risk assessment, and crop yield optimization.

Projects such as the Soil Biodiversity and Ecosystem Functioning (SFB) and the European Soil Biodiversity Observation Network (EU-SOILS) aim to assess the impact of land use changes and climate on soil organisms. These initiatives play a crucial role in guiding sustainable land management practices. Together with these and more recent EU projects (e.g., work is still underway in projects like BENCHMARKS or SoilGUARD), over the last two decades the European Union has developed, either nationally or at European level, several monitoring systems to track the condition of European soils. While originally developed to monitor changes in land use across Europe, the LUCAS (Land Use and Cover Area Frame Survey) program includes since 2009 a module on soils. This module initially developed to track the amount of carbon sequestration in European soils led to the establishment of what can become a long-term soil biodiversity monitoring network in the European territory (A. Orgiazzi et al. 2018).

The European Green Deal aims to transform the EU into a fair, prosperous, and sustainable society. Part of this initiative includes the adoption of various strategies and plans, such as the EU Biodiversity Strategy for 2030, a Zero Pollution Action Plan, an EU Climate Adaptation Strategy, and an EU Soil Strategy for 2030. The EU Biodiversity Strategy for 2030 emphasizes the need to protect soil fertility, reduce erosion, and increase soil organic matter through sustainable soil management practices. It also addresses contaminated sites and aims to update the 2006 Soil Thematic Strategy to combat soil degradation. The EU Soil Strategy for 2030 envisions achieving healthy soils by 2050 through voluntary and legislative actions. It proposes a Soil Monitoring Law supported by an impact assessment, addressing soil health indicators, monitoring provisions, and sustainable soil use. The 8th Environment Action Programme sets the objective of living well within planetary boundaries, highlighting the importance of addressing soil degradation and ensuring soil protection through legislative proposals. Institutional stakeholders, including the European Parliament, the Council of the EU, and others, have called for the development of an EU legal framework for soil. Global commitments related to soil, such as those under the Rio Conventions and UN Sustainable Development Goals, further emphasize the importance of soil health. Currently, there is a lack of comprehensive and harmonized soil health data across the EU. This legislative proposal (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0416) seeks to establish a coherent soil monitoring framework based on common definitions of healthy soil to support sustainable soil management and stimulate research and innovation. Multidimensional soil health data can improve drought and disaster management, climate change mitigation, and adaptation efforts, as well as support human health and biodiversity. Sustainable soil management practices are expected to yield economic and environmental benefits. The proposal also addresses soil contamination, aiming to reduce risks to

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human health and the environment by adopting a risk-based approach and promoting the polluter-pays principle. The legislation allows Member States a gradual and proportionate approach to implement soil governance, monitoring systems, soil health assessment, and sustainable soil management measures.

Effective management and conservation of biodiversity requires standardized and measurable indicators to assess its status and trends. To this respect, Essential Biodiversity Variables (EBVs) have emerged as a fundamental framework to address this need. As biodiversity faces unprecedented threats due to habitat loss, climate change, and invasive species, EBVs represent a pivotal approach to address these challenges by providing a structured framework for biodiversity monitoring and reporting. EBVs are quantifiable, essential components of biodiversity that encapsulate key dimensions of the natural world. They serve as fundamental metrics to gauge the state and trends of biodiversity across spatial and temporal scales (Pereira et al. 2013). The conceptualization of EBVs harmonizes biodiversity monitoring and facilitates data comparability, enabling robust assessments of ecosystem health and informing conservation strategies (Proença et al. 2017). Recently, soil specific essential biodiversity variables were defined (Guerra et al. 2021) (Figure 1) providing an holistic overview of how soil ecosystems should be monitored and studied, where soil organisms are intertwined with relevant soil chemical, physical, and functional properties, contributing to overall societal well-being. These soil EBVs include information on soil ecological functional aspects (e.g., soil microbial biomass and respiration), taxonomic and functional diversity, population abundance, and habitat traits.

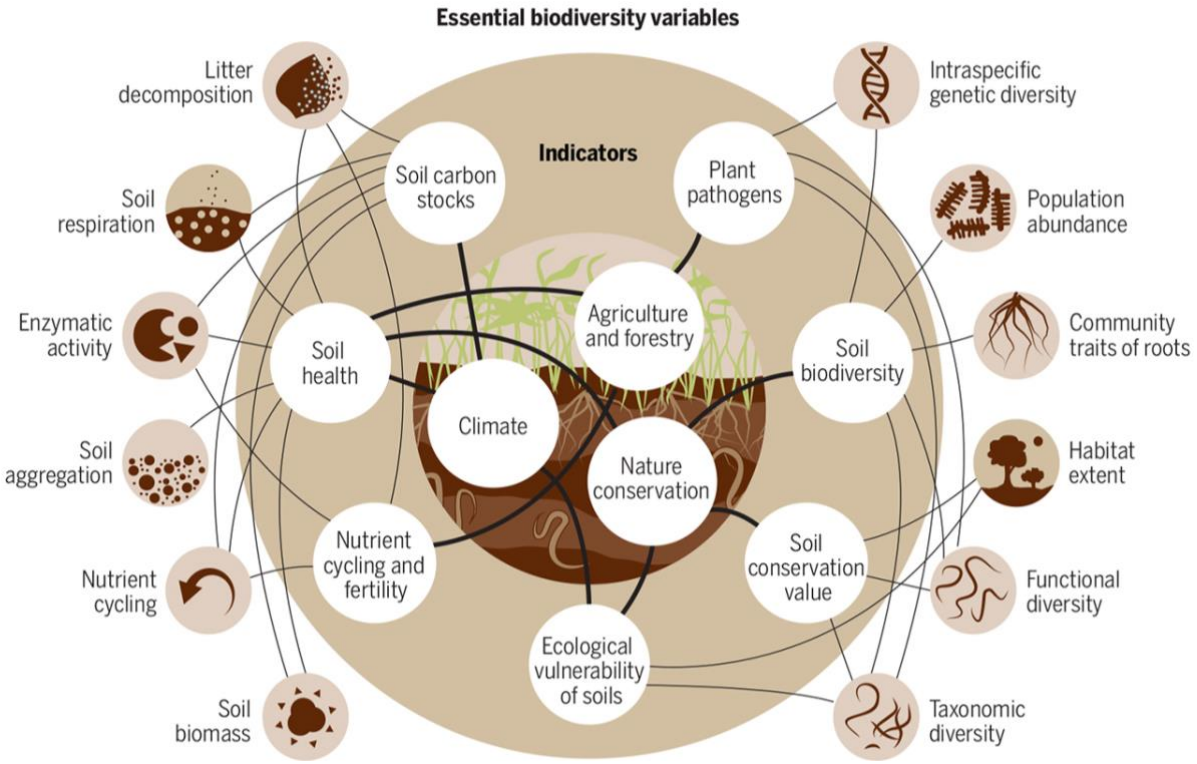

Figure 1 Links between global soil essential biodiversity variables (EBVs) (outer ring) that are prioritized by the Soil Biodiversity Observation Network (SoilBON) and policy sectors (center) through the use of soil ecological indicators (inner ring) (Guerra et al. 2021).

In this context, the Statistical Office of the European Union, known as EUROSTAT, conducts a regular survey called the Land Use and Coverage Area Frame Survey (LUCAS (Eiden, Vidal, and Georgieva 2002; Borrelli et al. 2022)) to assess land use, land cover, and changes in the European Union (EU) based on

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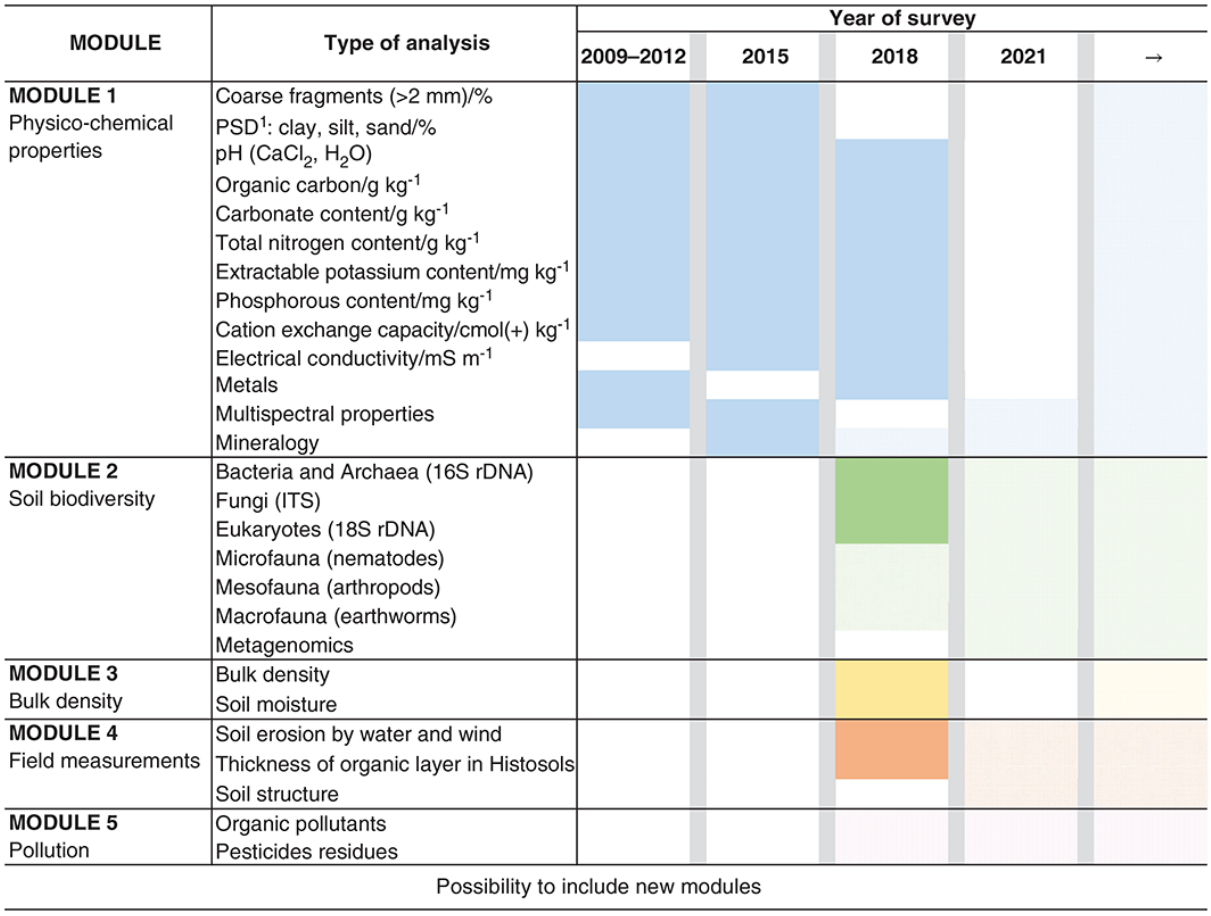
EU Parliament and Council decisions. This survey, initiated in 2008, occurs every three years and involves over a million georeferenced sampling locations covering the EU territory. Surveyors visit around 270,000 of these points in the field to verify classifications and collect additional data. LUCAS includes soil assessment as of 2009, initially in 25 EU member states. About 20,000 topsoil samples were collected, and various physical and chemical properties were analyzed. The goal was to create a standardized dataset of topsoil properties for the entire EU. The survey expanded to include Bulgaria and Romania in 2012 and locations at altitudes above 1000 meters in 2015. Electrical conductivity measurements were added to assess soil salinity issues. The third LUCAS Soil survey in 2018 (see Figure 2) was already conducted with around 26,000 sampling locations, adding properties like bulk density, soil biodiversity, visual soil erosion assessment, and organic horizon thickness measurement. LUCAS Soil is a substantial and freely accessible continental-scale soil database, including all land use types and benefiting various fields of research and informing policymaking. The ongoing scientific analyses of LUCAS Soil 2015 and 2018 samples and the current data preparation for the 2021 campaign offer opportunities for reviewing past data accessibility and discussing the future potential of LUCAS Soil as a tool for analysing soil-related processes.



