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Soil biodiversity knowledge and use worldwide: Results from a global survey

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Abstract

Soil biodiversity is a major component of global biodiversity, but remains poorly characterized in many locations, and is under threat mainly due to land use change and intensification. Detailed assessments of soil biodiversity and a better knowledge of the ecology and distribution of soil organisms worldwide are needed to address threats to soil function, and potential impacts on ecosystem service delivery. A worldwide expert survey was conducted in March 2022 to identify who is doing what, where and how, as well as the main gaps, pitfalls and opportunities across existing national initiatives and research. The questions addressed microbes, fauna and their activity in soils, community and functional assessments, inventories, mapping and monitoring activities, ecosystem services, applications, threats to soil biodiversity, education and communication activities, and public policies related to soil biodiversity. Over 2,000 responses were received, from >1,350 institutions and 135 countries, mainly from experts in research and academia. Respondents worked mostly with soil microbes, focusing primarily on bacteria (85%) and fungi (79%) and less on Archaea, Algae, soil viruses and lichens. Most applied genomic or molecular techniques, as well as activity and process measurements. Soil fauna was less studied overall, with few respondents active in taxonomy (19-34% depending on the taxon). Fifty countries reported inventories, and 48 had monitoring programs, though most (>65%) covered only microbes and fewer (<50%) addressed fauna taxa. A wide variety of methods were used to assess soil fauna and they were widely used as bioindicators. The survey highlighted the lack of studies on the valuation of multiple ecosystem services provided by soil biota, and the poor knowledge on public policies regarding soils and its biodiversity. We identified a need for harmonized global-scale sampling and measuring protocols that are integrated into conventional soil surveys and soil health assessments, as well as approaches that consider multiple taxonomic groups, to provide key information to support policy agendas aimed at soil conservation and sustainability and to propose a design for a Global Soil Biodiversity Observatory.

Keywords: biodiversity methods, conservation, public policies, ecosystem services, monitoring

1. Introduction

Soils are home to around 59% of the world's species (Anthony et al. 2023), sustaining life on earth and providing critical ecosystem services to human beings (Adhikari & Hartemink 2016). However, less than 1% of the world's soil biodiversity has been identified, casting light on the potential for further discoveries and the challenges in classifying, managing and protecting soil biodiversity (FAO et al. 2020).

Soil biodiversity and its contributions to people are threatened (Lindo et al. this issue), while an estimated one-third of the world's soils are degraded (FAO 2015). Global pressures on soils derived from land use intensification, urbanization, deforestation, pollution, invasive species and climate change (Phillips et al. 2024), associated with natural catastrophes such as droughts, fires, intense storms and flooding, are endangering soils and the biodiversity and ecosystem services they provide.

Recently, and fortunately, soil biodiversity has been receiving increasing attention, from individual farmers to supranational governmental groups (e.g., EU 2023), as the consequences of soil loss, land degradation, pollution and climate change begin to affect human lives across the planet (FAO et al. 2020, Köninger et al. 2022). On World Soil Day (December 5th) in 2020, the Food and Agriculture Organization of the United Nations (FAO) released a global report on the state of knowledge on soil biodiversity, covering current status, challenges and potentialities (FAO et al. 2020). Shortly thereafter, an international symposium with more than 5,000 participants from over 160 countries (FAO 2021a,b) showcased soil biodiversity work being performed worldwide but also called attention to the need for more sustainable use, management and conservation of soil biodiversity and for a Global Soil Biodiversity Observatory (GLOSOB).

In response to these challenges, the Global Soil Partnership Programme (GSP) established an International Network on Soil Biodiversity (NETSOB) in December 2021 to strengthen the data, knowledge, and capacities to support the conservation and sustainable use of soil biodiversity worldwide. NETSOB was also tasked with the design and implementation of GLOSOB to assess soil biodiversity and evaluate the effectiveness of conservation and management practices worldwide so that parties can comply with the goals of the Action Plan of the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity of the Convention on Biological Diversity (CBD) (CBD 2022).

However, to establish a GLOSOB, the variables and indicators that will be assessed and monitored (what) must be defined, as well as the methods to be used (how) by various stakeholders (whom) at particular sites and countries (where). Furthermore, we need to know the legal and policy frameworks at different levels, and the support (financial, infrastructure, trained personnel) available for such an initiative. For this purpose, in March 2022, NETSOB and GSP compiled a list of stakeholders and performed a global survey on soil biodiversity to assess the state of the art of monitoring, assessment, sustainable management and conservation of soil biodiversity worldwide, and lay the groundwork for the establishment of a GLOSOB. Here, we present the main results of this survey, focusing on the current status of work on the topic, the challenges associated with the assessment, management, use and valuation of soil biodiversity, and its conservation and legal protection worldwide.

2. Material and Methods

2.1 Stakeholders and potential recipients

Literature published between 2011 and 2021 using major soil biota taxa and functions was searched to create an up-to-date list of potential correspondents for the global survey (stakeholders). We used the two most extensive databases of academic disciplines, Web of Science (WoS) and Scopus, and a list of 49 main topics (Table S1) to retrieve all publications (articles, books, book chapters, reviews, conference proceedings, notes, letters, editorials, data articles, corrections and patents) related to soil biodiversity from 2011-2021. From the list of publications, the authors' data were extracted, including institution and e-mail, resulting in a list of over sixty-nine thousand e-mails, to which we added ~5,000 addresses of the participants of the FAO soil biodiversity symposium held in April 2021 (FAO 2021a,b). The concatenated list (removing duplicates) included over 70 thousand e-mails.

2.2 Main topics of the survey

The online survey was created using Survey Monkey (v. 11) and was sent out by e-mail with a link to complete the survey. The FAO released the survey on March 10 and respondents were given until March 31 to reply (3 weeks). It included 122 questions divided into 11 main sections (Table 1), though not all questions were obligatory, and the format of the survey allowed for partial completion, depending on the main focus (sections of the survey) of the respondent. Because the survey structure allowed for differential completion depending on the respondents and expertise, and because not all questions were obligatory, the number of overall respondents to each question was highly variable. The answers to each question were saved separately and the total number of respondents quantified. The full survey document is provided in the Supplementary information files.

The first section better identified the respondents, while the following sections of the survey identified the work focus of the respondent: the taxonomic expertise, involvement in various assessments, uses and applications of soil biodiversity in various fora and their knowledge on policies (Table 1). Most of the survey questions addressed the soil fauna (42 questions overall) or different groups of microbes and their activities (27 questions).

Microfauna included nematodes, protozoa, rotifers and tardigrades; mesofauna included invertebrates with body diameter between 100 µm and 2 mm; macrofauna included invertebrates visible to the naked eye (Ruiz et al. 2008), and megafauna included the vertebrates who live in the soil, or that have important impacts on soil properties. Protists were included in the microfauna, mainly for historical reasons rather than taxonomic, since there is still debate in the scientific community as to where they should best be placed (in microbes or microfauna). Many protists in soils are heterotrophic (mainly predators of other microbes), however autotrophic taxa like Algae are also present in soils, and both are important components of the soil foodweb dynamics (Geisen et al. 2018). Birds were included in the megafauna (though they are not often considered part of the soil megafauna; Orgiazzi et al. 2016), because they can be major soil bioturbators in some instances (Voorhies 1975, Smith et al. 2011, Maisey et al. 2018).

2.3 Data availability

All the data, including the number of respondents for each question and the contents of the replies for each of the 122 questions, are provided in the open-access repository Zenodo (Brown et al. 2024). Respondents and their identities, as well as their e-mails and any personal website links, were removed to maintain anonymity. Institutional websites were maintained if they did not identify the respondent(s) directly.

3. Results

3.1 General information on the respondents

The survey had 2,696 respondents, with 672 unwilling to provide e-mails or not agreeing to FAO use of the data

Table 1. A brief description of the topics addressed in the questions of the 11 main sections of the Global Survey on Soil Biodiversity, conducted by the FAO/GSP in March 2022.

