Review Article

Soil Quality: A Critical Review

Abstract

From plot to national scales, sampling, analysis, and visual inspection of soil are common methods used to evaluate its condition and potential for use. However, due to the complexity and site-specificity of soils, the legacy impacts of past land use, and trade-offs across ecosystem services, selecting relevant soil parameters and interpreting measurements are not simple tasks. Here, we go over the definition, methods of assessment, and choices and interpretations of indicators for soil quality and related concepts. We include the most widely used indicators of soil quality under agricultural land use. It has been observed that there has been limited implementation of explicit evaluation of soil quality for particular soil risks, soil functions, and ecosystem services. Additionally, there are few systems that offer clear schemes for interpreting measured indicator values. This restricts both policy and land managers' acceptance of them. We also discuss novel indicators that address significant but currently overlooked soil properties and processes, and we enumerate the critical steps in developing a scientifically sound procedure for assessing soil quality that will support management and policy choices that take into account the multifunctionality of soil. This necessitates far greater involvement from the relevant players, stakeholders, and end users than has been done in the past.

Keywords

Indicator, Ecosystem service, Land quality, Minimum data set, Soil capability, Monitoring, Soil fertility, Soil function, Soil health, Soil threat

1. Introduction

Along with water and air quality, soil quality is one of the three elements of environmental quality (Andrews et al., 2002). The primary determinant of water and air quality is the level of pollution that directly affects the health and consumption of humans and animals, as well as natural ecosystems (Carter et al., 1997; Davidson, 2000). On the other hand, soil quality is generally understood to mean "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994, 1996), rather than just the level of soil pollution. It is expressly stated by Doran and Parkin (1994) that human health is a component of animal health.

Comment [A1]: Abstract need to be more refined. Need improvement.

Comment [A2]: it might be written as "Assessing soil condition and potential usage involves a range of methods, from small-scale sampling to nationwide analyses. Despite their prevalence, these approaches face challenges due to the intricate nature of soils, their site-specific characteristics, historical land use impacts, and the need to balance various ecosystem services. Selecting pertinent soil parameters and interpreting measurements becomes a complex task. In this context, we delve into the definition, assessment methods, and the choices and interpretations of indicators related to soil quality. Our focus is on widely used indicators within agricultural land use. Notably, explicit evaluations of soil quality for specific risks, functions, and ecosystem services remain limited. Furthermore, there is a scarcity of systems providing clear frameworks for interpreting measured indicator values, hampering their acceptance by both policymakers and land managers. We explore innovative indicators that shed light on often overlooked soil properties and processes."

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In order to identify parallels, significant discrepancies, and omissions, we will critically examine soil quality articles and assessment tools in this work, with a focus on soil quality indicators. In order to achieve this, section 2 introduces pertinent concepts and terminologies, while section 3 provides an overview of several methods for assessing soil quality. This review focuses on measurements using analytical methods.Since visual soil evaluations have recently been evaluated, a quick presentation of the most significant methods utilising visual soil evaluation in the field is provided (Emmet-Booth et al., 2016). The selection of indicators for soil quality is covered in detail in section 4, including the criteria for indicators and techniques for determining a minimum dataset. After a list of the most often suggested indicators, there are sections on new indicators of soil quality that may have additional value as well as how to interpret indicator values, including how they might be combined to create an operational soil quality index and any drawbacks.We outline the essential actions needed for a successful assessment of soil quality in the findings (section 5) and examine the degree to which they have been put into practise thus far. In conclusion, improving soil quality is seen in the broader context of improving environmental quality, where it is integrated into a collaborative process of knowledge production between scientists and other stakeholders in the pressing shift towards sustainable resource use and management.

