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Towards a Global Soil Biodiversity Observatory (GLOSOB): science and policy backgrounds

George G. Brown[1,4]*, John Jacob Parnell[2], Monica Kobayashi[3], Talita Ferreira[4], Lucilia M. Parron[1], Maria Elizabeth Fernandes Correia[5], Ederson da Conceição Jesus[5], Guilherme M. Chaer[5], Marcia Reed R. Coelho[5], Cintia Niva[6], Leda Mendes[7], Maria Inês Lopes de Oliveira[7], Juaci Vitória Malaquias[7], Ozanival Dario Dantas da Silva[7], Luiz Fernando de Sousa Antunes[8], Rosa Corona-Cuevas[9] and Natália Rodríguez Eugenio[2]

[1] Embrapa Florestas, Estrada da Ribeira Km 111, Colombo, PR, 83411-000, Brazil.
[2] Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, Rome, 00153, Italy.
[3] Convention on Biological Diversity, Montreal, Canada
[4] Universidade Federal do Paraná, Rua dos Funcionários 1540, Curitiba, PR, 80035-050, Brazil.
[5] Embrapa Agrobiologia, Rodovia BR-465, Km 7, Seropédica, RJ, 23891-000, Brazil.
[6] Embrapa Suínos e Aves, BR153 km 110, Distrito de Tamanduá, Concórdia - SC, 89715-899, Brazil.
[7] Embrapa Cerrados, Rodovia BR-020, Km 18, Planaltina, DF, 73310-970, Brazil.
[8] Universidade Federal Rural do Rio de Janeiro, Seropédica, RJ, Brazil.
[9] Secretaria de Agricultura y Desarrollo Rural, Mexico City, Mexico, DF.
* Corresponding author, e-mail: george.brown@embrapa.br

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Abstract

The world's soils harbor an immense but as of yet inadequately measured and understood biodiversity, that perform essential ecosystem services in both undisturbed and agroecological and industrial agricultural systems. However, this vast natural resource is threatened by climate and land use change as well as unsustainable management practices, although the extent of these impacts on soil biodiversity and its vital functions for sustaining soil health and food security have not been adequately assessed worldwide. As part of the updated action plan of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, established originally by the Convention on Biological Diversity (CBD) in 2002, a Global Soil Biodiversity Observatory was proposed in 2020 to assess and monitor soil biodiversity worldwide. Here, we review the historical background (particularly as it relates to the CBD), as well as the scientific and political context of this decision. Furthermore, we provide guidance on and a framework to assess the potential to undertake soil biodiversity monitoring in different countries, using scientifically based and agreed criteria related to a minimum set and wider optional range of soil biological variables. Finally, recommendations for improving understanding and monitoring capacity as well as funding mechanisms and political support for these activities are also reviewed.

Keywords: Convention on Biological Diversity; soil health; monitoring; capacity building; international policies

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1. Introduction

Healthy soils are essential for human survival on earth. They also provide essential ecosystem services, and may be home to as much as 59% of the world's species (Anthony et al. 2023). Healthy crops grow on healthy soils, which help sustain healthy human populations (FAO et al. 2020). However, soils and their health are threatened by numerous human activities that may jeopardize food production, contaminate surface and ground water bodies, and compromise the achievement of the Sustainable Development Goals (SDGs) (FAO 2015, FAO et al. 2020, Lindo et al. this issue). According to the Status of the World's Soil Resources Report, over one-third of the world's soils are degraded, fueled by land-use intensification, salinization, burning and deforestation, actions which among other anthropogenic-induced drivers, reduce the ability of soils to function and support life on earth (FAO 2015).

Soils may be one of the most biodiverse habitats on earth, sustaining immense microbial and fauna populations: one handful of soil may contain more microorganisms than people living on the planet, and one m^3 of topsoil can have thousands of species (Giller 1996, Torsvik and Øvreås 2002).

Soil organisms are crucial for soil health, and are the source of many plant-protection products as well as foods and antibiotics for humans and other animals (Wall et al. 2015). Soil biota have co-evolved with soils and their activities contribute to important soil functions related to ecosystem service delivery, such as: mineral weathering (pedogenesis), nutrient mineralization and immobilization (nutrient cycling), soil pest regulation, soil structure formation (water storage, aeration, plant root growth), detoxification and immobilization of soil and water contaminants (water purification), shoot and root growth (provision of food, fiber and fuel), greenhouse gas exchanges and carbon sequestration (climate regulation), among others (FAO et al. 2020). Therefore, maintaining soil biodiversity is important to safeguard ecosystem service delivery from soils.

Soil biota are highly sensitive to soil management practices, and most threats to soil biodiversity are associated with human-induced degradation of land resources (soil, water and atmosphere) including: fire, deforestation, erosion, landslides, urbanization, surface sealing, soil compaction, agricultural intensification, loss of soil organic matter and carbon, soil acidification, nutrient imbalance, contamination, salinization and sodification (FAO et al. 2020, Lindo et al. this issue). Because soil biota often responds more rapidly to these changes and threats than soil chemical or physical parameters, it is highly useful as soil quality/health bioindicator (Bünemann et al. 2018). Hence, several countries have adopted a selected range of soil taxa and/or biological functions as indicators in soil quality monitoring and evaluation (Rutgers et al. 2019), and in December 2020 the European Union (EU) established an EU Soil Observatory (EC 2021) to generate policy-relevant and harmonized EU–wide soil data and indicators, including several soil biodiversity-related parameters (Maréchal et al. 2022). A comprehensive account with a detailed timeline of policies regarding soils was recently published by Zeiss et al. (2022), but we still must go a long way in terms of global policies to preserve soils and their enormous biodiversity, and to use them sustainably.

Soil biodiversity has been receiving major attention worldwide by various actors and stakeholders involved in soil and land use management, soil and nature conservation plans and activities, and in policy development and implementation, due to its increasingly recognized role in the delivery of important ecosystem services essential for human beings and the functioning of natural and anthropogenic ecosystems (FAO et al. 2020). Furthermore, there has been immense progress in the identification and description of soil biodiversity, particularly with the adoption of next-generation sequencing (Drummond et al. 2015, Hirsch et al. 2010, Labouyrie et al. 2023), and the increase in interest and capacity of many countries to study and tap into this vast natural underground world.

