SOILGUARD

Sustainable soil management to unleash soil biodiversity potential and increase environmental, economic and social well-being

Grant Agreement no. 101000371

D6.3 Comprehensive policy and conservation briefs and recommendations for soil management and conservation

WP	WP6 Conservation of soil biodiversity			
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List of Acronyms

CAP: Common Agricultural Policy

ECA: European Court of Auditors

EC: European Commission

ES: Ecosystem Services

EU: European Union

EUSO: EU Soil Observatory

FAO: Food and Agriculture Organization

IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IUCN: International Union for Conservation of Nature

LUCAS: Land Use/Cover Area Frame Statistical Survey

LULUCF: Land Use Change and Forestry

MEA: Millennium Ecosystem Assessment

NbS: Nature-based Solutions

NCP: Nature's Contributions to People

SBWF: Soil Biodiversity and Wellbeing Framework

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SSM: Sustainable Soil Management

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1. Summary

This deliverable summarizes the main preliminary results of SOILGUARD and provides a brief analysis of the background on EU soil policy and soil biodiversity conservation. It also includes several recommendations targeting EU decision-makers and conservation organizations.

To accomplish this, the results obtained in previous work packages (WP1, WP2, WP3, and WP6) were reviewed to identify relevant conclusions for EU policy-making and soil biodiversity conservation. Specifically, the analysis included Deliverable 1.3: Soil Biodiversity and Wellbeing Framework, Deliverable 2.2: Soil biodiversity status in European and international biogeographical regions, Deliverable 3.2: Report on the region- and biome-specific impact of climate stressors on soil biodiversity status and cascading effects on soil multifunctionality under different types of soil management, Deliverable 6.1: Assessment of SSM practices, and Deliverable 6.2: Guidelines to implement interventions in which soil biodiversity acts as an NBS.

For the policy brief, a selection of soil-related policies, regulations, and support mechanisms were reviewed, including the EU Soil Strategy for 2030, the Common Agricultural Policy (CAP), the EU Soil Mission, and the proposed EU Soil Monitoring and Resilience Directive and Nature Restoration Law, currently being discussed. Based on these results, specific policy recommendations were developed aiming to inform and support policymakers and relevant stakeholders.

In parallel, to elaborate the conservation brief, a bibliographic review was conducted to identify approaches, gaps, barriers, challenges, and solutions regarding soil biodiversity conservation and Nature-based Solutions. Based on SOILGUARD's research findings and previous conclusions, several recommendations were developed. These include recognizing the critical relevance of soil biodiversity, reinforcing the soil and land health framework, minimizing threats to soil biodiversity, and clearly defining soil biodiversity. Additionally, it is recommended to implement conservation-specific measures, mainstream Nature-based Solutions, scale up Sustainable Soil Management practices, and leverage the benefits of these practices.

The results and insights included in this document will be a basis for upcoming WP6 outcomes, specifically for *Deliverable 6.4: Policy and conservation brochure for wider dissemination*.

2. Introduction

Deliverable 6.3, titled "Comprehensive policy and conservation briefs and recommendations for soil management and conservation" is a report focused on EU policy and soil biodiversity conservation. This report results from two subtasks: *Subtask 6.1.2, which addresses* conservation community awareness on soil biodiversity and ES conservation, and *Subtask 6.2.1, which deals with* policies and frameworks to inform at EU level.

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The document begins by summarizing the main results of previous tasks from SOILGUARD, related to the development of the Soil Biodiversity and Wellbeing Framework, the analysis of soil biodiversity status in different land uses and regions, the management and climate change impacts on soil biodiversity and soil multifunctionality, the assessment of Sustainable Soil Management practices according to the IUCN Global Standard for NbS, and the guidelines to implement interventions. These results are described in Chapter 3. Chapters 4 and 5 introduce the definitions of soil biodiversity and the current status of soil biodiversity at the EU level.

Chapter 6, one of the main sections, is the policy brief. It includes a review of a selection of soil-related policies, regulations, and support mechanisms, as well as a set of policy recommendations which aim to inform and support policymakers and relevant stakeholders.

Chapter 7 is the second main section, the conservation brief. Similarly, it begins with a description of the state of the art on soil biodiversity conservation, including insights on soil biodiversity and nature conservation approaches. It also includes conservation recommendations oriented towards soil management and conservation organizations.

Finally, Chapter 8 presents a summary of relevant issues that should be considered regarding how soil biodiversity indicators and monitoring can be used for policy and conservation.

3. SOILGUARD main results

This section highlights a selection of the main research findings of the SOILGUARD's first activities, relevant to EU Soil Policy and Soil Biodiversity Conservation. These results should be considered as preliminary, requiring cautious interpretation.

3.1.1. *Soil Biodiversity and Wellbeing Framework*

The following section details the main conclusions from *Deliverable 1.3. Soil Biodiversity and Wellbeing Framework*. **The Soil Biodiversity and Wellbeing Framework (SBWF) conceptual structure, serves as a** guide for understanding **soil management, soil biodiversity, soil multifunctionality, NCPs, and wellbeing.** It emphasizes soil biodiversity conservation as a key part of land management within our broader socio-ecological system, which influences natural capital assets like soil biodiversity, by influencing ecosystem properties and functions (Figure 1). More information can be found in *Deliverable 1.3 Soil Biodiversity and Wellbeing Framework.*

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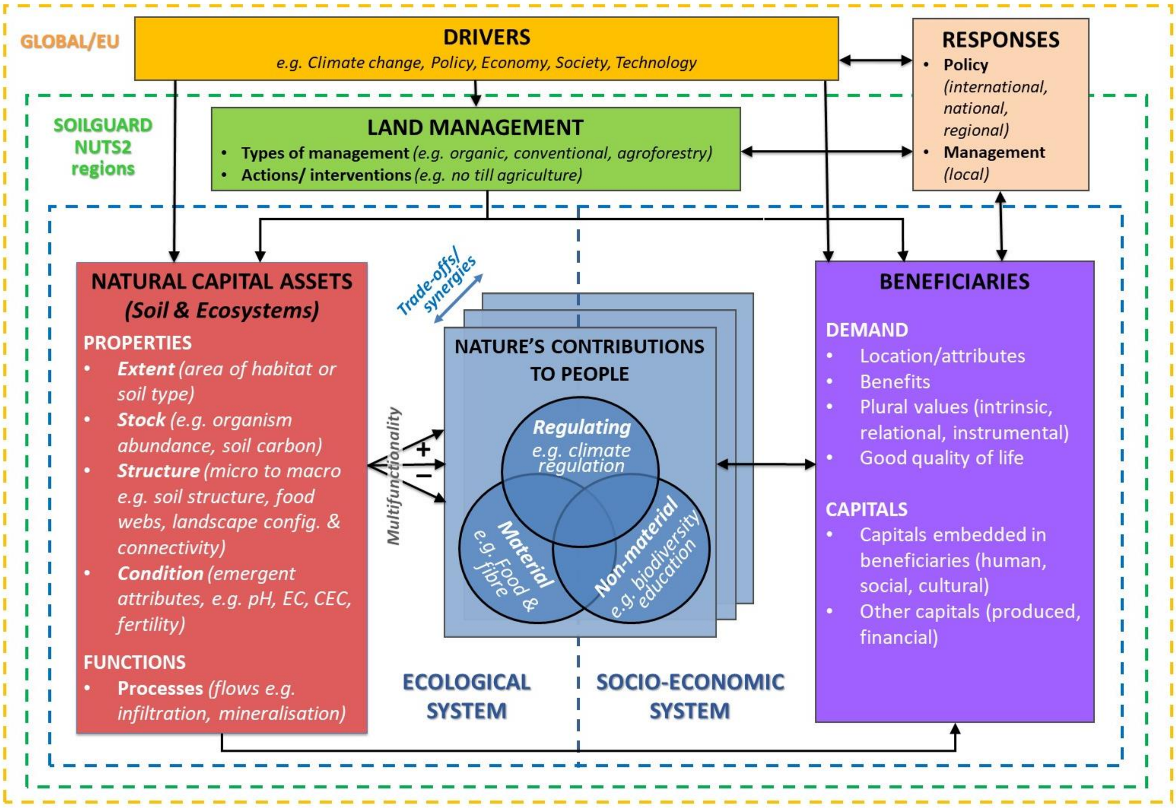

Figure 1.The Soil Biodiversity and Wellbeing Framework. Source: *Deliverable 1.3 Soil Biodiversity and Wellbeing Framework*

Accompanying the SBWF's conceptual guide, its analytical component offers various indicators and methods to assess natural capital assets and the benefits of NCPs. A specific proposal for these is included in *Appendix A.* Guerra et al. (2021) also suggest a set of soil ecological indicators, based on essential biodiversity variables (EBVs) and linked to current global targets and policies, to track the state and dynamics of global soil biodiversity and ecosystem functioning over time.

3.1.2. *Soil biodiversity across biogeographical regions*

The following sections detailed the main conclusions from the *Deliverable 2.2 Soil biodiversity status in European and international biogeographical regions.* This deliverable presented the results of the sampling campaign conducted to assess the status of soil biodiversity across ten locations - Buenos Aires (Argentina), West Flanders (Belgium), West Cameroon, Middle Jutland/Syddanmark (Denmark), South Transdanubia (Hungary), Latvia, Murcia (Spain), Chiangrai (Thailand), Southern Ireland and West Finland -, eight biogeographical regions (Atlantic, continental, Pannonian, Mediterranean, boreal, tropical humid, tropical savannah and temperate oceanic) and three land use types (cropland, grassland and forest). These conclusions include a description of differences across regions of indicators for the abundance, diversity, and complexity of the soil biome.

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Results show that there are significant differences on the abundance, composition and complexity of soil biodiversity across biogeographical regions. Overall, the soils of West Finland differed from other regions for having a more abundant soil biome, which also differed from other regions in terms of communities' composition and soil food web complexity. This can be caused not only by site effects but also by land use, since Finland is the only location containing forests. Among all other regions, we observed similarities in terms of abundance, diversity, and food web structure. Regarding soil organism diversity, there were limited differences in species diversity (alpha diversity) across regions, but clear differences in community composition (beta diversity). This suggests that conservation efforts should be oriented to all biogeographical regions and land uses to preserve species diversity and the heterogeneity of community compositions. Also, diversifying land use types and cropping systems could play a role in conserving biogeographical patterns of diversity.
The highest abundances of soil organisms among cropland sites, were detected in regions at higher latitudes, such as Middle Jutland/Syddanmark and Latvia had, with abundances of invertebrates comparable to those of grasslands in Southern Ireland. In these regions the low temperatures and level of precipitation favours organic matter stabilization and higher soil moisture, which provide a better environment for soil biota (Crowther et al., 2019; Hao et al., 2021; Song et al., 2017). Cropland is one of the land uses that can have higher impacts on soil organisms (Burton et al., 2023; Wardle, 1998) and lower organism abundance can be attributed to more intense soil disturbances (Song et al., 2017) and aridity (Hao et al., 2021). This is caused due to the intensity and frequency of anthropogenic disturbances, which can constrain part of the microorganisms (Drenovsky et al., 2010) as well as the low year-round plant cover and diversity, which limits the abundance and diversity of litter, exudates and plant hosts, on which fungi and bacteria depend.

West Flanders had an abundant but of low complexity, bacterial-dominated soil biome, although it showed the highest fungal and bacterial energy channels compared to all other regions, while grasslands in Southern Ireland had second-highest values. The intermediate levels of organism abundance seen in Southern Ireland can be explained by the fact that grassland represents an intermediate level of land use intensification between forest and cropland (Labouyrie et al., 2023). The continuous grass cover, the higher root density and the higher soil organic matter found in grasslands compared to croplands can sustain relatively high abundances of soil organisms.