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2. Ideas about the evaluation of soil

2.1. The fertility, quality, capability, quality, and health of the soil

Various concepts encompass different types of soil assessment.The primary interest in soil has historically been in its potential for agricultural productivity, aside from mineral mining. It's possible that assessments of the soil's potential for agricultural development were conducted prior to the existence of written records. Evidence can be found in the writings of Roman writers like Columella (Warkentin, 1995) as well as ancient Chinese works like "Yugong" and "Zhouli," which were written during the Xia (2070–1600 BCE) and Zhou (1048–256 BCE) dynasties, respectively (Harrison et al., 2010). Additionally, ethnopedology offers a number of native soil classifications that highlight signs that enable determination of a specific soil's appropriateness for a range of crops (e.g., Barrera-Bassols & Zinck, 2003). The idea of "soil fertility," which comes from German literature on "Bodenfruchtbarkeit," which is mostly correlated with crop yields, describes how suitable a soil is for agricultural output (Patzel et al., 2000). Based on this, soil fertility is defined by the FAO as "the soil's capacity to provide necessary plant nutrients and soil water in sufficient amounts and proportions for plant growth and reproduction in the absence of harmful substances which may inhibit plant growth" (www.fao.org). A nutritious soil "provides essential nutrients for crop plant growth, supports a diverse and active biotic community, exhibits a typical soil structure, and allows for an undisturbed decomposition," according to Mäder et al. (2002), who expand on this idea.

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2.2. Connecting ecosystem services and soil functions to soil quality

"The benefits which humans derive from ecosystems" is the definition of ecosystem services (Costanza et al., 1997). In addition to addressing a single ecosystem service, like the production of food, the early notion of soil quality was created by Doran and Safley (1997) and attempted to balance and portray the multifunctionality of soil. This has recently been further incorporated into the "functional land management" movement (Schulte et al., 2014), which evaluates the advantages and disadvantages of a multifunctional system for managing soil-based ecosystem services in agriculture as well as a wider range of land uses (Coyle et al., 2016).

3. Methods for evaluating the quality of soil

Since the 1990s, a vast array of instruments for evaluating and tracking soil quality have been accessible. Before going into greater detail about certain aspects of soil quality indicators in section 4.

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3.1. Analytical approaches to soil quality

We provide a summary of the major advancements in various nations here.In 1988, Canada launched one of the first national programmes to evaluate and track the quality of its soil (Acton and Gregorich, 1995). The programme used benchmark sites to evaluate changes in the soil over time, particularly with regard to the threats to the soil such as compaction, erosion, organic matter loss, acidification, and salinization (Wang et al., 1997). The data are still utilised in part to evaluate agri-environmental indicators that span soil, water, and air quality, even if the Canadian soil quality monitoring programme as such was not continuously maintained (Clearwater et al., 2016). Macdonald et al. (1998) introduced a coarser-scale GIS-based method to characterise mainly inherent soil quality.

3.2. Methods for visual evaluation of soil quality

The aforementioned methods of evaluating soil quality usually call for analytical laboratory space. More empirical, qualitative indicators that are easily evaluated in the field, produce quick findings, and improve communication between farmers and scientists are advantageous for approaches that focus on education and farmers (Beare et al., 1997).

For instance, a soil health score card was created for the Wisconsin Soil Health Programme that gathers farmer observations on the soil and plants in addition to a few questions about water quality and animal health (Romig et al., 1996). Developed in 2016, the GROW Observatory (http://growobservatory.org/) in Europe aims to provide farmers and other soil stakeholders with basic soil management tools, including instructional materials and field-based assessments.

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4. Indicators of soil quality

4.1. Conditions for indicators of soil quality

Different techniques to evaluating soil quality have found different needs for indicators of soil quality, although by no means all of them. Every article that outlines these specifications includes at least one conceptual criteria, such as the need that the indicator of choice be pertinent and related to a specific soil function, danger, or ecosystem service.

This is not very helpful, though, if the assessment of soil quality is not focused on a particular soil hazard, function, or ecosystem service.Practical criteria almost usually include simplicity of measurement and sampling, as well as cost and reliability considerations. Practical factors, such as the drawback of indicators requiring undisturbed samples, frequently contribute significantly to the rejection of otherwise appropriate indicators of soil quality (Idowu et al., 2008), which is a significant constraint from a scientific standpoint. Pedotransfer functions can provide a proxy value by measuring other properties, such as carbon and texture for bulk density, in cases where measuring a particular soil indicator—such as bulk density—is deemed too costly, too difficult, or impractical due to the stoniness of the soil (Reidy et al., 2016).