However, most countries in the world still do not have national-scale soil biodiversity inventories or monitoring programs, and there is a pressing need to develop standard soil biodiversity-related assessment methods, in order to promote harmonized data collection worldwide. Efforts such as these are crucial in order to build capacity and promote inventories, assessments and monitoring in-situ of soil biodiversity worldwide. Assessing biodiversity in multiple land use systems using standard methodologies and monitoring over time is required to understand the effects of different land uses and management systems on soil biodiversity, and the possible means of mitigating negative impacts on soils, their biodiversity and their ecosystem services. Knowing the temporal and geographical distribution of soil biodiversity will enable effective management, use and conservation of soil biodiversity. By knowing how, when and what to measure, we will be able to detect changes and trends that indicate whether soil management, use and conservation are being done in a sustainable manner.

Although there are still major gaps in this knowledge worldwide, standard methods are available, and can be proposed and adopted in order to generate the knowledge needed to advance in the conservation and sustainable management of soil biodiversity, in support of the SDGs worldwide. This is especially important considering the global pressures on natural resources derived from land use intensification, urbanization, deforestation and climate change, and often associated natural catastrophes such as droughts, fires, intense storms and flooding (FAO 2015).

Over the past few years, the Food and Agriculture Organization of the United Nations (FAO) has promoted extensive work on various aspects related to soil biodiversity, including the establishment of an International Network on Soil Biodiversity (NETSOB) in late 2021, and a proposal for a Global Soil Biodiversity Observatory (GLOSOB) at the fifteenth Conference of the Parties (COP) to the Convention on Biological Diversity (CBD) in Montreal, in December 2022. However, to establish a GLOSOB, we must first define: 1) what will be assessed and monitored (variables, indicators): 2) how it will be done (standardized methodologies); and 3) where (sites, countries). Additionally, we must consider capacity, funding mechanisms, and the legal and policy contexts available for such an effort. Therefore, in the present document, we present the main scientific and political contexts for the development of a GLOSOB, including background information used to identify the policy and legal frameworks and the scientific knowledge available for such an undertaking across countries worldwide.

2. Soil biodiversity, the CBD and the FAO: the historical context

Although FAO was founded in 1945, it has only been slightly over 20 years that the FAO has been promoting work on soil biodiversity. At the 5th COP of the CBD in Nairobi (2000), as part of the Multi-year Work Programme on Agricultural Biological Diversity, it was decided (Decision V/5) that FAO should facilitate the undertaking of case-studies, in a range of environments and production systems, on "the role of soil and other below-ground biodiversity in supporting agricultural production systems, especially in nutrient cycling" (CBD 2000). With the help of several consultants, case studies and background material on soil biodiversity were gathered over the following years, much of which was used as a basis for the FAO soil biodiversity portal website (now in the Soils portal: https://www.fao.org/soils-portal/soil-biodiversity/en/). Furthermore, an unpublished global survey on expertise in soil biodiversity was conducted by Drs. Dan Bennack and George Brown (September 2000), and accessible to users of the soil portal through the informal soil biodiversity expert network and newsletter.

The actions of FAO were further intensified after COP Decision VI/5 (CBD 2002) in The Hague, where the CBD decided "to establish the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity as a cross-cutting initiative within the Programme of Work on Agricultural Biological Diversity". It also invited "FAO and other relevant organizations, to facilitate and coordinate this initiative". Shortly after (June 2002), an international technical workshop on the biological management of soil ecosystems for sustainable agriculture, was organized by FAO and Embrapa Soybean in Brazil, which led to the publication of two seminal documents (Brown et al. 2002, FAO 2003), that provided essential case studies on the roles and importance of soil biodiversity, particularly in agroecosystems, and set the scientific foundation for the establishment of the initiative. These documents also highlighted the need for integrated soil biological management practices, and the adoption of three strategic areas of collaborative action by partners and countries:

1. Increasing recognition of the essential services provided by soil biodiversity across all production systems and its relation to sustainable land management;
2. Capacity-building to promote integrated approaches and coordinated activities for the sustainable use of soil biodiversity and enhancement of agroecosystem functions, including assessment and monitoring, adaptive management, and targeted research and development;
3. Developing partnerships and cooperative processes through mainstreaming and coordinated actions among partners to actively promote the conservation, restoration and sustainable use of soil biodiversity and enhanced contribution of beneficial soil organisms to the sustained productivity of agroecosystems.

These three areas were then adapted to constitute the three main objectives of the International Initiative, officially launched and adopted (Decision VIII/23) at the 8th COP of the CBD in Curitiba, Brazil (CBD 2006). This framework included 10 strategic principles, four main goals, three objectives and 13 activities (related to the three objectives). The four goals of the initiative were (CBD 2006):

1. Promote awareness, knowledge and understanding of key roles, environmental services, functional groups and impacts of diverse soil management practices, including those performed by indigenous and local communities, in different farming systems and agroecological and socioeconomic contexts;
2. Increase understanding of the role of soil biodiversity in agricultural production, traditionally applied land management practices and ecosystem and environmental health;

3. Promote the understanding of the impacts, ownership, and adaptation of sustainable soil-management practices as an integral part of agricultural and sustainable livelihood strategies; and
4. Promote the mainstreaming of soil biodiversity conservation into land and soil-management practices.

However, the initiative did not advance as hoped, and at the 9th COP (2008) in Bonn (Germany), the CBD urged FAO and other organizations to continue work on better understanding the status and role of soil biodiversity and the impact of management and other drivers on soil biodiversity (Decision IX/1; CBD 2008). Then, in 2010, at the 10th COP in Nagoya (Japan), the CBD requested FAO to provide a more in-depth review of the Initiative (Decision X/34), which was delivered only in 2018, at the 14th COP (CBD/COP/14/INF/42; CBD 2018) held in Sharm El Sheikh, Egypt. Therefore, soil biodiversity-related issues remained mostly unaddressed by the CBD until 2018, when in Decision XIV/30, FAO was requested, in collaboration with other organizations, to prepare a report on the state of knowledge on soil biodiversity, covering current status, challenges and potentialities, as well as to review the implementation of the initiative (CBD 2018).