We detected similar community composition of protists, nematodes, arthropods, and annelids across all regions. Soils originating from sites that strongly differed in terms of land use, climate, or cropping system, differed the most in bacterial and fungal community composition. This was the case for West Finland, West Cameroon, Chiangrai.

3.1.3. *Soil management and climate change impacts*

The following chapter summarizes the conclusions from the *Deliverable 3.2 Report on the region- and biome-specific impact of climate stressors on soil biodiversity status and cascading effects on soil multifunctionality under different types of soil management*. This document gathers the main preliminary results obtained from the experimental cases. These studies analysed multiple sites across

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biomes with in-situ climate change simulations to examine the impacts of climate change on soil biodiversity and multifunctionality in soils with contrasting management regimes. Different fields were analysed at each region. Fields were managed either in a conventionally more intensive way (i.e., conventionally managed cropland, mono-species high-input grasslands, and clear-cut forests) or alternatively (i.e. organically managed cropland, mixed-species low-input grasslands, and continuous cover forests). Droughts and heatwaves were simulated at each site using rain-out shelters and infrared heaters, respectively, to simulate the future climate scenarios projected through regional climate models.

Initial results suggest that **while organic agriculture tends to reduce crop yields and increase leaf damage it boosts soil carbon levels, nutrients, and biological activity, and enhances fungal communities**. The benefits for soil biodiversity were mixed and site-dependent, with some neutral, and negative impacts observed across different taxonomic groups.

Impacts on soil biodiversity

Initial explorations into soil biodiversity reveals significant site-specific variations. While management practices slightly influence biodiversity—accounting for about 2% of the observed differences—**it's the unique characteristics of each site that predominantly determine biodiversity levels, explaining 54-75% of the variance**. Drought impacts on soil biodiversity were generally minimal, varied by site, and were often masked by other drivers. Fungal, and more generally, eukaryotic communities showed less responsiveness to these changes compared to prokaryotes, highlighting the need for more detailed analyses.

Impacts on soil multifunctionality

Regarding soil functionality, results are highly specific to each region, but two general patterns emerge. First, **sustainable management generally enhances soil functionality, especially in cropland areas with low initial organic carbon, where the potential for improvement is greatest**. The experimental sites with the highest soil organic C levels showed the least positive effects of sustainable soil management. The latter result supports the notion that organic agriculture and other soil sustainable management approaches and techniques may be more beneficial in places with relatively low organic carbon levels (either under more arid conditions and/or in more degraded soils) and therefore with a stronger potential to enhance soil carbon storage. Little evidence was found in favour of, or against, conversions from clear cutting to continuous cover forestry on forest areas and from grass monoculture to grass mixtures on grasslands. However, **the positive effect of sustainable management generally weakens under drought conditions**, indicating that such management (conventional to organic management) might be most effective if focusing on those regions that are expected to suffer less from a drier climate in the future.

Soil biodiversity as mediator of the impacts of climate and management on soil functioning

The diversity of soil organisms plays a critical role in how soil ecosystems respond to climate change and management practices. **Generally, the interplay between soil biodiversity and functionality was**

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more beneficial under drought conditions, particularly for prokaryotes and fungi. However, this positive interaction tends to weaken in arid areas. **Soil biodiversity significantly influences how soil functions respond to changes in agricultural management, with most interactions being positive**. This suggests that organic farming, when combined with a richer soil biota, generally enhances soil functionality more effectively than when implemented on its own.

Synergies and trade-offs between ecosystem indicators

Results show that most soil functions are interlinked, showing positive correlations across different management and climate scenarios. These synergistic relationships suggest that it is possible to optimize multiple ecosystem functions simultaneously, and that a healthy soil does not necessarily need to trade-offs against productive (i.e. high crop yield) croplands and other land uses. Yet, these positive interactions are less prevalent when examined within the context of a specific management practice, whether conventional or more sustainable, suggesting that **multiple ecosystem functions can be more difficult to maintain simultaneously at high levels within a given agricultural management**. The notable exception is the positive correlation observed with soil enzymatic activities, which persisted across different management practices.

3.1.4. *Nature-Based Solutions and soil biodiversity*

The following chapter summarizes the conclusions from the *Deliverable 6.1 Assessment of SSM practices* and the *Deliverable 6.2 Guidelines to implement interventions in which soil biodiversity acts as an NBS.*

Nature-based Solutions (NbS) leverage natural processes and ecosystems to tackle environmental, social, and economic challenges, offering additional co-benefits in comparison with conventional or classical grey solutions that have neutral or negative impacts on ecosystems (European Commission., 2021). These strategies can be sustainable alternatives to enhance ecosystem functions and promoting human well-being and biodiversity.

Assessment of SSM practices

Sustainable Soil Management (SSM) practices were assessed using the assessment tool that was developed based on two key components: 1) The Self-Assessment Tool for IUCN Global Standard for Nature Based Solutions (NbS), to define the overall assessment structure and methodology, and 2) the Soil Biodiversity and Wellbeing Framework (SBWF) as the specific conceptual foundation. This evaluation was designed to identify the elements that need strengthening in the application of SSM practices and to guide the adoption of NbS.

Results indicate a **lack of sufficient impact on human well-being.** This was due to the fact that beneficiaries, outcomes related to human wellbeing, specific indicators, and benchmarks (especially at the local scale) were not identified, and there was a lack of resources and monitoring activities. While some criteria related to societal challenges, policy integration, and knowledge dissemination scored adequately, there remains considerable room for improvement (Table 1). More information about the assessment process can be found in *Deliverable 6.1 Assessment of SSM practices.*

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Table 1. Average scores obtained for the assessment per criteria. Source: Deliverable 6.1 Assessment of SSM practices

Criterion	Average score
SSM practices respond to the current state of the ecosystems and soil biodiversity	Partial
SMM practices recognise and respond to the interactions between the economy, society and ecosystems and integrate complementary interventions	Partial
Risks and trade-offs are identified, managed, and inform corrective actions and safeguards	Partial
SSM must address societal challenges that have been identified, thoroughly understood, and well-documented	Adequate
SSM practices have a positive impact on soil biodiversity and ecosystem integrity and the impact is periodically assessed	Partial
SSM practices have a positive impact on human wellbeing and the impact is periodically assessed	Insufficient
The stakeholders and beneficiaries have been identified and governance processes are participatory, inclusive, transparent and empowering	Partial
The rights, usage of and access to land and resources, along with the responsibilities of different stakeholders are acknowledged and respected	Partial
SSM practices are economically viable	Partial
Lessons learned are documented and shared	Adequate
SSM practices are managed adaptively, based on iterative learning	Partial
A monitoring and evaluation plan is implemented to assess unintended adverse consequences on nature and review the established safeguards.	Partial
Relevant policies, regulation frameworks and national and global targets are identified and considered in the SSM practices design	Adequate
SSM practices inform and enhance facilitating policy and regulation frameworks and contribute to national and global targets	Adequate

Specifically, there are four criteria with an adequate average score. The first one is the criterion regarding identifying, understanding and documenting societal challenges. The outcomes of the assessment point out that, there are still significant knowledge gaps due to insufficient documentation and a lack of context-specific information about societal challenges at the local scale. This is particularly notable considering that the main challenges may differ at various scales. The second criterion concerns how lessons learned are documented and shared. In this regard, while there are several experiences related to communication, often linked to commercial activities, advisory services, and the dissemination of science and research, other knowledge-sharing initiatives may lack systematization, specificity, or accessibility. The third criterion involves the identification and consideration of relevant policies, regulatory frameworks, and national and global targets in the design of SSM practices. The fourth criterion, with an adequate average score, is related to how SSM practices inform and enhance the facilitation of policy and regulatory frameworks, contributing to national and global targets. Even if the average score for these criteria is adequate, there is a significant margin for improving the performance of interventions in these aspects. This is noteworthy, especially

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considering that some of these criteria closely linked with how SSM practices positively impact human well-being, which has the lowest score.

On the other hand, most of the criteria have a partial score on average. The scores for the criteria that address how SSM practices respond to the current state of ecosystems and soil biodiversity, and the criteria that address how stakeholders and beneficiaries have been identified and involved in governance processes, are either partial or almost entirely partial in every case. Therefore, there was a very homogeneous result across the regions. The criterion referring to how SMM practices recognize and respond to the interactions between the economy, society, and ecosystems and integrate complementary interventions is the one with higher dispersion in the scores and less homogeneity across the region. This may suggest that the lessons learned from some regions could contribute to enhancing a greater alignment with this criterion in other cases.

Guidelines to implement SSM practices with a positive impact on soil biodiversity

This chapter aims to provide guidelines for implementing SSM practices, following the IUCN Global Standard for NbS. The results of the assessment of on-the-ground SSM practices detailed in *Deliverable 6.1 Assessment of SSM practices* were analysed and summarized to identify the barriers that should be overcome and to develop recommendations for better integrating those practices and interventions within the NbS framework. Specifically, this section gathers recommendations to facilitate the alignment of SSM practices with the criterion of the assessment that has the highest correlation with soil biodiversity conservation: SSM should have a positive impact on soil biodiversity and ecosystem integrity, and this impact should be periodically assessed. Recommendations related to other NbS aspects (economic, governance, human wellbeing, etc.) can be found in *Deliverable 6.2 Guidelines to implement interventions in which soil biodiversity acts as an NBS.*

To ensure that SSM practices have a positive impact on soil biodiversity and ecosystem integrity and the impact is periodically assessed **existing monitoring and evaluation plans should be strengthened with additional funding and human resources**. This criterion is not highly achieved, primarily due to the complexity around the understanding and assessment of soil biodiversity and ecosystem integrity, but also the fragmented administrative structures related to ecological issues and lack of resources specifically oriented for biodiversity and ecosystem integrity monitoring. Regarding croplands, various parameters are monitored as part of the efforts to oversee farming practices, being it labelled as organic or otherwise. Nevertheless, the consequential bureaucracy and controls, and the financial implication for farmers need to be considered. Reflections on the monitoring and evaluation activities, the simplicity and user-friendliness of monitoring and the funding allocated for these activities, could facilitate their feasibility and implementation.

There is a lack of identification and assessment of clear, specific and measurable outcomes for biodiversity and ecosystem integrity. Soil biodiversity conservation outcomes are difficult to measure and a monitoring system that goes into detail and that is sufficiently accurate to base management decisions upon is not available and is expected to be too expensive and time consuming. There are few

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documented measurements of the impacts of organic soil practices on biodiversity, and scalable results are notably scarce. There is currently insufficient data available on the soil biological status of the SSM at all scales and the available data is limited to certain ecological groups.

Considering the specific results for each biome. In grasslands, there is still limited information about the biological health of reduced diversity systems, which predominate in intensively managed grassland systems. Farmers are reporting improved structure and enhanced earthworm populations with more diverse swards. Some research is available on individual sites demonstrating soil biodiversity benefits as linked to the change in management. However, a larger scale assessment at the farm, landscape, and national levels is still lacking. Additionally, there is no large-scale monitoring system in place. In farmlands, one of the main observable outcomes is the abundance of earthworms. The significance of earthworms is acknowledged, and farmers assess their abundance, although not systematically. Additionally, general soil assessments, such as aggregate stability, are frequently conducted visually by taking a sample of soil and evaluating the way it crumbles. The lack of data and research on soil biodiversity, its impact, and the management practices that facilitate its proliferation are significant barriers in this regard. In forest areas systematic approaches to measure soil biodiversity conservation outcomes and ecosystem integrity are underdeveloped compared to above-ground features due to lack of interest, knowledge and resources for soil-related R&D.

