POLICY FORUM

Collembola, such as this *Acanthanura sp.* in North Queensland, Australia, can be useful indicators of soil quality and also the focus of nature conservation measures.

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BIODIVERSITY

Tracking, targeting, and conserving soil biodiversity

A monitoring and indicator system can inform policy

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Nature conservation literature and policy instruments mainly focus on the impacts of human development and the benefits of nature conservation for oceans and aboveground terrestrial organisms (e.g., birds and plants) and processes (e.g., food production), but these efforts almost completely ignore the majority of terrestrial biodiversity that is unseen and living in the soil (*1*). Little is known about the conservation status of most soil organisms and the effects of nature conservation policies on soil systems. Yet like "canaries in the coal mine," when soil organisms begin to disappear, ecosystems will soon start to underperform, potentially hindering their vital functions for humankind. Soil biodiversity and its ecosystem functions thus require explicit consideration when establishing nature protection priorities and policies and when designing new conservation areas. To inform such efforts, we lay out a global soil biodiversity and ecosystem function monitoring framework to be considered in the context of the post-2020 discussions of the Convention on Biological Diversity (CBD). To support this framework, we suggest a suite of soil ecological indicators based on essential biodiversity variables (EBVs) (*2*) (see the figure and table S3) that directly link to current global targets such as the ones established under the CBD, the Sustainable Development Goals (SDGs), and the Paris Agreement (table S1).

Soils not only are a main repository of terrestrial biodiversity, harboring roughly one-quarter of all species on Earth, but also provide a wide variety of functions (e.g., nutrient cycling, waste decomposition) and benefits (e.g., climate regulation, pathogen resistance); they regulate the diversity and functioning of aboveground systems, including their contributions to human well-being (*3*). If we do not protect soils for the next generations, future aboveground biodiversity and food production cannot be guaranteed. Nonetheless, recent calls to expand nature protection (*4*), as well as many other initiatives aimed to shape future environmental policies (*5*), do not consider the specific requirements of soil biodiversity and associated ecosystem functions (*6*, *7*).

Discussions and data concerning soils and their sustainability have long focused on either their vulnerability to physical impacts (e.g., soil erosion) or improvements to their food production potential (e.g., through fertilization). These narrow perspectives, often missing tangible indicators and disconnected from environmental monitoring, limit a wider discussion on the ecological importance of soil biodiversity and its role in maintaining ecosystem functioning beyond food production systems. The prevailing emphasis has also prevented soils from becoming a more mainstream nature conservation priority. Although initiatives to provide a more holistic representation of soils as ecosystem services providers exist [e.g., (*8*)], standardized and timely information to track policy targets related to soils is missing, particularly at global scales. These information gaps have precluded the delivery of a robust scientific message supporting the importance of soil biodiversity and have delayed the inclusion of soil biodiversity in nature conservation debates.

Unlike for physical and chemical soil properties, the high-resolution and molecular tools needed to investigate soil biodiversity and function have only recently been developed, and harmonized static datasets are just starting to emerge (*7*). Because of this, and because soil biodiversity monitoring is not prioritized at a national level, there is a lack of knowledge on soil biodiversity compared with above-ground plants and animals. In fact, most of the 196 Parties of the CBD do not have national targets (for 2011–2020) that explicitly consider soils, with very few specifically considering soil conservation and biodiversity.

CHALLENGES AND OPPORTUNITIES

Soil organisms, including nematodes, collembola, fungi, and bacteria, are responsible for a cascade of intricate soil functions (*3*) that underpin essential ecosystem services (e.g., climate regulation, soil fertility). As such, they require specific protection measures that go beyond protecting aboveground systems or reducing the application of surplus fertilizers and fungicides. Positive measures include the identification of soil biodiversity hotspots, endemisms, and priority habitats; the assessment of relevant drivers of soil biodiversity change; and the development of dedicated nature conservation policies. Additionally, most management decisions in conservation areas are not soil-specific or, when they exist, are focused on soil physical properties (e.g., reducing soil erosion) with no specific soil biodiversity conservation targets. With-