In the meantime, other initiatives took flight, particularly in the EU but also globally, e.g., with the implementation of the Global Soil Partnership (GSP) in December 2012. Hosted by FAO, the GSP is a voluntary partnership, aiming to position soils in the Global Agenda and to promote sustainable soil management. It involves governmental and non-governmental organizations, and has promoted many actions and decisions to improve soil management, soil quality and sustainability worldwide that have important impacts on soil biodiversity (https//www.fao.org/global-soil-partnership). Furthermore, the EU spearheaded the preparation of a European Atlas on soil biodiversity (Jeffrey et al. 2010) and then with the help of the Global Soil Biodiversity Initiative (GSBI), a science-led forum established in 2011, a Global Atlas on soil biodiversity was organized and published by a consortium of organizations (Orgiazzi et al. 2016). These documents set a baseline of knowledge on soils and their biological diversity (up to 2016), as well as a framework for future work on the topic, highlighting the many gaps in knowledge.

Hence, an updated state of knowledge report was catalyzed by the FAO/GSP and prepared during 2019 and 2020, and delivered on World Soil Day (December 5th) in 2020 (FAO et al. 2020). Over 300 professionals linked to soil biodiversity research and action worldwide participated in the report. Simultaneously, an online survey on soil biodiversity was performed by FAO/GSP from August to September 2019, and the results received from over 70 respondents from 57 countries were included in the global report (FAO et al. 2020). This represents one of the most important documents on soil biodiversity, advocating its global importance, and also highlighting major research challenges worldwide with less than 1% of the world's soil species identified. Furthermore, it revealed the immense difficulties involved in establishing priorities and policies to promote the protection and sustainable use of this vast natural resource, which remains mostly unknown.

Shortly after the release of the global report, the Global Symposium on Soil Biodiversity was organized in April 2021 as a online event. It was a joint effort of FAO, the GSP, the Intergovernmental Technical Panel on Soils (ITPS), the CBD, GSBI and the Science-Policy Interface of the United Nations Convention to Combat Desertification (SPI UNCCD). Over 5,000 participants from more than 160 countries (FAO 2021a,b) attended and showcased work being performed worldwide on soil biodiversity. The main aims of the symposium were to review the role of soil biodiversity and ecosystem services in tackling environmental problems, and promote its sustainable use and management by addressing the underlying causes of soil biodiversity loss and enhancing the implementation of sustainable practices (FAO 2021a). The outcome document of the symposium (FAO 2021b) had several important final recommendations, including:

- the establishment of a Global Technical Network on Soil Biodiversity (NETSOB) and a Global Soil Biodiversity Observatory (GLOSOB);
- the development of standard guidelines for measuring and monitoring soil biodiversity, in the laboratory and the field;
- the development of capacity building programs, and a booklet on soil-borne diseases;
- identification and information on management practices that conserve and promote soil biodiversity;
- the development of methods to assess the economic value of soil biodiversity;
- and the assessment of effective policies and legal instruments to control soil biodiversity loss.

The CBD's international initiative on soil biodiversity was reviewed during 2020, and a new Action Plan for the period of 2020-2030 presented and discussed at the 24th meeting of the Subsidiary Body for Scientific and Technological Advice (SBSTTA) in Montreal (CBD 2020). The updated Action Plan was adopted in COP decision XV/28 in Montreal at the end of 2022 (CBD 2022). The plan recognizes "the need to mainstream soil biodiversity across sectors and the need for integrated approaches to better address the complex interactions that come into play as the conservation and sustainable use of soil biodiversity usually involve economic, environmental, cultural and social factors" (CBD 2022).

Hence, the objective of the plan is "to mainstream soil biodiversity science, knowledge, and understanding into public policies, at all levels, and to foster coordinated action to invest in soil biodiversity assessments at the global level to safeguard and promote the conservation, restoration and sustainable use of soil biodiversity and its ecosystem functions and services, which are essential for sustaining life on Earth, while acknowledging that economic, environmental, cultural and social factors contribute to sustainable soil management, and to promote investment in soil biodiversity research, monitoring and assessment at the corresponding level" (CBD 2022).

The Plan includes a set of 13 global actions and 49 activities separated into four main elements: a) Policy coherence and mainstreaming (12 activities); b) Encouraging the use of sustainable soil management practices (11 activities); c) Awareness-raising, sharing of knowledge, technology transfer and capacity-building and development (10 activities); and d) Research, monitoring and assessment (16 activities). A summarized list of the proposed activities is provided in Table 1 and Table S1 (for the full list, see CBD 2022), and includes several assigned to FAO, which was invited, among others, to "align activities on soil biodiversity more closely with other FAO-related activities including the International Network on Soil Biodiversity and the Global Soil Biodiversity Observatory, to monitor and forecast the conditions of soil biodiversity and soil health as well as with regional and country offices in order to create synergies and provide broader support" (CBD 2022). The main focus of the GLOSOB will therefore be to "include/strengthen: taxonomy, novel technologies for species identification and quantification, standard operating procedures (SOPs), soil biodiversity mapping, soil health indicators, bioremediation, restoration of degraded soils, and soil microbiome" (FAO 2021a). The work to be performed by the GLOSOB will ultimately strengthen knowledge in all soil biodiversity groups (microbes, micro, meso, macro and megafauna).

