Food and Agriculture Organization of the United Nations

Outcome document

Keep soil alive, protect soil biodiversity

GLOBAL SYMPOSIUM ON SOIL BIODIVERSITY

19-22 April 2021

GLOBAL SOIL PARTNERSHIP

itps INTERGOVERNMENTAL TECHNICAL PANEL ON SOILS

Convention on Biological Diversity

GLOBAL SOIL BIODIVERSITY INITIATIVE

UNCCD SPI Science - Policy Interface

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19-22 April 2021

An event co-organized by:

FAO | Food and Agriculture Organization of the United Nations
GSP | Global Soil Partnership
ITPS | Intergovernmental Technical Panel on Soils
CBD | Convention on Biological Diversity
UNCCD-SPI | Science-Policy Interface of the United Nations Convention to Combat Desertification
GSBI | Global Soil Biodiversity Initiative

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Abbreviations

AMF | Arbuscular mycorrhizal fungi

AMR | Antimicrobial resistance

CBD | Convention on Biological Diversity

COP | Conference of Parties

EC | European Commission

FAO | Food and Agriculture Organization of the United Nations

GSBI | Global Soil Biodiversity Initiative

GSOBI21 | Global Symposium on Soil Biodiversity 2021

GSP | Global Soil Partnership

ITPS | Intergovernmental Technical Panel on Soils

SDGs | Sustainable Development Goals

SOC | Soil organic carbon

SOM | Soil organic matter

SSM | Sustainable Soil Management

UNCCD-SPI | Science-Policy Interface of the United Nations Convention to Combat Desertification

UNCCD | United Nations Convention to Combat Desertification

UNFCCC | United Nations Framework Convention on Climate Change

VGSSM | Voluntary Guidelines for Sustainable Soil Management

WSD | World Soil Day

Scientific and organizing committees

This outcome document, "Keep soil alive, protect soil biodiversity" was prepared and reviewed by members of the Scientific Committee (see below) in their personal capacities. This document is also based on the Report of the State of Knowledge of Soil Biodiversity: Status, Challenges and Potentialities, and is complemented by a book of proceedings, which presents extended abstracts of the various parallel sessions presented during the symposium.

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Summary

The Global Symposium on Soil Biodiversity (GSOBI) was jointly organized by the:

- Food and Agriculture Organization of the United Nations (FAO)
- Global Soil Partnership (GSP) and its Intergovernmental Technical Panel on Soils (ITPS)
- Convention on Biological Diversity (CBD)
- Global Soil Biodiversity Initiative (GSBI)
- Science-Policy Interface of the United Nations Convention to Combat Desertification (SPI-UNCCD)

The Global Symposium on Soil Biodiversity was held virtually on the FAO zoom platform from 19-22 April 2021. It was attended by over 5 000 participants (49 percent women, 51 percent men), representing more than 160 countries, including representatives of FAO Members, organizing institutions, academia, research institutions, the private sector, civil society, and farmers, as well as land users working on soil biodiversity and related fields.

The overall aim of the symposium was to gather updated scientific knowledge on soil biodiversity, review the role of soil biodiversity and ecosystem services in tackling environmental problems and to drive actions towards the implementation of the Revised World Soil Charter along with the Voluntary Guidelines for Sustainable Soil Management and the Protocol for the Assessment of Sustainable Soil Management. Specifically, the State of Knowledge of Soil Biodiversity Report and the GSOBI21 Symposium objectives were to provide evidence to support actions to protect soil biodiversity and promote its sustainable use and management by addressing the underlying causes of soil biodiversity loss and enhancing the implementation of sustainable practices.

The four-day symposium was structured around three main areas focusing on: Theme 1. State of knowledge on soil biodiversity; Theme 2. Soil biodiversity in action; and Theme 3. Soil biodiversity shaping the future of food systems.

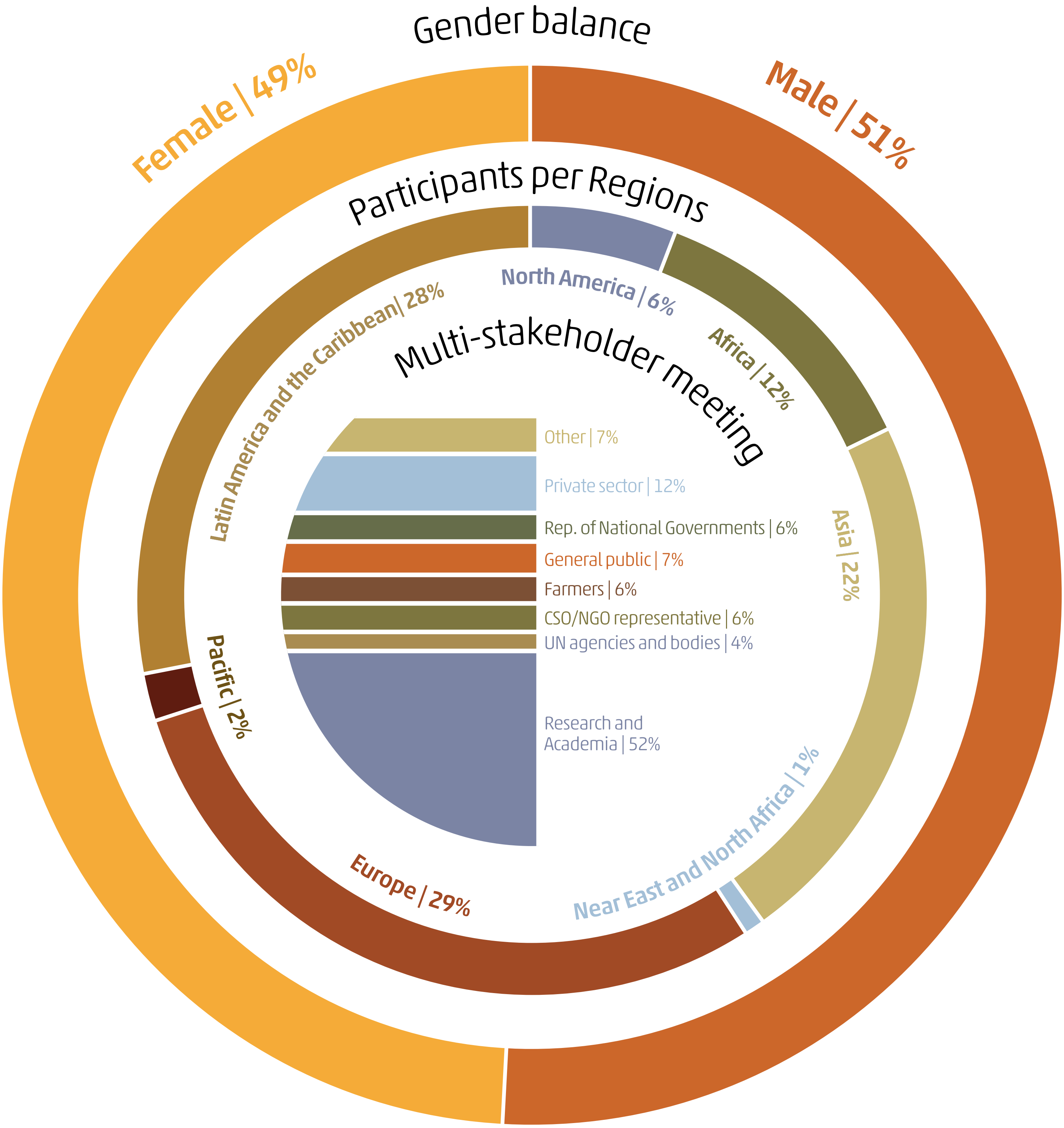
Participants engaged actively by presenting the results of their research, demonstrating that there has been a notable progression in the ability to measure, assess, manage and monitor soil biodiversity, from a national to a global level, albeit with the challenge of there being few standard protocols available. There had also been challenges in implementing sound policies that integrated soil biodiversity in the adoption of sustainable soil management practices by countries.

It was made clear that, going forward, there would be a need to:

- Strengthen and/or establish national soil information systems including soil biodiversity information.
- Provide a set of indicators to measure/monitor soil biodiversity and soil health.
- Invest in research on soil-borne diseases and scale-up soil biodiversity responses in the agricultural sector and in climate change mitigation and adaptation.
- Recognize soil biodiversity in the Sustainable Development Agendas.
- Promote targeted research on soil biodiversity and foster the application/use of these results in the different sectors.

