Soil Organisms 98 (2) 2026

pp. 203–210
DOI 10.25674/523

WORKSHOP REPORT

Visions for soil biodiversity and health indicators: outcomes from the World Biodiversity Forum 2026

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Received 30 June 2026 | Accepted 30 June 2026 | Published online 13 July 2026

Abstract

Soil biodiversity comprises ~59 % of all species worldwide and plays a fundamental role in maintaining ecosystem functioning, supporting food and water security, regulating climate, and sustaining human well-being. However, despite growing recognition of its importance, biological dimensions of soil health remain insufficiently represented in monitoring frameworks and environmental policy. The session "***Visions for Soil Biodiversity and Health Indicators***", held at the World Biodiversity Forum 2026 in Davos, Switzerland, brought together researchers and practitioners from international monitoring initiatives, national assessment programs, and technological innovation projects to discuss pathways toward robust and policy-relevant soil biodiversity indicators. The session highlighted recent advances in harmonizing soil biodiversity monitoring across scales, including efforts to integrate existing international protocols and establish globally comparable assessment frameworks. Contributions addressed the development of reliable biodiversity metrics, the integration of molecular and morphological approaches, and the challenges of translating complex ecological data into indicators suitable for environmental governance. Integrating well-established and emerging technologies, such as environmental DNA metabarcoding, artificial intelligence-based image recognition, automated sensor networks, and soil food-web analyses were presented as promising tools for improving the efficiency, scalability, and ecological relevance of soil monitoring. Several studies further demonstrated how soil biodiversity indicators can reveal responses to anthropogenic pressures, including land-use intensification and pesticide contamination, and contribute to the evaluation of soil restoration efforts.

SENCKENBERG
NATURE RESEARCH

ISSN 1864-6417 · eISSN 2509-9523
www.soil-organisms.org

Collectively, the presentations emphasized that future soil health assessments will require integrated approaches combining taxonomic, functional, and process-based indicators. The session underscored the importance of international collaboration, methodological standardization, and interdisciplinary research to support emerging soil monitoring legislation and global biodiversity targets. Advancing scientifically robust soil biodiversity indicators will be essential for safeguarding soil health and the ecosystem services upon which human societies depend.

Keywords Belowground biodiversity | Bioindicator | Ecosystem function | Monitoring | Soil health

Introduction

Soils underpin terrestrial biodiversity, food production, climate regulation, water quality, and numerous other ecosystem services that are essential for human well-being (Eisenhauer et al. 2026). Despite their central role in sustaining ecosystems and societies, comprehensive and policy-relevant assessments of soil health remain underdeveloped, particularly regarding biological dimensions (Maharjan et al. 2020; Guerra et al. 2021; Meersmans et al. 2024). While physical and chemical soil properties are routinely monitored in many national and international programs, indicators capturing the diversity, functioning, and resilience of soil biota are still fragmented across regions, disciplines, and monitoring frameworks (Guerra et al. 2021a, 2022). This is an important gap, as highlighted by multiple recent publications (**Box 1**).

Against this backdrop, the session "***Visions for Soil Biodiversity and Health Indicators***" was convened at

Box 1. The proposed European Soil Monitoring Law – recent calls in the scientific literature.

Recent literature broadly supports the proposed European Soil Monitoring Law as a landmark step towards addressing the long-standing gap in EU soil protection policy. Common themes include that widespread soil degradation in Europe, combined with fragmented monitoring systems and the historical absence of a dedicated soil legal framework, necessitates a harmonized approach to soil assessment, management, and restoration (Ginzky 2024; Mason et al. 2025; Panagos et al. 2024, 2025; Ginzly & Pieper, 2026). Panagos et al. (2025) emphasize that healthy soils are fundamental to European competitiveness and resilience, highlighting their importance for food security, biodiversity conservation, climate-change mitigation and adaptation, water regulation, ecosystem services, and ecosystem resilience (Hedde et al. 2026).

From a governance perspective, Ginzky (2024) argues that the proposed legislation has the potential to become an effective instrument for terrestrial ecosystem protection, but cautions that its success will depend on scientifically robust soil-health indicators, clearly defined thresholds, and mechanisms that translate monitoring results into management and regulatory action. Similarly, Mason et al. (2025) conclude that many Member States already possess substantial soil-monitoring infrastructure, but differences in sampling strategies, indicator selection, analytical methods, and reporting will require considerable harmonization to achieve comparable and interoperable datasets across Europe.