On World Soil Day in 2021, the GSP established the Global Technical Network on Soil Biodiversity (NETSOB) to strengthen the data, knowledge, and capacities to support the conservation and sustainable use of soil biodiversity. The activities of NETSOB are directed towards four main themes: 1) measurement, assessment and monitoring of soil biodiversity; 2) sustainable use/management and conservation of soil biodiversity; 3) economics of soil biodiversity; and 4) policies and legal instruments related to soil biodiversity. At its second annual meeting at FAO in January 2024, the NETSOB board decided to support the publication of synthesis papers on soil biodiversity, to help guide the establishment of GLOSOB and facilitate achievement of selected goals of the soil biodiversity Action Plan (Parnell et al. this issue). Several of these synthesis papers are published here in this special issue and represent important sources of information to guide future activities related to soil biodiversity, its discovery, its valuation, and monitoring worldwide (Brown et al., Correia et al., Jesus et al., Parron et al., this issue).

3. Uneven knowledge on soil biodiversity worldwide: the scientific context

Despite enhanced worldwide attention and a significant input of financial resources for soil biodiversity studies by the European Union through the Soil Deal (EC 2021) and the associated Horizon 2020 and Horizon Europe research calls, global maps of soil biodiversity are so far available for only a few taxa or groups of soil biota like nematodes (van den Hoogen et al., 2019), collembola (Potapov et al. 2024), earthworms (Phillips et al. 2019), macroinvertebrates (Orgiazzi et al. 2016), cyanobacteria (Cano-Díaz et al. 2020), and the soil microbiome (Bahram et al. 2018, Delgado-Baquerizo et al. 2021, Guerra et al. 2021b; Nayfach et al. 2021), with a special focus on bacteria (Delgado-Baquerizo et al. 2018) and fungi (Tedersoo et al. 2014, Liu et al. 2021). But a complete inventory of soil biota has yet to be performed at any particular site in the world, and most inventories have addressed only a limited number of taxa, either of microbes or of soil fauna, with few sites including a wider range of soil biota (e.g., Scheele & Verfondern 1988). This has always been a challenge in studies on soil biodiversity, as many different methods must be applied simultaneously to perform a detailed assessment, and many countries still lack trained taxonomists for the identification of various soil animal taxa (Römbke et al. 2016).

Additionally, current syntheses show a clear bias towards samples taken in developed or temperate-climate countries, and much further work is needed in developing nations and tropical and subtropical countries. Although national inventories for some taxa are available for some countries (Brown et al. this issue), and monitoring programs have been underway for over a decade in many European countries (Rutgers et al. 2019), only more recently have two major programs begun to monitor soil biodiversity at a wider geographical scale: in the EU through the Land Use and Coverage Area frame Survey (LUCAS) scheme (Orgiazzi et al. 2022) and worldwide with the SoilBON initiative (Guerra et al. 2021a).

Table 1. Summary of global actions and priority activities for member countries, as defined in different sections of the updated Plan of Action (2020-2030) for the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, in the Annex of CBD Decision XV/28 (CBD 2022).

Global Actions
1. Harmonize data collection and mapping
2. Include soil biodiversity in soil surveys
3. Implement monitoring network
4. Use soil biodiversity indicators
5. Strengthen education, research, and capacity building
6. Promote ecosystem-based approaches
7. Engage in ecosystem restoration
8. Encourage community involvement
9. Encourage awareness raising on soil biodiversity
10. Promote conservation and sustainable management
11. Perform impact assessments
12. Promote good agricultural practices
13. Identify funding sources for implementation

Policy coherence and mainstreaming activities	**Sustainable soil management activities**
1. Mainstream soil biodiversity globally	1. Enhance soil health and soil biota
2. Integrate soil biodiversity into policies	2. Use risk assessment procedures
3. Encourage sustainable soil management practices	3. Facilitate access to resources
4. Promote integrated ecosystem approaches	4. Encourage sustainable agriculture
5. Promote policies for soil biodiversity	5. Facilitate site-specific remediation
6. Develop policies for soil biodiversity	6. Prevent and control invasive species
7. Strengthen synergies for multiple actions	7. Conserve ecosystem services
8. Link soil biodiversity to heath	8. Promote resilience of Carbon-rich soils
9. Overcome barriers to adopt good practices	9. Support land degradation neutrality
10. Utilize existing tools at various levels	10. Implement ecosystem-based approaches
11. Include soil biodiversity in national strategies	11. Promote adaptation and disaster risk reduction
12. Promote spatial planning and monitoring	

Awareness and capacity building activities	**Research, monitoring, and assessment activities**
1. Promote soil biodiversity awareness	1. Enhance taxonomic capacities
2. Engage stakeholder groups	2. Integrate soil biodiversity into farming
3. Strengthen awareness of sustainable practices	3. Assess climate change risks
4. Use digital tools to promote best practices	4. Support integrated pest management
5. Enhance education on soil biodiversity and soil health	5. Qualify and quantify soil biodiversity
6. Support citizen science initiatives	6. Enhance information and data management
7. Build capacity among stakeholders	7. Facilitate fair and equitable benefits sharing
8. Protect, maintain and promote traditional knowledge	8. Mobilize participatory research and development
9. Foster partnerships for multi-disciplinary approaches	9. Develop assessment tools
10. Promote scientific cooperation and transfer of knowledge	10. Generate datasets on soil biodiversity
	11. Disseminate knowledge
	12. Harmonize monitoring methods and indicators
	13. Encourage regional cooperation
	14. Support community monitoring
	15. Promote research and capacity building in sustainable soil management
	16. Support commercial applications of soil biodiversity products

However, taxonomic coverage, particularly of LUCAS is still limited. Other global initiatives worth mentioning are evaluating the soil microbiome (see Bahram et al. 2018), the crop microbiome and sustainable agriculture (Singh et al. 2020), global tea decomposition, global soil macrofauna, earthworms and collembola (Djukic et al. 2022, Mathieu et al. 2023, Ganault et al. 2024, Potapov et al. 2020).