The recommendations presented in this document aim to support the development of policies and actions to encourage the full use of soil biodiversity in the various land use sectors.

Statistics of attendance



Background of the global symposium on soil biodiversity

In finding solutions to the impacts of a projected world population growth, the increase in food demand, as well as the ever-present need to eradicate poverty and malnutrition, we will need to rely more than ever on the sustainable use of soils and the ecosystem services they provide. Reversing soil degradation and restoring soil functions and soil health offer a considerable opportunity to address the importance of soil biodiversity in reversing the worldwide trend of degradation.

Sustainable soil management can be clearly identified as a crosscutting approach. It is at the heart of several global agendas and international policy frameworks, including the Sustainable Development Goals (SDGs) and multi-lateral environment agreements, in particular those related to biodiversity (CBD), desertification (UNCCD) and climate change (UNFCCC). Furthermore, soil biodiversity and sustainable soil management (SSM) will be pivotal to the success of the recently declared UN Decade on Ecosystem Restoration (2021-2030).

In 2002, at its 6th meeting in Nairobi, the CBD decided to establish an International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, as a cross-cutting initiative within the programme of work on agricultural biodiversity. The Food and Agriculture Organization of the United Nations (FAO), together with other relevant organisations, were invited to facilitate and coordinate this initiative.

The International Initiative for the Conservation and Sustainable Use of Soil Biodiversity has three main objectives:

I. The promotion of awareness raising, knowledge and understanding of key roles, functional groups and impacts of diverse management practices on soil biodiversity and soil health in different farming systems and agro-ecological and socio-economic contexts.

II. The promotion of ownership and adaptation by farmers of integrated soil biological management practices as an integral part of their agricultural and sustainable livelihood strategies.

III. The strengthening of collaboration among actors and institutions, while mainstreaming soil health and biological management into agricultural, land management and rehabilitation programmes.

Since then, some countries have been developing legal frameworks and adopting policies dedicated to the sustainable utilisation of agrochemicals, water protection, pollution prevention and waste management. These actions have contributed to some extent to soil protection, as well as consequent indirect effects on the conservation of different soil biodiversity components by addressing specific threats (e.g. nitrates, pesticides and invasive alien species). However, legal instruments and policies widely adopted and focused on SSM including soil biodiversity are needed, given its importance in multiples sectors and in ensuring the provision of fundamental ecosystem services.

Eighteen years after the launch of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, the full potential of soil biodiversity has yet to be realised. Scientists and scientific soil biodiversity networks have made substantial progress in researching this topic, however, there is a pressing need for the mainstreaming and scaling up of soil biodiversity in order to address the different challenges that ecosystems and population are currently facing.

In 2018, at the UN Biodiversity Conference held in Egypt, the Conference of the Parties (COP) to the Convention on Biological Diversity (CBD) invited FAO to prepare a report on the State of Knowledge of Soil Biodiversity. Additionally, the COP requested the Secretariat of the CBD, in consultation with FAO under the aegis of the Global Soil Partnership (GSP) as well as other interested partners, to review the implementation of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity.

During the upcoming COP 15, the Parties to the CBD will adopt a Post-2020 Global Biodiversity Framework towards the achievement of the 2050 Vision of "Living in harmony with nature".

There is an urgent need for a more integrated and coherent policy framework, where soil biodiversity protection is incorporated into other sectoral policies. Managing soil biodiversity has different components and challenges, making this task considerably different from the management of aboveground biodiversity.

During the World Soil Day celebrations in December 2020, the Report on the State of Knowledge of Soil Biodiversity: Status, Challenges and Potentialities, was launched as well as its Summary for policy makers. This report was the result of an inclusive process involving more than 300 scientists from around the world under the auspices of the FAO's GSP and the Intergovernmental Technical Panel on Soils (ITPS), the CBD, the Global Soil Biodiversity Initiative (GSBI) and the European Commission (EC). The report presents the state of knowledge on soil biodiversity, describing the threats and the solutions that soil biodiversity can provide to problems in different fields. These include agriculture, environmental conservation, climate change adaptation and mitigation, nutrition, medicine and pharmaceuticals, remediation of polluted sites as well as many others. It represents a valuable contribution to raising awareness of the importance of soil biodiversity while highlighting its role in finding solutions to today's global threats.

In this context, the Symposium outcome will contribute to the final deliberations and advocate for the endorsement of the revised plan of action for the implementation of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, and ultimately, contribute to the Post-2020 Biodiversity Framework. This Symposium gave the opportunity to openly discuss and channel efforts to build bridges between the actions of different stakeholders that could sometimes be perceived as fragmented or overlapping.

The main objectives of the symposium were to fill some critical knowledge gaps and promote discussion among policy makers, food producers, scientists, practitioners and other stakeholders on solutions to live in harmony with nature, and ultimately, achieve the SDGs through the conservation and sustainable use of soil biodiversity. The specific objectives of the symposium were to:

I. Examine the current scientific, technical, indigenous and traditional knowledge on the role of soil biodiversity on food production, human health and on sustaining biodiversity aboveground.

II. Identify knowledge gaps and explore opportunities for collaborative research, capacity building and technical cooperation.

III. Identify limitations and opportunities to promote the sustainable use of soil biodiversity, knowledge sharing and capacity building.

IV. Present effective and replicable methodologies, techniques, technologies and practices that promote sustainability, with a view to upscale those sustainable approaches to promote soil biodiversity conservation, the sustainable use of its resources and equitable participation in productive landscapes.

V. Identify policy options to protect soil biodiversity and encourage the adoption of practices that enhance it.

VI. Present national, regional and global initiatives that support the effective design, planning, implementation, monitoring and reporting of solutions and their contribution to the achievement of the SDGs.

VII. Helping build a broader appreciation of soil biodiversity and our dependence on the many benefits it provides.

Symposium themes, core questions and discussion summary

The symposium was organized in different sessions: a) an opening session with the Heads of UN organizations and conventions and other authorities; b) a session of keynote speakers portraying the status and challenges of soil biodiversity; c) 6 parallel sessions presenting research outputs from scientists; d) a poster session; e) thematic global presentations and closure session.

The aims of the parallel sessions were to promote discussion, generate conclusions and recommendations based on scientific evidence, define the way forward to prevent and minimize soil biodiversity loss, and to contribute to the know-how on assessing, measuring, monitoring, and sustainably managing soil biodiversity at all levels.

The identification of gaps in knowledge and regulations has led to the definition of a line of work for the future. In the lead-up to the symposium, core questions were developed as well as expected outcomes to the symposium for each theme, in order to stimulate discussion and help in identifying priority actions. Presentations in parallel sessions set the scene for debating and discussing the main topics. Finally, plenary sessions were held on the last day to present the results and the way forward.

The GSOBI21 themes are listed in the next section, followed by the way forward with the main discussions, recommendations and conclusions. Even if treated separately in this document, it should be emphasized that the three themes are interrelated.

The answers to the following core questions are the product of the presentations and discussions during the Symposium as well as inputs from the State of Knowledge of Soil Biodiversity Report (FAO *et al.*, 2020).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Theme 1. State of knowledge on soil biodiversity

Theme 1 aimed to discuss about the latest discoveries on taxonomic and genetic diversity of soil organisms, the benefits arising from soil biodiversity and the status of the world soil biodiversity, in order to strengthen dialogue between all stakeholders.

Core questions

I. What recent discoveries have been made on soil organisms' taxonomic and genetic diversity and their distribution patterns?

As soil biodiversity is lost, ecosystem functions are reduced (Wagg *et al.*, 2014). With over 40 percent of terrestrial genetic diversity housed below ground (FAO *et al.*, 2020), the conservation of soil biodiversity is a key component in maintaining genetic diversity, as well as ensuring optimum soil functioning. Rapid advancements in scientific research and technologies have supported the taxonomy and discovery of new species of soil biota, their distribution in soils around the world and the understanding of their contributions to our well-being. However, a large number of species of soil organisms in many regions of the world are still waiting to be discovered (Guerra *et al.*, 2020). Furthermore, the lack of taxonomists for many soil taxa is a real concern, not only for the future of soil biodiversity research programmes, but also in raising awareness of biodiversity loss. Hence, simplified methodologies and tools are needed for soil biodiversity assessment to promote wider accessibility and use in all regions of the world.