With the advancement of Soil monitoring legislation, more appropriate metrics could emerge in the near future. In this regard, there is a need of funding and human resources to improve an edaphic biodiversity monitoring methodology, that can be used at an adequate scale and build a systematic framework that address coordination challenges associated with conducting large-scale research. Moreover, the awareness raising of farmers and landowners with regards to soil relevance may imply the collection of more data and soil sampling. The search for more data on fertility or soil productivity could be synergetic with retrieving at the same time more data on soil diversity. Monitoring should include specific variables related to soil biodiversity and ecosystem integrity and define the frequency of assessment, the analyses that will be done to determine outcomes, and how information will be shared. Monitoring should provide enough information to indicate species or ecosystem recovery and potential adverse impacts. A baseline assessment of the indicator variables should be conducted considering the monitoring criteria.

The implementation of data collection and documentation processes on soil biodiversity, its impact, and the management practices that facilitate its proliferation, at short and long term and at different spatial scales are significant processes that would facilitate a higher fulfilment of this criterion.

4. Defining soil biodiversity

Soil is an ecological system rich in biodiversity that provides several Nature Contributions to People (NCP) that are essential for human wellbeing. The complex and heterogeneous physical and chemical nature of soils across multiple scales provides a wide range of habitats for a multitude of organisms

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that drive and regulate ecosystem functions (Orgiazzi, Bardgett, R.D., et al., 2016). For instance, processes involved in soil structure modification and carbon and nutrient cycles, such as decomposition of organic matter and nitrogen fixation, are closely interrelated with the activities of soil biota (Larbodière et al., 2020). As a result, soil biota represents one of the largest and most relevant reservoirs of biodiversity on Earth (Yang et al., 2018).

However, **while soil biodiversity exceeds that of other terrestrial systems by orders of magnitude, and has a critical role in providing environmental services, it is still underappreciated** and receives little recognition (FAO et al., 2020). Research on soil biodiversity has largely focused on the roles of specific groups of organisms, but knowledge of what biodiversity is present in soils in particular locations, and how soil species influence ecosystem functioning, is still scarce (Larbodière et al., 2020). The huge gaps in the documentation of soil biodiversity, especially of microorganisms, is a critical limitation to assess the conservation status of many soil biota. The 90-95% of soil biota remains unidentified (Larbodière et al., 2020).

Soil biodiversity and its role in ecosystem functioning is under pressure due to threats (Figure 2) which can have negative impacts on the delivery of several NCP (FAO et al., 2020). These threats include land-use intensification, pollution, soil erosion, compaction and sealing, acidification, wildfires, land degradation and desertification, climate change, the introduction of invasive species and acid rain (FAO et al., 2020, Orgiazzi et al., 2016, Larbodière et al., 2020, Tsiafouli et al., 2015). Martin et al. (2018) defines land use intensification as activities undertaken with the intention of enhancing the productivity or profitability per unit area of rural land use, including intensification of particular land uses as well as changes between land uses. These activities can include: land use conversion (e.g. from fallows to permanent crops), increasing inputs (labour, irrigation, chemicals, machinery) and crop or product change (often involving higher-yielding varieties, and normally involving specialisation or monocropping) (Martin et al., 2018). Specifically, intensive agricultural practices can include tillage, monoculture, removal of organic matter, synthetic pesticides and excess of fertilisers applications (FAO et al., 2020, Orgiazzi et al., 2016, Larbodière et al., 2020, Tsiafouli et al., 2015). Awareness and knowledge of soil biodiversity, its functional importance and how it responds to specific management practices are essential to better preserve belowground diversity and the important functions of these communities to maintain soil health (Orgiazzi et al., 2016, FAO et al., 2020).

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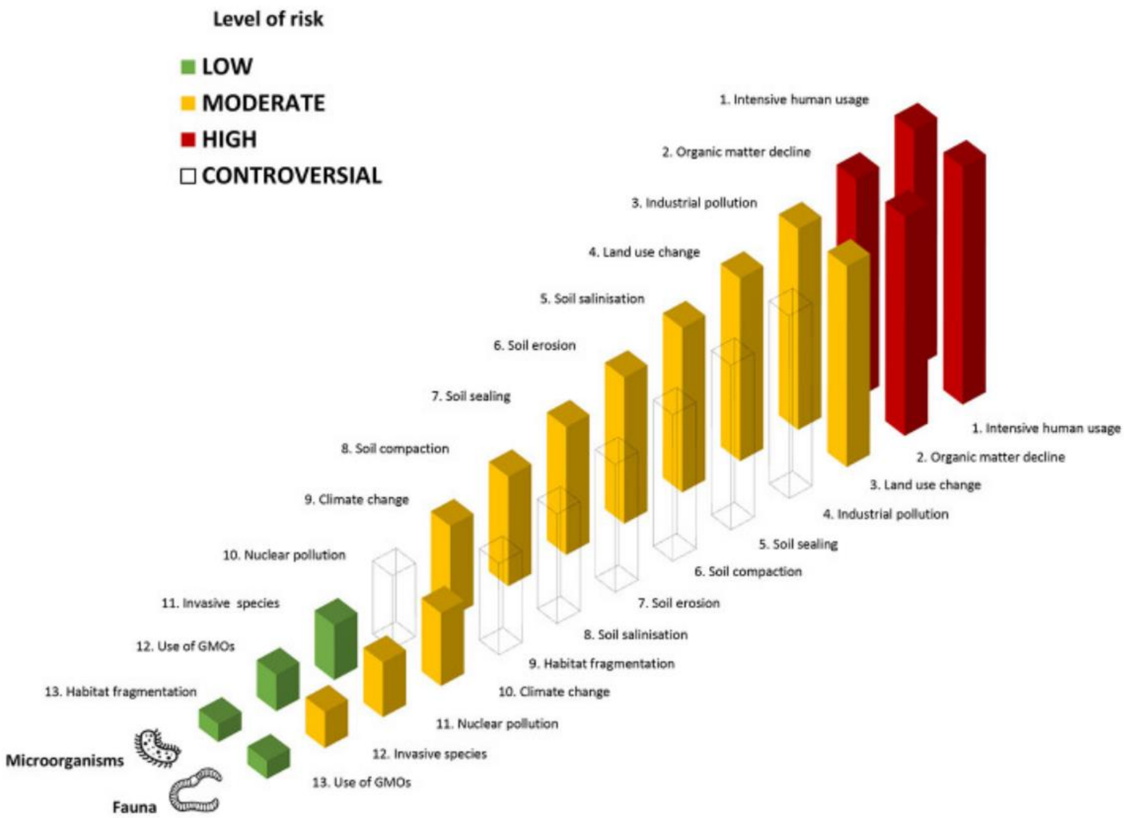

Figure 2.Level of risk associated with 13 potential threats to soil microorganisms and fauna, from least risky (smallest numbers) to most risky (largest numbers). Transparent bars indicate threats on which experts cannot agree, so they remain controversial and require more research. Source: Orgiazzi, 2022a, based in the work developed by Orgiazzi, Panagos, et al., 2016.

There are several definitions for soil biodiversity and soil biota:

- Soil biodiversity is defined by FAO et al. (2020) as "the variety of life belowground, from genes and species to the communities they form, as well as the ecological complexes to which they contribute and to which they belong, from soil micro-habitats to landscapes".
- Larbodière et al. (2020) consider that soil biota includes bacteria, fungi, algae, protists, viruses, nematodes, acari (including mites), collembola (springtails), annelids (primarily earthworms), macroarthropods (such as spiders, ants and woodlice) and vertebrates (like voles, moles and shrews), and also the plants whose root exudates provide food for soil organisms in a zone around the roots known as the 'rhizosphere'.
- In SOILGUARD, we analysed soil biodiversity by considering the abundance, biomass, diversity and complexity of the soil biome, targeting prokaryotes (encompassing bacteria and archaea) as well as eukaryotes (including fungi, protists, nematodes, arthropods, and earthworms).

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- IUCN has recently used the following working definition to tag soil biota on the Red List of Threatened Species: "Soil species are here defined for the IUCN Red List of Threatened Species as those organisms that spend a key part of their life cycle within a soil profile, or predominantly inhabit the soil-litter interface. This includes soil megafauna, macrofauna, mesofauna, microfauna/flora, fungi, and micro-organisms. Although we recognize that most plants play an important role in maintaining fertility, structure, drainage, and aeration of soil, these are not tagged as soil species for the IUCN Red List." This definition can be applied to evaluate the conservation status for populations of soil species from many taxonomic groups.

All definitions recognize the importance of a variety of life forms within the soil, emphasizing different aspects. The definition from FAO is broad and inclusive, covering genetic diversity, species, communities, and ecological complexes and emphasizes the full range of biodiversity from micro-habitats to landscapes. Larbodière et al. (2020) provides a list of soil biota examples and highlights the role of plants. SOILGUARD definition focuses on specific quantitative research measures (abundance, biomass, diversity) while the definition used by IUCN for the Red List of Threatened Species defines soil species with an approach for conservation, considering their life cycle and habitat within the soil profile or soil-litter interface excluding plants from being tagged as soil species.

As Orgiazzi, 2022 points out, **an official and common definition of soil biodiversity is still lacking there is an urgent need for clarity for the policy side**, since the different definitions of soil biodiversity can lead to completely different actions in terms of conservation initiatives. Policymakers require a clear definition of soil biodiversity to propose and monitor targeted measures linked with soil-specific species. Having a clear definition would be a significant step toward to facilitate the integration of soil biota into the legislative agenda for conservation (Orgiazzi, 2022).

Soil biodiversity conservation has received very low attention and funding in comparison to other environmental issues, and the importance of ecosystem services that depend on soil properties are not well understood but in the past decades, there has been an increasing awareness of the importance of these aspects (Orgiazzi, Bardgett, R.D., et al., 2016). In this sense, **there has been widespread interest among researchers, policymakers, and stakeholders in the use of the soil-health concept** (Lehmann et al., 2020). Even if there is currently no widely agreed definition for soil health, the versatility of this concept allows many stakeholders to adopt it and build consensus across different disciplines (Lehmann et al., 2020). Soil health is a concept intimately related to soil biodiversity and it significantly contributes to incorporating the biological perspective into soil management since it is based on recognizing that soil functions not only depend on physical and chemical properties but also on biological properties. Additionally, the concept of soil health is linked to the emerging One Health approach, which recognizes the interdependent relationships between the health of humans, plants, animals, and the environment (Lehmann et al., 2020). Soil health has been defined as the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant,

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animal, fungi and human health (Doran et al., 1996). The term soil health is often understood as a complementary term to soil quality (Laishram et al., 2012). In some cases, both terms are used as synonyms (Dollinger & Jose, 2018), while others argue that there is a distinction between the two concepts (Doran et al., 1996; Pankhurst et al., 1997). Soil quality analysis and assessments have traditionally focused on specific uses and needs, such as agriculture productivity, whereas soil health also considers other attributes of the soil, mainly associated with its biota, that are implicated in processes beyond the growth of a particular crop (Pankhurst et al., 1997). Other related concepts, including soil fertility and soil security, emphasize specific aspects of the role of soil in society, ecosystems, or agriculture (Lehmann et al., 2020). Nevertheless, soil health definition is evolving, and it is a concept that is gaining momentum in science and policy. In the European context, the Soil Mission stands out as one of the main examples of this trend. Complementarily, land health has defined as “the capacity of land, relative to its potential, to sustain delivery of ecosystem services” (Shepherd et al., 2015). Soil health and land health have been identified as points of common interest between agriculture and conservation actors that should be further explored (Larbodière et al., 2020).