Molecular methods, particularly metabarcoding are useful for assessing prokaryotic diversity, but their potential has yet to be fully developed for eukaryotic diversity assessment (Kirse et al. 2021). Hence, in many cases, metabarcoding rather than conventional methods has been used to assess soil microbial diversity. For instance, in LUCAS prokaryotic and eukaryotic diversity was assessed using metabarcoding techniques at 885 sites in 25 EU countries (Orgiazzi et al. 2022), though there have been efforts to expand measurements to include other taxa. On the other hand, SoilBON initially focused only on soil microbial and nematode diversity using a combination of techniques (Guerra et al. 2021a), so an additional team was developed to include a wider range of soil fauna taxa (Potapov et al. 2022), although not in its entirety, due to limited financial and human resources. Thus, SoilBON currently involves assessment of microbial and microfauna parameters in more than 80 countries and 700 sites, while soil fauna coverage (SoilBON Foodweb) is limited to around 240 sites worldwide (see https://soilbonfoodweb.org/; Figure 1).

In a Global Survey on Soil Biodiversity, sent to over 70,000 persons in March 2022, a total of 694 persons answered questions related to national soil biodiversity inventories and 379 provided answers regarding soil biodiversity monitoring, respectively (Brown et al. this issue). However, only 24 percent (n=164) confirmed the existence of inventories and only 34 percent (n=129) said there were monitoring programs in their countries. Hence, most countries lack inventories or monitoring programs, or respondents were unaware of their existence. Inventories were reported from 50 countries, while monitoring programs were identified in 48 countries, although many of them included only partial coverage of soil biodiversity variables (mainly microbes, fewer with soil fauna; Brown et al. this issue).

4. Participation in the Global Soil Biodiversity Observatory: a tiered approach

As there is an uneven capacity to perform assessment and monitoring of soil biodiversity variables worldwide, and only a select number of countries are currently doing monitoring at various levels (local, regional or national), a tiered approach to participation in GLOSOB activities has been recommended (Parnell et al. 2025a, b). To aid in this process, a preliminary classification of participating

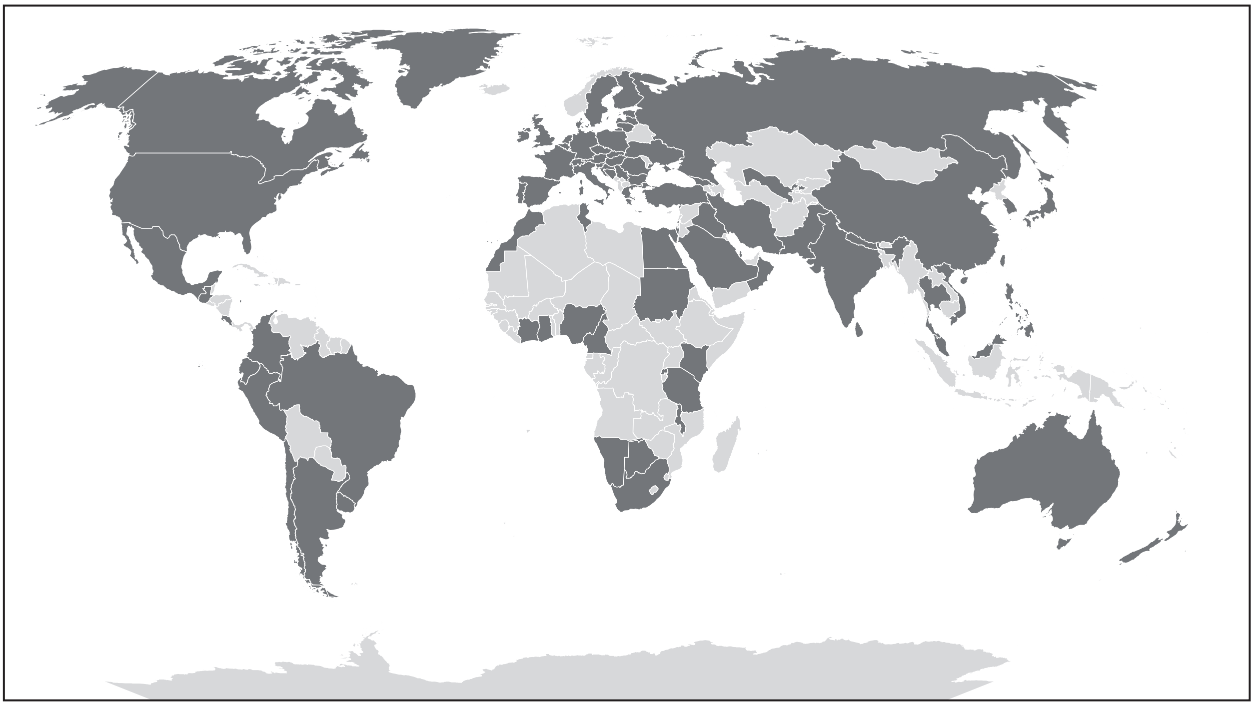

Figure 1. World map highlighting the countries participating in SoilBON Foodweb (in dark grey).

countries was performed depending on the ability of countries to assess the minimum list of essential biodiversity variables (EBVs) proposed by Parnell et al. (2025a,b), using information obtained from a literature review and the number of publications addressing each of these variables in the period of 2011 to 2021 (11 years). Further information can be found in Jesus et al. (this issue), Niva et al. (this issue), and Correia et al. (this issue), as well as the supplementary files (Table S2). For each variable, 0 publications in this time-period received a score of 3, while 1-2 publications received a score of 2, and 3 or more publications a score of 1. If the sum of all scores of the seven minimum variables was 7-10 the country was classified as belonging to Level 3; 11-14 to Level 2; and 15-19 to Level 1.