Several contributions in the symposium addressed soil organism taxonomy and distribution. For instance, Niva *et al.* (2021), found 6 potentially new species of enchytraeid in Brazilian Cerrado biome and more than 20 different species belonging to 8 genera in the region. Syamsudin, Kowara and Choesin (2021), collected 43 species of soil protozoa in post-coal mine recovered area in Indonesia. Sasmita *et al.* (2021), also in Indonesia, identified 27 major macroinvertebrate taxa (25 families, 21 orders) in Agroforestry systems there. Environmental DNA (eDNA), a promising tool for detecting global composition of soil eukaryotes, was used by Bellemain *et al.* (2021), to assess the degree of restoration of soil quality in polluted environments.

II. How have technological advances and traditional and indigenous knowledge supported soil biodiversity discoveries?

Sustainable soil management requires sound resource management at the watershed and landscape levels and beyond, which in turn requires models based on big data generated from soil-water-plant-atmosphere information. In addition, applications need to be developed for the recording of farming data, linking the information to remotely sensed databases and storage of data, and analyzing big data in order to provide management advice. Until now, information on soil biodiversity has not yet been included, but once it is aggregated into these models it may increase management strength, provided that sufficient knowledge is available regarding the diversity and functions of the soil microbiome.

Artificial intelligence has great potential in the assembly of data and the aggregation of information from multiple databases. Novel technologies at farm and landscape scales could become powerful tools in promoting the sustainable management of soils. Knowledge and technological advances at the microscale or macroscale could provide new perspectives on soil functions that may ultimately be transferred to novel technologies. The emerging novel technologies such as metagenomic, metabolomic, transcriptomic and volatilomic approaches provide useful information on soil biodiversity functions in addition to the taxonomic diversity of the soil microbiome. Advances in meta-genomics in identifying soil organisms and linking their structure to their function, coupled with an increase in experiments that manipulate diversity within and across energy channels, trophic groups, functional groups, taxa and genetic differences should help solidify links among agricultural management (including intensification), soil biodiversity and ecosystem functioning.

Biotechnological methods to describe impacts of agricultural practices on taxonomic and functional diversity of soil organisms are also advancing. Despite this progress, the importance of soil and the multitude of environmental services that depend on soil organisms are not well understood by society at large.

Effective and efficient monitoring tools are important in recording changes in soil biodiversity and establishing databases to link diversity with soil functions. The "Land Use/Cover Area frame statistical Survey Soil" (LUCAS Soil) is an extensive and regular topsoil survey that is carried out across the European Union to derive policy-relevant statistics on the impact of land management on soil characteristics, including soil biodiversity. LUCAS Soil represents the largest harmonised open-access dataset of topsoil properties available for the European Union. Soil BON supports the development of a global community for the observation, understanding and prediction of soil biodiversity, being a forum to network groups and advance standardized methods for observing soil biodiversity, including the integration of information across spatial, temporal and taxonomic scales.

Research devoted to the definition of biological indicators is making great progress, but the development of robust and reliable biological indicators remains a challenge. In England, a Long Term Monitoring Network is assessing soil properties that include the use of chemotaxonomic markers (PLFAs) and metabarcoding applied to some mesofauna samples. The Lazio Region in Italy financed a monitoring programme using the Biological fertility Index (BFI) to assess the degree of biological fertility of soil correlated with different production systems (Renzi *et al.*, 2017). The Pavia Province in the Lombardia Region (Italy) also initiated a monitoring programme, carried out by the Joint Research Centre of the European Commission (JRC) using several biological indicators, ranging from BFI to earthworms (Pompili *et al.*, 2006; Beone *et al.*, 2015).

During the symposium, several presentations focused on the use of different taxa, functions or integrated tools for measuring soil quality/health. A novel technique (SoilBio) based on two soil enzymes (arylsulfatase and beta-glucosidase) has been gaining increased recognition and use by farmers in Brazil (Mendes *et al.*, 2019),while the QBS-ar (Soil Biological Quality index using microarthropods) has been expanding, particularly in Europe, but also in other continents (e.g., Bolivia; Ledezma *et al.*, 2021).

Regarding global products, a paper on soil nematode abundance and functional group composition at a global scale was prepared using 6 759 georeferenced samples to generate a mechanistic understanding of the patterns of the global abundance of nematodes in the soil and the composition of their functional groups (van den Hoogen *et al.*, 2019). The first ever Global Soil Biodiversity Atlas used informative text, photographs and maps to answer and explain the factors influencing the distribution of soil organisms, how soil biodiversity supports food production, the pressures affecting soil life and the possible interventions to preserve it (Orgiazzi *et al.*, 2016).

Regarding the human side, the SDG 5 (Gender Equality) and SDG 8 (Decent Work and Economic Growth), highlighted women as an important member of farming communities around the world. Women form a major part of agricultural development with traditional knowledge and skills in farming being closely tied to the maintenance and improvement of land productivity (UNCCD, 2019). Women's contributions also include knowledge and respect for soil organisms and their role in supporting farming practices. For example, China assessed the status and trends of soil biodiversity in various ways, including a comprehensive assessment of the status and trends, scientific knowledge, innovations and practices of farmers, indigenous and traditional knowledge and maps (FAO *et al.*, 2020).

III. What is the latest knowledge on the ecosystem services delivered by soil biodiversity?

A wide range of soil organisms including ecosystem engineers and beneficial microorganisms like mycorrhizal fungi and N_2 fixing bacteria (symbionts in roots) play key roles in providing ecosystem services such as soil fertility improvement, soil formation and maintenance, nutrient cycling and plant primary productivity enhancement (Figure 1). Although a number of tools exist to assess ecosystem services in the context of land management, few fully integrate soil biodiversity and most are applicable only to developed countries (Grêt-Regamey *et al.*, 2017).

To overcome these obstacles and to sustain soil functions at specific levels, knowledge on how soil food webs respond to specific management and restoration regimes under the perspective of global climate change is essential. To this end, it is crucial to focus research on better understanding the links among biodiversity attributes and soil functions and ecosystem services (de Vries *et al.*, 2013; See Figure 1), among abiotic properties, soil organisms and climate (Bhusal, Tsiafouli and Sgardelis, 2015;

Orgiazzi and Panagos, 2018) and to develop efficient monitoring tools and maps by up-scaling the bio-indication potential to the scales that are important for management decisions (Stone *et al.*, 2016; van den Hoogen *et al.*, 2019., Mendes *et al.*, 2021b). For instance, a soil health index integrating soil enzyme activity and soil chemical fertility has been rapidly adopted by dozens of commercial soil analysis laboratories in Brazil to provide a way of quickly highlighting good and bad practices (Mendes *et al.*, 2021a and Mendes *et al.*, 2021b).

That said, human activities and interventions play a critical role on the outcome of soil functioning. Human-induced changes, such as the intensification of land use, can modify soil structure and abiotic properties as well as the structure, composition and diversity of the soil food web, thereby influencing ecosystem service delivery (Figure 1). Soil health, as well as various SDGs depend on the maintenance of the four major biodiversity-based soil functions (carbon transformation, nutrient cycling, formation of soil structure, and biodiversity regulation). Unfortunately, all these functions are recognized as being under threat (Gardi, Jeffery and Saltelli, 2013).