It is crucial to deepen our understanding of the relationships between soil biota and soil functions and to agree upon clear definitions that allow us to work together and overcome barriers related to its ambiguity.

5. Soil biodiversity at EU level

Recent studies points out that soil is likely home to 59% of life including everything from microbes to mammals, making it the singular most biodiverse habitat on Earth (Anthony et al., 2023) and therefore its conservation is crucial for sustaining global to local food chains. **By 2050, soil will need to support nearly 10 billion people** (World Resources Institute, 2019), providing them with food and clean drinking water. Soils are the largest carbon reservoir of the terrestrial carbon cycle. Moreover, the ability of many soil types to absorb water can minimize flooding events and drought risks. These features make soils vital for climate change efforts (European Commission, 2021a). Healthy soils are **integral to the EU's climate, biodiversity, and economic goals.**

The EU's diverse soil types, covering 24 of the world's 32 major groups (European Commission, 2005), are a valuable asset that must be safeguarded for future generations. However, it is estimated that more than **60% of EU soils are currently unhealthy**, strongly impacted by issues such as erosion, compaction, pollution, and biodiversity loss (European Commission, 2020a).

Agricultural land management can significantly impact soil's physical, chemical, and biological characteristics (Jangid et al., 2008; Garcia-Orenes et al., 2017). For instance, in the Mediterranean region of Southern Europe, climatic challenges such as limited and sporadic rainfall and frequent droughts lead to soil erosion and degradation, that can be exacerbated by poor land management (Caravaca et al., 2002).

Agriculture utilizes over 45% of Europe's land, and soil loss through erosion across the European Union at an average of 2.46 tons per hectare annually, costs the agricultural sector about 1.25 billion Euros

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annually (Panagos et al., 2017). Consequently, SSM practices also have a potential economic benefit that should not be ignored.

Not only does agriculture provide an opportunity to restore soil health across Europe, but it could also play a significant role into improving soil capacities to mitigate climate change effects. It is increasingly recognized that Nature-based Solutions (NbS) have the potential to improve soil health and enhance its capacity to mitigate and adapt to the effects of climate change. NbS have been defined at the 5th session of the United Nations Environment Assembly as "*actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits*" (UNEP, 2021).

There are a wide range of approaches to sustainable agriculture, including: agroecology, nature-inclusive agriculture, permaculture, biodynamic agriculture, organic farming, conservation agriculture, regenerative agriculture, carbon farming, climate-smart agriculture, high nature value farming, low external input agriculture, circular agriculture, ecological intensification, and sustainable intensification. These approaches can share many environmentally-friendly practices, such as: crop rotation, cover and companion cropping, mixed and intercropping, the reduction of synthetic pesticide and mineral fertiliser use, no or minimal tillage, lower livestock densities, managed and free range grazing, as well as: crop diversification, mixing farming and forestry, mixed crop and animal farming, nutrient balancing, recovery and reuse, and the inclusion of landscape elements such as hedgerows and flower strips (Oberc & Schnell, 2020).

IUCN is currently working on the identification of sustainable agriculture practices that can be considered as Nature-based Solutions, looking not only at the environmental dimensions of these approaches and practices, but also at the social and cultural components of their sustainability. The IUCN Global Standard for Nature-based Solutions and the related self-assessment tool could be considered when determining which practices can be deemed agricultural NbS.

6. Policy brief: EU Policy for Sustainable Soil Management, Soil Biodiversity and Soil Multifunctionality

6.1. Background on EU soil policy

Healthy soils are fundamental to achieving climate neutrality, supporting a clean and circular economy, preventing desertification and land degradation, and reversing biodiversity loss. They are vital for producing safe and nutritious food and thus protecting human health (FAO et al., 2020).

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6.1.1. *EU Soil Strategy for 2030*

The EU soil strategy for 2030 (European Commission, 2021a) outlines a comprehensive approach to ensure the protection and restoration of soils, aiming for sustainable use. This strategy envisions healthy soils by 2050, with specific milestones set for 2030, including the promotion of a Soil Health Law to establish uniform standards for environmental and health protections across the EU.

Furthermore, the EU soil strategy is bolstered by the 'A Soil Deal for Europe' mission (European Commission, 2021b) as part of the soil protection framework for the EU, which leverages research and innovation to discover and implement solutions for soil health restoration. European bodies such as the Joint Research Center are contributing to the implementation of the EU soil strategy with the creation of the EU Soil Observatory (EUSO)[1], alongside partnerships such as the European Joint Programme (EJP SOIL)[2]. These initiatives not only support the strategy's implementation, but also integrate it with the EU's biodiversity and climate adaptation strategies, thus contributing towards the Green Deal's objectives.

The EU soil strategy for 2030 medium-term objectives, to be achieved by 2030, include combating desertification, restoring degraded lands and soils, and achieving a land degradation-neutral status in alignment with Sustainable Development Goal 15.3 (United Nations, 2015). Efforts also focus on the restoration of significant carbon-rich ecosystems. The EU targets a net greenhouse gas removal of 310 million tonnes of CO_2 equivalent annually from the land use, land use change and forestry (LULUCF) sector (European Commission, 2021c). Other medium-term objectives are to attain good ecological and chemical status in surface water and good chemical and quantitative status in groundwater by 2027, reduce nutrient losses and pesticide use by 50% (European Commission, 2020b), and make substantial progress in cleaning up contaminated sites.

By 2050, the Strategy outlines the long-term objectives to reach no net land take (European Commission, 2011) and lower soil pollution to safe levels for human health and ecosystems, supporting a toxic-free environment (European Commission, 2021d). The EU aims to achieve overall climate neutrality, with an interim target of land-based climate neutrality by 2035 (European Commission, 2021e). By means of accomplishing these objectives, the EU plans to establish a society that is resilient to the inevitable impacts of climate change (European Commission, 2021f).

6.1.2. *EU SOIL Monitoring and Resilience Directive*

In June 2023 the European Commission tabled a proposal for a Soil Monitoring and Resilience Directive (European Commission, 2023), setting aside from the Soil Health Law originally envisioned by the EU soil strategy for 2030. The European Parliament adopted its position on the proposal in April 2024 (European Parliament, 2024a).

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The directive, currently under discussion, aims to establish a robust, EU-wide soil monitoring framework to ensure soil health by 2050—integral to the EU's zero pollution goal. It mandates a uniform definition of soil health and a comprehensive monitoring framework, in order to support Member States in the regeneration of degraded soils and the promotion of sustainable soil management practices. It further requires Member States to identify, investigate, and remediate contaminated sites, incorporating the polluter-pays, precautionary and proportionality principles to mitigate human and environmental risks.

Following the modifications introduced by the European Parliament in April 2024, Member States are granted autonomy in defining soil health indicators and practices appropriate to their specific conditions, while maintaining the requirement to address soil contamination comprehensively. Moreover, the directive includes provisions to protect land managers' private data and does not impose legally binding timelines for soil health improvement. The legislation also mandates the creation of a public registry of potentially contaminated and contaminated sites at the latest four years after entry into force of the Directive, aiming for transparency and accountability.

Based on initial assessments and trend analysis to be carried out, the Commission will review the directive's effectiveness and propose necessary amendments to accelerate progress towards the 2050 soil health goals. This includes a five-level soil health classification to facilitate targeted management and restoration efforts, categorizing soils as classes from 'high soil ecological status', 'good ecological status', 'moderate', 'degraded soils' to 'critically degraded soils', as it was proposed by the European Parliament.

Soils assessed as having high or good ecological status are recognized as healthy. This classification system aims to enable Member States to more precisely monitor soil conditions and prioritize intervention measures. It also provides a structured approach to soil management, allowing for targeted actions to restore degraded soils and prevent further deterioration.

6.1.3. *Common Agricultural Policy (CAP)*

Covering the period 2014-2020, the European Court of Auditors (ECA) assessed whether the Commission and the Member States made effective use of available EU tools –namely the CAP and the Nitrates Directive- for managing agricultural soils and manure sustainably (European Court of Auditors, 2023). The report concludes that the '*often unambitious'* definition and requirements of the standards and limited national targeting, the available tools were not used sufficiently and that there remains considerable scope to improve soil health. Additionally, the ECA recommends a series of measures to be adopted by the Commission for the 2023-2027 CAP.

The current Common Agricultural Policy (CAP) for 2023-2027 (European Commission, 2018) is structured around ten core objectives that **seek to promote a balanced approach to agricultural development, emphasizing economic viability, social equity, and environmental stewardship**. The CAP strategic plans, devised by Member States, are designed to be tailored to local agricultural and environmental contexts, ensuring that the policy's implementation is as effective as possible in addressing specific regional needs while contributing to EU-wide goals.

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The current CAP includes specific measures aimed at reducing agricultural emissions, enhancing biodiversity, and promoting the sustainable use of natural resources. A key measure in this context are the so-called **'eco-schemes' for farmers that voluntarily adopt practices that improve soil health**, which are incentives to increase water efficiency, and reduce reliance on chemical inputs. The **support for rural development** includes also environment and climate related aspects. Finally, the current CAP also includes the **enhanced conditionality framework**, which set out standards for public, plant, and animal health and welfare that farmers must comply with, including maintaining permanent grasslands and safeguarding wetlands and peatlands. This framework also sets out conditions for the management of residues, tillage management, soil cover, crop rotation, among others, thus restricting activities that could harm habitats, such as the seasonal cutting of hedges and trees.

The CAP continues to be a cornerstone of policy making in the EU, regulating almost all the farmlands in the EU's territory, directly and indirectly impacting also other land uses. The CAP is a dynamic policy instrument that evolves in response to emerging challenges and scientific insights. Through such integrative and adaptive measures, the **CAP is a big part of the EU's strategy to foster a sustainable and just agricultural system**. Ongoing revisions and updates to the CAP would be expected to further align its objectives with the European Green Deal, particularly in terms of biodiversity conservation and carbon neutrality.

6.1.4. *Nature Restoration Law*

The EU Biodiversity Strategy for 2030 aims to put Europe's biodiversity on the path to recovery by 2030, benefiting people, the environment, the climate, and the economy. It features an ambitious plan to restore EU nature and several significant commitments, such as proposing legally binding targets for restoring nature. These targets focus on rehabilitating degraded ecosystems, particularly those critical for carbon capture and storage and for reducing the effects of natural disasters.

In response, an EU Nature Restoration Law (European Parliament, 2024b) is being negotiated since 2022, being the first law that sets legally binding, time-specific restoration targets both in the EU and globally. Initially, EU member states will develop national restoration plans up to June 2032, with outlines that extend beyond this date. By June 2032, they are expected to submit detailed plans for the next ten years up to 2042, and outline strategies up to 2050. They will then update these plans by June 2042 for the period until 2050.

Article 11 of the proposed Nature Restoration Law sets out Member States to put in place the restoration measures necessary to enhance biodiversity in agricultural ecosystems. Additionally, it establishes that Member States shall put in place measures to achieve an increasing trend of at least two out of the three following indicators for agricultural ecosystems: a. grassland butterfly index; b. stock of organic carbon in cropland mineral soils; and c. share of agricultural land with high-diversity landscape features. These targets have clear implications for improving the uptake of SSM practices in agricultural ecosystems.

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This article establishes that Member States shall aim to restore organic soils in agricultural use constituting drained peatlands, and that those measures shall be in place on at least: a. 30 % of such areas by 2030, of which at least a quarter shall be rewetted; b. 40 % of such areas by 2040, of which at least a third shall be rewetted; c. 50 % of such areas by 2050, of which at least a third shall be rewetted.

