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Soil quality indicators: critical tools in ecosystem restoration

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Abstract

Defining clear goals for ecosystem restoration, and developing effective tools to assess and monitor progress, are critical to achieve restoration success. Soil quality indicators can be valuable assets for ecosystem monitoring and assessment. Recent advances in the development of methodologies for soil analyses, including sensing techniques or molecular methods, provide unprecedented opportunities to integrate soil indicators in restoration programs. Despite the substantial potential benefits of using these indicators as tools in ecosystem restoration, the calibration and establishment of global soil parameters remains a challenge due to large variability in soil, climate, and ecosystem types. This review provides an overview of the current knowledge of soil quality indicators in the context of ecosystem restoration. Examples of relevant soil physicochemical and microbiological indicators, and current and novel methodologies for their assessment, are presented. Furthermore the benefits and challenges for the global integration of these indicators in ecosystem restoration programs are discussed.

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Soil health, Soil organic carbon, Soil microbial communities, Sustainable Development Goals (SDGs), Land degradation.

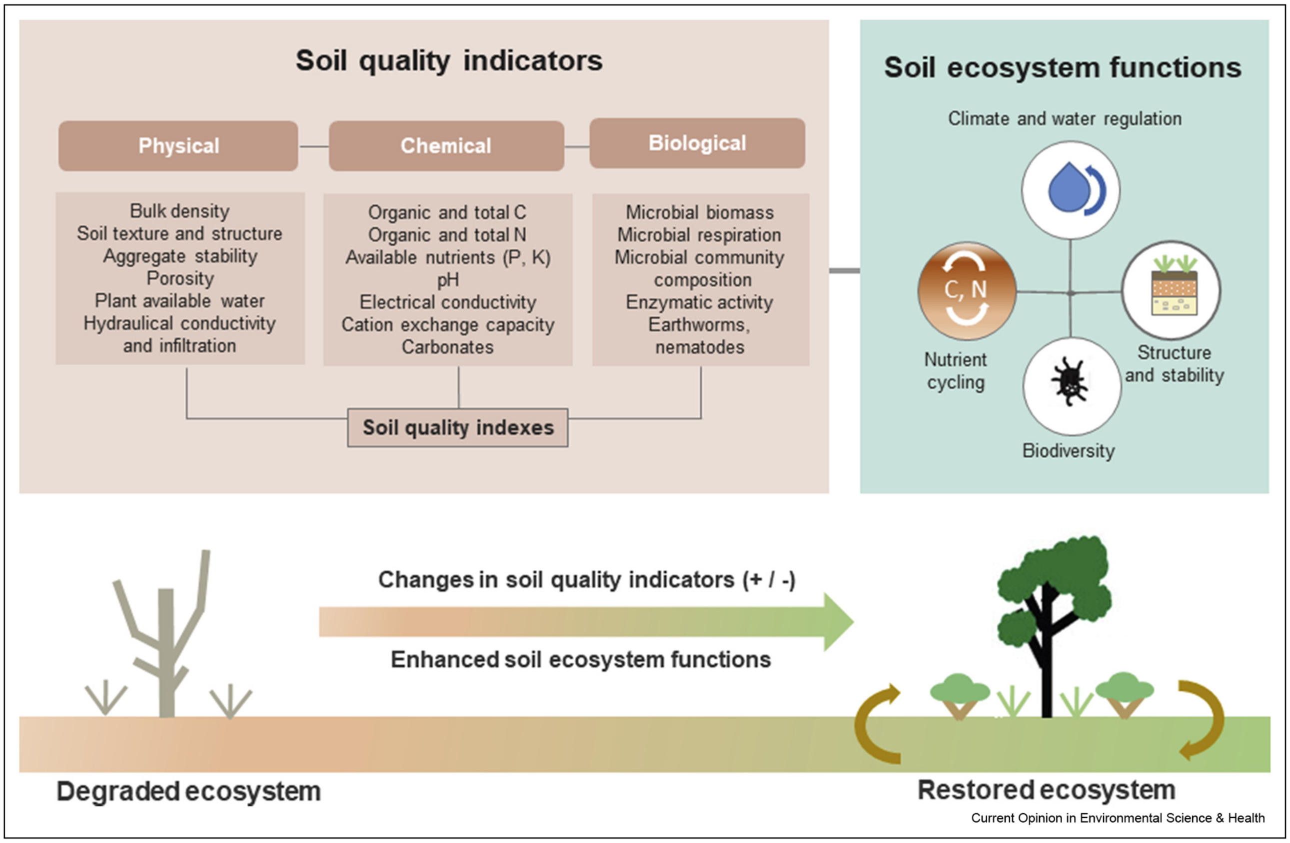
Introduction

Land degradation and loss of biodiversity are two of the most pressing global problems affecting terrestrial ecosystems [1]. Approximately 23% of the globe's terrestrial surface is currently affected by some form of degradation, with 5–10 million additional ha being affected annually, and about 1.5 billion people negatively impacted by land degradation globally [2,3]. Reducing degradation and restoring currently degraded lands are therefore urgently needed actions to maintain ecosystem function and productivity, mitigate climate change, preserve biodiversity, and secure food production and resource provision [4,5]. The global community has accordingly set specific targets for ecosystem restoration, including the universal, integrated and transformative "2030 Agenda for Sustainable Development" (adopted by the United Nations General Assembly) that defines 17 Sustainable Development Goals (SDGs). Many of these goals are strongly linked to land management and set targets to restore degraded land and soil over the coming decades [4], underpinning the importance of achieving a land degradation-neutral world [2]. Global efforts such as the Bonn Challenge, a global aspirational goal to restore 150 million hectares of the world's degraded lands by 2020 and 350 million hectares by 2030, aim to support progress towards various SDGs.