PSD[1], particle-size distribution.
Different modules form the overall structure of the survey; each module corresponds to different types of analyses. The analyses are repeated at a standard time interval, namely every 3 years. Types of analyses already established (full colour cells) for the campaign scheduled for 2018. Possible analyses for 2021 (dotted cells) are still under discussion and there will be the opportunity to implement the survey further by including new modules.

Figure 2 Structure of LUCAS Soil survey over the sampling years (A. Orgiazzi et al. 2018).

Following on this point, this monitoring approach requires a holistic approach that encompasses various European soil-related Essential Biodiversity Variables (EBVs) and employs standardized monitoring systems at the European level to track the status and dynamics of soil biodiversity and ecosystem functioning over time. These EBVs should cover four key dimensions of soil systems, including soil physics, soil chemistry, soil biodiversity, and soil ecosystem functions, all of which are

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linked to specific ecological indicators (see Figure 1). The European soil research community has been mobilised to tackle these issues, and participate and lead several national and European efforts to monitor soils and their biodiversity. However, these initiatives often rely on static, fragmented soil biodiversity data without temporal resolution or coordination. While a European soil monitoring network may not have the granularity to distinguish specific management practices, it can highlight successful examples of conservation efforts focused on European soils. This can serve as a valuable reference point for comparisons among European regions and countries, aiding in the development of more effective soil conservation policies. As mentioned before, effective soil monitoring is essential for addressing various environmental challenges in Europe, including nature conservation, land degradation, climate mitigation and adaptation, forestry, and food security. This monitoring initiative, also as part of the current soil monitoring law, requires collaboration with local partners across diverse ecosystems and environmental conditions. It also entails capacity-building and knowledge-sharing mechanisms, as well as the creation of an open global repository of soil biodiversity resources. Currently, soil biodiversity monitoring in Europe can be seen as a multi-tiered approach that involves European (LUCAS Soils) coordinated sampling, cross-laboratory standardization, data aggregation, validation, and reporting, leading to a comparable mosaic of soil biodiversity and functional assessments across Europe. The goal is to place soils and their biodiversity at the forefront of European sustainability discussions. This effort is already underway in Europe, where several research projects together with European institutions are providing essential biodiversity data to inform European policies, including the European Biodiversity Strategy for 2030. While still not fully in place, a soil monitoring program in Europe based on EBVs and derived indicators, can provide crucial tools to gauge progress towards conservation and economic targets in the coming decades. It can also act as an early warning system, signaling the success or failure of current policies in preserving and enhancing soil quality and health across European landscapes.

1.2. Showcase goals

This showcase aimed to develop soil essential biodiversity variables to test the capacity of current datasets and monitoring frameworks to provide relevant information on the distribution and future trends of key soil biodiversity variables. Here we are testing two data streams, one from a standardized sampling scheme, the LUCAS soil survey, and one from a combination of multiple expert and citizen science data (e.g., using data from EdaphoBASE and GBIF). This showcase also uses several modeling frameworks to assess the distribution and condition of specific soil EBVs and, where possible, allow prediction of these variables for future conditions.

2. Showcase participatory design

2.1. Stakeholders' engagement process

Stakeholder engagement is an important step to validate and specify the essential biodiversity variables selected. In the case of this showcase, we developed a dual approach. On one hand we developed a working group targeting researchers, and in parallel targeted meetings with institutional stakeholders were held to have more direct input in the decision making process. Regarding the latter, we had three key meetings with stakeholders at the European Environmental Agency, the Joint Research Center, and from German soil and biodiversity monitoring agencies, including the Federal Agency for Nature Conservation (Bundesamt für Naturschutz), both at the begginign and at the end of the process. This targeted consultation with stakeholders that have interests at different scales allowed us to have a better grasp on the needs and limitations related to the selected EBVs. At the same time, these stakeholders represent at the same time users (e.g., EEA) and data providers (e.g., in

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the case of the JRC and the BfN) with deep knowledge on the available information on soils and soil biodiversity. Regarding the workshop with researchers, this was held in the beginning of the process to allow for an early discussion and integration of critical comments. This workshop included input from researchers with expertise in soil ecology, geomorfology, microbiology, soil macroecology, remote sensing, ecological modelling, and statistics. While we tried to engage a diverse group of stakeholders, at this stage we did not include policy makers nor were we able to involve expertise in social sciences that would be relevant to assert the capacity of the selected EBVs or indicators to support the assessment of soil ecosystem services.

2.2. Key inputs from stakeholders

From the meetings held, three points were raised:

i) first, stakeholders stressed the need to use currently readily available and open data. This would not only ensure the continuity of such dataset production (e.g., like in the case of the datasets curated by the European Soil Data Centre (ESDAC) or the data streams related to GBIF), but also the promotion of open access standards that facilitate transparency and data accessibility. From our consultation, these datasets include point data from the LUCAS sampling framework, modelled data for specific soil properties available at the ESDAC website, point data for soil species distribution available both in the EdaphoBASE and GBIF data portals, among others;

ii) the use of models should be diverse to include multiple data sources and levels of expertise. The aim is to produce a showcase that highlights the potential use of current available information rather than producing a single EBV. This will allow multiple stakeholders to identify their specific roles in the production of such soil based EBVs and clarify how different EBVs can be used to model different functions or ecosystem services;

iii) when possible, modelling frameworks should include and be prepared to ingest climate and land use prediction data. When optimising models to describe current conditions, it is often the case that we would have to use the best available datasets to represent those conditions. These datasets often are not the same as the ones used to estimate future conditions and/or create policy relevant information. The feedback was to use, when possible, a combination of both state of the art datasets to represent current conditions and equivalent datasets to represent future conditions;

All these point were fully integrated in the process of identifying and calculating the different EBVs that were selected for this Showcase.

3. Policy targets

3.1. Reporting needs and data gaps

The European Union has been actively implementing environmental measures over the past three decades with the goal of enhancing the quality of the environment for its citizens and ensuring a high quality of life. While EU law contains various provisions related to environmental protection, there is a significant gap in the existing legal framework when it comes to soil. To address this gap, a proposal on soil health has been introduced to establish a comprehensive and coherent EU-level framework for soil management, currently addressed in the context of the Soil Monitoring Law. This proposal serves to complement and reinforce existing environmental legislation in several key areas. Firstly, it addresses soil contamination, including historical contamination, aligning with directives such as the Industrial Emissions Directive, the Waste Framework and Landfill Directives, the Environmental

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Liability Directive, and the Environmental Crime Directive. By doing so, it contributes significantly to the protection of human health, which is a central objective of EU environmental policy.

Healthy soils possess the natural ability to absorb, store, and filter water, and as a result, the proposal is expected to support the objectives of several other directives, including the Water Framework Directive, the Groundwater Directive, the Nitrates Directive, and the Environmental Quality Standards Directive. It addresses soil contamination and erosion while enhancing soil water retention. Additionally, healthy soils play a crucial role in flood prevention, aligning with the objectives of the Floods Directive. The proposal contains provisions on sustainable soil management also complement existing EU legislation related to nature, such as the Habitats and Birds Directives. By improving biodiversity and preventing soil erosion, it supports the habitats of wild pollinators that nest in soils and contributes to reducing air pollution. Healthy soils serve as the foundation for life and biodiversity, including habitats, species, and genes. Furthermore, the knowledge, information, and data collected under the monitoring requirements outlined in the proposal for a Soil Monitoring Law are expected to enhance the assessment of environmental impacts related to projects, plans, and programs conducted under the Environmental Impact Assessment Directive and the Strategic Environmental Assessment Directive. In the framework of the Soil Monitoring Law, only soil respiration is taken as a viable EBV (although the proposal refers to it as an indicator) but this Deliverable aims to go beyond that to provide a more comprehensive overview of the available ready to use information.

In specific terms, the proposal for a soil monitoring law aligns with several other EU environmental policy initiatives, including: i) the EU Biodiversity Strategy for 2030, which aims to protect nature within the EU and includes a proposal for a regulation on nature restoration in which soils play an important role from an ecological point of view. The proposed regulation seeks to restore 20% of the EU's land and sea by 2030 and all ecosystems in need of restoration by 2050, with synergies between this proposal and the soil health proposal; ii) the Zero Pollution Action Plan, which envisions reducing air, water, and soil pollution to non-harmful levels by 2050. This proposal aligns with efforts to revise and strengthen existing EU legislation in the air and water sectors and legislation related to industrial activities; iii) the Circular Economy Action Plan, which outlines measures to reduce microplastics and evaluates the Sewage Sludge Directive governing the quality of sludge used in agriculture; and the Chemicals Strategy for Sustainability, which aims to protect citizens and the environment from potentially hazardous properties of chemicals while recognizing their importance to modern society.

3.2. Cross-policy contributions

Due to its encompassing nature, the European monitoring of soil biodiversity aligns seamlessly with several key EU policies and initiatives across various sectors, namely:

European Green Deal and EU Policy Objectives: soil biodiversity monitoring serves as a vital component of the European Green Deal and contributes to EU policy objectives such as achieving climate neutrality, promoting resilient nature and biodiversity, reducing pollution, establishing sustainable food systems, and enhancing human health and well-being.

European Climate Law: The objectives of implementing soil biodiversity monitoring across Europe are harmonious and synergistic with the European Climate Law. They support EU climate change adaptation goals by bolstering resilience and align with the ambition of achieving a climate-neutral Europe by 2050. Carbon sequestration in soils is a crucial aspect of this endeavour, balancing greenhouse gas emissions even after a robust decarbonization process.