Section	No. questions	Brief description of questions
General information	15	Full name, gender, e-mail address, country and region, institution and type, ecoregions of the world working in, main applied aspects and land use types studied, geographic level working at, and which main groups or organisms working with
Microbes & microbial activity	27	Focus group, methods for culture-dependent and independent methods, genomic and molecular taxonomy, fingerprinting, phenotypic or direct identification, microbial activity/processes, microbial respiration and biomass, mycorrhizae, decomposition, sequencing platforms and genetic markers used, purposes of studies, enzymes assessed, availability to support SOP development
Microfauna (including Protists)	9	Substrate studied, extraction methods and references, purpose of studies, main taxa evaluated, taxonomic expertise, availability to support SOP development
Mesofauna	13	Litter or soil focus, direct and indirect extraction methods, primary references/ extractors used, main taxa evaluated, purpose of studies, taxonomic expertise, availability to support SOP development
Macrofauna	13	Same as above (mesofauna)
Megafauna	7	Purpose of studies, references to methods used, main taxa evaluated, taxonomic expertise, availability to support SOP development
Community level & functional assessments of soil biodiversity	4	Main methods and references used, availability to support SOP development
Soil biodiversity inventory, mapping & monitoring activities	11	Kind of assessments, knowledge of national inventories, monitoring programs and datasets, main taxa evaluated, geographic scope of monitoring, involvement in mapping and at which scale
Ecosystem services, applications, and threats to soil biodiversity	11	Which ecosystem services assessed, what indicators used, which economic valuations conducted and what approaches and methods used, what practical applications assessed, what threats evaluated, barriers for further uses identified
Education & communication activities	6	Methods used and references, main target audience
Public policies related to soil biodiversity	6	Knowledge of legal frameworks and public policies at different levels (national and international), types of policies and their main focus, measures to protect soil biodiversity

being gathered. The remaining 2,024 respondents were from over 1,350 institutions, and a total of 135 countries completed at least part of the survey (Figure 1). Most were from Europe and Eurasia (39%), Asia (22%), Latin America and the Caribbean (17%), and USA+ Canada (12%). However, around half of the respondents came from only 12 countries (USA, India, Italy, Brazil, Spain, Canada, Germany, Mexico, France, China, Australia and the United Kingdom, in decreasing order of number of respondents).

The percentage of respondents in each country (proportionate to the number that received the survey), taken as a proxy of overall interest in the survey, was negatively related to its Human Development Index (Figure 2). Hence countries with smaller indices generally had higher motivation to answer the survey, although these countries also had fewer invitations overall, due to the number of specialists identified in these countries with the bibliographic review.

Around half of the overall respondents worked in educational institutions, and 35% in research organizations (Figure S1A). Self-employed individuals were removed from the analysis, as institutions were considered the main stakeholders in the scope of this activity. Civil society organizations and NGOs represented 3% or less of the respondents, likely because the survey prioritized respondents with academic backgrounds (taken from publications) but also because few such organizations are active in soil biodiversity. For instance, a search in the Worldwide NGO Directory with over 54 thousand members (WANGO 2024) using the keyword "soil" returned only 17 entries (13 January 2024), of which around half do not cover soil biodiversity.

In terms of the main topics (survey sections) addressed by the respondents (Table S2, Figure S1C), microbes (65% of respondents) and their activities (73%) were the most evaluated. Functional approaches related to soil biodiversity, such as community level or ecosystem services (52-53%), were also important attributes evaluated by the respondents. Around half worked with educational aspects and communication of soil biodiversity, but a low proportion of respondents (5-28%) actively worked with soil animals (Table S2). Finally, public policies were also little addressed (8%), which was expected as the survey respondents were mostly from academia.

Two-thirds of the respondents worked on issues relating soil biodiversity to agriculture, forestry and pastoral activities (Figure S1B). On the other hand, environmental conservation and awareness tools related to soil biodiversity were less addressed by the respondents (30 and 25%, respectively), showing that an applied production-oriented focus still dominates work on soil biodiversity. This was confirmed by the land uses in which the respondents most studied: these were precisely production systems, including annual and perennial crops, integrated land use and forestry systems (Figure S1D). However, many respondents also said they worked in natural ecosystems (40%) and grasslands (30%). Interestingly, although most of the world's population lives in urban areas, the number of respondents working in these was relatively low (16%).

3.2 Research on soil microbes and microbial-related functions

Most of the work on microbes focused on bacteria (85%) and fungi (79%) and a much smaller proportion on Archaea (25%), Algae (14%), soil viruses and lichens (8% each) (Figure S2A). Just over half (54%) of the respondents said they worked with culture-dependent methods to study microorganisms, mainly evaluated

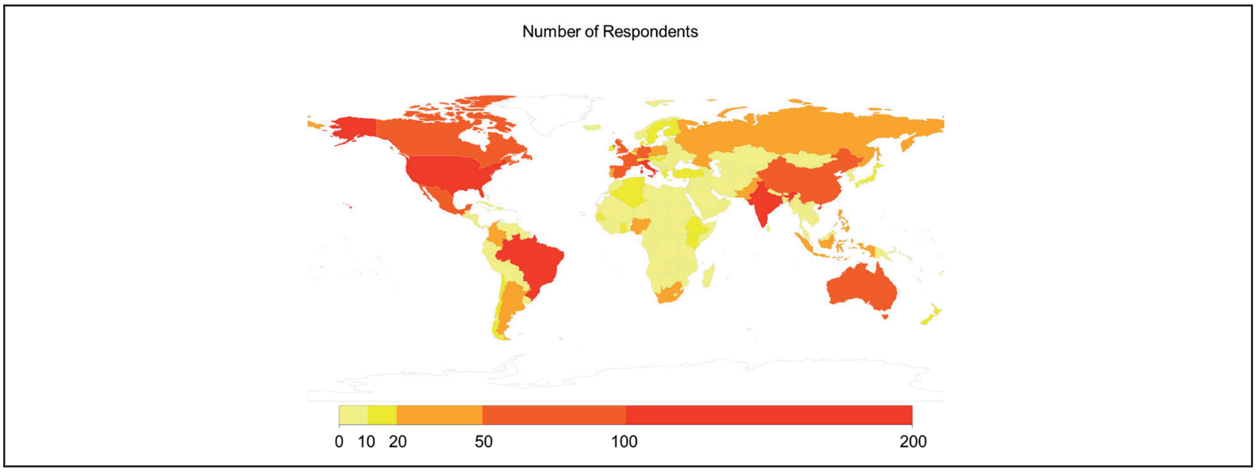

Figure 1. Geographic distribution of the 2,024 survey respondents, classified by the total number of respondents per country.

using genomic or molecular (76%) and phenotypic (67%) methods (Table 2). Culture-independent methods were used by 75% of the respondents, especially to study prokaryotes and fungi (Figure S3). Interestingly, fingerprinting methods (especially DGGE and PLFA) were still widely used by the respondents (Figure S4), probably because these methods (especially PLFA) provide useful complementary information on the studied microbes (Lewe et al. 2021, Willers et al. 2015). Most respondents used the Illumina platform (Table S3) to characterize culture-dependent and culture-independent microbes.

A total of 884 respondents affirmed that they worked with either microbial activity or microbial process measurements (Table S2). Soil respiration (60%), enzymatic activity (58%), mycorrhizal colonization (41%), N mineralization (39%) and decomposition methods (35%) were the most studied (Figure S2B). Around two-thirds of respondents (n=535) chose basal respiration under laboratory conditions, whereas field measurements accounted for half of the answers (Figure S5). Among the enzymes, phosphatases were the most used (68%) by respondents (n=544), followed by beta-glucosidase (54%), urease (42%), cellulases (47%) and proteases (32%). All other enzymes were used by less than one-third of the respondents (Figure S2C).

Most (91%) respondents (n=468) who worked with arbuscular mycorrhizal fungi (AMF) used histochemical staining and light microscopy-based techniques, and only 22% used glomalin quantification techniques in their studies (Figure S6). Regarding process measurements, 35% of the respondents used decomposition (Figure S2B), mainly measured with litterbags (76%), rather than with tea bags or other methods (Figure S7).

A total of 634 respondents said they worked with quantitative determinations of soil microbial biomass (Table S2). Fumigation-incubation (Jenkinson & Powlson 1976), fumigation-extraction (Vance et al. 1987), substrate-induced respiration method (Anderson & Domsch 1978) and fungi ergosterol quantification (Zelles & Alef, 1995) were used, by 33%, 46%, 36% and 18% of the 569 survey respondents, respectively (Figure S8).

A similar proportion of the respondents (n=860 for activity and 606 for biomass) used soil microbial activity and biomass measurements to assess the impacts of land management and land use (76% and 81%, respectively), followed closely by the impacts on soil properties and ecosystem services (75% and 73%, respectively)