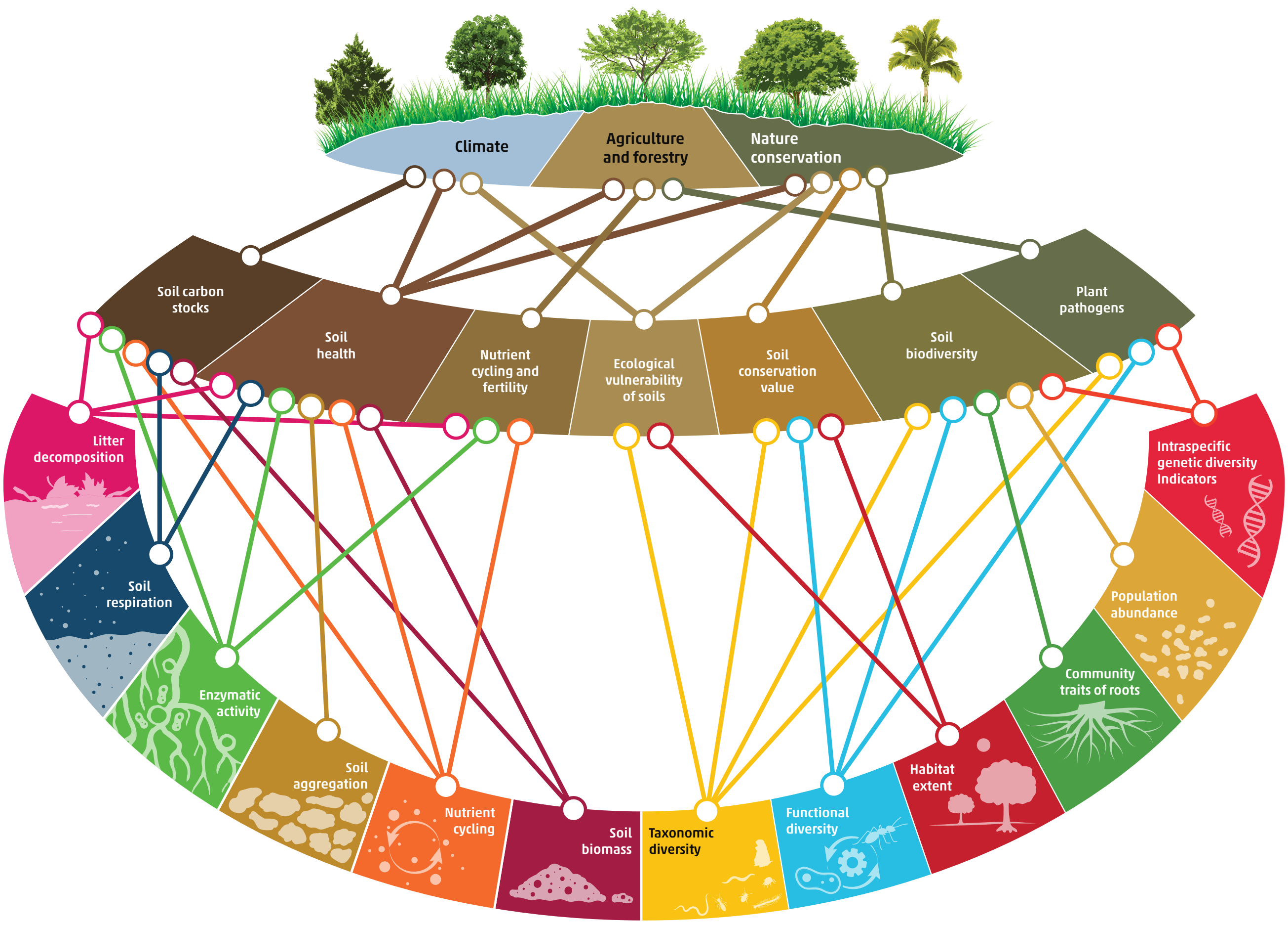

Figure 1. Links between essential soil biodiversity variables (EBVs) (outer ring) as prioritized by the global Soil Biodiversity Observation Network (SoilBON) and policy sectors (top of the figure) through the use of soil ecological indicators (center of figure). Thin lines correspond to links between EBVs and soil indicators; thicker lines refer to links between each soil indicator and specific policy sectors. The EBVs for soil systems are proposed as a holistic system approach, where soil organisms are intertwined with relevant chemical, physical and functional soil properties, contributing to overall societal well-being. Source: modified from Guerra, *et al.* (2021).

IV. What is the status and projected trends of soil biodiversity (global/regional/national levels)?

The important role of soil biodiversity in ecosystem functioning and the provision of ecosystem services can be threatened by human activities as well as by natural disasters, although the latter may also be influenced by human-induced changes. These include deforestation, urbanization, agricultural intensification, loss of soil organic matter/carbon, soil compaction, surface sealing, soil acidification, nutrient imbalance, contamination, salinization, sodification, desertification, wildfires, erosion and landslides. The State of Knowledge of Soil Biodiversity Report (FAO *et al.*, 2020) provided an overview of the potential regional and global threats on soil biodiversity, showing that the most widespread threat to soil biodiversity in the world was the loss of soil organic matter (SOM) and soil organic carbon (SOC), and that this could be associated with other threats such as deforestation and agricultural intensification (both linked with land use change) and with climate change (particularly in tundra). This highlights the importance of sustainable management and conservation practices, in order to maintain this essential biological resource in soils.

Greater efforts are needed to understand the impacts of multiple direct (such as intensive land use) and indirect (such as climate change) anthropogenic threats to soil biodiversity (Veresoglou, Halley and Rillig, 2015; Orgiazzi *et al.*, 2016). This is of particular importance, as threats to soil biodiversity do not only co-occur but can have additive, interactive or synergistic effects, reducing soil biodiversity to even lower levels than what we would expect to find based on single driver studies (Thakur *et al.*, 2018). Taken together, it is likely that the combined global change factors reduce biodiversity of native species, while being partly compensated for by the increasing spread of cosmopolitan species. The combined global change effects are predicted to be context-dependent, that is, differing by biome, organism group and relative effect on dominant vegetation or its shift.

Unfortunately, the available knowledge of the impacts of these threats on soil biodiversity and function is highly variable, depending on the threat and the region, as well as the target biota (macro, meso, or microfauna and microbes, for example). It is now relatively easy for many environmental variables (such as temperature and land cover) to be mapped and monitored for change, using data collected by remote sensing (satellites). However, these still do not provide direct information on the state of the organisms present (diversity and populations). These must be derived from case studies performed throughout the world in the different ecoregions and include a range of taxa, with distinct functions in soils, so that the risk to soil biodiversity and function can be better assessed. In addition, syntheses of available data on the impacts of these threats to soil biota (as many potential representative groups/taxa as possible) and support to obtain missing data are needed in order to produce accurate maps that reflect the true potential impacts of these threats on soil life worldwide. Much progress has been made in some areas, for instance with the adoption of standardized laboratory protocols for the measurement of multiple taxa and functions through SOILBON (Guerra *et al.*, 2021), though wider geographic representation and range of taxa and functions are desirable. The Global Tea-composition Initiative (Djukic *et al.*, 2021), using standard tea-bags as proxy for litter decomposition measurements has also promoted an improved understanding of local, regional and global impacts of drivers on this process, although some detritivore macrofauna are excluded from the process due to the small mesh-size.

V. How can we best measure, map, monitor and report on soil biodiversity? What are the most useful indicators organisms?

The diversity of soil invertebrates is of particular importance for the provisioning of multiple ecosystem functions and services across ecosystem types, including soil erosion control and nutrient cycling (Soliveres *et al.*, 2016). With the advent of novel methods, particularly molecular techniques, researchers have been able to move beyond a focus on individual species. Scientists have begun to show how the hugely diverse soil microbiome is tied to pathogen control, plant health, increased yield and an increased ability to overcome abiotic stress. Especially in the last decade, method advances including molecular sequencing techniques and “big data” analytical tools have helped to identify species living in soils and their communities.

In order to be able to define which regions of the world need protection, sufficient information must be available on the status and trends of soil biodiversity, including data on as wide a range of taxa as possible, from as many locations as possible. But, according to the country responses to the soil biodiversity survey[1], while some countries (e.g., Netherlands, United Kingdom of Great Britain and Northern Ireland, France, etc.) have established indicators and monitoring tools for soil biodiversity, the majority of countries still lack the knowledge, capacity and resources to implement soil health principles and adopt best practices for soil biodiversity enhancement (FAO *et al.*, 2020).

Furthermore, few organisms/taxa have been analyzed at a global level, mainly due to limited data. For example, the abundance and/or diversity of earthworms and nematodes have been relatively well studied worldwide, and some recent studies have even produced global maps, although sampling has been clearly geographically biased towards the Northern hemisphere, particularly European countries (Philips *et al.*, 2019; van den Hoogen *et al.*, 2019). However, most of the other soil invertebrates, including soil-dwelling larval stages of flying insects that represent a major biodiversity pool in terrestrial ecosystems, have been woefully neglected in biodiversity databases and assessments, as well as in conservation actions and policies (Eisenhauer, Bonn and Guerra, 2019).