Land Use, Land Use Change and Forestry (LULUCF) Regulation: soil biodiversity monitoring complements the revised LULUCF Regulation, which aims to reduce net emissions by 55% by 2030. The

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LULUCF Regulation necessitates increased climate ambition in land use policies among EU Member States. The monitoring of soil carbon stocks and nature-based climate mitigation in soils, as advocated by the proposal, aligns seamlessly with the objectives of the LULUCF Regulation.

Certification Framework for Carbon Removal: soil biodiversity monitoring can support the proposed certification framework for carbon removal aligns with the initiative to deploy high-quality carbon removals through a voluntary EU certification framework. This framework is instrumental in enhancing soil's capacity to absorb and store carbon. Regenerating healthy soil, in turn, increases its carbon sequestration potential and the generation of carbon removal credits. The creation of soil districts and related data and knowledge, as proposed, facilitates the implementation of carbon removal certification.

Value of Healthy Soil: Certification of healthy soil is expected to elevate the value of carbon removal certificates, garnering greater social and market recognition for sustainable soil management and associated food and non-food products. This is likely to stimulate private financing, with businesses supporting ecosystem services and sustainable practices related to soil health. Additionally, certified healthy soil may increase the overall land value for purposes like collateral, sale, or succession.

Farm to Fork Strategy: soil biodiversity monitoring also aligns with the Farm to Fork Strategy's objective to reduce nutrient losses while maintaining soil fertility. It contributes to creating a more resilient EU food system.

Common Agricultural Policy (CAP): importantly, soil biodiversity monitoring supports CAP's efforts to enhance the environmental performance of the agricultural sector. It incorporates mandatory environmental and climate conditions under the CAP, including soil management practices. By strengthening the CAP's innovation dimension, it encourages initiatives that address soil health issues.

Farm Sustainability Data Network (FSDN): soil biodiversity monitoring is consistent with the transformation of the Farm Accountancy Data Network into a Farm Sustainability Data Network as outlined in the Farm to Fork Strategy. The FSDN will collect farm-level sustainability data, including soil management practices, aiding in benchmarking and advisory services for farmers.

Beyond these policies, soil biodiversity monitoring plays a significant role in addressing the goals of the European Habitats Directive by expanding taxonomic monitoring to an integral component of ecosystems that plays a crucial role in supporting various plant and animal species. The Directive also emphasises the restoration and maintenance of habitats in a favourable conservation status, therefore, soil biodiversity monitoring provides essential data to evaluate the success of habitat restoration efforts.

4. Essential Biodiversity Variables design

4.1. EBV design characteristics

From the soil specific EBVs listed in Section 1, two soil-related EBVs were selected for the EuropaBON list (https://github.com/EuropaBON/EBV-Descriptions/wiki). These are the 'Functional Composition of soil biota' and the 'Community Biomass of soil microbes', representing soil biodiversity and functioning respectively. Both soil-related EBVs are part of the EBV class 'Community composition' from the 'Terrestrial' realm category. Beyond these, we will also consider two other EBVs corresponding to the

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'Taxonomic Diversity of Soil Biota' (Community Composition) and 'Species distributions' (Species Populations).

- '**Functional Composition of soil biota**' (EBV Class: Community Composition) describes the functional composition and diversity of soil biota based on morphological, physiological, phenological and behavioural traits or functional/taxonomic groups. It can be measured by diversity metrics such as the functional group diversity across the whole soil community (e.g. richness of soil functional groups present in a community), the species or OTU diversity within functional groups (e.g., diversity of Ectomycorrhizal fungi), or other functional diversity indices that can include functional traits when available (e.g., functional richness or functional divergence).

- '**Community Biomass of soil microbes**' (EBV Class: Community Composition) refers to the estimated biomass of the living component of soil organic matter (bacteria, fungi and protozoa) within contiguous spatial units (grid cells) across the EU over time. It can be measured by metrics such as the mass of soil microbes (i.e., bacteria, fungi and protozoa) per mass of dry soil, the mass of soil microbes per area. This EBV is also related to microbial activity such as microbial basal respiration, potential basal respiration, or the respiratory quotient (qO2; the ratio of basal respiration to microbial biomass). These last three variables refer to the EBV class ecosystem function.

- '**Taxonomic Diversity of soil biota**' (EBV Class: Community Composition) refers to the diversity of key soil biota such as earthworms, collembola, fungi, bacteria, etc. It can be measured by diversity metrics such as richness or Shannon diversity of species or OTUs for a given taxonomic group (e.g. Annelida, Rotifera, Fungi). It can also be estimated from the stacked distributions of species in a given taxon (**Species Distributions**; EBV Class: Species Populations).

All EBVs were calculated using the 1km^2 scale. In terms of the temporal resolution, it should vary from 3 to 6 years, which is the temporal resolution of the LUCAS sampling survey (see section 4.2). Yet, for the examples shown here, we are using a space for time substitution to be able to represent all variables in both dimensions since there is no current data readily available to make temporal estimations.

4.2. Input biodiversity data

The LUCAS (Land Use/Land Cover Area frame Survey) survey represents the main initiative aimed at overcoming the soil monitoring gaps that have prevailed in the past at the European scale. It uses advanced sampling techniques to gather comprehensive data on various aspects of soil, including its properties, biodiversity, and ecological functions (Alberto Orgiazzi et al. 2022; Smith et al. 2021). The LUCAS survey covers the two soil EBVs, which are measured every 3 years (starting in 2018) from 885 sites encompassing all the terrestrial land covers in Europe (Table 1). 'Community Biomass of soil microbes' is measured through standardized protocols in the centralised lab in Leipzig. After a coordinated sampling across European countries, soil samples are stored on ice and transported to Ispra, Italy. From there, they are transported to Leipzig, Germany, for the measurement of potential basal respiration, microbial biomass by substrate-induced respiration, and respiratory quotient. A random subset of samples is transported from Ispra to the Centro de Edafología y Biología Aplicada del Segura-Consejo Superior de Investigaciones Científicas (CEBAS-CSIC, Murcia, Spain) for the measurement of ester-linked fatty acid methyl esters (FAMEs) as indicators of bacterial and fungal biomass. A detailed description of the methods used to do these measurements can be found in (Smith et al. 2021). Measuring the 'Taxonomic Diversity of soil biota' or the 'Functional Composition of soil biota' requires a more comprehensive approach to sample the whole soil biota, and their functional

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attributes for the latter. For this, the LUCAS survey employs eDNA metabarcoding, which offers a standardized and cost-effective way to cover all kingdoms of life in soil samples. Details on the methods used to extract and process eDNA from soil samples can be found in (Alberto Orgiazzi et al. 2022). From eDNA data, the diversity of several taxa from the soil can be assessed to assess the 'Taxonomic diversity of soil biota' (e.g., (Labouyrie et al. 2023; Köninger et al. 2023)). The functional aspect can be added by using existing functional databases allowing to assign different soil taxa to functional groups (e.g. FungalTraits for Fungi (Põlme et al. 2020)). Data collected from the LUCAS survey is available at the European Soil Data Center (ESDAC). Yet, it's important to note that eDNA metabarcoding may have some biases, favouring the detection and taxonomic resolution for microbes and microfauna, while potentially underrepresenting or providing less resolution for macrofauna, due to lower DNA presence in the soil. To achieve a more complete soil biota assessment of macrofauna taxa, other existing non-commercial data infrastructures can be used, such as Eudaphobase (Table 1), which combines data from heterogeneous sources on soil animals, their distribution and habitat parameters of their sites of occurrence and makes these data available to the public. Other databases, from global to local, may exist for specific soil taxa, but will not be described here (e.g., section 4.3.2 for the case of earthworms).

Table 1 Raw data availability and access

DATASET TITLE	**LUCAS Soils**	**EUdaphobase**	**GBIF**
Raw data collection design	Over ~20000 soil sampling points across all EU member states revisited every 3 years (starting in 2009) Currently a small fraction (885 plots [2018], 1500 plots [2022]) of samples are used to measure microbial biomass and activity metrics and address taxonomic composition of living components of topsoil. Started in 2018 across all EU-MS, sampled every 3 years Minimum sampling unit likely adequate for 1 x 1 km spatial resolution (https://esdac.jrc.ec.europa.eu/public_path/shared_folder/doc_pub/JRC105923_LUCAS2018_JRCTechnicalReport.pdf).	Non-commercial data infrastructure developed by the Senckenberg Museum of Natural History Görlitz in Germany. Combines data from heterogeneous sources on soil animals, their distribution and habitat parameters of their sites of occurrence and makes these data available to the public (open access). The data originate from the scientific literature, unpublished results of field studies (theses, reports), collections of museums and research institutions as well as raw data from research studies and well-founded observations.	Non-commercial data infrastructure. Combines data from heterogeneous sources on soil animals and microbes related to their occurrence, making these data available to the public (open access). The data originates from the scientific literature, monitoring programs, citizen science, unpublished results of field studies (theses, reports), collections of museums and research institutions.
Monitoring programs	The LUCAS Soil module is coordinated by the European Commission's Joint Research Centre (JRC). This survey represents the first attempt to construct a pan-European topsoil database, which can serve as a baseline for EU-wide soil monitoring (A. Orgiazzi et al. 2018). It has a standardized sampling procedure & central laboratory for measurements and samples processing.	N/A	N/A

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Types of data access	Open access. Data is available and downloadable after registration.	Open access. The data warehouse is publically available (open access) via a web-based browser portal.	Open access. The data warehouse is publically available (open access) via a web-based browser portal.
Data repositories	Database creation on European Soil Data Center (ESDAC). https://esdac.jrc.ec.europa.eu/projects/lucas	EUdaphobase will adapt the soil-zoological data platform "Edaphobase" to a pan-European data warehouse for soil biodiversity.	Data available through the GBIF repository at www.gbif.org
Persistent identifier(s)	N/A	N/A	N/A
Metadata description	Microbial biomass is measured from topsoil samples with substrate-induced respiration; units [µg Cmic g soil dw-1]. Other related measurements: Respiratory quotient, basal respiration. Metagenomics with DNA metabarcoding, including primers for Bacteria and Archaea (16S rDNA), Fungi (ITS) and Eukaryotes (18S rDNA), which includes microfauna (e.g., nematodes), mesofauna (e.g., arthropods), and macrofauna (e.g., earthworms).	Currently includes data on Nematoda, Collembola, Oribatida, Gamasina, Chilopoda, Diplopoda, Isopoda, Enchytraeidae, and Lumbricidae, their distribution and habitat parameters of their sites of occurrence. Data types comprise modern taxonomic nomenclatures and synonyms, geographical references, quantities of collected organisms, soil parameters, vegetation, meteorological data, sampling and extraction methods, identification methods, preparation techniques and behavioural data.	Occurrence data of selected earthworm species using the Darwin Core standard
Quality control	LUCAS general survey's results undergo a rigorous quality assurance process. Initially, an automated check ensures data completeness and consistency, either during data compilation or when uploaded to a central repository. Subsequently, regional or central offices conduct visual inspections of all surveyed points. Data points needing correction or clarification can be returned to field contractors for rectification. The same applies to the analytical information.		