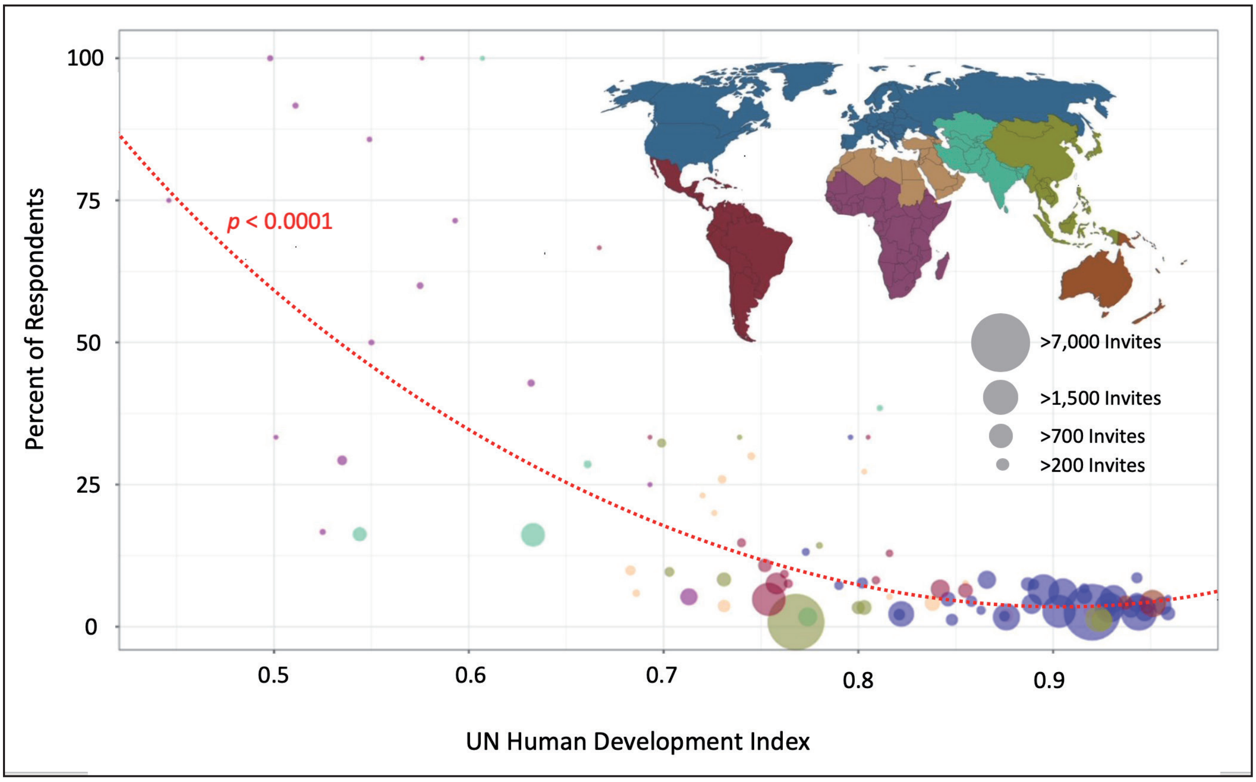

Figure 2. Regional distribution of survey respondents plotted against United Nations Human Development Index. X-axis represents the United Nations (UN) Human Development Index for each nation (colors represent global regions in the UN Sustainable Development Goals framework). Y-axis represents the percentage of respondents to the survey. Marker size indicates the number of individuals invited to participate in the survey for each nation. Dashed line indicates the relationship between variables (JMP Pro 17).

(Table 3). Other important uses of soil microbial activity and biomass measures included surveys (47% and 38%, respectively), as bioindicators (34% and 33%, respectively), and for bioremediation purposes (30%). Other relevant uses, particularly important for production systems, were for nature-based solutions (23%) and pest and disease control (17%-20%).

3.3 Soil microfauna

Only a small proportion (19%) of the total respondents (n=1,883) said they worked with soil microfauna, including protists (Table S2). More than half (55%) worked with free-living, followed by plant-parasitic nematodes (41%), while only 21% worked with protozoa (Figure 3A). Respondents mostly used microfauna to evaluate the impacts of land management and land use (71%), followed by their effects on soil properties and ecosystem services (61%) (Table 3). Other important uses were for taxonomic purposes or biodiversity surveys (49%) or as bioindicators (35%). Around one-third of the respondents (n=314) used molecular techniques to describe and study these organisms, although direct counting or decanting and sieving were equally popular (Table S5), particularly as few molecular libraries can currently assign names to the sequences obtained (Geisen et al. 2018).

3.4 Soil mesofauna

As observed with the soil microfauna, few (22%) of the respondents (n=1,852) said they worked with soil mesofauna (Table S2), which were obtained mainly by hand-sorting (74%) or Berlese or Tullgren-type funnels (82%) (Table S4). The more efficient high-gradient Kempson apparatus was only used by 11% of the respondents, while the simple pit-fall trap (and its derived Provid method; Antoniolli et al. 2006) to

Table 2. Proportion of survey respondents (% of total, with number shown in parentheses) using different methods to characterize culture-dependent and culture-independent microbes. Proportions over 50% are highlighted in bold.

Methods	Culture-dependent (n=687)	Culture-independent (n=933)
Genomics/Metagenomics and molecular taxonomy of cultivated microbes	**76**	49
High-throughput sequencing, Barcoding or Metabarcoding/ Metataxonomics	**59**	**62**
Phenotypic characterization and direct identification	**67**	21
Fingerprinting	45	23
Transcriptomics or Metatranscriptomics	16	11
Metabolomics	18	13
Proteomics or Metaproteomic	8	5
Quantitative PCR	NA	43
Community-level physiological profile	16	NA
MALDI-TOF Mass Spectrometry	9	NA
Microarrays	NA	5
Other	6	5

Table 3. Purposes of evaluating various taxa, groups or functions of soil biota (microbes and fauna), as defined by the survey recipients. The purposes are arranged vertically, considering overall percentages from higher to lower. The numbers in parentheses indicate the number of respondents, and the answers represent the proportion of respondents. Numbers in bold represent proportions greater than 50%. NA=Not Applied

Purpose	Microbes (n=899)	Microbial activity (n=860)	Microbial biomass (n=606)	Microfauna (n=326)	Mesofauna (n=409)	Macrofauna (n=487)	Megafauna (n=91)
Impacts of management practices and land use systems	**72**	**76**	**81**	**71**	**73**	**73**	**70**
Impacts of organisms on soil properties and ecosystem services	**70**	**75**	**73**	**61**	**55**	**58**	48
Taxonomy, biodiversity surveys	**62**	47	38	49	**61**	**55**	43
Bioindicators	32	34	33	35	48	39	NA
Monitoring	24	22	23	28	34	35	43
Bioremediation	28	30	30	13	7	10	NA
Education/awareness raising	19	19	17	24	23	25	31
Pest and disease control	23	20	17	27	11	15	15
Nature-based Solutions	22	23	23	17	11	12	28
Laboratory analysis and assays	19	21	17	15	11	12	12
Biotechnology, pharmaceuticals, food or other industry	21	18	13	6	2	3	4
Risk assessment and ecotoxicology	12	12	12	11	13	13	11
Mapping	9	8	9	9	11	13	26
Human and animal health	8	6	5	8	4	4	14
Economic valuation	4	3	2	4	2	3	11
Other	3	3	1	3	4	3	4

capture mesofauna were more widely used (36%). Most respondents (n=409) studied the impacts of land management practices and land use systems on the soil mesofauna (73%), followed by taxonomy and biodiversity surveys (61%), the impacts of mesofauna on soil properties and ecosystem services (55%), and their use as bioindicators (48%) (Table 3). Most of the respondents (n=400) indicated they worked with springtails (48%), mites (43%), or beetles (31%), while fewer worked with the other mesofauna groups (Figure 3B).

3.5 Soil macrofauna

Just over one-fourth of the respondents (28%) said they worked with soil macrofauna (Table S2), and most of them (68%) extracted the animals from both the litter and the soil, using either direct extraction or a combination of direct and indirect extraction (Table S4). Soil hand-sorting was the most common (91%) direct extraction method used, while Berlese or Tullgren funnel extraction (58%) and pitfalls were the most commonly used indirect methods (Table S4). A relatively higher proportion of respondents (28%) used Winkler extraction than the more efficient Kempson-type extraction apparatus (10%).

Ecosystem engineers were the taxa most studied by the respondents, particularly the beetles (39%), ants (28%), and earthworms (25%) (Figure 3C). The main purposes for studying these animals reflected their potential uses and showed a high proportion of studies related to the impacts of land management practices and land use systems (73%), followed by the effects of macrofauna on soil properties and ecosystem services (58%), taxonomy and biodiversity surveys (55%), and their use as bioindicators (39%) and in monitoring programs (35%) (Table 3).