Comment [A10]: soil indicator, i.e. bulk density, is

4.2 Techniques for choosing a minimum dataset

Collinearity and the complexity of the interactions between indicators and management alternatives can both rise with the quantity of indicators. Furthermore, measurement expenses can quickly become unaffordable, particularly when comprehensive soil biological parameters are taken into account (O'Sullivan et al., 2017). For these reasons, a minimum dataset must be used to analyse the maximum number of soil quality indicators on a given set of samples.This choice was made using expert judgement in the first minimum datasets that were suggested (e.g. Doran and Parkin, 1994). Statistical data reduction through multivariate techniques like multiple regression (Kosmas et al., 2014), principal component analysis (PCA), redundancy analysis (RDA), and discriminant analysis (e.g. Andrews and Carroll, 2001; Lima et al., 2013; Schipper and Sparling, 2000; Shukla et al., 2006) became more popular as a result. Following this initial reduction of data, the number of indicators can be further reduced by simple or multiple correlation analysis (Andrews and Carroll, 2001; Kosmas et al., 2014). In some cases, this is followed by the application of expert judgement to select only one highly correlated soil property out of two or more (Sparling and Schipper, 2002). The final number of indicators chosen using these methods usually falls between six and eight. Validation of the minimum dataset is crucial, for example by examining its relationship to predetermined and independently measured management goals. This is because soil properties that are relevant for soil functioning but do not show much variation in a given study will not be included in the minimum dataset (Andrews and Carroll, 2001).

4.3. Often suggested markers of soil quality

We reviewed 65 minimal datasets of measured soil characteristics proposed in 62 publications in order to determine the most often suggested (combinations of) soil quality indicators. A specific categorization of measurable indicators was necessary due to the abundance of terms and methodologies; for example, aggregate stability, shear strength, tilth and friability, structure, consistency, and slake test were combined into a single category called structural stability. We attempted to cover the entire world by including both reports on national monitoring programmes and peer-reviewed academic articles on methods for assessing soil quality. Since assessing soil quality involves a number of steps, from choosing indicators to defining objectives to interpreting indicator values, we only included studies that addressed multiple steps and, therefore, had a certain conceptual and generalizable character.

As a result, research that completely focused on comparing a set of indicators across various management systems was disqualified. We observed that increasing the number of analysed datasets from 45 to 65 during the compilation rarely affected the result, despite the possibility that we may have overlooked several publications, particularly from national assessment systems. As a result, we are certain that our analysis presents a reliable image of the most widely used soil quality indicators.The most often suggested indicators of soil quality are pH, total organic matter/carbon, and various water storage indicators.

4.4. New markers of soil quality

When new or additional soil quality indicators are clearly valuable from the standpoint of the management objectives for a given scenario, they should be incorporated into minimal datasets. Future plans for measuring soil quality appear to be promising in light of recent advances in soil research, particularly in the area of soil biology but also in spectroscopy and other disciplines. We briefly cover these innovations below, which have the potential to significantly alter methods for assessing soil quality. They range from biological and biochemical indicators to data acquisition and high-throughput techniques.The functioning of soil is largely dependent on soil organisms. Thus, the inclusion of biological and biochemical indicators can significantly enhance evaluations of soil quality (Barrios, 2007).

Furthermore, in order to link abiotic soil characteristics to (changes in) soil functions in terms of biochemical and biophysical transformations as well as (possible) aboveground vegetation performance, the evaluation of biological indicators of soil quality is necessary (Lehman et al., 2015). However, black-box metrics like microbial biomass and soil respiration constitute the majority of the time when soil biological indicators are included in soil quality assessments. More precise indicators, including those based on nematodes (Stone et al., 2016b), (micro) arthropods (Rüdisser et al., 2015), or a variety of soil biota (Velasquez et al., 2007), have not been proposed much, despite their obvious promise. This may be because they call for specialised knowledge and abilities. Unfortunately, because soil biotaarehighly susceptible to environmental changes, they are thought to be the most sensitive indicators of soil quality (Bastida et al., 2008; Bone et al., 2010; Kibblewhite et al., 2008a; Nielsen and Winding, 2002). Particularly, indicators of soil-borne illnesses are desperately needed (Kyselková et al., 2014; Liu et al., 2016; Trivedi et al., 2017). Soil suppressiveness—which is characterised as a soil's innate ability to lower the incidence of plant diseases—becomes relevant in this setting (Hornby, 1983).