Level 3 includes countries with monitoring programs already under way and those with publications addressing the minimum set of variables proposed, demonstrating their ability to begin monitoring immediately (Table 2). Although few countries may currently have financial support for these activities, they possess full technical capacity to begin monitoring programs including the minimum set of proposed variables (EBVs). This level corresponds to at least Tier 1 of GLOSOB participation as proposed by Parnell et al. (2025a, b). Countries at this level include many of the countries already performing soil biodiversity monitoring (Brown et al. this issue), as well as some countries involved in the SoilBON Foodweb network (Figure 1). Level 2 countries include those that either have or do not have monitoring programs

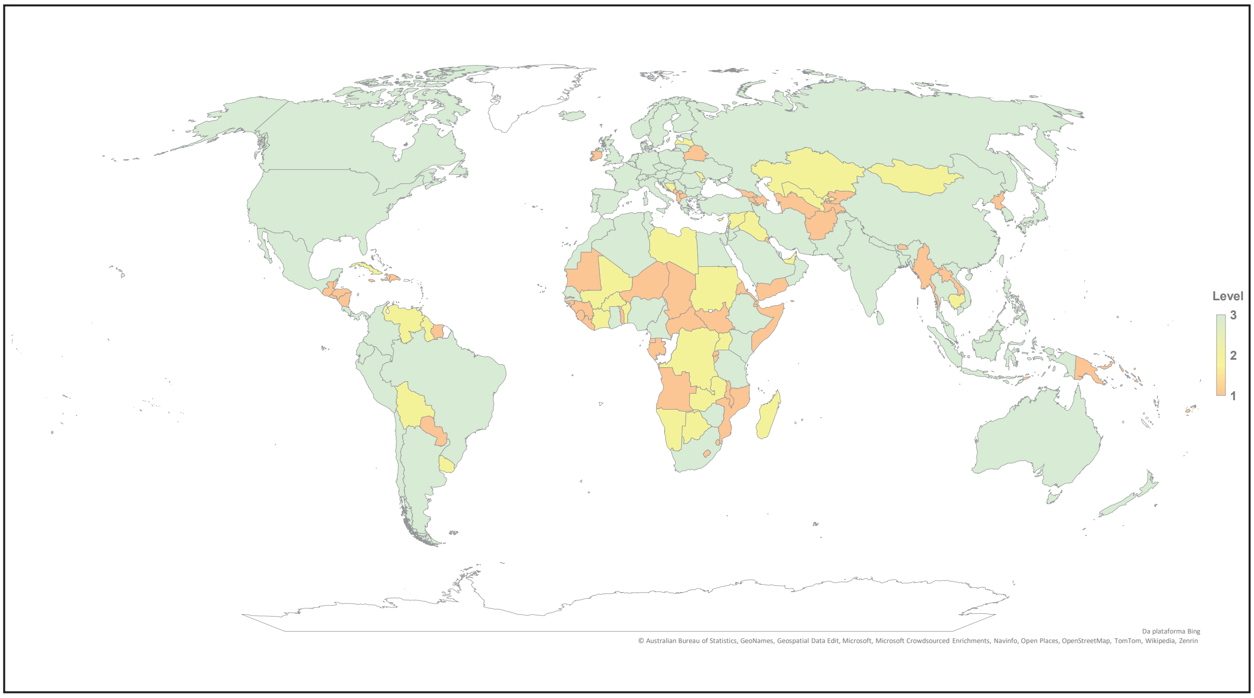

Figure 2. Countries in each major continent classified according their potential level of participation in GLOSOB activities, based on the literature review. Green countries represent level 3 level with full capacity to begin monitoring activities immediately. Yellow countries represent level 2 with moderate capacity to begin GLOSOB activities. Orange countries represent level 1 with limited capacity to initiate and perform GLOSOB monitoring programs.

Table 2. Classes of participation level in GLOSOB activities, based on capacity to initiate and perform GLOSOB monitoring programs, using the list of minimum Essential Biodiversity Variables (EBVs) to measure soil biodiversity in-country (see Parnell et al. this issue).

Level 3	**Level 2**	**Level 1**
Countries with ongoing soil biodiversity monitoring programs, and able to begin monitoring immediately using the list of EBVs	Countries needing some adjustments in order to begin monitoring of minimum EBVs	Countries that require support for building capacity and/or infrastructure to perform monitoring of EBVs

but do not yet possess full capacity to monitor the minimum variables. These countries will need support of some kind (financial, infrastructure, human resources, capacity building) in order to begin GLOSOB activities (i.e. achieve Tier 1 of the EBVs). Finally, level 1 countries would be those that do not have monitoring programs and have limited current capacity to perform monitoring, and that will need significant support (financial, human resources and infrastructure as well as capacity building) to begin GLOSOB activities. The countries in each level are shown in Figure 2, and the complete classification of each country according to number of publications for each of the minimum soil biodiversity variables is provided in the Supplementary Files (Table S2).

5. Capacity building and financial issues

Without adequate and continuous funding, monitoring of soil biodiversity through the GLOSOB will be impossible. Long-term financial commitments are needed for at least 5-year and preferably 10-year duration projects involving national-level and/or international-level research groups. A recent example of this is the EU call on Research and Innovation actions to support the implementation of the Soil health and Food Mission (HORIZON-MISS-2022-SOIL-01).

Recognizing that often long-term commitments from governments are extremely difficult due to single-term budgets (ranging from 4-5 years) and the variable annual budgets allotted to particular ministries or government funding agencies, plans should be made for programs that surpass the particular length of government-terms. Additionally, if any private or non-governmental funding sources become involved, special care should be taken to avoid any associated property rights and benefit sharing of the data and monitoring results by the funding agency, in order to avoid future difficulties in data use and sharing.

Countries with financial limitations or lack of capacity to perform long-term monitoring could be assisted by others, particularly if they have the personnel to perform the task but not the funding needed to do so. "God-father/mother" promoting funding agencies or countries should be scoped to find alternatives for these situations. On the other hand, countries that lack human resources, but have the financial resources to perform monitoring could be targeted for focused capacity building programs, assisted by countries, intergovernmental agencies (e.g., FAO, GSP, CBD) international initiatives (e.g., GSBI, SoilBON), and researchers who have experience with monitoring. Short courses and intensive training sessions lasting from 40 h to 4 weeks could be prepared by specialists, and offered to the interested parties/countries either in hybrid mode (online) or in-person, in order to complement capacity to perform GLOSOB monitoring schemes (Table 3).

Finally, countries interested in monitoring but with neither the human nor the financial resources for this purpose may approach the GSP and supporting technical networks for assistance and advice to build capacity and begin GLOSOB activities (Parnell et al. this issue). A

Table 3. Some proposed capacity building mechanisms at short and medium to long-term basis for countries that do not have the skills needed to perform monitoring within the GLOSOB framework.