Studies have identified taxonomic groups that may serve as potential indicators to assess the sustainability of agricultural soil management and to monitor trends in soil condition and functions over time (Paula *et al.*, 2014; Kaiser *et al.*, 2016; Trivedi *et al.*, 2016). For example, Rutgers *et al.* (2019) predicted relative soil biodiversity in several European countries using six biological soil attributes and five chemical soil attributes together (i.e., total organic carbon, total nitrogen, total phosphorous, pH, clay content, abundance, Shannon diversity index and richness of earthworms, microbial biomass and bacteria). Soil microarthropods like Collembola and Acari have also been useful as biological indicators of soil quality and of anthropisation, including urbanization and contamination. The QBS-ar index (Soil Biological Quality index using microarthropods) is an expeditious and inexpensive index that may represent a good first step to evaluate soil condition in degraded and natural landscapes (Menta *et al.*, 2018).

Research devoted to the definition of biological indicators is making great progress, but the development of robust and reliable biological indicators remains a challenge. Based on the country responses to soil biodiversity survey (FAO *et al.*, 2020), the following examples reflect the effort of some countries regarding the use of biological indicators in soil quality assessment:

- In Finland, the estimation of earthworm abundance and biodiversity is incorporated in the arable soil quality assessment tool developed for farmers ("Peltomaan laatutesti").
- In the United Kingdom of Great Britain and Northern Ireland, earthworms have been suggested as an indicator for the England Chemicals Strategy, which seeks to enable society to enjoy the benefits from chemistry in a safe sustainable way. Furthermore, in England, the Long Term Monitoring Network, a small network of 37 National Nature Reserves has been assessed for soil properties, including phospholipid-derived fatty acids (PLFAs), terminal restriction fragment length polymorphism (T-RFLP) and mesofauna, with some of the mesofauna samples being subject to metabarcoding.
- Germany reported that there are as yet, no nationally implemented indicators for evaluating soil biodiversity related to the respective services/threats. However, there are numerous debates about how such indicators could be defined.
- France reported that regarding ecotoxicology and soil pollution, the country is managing polluted sites, the use of organic wastes in agriculture and fertilizers, soil improvers, and pesticides commercial authorization procedures. The genetic diversity has been catalogued in maps, by monitoring and a country atlas. Regarding projects, the AgroEco-Sol has provided transfer of technology and expertise to agricultural development actors in order to develop a soil microbiology analysis chain with indicators. The Agence de l'Environnement et de la Maîtrise de l'Énergie is funding research on the evaluation of impacts of polluted sites on

1 The main objective of the soil biodiversity survey was to present the state of assessments that countries had reported on the level of their current knowledge of soil biodiversity, identifying the main drivers responsible for any negative impact on below-ground biodiversity over the last ten years and provide information on how the soil biodiversity has been monitored.

ecosystems (including soil organisms) and on the development of soil bioindicators to assess polluted sites. France also reported information systems at different levels: within the scientific interest group "Soil" (in French, GIS Sol – groupement d'intérêt scientifique "Sol"), the soil monitoring network (RMQS – réseau de mesure de la qualité des sols) looking at soil microbes at the national level (ECOMIC-RMQS) and global soil biodiversity for Brittany (RMQS-BIODIV).

- The Republic of Moldova has a partially developed assessment system with indicators, criteria, statistical parameters and scales of soil biota.
- The Italian Society for Soil Sciences (SISS) has established a working group on soil biological monitoring through microarthropods (QBS-ar), which has organised three workshops on the topic and is divided into eight subgroups (with approximately 60 participants). It has also established the School of Soil Biodiversity and Bioindication to spread the knowledge on biodiversity of soil and its importance on sustainable soil management.
- The Netherlands reported on the Biological Indicator for Soil Quality within the Netherlands Soil Monitoring Network. However, national monitoring terminated in 2014, with capacity and expertise being reduced or lost. Recently, a more limited set of indicators has been defined and will be further developed for practical application. The ambition is to include organic matter (total and labile), bacterial and fungal biomass, nematode diversity and earthworm number and diversity (Hanegraaf *et al.*, 2019).

The recently established Soil BON will be coordinating the gathering of soil biodiversity data comprehensively and over extended periods of time in a selected number of sites worldwide, using a selected number of taxa and functions (Guerra *et al.*, 2021). An internationally recognised standard protocol will be applied at each site, in order to monitor biodiversity and functions, generating the so-called Essential Biodiversity Variables (EBVs); the key parameters for measuring biodiversity. These will feed into the Group on Earth Observations Biodiversity Observation Network (GEO BON), established in 2005; a global initiative that aims to improve the acquisition, coordination and delivery of biodiversity observations and related services to users including decision-makers and the scientific community.

Theme 2. Soil biodiversity in action

Theme 2 aimed to review the role and the application of soil biodiversity in the field. Experts presented effective and replicable methodologies, techniques, technologies and practices that promote the conservation and sustainable use of soil biodiversity. The overall view was to upscale those sustainable approaches to improve productivity, accelerate biodiversity conservation along with the sustainable use of its resources, as well as guaranteeing the equitable participation in productive landscapes.

Core questions

I. **What are the main drivers of soil biodiversity loss and what are the consequences? How do losses vary across environments? Can loss of soil biodiversity be reversed?**

Biodiversity losses can negatively affect the supply of ecosystem services, such as food and fibres, water quality, biodiversity conservation, nutrient cycling, soil structure formation, among others. There are important regional differences in the relevance and role of threats to soil biodiversity and functioning, depending on various abiotic and human factors. These include climate, the extent of industrialization, the area of different types of native vegetation, and anthropogenic land uses (especially urbanization, agriculture and forestry), as well as the level of protection of soil resources, among others (FAO *et al.*, 2020). According to expert opinion, the main threats to soil biodiversity and function are not the same in the six world regions (FAO *et al.*, 2020): Asia, South West Pacific, Latin America and Caribbean, North America (excluding Mexico), Europe and sub-Saharan Africa. No inputs from specialists were received for Eurasia, North Africa and the Near East. Furthermore, they are not the same in all ten of the world's ecoregions (classified according to WWF: Olson *et al.*, 2001). The ecoregions with the highest number of threats are the deserts and dry shrublands, tropical and subtropical grasslands, and the temperate broadleaf and mixed forests (Table 1).

Invasive species also represent an important threat, particularly in Mediterranean and temperate forests and tundra. Terrestrial invasive species can arise from any level of biological organization ranging from viruses and microbes (bacteria and fungi) to invertebrates, plants, and mammals. Non-native soil invertebrates can have dramatic negative impacts on native plants, the litter layer, microbial communities and soil animals.

The most widespread threats to soil biodiversity worldwide are the loss of SOM and SOC (food for the soil biota), deforestation and agricultural intensification (Table 1), both of which affect SOM stocks.

Agricultural intensification also affects the specific functions soil animals perform:

- Soil tillage causes loss of larger soil fauna and disruption of soil food webs and fungal hyphal networks.
- The misuse or overuse of fertilizers may have a negative impact on soil microbial communities and fauna.
- Large shifts in pH caused by lime application impose stress on native microorganisms, affecting their growth and reducing ecosystem resilience to disturbance.
- Monocultures limit the presence of beneficial bacteria, fungi and insects, contributing to ecosystem degradation and facilitating the spread and expression of soil-borne diseases.

Table 1. Threats to soil biodiversity in global Ecoregions

Ecoregion	Main threats
Tropical and subtropical forest	Deforestation Agricultural intensification
Tropical and subtropical grassland	Deforestation Loss of SOM and SOC Soil compaction and sealing Fire Erosion and landslides
Mediterranean forest, woodland and shrubland	Urbanization Land degradation Fire Invasive species
Montane grassland and shrubland	Agricultural intensification Loss of SOM and SOC
Desert and dry shrubland	Loss of SOM and SOC Salinization and sodification Land degradation Fire Erosion and landslides Climate change
Temperate broadleaf and mixed forest	Deforestation Urbanization Agricultural intensification Loss of SOM and SOC Invasive species
Temperate grassland	Agricultural intensification
Temperate and boreal coniferous forest	Fire Invasive species
Tundra	Loss of SOM and SOC Climate change Invasive species
Boreal Forests/Taiga	Deforestation

The impact of these threats on soil biodiversity has been widely assessed using bioindicator taxa and functions; conversely, bioindicators have also been used to assess recovery of biodiversity and function in soils. However, global and regional syntheses, together with comparisons based on actual data for threats and indicator taxa and/or functions are still needed. Several contributions in the symposium addressed threats and their impacts on soil biodiversity/function, as well as the recovery of biodiversity and function in soils after soil amelioration practices or the adoption of improved management techniques.

