POLICY FORUM

Soybean is harvested in Brazil for animal feed in Europe and China, where nitrogen and other nutrients accumulate. This is an example of worldwide connections of soils and soil health.

SOIL HEALTH

Soil biodiversity needs policy without borders

Soil health laws should account for global soil connections

By **Wim H. van der Putten[1,2], Richard D. Bardgett[3], Monica Farfan[4,5], Luca Montanarella[6], Johan Six[7], Diana H. Wall[4,5]**

Soil biodiversity is crucial for healthy soils, on which we all depend for food, human health, aboveground biodiversity, and climate control. It is well known that land use intensification, climate change, environmental pollution, and mining activities degrade soil biodiversity. However, most current and intended policies on soil protection not only lack a holistic view on how biological, physical, and chemical components of soil health are integrated but also overlook how soils across national borders and continents are connected by human activities. The challenge is to use recent advancements in understanding the distribution and functional roles of soil biodiversity in developing policy on restoring and protecting soil health across borders. Thus, policy should focus not only on soils within a nation or union of nations but also on preventing negative footprints on each other's soils.

Numerous factors—such as urbanization, automation, disease outbreaks, natural disasters, and even wars—influence how land is used, which affects the capacity of soils to perform multiple functions, also called soil health (*1*). Searching for sustainable land use while providing food and feed for a more demanding population and dealing with growing demands on land for multiple other functions requires insights into the many factors that influence land use. Often, land use options are considered trade-offs, and the challenge is to search for win-win options, for example, climate change mitigation by biodiversity restoration. A transdisciplinary approach may help to understand possibilities and trade-offs to achieve a more sustainable society (*2*). Although an awareness that healthy soils are the basis of a healthy society is growing, anchoring this view into policy is still a challenge.

Soil protection requires an integrated legal framework to address the multitude of processes that are involved in land degradation, but most existing soil laws that should protect soils now focus on single issues, such as desertification or soil contamination. Moreover, soil protection laws are mostly national (*3*), although soil protection does not stop at national frontiers. For instance, current climate change caused by poor land use and industrialization outside sub-Arctic regions causes melting of the permafrost, which in turn exacerbates climate change through the release of carbon dioxide and methane to the atmosphere.

Although it is widely acknowledged that plants, birds, butterflies, and many other animal species need to be protected, little explicit attention exists for protecting soil biodiversity (*4*). The European Union (EU) Soil Strategy for 2030 (*5*) has been set up to combat declining soil health in Europe and beyond. The ambition is to have healthy soils in the entirety of Europe by 2050. An important aspect of this ambition is that the EU is planning to propose a binding European Soil Health Law in 2023. To the best of our knowledge, this is the first and most inclusive soil health protection law that recognizes the ecosystem services provided by healthy soils and the need to protect those services for future generations. Proposing a soil health law is an important step toward a sustainable society; however, the real challenge is to make it work.

To make the EU's Soil Health Law operational, soil health needs to be measurable. Different from soil quality, which is largely chemical in focus and mostly used to characterize the status of soil to sustain crop productivity, soil health is a more holistic concept (*6*). It is based on the recognition of the ecosystem services that soils provide. As defined in the EU soil strategy, soils are healthy when they are in good chemical, biological, and physical condition and are able to continuously provide as many of the ecosystem services as possible. Soil health addresses the sustainability goals set by the United Nations (UN), which have been adopted by many countries. However, finding effective, easy-to-measure indicators for soil health is challenging, because there is no one-size-fits-all indicator for all circumstances, just as in the case of soil quality (*7*).

STRUGGLE FOR INDICATORS

Measuring soil health requires information on biological, chemical, and physical properties of soil, the obtainment of which is a substantial effort that will be too costly for

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individual landowners. For example, soils contain an immense amount of biodiversity. One handful of soil might contain more than 5000 taxa, including species of viruses, bacteria, archaea, fungi, protists, nematodes, earthworms, and other small invertebrates. These organisms feed on live plant material, organic debris, and on each other as part of an intricate belowground food web. Analyzing the full soil biodiversity of every piece of land at time intervals that are realistic for soil biota is costly. Therefore, the EU Soil Strategy has proposed an EU-wide scheme to enable landowners to perform soil analysis with the "test your soil for free" initiative.

These free tests are a great preliminary step, but the numerous tests that are available are not all equally well calibrated. Because soil biota perform many different functions, there is no species that can represent all. Some species provide soil structure by converting plant litter into plant-accessible nutrients and others determine whether soils produce or consume greenhouse gases, whereas certain soil biota provide plants with protection against natural enemies, both below and above the ground (*6*). In addition, mutualistic symbionts, such as mycorrhizal fungi and nitrogen-fixing bacteria, play an important role in enhancing soil fertility, and they may protect plants against soilborne pathogens and root-feeding herbivores.