Recent discussion has increasingly focused on the implementation of the proposed legislation rather than its overall rationale. Two recent papers highlight the need to translate the broad concept of soil health into scientifically defensible, operationally feasible indicators that can be consistently applied across diverse European soils (Panagos et al. 2025; Zwaan et al. 2026). Both emphasize that biological indicators should become a core component of future monitoring schemes, because soil biodiversity and ecosystem functioning underpin many of the ecosystem services the legislation seeks to protect. At the same time, they recognize important scientific challenges, including defining ecological reference conditions and thresholds, integrating biological with physical and chemical indicators, accounting for regional variability, and balancing scientific rigor with practical implementation.

Taken together, these recent publications suggest broad scientific support for the European Soil Monitoring Law while emphasizing that its long-term effectiveness will depend on successfully aligning scientific definitions, indicator development, monitoring methodologies, governance mechanisms, and implementation capacities across Member States. They also reinforce the emerging consensus that integrated assessments combining physical, chemical, and biological indicators—including measures of soil biodiversity and ecosystem functioning—will be essential for operationalizing soil health within future European monitoring frameworks.

the Fourth World Biodiversity Forum (WBF2026) in Davos, Switzerland (**Figure 1A, B**). The Forum, held under the theme "***Leading Transformation Together***" brought together scientists, practitioners, policymakers, and societal stakeholders to advance solutions for halting biodiversity loss and implementing global biodiversity commitments (**Figure 1C**). Within this broader context, our session provided a platform for discussing how soil biodiversity (see FAO definition in **Box 2**) can be systematically incorporated into soil health (see FAO definition in **Box 2**) assessments and environmental decision-making (**Figure 1D**). Moreover, the session built on a long history of soil-centered sessions at the WBF, stressing the intrinsic value of soil biodiversity (WBF2020; Phillips et al. 2020), highlighting the frontiers in soil ecological research (WBF2022; Eisenhauer et al. 2022), and summarizing the existing knowledge and outlining pressing research questions with regards to the functional significance of soil biodiversity (WBF2024; Eisenhauer et al. 2026).

Box 2. Definitions of soil biodiversity and soil health.

Soil biodiversity. The Food and Agriculture Organization (FAO) defines 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" (FAO, GSBI, 2020)

Soil Health. „Soil health is the capacity of soil to function as a living system, with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production" (FAO, 2008).

Harmonizing soil biodiversity monitoring across scales

A recurring theme throughout the session was the urgent need for harmonized monitoring approaches. Global biodiversity and soil-health initiatives increasingly recognize that biological indicators must become a central component of soil assessment frameworks. However, differences among existing protocols, standards, and analytical approaches continue to hinder comparability among datasets and regions (Guerra et al. 2021b).

One contribution outlined ongoing efforts to integrate existing international monitoring frameworks into a coherent global system. Existing initiatives already cover a broad spectrum of soil biological variables, including microorganisms, soil fauna, ecosystem processes, and functional traits. Nevertheless, methodological inconsistencies and uneven accessibility of protocols currently limit interoperability. A proposed ***tiered framework*** would provide globally accessible baseline methods while accommodating more advanced approaches in regions with greater analytical capacity (Parnell et al. 2025). Such ***harmonization*** could facilitate integration of soil biodiversity data into international observation systems and biodiversity-policy processes.

The importance of comparability was also emphasized by presentations examining transnational monitoring networks and European biodiversity initiatives. Pilot studies conducted across multiple countries demonstrated how ***standardized sampling designs*** can generate comparable information on soil organisms ranging from microbes to macrofauna. Even if no single protocol fits every soil, we need to use a shortlist of cross-calibrated and openly available protocols to adequately assess soil biodiversity across environmental contexts. At the same time, speakers highlighted the need to translate complex biodiversity data into indicators that are meaningful for stakeholders and decision-makers. ***Essential Biodiversity Variables*** (Guerra et al. 2021a, 2021b; Lumbierres et al. 2025) and related metrics were presented as promising tools for bridging this gap.

Developing reliable soil biodiversity indicators

Several contributions addressed a fundamental challenge in sensitive and target-specific indicator development: ensuring that measurements are ***reliable, reproducible, and ecologically meaningful***. Recent technological advances, particularly in molecular ecology, have revolutionized our ability to characterize soil communities. However, translating these data into robust indicators remains a major scientific task.