Appropriate global indicators will help countries to measure the progress they are making towards achieving objectives, and to understand which areas to prioritise and allocate resources to [6]. Thus, adequate selection of soil indicators, effective implementation, and appropriate monitoring methodologies will be decisive in order to achieve the SDGs based on soil resources [7]. Soils are major land components and are dynamic systems that generate multiple functions [8,9] (Figure 1). These soil functions support the delivery of key ecosystem services such as climate and water regulation, carbon sequestration, or nutrient cycling [10,11], all of which can be seriously affected in degraded ecosystems. Ecosystem restoration should aim to not only recover the soil's capacity to support vegetation establishment, but also to re-establish ecosystem functions and services [12,13]. Most soil ecosystem functions are difficult to assess directly and are therefore frequently inferred from measurable soil properties such as soil quality indicators, which can cover a broad range of soil physical, chemical and biological characteristics [14,15] (Figure 1).

This review (i) provides an overview of the current knowledge of soil quality indicators in the context of ecosystem restoration; (ii) presents examples of soil physicochemical and microbiological indicators and current and novel methodologies for their assessment and; (iii) discusses the benefits and challenges of integrating these indicators in global restoration programs.

Figure 1



Soil quality indicators (SQI) include a range of soil physical, chemical and biological characteristics, and are connected to key soil ecosystem functions such as climate and water regulation, nutrient cycling, land structure and stability, and soil microbial and plant biodiversity. SQI can help in guiding restoration, predominantly with respect to understanding the role of soil properties and plant–soil relationships that promote revegetation and enhance soil ecosystem function.

The multi-dimensional nature of soil quality: the more indicators the better?

Soil quality has commonly been defined as 'The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation' [16]. The original concept of soil quality is continuously evolving and has been further elaborated as soil health to present the soil as a finite non-renewable and dynamic living resource [17]. Although some authors maintain that these terms should be differentiated [9], both concepts are considered equivalent and frequently used interchangeably [17]. The term "soil quality", preferred by researchers, will be used in this review, acknowledging explicitly the important role of soil biota and related soil functions. In the last three decades, several authors have highlighted the importance of using indicators of a different nature (physical, chemical, and biological) to achieve a clear understanding of soil quality [14,15,18]. More recently, new dimensions have been added to this approach in order to develop appropriate soil indicators for sustainable soil management, e.g. social well-being and economic dimensions [19,20]. Traditionally, physical and chemical attributes have been the main indicators used to assess soil quality. Soil organic carbon, total N and pH, among the chemical properties, and particle size distribution, bulk density, available water, soil structure, and aggregate stability among the physical characteristics [21], are arguably the most widely used parameters to assess soil quality.