Capacity building	Field team training	Lab team/analysis training	Research capacity
Type and duration	Short-course (40 h) hybrid or in-person	Specialization course (4 weeks), hybrid or in-person	Thematic PhD (3-4 yrs) or Post-doc (6+ months) for researchers
Mode	Separate courses for each EBV (field sampling protocols, transport, storage, and pre-treatment	Separate courses for each EBV (laboratory methods, analyses)	National or international university programmes and laboratories
Topics addressed	Basic principles, concepts, methods in the field	Basic principles, concepts, methods and practices in the lab	Soil biodiversity-geared courses (PhDs); Specialized topic(s) laboratory training (post-doc)

large number of African (29), Asian (17) and an important number of Central American and Caribbean (18), European (12) and Pacific (15) countries were identified as being in this situation (Figure 2), although national assessments following the scheme in Figure 3 should be performed in order to finalize this assessment based only on numbers of publications addressing the EBVs.

If funding is available and the country identifies the appropriate institutions and researchers to be involved in capacity building, these could be considered within a decision-based framework. Funding for long-term capacity building will be particularly important in order to increase capacity of countries where there are no trained professionals able to perform monitoring. For this purpose, graduate degree granting agencies, and international universities with programs geared towards soil biodiversity research could be approached in order to provide adequate training (Table 3).

Cost of monitoring a single site for soil biodiversity variables can vary significantly between countries, but much of the work to establish soil fauna biodiversity is not very expensive, particularly if traditional morphological taxonomy is used rather than molecular methods, when taxonomists are available to identify the organisms collected. The largest cost will be associated with personnel hours for the sampling, sample processing (extractions, separations) and identification, with the latter generally involving long-term capacity building in taxonomy. Equipment to perform mesofauna and microfauna extraction can be built relatively easily and at low-cost (see e.g., SoilBON Foodweb website and Potapov et al. 2022), and once built can be used for long-term monitoring, reducing per-sample costs.

Although costs of molecular analyses, particularly gene sequencing, have dropped considerably over the last 20 years, these costs vary largely between countries. Ideally, sequencing hubs within-country should be made available and used for the monitoring program, in order to reduce costs and potential differences between laboratories, sequencer equipment and personnel performing the analyses. These analyses, generally needed for studies of microbial diversity will have to be scaled according to the number of sites and the resources available in-country. Multilateral sources such as the United Nations Environmental Programme (UNEP)-based funds provided by the Global Environment Facility (GEF) should also be targeted (and were mentioned in the Action Plan; CBD 2022), in order to promote monitoring programs worldwide, particularly in level 1 or 2 countries that have financial limitations for GLOSOB activities. These funding incentives should also be geared towards countries that need further infrastructure

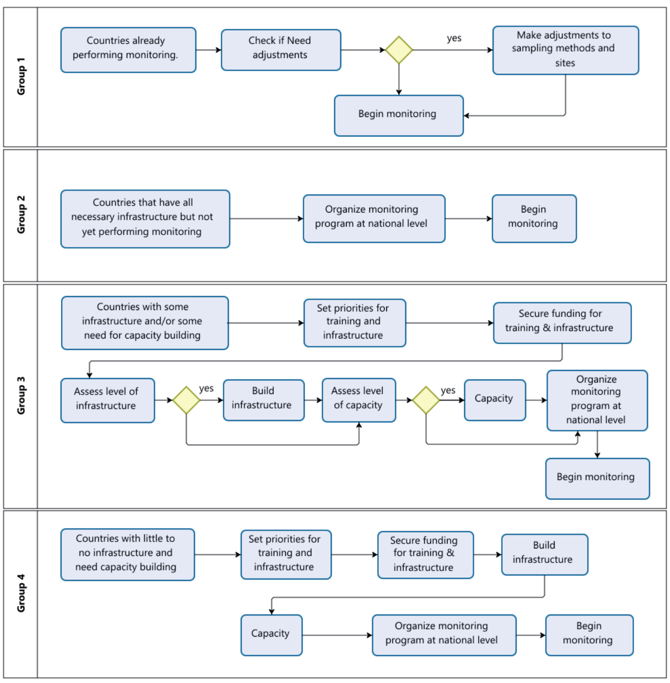

Figure 3. Decision-based process of grouping countries according to their current activities and ability to perform monitoring of soil biodiversity variables, depending on available infrastructure, human and financial resources.

development to begin monitoring programs, or that have the infrastructure but need capacity building in order to start them. The Global Taxonomy Initiative (Abrahamse et al. 2021) should also be adjusted at global and national-levels to include soil-dwelling taxa for an enhanced ability of countries to monitor and identify soil organisms. Additionally, large NGOs and foundations that support programs related to biodiversity and the achievement of SDGs, such as the Bill & Melinda Gates Foundation or similar philanthropic sources could be approached to assess possible support for GLOSOB activities. Finally, other initiatives, research institutions, and industry groups exploring soil biodiversity should coordinate with national sampling and protocols.

6. Recent advances in policy and legal issues for the assessment and use of soil biodiversity

Despite increasing attention paid to the importance and role of soil biodiversity in natural and anthropogenic ecosystems, soil biodiversity is still ineffectively protected by current public policies (Montanarella & Panagos 2021, Zeiss et al. 2022). Neither the preservation of soil functions nor the mitigation of soil threats are comprehensively regulated by legislation, and soil protection is generally a by-product of different provisions which are mainly preventive, qualitative, and often non-binding (Stankovics et al. 2018, Zeiss et al. 2022). Conversely, research and efforts addressing soil ecosystem functions and the intrinsic value of soil biodiversity such as those proposed in GLOSOB could support the development of conservation and management policies, including the establishment of new protected areas, and more emphasis to the conservation and sustainable management of soils, their biodiversity and ecosystem functioning.