For instance, the Soil Biological Quality based on soil arthropods (QBS-ar index) is used to investigate the soil biological quality in the Veneto region of Italy. This served to identify reference values according to different land uses and to highlight soil degradation or pollution (Pocaterra and Ragazzi, 2021). According to a recent report, most studies focusing on arbuscular mycorrhizae (fungal functional groups) found that they would contribute to the optimization of agroecosystems, recovery of highly anthropised areas and conservation of natural ecosystems in Colombia (Landínez-Torres, Solveig and Nicola, 2021).

Sofo and Ricciuti (2021) demonstrated that the adoption of sustainable agronomic practices (S_{mng} system) nearly tripled the abundance of earthworms while the abundance of other soil macrofauna doubled. Hallam (2021) highlighted that boosting earthworm populations would be a worthwhile practice to ensure successful and sustainable land reclamation and soil quality improvement.

Huerta Lwanga *et al.* (2021) observed that glyphosate and its residue AMPA concentrations in soils were higher in soybean fields -remaining in the soil even years after being applied- than in maize and other non-managed areas in Yucatan, Mexico. Both compounds are inversely correlated with the number of morphospecies and abundance of macroinvertebrates.

Niva *et al.* (2021) included Enchytraeidae density and the generic composition in two phytophysiognomies of Cerrado Biome in the monitoring of soil biological quality, soil biodiversity loss and sustainability of production systems.

Christmann (2021) demonstrated that Pollinator-Loss-Syndrome also fuelled the deterioration of soil biodiversity, therefore conservation measures for soil biodiversity and combating erosion would be hampered without pollinators.

The participatory learning action (PLA) not only helped sustain and increase soil biodiversity, but also helped in production diversity, since a farmer's choice of tools and techniques had an enormous influence on the factory of life, as observed by Sharma and Joshi (2021).

The re-carbonisation of Chilean soils using *Pinus radiata* roofs enhanced SOC sequestration that was fixed in ranges of 22 to 44 tonnes / ha, playing a fundamental role in the nutrition and fertility of forest soils while promoting soil biodiversity (Francke-Campaña, 2021).

Houšková, Bušo and Makovníková (2021) assessed good agricultural practices, showing the positive effect that these practices had on soil moisture content, biodiversity and soil structure stability, concluding that these findings could be used for further studies determining other methods of sustainable soil use.

Ortega (2021) focused on developing and testing different diversified cropping systems under low-input practices in order to increase land productivity and crop quality, thus combating the adverse effects of agricultural intensification.

II. How can soil biodiversity support the transformation of agricultural systems toward achieving sustainable intensification?

Today, farmlands dominate 38 percent of the global land surface and the demand for agricultural commodities is projected to increase from 70 to 100 percent by 2050 (Zabel *et al.*, 2020). Agricultural production is driven by economic growth; therefore, pressure on agricultural systems will increase in the next decades. Sustainable intensification (SI) is a term that has increasingly been used to describe the agricultural production systems that will be needed to feed a growing global population whilst ensuring adequate ecosystem service provision (Franks, 2014). This means that agricultural productivity needs to increase, while the provision of ecosystem services -such as the provision of habitats for biodiversity, clean water and air, nutrient cycling and climate change mitigation- are not affected and are even improved.

In 2015, food-system emissions amounted to 18 gigatonnes of CO_2 equivalent per year globally, representing 34 percent of total greenhouse gases (GHG) emissions. The largest contribution (71 percent) came from agriculture and land use/ land-use change activities (Crippa *et al.*, 2021). According to Cassman and Grassini (2020), a 50 percent yield increase on existing farmland in tandem with a 50 percent decrease in negative environmental externalities would provide useful initial targets for establishing national SI research portfolios. The required science must come from a wide array of disciplines including basic and applied sciences that extend well beyond traditional agricultural sciences to embrace computer and computational sciences (including 'big data' analytics), landscape ecology, and molecular biology to name a few.

Studies across different agricultural systems provide compelling evidence that soil biodiversity can directly support agricultural production and environmental integrity. The link between soil biodiversity and the primary soil functions of carbon transformation, nutrient cycling and soil structure required for plant productivity are clear (Figure 1). In achieving our goals of reconciling high food yields associated with high-intensity agriculture with agricultural practices that protect and promote soil biodiversity, the recommendations are also clear. No or minimum till practices that minimize soil physical disturbance are required alongside inter- and multi-cropping systems that provide more diverse food production, enhance plant-soil interactions and prevent soil erosion (compared to fallow). Agricultural systems also benefit from the addition of organic amendments that enhance soil carbon, help retain moisture, and are reservoirs for nutrients, while soil biodiversity can act as biofertilisers when applied as biological inoculants.

III. How can soil biodiversity support the One Health approach?

The health of animals, people, plants, soils and the environment is interconnected. The One Health is an integrated approach that recognizes this fundamental relationship and ensures that specialists in multiple sectors work together to tackle health threats to animals, humans, plants and the environment.

The One Health priorities include:

- The strengthening, monitoring, surveillance and reporting systems at all levels to prevent and detect animal and zoonotic disease emergence and control disease spread.
- Understanding risk factors, including socioeconomic and cultural contexts, for disease spill over from wildlife to domestic animals and humans, in order to prevent and manage disease outbreaks.
- Developing capacities at all levels for better coordination and information-sharing among institutions and stakeholders.
- Reinforcing veterinary and plant health infrastructure, as well as safe food and animal production practices from farm to table.
- Increasing the capacities of the food and agriculture sectors to combat and minimize the risks of antimicrobial resistance (AMR).
- Promoting food safety at national and international levels.

FAO also promotes Sustainable Agri-food systems to transform and reorient agriculture towards climate resilience and sustainability. FAO views biodiversity as the basis of food security and promotes its sustainable use for food security, human well-being and development worldwide. It hosts the Commission on Genetic Resources for Food and Agriculture and the International Treaty on Plant Genetic Resources for Food and Agriculture. Both aim to reach international consensus on policies for the sustainable use and conservation of genetic resources for food and agriculture.

Soil biodiversity has a direct impact on our health by boosting the nutrient content of our food, protecting us from foodborne illness, and modulating our immune response (FAO *et al.*, 2020). The provisioning of safe and nutrient-rich plants and clean water for consumption is directly linked to the quality of the soil system, as well as our ability to produce sustainable agricultural crops, and supports the SDGs 1, 2, 3 and 6 (No Poverty, Zero Hunger, Good Health and Well-Being, and Clean Water and Sanitation). Soil biodiversity also underpins supporting and regulating services like soil formation and the prevention of erosion, climate change mitigation through carbon sequestration and pest management that facilitate Sustainable Cities and Communities where access to clear air and water improves human health. In addition, cultural ecosystem services, such as the provision of a sense-of-place, aesthetic relief or inspiration, as well as enhancing social relationships and security, can all reduce stress and improve human health. Finally, soil holds the potential for combating antimicrobial resistance and fungicide/herbicide/insecticide resistance.

IV. What are the currently successful methodologies, techniques, technologies and practices in place that promote soil biodiversity conservation, sustainable use of its resources and equitable participation in productive landscapes? How can we upscale biodiversity-based solutions and other sustainable approaches?

There are many tools available for the assessment of soil biodiversity that can monitor and therefore promote conservation – the challenge may be to select the best ones for each situation among too many options. Many different tools exist, from expensive, 'deep' sequencing techniques that generate large amounts of data, to simpler, faster, more cost-effective tools such as enzyme assays and visual assessments for microbial biomass and ratios. Biotechnological methods that describe the impacts of agricultural practices on taxonomic and functional diversity of soil organisms are also advancing. Gene markers can also be used for specific functions such as carbon cycling and soil aggregation. Equally, we still need appropriate species-level bioindicators such as nematodes, soil arthropods, and earthworms in order to observe and monitor how well the system is 'operating'. We also need to be using the appropriate methodologies, as well as the appropriate statistical tools for the data, which have become easier through increased collaborations, open access databases and global repositories.

The adoption of agricultural systems based on plant diversification such as agroforestry (Sasmita *et al.*, 2021), associated (or not) with syntropic agriculture (Andrade, Pasini and Rubio-Scarano, 2020) or synecoculture (Funabashi, 2021), mainly by small holder farmers, and crop-livestock integrated systems, shows that biodiversity conservation practices have become increasingly common around the world, including in the tropics. However, studies measuring the conservation/ improvements of soil biodiversity in these agricultural systems are still needed at all levels (microbiota and fauna).