4.3. The EBV model

Different models were used to create the different soil-related EBV outputs. Here we present in detail the methods used to create each EBV output map, including which data was used and how it was processed to obtain the EBV value, a description of the model used and the selected parameters, the performance of the model and how uncertainty of the model was assessed. In some cases, e.g. for the community biomass of soil microbes, different methods were used, as they were developed for different aims.

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4.3.1 'Functional Composition of soil biota' (EBV 64)

Input data

Soil biodiversity data was obtained from the LUCAS survey from 2018 (Origiazzi et al 2018). Raw eDNA data for eukaryotes (18S) and prokaryotes (16S) was obtained from the ESDAC platform and cleaned following a standard bioinformatic pipeline using DADA2 (Callahan et al. 2016) to obtain amplicon sequence variants (ASV) with taxonomic annotations. Eukaryote data was separated into Animals and Protists, and the rest discarded for this task. Protists were classified into functional groups using the functional information available in (Adl et al. 2019). Due to the low taxonomic resolution of the 18S marker for animals, these were classified into the key soil taxa, and only nematodes were functionally annotated using the NINJA platform (Sieriebriennikov, Ferris, and de Goede 2014). Bacteria ASVs were functionally annotated using FAPROTAX (Louca, Parfrey, and Doebeli 2016). For fungi, OTU tables with taxonomic and functional annotations, derived from the ITS marker, were obtained from (Labouyrie et al. 2023). For each broad taxonomic group, i.e., Bacteria, Protists, Fungi and Animals, the diversity of the functional groups identified was estimated using the Shannon diversity, i.e., the exponential of the Shannon entropy.

Covariates related to land cover and soil physical and chemical properties, including percentage of coarse, sand, clay and silt, bulk density, pH, total nitrogen, potassium and phosphorus were also obtained from the LUCAS survey. For projections across Europe we used the values from the available maps in the ESDAC. Climatic data was extracted from CHELSA v1.2 in the period from 1990 to 2020. Soil degradative processes such as soil erosion, soil pollution (i.e., heavy metals content) and soil compaction were also accessed through the ESDAC platform or obtained directly from the EEA.

Model description

For each response variable, i.e., the Shannon diversity of the selected 28 functional groups, the dataset was first preprocessed by handling missing values, feature scaling, and encoding categorical variables, where applicable. A Random Forest regression model was employed to capture the effect of complex interactions between the previous environmental variables on the diversity of the different functional groups. The mean squared error was set as the optimization criteria and optimised key hyperparameters of the random forest algorithm (maximum tree depth, maximum features per tree) on a hold out validation set. The model was implemented using Python's scikit-learn library. To assess the ability of the model to generalise to new settings, each observation was assigned according to its location to a grid cell (~100km). Afterwards, a random partition of the grid cells into 10 subsets for spatial block cross validation was generated. For each fold in turn, a regression model was trained on observations of the remaining folds and evaluated on its observations. The model's predictive performances were assessed using Mean Squared Error (MSE), the R-squared (R^2) and the coefficient of determination (Spearman's rho^2). Finally, the cross validation process resulted in 10 fitted models. An ensemble of these models was used to predict the average and variance of the diversity of each trophic group and the overall functional composition of soil biota (Figure 3, Figure 4).

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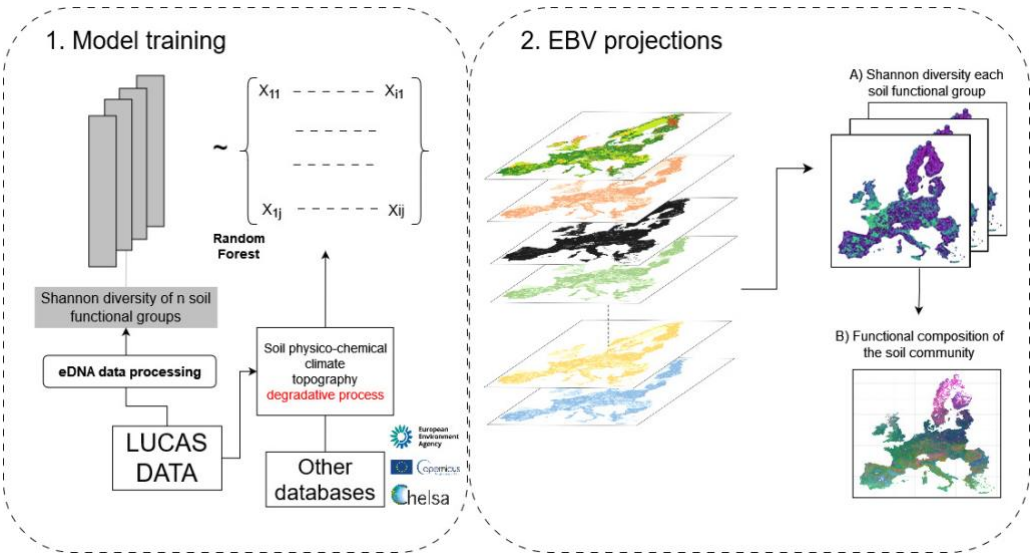

Figure 3 Workflow representation for modelling the **'Functional Composition of soil biota'**. The EBV model was trained on data for measured samples, consisting of the diversity of 28 functional groups of soil biota, the environmental dataset and soil degradative processes. Environmental projections across Europe were used to build the EBV maps for each functional group and then for the overall functional composition of the soil biota by making a PCA with all the modelled functional groups.

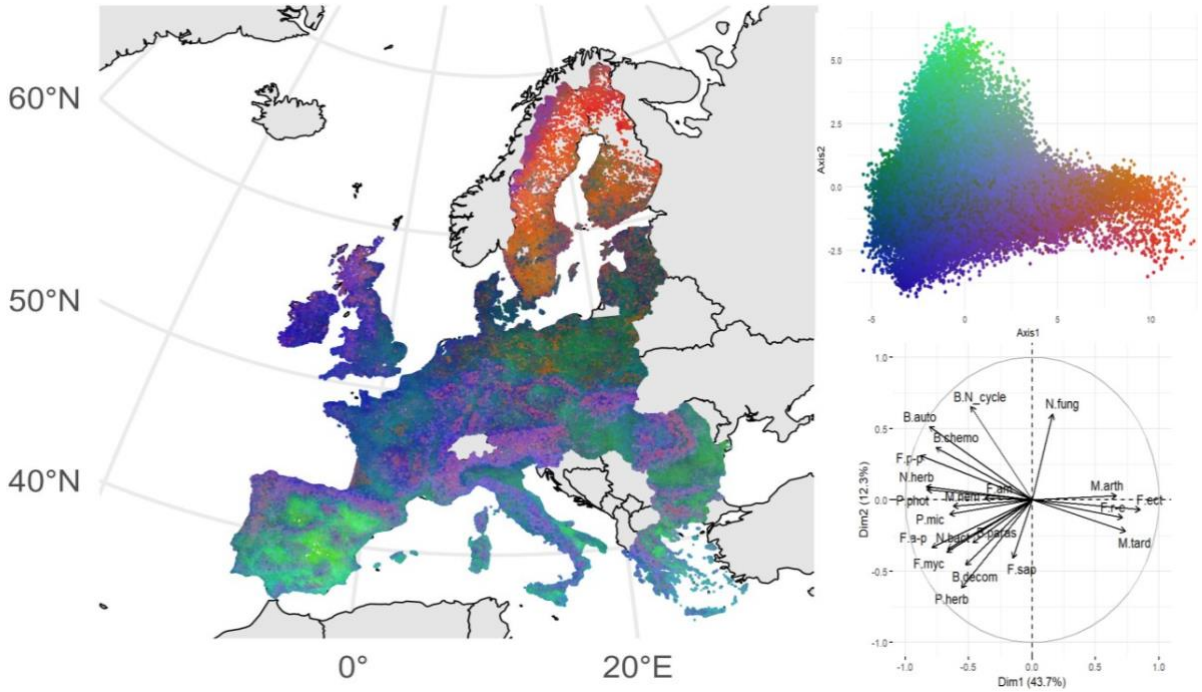

Figure 4 'Functional Composition of soil biota'. Here represented by the first two axes of a PCA created from the diversity of 28 functional groups across Europe are presented in the figure using a RGB colour space. Different colours represent a different functional composition that can be characterized from the right panels. While we use here this representetaion to provide an overview of the variability in functional conditions, the EBV should be represented with an Alpha diversity metric.

Model performance

The ensemble models for across functional groups had an average±error R2 of 0.47±0.006, a MSE of 2083.2±392 and a coefficient of determination of 0.78±0.002 .

Uncertainty assessment

The uncertainty of the model was estimated using the coefficient of variation (CV), which assesses the consistency or variability of predictions across the individual models in the ensemble. The coefficient

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of variation is a relative measure of variation and is defined as the ratio of the standard deviation to the mean. It indicates how much the predictions of individual models deviate from the ensemble's mean prediction. The CV of all the ensemble models for the different functional groups was summed, and the areas having a probability above 0.9 of the total distribution of the summed CV were considered as uncertain.

4.3.2 'Taxonomic diversity of soil biota'

Input data

Available occurrence data of earthworm species from the Global Biodiversity Information Facility (GBIF; (GBIF.org 2022)), Edaphobase (Edaphobase.org 2021), and other existing large datasets were collected (Figure 5). After data collection, records collected before 1970 were removed to estimate current rather than past species occurrence patterns. The R package CoordinateCleaner was used to exclude data with common spatial and temporal errors. It was manually checked that record exclusion was appropriate. Records removed included those from GBIF with coordinate uncertainty of more than 1 km, non-observational records (i.e. keeping only living specimen, human observation, or preserved specimen), records that were based on less than one observation, and those describing not species but higher taxonomic levels. The combined dataset contained 98,732 occurrence records of 142 unique earthworm species collected across 45 European countries. The occurrence records were spatially thinned to adjust for sampling bias caused by varying sampling density and resolution. To avoid overfitting and increase robustness of the models, only the 41 species that were observed in at least 10 grid cells were kept. Background data for the 41 focal species (i.e., number of records ≥10) was generated with the R package biomod2 by randomly sampling 10,000 grid cells within the spatial extent of the environment for each species. Four groups of environmental descriptors were included in the model, namely climatic, land-use, topographic and edaphic factors. The CORINE Land Cover dataset from 2012 was used as a land-cover baseline. All environmental data were reprojected into a 2 km2 and 5 km² grid system by either up- or downscaling, and standardized by dividing mean-centered values by their respective standard deviations. The variables were reprojected into WGS84 using ArcGIS v10.7.1, if necessary, but merged them into one table in R to avoid conflicts with missing data. Areas with one or more missing values in environmental variables were excluded. The R package usdm was used to check for correlation and collinearity between variables. Variables with r>0.8 (correlation coefficient of Pearson) and variable inflation factor VIF≥10 were excluded from further analysis. To avoid overfitting, the ten most important predictors for the focal earthworm species of the 24 least correlated predictors were identified. Future predictions of mean annual temperature (T) and seasonality of precipitation (P) were downloaded from CHELSA v1.2 for all available IPCC scenarios (n=15) and the time period from 2041 to 2070. The 3 Shared Socio-economic Pathways are SSP1 (with the Representative Concentration Pathway [RCP] 2.6): Sustainability, additional radiative forcing of 2.6 watt/m² by 2100; SSP3 (RCP 7.0): Regional Rivalry, 7 watt/m², middle to upper range of the bandwidth of all scenarios; and SSP5 (RCP 8.5): Fossil-fueled Development, 8.5 watts/m², upper edge in the range of scenarios described in the literature (SSPs; (Birch 2014)). The 5 Earth system models are GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL.