3.6 Soil megafauna

Very few (5%) of the survey respondents (n=1,826) worked with soil megafauna (Table S2), with the majority (46%) of them (n=81) replying that they worked with rodents, birds (26%) and snakes (21%) (Figure 3D). Their work mostly evaluated impacts of land management practices and land use systems (70%), followed by the effects of vertebrates on soil properties and ecosystem

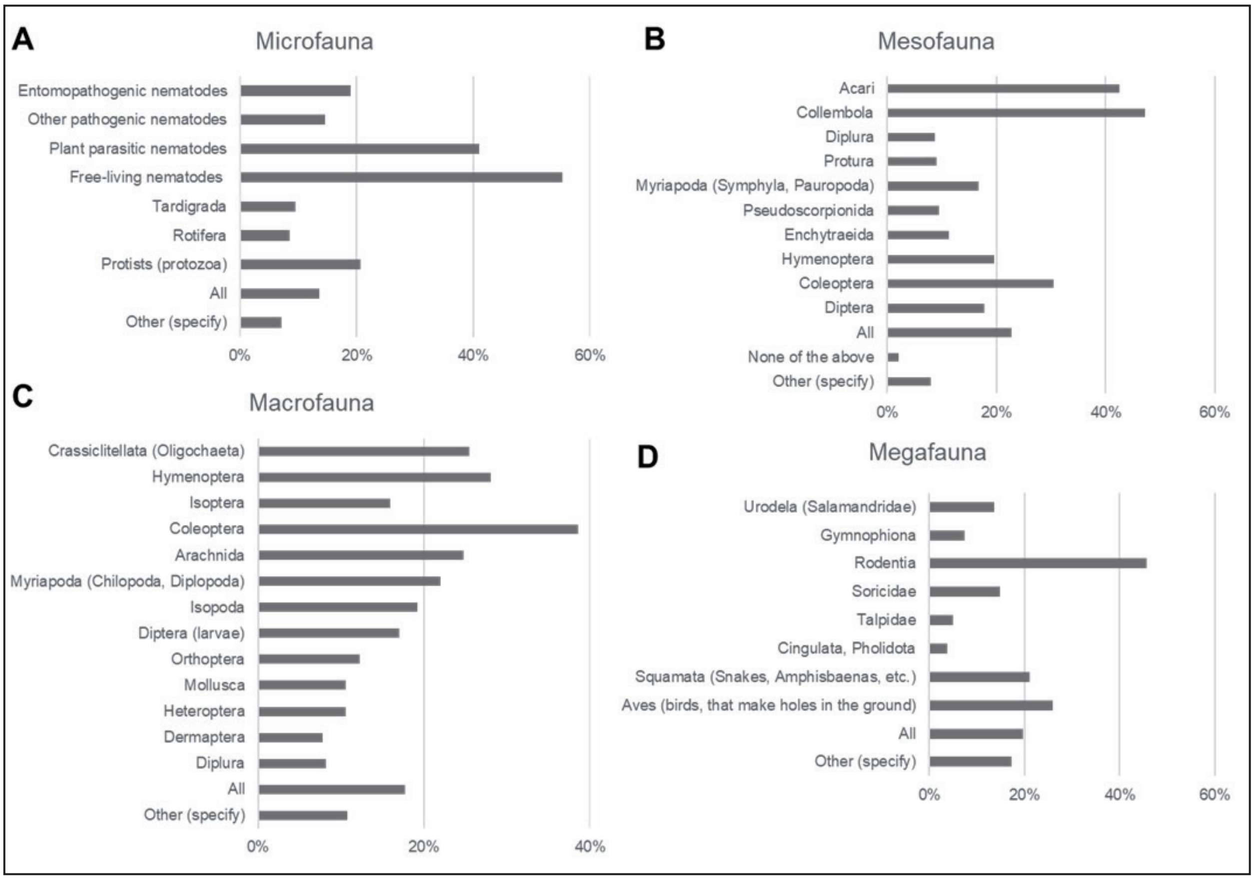

Figure 3. Proportion of the different respondents who worked with various members of the taxa belonging to the soil microfauna (**A**), mesofauna (**B**), and the macrofauna (**C**) and megafauna (**D**). Values represent proportions relative to the total number (variable n) of respondents, with A, n = 295; B, n = 400 respondents; C, n = 464 for mesofauna and D, n = 81 for macrofauna

services (48%), taxonomy and biodiversity surveys (43%), and their use in monitoring programs (43%) (Table 3). Interestingly, 31% of the respondents (n=91) said they worked with educational or awareness-raising activities and 27% with nature-based solutions associated with vertebrates, highlighting the particularly charismatic value of these larger soil animals.

3.7 Community-level and functional assessments

Overall, 53% of the respondents (n=1822) said they worked with community level or functional assessments involving soil organisms (Table S2), highlighting that these more applied approaches are relatively well used by the community involved in soil biodiversity work. Among the measurements most used (51%) by the respondents (n=914) was that of e-DNA (Figure 4). The study of soil organisms‘ impact on decomposition via litter bags, tea bags, or bait lamina was the second most used approach, followed by foodweb and trait-based studies and the use of semi-field models like Terrestrial Model Ecosystems (TMEs; Knacker et al. 2004), micro-, meso- or macrocosms. Conversely, few respondents used ecotoxicological tests for habitat function, feeding activity measurements or bioturbation to assess ecological functions of soil biota.

3.8 Inventories, monitoring and mapping activities

Only 50 (out of 135) countries reported soil biodiversity inventories and 48 reported monitoring programs, with a total of 40 having both activities (Figure 5). Furthermore, only 34% of the respondents (n=379) reported monitoring programs, while only around one-quarter of the respondents (n=694) were aware of national inventories, or involved in mapping exercises in their countries (Figure 6A). In fact, 45% were unaware of soil biodiversity inventories in their countries. Most (78%) of the inventories included microbes, and almost half included various invertebrates (Figure 6B). National (58%) and local-level (43%) monitoring programs were more common, while state or provincial monitoring were less (32%) prevalent (Figure S9).

Two-thirds of the monitoring programs involved microbes, while a smaller proportion of them included invertebrates, and even fewer (15%) addressed soil vertebrates (Figure 6B). Regarding the purpose of the work performed on soil biodiversity, most claimed they were assessing soil microbial or fauna communities. In comparison, only around one-quarter of the respondents were involved in innovations and practices performed by farmers, and even fewer studied endangered species or indigenous and traditional knowledge (Figure 6C).

3.9 Uses and applications of soil biodiversity worldwide

Soil microbes were studied/used by the respondents (n=773) mainly for plant growth promotion (59%), as bioindicators of soil health (58%), and for biological nitrogen fixation (48%) (Figure S10A). From the listed uses, potassium solubilization, monitoring of antimicrobial resistance, and industrial applications were among the least explored, with only 3% of uses not corresponding to what was listed in the survey. Other applications, such as microbes in biological inventories, phosphate solubilization, bioremediation, biological control of pests and disease, and taxonomical studies, varied between 34% and 18%.

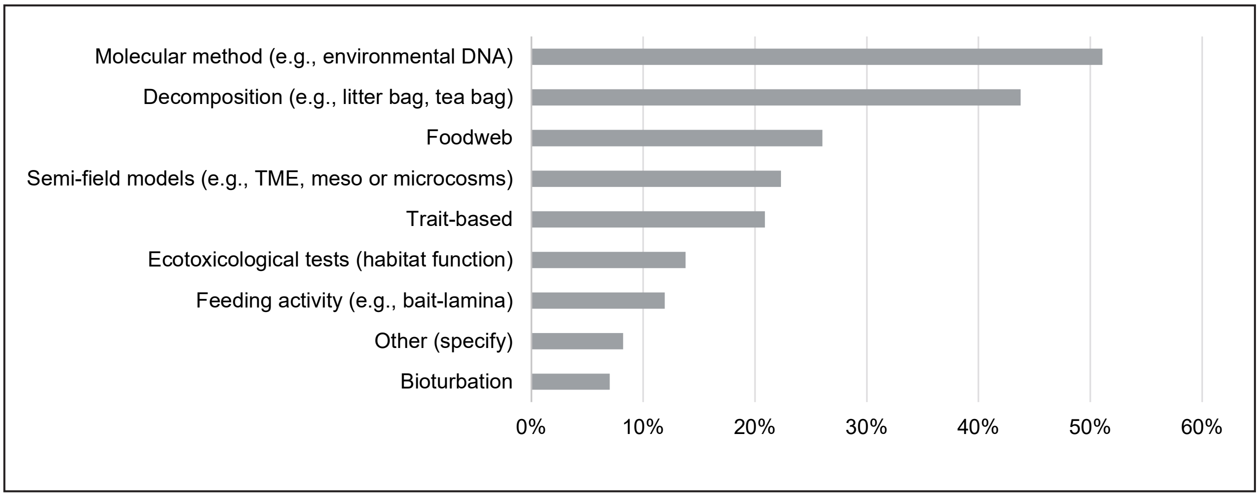

Figure 4. Main methods and approaches used by respondents (n = 914) to evaluate microbial and fauna communities and their functions in soils.

On the other hand, soil fauna was used mainly as bioindicators of soil quality and health (57%), to optimize nutrient cycling (43%), to promote plant growth (40%), and in biodiversity inventories (36%) (Figure S10B). Other less frequent uses were for composting/decomposition of organic materials (30%), assessments and monitoring of soil pollution (28%), inoculation to increase plant productivity or soil restoration (24%), and as biological control agents of pests and diseases (24%).

Respondents identified two main barriers to implementing better soil biodiversity uses/applications in their countries: lack of financial resources (66%) and lack of information and knowledge (63%). Other important barriers were institutional and policy constraints (43%), lack of research (41%), capacity and infrastructure (34-38%), and overly theoretical approaches (26%) related to soil biodiversity.