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4.5. Understanding the values of the indicators

An indicator is only helpful if reference values are provided and its value can be understood without a doubt. According to Doran and Parkin (1994), reference values for a specific indicator can come from two different types of soils: natural soils, which might not be suited for agricultural production, or soils with maximum production and/or environmental performance. For instance, in the Netherlands, ten reference soils with good soil biological quality were chosen from 285 locations that had been under observation for more than a decade (Rutgers et al., 2008). These reference soils (e.g., arable land on clay soil) illustrate particular combinations of soil type and land use. With the percentiles provided as a way to express the frequency distribution, soil quality indicators at a given site may thus be compared to those at the reference site as well as to the mean value, and the 5% and 95% percentiles of all sites under a certain land-use. The reference might not be at an optimal state in every parameter, which is a significant disadvantage of this strategy (Rutgers et al., 2012).

4.6. Creating an index of soil quality and substitutes

Notwithstanding Sojka and Upchurch's (1999) determination that this was not feasible, other investigations into soil quality have attempted to find a means of combining the data acquired for each soil quality indicator into a single soil quality index. For instance, to get the general indicator of soil quality (GISQ), Velasquez et al. (2007) added up the contributions of each of the five sub-indicators: hydraulic characteristics, chemical fertility, aggregation, organic matter, and biodiversity. An additive index in the SMAF produces a number between 1 and 10 (Andrews et al., 2004).Nonetheless, a weighting mechanism is required if the evaluated soil functions or ecosystem services have drastically differing relative priorities.

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5. Conclusion

Our analysis has shown how the goals, instruments and procedures, and general methodology of soil quality evaluation have evolved throughout time. The assessment of soil quality involves a number of phases, some of which are addressed in varying degrees by the numerous methodologies that have been developed over the past three decades and discussed in this article. A basic place to start would be with a precise statement of the goals, such as if the purpose of the soil assessment is to inform management decisions, serve as a teaching tool, or be a component of a monitoring programme. Likewise, to boost the adoption of the created assessment approach, target users should be identified and included from the start. A similar strategy has been used in the Horizon 2020 project LANDMARK, where stakeholder workshops were initially used to determine the assessment of soil functions and indicators (http://landmark2020.eu/ work-package/work-package-1/). Applying stakeholder-based evaluation calls for various instruments depending on the level of knowledge. For instance, farmers can use visual soil assessment tools to understand the condition of the soil structure in the field. However, laboratory measurements are necessary to gain a more detailed understanding of productivity. These can be obtained, for example, from Cornell Soil Health Assessment (Moebius-Clune et al., 2016) and from newly developed commercial soil testing services that use spectroscopic methods (see section 4).

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In order to fully utilise soil quality indicators and to convert the interpretation into suitable management and policy recommendations, reference or threshold values are needed. Mathematics developed in ecological risk assessment (Karlen et al., 2001; Rutgers and Jensen, 2011) can be applied to the assessment of the (dis)agreement of results obtained from different lines of evidence (e.g. sets of indicators based on physical, chemical, or biological parameters; see e.g. Velasquez et al., 2007).

Although it is frequently requested, an overall soil quality index is actually not particularly significant because it is ideal to evaluate soil quality in connection to certain soil functions.

When communicating with stakeholders, target users, and the general public, a graphical depiction of a soil's performance in fulfilling its multiple roles works far better than computing an overall index. Depending on the range of soil risks and ecosystem services at risk, various sets of soil quality indicators will be applied with varying weightings in practise, as stated by the "stakeholders."

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