Comparative analyses from multiple European projects revealed substantial differences between biodiversity estimates obtained through traditional morphological identification and those derived from environmental (e)DNA-based methods. Molecular approaches often detect greater taxonomic richness, can capture otherwise overlooked components of soil biodiversity, or capture

DNA remains of past soil biota that had disappeared (years ago). Yet ***discrepancies between methods*** raise questions about interpretation and the comparability of resulting indicators. Presenters argued that future monitoring programs will require systematic cross-validation, standardized workflows, and integrated data platforms combining biological, environmental, and land-use information. We need to avoid making fast conclusions based on molecular, especially eDNA-based, methods without collecting robust evidence on how their results can be interpreted in relation to biodiversity status and change.

The challenge extends beyond measuring biodiversity itself. Indicators intended to inform policy must be capable of distinguishing between different states of soil condition and assess the effectiveness of supporting measures. Experiences from large-scale German monitoring efforts illustrated how extensive biodiversity surveys can establish reference conditions across habitats and land-use gradients. Such datasets provide a foundation for ***defining biological benchmarks*** and evaluating whether soils can be classified as healthy or degraded and in need of restoration.

Emerging technologies for soil monitoring

Technological innovation emerged as another major focus of the session. Several speakers demonstrated how novel tools can overcome longstanding limitations in soil biodiversity assessment.

Studies conducted across Switzerland showcased the potential of environmental DNA metabarcoding and artificial-intelligence-based image analysis for large-scale monitoring of soil fauna. By ***combining molecular detection techniques with automated species recognition***, researchers are beginning to generate biodiversity information at unprecedented spatial scales. These approaches offer opportunities to accelerate data acquisition, reduce dependence on scarce taxonomic expertise, and improve the scalability of monitoring programs.

At the same time, presenters emphasized that technological advances should be accompanied by careful evaluation of uncertainty, reference databases, and methodological limitations. ***Integrating multiple approaches*** rather than relying on a single technique