Similarly, article 12 sets out Member States to adopt restoration measures necessary to enhance biodiversity of forest ecosystems, achieving an increasing trend at national level of the common forest bird index, as well as achieving an increasing trend at national level of at least six out of seven of the following indicators for forest ecosystems: a. standing deadwood; b. lying deadwood; c. share of forests with uneven-aged structure; d. forest connectivity; e. stock of organic carbon; f. share of forests dominated by native tree species; g. tree species diversity.

The proposed Nature Restoration Law sets out Member States to ensure by 31 December 2030 that there is no net loss in the total national area of urban green space and of urban tree canopy cover in urban ecosystem areas (article 8), and to put in place the restoration measures necessary to enhance biodiversity in agricultural ecosystems (article 11).

Member States are tasked with defining the specific actions they will implement in their national restoration plans to achieve these goals.

6.1.5. *EU Mission Soil*

In the context of Research and Innovation, the EU Mission 'A Soil Deal for Europe', one of the five European Missions (European Commission, 2021b), was launched under the Horizon Europe research and innovation programme for the years 2021-2027. Its objective is to address the urgent need for soil restoration and sustainable management across Europe. The mission seeks to support the development of new technologies and methodologies for soil health improvement. The establishment of 100 living labs and lighthouses facilitates the real-world testing and application of these innovations, promoting their adoption across various European landscapes.

The mission's objectives cover the reduction of desertification, conservation of soil organic carbon, prevention of soil sealing, enhancement of soil structure, and improvement of soil biodiversity. Each objective is targeted through specific research initiatives and practical projects that are monitored for their effectiveness and scalability. By focusing on these areas, the mission aims to make a substantial impact on soil health by 2030, setting the stage for continued advancements in the following decades.

As part of the mission's initiatives, the Mission Soil Manifesto was introduced in April 2023 to foster local engagement and mobilize various stakeholders, including regions, municipalities, organizations, businesses, and individuals. This non-legally binding document emphasizes the essential role of soil in human life and nature, highlighting that soil is the foundation for food production, clean water, biodiversity, and climate regulation (European Commission, 2023b). The Manifesto calls for urgent action to protect and restore soils, recognizing that over 60% of soils in the EU are in an unhealthy

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state. By signing the Manifesto, stakeholders commit to contributing to soil protection and restoration efforts, aligning with the mission's broader goals of creating a sustainable future based on healthy soils.

Public engagement and education are also central to the mission's strategy. By raising awareness of the importance of soil health and promoting soil literacy, the mission strives to cultivate a societal appreciation for sustainable soil management. This educational component is crucial for building long-term support for soil conservation policies and practices.

6.2. Policy Recommendations

Building on insights from SOILGUARD's preliminary research findings, this section outlines policy recommendations aiming to support and enhance soil biodiversity and sustainable management practices within current policy frameworks.

6.2.1. *Promotion of eco-schemes and sustainable agricultural practices*

Preliminary results from SOILGUARD suggest strong benefits of shifting from conventional to organic agriculture in croplands and indicate that diversifying land use types and cropping systems could help conserve biogeographical patterns of diversity. It is important to note that a just transition to such a food production system should take place, which considers expenses derived to the whole food chain and in particular to producers.

Broadening the scope of CAP eco-schemes to include and financially support a wider array of proven stainable Soil Management (SSM) practices can provide economic incentives for landowners and farmers who adopt SSM practices.

Sustainable agriculture management practices may involve the use of cover crops, crop rotation, reduction of synthetic pesticide and mineral fertiliser use, mulching, maintenance of crop residue cover on the soil and reduced tillage, soil organic amendments and the maintenance of non-productive elements and crop residue cover on the soil, among others.

In grasslands, specific practices can include fostering plant diversity, incorporating species with legumes and deep roots, managing fertilization type and quantity, and avoiding overgrazing as sustainable practices for preserving soil biodiversity. **It would also help to encourage Member States to implement Strategic Plans that emphasize soil health** through SSM practices to enhance soil biodiversity and reduce erosion and chemical input dependency. Adapt Strategic Plans for areas with a short growing season due to long and cold winters.

Finally, a potential improvement of the conditionality framework by linking CAP payments more directly to compliance with sustainable soil management practices could also be helpful. This

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adjustments over time could be featured in the new delivery model of the CAP, which should be used to support the sustainability of European agriculture. Environmental ambition in the conditionality framework should continue to rise, not the other way around.

6.2.2. *Build on the Directive on Soil Monitoring and Resilience*

Considering the Soil Biodiversity and Wellbeing Framework being developed by SOILGUARD can help to establish clear, measurable indicators for soil health, biodiversity and multifunctionality within the EU-wide monitoring framework. This would include systematizing soil health data collection methods across Member States to ensure consistent monitoring and to facilitate data-driven policy making. Appendix A includes a set of indicators and its relationship with the Soil Biodiversity Wellbeing Framework.

Based on SOILGUARD's preliminary results which suggest site-specificity of soil biodiversity in response to management, **Member States would benefit from having a margin of flexibility in adapting soil health practices to local conditions, while maintaining elevated and consistent standards for contamination and degradation remediation**. A periodic review of soil health classifications should enable adaptation as necessary based on emerging scientific insights and monitoring data. Moreover, SOILGUARD research suggests that **conservation efforts should be oriented to all biogeographical regions and land uses to preserve species diversity and the heterogeneity of community compositions**.

Additional suggestions to consider in the Directive on Soil Monitoring and Resilience could entail:

- Use of organic fertilizers and reduction of mineral fertilizers as it significantly enhances soil biodiversity (Heinen et al., 2023). Some issues might difficult the transition from conventional to organic production and thus need further assessments such as risks associated with Antimicrobial Resistance (AMR).
- Reduction of synthetic pesticides and organic pollutants as microplastics (Gunstone et al., 2021).
- Implementation of sustainable practices adapted to each context: Crop rotation, cover and companion cropping, mixed and intercropping, the reduction of synthetic pesticide and mineral fertilizer use, no/ conservation/minimal tillage, lower livestock densities, crop diversification, or the inclusion of landscape elements such as hedgerows and flower strips (Doran & Zeiss, 2000; FAO et al., 2020; Orgiazzi et al., 2016; Lynch, 2022; Mann et al., 2019; Brussaard et al., 2007; Ghimire et al., 2014).
- Manage livestock density to prevent soil compaction and soil pollution through biocides such as antibiotics and antiparasitic agents present in manure (Byrnes et al. 2018).
- It would be desirable to include binding targets on soil management, which build upon open discussions with relevant stakeholders. Those binding targets could be inspired by the principles established in Annex III on sustainable soil management. As agriculture is the main use of land (Eurostat, 2021), and intensive agriculture poses a threat to soil health (European

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Court of Auditors, 2019), promoting sustainable agriculture practices such as the ones listed above, could have a major positive effect for protecting soils in the EU.

Further developing the EU Soil Observatory (EUSO), including information on contaminated sites and restoration efforts as mandated by the Soil Monitoring and Resilience Directive would also be beneficial, as it would enhance access to public information and public participation, thus increasing transparency and facilitating community involvement. Additionally, the EUSO should enable broader public and private monitoring of beneficial conditions for the implementation of SSM practices.

6.2.3. *Implementation of the Nature Restoration Law*

Article 11 of the Nature Restoration Law sets out Member States to put in place the restoration measures necessary to enhance biodiversity in agricultural ecosystems. Additionally, it establishes that Member States shall develop measures to achieve an increasing trend of at least two out of the three following indicators for agricultural ecosystems: a. grassland butterfly index; b. stock of organic carbon in cropland mineral soils; and c. share of agricultural land with high-diversity landscape features.

SOILGUARD results suggest that the **national restoration plans that Member States would need to develop in the context of the proposed Nature Restoration Law would benefit from setting out time-specific targets** with a soil focus, and should support SSM practices aiming at increasing soil organic carbon stocks, enhancing the presence of high-diversity landscape features in agricultural land, adapting to geographically specific conditions and allowing for flexibility in relation to evolving scientific knowledge.

6.2.4. *Leverage Nature-Based Solutions (NbS) for soil health*

Nature-based Solutions (NbS) harness natural ecosystems and processes to address various environmental, social, and economic issues. These approaches, which can include sustainable agriculture practices, provide sustainable alternatives to conventional methods. By improving ecosystem functions, they enhance human well-being and support biodiversity. **Promoting the application of NbS to soil management challenges** has the potential to enhance ecosystem functions and biodiversity.

Additionally, ensuring that NbS are integrated into EU soil-related policies and conservation strategies can maximize ecological, social, and economic benefits. Knowledge exchange and collaboration between regions can significantly enhance the implementation of NbS, as SOILGUARD results indicate heterogeneous results across different regions. In this context, **sharing successful case studies and lessons learned can improve adherence to best practices regionally and globally**. Regional workshops, training programs, and networks can also facilitate this exchange.

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7. Conservation brief

7.1. Background on soil soil biodiversity and nature conservation approaches

Protected and conserved areas are the foundation of biodiversity conservation. However, soil biodiversity is often overlooked in nature conservation literature and interventions. There is a critical difference between soil, water, and air when it comes to nature conservation measures. Soil is mostly owned by economic actors, unlike air and water, making it more difficult to implement stricter regulations. However, sustainable soil management and conserving soil biodiversity can bring massive benefits to land health and society (Larbodière et al., 2020). Agriculture, forest management, and conservation can advance through a shared agenda focused on a common vision and agreed practices based on mutual benefit and the recognition of the dependence of human well-being on nature and specifically on soil biodiversity and its functions.

Most management decisions in conservation areas have limited effects on the protection of soil organisms and functions (Guerra et al., 2021). This is due to the lack of measures specifically oriented toward soil biodiversity conservation, as most soil-oriented practices are mainly focused on the physical aspects of soil, such as reducing soil erosion (Guerra et al., 2021). Specifically, Zeiss et al. (2022) points out that **current protected areas do not necessarily contribute to protect soil biodiversity conservation and its ecosystem functions** because the selection of sites for conservation 1) do not consider soil biodiversity, associated ecosystem functions, or the value of belowground ecosystems and 2) fail to prioritize establishment of protected areas and conservation objectives over the goals of particular stakeholder.

Beyond protecting aboveground systems, **soil biodiversity and its ecosystem functions require explicit consideration and specific protection measures** when establishing new nature protection and conservation initiatives (Guerra et al., 2021). General agreements on conservation and agricultural practices related with soil built the basis for many of the positive effects of nature protection, but they usually disconnect soil biodiversity and related ecosystem functions from mainstream nature conservation, framing it almost exclusively as a driver of food production (Zeiss et al., 2022).

Protection of individual species is another form that conservation action can take, but the complexity in soil and the lack of knowledge about soil biota implies a relevant challenge for implementing this approach for conserving soil biodiversity (FAO, s. f.). In this regard, IUCN is initiating a working group to guide identification of threatened soil species including compiling knowledge on their distributions, threats and potential conservation measures to implement. Additionally, it should be considered that, as Setälä et al. (2005) highlights, even if some soil species have a key role in some soil processes, such as nitrification, functions mainly depend on the architecture of the soil food web. Also, beyond the role of each specific species, (Wohl et al., 2004) showed that functional redundancy supports biodiversity and ecosystem functions so the loss of any one species within a functional group,

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may cause changes in a given process, even if other members of the functional group are supposed to provide an equivalent substitute for the role of the missing species.