3.10 Soil biodiversity-related ecosystem services and their valuation

Just over one-half of the respondents said they worked with ecosystem services related to soil biodiversity (Table 2). Of the services listed, most involved nutrient cycling (decomposition, N_2 fixation, mineralization, etc.), while around one-half addressed biodiversity conservation (Figure 7). Climate regulation, soil formation and erosion and flood control were addressed by around one-quarter of respondents, but all other services were evaluated by less than 23% of the respondents, and pollination, seed dispersal, and biotechnological or health-related services were particularly poorly represented.

In terms of the valuation methods, most of the respondents (n=312) chose market-based techniques (56%), with revealed (observed from actual choices made when people face real trade-offs) preferences (38%) and declared (what people say they will choose or prefer when asked) preferences (26%) being less used (Figure S11A). Among those that used revealed preferences methods, most respondents (n=287) mentioned mitigation or restoration (61%) and replacement cost (42%) methods (Figure S11B). Among the respondents (n=223) that chose declared preference (willingness to pay), most (71%) worked with choice experiments, compared with contingent valuation (40%) (Figure S11C).

3.11 Education and communication activities

Around one-half of the respondents said they were active in education and communication activities (Table

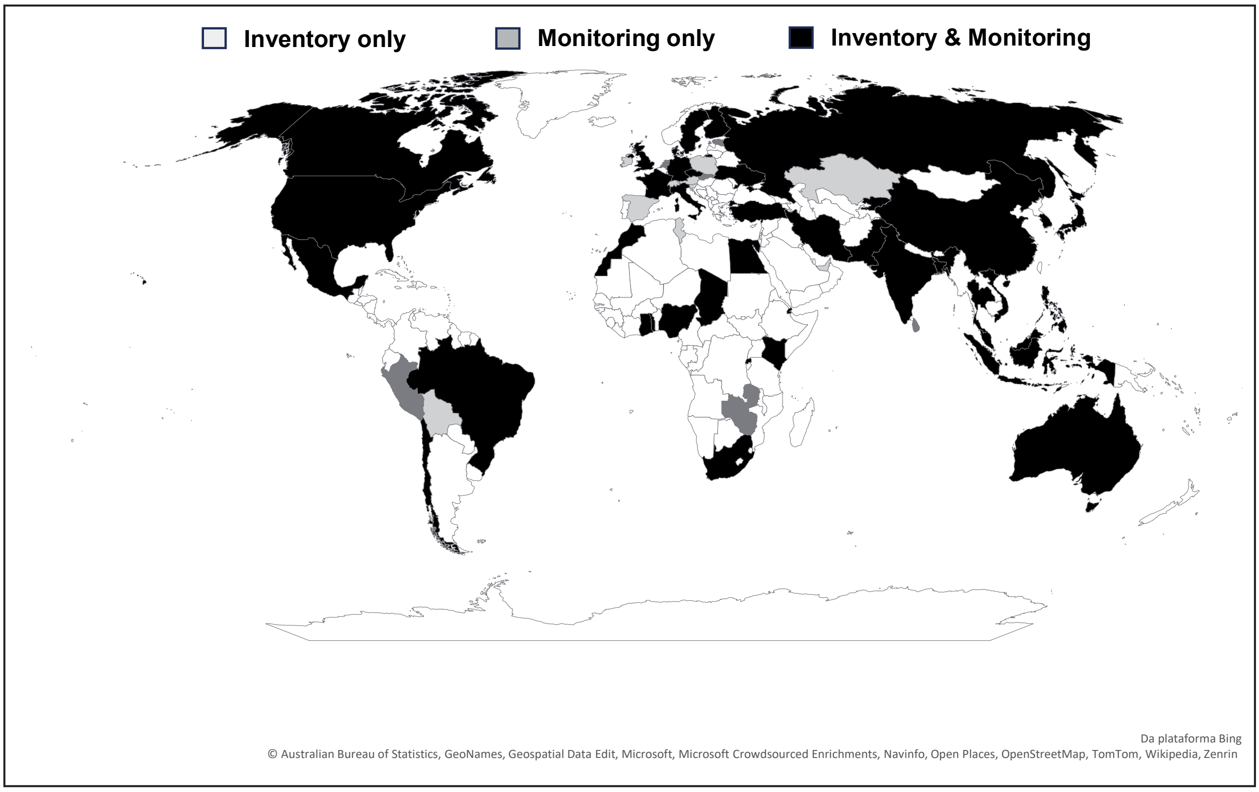

Figure 5. Countries that reported soil biodiversity inventories (light grey) or monitoring (dark grey) programs or both activities (colored in black), including any type of soil taxa (from microbes to megafauna) in the Global Survey. Countries in white did not report any of these two activities.

2). Their main target audiences were university-level students (77%), researchers (44%) and farmers (42%), with a smaller proportion of outputs geared towards basic-level education students and the general population (29% each, respectively; Figure S12). Policymakers (18%) and community organizations (22%) were less of

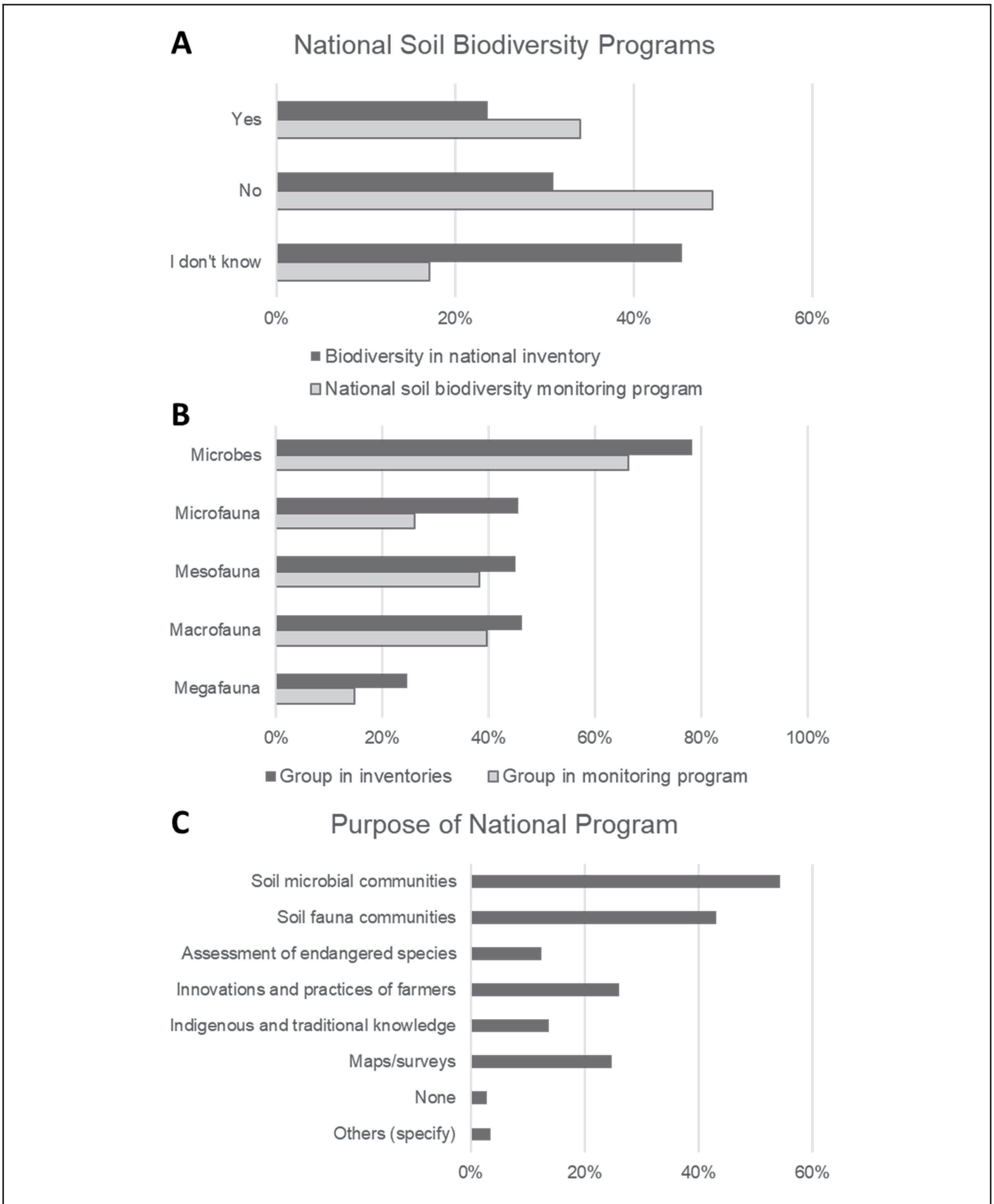

Figure 6. Level of knowledge regarding the existence of soil biodiversity inventories and monitoring in the countries of the respondents of the soil biodiversity survey (A). Taxa involved in the inventories and monitoring programs (B). Purpose of the national soil biodiversity assessments (C). Values represent proportions relative to the total number (variable n) of respondents, with A, n = 694; B, n = 379; C, n = 162.

a target, and indigenous communities were only targeted by a small number of respondents (9%).