V. What kind of actions should be taken to prevent and control the introduction of non-indigenous plants, animals, microorganisms, genes and diseases that could negatively impact the different components of soil biodiversity?

Soil biodiversity is part of an integrated living system driven by mutualisms and complex food webs, in which humans also participate. A healthy soil is a dynamic system with a diverse and complex assemblage of soil organisms whose interactions determine functional capacity. The integrity of soil biodiversity in all of its many facets, and not only some components of it, must be preserved.

The following preventive activities are key to promoting soil health:

- Promote on-farm use of beneficial soil microorganisms for biological control of pests and diseases and enhancement of plant nutrition.
- Monitor traditional and artisanal methods for sourcing of indigenous microorganisms by smallholder farmers and evaluate efficiency of their use.
- Avoid monocultures and promote crop rotations, green manure, cover cropping, manure and compost application, agrobiodiversity, syntropic agriculture, etc.
- Promote the use of biofertilisers.
- To reduce fertiliser inputs, develop mycotrophic crop varieties that substitute fertiliser supplementation for symbiotic nutrient uptake.
- Reduce tillage to maintain the fine-scale spatial structure necessary for intact hyphal networks to evolve over time through multi-level selection.
- Maintain host plant continuity by planting mycotrophic cover crops or perennial crop varieties.
- Add spatial or temporal diversity through crop rotation, intercropping, or other polyculture practices.

VI. What are the most effective knowledge sharing and capacity building approaches to raise awareness on the better use of soil biodiversity into agricultural practices?

The successful use of scientific knowledge by farmers relies on transforming scientific findings into easy to understand information and readily available tools. Open access to information and global data repositories, alongside accessible education programs are also important components of knowledge sharing, and together may provide new opportunities for employment to people who span boundaries between science and policy, science and education, and science and industry. Citizen science initiatives have also proven successful in transferring scientific research results to stakeholders, such as policy makers, farmers and the general population.

VII. What are the methodologies, techniques, technologies and practices in place to monitor antimicrobial residues in soil and their impact on biodiversity and antimicrobial resistance?

Soil pollution and antimicrobial resistance constitute a serious threat to belowground biodiversity. Its loss or modification negatively impacts above-ground biodiversity and human wellbeing as soil contaminants and antimicrobial resistance bacteria can enter the food-web.

The soil is the recipient of a spectrum of antimicrobial residues and antimicrobial resistance genes and bacteria that we release in the environment. Some soil-dwelling heterotrophic bacteria use antibiotics as a carbon source (Dantas *et al.*, 2008), implying that their activity might decrease the antibiotic residue concentrations in soil environments. The effects of antibiotic resistance genes and bacteria on soil biodiversity have been investigated (Martinez 2009; van Goethem *et al.*, 2018) and several studies have emphasized the importance of antibiotic resistance genes for bacterial ecophysiology at the ecosystem level. In addition to promising discoveries of new antibiotics from highly diverse soil microbial communities, soil biodiversity holds other potentialities for medical practice. For example, the biodiversity of soil viruses offers the promise of bacteriophage therapy for alternative treatment of bacterial infections in humans and plants.

While soil biodiversity is essential to ecosystem functions and services, it remains a largely unexplored area and understanding it is key to providing for our future health, wellbeing and food security as well as that of our planet.

Theme 3. Soil biodiversity shaping the future of food systems

Theme 3 aimed to discuss legislation, policies, international frameworks and financial mechanisms for mainstreaming soil biodiversity across government and society, reducing the direct pressures, promoting sustainable use and improving the status of soil biodiversity through safeguarding ecosystems, genetic diversity and the functions and services provided by them.

Core questions

I. What are the contributions of soil biodiversity to implement policies addressing sustainability challenges including the SDGs?

Soil biodiversity is critical for soil functioning and food production but has been largely ignored in global, regional and national policies including those that address land management, food security, climate change, biodiversity conservation and land degradation. This is very much down to the differences between belowground and aboveground biodiversity, with policies aimed at aboveground biodiversity failing to ensure the protection of soil biodiversity. Therefore, policies and legal frameworks are urgently needed that specifically value and protect soil biodiversity. The management of soil biota provides common ground for achieving the SDGs, and could form the basis for the conservation of many endangered plants and animals. This aspect could and should be considered or highlighted in future biodiversity policies and initiatives.

II. How can we bring soil biodiversity concerns into agricultural sectors and cross-sectoral mainstreaming approaches (such as land tenure, landscape management, ecosystem rehabilitation, food security and nutrition, small holders and family farmers, public health and forestry)?

Particular actions that have proved to be effective for mainstreaming soil biodiversity are the promotion of urban and peri-urban agriculture, demonstration plots and monitoring networks in agricultural areas and participatory work with farmers and relevant stakeholders to define indicators and testing areas in order to formulate policies.

Emerging policies and development of new regulations on soil protection at all levels are an opportunity to introduce soil biodiversity indicators (see item V of Theme I), as long as they are tested and validated.

A widespread adoption of biodiversity-friendly soil management practices (see item V of Theme 2), such as the application of biofertilisers, will only be achievable through standardisation and quality control, in order to minimise the risk of misuse that would lead to negative counteracting effects for the users.

The One Health Approach should always be adopted as the basic frame for any policy development fostering soil biodiversity.

III. What are the economic incentives, subsidies and financial mechanisms that could support soil biodiversity and sustainable production? Can they be realigned, and how?

At present there are few regions that receive financial incentives to support adoption of sustainable soil management including soil biodiversity. Some examples include the provision of partial subsidies for Indian farmers to buy biofertilisers, coupled with state-supported biofertiliser quality control. But a methodology for the economic valuation of soil biodiversity is still missing, despite the enormous complexity of the soil ecosystem and the incomplete or lack of knowledge around many of the ecosystem services it provides.

The development of such mechanisms will be strengthened as long as research on site-specific soil biodiversity indicators advances. They will be more effective when included in the One Health Approach.

From GSOBI21 to mainstreaming soil biodiversity in all sectors: discussion, conclusions and recommendations

Discussion summary

We define soil biodiversity 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. Soil biodiversity is essential for most of the ecosystem services provided by soils, which benefit soil species and its multiple interactions (biotic and abiotic) in the environment. Soil biodiversity also supports most surface life forms through the increasingly well understood links between above and belowground. For humans, the services provided by soil biodiversity have strong social, economic, health and environmental implications (FAO *et al.*, 2020). The important role that soil biodiversity plays in ecosystem functioning and the resulted services can be threatened by unsustainable human activities, climate change as well as human-induced natural disasters.

Despite the clear importance of soil biodiversity in the provision of essential ecosystem services for human well-being, its proper use and management is yet to be fully realised. It is only just over a decade ago that initiatives and research networks were established to contribute to the know-how for the conservation, use and sustainable management of soil biodiversity. These include the establishment of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity in 2002, the establishment of the Global Soil Biodiversity Initiative in 2011 and the Global Soil Partnership in 2012, together with the publications of the Global Soil Biodiversity Atlas in 2016, and the State of Knowledge of Soil Biodiversity in 2020. Since then, soil biodiversity has started to emerge as an alternative solution to global challenges and not only as an academic field. Some countries are starting to use soil biodiversity in different areas such as agriculture, food safety, bioremediation, climate change, pest and disease control and human health. Some regions, like the European Union, have set up action plans for sustainable production, consumption and growth in order to become the first climate-neutral region in the world by 2050; healthy soils and soil biodiversity are important components of the European Green Deal. In addition, some national institutions, research centres, networks, universities and schools are starting to include soil biodiversity in their programmes. Some of them are also conducting research on technological innovations as well as on traditional and agroecological approaches related to soil biodiversity use and conservation (e.g. research, practical application, assessment, indicators and monitoring).

The State of Knowledge of Soil Biodiversity Report (FAO *et al.*, 2020) and other knowledge products developed by initiatives such as the GSBI and Soil BON, highlight that knowledge of soil biodiversity is growing due to recent technological advances and awareness of its value. But despite the substantial progress in current knowledge about the global distribution of soil biodiversity and its functions (Crowther *et al.*, 2019; van den Hoogen *et al.*, 2019), about new taxa, novel technologies, powerful environmental remediation tools, approaches (syntropic farming, synecoculture, etc.), artificial intelligence and molecular tools, only around 1 percent of soil organisms have so far been identified and soil biodiversity loss remains one of the main global threats in many regions of the world (FAO, 2015).