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out such measures, nature conservation has limited effects on the protection of soil organisms and their functions. For example, although expansion of protected areas has demonstrated benefits for protecting birds and mammals, there is little to no benefit to belowground diversity (*1*). To prioritize soils for nature conservation worldwide, policymakers require up-to-date data as well as transparent, reliable, and unbiased policy-ready indicators that are critical to providing a measure of success or failure of policy agendas (*4*, *5*). Recent efforts to describe the macroecological drivers and patterns of soil biodiversity (*9*), the general lack of comparable temporal data (*7*), the limitations to the development of coordinated large-scale monitoring efforts (*2*, *7*), and the enormous number of undescribed soil-dwelling species have all impeded the production of reliable assessments of soil biodiversity change (*9*). As a consequence, to date, most policies are informed by sparse information on soil chemistry (e.g., soil carbon) or on impacts to soils (e.g., soil erosion), and until recently we did not have the right instruments to inform policy-makers on soil ecological changes and impacts. With recent advancements in DNA technology, methods to integrate diversity and functional data, and international agreements for soil research [e.g., the recently endorsed resolution by the Food and Agriculture Organization (FAO) 27th Session of the Committee on Agriculture on the international exchange of soil samples for research purposes], we now have the resources, initiative, and technology to support the large-scale generation of this soil ecological knowledge.

Excluding soil biodiversity and associated ecosystem functions from nature conservation targets means that policies may fail to represent them and may render soil biodiversity and critical ecosystem functions more vulnerable to global change. Below- and aboveground diversity do not necessarily follow similar ecological patterns (*6*), which suggests that even when the focus is on restoring wild areas or increasing carbon sequestration (*10*)—both seen as positive outcomes of nature conservation—such practices might not have the same positive effects on soil organisms and their associated functions (*1*). Moreover, although constrained by current knowledge and logistic limitations (*7*), available studies already show the scale at which climate and land-use change, pollution, and other types of threats directly affect soil systems (*11*), pointing to the urgent need for policies to be based on a more comprehensive view of these terrestrial ecosystems (*7*, *9*).