Soil organic carbon in particular has been the 'star' indicator of soil quality for decades [9,22]. Soil organic carbon is linked to numerous soil functions, but is also the major carbon sink in terrestrial ecosystems, and is thus critical for climate change adaptation and mitigation strategies [23,24]. Several studies at local, regional, or global scales, have focused on the study of soil organic carbon as an indicator of soil degradation or recovery [12,15,25]. An increasing number of studies (reviewed in Refs. [26,27]) are reinforcing the crucial role that the soil biological component plays in soil quality assessments. The soil biota is responsible for countless functions of the soil ecosystem and, in addition, may respond rapidly to ecosystem changes, e.g. following ecosystem disturbance or recovery [28]. According to several recent studies, individual soil properties may not be adequate indicators of the soil status or can be interdependent and confound the effects of ecosystem or land changes [26,29]. Moreover, some studies suggest that using many variables can result in reduplication when variables are highly correlated [27,30].

To acknowledge the multi-dimensionality of the soil system and reduce variable collinearity, there is a growing trend to use soil indexes based on a combination of soil quality indicators to assess ecosystem changes [31,32]. Soil quality indexes have been defined as the 'minimum set of parameters that, when interrelated, provide numerical data on the capacity of a soil to carry out one or more functions' [26]. These indexes can range from simple quotients such as the metabolic quotient (qCO2) (respiration to microbial biomass ratio) or the F:B ratio [15,18], to multi-parametric indexes (reviewed in Refs. [26,27]). Another example of an integrated approach to assess and monitor soil function or quality in restoration is the broadly used landscape function analysis (LFA) [33]. The LFA is a visual assessment procedure based on measurable soil that uses indicators of soil biogeochemical properties and processes, and generates indices of soil function [34].

Recent advances and novel approaches in the assessment of soil quality indicators

The emergence of highly specified molecular technologies provides unprecedented opportunities to further unravel plant-soil feedbacks and interactions during ecosystem recovery [35,36]. Similarly, new spectroscopic techniques, including near-infrared spectroscopy, portable X-ray fluorescence, and remote sensing; and other non-destructive techniques such as X-ray tomography, offer the opportunity of measuring a broad range of soil chemical, physical, and biological parameters in a fast and cost-effective way [30,37].

A number of techniques are currently available to determine soil microbial characteristics such as microbial biomass and respiration, and many have been used to assess restoration success. These include biogeochemical and physiological approaches (e.g. chloroform fumigation extraction, substrate induced respiration, the 1-day CO_2 test) or metabolic techniques (e.g. measurement of enzymatic activities) [12,15,18,38]. Other methods such as stable Isotope Probing, phospholipid fatty acid analysis, and DNA probing have helped to link soil biodiversity to soil processes [30].

These 'black-box' measurements are now being complemented with more informative measures of soil biota based on molecular techniques. The living microbial component of soil represents only 0.1−0.3% of total soil volume in most soils, and yet is essential to overall soil quality, facilitating 90% of soil ecosystem functions [8]. Shifts in microbial community composition following restoration have been related to changes in ecosystem functions. Thus, the characterization of the soil microbial community is being increasingly used to determine the response of soils to environmental changes such as stress and disturbance, and as an indicator of ecosystem recovery [12,18].

The detection of genomic DNA from microbial species in soil has improved the knowledge of unculturable microorganisms and led to a superior understanding of potential soil metabolic pathways [35,39]. By harnessing 'omics' technologies that are now available and financially feasible, such as metagenomics, metatranscriptomics, and proteomics, important advances in understanding soil functionality are being accomplished [40]. But, despite these developments, our ability to link most microorganisms to their metabolic roles within a soil community is far from complete. In addition to the difficulties in capturing the high soil diversity and variability, methodological biases remain an enormous challenge for microbial community characterization [39]. These biases can include soil sampling, DNA extraction, contributions of extracellular DNA, sample preparation, and sequencing protocols among many others [36]. Metabolomics is an emerging complementary approach to soil metagenomics studies as it can provide direct insights into the functioning of soil microbial communities within their environment [41]. Exometabolomics, which focuses on the characterization of extracellular small metabolites, has shown potential for advancing our understanding of the linkages between microbial diversity and ecosystem functioning, e.g. connecting soil carbon dynamics to microbial communities [42].