Protected areas and species have long been the most important tools in conservation, but **nature conservation has experienced a paradigm shift** that has more recently evolved from focusing solely on nature, to integrate social and economic aspects and change from protection towards sustainable use and restoration (Hummel et al., 2019; Cohen-Shacham et al., 2019). In this regard, sustainable use was 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 (Convention on Biological Diversity, 1992).

Even though the relationship between biodiversity and human well-being has often been historically acknowledged in traditional knowledge and many indigenous peoples' belief systems, **the key role that ecosystems play in supporting human well-being has been more widely recognized in scientific literature since the 1970s, through the ecosystem services framework** (Hummel et al., 2019; Cohen-Shacham et al., 2019, Cohen-Shacham et al., 2016). Perspectives on nature conservation have recently broadened beyond an exclusive focus on the protection of wilderness and wild, charismatic, threatened species to approaches that integrates measures oriented towards the use and protection of landscapes and ecosystems (Cohen-Shacham et al., 2016; Hummel et al., 2019).

In this context, **the conservation agenda embraced a more systemic and holistic perspective to deal with complex and dynamic issues, as evidenced by the establishment of the Ecosystem Approach,** which was endorsed and adopted by the CBD in 1995 (Cohen-Shacham et al., 2016, CBD, 2004). In this regard, Zeiss et al. (2022) suggests an integrative approach that implement an ecosystem approach to target the conservation of soil biodiversity and soil ecosystem functions in order to amplify the recognition of the ecological contribution of soils and soil-living species and avoid focusing on a few popular species. This proposal includes 8 steps: expand existing activities, consider a full ecosystem approach, set baselines as references, monitor threats to soil biodiversity and ecosystem functioning, define species lists for nature conservation, establish a soil indicator system, improve access to information for all stakeholders, and identify priority areas for soil ecosystem (Figure 3).

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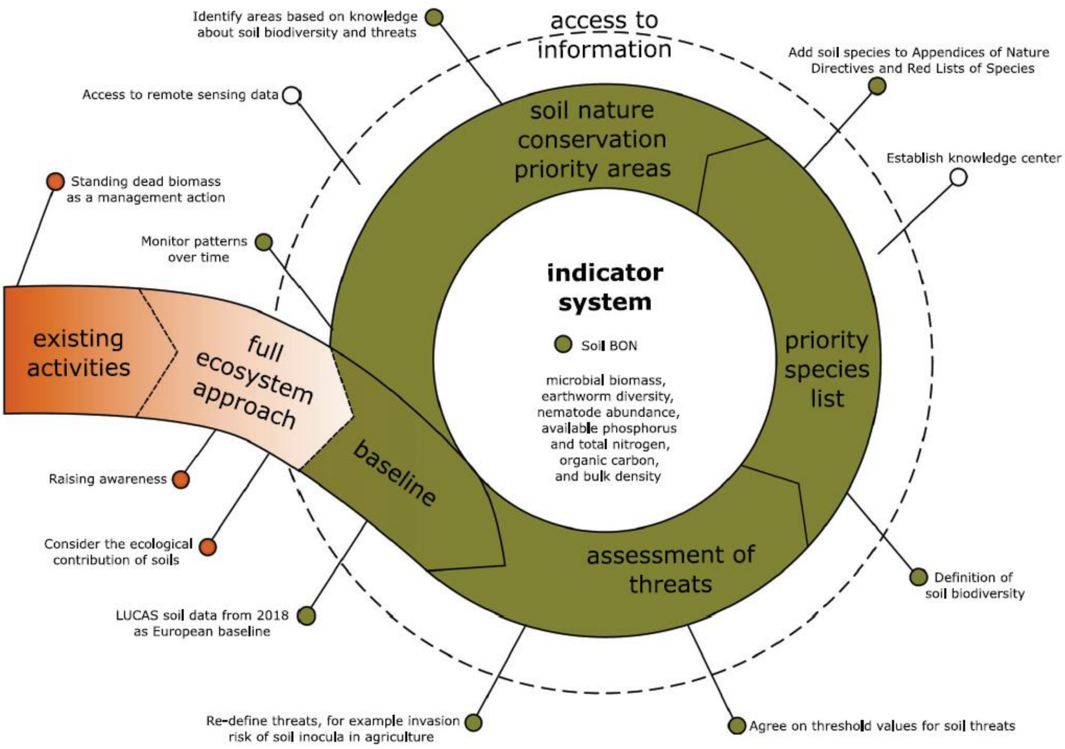

Figure 3. The cycle of targeting soil ecosystem conservation from an integrative perspective, starting with existing management actions, which go hand in hand with a full ecosystem approach in conservation. Baselines serve as reference for temporal studies that improve investigation and monitoring of threats. Soil organisms are included in species lists, from which priority areas for soil biodiversity can be identified and managed. Source: Zeiss et al., 2022.

Additionally, **the soil food web approach** (Figure 4), is a concept closely related to the ecosystem approach that It provides a way to 1) describe soil biodiversity as an ecological network, 2) quantify its role in soil ecosystem functioning and 3) analyse the biological mechanisms underlying soil ecosystem functioning and the relationship between the structure of the soil biological community and soil ecosystem processing, as the food web interactions represent flows of matter, energy and information (FAO et al., 2020).

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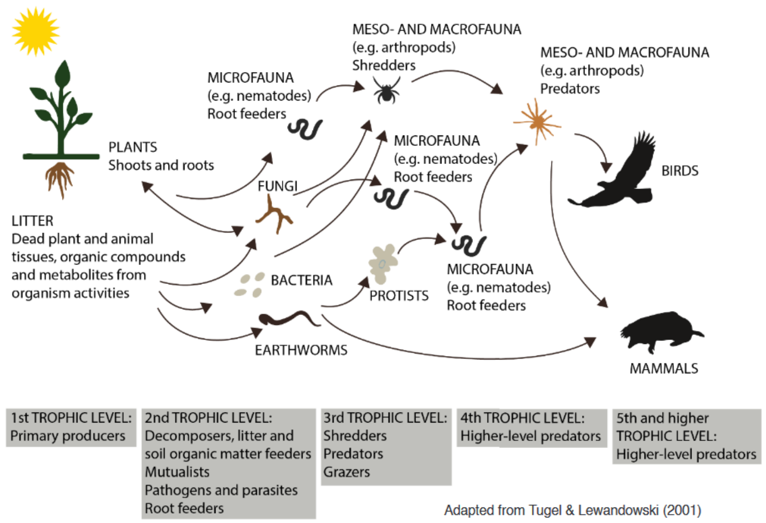

Figure 4. Soil food web representation, including possible feeding connections in a soil ecological community. Source: Larbodière et al., 2020

In 2005, the Millennium Ecosystem Assessment (MEA), provided a strong evidence base linking global ecosystem degradation to the reduced provision of ecosystem services and a decline in human wellbeing. To reverse this decline, and recognising the interdependence of people and nature, the MEA called to action for improved **conservation, restoration and sustainable ecosystem management** (Millennium Ecosystem Assessment, 2005). More recently, the Intergovernmental science policy Platform for Biodiversity and Ecosystem Services (IPBES) has introduced the concept' **Nature's Contribution to People** (Díaz et al., 2018) to broaden the scope of the widely-used Ecosystem Service framework, emphasize the importance of cultural context and values and include diverse and less-represented knowledge systems (Cohen-Shacham et al., 2019). Nature's contributions to people are all the contributions, both positive and negative, of living nature (i.e. diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life for people (IPBES, 2019).

In this regard, SOILGUARD has significantly contributed to raising awareness about the critical role of soil organisms in numerous ecological processes that support a wide range of NCP essential for human well-being (FAO et al., 2020; Orgiazzi, Bardgett, R.D., et al., 2016). These processes benefit society by contributing to the delivery of material, regulating and non-material NCPs (Table 2). Beneficial contributions from nature include such things as food provision, water purification, flood control, and artistic inspiration. The specific proposal of the SBWF for valuing soil-mediated NCPs and the link between them and human wellbeing and quality of life dimensions is included in *Appendix A.*

Table 2. Soil-mediated nature's contributions to people included in the SBWF. Columns are lists, do not read across.

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NATURE'S CONTRIBUTIONS TO PEOPLE		
Material	**Regulating**	**Non-material**
Food and feed production Energy production Production of materials Production of medicinal resources	Habitat creation and maintenance Pollination and dispersal of seeds and other propagules Regulation of air quality Regulation of climate Regulation of freshwater quantity, location and timing Regulation of freshwater and coastal water quality Soil formation, protection and decontamination Regulation of hazards and extreme events Regulation of detrimental organisms and biological processes	Learning and inspiration Physical and psychological experiences Supporting identities Maintenance of options

Beyond the relevance of NCP for soil biodiversity conservation, **the emergence of NbS offers a significant opportunity for innovation**, providing positive impacts and offering additional co-benefits in comparison with conventional or classical grey solutions that have neutral or negative impacts on ecosystems (European Commission., 2021). NbS are also part of the shift experienced in nature conservation that was previously described, since in the context of NbS, people are not considered as passive beneficiaries of nature and a driver of environmental degradation. Rather, they are seen as proactive agents who proactively protect, manage or restore ecosystems to address several societal challenges such as climate change, disaster risk reduction and biodiversity loss (Cohen-Shacham et al., 2019). Thus, the concept of NbS facilitates an approach that balances conservation and development goals.(Larbodière et al., 2020). Specifically, IUCN defines NbS as "Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016). NbS offers significant opportunities for innovation even if many NbS interventions still face significant challenges in terms of up-scalling and monitoring (European Commission., 2021) and the lack of operational clarity hinders the credibility and applicability of new concepts like NbS (Cohen-Shacham et al., 2019).

There are several management systems and practices that, compared to conventional may have a positive impact on soil biodiversity. Some of these practices are framed under the NbS concept, although they may not strictly follow the established principles and criteria. It should also be

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considered that, even if there is a lack of knowledge and practical experiences that explicitly relate NbS and soil biodiversity, there is a history of managing nature in ways that provide benefits for society, without using the NbS framework. In this regard, it should be noted that there are many interventions that fall under the NbS umbrella that are not always explicitly considered as such on the ground.

In the SOILGUARD project we have considered the following management regimes 1) organic agricultural management practices according to EC guidelines in farmland biome, 2) diverse mixed-species with low-fertilizer input in grassland biome and 3) continuous cover in forest biome, but **there are other practices and management systems that may have a positive impact on soil biodiversity.**

Specific farm management practices may include crop diversification, cover crops, mulching, reduced tillage, soil organic amendments and the maintenance of non-productive elements and crop residue cover on the soil (Doran & Zeiss, 2000; FAO et al., 2020; Orgiazzi et al., 2016; Lynch, 2022; Mann et al., 2019; Brussaard et al., 2007; Ghimire et al., 2014). Regenerative agriculture could be highlighted, as it is an agricultural production system specifically focused on enhancing and sustaining the health of the soil (Oberč & Arroyo Schnell, 2020). In agricultural grasslands, specific practices may include plant diversity, the presence of legume and deep roots species, the level and type of fertilization and the absence of overgrazing should be highlighted as best practices for soil biodiversity conservation (Zhao et al. 2015; Ryan et al., 2023; Reed & Morrissey, 2022). In forest areas, lowering the intensity of timber harvesting in specific forest management regimes, the maintenance of dead wood, coarse woody debris, large legacy trees and refugee plants, as well as preservation of the forest floor can also have positive impacts on soil biodiversity (Peura et al., 2018; Heinonen et al., 2017; Eyvindson et al., 2018; Triviño et al., 2017; Simard et al., 2021). In this regard, closer-to-nature forest management (European Commission, 2023), offers a framework to promote biodiversity-friendly and adaptive forest management. Additional information about how other management aspect influence soil biodiversity is included in the chapter 4.3 Sustainable Soil Management and soil biodiversity in SOILGUARD biomes of *Deliverable 6.2: Guidelines to implement interventions in which soil biodiversity acts as an NBS.*

From a wider perspective, other **approaches that may have a positive impact on soil biodiversity** can include soil and land restoration, soil erosion prevention and control, reforestation, bioremediation, adaptive fire management, sustainable land management and conservation, soil-oriented rewilding, and several sustainable agriculture approaches such as conservation agriculture, regenerative agriculture, agroforestry, organic farming, and agroecology*,* among others (FAO et al., 2020; Orgiazzi, Bardgett, R.D., et al., 2016). Finally, Sustainable Soil Management (SSM), is defined as a management regime that maintain or enhance soil-related services without significantly impairing either the soil functions that enable those services or biodiversity (FAO, 2017).