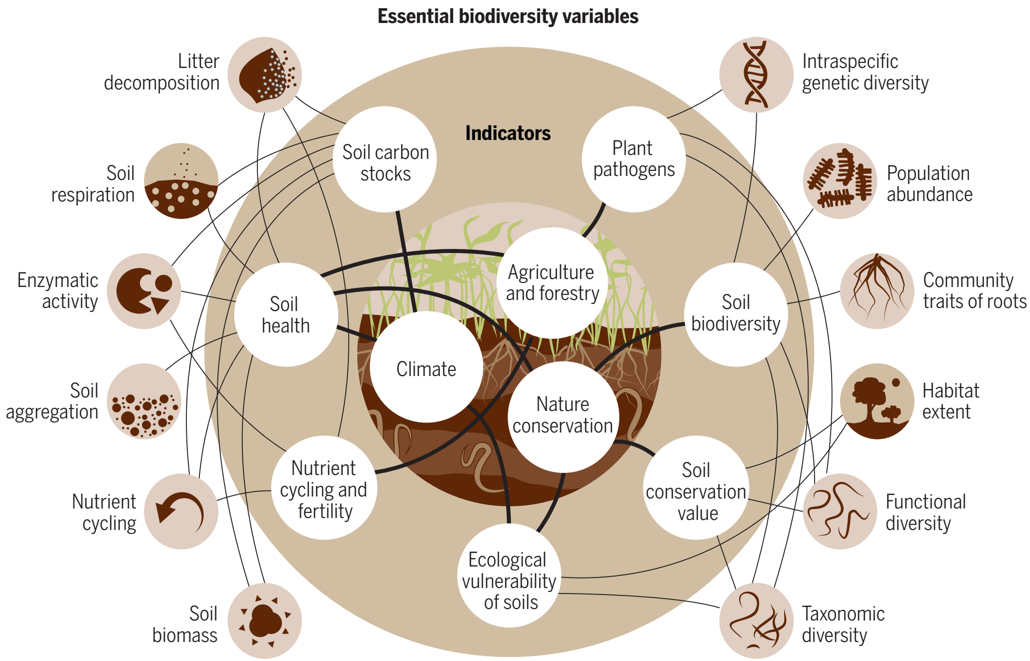
WORLDWIDE MONITORING

To fully comprehend the role of terrestrial biodiversity in the context of climate change, sustainable development, and nature conservation, we must invest in understanding what lies belowground. This requires a holistic system approach (see the figure) that includes definitions of a wide variety of soil-related EBVs, as well as standardized international monitoring systems (*12*) to track the state and dynamics of global soil biodiversity and ecosystem functioning over time. These EBVs encompass four complementary dimensions of soil systems (soil physics, soil chemistry, soil biodiversity, and soil ecosystem functions) and relate to specific ecological indicators (see the figure, inner ring, and table S3). This effort will be facilitated by existing mechanisms designed to mainstream the use of data and derived indicators to inform decision-making and policy-making, such as the Biodiversity Indicator Partnership and the U.N. System of Environmental Economic Accounting.

To this end, the global soil research community has started to organize itself to respond to the challenge. Efforts such as the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity, the Global Soil Biodiversity Initiative, the Global Soil Partnership (GSP) of the Food and Agriculture Organization, and the Status of the World's Soil Resources Report reflect how the international community has started to pay greater attention to the loss of biodiversity in agricultural soils. Indicators related to soil health have also emerged, although these mostly rely only on physical and chemical parameters without any functional or biodiversity aspect explicitly included (*13*). The recent Global Soil Biodiversity Assessment for the CBD and the updated plan of action for the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity are two other recent steps to elevate the policy status of soil biodiversity and increase soil literacy. However, all these initiatives rely on static fragmented soil biodiversity data without any temporal resolution or coordination.

Linking soil biodiversity to policy

Links between global soil essential biodiversity variables (EBVs) (outer ring) are prioritized by the Soil Biodiversity Observation Network (SoilBON) and policy sectors (center) through the use of soil ecological indicators (inner ring; table S3). 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 (table S2), where soil organisms are intertwined with relevant soil chemical, physical, and functional properties, contributing to overall societal well-being. See table S1 for further information on links to specific policy targets and policies. See table S2 for details of the EBVs.



We therefore must move beyond snapshots of soil biodiversity data and relay concrete input for temporally and spatially explicit soil biodiversity and ecosystem function indicators. As an example, in the context of the post-2020 discussions of the CBD, there is a focus on the protection of critical ecosystems. By assessing the state and trends of soil conservation value (see the figure and table S3), inherently including soil biodiversity information, we would be able to directly determine the extent to which countries are in line with this target. More important, we can support the identification of critical ecosystems that include soil communities.

In response to this need, we established the first global Soil Biodiversity Observation Network (SoilBON; https://geobon.org/bons/thematic-bon/soil-bon) under the umbrella of the Group on Earth Observations Biodiversity Observation Network (GEOBON) to systematically collect and sample observational data worldwide on the condition of soil biodiversity and functions. With the aim of including researchers working on all continents, we have proposed a plan to overcome legal limitations (e.g., centralizing requirements to comply with the Nagoya Protocol) and operational limitations (e.g., by providing funds to support researchers across the world) (*7*) to produce the first globally standardized time series on the condition of soil biodiversity and ecosystem functions (see the figure). Using lessons learned from and integrating methods used in other initiatives [e.g., (*2*, *12*, *14*)] and co-funded by multiple institutions around the world, this program will implement standard protocols across the entire monitoring infrastructure (see table S2) to systematically assess both soil biodiversity and soil ecosystem functions in both protected and nonprotected areas (*6*).

