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Soil biodiversity and bioindication: From complex thinking to simple acting

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ABSTRACT

Water and air quality have long received much attention from scientific and legislative institutions, and public awareness for these issues is good, but soils have long been comparatively ignored. Soils contain a very high, but mostly unknown biodiversity, and soil biology remains an understudied topic. Soil organisms are a key factor for soil development and in turn depend on soils as a habitat. Bioindication tools based on a fraction of known soil diversity are certainly imperfect but are implemented in order to achieve soil protection goals at policy level. Bioindication tool selection results from compromises between biological and socioeconomic (e.g. effectiveness, cost) constraints. A further challenge is the multi-functional uses of soils and divergent interest, which hampers progress in regulatory policy. Soils are considered as an economic resource (i.e. surface) and their value therefore strongly relies on the land-use type (agriculture, industry, "unproductive" biotope, etc). But soils are also a natural resource (i.e. volume) which environmental and societal functions depend on its intrinsic properties and biological quality. In this article I review the reasons for the low interest in soils, and particularly their biological component, among politicians and the public, and show the existing gap between soil biodiversity and soil policy. In Switzerland, direct and indirect approaches are used to regulate and monitor soils but these do not include biological parameters.

1. Why are soils not considered at the policy level as a resource like water or air?

Like water or air, soils are universally considered as an irreplaceable, limited natural resource that requires protection from degradations, and that should be used sustainably and preserved for future generations. Moreover, in the last decades, soil quality and soil functions, and in particular its intrinsic biodiversity, have become a matter of increasing attention at the scientific and policy levels [1–4]. This increasing interest for soil biology has unfortunately led to a multiplication of concepts of soil fertility, soil health or soil quality, which cause confusion. In an agricultural context, soil fertility is usually restricted to nutrient management and the prevention of nutrient deficiencies. Soil health refers more globally to the "capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal production, maintain or enhance water and air quality, and promote plant and animal health" [5]. According to the Swiss law the soil is deemed fertile when it consists of a site-specific, diverse and biologically active habitat, which entails a typical soil structure as well as undisturbed capacity to decompose organic matter. In addition, soils should allow adequate plant production both in terms of quantity and quality; in this case, the significance of soil fertility fits with the concept of soil health. The concept of soil quality is more elusive; it relies on the capacity of a soil to function and reflects its living and dynamic nature [6]. Despite the controversial essence, due to its versatile nature, which mainly depends on soil management or use, in laws soil quality usually refers solely to specific thresholds of pollutant concentrations [7].

Despite some similarities in the challenges of conservation between soils, air and water, these three objects differ considerably. Soil is a highly complex media, spatially heterogeneous and temporally variable, much more so than air or water [8–10]. Soils contain an incredible diversity of structure and potential habitat for organisms, ranging from micrometer to centimeter scale, or from the active rhizosphere or drilosphere to thin water films adsorbed to the pore space [11]. But above all, soils are biologically active: not only are they a habitat for living organisms, they are formed by these organisms and without their presence their development is hindered. Despite the essential biological component of soils, soil biodiversity remains partly invisible [12–14], which is one of the reasons why it is comparatively understudied and poorly considered at policy level. Moreover, the physical, chemical and biological properties of soils interact in a complex way to sustain the diversity in their functioning. Understanding this complexity is a challenge for researchers and even more so for the general public.

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Another difficulty arises from the potential economic value of the soils. They are used by society for crops and goods production, housing and industrial development, recreation and protection against hazards and actually, their value is not related to their intrinsic quality but to the value of derived products (yield crop, square meter price of housing or office, etc.). Soils are integrated into spatial planning process that considers places and their accessibility rather than the intrinsic functions of the soils. Finally, unlike water or air, soils are usually privately owned and the implementation of legal regulation is therefore a matter of political debate.

Nevertheless, since about one or two decades, more attention is devoted on soil at the policy level and legal protection acts were implemented in some countries [9,10,15,16]. In order to achieve protection goals, a need for indicators of soil health is emerging, particularly for indicators related to the biological component of the soil.

2. Reasons for current lack knowledge and awareness for soil biodiversity

The limited integration of soil biology in policies and the general lack of awareness for the value of soil biodiversity primarily reflect the complexity of biological soil functioning, but this in turn reflects the lack of basic knowledge about soil biota, particularly for small-bodied taxa [17]. Poor taxonomic expertise and methodological difficulties, especially inadequate sampling techniques that underestimate the soil biota, limit research progress in soil biodiversity and partly explain the existing gap in knowledge [18].