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7.2. Soil biodiversity conservation recommendations

7.2.1. *Recognizing the critical relevance of soil biodiversity*

Soil is an ecological system rich in biodiversity that provides Nature Contributions to People (NCP) that are essential for life and the critical relevance of soil biodiversity should be increasingly recognised and valued. **Soil biodiversity conservation should receive increasing attention and funding** to develop knowledge and to deepen our understanding of the relationships between soil management, soil biota, soil functions and human wellbeing and amplify the recognition of the ecological contribution of soil-living species form an ecosystem approach. Soil biodiversity should be increasingly included in biodiversity assessments or other similar conservation plans and the underlying ecological mechanisms of SSM that supports soil biodiversity, NCP and human wellbeing should receive increasing attention in the agriculture sector and in society as a whole. The Soil Biodiversity and Wellbeing Framework could be a useful tool in this regard.

7.2.2. *Reinforcing the soil and land health framework*

Soil health is a concept intimately related to soil biodiversity and it significantly contributes to incorporating the biological perspective into soil management since it is based on recognizing that soil functions not only depend on physical and chemical properties but also on biological properties **Soil health has been defined as the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, fungi and human health.** In the recent years, policymakers, scientists, and practitioners have increasingly adopted the soil health concept, in part due to its flexibility and the ability of different stakeholders to use it in their own way. Complementarily, land health has defined as “the capacity of land, relative to its potential, to sustain delivery of ecosystem services” (Shepherd et al., 2015). Soil health and land health have been identified as points of common interest between agriculture and conservation actors that should be further explored (Larbodière et al., 2020). Reinforcing the soil health from the scientific and technical perspective (e.g., developing soil health indices and indicators) and operational perspective (e.g. testing this concept on the ground, developing guidelines for communication and dissemination) would substantially advance soil biodiversity conservation and awareness.

7.2.3. *Minimizing soil biodiversity threats*

Soil biodiversity and its role in ecosystem functioning are often threatened and can have a negative impact on the delivery of Nature Contributions to People. These threats include land-use intensification, pollution, soil erosion, compaction and sealing, acidification, wildfires, land degradation and desertification, climate change, the introduction of invasive species and acid rain (FAO et al., 2020, Orgiazzi et al., 2016, Larbodière et al., 2020, Tsiafouli et al., 2015). Martin et al. (2018) defines land use intensification as activities undertaken with the intention of enhancing the

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productivity or profitability per unit area of rural land use, including intensification of particular land uses as well as changes between land uses. These activities can include land use conversion (e.g. from fallows to permanent crops), increasing inputs (labour, irrigation, chemicals, machinery) and crop or product change (often involving higher-yielding varieties, and normally involving specialisation or monocropping) (Martin et al., 2018). Specifically, intensive agricultural practices and can include tillage, monoculture, removal of organic matter, synthetic pesticides and excess of fertilisers applications (FAO et al., 2020, Orgiazzi et al., 2016, Larbodière et al., 2020, Tsiafouli et al., 2015). Awareness and knowledge of soil biodiversity, its functional importance and how it responds to specific management practices are essential to better preserve belowground diversity and the important functions of these communities to maintain soil health (Orgiazzi et al., 2016, FAO et al., 2020).

7.2.4. *Defining soil biodiversity*

There are several definitions of soil biota and soil biodiversity (Table 3). Each definition emphasizes different aspects and has a different use, but they all recognize the importance of various life forms within the soil while emphasizing different aspects. An official and common definition of soil biodiversity is still lacking and there is a need for clarity for policy development and implementation as the different definitions of soil biodiversity can lead to completely different actions in terms of conservation initiatives. Policymakers require a clear definition of soil biodiversity linked with soil-specific species. **An inclusive, general and broad definition of what counts as a soil species would be a significant step toward to facilitate the integration of soil biota into the legislative agenda for conservation, ensuring that all soil biodiversity is included within an umbrella term .** Additionally, defining soil biodiversity would enhance our understanding of soil biota and its role.

Table 3. Soil biota definitions

Reference	Soil biodiversity/biota definition
FAO et al. (2020)	Soil biodiversity is 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
Larbodière et al. (2020)	Soil biota include bacteria, fungi, algae, protists, viruses, nematodes, acari (including mites), collembola (springtails), annelids (primarily earthworms), macroarthropods (such as spiders, ants and woodlice) and vertebrates (like voles, moles and shrews), and also the plants whose root exudates provide food for soil organisms in a zone around the roots known as the 'rhizosphere'
SOILGUARD	Soil biodiversity by considering the abundance, biomass, and diversity of soil organisms, targeting prokaryotes (encompassing bacteria and archaea) as well as eukaryotes (including fungi, protists, nematodes, arthropods, and earthworms).
IUCN definition for soil biota used by the Red List of Threatened Species	Soil species are here defined for the IUCN Red List of Threatened Species as those organisms that spend a key part of their life cycle within a soil profile, or predominantly inhabit the soil-litter interface. This includes soil megafauna, macrofauna, mesofauna, microfauna/flora, fungi, and micro-organisms. Although we recognize that most plants play an important role in maintaining fertility, structure, drainage, and aeration of soil, these are not tagged as soil species for the IUCN Red List.

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7.2.5. *Implementing soil biodiversity conservation specific measures*

Soil biodiversity and its ecosystem functions require consideration and specific local protection measures when managing or establishing nature protection areas and conservation initiatives. Beyond the abiotic physical aspects of soil, these initiatives should integrate measures specifically oriented toward soil biodiversity conservation, considering associated ecosystem functions and the value of belowground ecosystems.

Considering that there are significant differences on the abundance, composition and complexity of soil biodiversity across biogeographical regions and land uses, **conservation efforts should be oriented to all biogeographical regions and land uses** to preserve species diversity and the heterogeneity of community compositions.

The complexity of soils, especially the limited knowledge about soil biota, implies a relevant challenge for implementing protection of individual species approaches for conserving soil biodiversity and conservation efforts should be dedicated beyond specific soil species that have a key role in soil processes.

Considering that site-specificity of soil biodiversity in response to management has been demonstrated specific practices and management systems should directly respond to evidence-based assessment of the current state of the ecosystem and prevailing drivers of degradation and loss. Conservation measures should be based on a well-founded understanding of the current state of the ecosystems concerned. The baseline assessment needs to be broad enough to characterise ecological state, drivers for ecosystem loss and options for net improvements, making use of both local knowledge and scientific understanding where possible. Additionally, lessons learned from past intervention on each specific site should be taken into account.

To ensure the long-term protection of species targeted for conservation, it is crucial to incorporate spatially explicit information about soils into planning documents. This requires mapping and delineating soil characteristics, aligning real-time field studies with conservation planning. If data at the needed scale do not exist, conservation plans should try to allocate resources for field collections, sample processing, and data analysis. This is especially needed as the soil type present will influence patterns in local soil biodiversity.

7.2.6. *Mainstreaming Nature-based Solutions*

NbS offers a significant opportunity for innovation, providing long-term, tangible and positive impacts across society, and offering additional co-benefits in comparison with conventional grey solutions. NbS are actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. Considering people as proactive agents who, beyond environmental degradation, can protect, maintain, manage or restore ecosystems to address several societal challenges having a

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positive impact on soil biodiversity offers multiple opportunities to integrate nature conservation in land management.

7.2.7. *Scaling up Sustainable Soil Management practices*

Finally, Sustainable Soil Management (SSM), is defined as a management regime that maintain or enhance soil-related services without significantly impairing either the soil functions that enable those services or biodiversity. **There are several management systems and practices that, compared to conventional may have a positive impact on soil biodiversity.** In the SOILGUARD project we have considered the following management regimes 1) organic agricultural management practices according to EC guidelines in farmland biome, 2) diverse mixed-species with low-fertilizer input in grassland biome and 3) continuous cover in forest biome, but there are other practices and management systems that may could be considered.

Specific farm management practices may include crop diversification, cover crops, mulching, reduced tillage, soil organic amendments and the maintenance of non-productive elements and crop residue cover on the soil. In agricultural grasslands, specific practices may include maintaining plant diversity, the presence of legume and deep roots species, the level and type of fertilization and the absence of overgrazing should be highlighted as best practices for soil biodiversity conservation. In forest areas, lowering the intensity of timber harvesting in specific forest management regimes, the maintenance of dead wood, coarse woody debris, large legacy trees and refugee plants, as well as preservation of the natural forest floor can also have positive impacts on soil biodiversity. In this regard, closer-to-nature forest management, offers a framework to promote biodiversity-friendly and adaptive forest management inspired by natural disturbance dynamics.

From a wider perspective, other **approaches that may have a positive impact on soil biodiversity** include soil and land restoration, soil erosion prevention and control, reforestation, bioremediation, fire management, sustainable land management and conservation, soil-oriented rewilding, and several sustainable agriculture approaches such as regenerative agriculture, conservation agriculture, agroforestry, organic farming, and agroecology, among others. Also, diversifying land use types and cropping systems could play a role in conserving biogeographical patterns of diversity.

Sustainable soil management practices should be scaled up at different levels (policy, on the ground, institutionally) to build capacities, develop services, and mobilise farmer communities and organisations. Emphasis should be placed on creating conditions that enable farmers to sustainable implement these practices, including measures that reduce the risks of transition. Specific efforts should be oriented to overcome behavioural, organisational, social, political, financial and economic barriers to adoption considering that in many cases, farmers and land managers have little incentive to protect the ecosystem assets from which NCP are derived.

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7.2.8. *Leverage the benefits of Sustainable Soil Management practices*

Sustainable management (organic agricultural management practices in croplands, diverse mixed-species with low-fertilizer input in grasslands biome and continuous cover in forests among others) can enhance soil functionality in comparison with conventional management (e.g., conventional intensive agriculture, monoculture grasslands and clear-cutting rotational forestry). This is especially relevant in croplands and areas with low initial organic carbon, where the potential for improvement is greatest. However, the positive effect of sustainable management generally weakens under drought conditions, so **conventional to organic management conversions could be more beneficial if focusing on those regions that are expected to suffer less from a drier climate in the future**.

Also, diversifying Sustainable Soil Management could be a useful approach for maximizing ecosystem functions. Positive synergies between soil functions are less prevalent within a specific management system, whether sustainable or conventional, suggesting that **multiple ecosystem functions can be more difficult to maintain simultaneously at high levels within a given agricultural management**.

There are usually strong benefits for soil biodiversity of shifting from conventional to organic agriculture in croplands, with little evidence in favour of, or against, conversions from clear cutting to continuous cover forestry on forest areas and from grass monoculture to grass mixtures on grasslands. Local and site conditions strongly influence soil biodiversity, so management practices and monitoring indicators should consider these specific conditions since management effects seem to be highly site dependent.