Nature-based solutions offer the best route to achieve human well-being, tackle climate change and protect our living planet. Yet, nature is in crisis. We are losing species at a rate a thousand times greater than at any other time in recorded human history and one million species face extinction (Dasgupta, 2021). We must take advantage of this momentum and the great interest and concern that exists about soil biodiversity loss, to implement sound policies and actions for the conservation, management and sustainable use of soil biodiversity.

Conclusions

The GSOBI21 brought together participants from the organizing institutions, FAO Members, academia, the private sector, civil society and farmers, as well as scientists and land users working on soil biodiversity and related fields. Their common goal was to contribute to the know-how on assessing, measuring, monitoring, and sustainably managing soil biodiversity at all levels. Over 5 000 participants from more than 160 countries attended the GSOBI21, reflecting the great interest in the subject.

Scientists from around the globe were active in presenting the results of studies describing the current state of soil biodiversity, the gaps for its sustainable use and management, and the risks posed to food production, human health, sustaining biodiversity aboveground, climate change mitigation and environmental remediation. They analysed and discussed the limitations and opportunities in promoting the sustainable use of soil biodiversity, and the use of novel technologies in an applied and research way. National, regional and global initiatives/networks presented their actions to support the sustainable management and monitoring of soil biodiversity.

Experts at the symposium recognised that there is convincing scientific evidence that the loss of soil biodiversity and its habitats poses a global threat to food security and food safety, nutrition and human health, biological control of pests and diseases (more than ever during the global pandemic), climate change mitigation/adaptation, nature-based solutions, (re-)emergence of zoonotic diseases and life on earth.

Furthermore, experts at the symposium recognized that there had been notable progress in soil biodiversity in:

- National/regional/global initiatives and networks.
- Greater computing power.
- Machine learning approaches.
- Molecular tools to describe unknown biodiversity (eDNA, PLFAs, tRFLP, etc.).
- Novel technologies (metagenomic, metabolomics, transcriptomic and volatilomic), providing useful information on microbial functions in addition to taxonomic diversity.
- Artificial intelligence for the assembly of data and the aggregation of information from multiple databases.
- Discovery of new taxa.
- New approaches towards reduction of agrochemical inputs and sustainable soil management (syntropic farming, synecoculture, etc.).
- Integral use of organisms such as microbes (bioaugmentation), plants (phytoremediation) and earthworms (vermiremediation) as powerful environmental remediation tools, and
- Overall awareness on the value of ecosystem services provided by soils and soil biodiversity.

However, and despite these advances, soil biodiversity still needs to:

- Be recognized by all the Sustainable Development Agendas including the Global Biodiversity Framework post-2020 (with clear targets and indicators).
- Be strengthened in targeted research and its implementation in all sectors be reinforced.
- Be prioritized in knowledge development actions (most biota remains unknown and un-named).
- Be better monitored (lack of data/information, standard protocols, geographical balance, soil information systems).
- Be better analysed (enhance capacity development in new methods, tools and strength fields like taxonomy), and
- Be sustainably used and managed: incentives or payments for ecosystem services provided by soils should be established; ecosystem restoration should include soil biodiversity/soil health as its basis; bioremediation should be scaled-up to address soil pollution; investment in research on soil-borne diseases and scaling-up of soil biodiversity responses in the agricultural sector and climate change mitigation/adaptation, soil health (including

biological indicators) should be mainstreamed into the One Health Approach, agri-food systems, microbiome, and AMR.

After GSOBI21, the FAO's Global Soil Partnership is committed to facilitate the execution of the implementation Plan of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity and the implementation of this Outcome document "Keep soil alive, protect soil biodiversity". Key activities in the implementation of this Outcome document will be the establishment of the Technical Network on Soil Biodiversity (NETSOB) and its four working areas; the establishment of the Global Soil Biodiversity Observatory (GLOSBO); the establishment of expert working groups to develop guidelines, booklets, field manuals and action plans, to contribute to the know-how on assessing, measuring, monitoring, and sustainably managing soil biodiversity at all levels.

Countries, national focal points, and especially decision-makers are encouraged to use this outcome document and move into implementation of the recommendations at all levels.

Recommendations

Main recommendation: Execute the Implementation Plan of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity and the implementation of this Outcome document "Keep soil alive, protect soil biodiversity"

Under the umbrella of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity (from the CBD), a **Technical Network on Soil Biodiversity (NETSOB)** will be established as part of the GSP technical networks. The main objective of the NETSOB will be to strengthen the data, knowledge, and capacities for supporting the conservation and sustainable use of soil biodiversity. The network will address four main themes: **Theme 1** on measurement, assessment and monitoring of soil biodiversity; **Theme 2** on sustainable use/ management and conservation of soil biodiversity; **Theme 3** on the economics of soil biodiversity; and **Theme 4** on policies and legal instruments related to soil biodiversity.

An open call for experts on soil biodiversity and other interested stakeholders will be made to join the network and its different working groups in relation to the four themes (*i.e.* monitoring, management, economics, and policies).

Theme 1: Measuring, assessing and monitoring soil biodiversity

Recommendation 1: Establishment of the Global Soil Biodiversity Observatory

The main objective of the **Global Soil Biodiversity Observatory (GLOSBO)** will be to strengthen knowledge in all soil biodiversity groups (microbes, micro, meso, macro and megafauna). The GLOSBO areas of work should 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.

Recommendation 2: Development of guidelines for measuring, assessing and monitoring (MAM) soil biodiversity

The main objective of the MAM soil biodiversity guidelines will be to provide the latest knowledge on how to measure, assess and monitor soil biodiversity data/information in a harmonized approach. The guidelines should include *ad hoc* standard field and laboratory protocols for measuring biological activity and biological diversity (including novel technologies), *ad hoc* standard protocols for mapping soil biodiversity at farm and national scale (with an emphasis on hot spots and not studied areas) and *ad hoc* standard protocols to analyse soil biodiversity data/information.

Recommendation 3: Development and implementation of a capacity-building programme on soil biodiversity including national assessments, monitoring, good management practices and restoration

This applies to all UN members in need of such capacity. Priority should be given to countries lacking national information on soil biodiversity and using global datasets with focus on areas where data is missing.

Theme 2: Sustainable use/management and conservation of soil biodiversity

Recommendation 4: Development of a field manual on soil biodiversity management that addresses soil biodiversity loss/conservation

The main objective of the field manual on soil biodiversity management will be to strengthen the knowledge on how to manage/use soil biodiversity in a sustainable way. The field manual will be addressed to farmers and project developers and should contain the best available sustainable soil management (SSM) practices to manage/conserve soil biodiversity, including "science-based case studies". This field manual should be the basis for the capacity-building programme mentioned in recommendation 3.

Recommendation 5: Development of a technical booklet about the main soil-borne diseases

The main objective of the technical booklet will be to identify the main soil-borne diseases and how to prevent and combat them. The technical booklet will be addressed to farmers and project developers and should contain the main soil-borne diseases per region, including case-studies.

Theme 3: Economics of soil biodiversity

Recommendation 6: Development of the methodology for the economic valuation of soil biodiversity

The main objective of the methodology is to provide indicators for the economic valuation of the ecosystem services provided by soil biodiversity. The economic valuation will be addressed to policymakers, project developers, environmental economists and researchers. The methodology should built on the results of a global questionnaire on the state of the art of economic valuations of ecosystem services and economic valuation of the ecosystem services provided by soil biodiversity, and of the negative externalities produced by the agricultural sector.

Theme 4: Policies and legal instruments of soil biodiversity

Recommendation 7: Performance of an assessment of effective policies and legal instruments to control soil biodiversity loss

The main objective of this recommendation will be to assess policies and legal instruments to control soil biodiversity loss at national, regional and global levels and identify best practices to scale up and replicate successful examples. The assessment should initiate with a global stocktaking exercise on the state of the art of policies and legal instruments to control soil biodiversity loss, to analyse major gaps in the development/implementation of policies regarding the control of soil biodiversity loss at global, regional and national levels and to feed the SoiLEX database.

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The Global Soil Partnership (GSP) is a globally recognized mechanism established in 2012. Our mission is to position soils in the Global Agenda through collective action. Our key objectives are to promote Sustainable Soil Management (SSM) and improve soil governance to guarantee healthy and productive soils, and support the provision of essential ecosystem services towards food security and improved nutrition, climate change adaptation and mitigation, and sustainable development.

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