3.12 Legal instruments and public policy frameworks

Many respondents (42%) had little knowledge of legal frameworks (laws, norms, protocols) related to the conservation and sustainable management of soil biodiversity in their spheres of action (Figure 8). Furthermore, 19% of them stated that there were no legal frameworks in place for this purpose, while 39% stated there were. Of these, 24 were European countries, 14 were in Africa, 13 were in Asia, 11 were in Latin America and the Caribbean, and only one (Australia) in Oceania.

Two-thirds of the respondents did not know any public policies regarding soil biodiversity in their countries (Figure 8). This was further confirmed by the lack of knowledge of a similar proportion of respondents regarding national/regional and international measures in place to protect soil biodiversity. Unfortunately, less than 13% of the respondents affirmed they knew of legal policies related to biodiversity in place at both the national and international levels.

4. Discussion

4.1 Survey respondents: a globally skewed distribution of knowledge and experts

Survey respondents were from 135 countries, but most were in the Global North, highlighting a previously identified skewed global distribution of work on soil biodiversity (Cameron et al. 2019, Guerra et al. 2020). Differences in infrastructure, including internet access, public policies and career enhancement in topics related to soil biodiversity conservation may contribute to the disparity of replies from each country. For instance, the number of respondents from China was relatively small, considering its large scientific community.

Although the proportion of responses (4%) was low considering the large number of recipients, the 3-week response period still resulted in over 2,000 usable responses. Few respondents had to answer all 122 questions since the survey was designed to direct them only to their particular expertise. Nevertheless, the proportion of experts answering the survey in countries receiving the highest number of invites was low, usually <10% (Figure 2). An important issue to consider in this low proportional response is the pandemic-induced burnout of many professionals working in government, research, teaching and educational institutions (Gewin 2021), the survey's main target(s).

Despite the skewed distribution, we found that the percentage of respondents (relative to the number of invitees) was inversely related with the Human Development Index for the corresponding country (Figure 2), indicating a high motivation of experts in resource-limited countries to answer the survey, where threats to soil biodiversity may be higher (Guerra et al. 2020). Furthermore, the amount of information obtained and the geographic and thematic coverage of the present survey are unique so far, and it represents a precious resource and an excellent source of information regarding who is doing what, where and how related to soil biodiversity worldwide.

4.2 Soil biodiversity and activity assessment: the need for standard approaches and methods

A significant majority (91%) of respondents identified as specialists in various taxonomic levels, with approximately two-thirds engaged in research on soil microbes. The survey results confirmed a trend consolidated during the last decades of relying increasingly on molecular methods to characterize microbial diversity (Delmont et al. 2011, Labouyrie et al. 2023, Yarza et al. 2014). Evidence of this was seen in the use of e-DNA by the highest number of respondents in the assessment of microbial and fauna communities and their functions in soils (Figure 4). Although applied mostly for microbes, this technique has been proven increasingly useful to assess overall (plants, microbes, vertebrates and invertebrates) species diversity in terrestrial and aquatic habitats (Kirse et al. 2021, Nørgaard et al. 2021, van der Heyde et al. 2022) as well as soil health changes (Xing et al. 2024).

The reduction in sequencing costs and the enhanced performance of sequencing machines have made genome sequencing readily available to a wide range scientists worldwide and have revolutionized the study of microbiology (Di Bella et al. 2013, Jo et al. 2020). This widespread use has also been facilitated by the availability of large databases such as the Genbank of the National Center for Biotechnology Information (NCBI), the European Nucleotide Archive (ENA), and the DNA Data Bank of Japan (DDBJ) (Benson et al. 2012, Fukuda et al. 2021, Harrison et al. 2021).

Nevertheless, methods for taxonomic and phenotypic analyses varied substantially, encompassing at least nine different culture-independent techniques for bacterial identification. Furthermore, many different methods were used for microfauna assessment, and although soil enzyme activity methods were not addressed in the survey, nearly 50 internationally recognized methods are available (Nannipieri et al. 2018). This variation hampers our ability to develop unified global models and maps of soil biodiversity. Efforts are underway to standardize measurements of several soil enzymes (arylsulfatase, beta-glucosaminidase, phosphatases and dehydrogenase) for

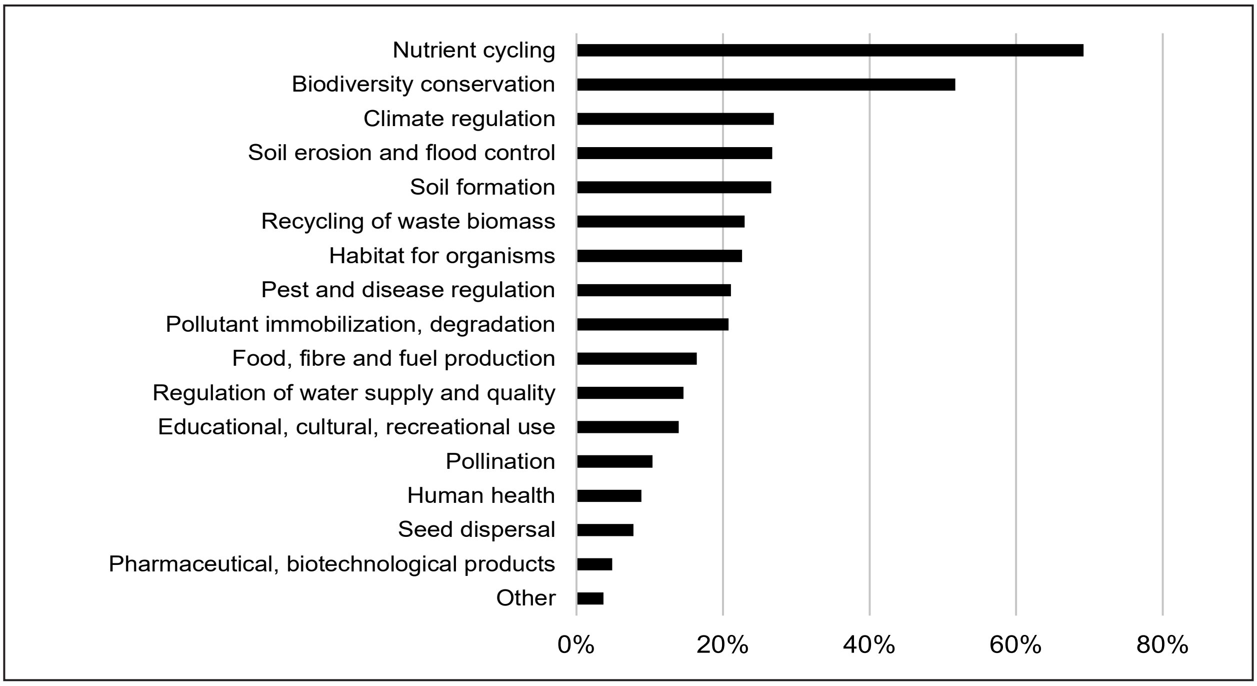

Figure 7. Ecosystem services worked on by the survey respondents. Values represent proportions relative to the total number of respondents, (n = 925).