Deepen our understanding between soil management practices, its impact on soil biodiversity and their co-benefits beyond the specific production of the main product might facilitate the increasing deployment of sustainable practices.

8. Soil biodiversity indicators and monitoring

Biodiversity monitoring is necessary to guide and assess policy action and conservation interventions to understand if measures effectively deliver the intended outcomes. Up-to-date data and transparent, reliable, and unbiased soil indicator systems that allow assessment of soil ecosystem status and conservation vulnerability are critical to providing a measure of success or failure of policy and conservation agendas (Guerra et al., 2021). Specifically, stablishing a baseline and update it with new data is needed for adaptative management in soil biodiversity conservation (Zeiss et al., 2022). Baselines should also facilitate the investigation of threats to soil biodiversity and soil ecosystem functions, the definition of thresholds for threat levels and the estimation of future changes in extinction patterns and the provision of soil functions, for example, by taking the latest Land Use/Cover Area frame statistical Survey (LUCAS) soil biodiversity data (Zeiss et al., 2022). This monitoring effort must be accompanied with capacity-building and knowledge-sharing mechanisms to give open access

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to the information and with initiatives for data standardization, analysis and synthesis (Guerra et al., 2021).

However, **there is a lack of soil biota monitoring,** there is only information for few soil organisms and standardized and timely information to track policy targets related to soils is missing, particularly at global scales (Guerra et al., 2021). As a consequence, the lack of indicators to measure and monitor soil biodiversity is a barrier to mobilizing actors, setting ambitious targets, and assessing policy impact (Dussán López, 2023), delivering a robust scientific message supporting the importance of soil biodiversity and ultimately include soil biodiversity in nature conservation debates (Guerra et al., 2021). Guerra et al. (2021) also identifies some of the causes for this lack of soil biodiversity monitoring: 1) difficulties to develop coordinated large-scale monitoring initiatives, 2) the high number of undescribed soil species and the scarce information on their population dynamics, 3) the recent development of tools to characterise soil biodiversity, 4) the lack of prioritization at national level and 5) a focus on physical and chemical aspects (such as soil erosion and soil carbon) as biological properties are generally considered more challenging to measure, predict, or quantify (Lehmann et al., 2020).

The establishment of a monitoring framework by Member States, as proposed by the Soil Monitoring Directive, based on common soil descriptors and criteria, **would be of great help to understand the conditions of our soils and track progress towards improving their health.** Although the proposal in Annex I of the Directive sets a number of important criteria and soil descriptors for monitoring and assessing the health of soils, they do not cover soil biodiversity. The only listed soil descriptor indirectly related to biodiversity is soil basal respiration. This soil descriptor would however not provide information on diversity, and neither a robust indication of biological structural or functional health. Based on SOILGUARD expertise and considering the importance of soil biodiversity for ecosystems (Nielsen et al., 2015; Wagg et al., 2014), Annex I should include further mandatory soil biodiversity indicators.

Monitoring should be able to take into account complexity, site and scale effects and reflect progress towards achieving soil health in order to incentivise practitioners. Unfortunately, the proposed one-out- all-out principle in the Soil Monitoring Directive – only considering a soil healthy when it meets all criteria listed in Annex I - would not allow to show progress. Instead, tracking improvements in trends in soil health would allow to understand progress towards achieving healthy soils, and identify in which areas efforts are most needed.

Biodiversity is context-specific, and there are no one-size-fits-all indicators or monitoring methodologies (Dussán López, 2023). Soil sampling protocols must be adapted to the local soil types, eg., natural soils have often variable layers as they are not homogenized by human activities as cultivated soils. For example, the suggested LUCAS sampling design is not optimal for soils in forests and peatlands optimal for soils in forests and peatlands, as deeper sampling is needed to obtain correct understanding of soil C stocks. Furthermore, often deeper soil sampling is needed to obtain correct understanding of soil carbon stocks. Future soil monitoring efforts should be better connected to

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existing aboveground monitoring as land use and productivity determine greatly soil characteristics, and this is also the only way to understand causal relationships. In the case of LUCAS, more detailed aboveground descriptions should be included into the monitoring to increase the utility of the soil data. Given the time scale of soils, it might be more suitable to concentrate monitoring efforts in a longer sampling history, and to prioritise obtaining good quality aboveground data rather than high quantity of samples.

Developing an agreement on soil biodiversity indicators that can be used as quantitative tools to assess soil health is one of the major challenges. These indicators need to be robust, meaningful, and easy to measure and interpret and consider soil heterogeneity, site-specific nature of soil management, and varying ecosystem services with sometimes conflicting needs. In this regard **the Land Health Monitoring Framework seeks to overcome that barrier through a flexible methodology** that uses existing tools to assess functional and habitat diversity by measuring diversity at various scales, including belowground, aboveground, habitat-level and national impact (Dussán López, 2023).

The analytical part of the Soil Biodiversity and Wellbeing Framework can also provide provides a structured set of specific and measurable indicators, and the methodologies for assessing them that could be used for developing monitoring.

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Appendix A. Indicators included in the Soil Biodiversity and Wellbeing Framework

Complementary to the conceptual part of the SBWF and the natural capital assets, the analytical part provides a structured set of specific and measurable indicators of valuation and the methodologies for assessing them.

Table 4 defines the attributes and elements that compose the Natural Capital Assets. These include: extent-the area of a particular habitat, soil type or geology, stock- the quantity of something that is directly measured, condition- a context-dependent measure of the quality of the stock, functions- functions or processes that occur within soils

Table 4. The Natural Capital Assets included in the SBWF.. Columns are lists (i.e. do not read across). Source: *Deliverable 1.3. Soil Biodiversity and Wellbeing Framework.*

NATURAL CAPITAL ASSETS			
Extent	**Stock**	**Condition**	**Function (process)**
• Area of ecosystem / habitat type (e.g. cropland, grassland and/or forest)	BIODIVERISTY STOCKS • Total soil microbial biomass • Abundance of bacteria, archaea, fungi, protists, nematodes, collembola, microarthropods, mites, earthworms in the bulk soil • Abundance of functional genes (e.g. nutrient cycling, pathogenesis, antibiotic resistance genes and/or resources for biotechnology)	BIODIVERSITY STRUCTURE • Soil food webs/ networks metrics, e.g. biomass of fungal and bacterial energy channels • Diversity of soil bacteria, archaea, fungi, protists, nematodes, collembola, mites, earthworms, virus • Diversity of functional genes (e.g. nutrient cycling, pathogenesis, antibiotic resistance genes and/or resources for biotechnology)	• Plant biomass production • Soil potential respiration • Carbon (C) sequestration • Methanogenesis • Potential N mineralization • Denitrification • Litter decomposition • Soil enzymatic activities (associated with C, N, P cycling) • Leaching of nutrients (NO3/PO3) • Leaf, stem or root damage (insect and fungal pathogen) • Reduction in efficacy of antibiotics • Soil erosion / soil loss • Infiltration

Table 5 highlights the soil-mediated nature's contributions to people (SmCP) given the different valuation methods, which have been included in the development of the integrated valuation approach of *Deliverable 4.2 Report on Region-Specific Economic and Socio-Cultural Values of Soil-Mediated Contributions to People (SmCPs).* The indicators have been selected based on criteria of measurement feasibility and harmonization, where possible. The linkage of soil biodiversity, soil multifunctionality and SmCP data through tailored models facilitates precise quantification of the crucial role of soil organisms in orchestrating the delivery of each measured soil function and the

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contribution to human wellbeing. This expansion involves specific valuation methods, employing biophysical, economic and socio-cultural indicators capturing the plurality of values for different SmCPs. This approach is rooted in the acknowledgment that nature's values, spanning instrumental, relational, and intrinsic dimensions, are shaped by diverse worldviews and knowledge systems.

Table 5. Links between SmCP, beneficiaries, values in the SBWF. Indicators and methodologies are selected based on criteria of measurement feasibility and harmonization, where possible. Source: *Deliverable 1.3. Soil Biodiversity and Wellbeing Framework.*

Soil-mediated nature's contribution to people (SmCP)		Beneficiary	Biophysical & monetary indicators (examples)	Valuation methods for biophysical and monetary indicators (examples)	Valuation methods for socio-cultural indicators (examples)
Food and feed production	Material	Farmers, public	Crop yield (ton / [ha x yr]) to market prices ($ / ton) *(48)*	Market price method	Preference assessment
Energy production	Material	Public	Energy production (MWh / [ha x yr]) to market prices ($ / MWh)	Market price method	Preference assessment
Production of materials	Material	Farmers, public	Biomass production ((ton / [ha x yr]), market prices ($ / ton) *(48)*	Market price method	*Preference assessment*
Production of medicinal resources	Material	Public	Aromatic/medicinal crop yield (ton / [ha x yr]) to market prices ($ / ton)	Market prices method	Preference assessment
Regulation of freshwater quantity (Flood regulation)	Regulating	Public	Costs of alternative measures for provide the same service (e.g. water storage) ($ / m3) *(54)*; WTP for a reduction in flooding risk or an increase in water storage capacity (€ / person x yr)*(55)*	Cost-based methods, stated- preference methods (e.g. discrete choice experiment)	Preference assessment
Regulation of detrimental organisms (Biological control)	Regulating	Farmers	(Avoided) costs of pesticide application ($ / ha)	Cost-based methods	Preference assessment
Soil formation and protection (Soil erosion prevention)	Regulating	Public	Costs of soil erosion prevention ($ / metric tons soil); WTP for increased soil stability (€ / person x yr)	Cost-based methods, stated-preference methods (e.g. discrete choice experiment)	Preference assessment

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Soil formation and protection (Nutrient cycling)	Regulating	Public	Available N and P (mg / kg soil) to market prices of fertilizer ($ / kg)(54); WTP for changes in nutrient load (€ / person x yr)	Market prices, cost-based methods (e.g., replacement costs), stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Climate regulation	Regulating	Public	Carbon sequestration (CO2eq in ton / ha x yr) to social costs of carbon ($ / ton) (54); WTP for carbon sequestration (€ / person x yr)	Cost-based methods (e.g. damage costs), stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Habitat creation	Regulating	Public	WTP to preserve habitat provision (€ / person x yr)	Stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Pollination	Regulating	Public	Costs of alternative measures provide the same service (e.g., honeybee stocking) ($ / ha) (63); WTP for pollination (€ / person x yr)	Cost-based methods, stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Regulation of air quality	Regulating	Public	WTP to preserve air quality (€ / person x yr)	Market prices, cost-based methods, contingent valuation (e.g. discrete choice experiment)	Preference assessment
Regulation of freshwater quality	Regulating	Public	Costs of decontamination of nutrient loads ($ / kg N/ P)	Cost-based methods, stated-preference methods (e.g. discrete choice experiment)	PPGIS
Regulation of hazards and extreme events	Regulating	Public	Costs for avoided damages	Cost-based methods, stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Physical and psychological experience (Tourism)	Non-Material	Public, tourists		Revealed-preference methods; Stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Physical and psychological experience (Aesthetic landscapes)	Non-Material	Public, tourists	WTP for increased heterogeneity of landscapes (€ / person x yr)	Stated-preference methods (e.g. discrete choice experiment)	Preference assessment

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Learning and inspiration (Biodiversity education)	Non-Material	Public	WTP for an increased provision of learning and inspiration ($ / person x yr)	Stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Supporting identities	Non-Material	Public		Stated-preference methods (e.g. discrete choice experiment)	Preference assessment
Maintenance of options	Non-Material	Public		Stated-preference methods (e.g. discrete choice experiment)	Preference assessment

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