Model description

The maxent function from dismo in R (https://cran.r-project.org/web/packages/dismo/dismo.pdf) was used to perform Species Distribution Models (SDMs) for each of the 41 species present in more than or exactly ten grid cells (~2 km²) (Figure 5). Models were allowed to be tuned individually and the same pseudo-absence dataset as for model fitting used. To identify the top ten variables for determining earthworm distribution, permutation importance was extracted, by permuting the values of each predictor and comparing the resulting reduction in training Area Under Curve (AUC) values. A large reduction in AUC (i.e., high permutation importance) indicates that the model is strongly influenced by that predictor. For species with n≥100 occurrences, ten variables with the highest median permutation importance across the 19 species were selected. Accordingly, the ten predictor variables

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used for Species Distribution Modeling were annual mean temperature, precipitation seasonality, distance to coast, proportion of area covered by agriculture, soil pH, phosphorus content, cation exchange capacity, elevation, clay+silt content, and human population density (Zeiss et al. 2023). The 19 earthworm species with ≥100 records were modelled to avoid overfitting, and the ten algorithms available in biomod2 (Thuiller et al. 2016) with adapted parameter settings were used. Committee averaging scores of the predictions, ten-fold cross-validation (80:20%), and True Skill Statistic (TSS) were used to improve model performance during ensemble building. The committee averaging score is the average of the binary predictions of the individual models, giving both a prediction and a measure of uncertainty. If the prediction is close to 0 or 1, all models agree to predict 0 and 1, respectively, while a prediction around 0.5 means that half of the models predict 1 and the other half 0. During individual model building, less weight was given to older species observations as they do not necessarily correspond to current species' occurrences. For model evaluation, the Cohen's Kappa, area under the receiver operating characteristic curve (AUCROC), and TSS from BioMod output were used.

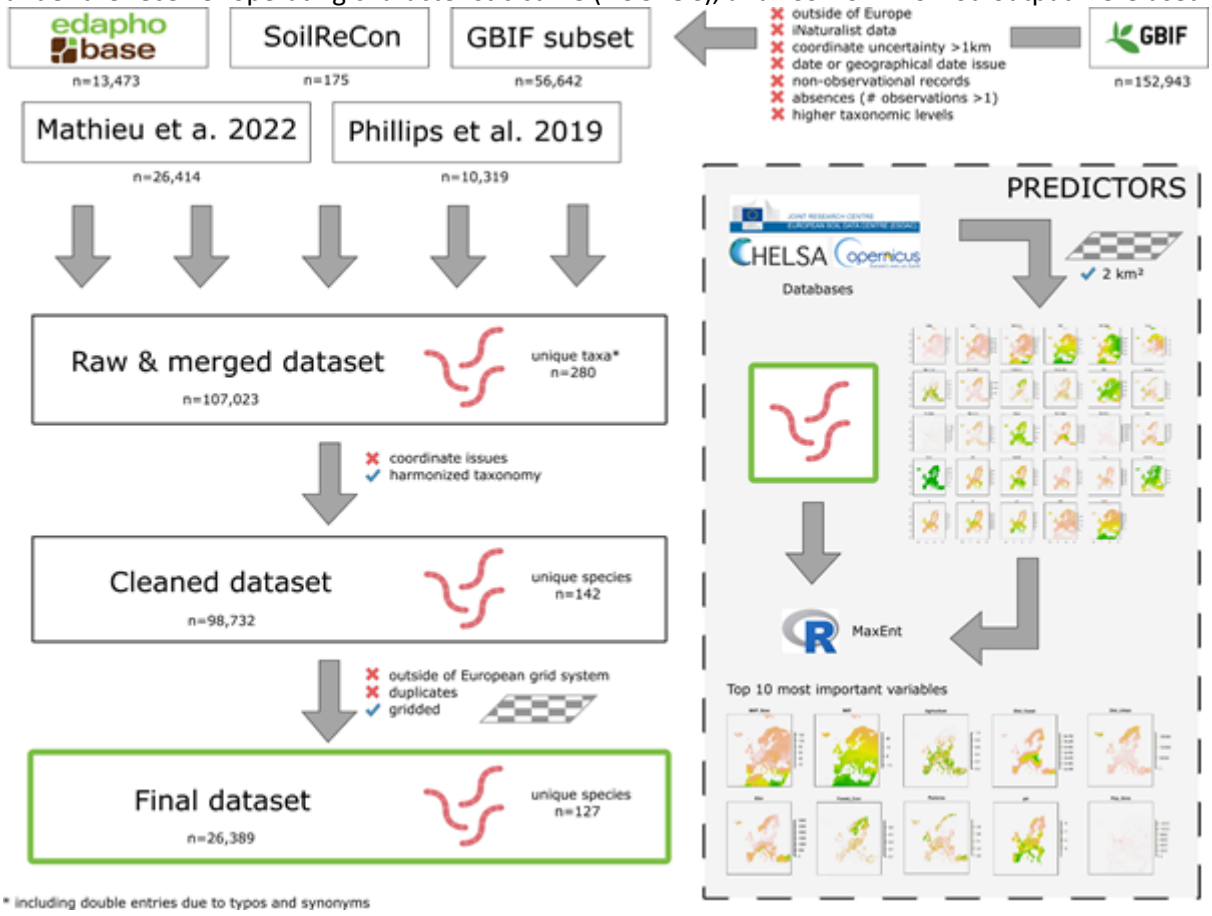

Figure 5 Workflow representation for modelling the **Taxonomic Diversity of Earthworms** from (Zeiss et al. 2023). Building the species occurrence (left side) and environmental dataset (predictors, gray panel). n - Number of occurrence records before and after cleaning or spatial thinning. Earthworm icon was designed by Iconjam (flaticon.com).

The distribution of the 19 earthworm species was predicted and mapped with the best-performing models (i.e., the one with highest TSS) in R . The discrete presence-absence maps, which were derived from probability maps and model-specific probability threshold giving highest TSS, were summed to get the number of species per grid cell (i.e., Taxonomic Diversity, Figure 6). All maps were cropped to the area in which prediction uncertainty, averaged across the 19 species distribution models, was lower than 0.1 (= mean and median uncertainty). The resulting investigated area spanned 864,140 km² (i.e., 172,828 grid cells à 5 km²). The future distribution and species richness of earthworms was projected using current land cover, topographic and soil variables together with future climate

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variables. Only future climate variables were used, as we were interested in the potential climate effect rather than interactive effects of land cover and soil variables under future scenarios. Future earthworm distributions were predicted with 3 environmental datasets: both future climate variables (T and P); future T and current P; and current T and future P, resulting in 45 future projections per species. One ANOVA (lm function) including the ten environmental predictors was performed to compare the 3 future projections of each scenario (factorial; T, P, TP) and to evaluate potential climate effects on the predicted species richness averaged across the 15 climate scenarios.

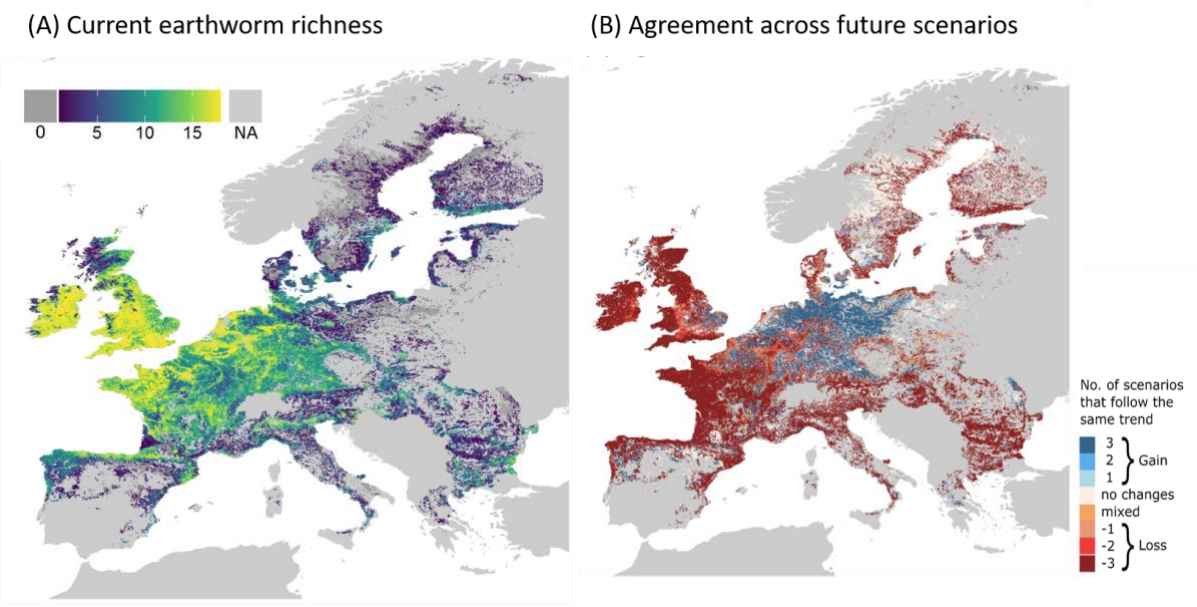

Figure 6 Output map for the EBV **'Taxonomic diversity of soil biota'** represented by earthworm species rchiness. (A) Spatial distribution of the current predicted overall species richness calculated as the number of species (max. 19 species) being present with a probability higher than the species-specific threshold with maximum TSS value. Dark gray areas indicate species richness values of 0. (B) Agreement across the 3 different Shared Socioeconomic Pathway (SSP) scenarios. Gain represents areas in which gain of species richness is predicted in 3/2/1 scenarios, while remaining scenarios predict no change; loss represents areas in which loss is predicted, and mixed represents areas in which different scenarios predict gain and loss. Light gray areas were not predicted based on the extent of the environmental dataset. Modified from (Zeiss et al. 2023).