Likewise, although soil types have been relatively well described at a regional scale, local soil conditions can be highly variable. For example, soils are made up of different layers, or horizons, with contrasting physical, chemical, and biological characteristics. Proper quantification of biological, physical, and chemical soil properties at realistic spatial and temporal scales requires intensive soil sampling and laboratory analyses. Implementation of this information in a soil health law requires indicator values that are as simple as possible and can be used to propose measures to be implemented locally. For instance, the proposed establishment of EU-wide Soil Health Districts will enable a locally adapted approach. The first precursors of these districts are the 100 Living Labs and Lighthouses to be established within the research mission of the EU named "A Soil Deal for Europe." This regionalized consideration of soils mirrors a similar successful approach in the United States that established operational Soil Conservation Districts, which have been the key to the success of the US Soil Conservation Act of 1935. This act reversed the "dust-bowl syndrome" that caused displacement and hunger for millions of Americans.

Farmers are strongly focused on controlling pathogens and root feeders using chemical crop protection, crop rotation, or intercropping. However, excessive use of chemical fertilizer and soil tillage, as well as narrow crop rotation, enhance the abundance of crop growth–reducing plant-parasitic nematodes but reduce the abundance of most beneficial soil fungi (*8*). This makes intensive agriculture vulnerable to extreme drought and rainfall events, which increases the need for irrigation and drainage of soils. Meanwhile, fertilizers, biocides, and mechanical soil tillage are increasingly needed to grow high-yielding crop varieties. Implementation of a soil health law requires assessments that inform on the complexity and functioning of the entire soil food web. The question remains whether there are simple indicators for such complexity.

It will also be challenging to find natural soils that can act as a reference for healthy agricultural soils. In natural ecosystems, burrowing soil organisms such as earthworms promote soil structure and water infiltration, decomposing bacteria and fungi recycle organic and mineral nutrients by breaking down plant litter and root excretion products, and symbiotic and mutualistic microbes, as well as soilborne pathogens, may have a positive role in suppressing dominant plant species, thereby promoting the coexistence of multiple species in natural grasslands, forests, and other ecosystems. Moreover, belowground biota are indirectly involved in the control of aboveground enemies, including pathogenic bacteria and fungi and shoot-feeding insects. In densely populated industrialized parts of the world, it is likely that most, if not all, soil is affected by human activities. The challenge for soil laws will be how to develop gold standards for healthy soils.

ASSESSING SOIL BIODIVERSITY

The Convention on Biological Diversity defines biodiversity as the variation in life from genes to ecosystems and landscapes. This confronts comprehensive soil biodiversity monitoring with several challenges. At the genetic level, the species concept is less clear for microbes than for plants or animals, so that microbes are identified as operational taxonomic units (*9*). These approaches are often used for analyzing community composition, both of microbes and small invertebrate fauna that occur in soil. Detailed studies of soilborne pathogens, root parasites, and model organisms have revealed a high level of genetic diversity in individual species. Examples include the genetic population structure of soilborne pest and pathogen species, such as that of fungi that cause plant wilting. However, these analyses may be too detailed for general soil health assessments.

Molecular identification, through DNA or RNA barcoding, is widely used to characterize the diversity and community composition of microbes, protists, nematodes, and other taxonomic groups of soil organisms. The use of metagenomics and metatranscriptomics can assist in assessing soil microbial communities and their functional potential. However, challenges remain in developing uniformly standardized methods to conduct sample collection and analyses (*10*). This standardization is needed because expressions of units of species and individuals vary from numbers per weight or volume of soil to numbers per square meter(s), which makes comparisons across studies and taxonomic groups challenging (*11*). The use of environmental DNA (eDNA) might provide more uniformity and practicality for biodiversity assessments, provided that they are well calibrated (*12*).

Using new molecular identification techniques may help to determine which soil species can be found where and whether they are threatened or not. The current lack of knowledge hampers policy on soil biodiversity protection. It is unknown whether certain soil organisms should be placed on a "red list" of species that are threatened by extinction (*1*). There are several examples of highly sensitive ecosystems in which single soilborne species perform essential functions, such as the southernmost bacteria-eating nematode *Scottnema lindsayae*, which lives in the dry valleys of Antarctica and is threatened by climate warming. This nematode plays a crucial role in nutrient cycling.

There are also examples of invasive soil organisms, such as the oomycete *Phytophthora cinnamomi*, which destroys forest vegetation in Australia, and invasive earthworms that change nutrient cycles in North American forests. The EU soil strategy makes explicit reference to the need to assess the risk of alien flatworm species for their potential inclusion in the list of "invasive alien species of Union concern," in line with the EU Invasive Alien Species Regulation. Nevertheless, the concepts of rarity and invasiveness, which are well accepted for plants and aboveground animals, remain largely unused for soil biodiversity protection across the globe.

When considering the substantial efforts that will be required to design and undertake representative soil sampling, key questions arise: What sort of data are needed and for what purpose, and how can this information be collected and made available to all? It is likely not necessary to first identify and describe all species of soil biota before using the presently available information for biodiversity protection. An alternative to species identification is to qualify soil biota according to traits, such as nitrite oxidizers or cellulose degraders. This functional approach has also been used to develop food web models to analyze carbon and nitrogen flows through soils.