Although a global network will not have the resolution to distinguish among specific management practices, it can call attention to good examples of nature conservation focusing on soils and can be used as a global reference for comparison across regions and countries, thereby contributing to more effective soil conservation policies (see the figure and table S1). By identifying connections between soil ecological indicators and various reporting needs related to policy targets (see table S1), we provide a road map for researchers and policy-makers (see the figure and tables S1 and S2) on the priorities for data collection and on how to integrate such information into policy design.

Effective soil monitoring is needed to increase our capacity to mitigate ongoing global environmental changes (*11*) and inform policy sectors as different as nature conservation (e.g., SDG Target 15.1), land degradation (SDG Target 15.3), climate mitigation and adaptation (e.g., Paris agreement 2015), forestry (e.g., United Nations Decade on Ecosystem Restoration), and food security (e.g., SDG Target 2 and European Union Common Agricultural Policy) (table S1). Such a global initiative will not be possible without a wide network of local partners that cover different ecosystems and environmental conditions. This includes providing support to colleagues working in developing countries and establishing a centralized global analysis network across different volunteering institutions that allows for a high level of standardization and analytical power, and that can be extended to potential new partners or initiatives following the same standards [e.g., with regional or thematic focus (*14*), or focusing on data harmonization and synthesis]. In addition to increasing the quantity and quality of available soil ecological data worldwide, locally produced data and information will also become comparable between countries and projects thanks to the emerging collaboration with the Global Soil Laboratory Network of the GSP.

This program must include a strong commitment to capacity-building and knowledge-sharing mechanisms (Post-2020 CDB Goal D), as well as an open world archive of soil biodiversity resources. It provides a multi-tiered approach (globally coordinated sampling and harmonization using reference laboratories, cross-laboratory standardization and protocols, data aggregation using a clear set of EBVs and policy-relevant indicators, cross-initiative and cross-time validation and reporting) on which other networks, countries, and regions can build to create a comparable global patchwork of soil biodiversity and functional assessments. The goal is to create a program that builds on available assessments [e.g., the Global Soil Biodiversity Assessment (*15*)] to deliver valuable information on the state and trends of soil biodiversity and functions to support current policy-making and help reshape it to bring soils and their biodiversity to the center stage of global sustainability thinking. A first example is under way in Europe, where a partnership between SoilBON and several research institutions aims to provide essential biodiversity data to inform current and future European policy (e.g., the European Biodiversity Strategy for 2030; see the figure).

We aim for a future where the conservation value of giant earthworms [e.g., *Rhinodrilus alatus* (Righi 1971)] or endemic fungi [e.g., *Lactarius indigo* (Schwein 1822)] is recognized and their ecology is properly protected by nature conservation measures (e.g., establishing no-tillage areas or promoting environmental compensation schemes that explicitly include soil-related measures such as deadwood management plans that favor soil invertebrates and fungi). Local soil biodiversity should be considered when designing conservation areas and highlighted when implementing appropriate management efforts. To do this, we propose a complementary set of ecological indicators that considers the multiple facets of soil ecology (between biodiversity and key ecosystem functions) and provides a comprehensive overview of soil systems. These indicators were developed to address specific societal needs (e.g., soil health, nutrient cycling and fertility, or plant pathogens) but also to extend the use of soil ecological data to other policy realms [e.g., nature conservation (soil conservation value, soil biodiversity); climate action and land degradation neutrality (ecological vulnerability of soils, soil carbon stocks)]. If considered across the policy spectrum (table S1), these indicators will provide baseline data and methodologies to map and assess the current state and temporal trends of global soil biodiversity and functions, and to identify the regions that are more vulnerable to abrupt ecosystem shifts in the context of future climate and land-use change.

An international soil monitoring program based on EBVs and holistic indicators such as those presented here will provide the tools to assess how far we are from conservation targets in the next decades, acting as an early warning system of how current nature conservation measures are succeeding or failing in the conservation of soil biodiversity and functions. ■

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SUPPLEMENTARY MATERIALS

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