Model performance

SDMs for the potential current and future distributions of the 19 highly recorded species of earthworms showed generally good performance (mean: Kappa=0.53 [SD 0.12], AUC=0.93 [SD 0.04], TSS=0.70 [SD 0.13]).

Uncertainty assessment

Uncertainty was estimated as the coefficient of variation of each SDMs under current climatic conditions and varied between species.

4.3.3 'Community Biomass of soil microbes' (EBV 61)

4.3.3.1 Current distribution

Input data

Data was obtained from the LUCAS survey from 2018 (A. Orgiazzi et al. 2018). Variables included to represent the EBV were: potential basal respiration, microbial biomass and respiratory quotient. Samples from 185 grasslands, 289 forests , 347 croplands and 64 samples from other land-cover types including shrublands, bare land, and urban areas were included. Covariates included soil, climatic and geographical variables, i.e., soil organic carbon content, soil water content, sand content, pH, annual

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precipitation, annual temperature, mean temperature of the 30 days preceding sampling, total precipitation of the 30 days preceding sampling, latitude and elevation. Soil properties were taken from the LUCAS 2018 survey, and climate data were obtained from online databases.

Model description

Structural equation models (SEMs) were constructed using lavaan version 0.6.5. A general model was built to unravel drivers of soil microbial respiration and biomass without any regard to land cover; so, for this model, all available samples from the full range of land-cover types of the LUCAS Soil Biodiversity survey were included. To investigate whether and how different land-cover types affect soil properties in different ways, multigroup analysis were used to consider the effects of three broad land-cover types (forest, cropland and grassland) individually, creating an SEM for each land-cover type, to explore potential differences in the relationships between soil, climate, geographical and microbial parameters. This enables more precise predictions of soil microbial properties and carbon, as models are parameterized to the conditions of the different land-cover types. The underlying structural equations of the SEMs were used to create predictive maps of respiratory quotient, potential basal respiration and microbial biomass across the European Union with a monthly step for 2018 and then aggregated to obtain an average for the year (Figure 7). This was done because predictions are specific to a 30-day time period, due to inclusion of the mean temperature and total precipitation in the 30 days before sampling. Predictions were made for the three respective land-cover types and then aggregated to a single spatial representation across Europe. Sand content, pH, and carbon maps came from studies published by the European Soil Data Center (ESDAC), based on LUCAS 2009/2012 soil property data. The predictive maps do not include any urban areas or areas above 1,000 m a.s.l., as these were not included in the modelled organic carbon map we used as input and were not (well-)represented in the LUCAS data used to create the models.

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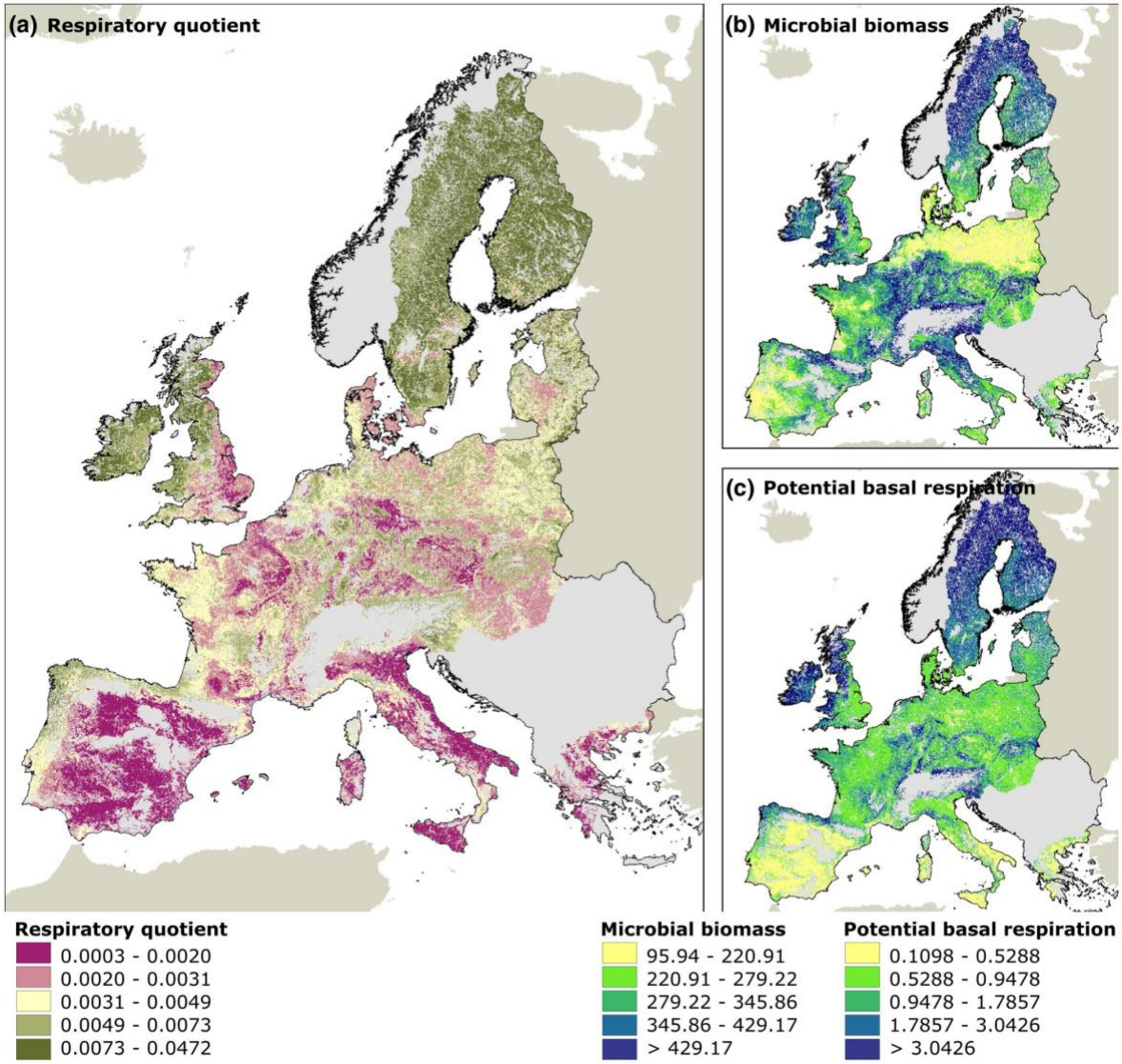

Figure 7 Output maps for the EBV **'Community Biomass of soil microbes'** taken from (Smith et al. 2021). Predictive maps of mean (a) respiratory quotient, (b) microbial biomass and (c) potential basal respiration at 20 ºC, and in 2018 across the European Union, excluding altitudes over 1,000 m, created by averaging the predictive maps created for each month of 2018.

Model performance

The R^2 of the general model was 0.487. The R^2 of the models for each land cover type were: 0.359 for grasslands, 0.404 for croplands and 0.655 for forests.

Uncertainty assessment

The environmental coverage of the current sampling design was estimated to evaluate the spatial uncertainty of the predictions using the Mahalanobis distance, which estimates a multidimensional distance, and defined outliers as the 97.5% quantile of the chi-squared distribution with n degrees of freedom. This algorithm permitted identifying regions where the predictive maps were more or less reliable (Figure 8).

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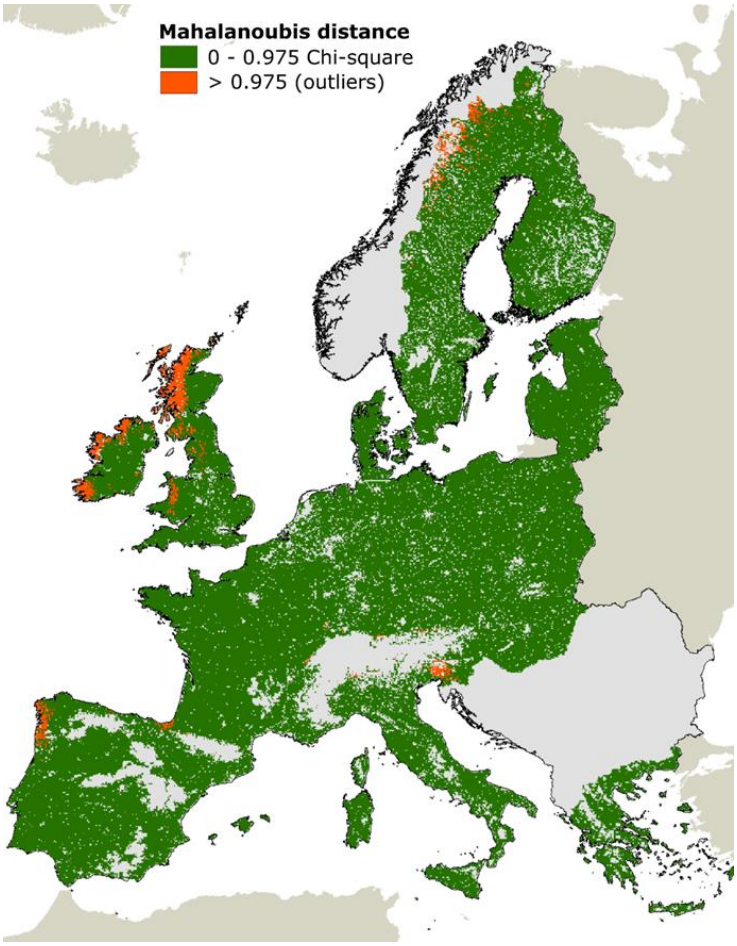

Figure 8. Extrapolation of uncertainties associated with the survey used in this study. This map represents those locations for which environmental conditions are better covered by our samples. Overall, our dataset covers a wide range of the terrestrial environmental conditions found in Europe, the rest being considered as outliers in respect to the conditions covered by the sample sites used in this study (for this purposes an outlier is a location that has a value above the 97.5% quantile of the Chi-squared distribution; in red).

4.3.3.2 Future scenarios

Input data

The variable response used was the microbial biomass from the LUCAS 2018 survey. Predictors included variables of soil chemical and physical properties, topography, climate, and land cover. Because soil chemical variables may depend on the climate, their values were predicted first for the different SSP, using the same model. These predictions were then used to predict the value of the microbial biomass in the future. Future predictions of climatic variables were downloaded from CHELSA v1.2 (Karger et al. 2017) for all available IPCC scenarios (n=15) and the time period from 2041 to 2070. The 3 Shared Socio-economic Pathways are SSP1 (with the Representative Concentration Pathway [RCP] 2.6): Sustainability, additional radiative forcing of 2.6 watt/m² by 2100; SSP3 (RCP 7.0): Regional Rivalry, 7 watt/m², middle to upper range of the bandwidth of all scenarios; and SSP5 (RCP 8.5): Fossil-fueled Development, 8.5 watts/m², upper edge in the range of scenarios described in the literature (SSPs; (Pörtner & Roberts 2022)). The 5 Earth system models are GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL.