At the supranational level, the EU Soil Strategy (EC 2021b) set up a framework to protect and restore soils, ensuring that by 2050: 1) all EU soil ecosystems are healthy and more resilient and can therefore continue to provide crucial services; 2) there is no net land take and soil pollution is reduced to levels that are no longer harmful to the health of people and ecosystems; and 3) protecting soils, managing them sustainably and restoring degraded soils become a common standard. One of the main actions of this strategy was to propose new legislation, aiming to enhance the poor soil health measured by the EU Soil Observatory in European soils (see EU soil health dashboard at https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/).

The proposal of a new soil law was launched in July 2023 (EC 2023), but was met with disappointment in some circles due to lack of legally binding objectives and insufficient focus on soil biodiversity (EEB 2023). After a period of revision, in April 2024 the new law introduced an EU-wide monitoring framework using standardized assessment methods of selected soil health indicators (provided in Annexes I and II of the law). Although a significant improvement over the first version (2023), that only included basal respiration as a measurement associated with soil biodiversity, the new law is still highly focused on microbial processes (microbial biomass and respiration) and the abundance and genetic diversity of soil microbes (fungi, bacteria, archaea, and nematode functional groups). Larger groups of soil fauna responsible for important soil functions and catalyzers of microbial activity in soils are only optional assessments (and only using barcoding with cytochrome oxidase I) in the first tier of obligatory variables for all countries.

Currently, the most relevant and crucial global policy framework addressing biodiversity (including soil biodiversity) is the CBD with its Action Plan for soil biodiversity (CBD 2022), as explained earlier. However, other derivatives of the CBD, including the Access and Benefit Sharing (ABS), and the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization (CBD 2011) are also important. The Nagoya Protocol defines since 2014 the international legal framework for access and utilization of genetic resources and Traditional Knowledge. It also sets the general principle that benefits must be shared in a fair and equitable manner with the providing countries.

In the context of Access and Benefit Sharing, genetic resources have a broad meaning that goes well beyond DNA or RNA. They include any material of plant, animal, microbial or other origin containing functional units of heredity and that are of actual or potential value. Genetic resources can be wild, domesticated or cultivated. Traditional knowledge includes the traditional knowledge, innovations and practices of indigenous and local communities embodying lifestyles relevant for the conservation and sustainable use of biological diversity. Use of genetic resources refers to research and development on the genetic and/or biochemical composition of genetic resources, including through the application of biotechnology. These multiple levels of biodiversity pose particular challenges not only to researchers, but to all those who want to access its potential economic benefits.

The solutions to the challenges with permits related to the Nagoya Protocol are country-based. Each signatory country has national legislation and regulations that give effect to the CBD and the Nagoya Protocol. On the other hand, the principles set by the Nagoya Protocol are implemented in domestic legislation of the providing countries. It is up to them to decide whether they require the fulfilment of Access and Benefit Sharing obligations, particularly when studies are only taxonomic (i.e., identification of biodiversity, without potential economic benefits). For example, in Brazil researchers need permits in order to collect biological material (including plants, animals and microorganisms), as well as to access its genetic diversity, which must be registered in a national online system (Sistema Nacional de Gestão do Patrimônio Genético e do Conhecimento Tradicional Associado - SISGEN).

Both researchers and the industry must comply with national and international policies and regulations, as they are at the heart of the access to genetic resources. However, researchers are often unaware of the legislation and frequently perceive it as a hurdle instead of an enabler. The Nagoya Protocol recommends that the parties create conditions to promote and encourage research particularly in developing countries, by simplifying access for non-commercial research purposes, considering the need to address a change of intent for such research (CBD 2011). Governments can facilitate solutions by making information more accessible with community involvement. Another step toward this goal is improved communication between national ministries. Better within-country coordination can help improve international commitments to fulfill measurable targets.

However, considering the potential economic benefits derived from soil biodiversity (Parron et al. this issue), and the ease by which soil particles containing microorganisms can be transported worldwide, appropriate implementation of the Nagoya Protocol is crucial to avoid spread, unintentional or otherwise. For instance, the market value of nitrogenous fertilizers avoided by using N_2-fixing bacteria in Brazilian soybean production may amount to as much as 15.2 billion USD yr^1 (Telles et al. 2023). Many potentially important medicinal properties can be found in the soil biota (Anderson 2009), and a global search identified many active soil biota-derived patents (Jesus et al. this issue).

7. Conclusion: Towards a concerted global soil biodiversity observatory

The GLOSOB is a timely response from the international community to improve knowledge on soil biodiversity and to monitor the impact of human activities on soil biodiversity and the ecosystem services that it provides. GLOSOB aims to forecast the status of soil biodiversity and soil health following a country-driven and tiered approach where countries will be responsible for measuring, monitoring and reporting soil biodiversity in agreed sites according to standard methodologies/protocols of NETSOB, and according to their abilities to assess EBVs.

Providing baseline values for the status of soil biodiversity and related ecosystem functions worldwide in a variety of land uses, will help assess and compare soil health and ecosystem service delivery under future climate or management change scenarios (Zeiss et al. 2022). Monitoring and assessment should identify key threats to soil health and food security in major land use systems and propose sustainable management and restoration practices, while obtaining reference values in undisturbed sites in the country's main soil types. Assessing and monitoring soil biodiversity will also help determine management practices most appropriate for different crops, soil and climate types. Case studies and guidebooks on implementation of management practices being compiled by NETSOB and made accessible to all producers will be an invaluable tool for building and maintaining biodiversity and the ecosystem services they provide. We also recommend that scientists and policymakers engage with the public through simple and illustrative information campaigns to raise awareness regarding the importance of soil biodiversity and its relationship with agricultural and forest management (Vanermen et al. 2021).

GLOSOB's work will also serve as a framework for policy development. Countries can identify good practices and promote implementation of those practices particularly in soil biodiversity hotspots. Additionally, national capacity building on state-of-the-art tools and practices can be effectively adopted. National initiatives to protect soil biodiversity will result in maintaining soil ecosystem services that improve food security, mitigate climate change, and combat desertification. Finally, the identification of critical soil ecosystems for the conservation and delivery of critical ecosystem services and maintenance of species richness will also help highlight the important role of soil biota and their activities as part of sustainable soil use and biodiversity conservation for present and future generations.

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