The decline of soil biodiversity is one of the eight identified threats for European soils [15]. Despite the Rio Conference in 1992 and the popularization of the biodiversity concept, to date, no legislation or regulation is specifically targeted toward soil biodiversity, be it at international, European, or Swiss level. In a broad sense biological diversity refers to the "variety of life", which includes "diversity within species, between species and of ecosystems" (Convention on Biological Diversity). Soil biodiversity should therefore be considered at the same levels. However, an accurate estimation of specific biodiversity remains difficult because its assessment should include both active and passive geobionts, i.e. organisms that spend their whole life in soil as well as species that temporarily live in soil [11]. At global and local scales, the broad diversity of ecosystems is closely related to the diversity as well as the spatial and temporal variability of soil types and their specific biota. Obtaining a reliable overview of this complexity is a major challenge for biodiversity assessment and estimates of its decline.

Studies that monitor soil diversity mainly show global figures and emphasise simple facts that are understandable for the general public, for example, that just one teaspoonful of soil may contain thousands of species, millions of individuals and hundreds of meters of hyphae or that "there are more than 10^{16} prokaryotes in a ton of soil compared to a mere 10^{11} stars in our galaxy" [19]. However, accurate knowledge about soil organisms and their ecosystem functions are still missing.

A possible way to enhance the political awareness of soil biodiversity is to consider the essential services to human society that functions of soil organisms sustain [20]. Most of these services are supporting services, such as nutrient cycling or water quality, which benefit the human society directly or indirectly. The genetic resources of soil microorganisms may lead to development of new pharmaceutical products or other services that directly benefit the human society.

3. The challenging quest for soil bioindicators

Management of complex soil resources requires establishing an initial, reference status. It also requires long-lasting monitoring in order to determine the changes in resource quality and quantity. Estimation of soil quality is often carried out indirectly through the value of products (e.g. crop yields), but as the soil system is enhanced by agrochemical inputs or management practices such as plowing, the natural state cannot be properly assessed. On the other hand, direct measurements of specific soil properties (such as pH, porosity, etc.) provide useful clues about soils; however, they indicate the current state of one selected property and, as they vary at different time scales, they do not provide global information. The ideal accurate, sensitive and reproducible indicators that could integrate the soil quality changes over time have still not been identified.

Indicators currently used are mainly based on chemical and physical parameters. For chemical factors, a number of critical "threshold" levels are accepted at the national scale. However, chemical and physical indicators generally require long periods before the effects of human impacts or management practices can be detected [21]. On the contrary, the soil biota reacts sensitively to modifications and therefore biological indicators are suitable for early diagnosis of degradation processes [5]. Two concepts are distinguished: bioindicators and biomonitors. Bioindicators are organisms or communities of organisms, which provide information on the quality of the environment. Biomonitors hold quantitative information of the quality of the environment, using programs of surveys in order to provide a time series [22].

The use of ecological indicators for the global assessment of water quality is quite well known (for instance the French IBGN [23]), but for soils, a fully efficient bioindicator toolbox does not yet exist. To develop this toolbox a reference framework is ideally needed: Communities of soil organisms occurring in a range of natural or close to natural soils are used as reference against which communities of anthropogenic or naturally disturbed environments can be compared to assess the degree of perturbation. Nevertheless, several European countries have developed biological survey networks. Of these, the most complete is the Dutch "Biological Indicator of Soil Quality" (BISQ) which is integrated into the still existing abiotic soil monitoring program. For more than 10 years, numerous edaphic organisms were sampled, bacterial biomass and genetic diversity was determined and ecological processes such as carbon or nitrogen mineralization were measured [24]. In Italy, a new method, based on soil microarthropods (QBS index), provides a useful tool for large-scale monitoring and was already implemented by some Regional Environmental Protection Agencies [25]. The objective of French project ECOMIC-RMQS, set up in 2006, is to characterize the density and diversity of microbial communities with the aim to introduce biological diversity in the national soil monitoring network [4].

Changes in the biological components of soils are complex processes and can hardly be detected from the surface or inferred from soil by-products. Knowledge about how organisms react to human direct (contamination, erosion) or indirect (atmospheric carbon dioxide increase, etc.) impacts on soils is still fragmentary. The available data shows that soil organisms respond to the soil organic matter content (e.g. in soil structuring processes) [e.g [26].], but also to chemical inputs such as heavy metal [e.g [27,28].] or organic contaminants [e.g [29].], and to change of physical properties (e.g. compaction). Biological modifications due to invasive species or to the introduction of genetically modified species certainly affect diverse soil communities and interactions between functional groups of biota, but causal relations are difficult to establish because of the complexity of the soil food webs. This aspect is highlighted in a study [30] on elevated concentrations of atmospheric carbon dioxide in model ecosystem that showed the complexity of interactions between diverse groups of organisms. Increased photosynthesis, due to elevation of carbon dioxide, raised the dissolved organic carbon in soil, leading to modification of