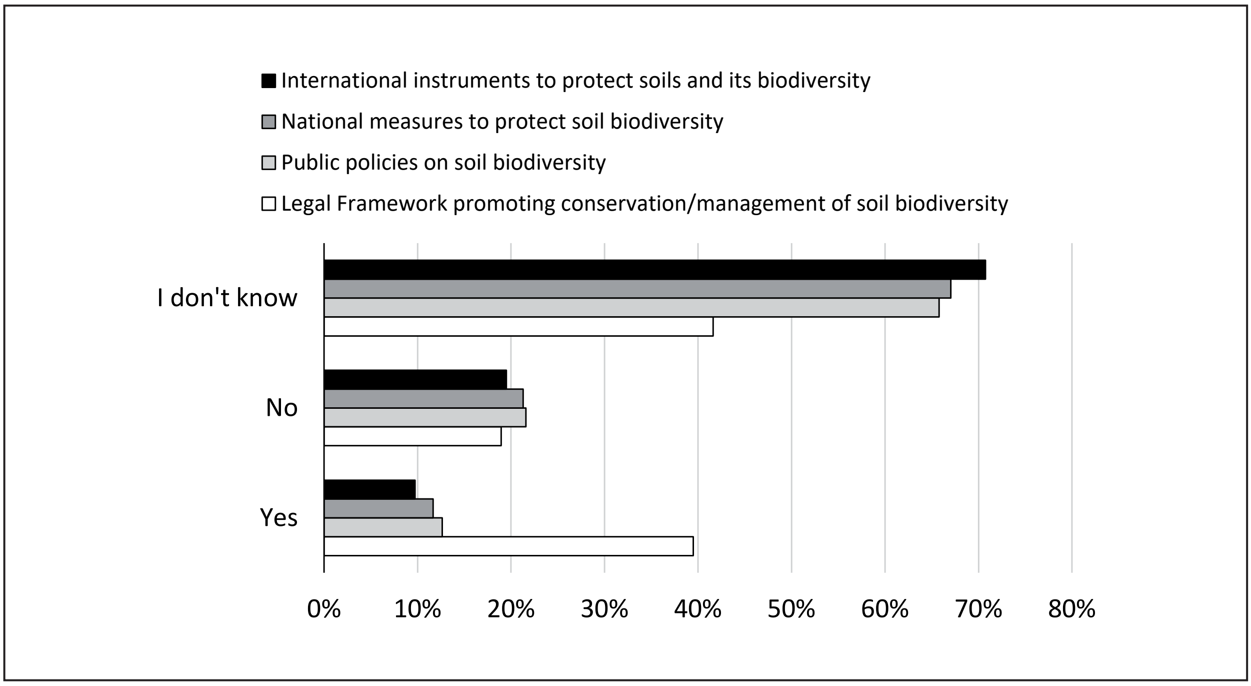

Figure 8. Knowledge by the survey respondents of: legal framework (laws, norms, protocols) at different levels (local, national, regional or global) that promotes the conservation and the sustainable management of soil biodiversity (n = 1738); public policies in-country on soil biodiversity (n = 1724); national measures in place to protect soil biodiversity in-country (n = 1681); and international legal instruments to protect soils that are relevant to soil biodiversity (n = 1676). Values represent proportions relative to the total number (variable n) of respondents.

global soil use by the Global Soil Laboratory Network (Glosolan). Despite limitations (Wade et al. 2018), the same has been already done for soil respiration and microbial biomass (Franzluebbers 2021, FAO 2024), but interpretation guides for global soils and management systems are still lacking. Although standardized approaches for worldwide adoption are available and being applied in global initiatives (e.g., SoilBON, Guerra et al. 2021; Global Soil Laboratory Network – Glosolan of the FAO), national laboratories frequently adopt very different methods, and capacity building is needed in many countries (Benedetti & Caon 2021) to achieve an optimum GLOSOB implementation (Brown et al. this issue).

In terms of the soil meso and macrofauna, heat extractors continue to be the main means of obtaining these organisms from soil samples, and this has not changed considerably since the late 1960's and early 1970's, when Edwards and Fletcher (1971) found that 75% of the soil zoologists who responded to their survey used these methods. The relatively low proportional use of higher-efficiency methods (Edwards 1991) may be due to the higher maintenance costs and difficulty of building high-gradient extractors. Pitfall traps and heat extractors still constitute one of the most easily applicable methods to obtain both meso and macrofauna taxa active on the soil surface (Brown & Mathews 2016, Junod et al. 2023).

To assess functional effects of the soil biota, foodweb approaches (e.g., Brussaard et al. 2007, Potapov et al. 2023) were widely used, followed by controlled studies with confined biotic communities (e.g., Burrows & Edwards 2004, Huhta et al. 1991) and trait-based approaches, promoted by the availability of trait databases (e.g., BETSI; Joimel et al. 2021, Pey et al. 2014). However, even though ecosystem functions are driven by multiple trophic levels of soil organisms (Delgado-Baquerizo et al. 2020; Soliveres et al. 2016), 45% of all respondents studied only microbes, and only one-third examined more than one taxonomic group or level (microbes, microfauna, mesofauna, macrofauna, vertebrates) of soil organismal diversity (Figure S13). Such an approach is critical for a comprehensive understanding of terrestrial biodiversity and its impact on ecosystem services (Geisen et al. 2019; Guerra et al. 2021). Less than 16% of respondents were involved in initiatives including three or more soil organism groups, underscoring a significant gap encompassing research on a wider range of soil biota. Although there were a few concerted efforts in certain areas, these results reveal a pervasive underrepresentation of integrated soil biodiversity research involving multiple taxonomic groups. Minimally, biodiversity and ecosystem function should be examined at three levels, including large and medium-sized organisms and microbes. This ensures inclusion of taxa like macro and mesofauna that regulate the flow of resources across organism levels (Lavelle et al. 2016) and the smaller, more abundant organisms such as microbes and microfauna that drive ecosystem functions (Delgado-Baquerizo et al. 2020).

4.3 Classifying soil biodiversity: the taxonomic deficit

Considering all of the soil fauna groups, a very small proportion of the respondents worked with taxonomy, and this was particularly critical for the megafauna (only 19%) and the microfauna (26%). The low number of experts overall highlights the desperate need for more capacity building and permanent positions for taxonomists, who are increasingly applying integrated methods, including DNA sequencing, to aid in the identification and description of new soil species (Rheindt et al. 2023). As mentioned previously, e-DNA appeared as a widely used tool for identification of soil biodiversity, despite the frequent lack of taxonomic details like species binomials for many of the sequences obtained (Ramírez et al. 2014, Wu et al. 2011).

4.4 Uses of soil biodiversity: reaching wider

The majority of survey respondents assessed the impact of management practices on soil biota, highlighting their essential role in maintaining soil biodiversity and function. Soil biota (microbes and fauna) were also extensively used to evaluate environmental and soil quality worldwide. In fact, many taxa were mentioned and have been widely used as bioindicators, e.g., protozoa (Foisner 1997), nematodes (Bongers & Ferris 1999), springtails (Machado et al. 2019), mites (Behan-Pelletier 1999), earthworms (Paoletti 1999, Römbke et al. 2005, Rutgers et al. 2019), ants (Lobry de Bruyn 1999, Ribas et al. 2012), termites (Duran-Bautista et al. 2020), beetles (Davis et al. 2004, Koivula 2011), millipedes (Paoletti et al. 2007), and isopods (van Gestel et al. 2018).

Microbes are vital to soil fertility and plant production, and their use for plant growth promotion was the main application of these organisms, besides bioindicators (Figure S10). This included inoculation for biological nitrogen fixation, particularly for legume production (e.g., soybeans in Brazil; Telles et al. 2023), and their role as bio-control agents. Microfauna are the most abundant multi-cellular organisms worldwide (van den Hoogen et al. 2019; Geisen et al. 2019), performing a wide range of essential ecosystem services and disservices, acting as economically important pests and pathogens of plants and animals (Geisen et al. 2019, Wall et al 2015).

However, in addition to the fundamental contributions to ecosystem functions and services, the use and applications of microbes and fauna are essential as potential sources of pharmaceutical and biotechnological products (Anderson 2009). Nonetheless, few respondents mentioned their use related to human and animal health, highlighting an important gap for future research and application of soil biota.

4.5 Soil biodiversity conservation and sustainable management: the need for policies and awareness-raising

There are few policies worldwide and within many countries regarding the protection and sustainable use of soil biodiversity (Zeiss et al. 2022), and there was a generalized lack of knowledge on these topics by respondents. Although this may be due to the survey population being predominantly from the academic field, it highlights the need for a better science-policy interface to enhance knowledge exchange between all stakeholders, and mainstreaming of policies that effectively contribute to the conservation and sustainable use of soil biota. Conversely, 42% of respondents said they worked with farmers (Figure S12), where the results of research can have a more direct impact on soil management and conservation practices.

Similarly, few environmental conservation programs target soil biota, except for the few red-listed soil animals, i.e., part of the list of invertebrates considered in some level of danger of extinction (Eisenhauer et al. 2019, Phillips et al. 2017). Furthermore, there are still many blind spots in soil biodiversity research, as confirmed by this survey. Many of these appear to be concentrated in countries that may have very high biodiversity levels (mega-diverse countries) or with important biodiversity hot-spots (Guerra et al. 2020, 2022, Myers et al. 2000). Hence, further efforts are needed to fill these "blind-spots" and increase soil biodiversity knowledge worldwide.

4.6 Valuation of soil biodiversity and ecosystem services: merging ecology and economics

Soil ecosystem services refer to the actions of soil organisms in providing various known ecosystem processes that benefit people (Adhikari & Hartemink 2016, Pascual et al. 2015). The results from the survey showed that there is an important body of knowledge associated with soil ecology, linking ecosystem services and processes of soil biodiversity to the value of natural capital. However, several important and highly valuable services for human societies were little addressed by soil experts. Pollination was one case in point: although around 75% of the solitary bee species make their nests in the ground (Antoine & Forrest 2021), and many of them are important pollinators of crops and forestry species (Freitas et al. 2006, Freitas & Pereira 2004), less than 10% of respondents studied this phenomenon. The role of soil organisms in human health and pharmaceutical or biotechnological products was also poorly addressed, highlighting the need for further attention by soil scientists to these vital research topics (Wall et al. 2015). This may also indicate a disconnect between the genetic and environmental potentials of soil organisms and the conservation and monitoring of soil biodiversity.