ENHANCING SOIL LITERACY

Despite the challenges of analyzing soil biodiversity, progress has been made in bringing soil biodiversity to a wider audience. For example, the publication of global maps of diversity within taxonomic groups—bacteria, (mycorrhizal) fungi, nematodes, microarthropods, and earthworms—has raised some awareness of the enormous diversity of life in soil and how it is distributed, as has the recent production of the Global Soil Biodiversity Atlas (*13*) and the first Global Soil Biodiversity Assessment (*1*). These publications provide the most up-to-date syntheses of the current status of soil biodiversity and have stimulated the initiation of the International Network on Soil Biodiversity (NETSOB), which aims to become a network of Global Soil Biodiversity Observatories (GLOSOBs).

How soil observatories will work and what will be measured is still under development. Ideally these will be sites where soil biodiversity is monitored over longer periods with standardized protocols to quantify consequences of global changes in climate, land use, invasive species, erosion, and other changes that require detailed and long-term monitoring efforts. These observatories will complement the global Soil Biodiversity Observation Network (SoilBON) and EU Land Use and Coverage Area frame Survey (LUCAS) program, which have started to collect soil biodiversity information from numerous sampling sites across Europe. These large-scale monitoring programs may also be linked to evaluations of the EU's Soil Health Law and national surveys and to citizen science activities on soils and soil biodiversity, such as the Dutch Soil Animal Days project. Public availability of data from such surveys will facilitate further use.

WORLDWIDE SOIL CONNECTIONS

Restoring soil health in one region also requires attention to its consequences in other regions of the globe. Worldwide, soils and soil biodiversity are connected through international trade, climate change, invasive exotic species, tourism, atmospheric composition, pollutants, and other environmental changes. Improving soil health in the EU may have planned or unplanned side effects elsewhere on the globe. Those side effects need to be monitored for policy improvement. For example, intensive animal farming in industrialized countries requires additional feed from other locations. The resulting flow of resources (e.g., nitrogen, phosphorus, potassium) may degrade soil biodiversity and soil health in both feed-production and feed-consumption locations. At feed-production locations, soil biodiversity may decline as a result of lowered soil organic matter content and export of nutrients, whereas in feed-consumption locations, excessive availability of manure results in nutrient enrichment of soil, shifts to bacteria-based soil food webs, and increased abundance of soil parasites and pathogens.

The global transport of nutrients has major consequences for adaptation and mitigation under climate change. For instance, both the loss of soil organic matter in feed-production regions and the shift to bacteria-based soil food webs in feed-consumption regions result in lowered soil stability (*14*). As a result, soils in both feed-production and feed-consumption locations will be more sensitive to climate change–induced extreme weather events. Restoring circularity by bringing back manure to feed-production areas is one option for addressing these imbalances, but that would increase global transport. Another possibility is to reduce the distance between feed production and consumption and close cycles within regions. Restoring circular food systems and therefore soil health will be a major challenge for enhancing sustainable food production and will require transdisciplinary research approaches that involve not only socioecology, economics, and other relevant disciplines but also a wide variety of stakeholders, practitioners, and policy-makers.

The decisions of farmers are influenced by numerous external factors, such as the price of land and the price of fertilizers, crop protection chemicals, and agricultural products on the world market. As a result, local soil conditions, including soil biodiversity and health, are influenced by national and global decisions, such as on trade and environmental protection. Soil health policy will also influence human decisions; for example, farmers may decide to move industrialized agricultural practices to less-industrialized countries. Thus, wherever enacted, soil health laws will need to account for these side effects to prevent soil health gain in one region from resulting in soil health loss elsewhere. Therefore, global networks of soil observatories—such as those initiated by SoilBON, LUCAS, and the Food and Agriculture Organization of the United Nations' International Network on Soil Biodiversity—need to be embedded into "living labs" that test experimental approaches under real-life conditions. In these living labs, researchers need to collaborate with all stakeholders to co-create knowledge that leads to sustainable development (*15*). At the core of such global approaches is the agreement between science and society on common definitions and gold standards of soil health.

PRESERVE WHAT IS HERE

It is essential that what is already here is protected and preserved. Draining carbon-rich soils, harvesting carbon from the remaining peatlands, or destroying pristine soil biodiversity to convert land for yield maximization of single crop species might generate short-term profit for some but are self-destructive for society as a whole in the long term. Moreover, climate change mitigation activities need to acknowledge the roles of soils in global biogeochemical cycles. Planting trees in natural grasslands and peatlands, for instance, can have undesirable consequences for biodiversity and the huge amounts of carbon in their soils. Real action is urgently needed to prevent vast amounts of fertile topsoil from being washed away in waterways and onto ocean floors. It takes only a few years to destroy what nature has built over centuries. Therefore, the protection of soils, soil biodiversity, and soil health should be high on the policy list of all nations and regions, because dead soil does not provide a sustainable business model anywhere. ■

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ACKNOWLEDGMENTS

All coauthors contributed equally to this work.

10.1126/science.abn7248

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Science, **379** (6627), .
DOI: 10.1126/science.abn7248

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