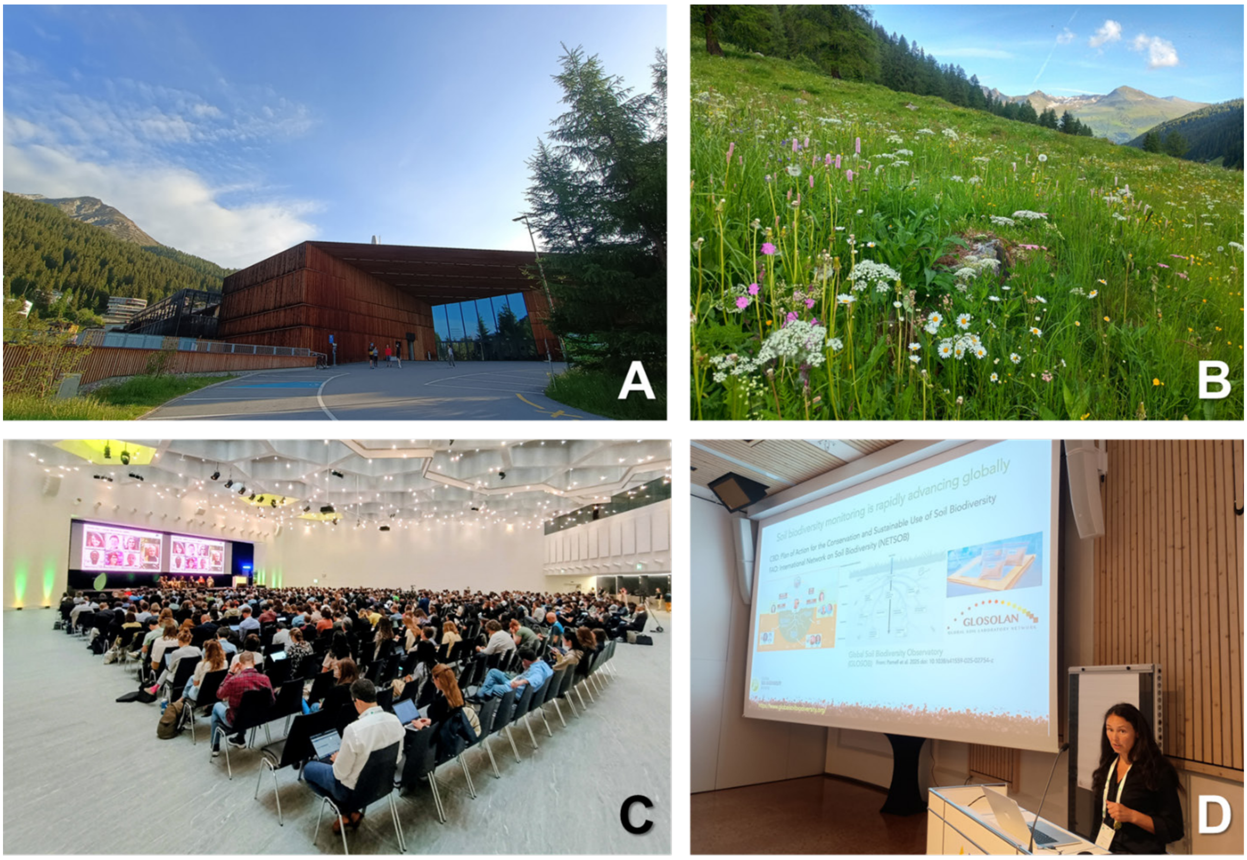

Figure 1. Impressions from the World Biodiversity Forum 2026 in Davos, Switzerland (June 14-19). The venue of the conference (**A**) in the beautiful mountainous landscape of Davos (**B**). Opening plenary discussion of the conference with >1,100 participants from >70 countries as well as different disciplines and sectors (**C**). Opening talk of the session on Soil Health by Zoë Lindo, Western University, Ontario, Canada (**D**). Photos: Nico Eisenhauer.

may ultimately provide the most reliable basis for biodiversity assessment.

Beyond biodiversity monitoring itself, new sensor technologies are also transforming our ability to characterize soil processes. One contribution introduced a ***wireless monitoring network*** capable of continuously recording soil moisture, temperature, pH, conductivity, and carbon dioxide dynamics in restoration landscapes. Continuous measurements provide valuable insights into temporal dynamics that are often missed by conventional sampling campaigns and can support adaptive management in conservation and restoration projects.

Soil biodiversity responses to environmental pressures

Several presentations explored how soil biodiversity responds to anthropogenic pressures and environmental change. A particularly striking example concerned the widespread occurrence of ***pesticide residues in soils*** across agricultural and non-agricultural landscapes. Analyses spanning Switzerland (Riedo et al. 2021; Barmettler et al. 2025; 2026), Europe (Königer et al. 2026), and multiple continents demonstrated that pesticide contamination is not restricted to intensively managed agricultural systems. Residues were frequently detected in natural habitats as well. Across large datasets, pesticide occurrence emerged as an important factor shaping soil biological communities, influencing both biodiversity patterns and ecosystem functions. Evidence indicates that pesticide exposure can alter nutrient cycling processes and reduce the abundance of beneficial organisms, while simultaneously favoring taxa capable of degrading chemical compounds. These findings highlight the importance of ***incorporating information on chemical pressures into future soil-health assessments***.

More broadly, the presentations illustrated how soil biodiversity indicators can help identify environmental stressors and provide ***early warning signals*** of ecosystem degradation. Such indicators are increasingly relevant as policymakers seek reliable tools for monitoring progress toward biodiversity and sustainability targets.

Functional perspectives: soil food webs as indicators of soil health

Beyond taxonomic diversity, several discussions focused on ecological functioning as a central component of soil health. Soil food webs integrate interactions among microorganisms, invertebrates, plants, and organic matter, thereby linking biodiversity directly to ecosystem biogeochemistry (Lejoly et al. 2026).

Recent research employing ***energy-flux approaches*** (Barnes et al. 2018) has begun to reveal consistent patterns in soil food-web organization across climatic regions and land-use systems (Romera et al. 2025, Potapov et al. 2026; Barnes et al. 2026). Comparative studies presented during the session demonstrated that environmental gradients and land management strongly influence how energy flows through soil communities. Climate and ecosystem development have predictable effects not only on the overall energy flux, but also on the turnover rate and ***trophic pathways*** such as green-to-brown balance and thus functional relationships within food webs. Interestingly, different agricultural practices have divergent effects on energy fluxes, implying that land-use choices directly control the engine of soil health – namely, soil food webs.

These findings suggest that further systematic studies on soil food-web structure and functioning across environmental gradients and land-use practices may provide particularly informative indicators of soil condition. By capturing ecosystem processes rather than solely species numbers, functional indicators could help establish mechanistic links between biodiversity and soil health. Emerging technologies, including automated image-based analyses, may soon make such assessments feasible at larger scales.

Conclusions and outlook

The session clearly demonstrated that soil biodiversity is moving from the margins toward the center of soil-health assessment. Advances in molecular ecology, artificial intelligence, sensor technology, and ecological theory are generating unprecedented opportunities to monitor soil life and its functions. At the same time, the discussions highlighted the need for harmonized methodologies, robust reference systems, and internationally coordinated monitoring frameworks.