Model description

To predict the future scenarios of soil chemical properties and further '*Community Biomass of soil microbes*', the same model described in 4.3.1 was used. The results are given in Figure 9.

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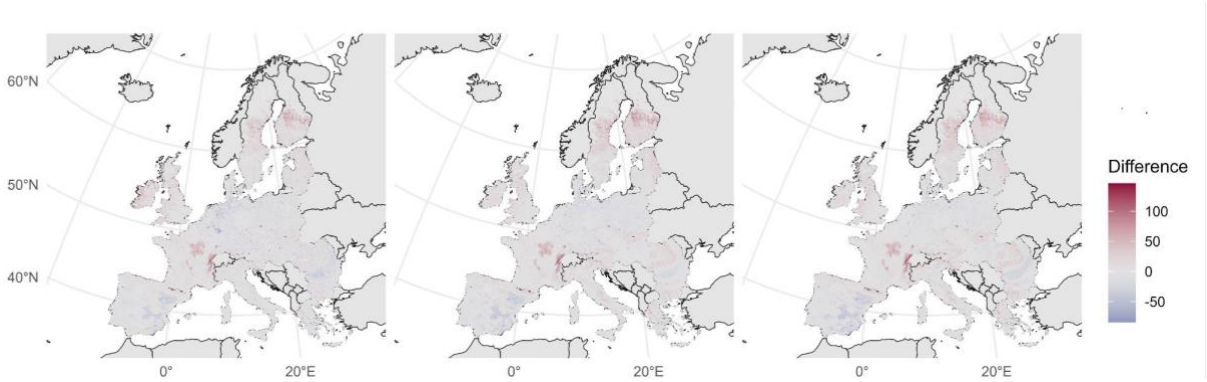

Figure 9 Output map for the future projections of the EBV **'Community Biomass of soil microbes'.** Differences in microbial biomass compared to the current scenario for the 3 different Shared Socioeconomic Pathway (SSP) scenarios: SSP1 in the left, SSP3 in the center and SSP5 in the right. Gain represents areas in which microbial biomass is predicted to increase (red), while loss represents areas in which loss in microbial biomass is predicted (blue).

Model performance

The ensemble model had an R2 of 0.85, a MSE of 24038.72 and a coefficient of determination of 0.87.

Uncertainty assessment

The uncertainty of the model was estimated using the coefficient of variation (CV), which assesses the consistency or variability of predictions across the individual models in the ensemble.

4.4. EBV-derived policy indicators

The use of soil-related EBVs can significantly improve the evaluation of ecological soil conditions, thereby facilitating a more comprehensive assessment of ecosystem health. This approach holds particular relevance within the context of nature restoration legislation targets of evaluating the state of habitats and ecosystems, and in the context of the proposal for a Soil Monitoring Law, which reinforces the pressing need to prioritise soil monitoring for protection and restoration efforts in Europe. For this aim, valuable insights drawn from previous experiences with other environmental compartments and directives can provide valuable guidance (Beck et al. 2005). For instance, the concept of ecological status, as defined in the European Water Directive Framework (WDF, European Commission, 2000), presents an integrated assessment that takes into account the various ecological facets of aquatic ecosystems. This framework employs a range of ecological indicators, encompassing both biological and physico-chemical parameters, to evaluate the condition of habitats. It sheds light on the anthropogenic influences impacting ecosystem well-being and contributes to the formulation of sustainable management strategies. In this framework, when there are slight but not significant deviations of indicators from their natural or undisturbed states, the ecosystem can be designated as having a "high" ecological status, which is to become a mandatory target for management (Birk et al. 2012). In the context of soils, the undisturbed state refers to the natural condition of the soil system preceding any human intervention, but it can also denote the ecologically favorable state within a specific habitat type.

The assessment of soil ecological status forms the base upon which complementary policies can be developed, as depicted in Figure 1. One such policy initiative involves devising concrete strategies for the restoration or enhancement of soils categorized as degraded or in a moderate state. Another significant policy priority centers on identifying strategic areas for the conservation of soil taxa and the ecosystem services they provide. When evaluating the attainment of good ecological status for soils, the identification of restoration potential or soil nature conservation areas necessitates the consideration and protection of the diverse ecological dimensions supported by soils. This includes

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their biodiversity, community composition, uniqueness, and the spectrum of ecosystem services they contribute to (Guerra et al. 2022). Preserving these areas requires tailored approaches for restoration and conservation to ensure their preservation (Zeiss et al. 2022). Here, we present the framework developed to assess the ecological status with the use of soil related-EBVs produced as detailed in 4.3, to further identify areas of high restoration potential.

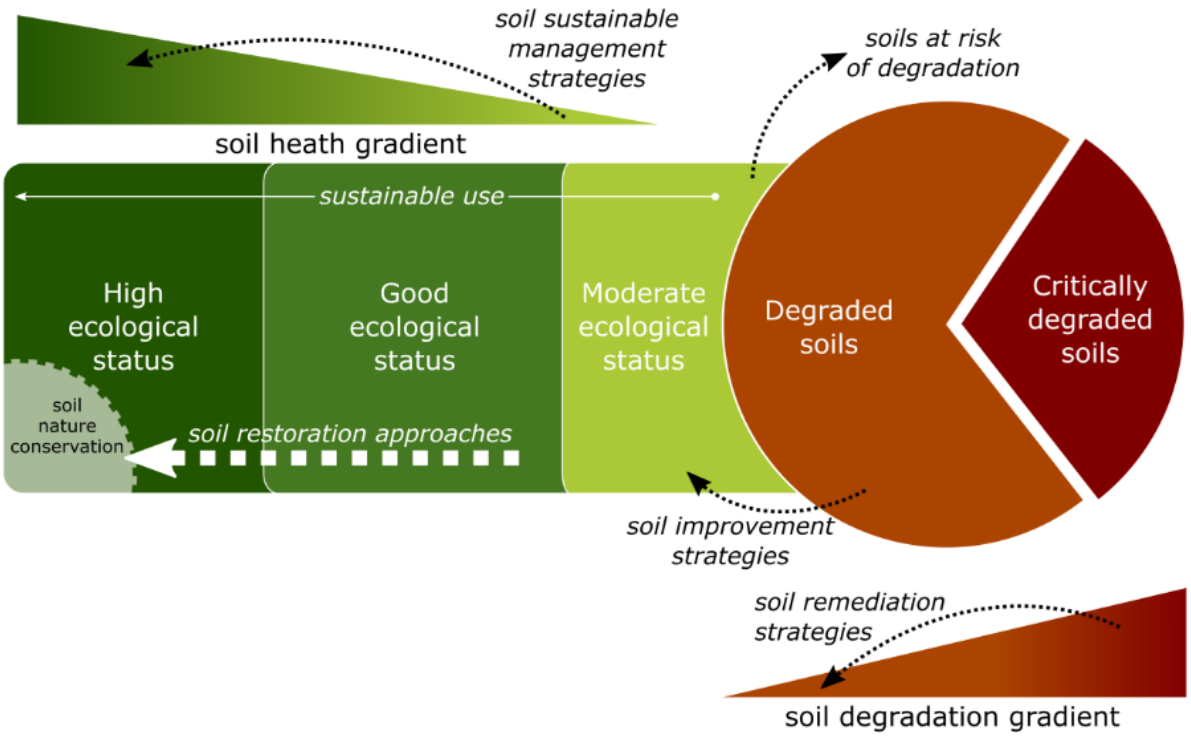

Figure 10 Schematic representation and classification of the ecological status of soils. In green, a gradient of healthy soils is shown from “high ecological status”, referring to soils with high biological and functional activity and structure, to “moderate ecological status”, referring to still non-degraded soils with moderate levels of biological and functional activity, both estimated when comparing to the same reference system (e.g., a combination of biogeographical region and land-use type). In dark orange and red, the soil degradation gradient is shown from “critically degraded soils”, referring to soils with high levels of degradation and cumulative impacts resulting from severe or continued disturbances, to “ degraded soils”, referring to soils with severe loss of function and/or biological activity but with less cumulative impacts. Black dashed arrows indicate different strategies for the improvement of the soil's ecological status and the potential for healthy soils to be sustainably used (e.g., for agricultural production) and to be spared for nature conservation of soil organisms.

4.4.1. Methods for producing EBV-derived state indicators and trends

The ecological status of the European soils can be categorized into the following categories: critical degraded soils, degraded soils, moderate status, good status, high status, as exemplified in Figures 10, 11 and 12. The European commission has already established a procedure to classify degraded soils. In their approach, soils with at least one soil degradation process being above the defined threshold by the EEA, are considered as degraded. For simplification, soils with more than 1 degradation process above the threshold can be classified as critically degraded. The rest of the soils can then be classified into moderate, good or high status. For this, a ‘reference undisturbed state’ is needed to serve as a baseline to compare the current EBVs state. A solution is to use the predictions of the model used to create the EBVs (see section 4.3), but setting to 0 or the minimum all the soil degradation processes. For this, soil degradation processes need to be included from the beginning in the model predictors

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(e.g., see model described in 4.3.1). This 'reference undisturbed state' indicates the expected value of EBVs in a scenario where no soil degradation processes exist.