Few respondents studied soil formation (26%), or soil erosion and flood control (30%), services that are affected by most bioturbating animals and some microorganisms in soils, and that can be more easily valued using replacement cost methods or proxies to quantify changes in land-use and land cover change (e.g., Plaas et al. 2019, Schon et al. 2020). Furthermore, other services like pest and disease control, food, fiber and fuel production and quality, as well as atmospheric composition and climate regulation services, that can all be relatively easily quantified and valued using market costs or replacement costs were also little studied. The small proportion of respondents studying plant production (16%, Figure 7), contrasts with the high number who said they used microbes (57%) and or soil fauna (39%) for plant productivity enhancement (Figure S10). Some soil animals are active in seed dispersion (e.g., ants, earthworms, vertebrates), and this is another much-neglected field of research, which was addressed by only 8% of the respondents. Finally, important services related to environmental quality and pollution control, such as the recycling of waste biomass and the immobilization/degradation of pollutants and soil reclamation services, which can generally be valued using replacement costs, were addressed by only 22 and 19% of the respondents.

The survey also showed that the capture of the value of soil biodiversity is related to the method used. However, there is still much further work to do in this regard, particularly in applying the valuation methods to existing measurements in the field. This exercise is essential if subsidy efforts like payments for ecosystem services (PES) involving better management and conservation of soils and their biodiversity are to be implemented and to make the value of their ecosystem services explicit to society and policymakers in particular (Richter et al. 2021). But research on the economic valuation of ecosystem services provided by soil biodiversity is still developing and not yet comprehensive (Adhikari & Hartemink 2016, Parron et al. this issue). Preliminary estimates of the value of ecosystem services provided by biodiversity of Earth are on the order of trillions of US dollars annually (Costanza et al. 1997, 2014). However, global estimates of all services associated with soils and its biodiversity are still lacking, with the only preliminary and incomplete estimate (over 1.5 trillion USD $year^{-1}$; Brown et al. 2018) performed many years ago by Pimentel et al. (1997).

4.7 Monitoring and mapping efforts: towards a Global Soil Biodiversity Observatory

Few countries worldwide have good knowledge of the biodiversity of organisms living in their soils, and most of the available inventories (Figure 4) appeared to have targeted only a limited number of taxa (Figure 6). Furthermore, soil biodiversity monitoring programs were implemented in only 48 countries and have focused on only a few taxa (Figure 6), and on soil quality aspects in production systems (Bünemann et al. 2018, Rutgers et al. 2019). Major gaps were evident and involved mostly countries in Africa and the Near East, although several European and Latin American countries also lacked monitoring or inventories.

In late 2021, the European Union launched the EU Soil Strategy to improve soil protection as part of the EU Biodiversity Strategy 2030 (Montanarella & Panagos 2021). As part of this effort, the "Soil Deal for Europe", has provided major funding towards reaching solutions that conserve soil biodiversity, prevent soil degradation and assist in its remediation and restoration (Köninger et al. 2022). Furthermore, the EU Soil Observatory has been streamlining soil monitoring and indicator development within the EU partner countries up to 2030, establishing over 100 "living laboratories" and "lighthouses" (see https://prepsoil.eu/living-labs-and-lighthouses/map), where managers (e.g., farmers), researchers and other partners and institutions are maintaining and significantly improving soil health in a real-life setting (EU 2021, 2023).

Despite current advances in monitoring and inventorying soil biota worldwide, several steps must be taken to guarantee a successful global soil biodiversity observatory. The first step is to map the players (stakeholders) worldwide, identifying the people working on the topic and the sites (countries) where observations are more feasible (see Brown et al. this issue). The next step is to identify the main indicators to be used as biodiversity and function variables, and the main methods that must be used for their assessment in a standardized manner (see Parnell et al. this issue). Through the global survey we identified the main stakeholders involved in assessing, measuring and monitoring soil biodiversity, and the main indicators and methods used to assess biodiversity and the functional roles of soil biota in ecosystems worldwide. Although not all these methods are standardized, and there was considerable variability in the methods used worldwide, several efforts are underway to provide standard, reproducible and simplified assessment and monitoring methods that can be adopted worldwide. One of them is that of SoilBON, for both microbes (Guerra et al. 2021a) and fauna (Potapov et al. 2022). Another effort is currently underway by NETSOB, linked to the FAO's Global Soil Laboratories Network (GLOSOLAN). These efforts are working together to standardize several soil microbial and fauna measurements for worldwide use in a Global Soil Biodiversity Observatory. Standard analysis manuals and training materials have been provided by GLOSOLAN for various chemical and physical measurements (see https://www.fao.org/global-soil-partnership/glosolan-old/repository/standard-operating-procedures/en/), and similar materials are planned for several soil biodiversity-related variables in the near future.

The SoilBON initiative currently involves shipping soil samples from all sites to central hubs for analysis mainly in Europe and North America, a process frequently limited by national and international legislations (e.g., Nagoya Protocol, national biodiversity laws). For a global monitoring scheme to operate more effectively, analyses of soil biodiversity-related variables in local laboratories should be prioritized, and selected variables could be analyzed simultaneously in regional or global laboratories to provide quality assurance. Furthermore, national capacities should be built up with local human and institutional resources for analyses that are not performed locally. This bottom-up approach is also needed to promote country-driven initiatives, projects and, ultimately, legislation regarding sustainable use, management and conservation of soil biodiversity. This will also reduce the risk of concentrating knowledge, data and resources on soil biodiversity from resource-deficient countries in the richer developed or developing countries.

5. Future Perspectives

The survey identified several important gaps which must be addressed to move forward towards a better understanding and sustainable use of soil biodiversity worldwide (Box 1) such as: 1) increased support for soil biodiversity work, including capacity building (taxonomy, genetics, bioinformatics), as well as financial and institutional support for the countries/stakeholders that cannot fund their monitoring activities, or perform the measurements and analyses in-situ; 2) increased multi-taxa assessments in global biodiversity hot-spots and in urban areas using standard methodologies; 3) increased awareness of the role and value of soil organisms and their functions for ecosystem service delivery, including those related to human, plant and animal health; 4) increased policy support and legal frameworks associated with soil biodiversity protection and sustainable management.

Unfortunately, despite its potential contributions to soil ecosystem service delivery and human well-being, soil biodiversity continues to be little considered by policymakers (Montanarella & Panagos 2021). Even the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) has made little effort to support soil biodiversity and its role in its reports (IPBES 2019, Guerra et al. 2021a). Further work on estimating the value of soil-based ecosystem services and the role of soil biota in providing these services is sorely needed, particularly considering that these ecosystem services are under increasing pressure and considerable deterioration because of human activities worldwide (IPBES 2018, FAO 2015, FAO et al. 2020).

Scientists and policymakers must raise awareness of soil biodiversity and related policies to acknowledge the importance of soil biodiversity and its value for society. They must also develop adequate policies supporting soil biodiversity conservation and management both nationally and internationally. Support for these tasks should come from international networks and conventions (e.g., GSP, CBD, etc.), initiatives (SoilBON, Global Soil Biodiversity Initiative), national-level institutions (e.g., Soil Science, Microbiological, or Entomological societies) and government agencies (e.g., Ministries of Environment, Forestry and Agriculture), as well as from bottom-up movements, where scientists, farmers, the civil society, NGOs, farmer cooperatives and corporations can provide the needed pressure and human resources to establish observatories similar to the "living laboratories" and lighthouses of the EU Soil Mission. With these, we expect soil biodiversity to fully emerge from its black box and take its place at the decision table of stakeholders involved in the conservation and sustainable management of terrestrial ecosystems worldwide.

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Box 1. Highlights of the main results and gaps revealed by the global soil biodiversity survey.

Main results of the Global Survey	Main gaps identified
• Few taxonomists of soil animals overall • Lack of research with multiple taxa or groups of organisms • Wide range of assessment methods used for microbes, functions and fauna • Molecular methods widely used, but morphological and activity methods also • Main focus on land use and management impacts and functional roles of soil biota • 50 countries had inventories of some soil biodiversity taxa • 8 countries performed monitoring of some soil biodiversity taxa • Few studies on valuation of soil biodiversity and its ecosystem services • Lack of knowledge of public policies related to soil and its biodiversity	• Standard methods for measuring soil biodiversity needed for global observatory • More integrated studies involving multiple taxa and groups • Increase capacity building in morphological and molecular taxonomy • Support for soil biodiversity assessments and surveys, especially in global hotspots • Foster research on soil biodiversity in urban areas • Include biodiversity measures in conventional soil surveys • Increase awareness of the role and importance of soil biodiversity for ecosystem service delivery • More research on the role of soil biota in human and animal health • Perform monetary valuation of multiple ecosystem services of soil biodiversity • Policy and legal frameworks to protect and restore soil biodiversity at various governance levels

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Author contributions.

GGB, TF, MEF, CCN, ECJ, MILO, LFSA, LMP, MRC, GMC, ICM, RG, DW, IV, JM, NRE and RCC contributed to the conceptual design and contents of the survey. TF and JM prepared the survey online. IV and JM e-mailed the survey to all recipients. GGB wrote the first draft and all authors provided comments and suggestions.

Competing interests

The authors declare no competing interests for this work.

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