A central conclusion emerging from the session was that ***no single indicator*** will adequately capture the complexity of soil health. Instead, future frameworks will likely require ***combinations of taxonomic, functional, and process-based metrics*** that can be applied consistently across regions and scales. Such integrated approaches will be essential for supporting biodiversity conservation, sustainable land management, and implementation of international policy commitments (Zwaan et al. 2026) (**Box 3**).

Box 3. Solutions & recommendations for improving soil health and soil biodiversity when the political window opens. What is the package that soil ecologists propose based on an open panel discussion?

Monitoring

- ■ Establish long-term, harmonized, and open-access soil biodiversity and soil health monitoring programmes.
- ■ Adopt standardized sampling, laboratory, analytical, and bioinformatics workflows while accounting for observation efficiency and enabling transfer functions among methods appropriate for different soils.
- ■ Implement tiered monitoring approaches that combine globally accessible baseline methods with more advanced approaches (e.g. combinations of widespread DNA metabarcoding, AI-assisted image analysis, and soil food-web analyses) where analytical capacity permits.
- ■ Combine morphological, molecular, abundance-, biomass-, trait-, and process-based indicators rather than relying on a single method.
- ■ Include key environmental pressures (e.g. chemical residues, land use, climate, soil physicochemical properties) in monitoring schemes.
- ■ Develop and maintain high-quality taxonomic reference collections, DNA and image reference databases, and curated bioinformatics resources.
- ■ Invest in capacity building, taxonomic expertise, and training to ensure long-term monitoring capability.

Assessment and interpretation

- ■ Define scientifically robust reference conditions (baselines) for major soil types, ecosystems, and land-use categories.
- ■ Develop ecologically meaningful thresholds and trigger points that distinguish healthy from degraded soils and guide management interventions.
- ■ Integrate physical, chemical, and biological indicators into composite soil-health assessments while retaining the possibility to interpret individual indicators.
- ■ Evaluate temporal trajectories („change over time“) in addition to static indicator values.
- ■ Consider taxonomic, functional, and food-web indicators to strengthen mechanistic links between biodiversity and ecosystem functioning.

Management and implementation

- ■ Improve soil literacy and awareness in society via multiple pathways including science-art integrations and transdisciplinary events.
- ■ Develop evidence-based best-practice handbooks that explain both recommended management actions and their ecological mechanisms.
- ■ Promote management practices that maintain or enhance soil organic matter and biodiversity, including diversified crop rotations, continuous soil cover, organic amendments, extensive grasslands, and deadwood retention where appropriate.
- ■ Reduce reliance on synthetic pesticides through integrated pest management, biological control, disease-resistant crop varieties, mechanical weed control, and robotic technologies.
- ■ Encourage consumer demand for sustainably produced food to stimulate biodiversity-friendly agricultural practices.
- ■ Recognize the economic value of healthy soils by incorporating the costs of soil degradation and the benefits of preventive management into decision-making.

As countries move toward new soil-monitoring legislation and biodiversity targets, the development of scientifically robust and operationally feasible soil biodiversity indicators becomes increasingly urgent. When the political window opens, we need to be ready to deliver an actionable plan (Box 3). The contributions presented at WBF2026 demonstrated that the scientific community is making substantial progress toward such a plan (**Box 3**), but continued collaboration among monitoring initiatives, researchers, policymakers, and stakeholders will be crucial for transforming scientific knowledge into effective tools for safeguarding the living foundation of terrestrial ecosystems.

Acknowledgments

We sincerely thank all speakers and participants of the session *“**Visions for Soil Biodiversity and Health Indicators**”* at the World Biodiversity Forum 2026 in Davos for their valuable contributions and stimulating discussions. We are particularly grateful to Zoë Lindo, Marcel van der Heijden and colleagues, Sylvain Lanz and colleagues, Silvia Pieper and colleagues, Julia Seeber and colleagues, Christopher Akiba Wang, and Jacinta Plucinski for sharing their research and perspectives. Their contributions highlighted both the scientific advances and practical challenges associated with developing robust, scalable, and policy-relevant indicators of soil biodiversity and soil health.

We further thank the organizers of the World Biodiversity Forum 2026 for providing an inspiring environment that fostered dialogue across disciplines and sectors. The Forum offered an important opportunity to strengthen collaborations among researchers, practitioners, and decision-makers working toward the conservation and sustainable management of soils as a foundation of biodiversity and ecosystem functioning.

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