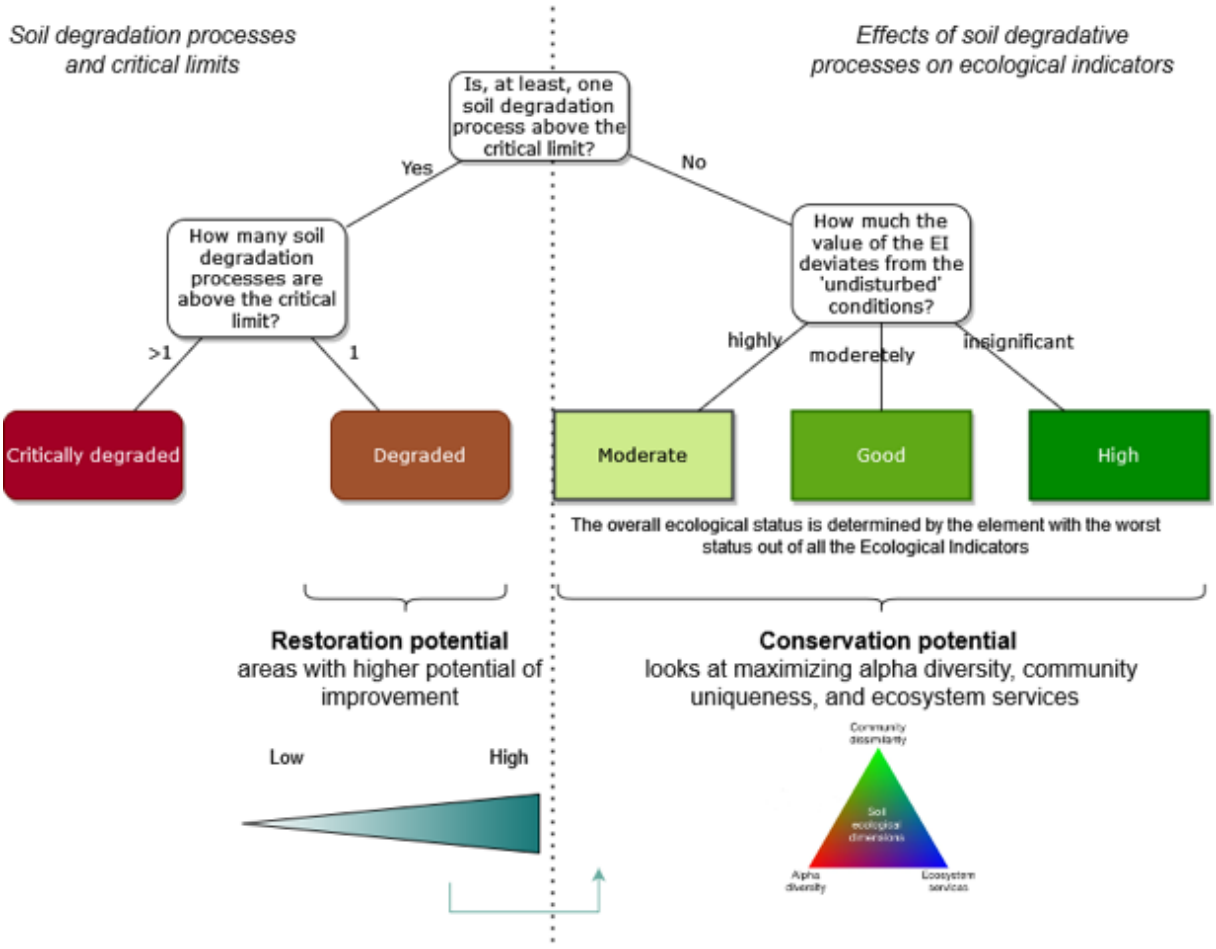

Figure 11 Worflow for the classification of European soils based on their ecological status and to implement indicators for restoration and conservation.

Next, the percentage of difference between the current EBV state and the 'reference undisturbed state' can be calculated to define the ecological status of soil. If the difference between states is statistically high, it means that the site is very distant from the modelled reference conditions, so it can be considered as having a moderate state for a given EBV or EBV metric. If the difference is intermediate, the site can be classified as having a good status. If the difference is low or insignificant, i.e., the value of the indicator is similar to the value expected from the reference conditions, then it can be considered as having a high status. The overall ecological status classification for a soil area (pixel 1km) is determined by the element, i.e., EBV or EBV metric, with the worst status out of all the ecological indicators following the 'one out, all out' principle used in the WFD (European Communities, 2005). It is advisable to conduct a separate evaluation based on habitat or land cover types and biogeographical regions. This is crucial due to the unique characteristics exhibited by certain soils, which may be atypical by nature and constitute rare habitats for biodiversity or unique landscapes. Alternatively, some soils may have undergone significant human modifications, such as those found in agricultural landscapes. These distinctive features should be duly considered when defining soil conditions and establishing the prerequisites for maintaining a healthy soil environment.

In order to effectively enhance degraded soils through soil improvement strategies, it is imperative to assess the potential for their restoration. One approach to evaluating this potential is by considering the percentage of difference between the current EBV state and the 'reference undisturbed state' used to assess the ecological status of soils (Figure 12). A high difference between the current state and the

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reference state signifies a significant potential for improvement for a given EBV. This potential can be realised through the implementation of effective management strategies aimed at mitigating soil degradation processes.

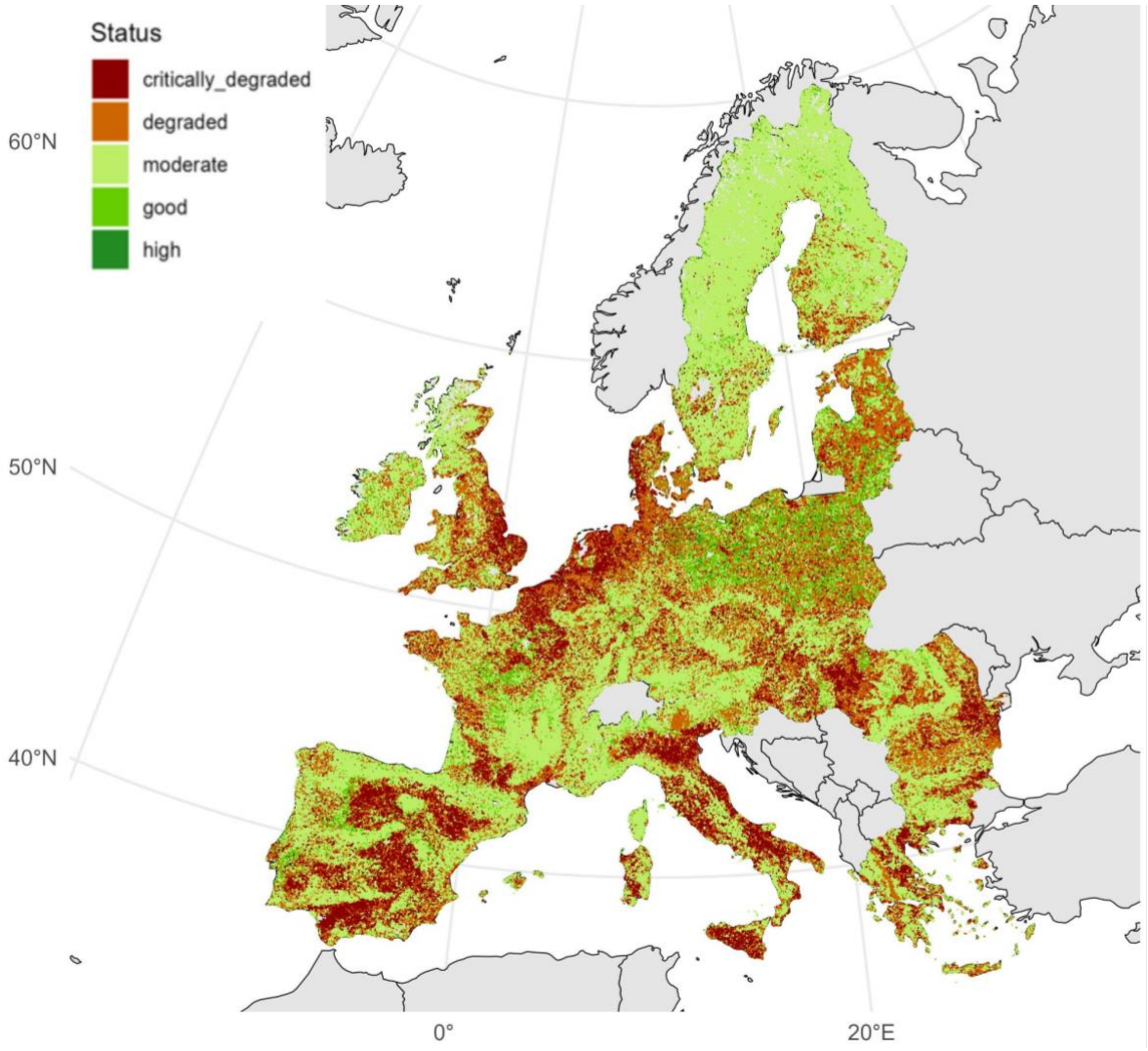

Figure 12 Representation of the soil ecological status assessments in Europe. Degraded soils refers to soils one (degraded) or more (critically degraded) soil degradation process being above the critical limit (defined by the EEA). The rest of the soils were classified into moderate, good or high based on the deviation of soil-related EBV metrics from an undisturbed reference state.

4.4.2. Relevance of the new EBV product for policy reporting as compared to customarily used data flows.

Current soil health assessments predominantly focus on categorizing soil conditions based on indicators related to soil degradation, such as erosion and heavy metal concentrations. These assessments designate soils as degraded when specific indicators exceed predefined thresholds, often referred to as critical limits, as mentioned above. Typically, these assessments rely on physical and chemical measurements, including soil pH, carbon content, nutrient availability, chemical levels, and soil texture. While these indicators provide valuable insights into soil health, they may not capture the full complexity of soil biodiversity and functioning (Römbke et al. 2005). Integrating EBVs related to soil biodiversity and functions into these assessments, as shown in the previous section, may help to address this limitation. These EBVs are rooted in the functional roles that soils play in supporting vital ecosystem processes such as carbon sequestration and rely on biological measurements,

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encompassing soil biodiversity, activity levels, and biomass. The incorporation of soil biotic and functional EBVs offers a more comprehensive perspective on soil health and quality, enhancing our ability to refine the classification of soil ecological status. By integrating these novel indicators into soil health assessments, we can attain a more holistic understanding of soil conditions. This, in turn, contributes significantly to enhancing the accuracy of soil ecological status classifications, making our policy reporting more robust and informed (Figures 10 and 12).

5. Discussion

5.1. Advantages and caveats of the EBV result

The main caveat of the current approach is its limitation in terms of taxonomic resolution. The current datasets and the current knowledge about the taxonomic identity of many soil organisms is still limited both in Europe and in the world. This is also where the EBV approach has particular advantages by allowing a better representation of the distribution of particular species and the study of the potential effects of climate and land-use change. By using a limited pool of data for a particular species or function and transforming it into continuous representations of its distribution, EBVs provide a good baseline for decision making but also to improve the quality of monitoring by identifying critical areas that require further attention.

5.2. Breakthroughs and lessons learned:

Being able to represent the taxonomic and functional diversity of soil organisms for Europe is an important step to show the potential that the current datasets (including LUCAS Soils) already have. This also led to the classification of European soils into an ecological indicator depicting their ecological status. In both cases, particularly in the framework of the current soil monitoring law that is being discussed, these are valuable information to the identification and followup of the health of European soils. Both goals (identifying healthy soils and tracking their progress), would benefit from more spatially, and more importantly, temporally extended datasets so that the analyses benefit from more up to date information.

5.3. Outstanding challenges and proposed solutions

Overall, no outstanding challenges were identified. That said, there is still a significant lack of validation of the soil organisms observations found in GBIF. This is mainly driven by the important amount of citizen science data coming from iNaturalist directly to GBIF. While this information maybe relevant for other taxonomic groups, in the case of soil organisms, the identification and classification is often flawed (e.g., a great number of miss identifications of *Lumbricus terrestris* since this is one of the most common earthworms present in Europe). Therefore, there is the need for a great deal of data curation prior to the use of such datasets in modeling approaches. At the same time, the LUCAS dataset, while now the coverage is improving with the 2022 sampling, still lacks representation of more extreme conditions (e.g., holgy polluted sites, higher elevations), particularly for the subset regarding soil biodiversity and function. That said, we were also able to show (Figure 8) that this is overall a minor issue when considering the European terrestrial systems.

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