Integrating soil quality indicators into ecosystem restoration practice: challenges and opportunities

Ecosystem restoration may hold several meanings for different audiences, from habitat restoration or landscape rewilding to mine reclamation or rehabilitation [43,44]. The terms passive and active restoration have been frequently used to distinguish natural succession (or minimal active restoration measures) from heavy interventions [45]. But despite the different existing approaches, most studies agree that developing clear goals for restoration, as well as effective tools to assess and monitor progress, is critical to achieve restoration success [13,46]. This usually involves a broad understanding of the multiple biotic and abiotic factors and environmental attributes of analog and target ecosystems [47]. Many studies have found that soil quality indicators are a valuable asset for ecosystem monitoring and assessment in restoration programs [12,18,29,31]. These indicators can help in guiding restoration science and practice, predominantly with respect to understanding the role of soil properties and plant–soil relationships that promote revegetation [48].

Selecting appropriate soil indicators may be challenging and different criteria have been proposed [49,50]. Most studies agree that effective soil indicators for restoration assessment need to be sensitive to ecosystem changes and ideally should provide information about the function, composition and structure of the environment integrating the complexities of the soil ecosystem [31,51]. Simultaneously, selected indicators should remain as simple as possible to facilitate their application and interpretation, which remains a challenge because most cases lack a linear relationship between indicator value and soil function [31]. The amount and type of soil quality indicators or indexes needed to monitor and assess restoration progress depends on the purpose and scale of evaluation, and ultimately on the time and spatial scales [12]. Dynamic indicators such as enzymatic activity, microbial activity and biomass, pH, and available nutrients, may be important in the short-term to detect initial ecosystem responses; however, because of the large spatial and temporal variability of soil ecosystems, 'slow-change' indicators, e.g. soil structure or water holding capacity, can be more appropriate to highlight impacts on inherent soil characteristics [15,18]. Regardless of the type of indicator or index used, several studies note the importance of identifying standard baseline values for reference and optimal ranges of selected indicators or indexes [27]. Overall, most studies agree that an integrative approach including short- and long-term monitoring is essential to increase the success of restoration efforts. For example, time-series data over long periods may be extremely valuable to understand drivers of ecosystem changes. However, long-term experiments are often jeopardized by the duration of research projects and lack of sufficient funding [48].

Conclusions and future perspectives

In the context of global environmental change and increased land degradation, it is critical to understand the recovery of soil ecosystems as a fundamental and linked process in the resilience, function, and restoration of degraded lands. There are extensive discussions surrounding the characteristics that define and measure successful restoration, monitoring and assessment of restoration projects. The broad recognition of the central role of soil quality in ecosystem restoration programs, and the importance of using a variety of indicators, including physical, chemical and biological, will be key to achieve international goals. New advances and promising techniques might allow a mechanistic understanding of the links between plant soils and microbes that would facilitate monitoring and assessment of ecosystem recovery. Nonetheless, due to the absence of standard operating procedures and established threshold values, using highly specialised techniques can be sometimes impractical for managers, and simple cost-effective soil indicators might be more appropriate for effective assessment of soil quality.

Overall, despite the fact that potential benefits of using soil quality indicators as tools in ecosystem restoration programs is substantial, the calibration and establishment of global parameters remains a challenge due to the large variability in soil, climate and ecosystem types. Although considerable efforts are being made for improving soil data collection and monitoring systems, the spatial extent of global, regional and local soil quality indicators has to be considered and integrated into ecosystem restoration practices [7]. New initiatives towards global harmonization of soil data and information, such as the Global Soil partnership [52], the Global Soil Biodiversity Atlas [53] or the Earth Microbiome Project, [54] will be crucial for data standardisation at different spatial scales, which in turn will facilitate the integration of soil quality indicators into global restoration programs.

Conflict of interest

The author does not have any conflict of interest.

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