Soil quality and health key indicators

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Key points

- The passage from the concepts of soil fertility to soil quality and soil health.
- Main principles in the use and selection of soil indicators.
- Considering spatial and temporal variations.
- Most commonly used soil quality and health indicators.

Introduction

Water and air quality are usually assessed considering their degree of pollution, as it impacts directly the health of humans and animals, and natural ecosystems. The soil quality concept is more complex, not only because soil encompasses solid, liquid, and gaseous phases, but also because soils can be used for a larger variety of purposes. Soil quality is not limited to the degree of soil pollution but is commonly defined much more broadly as "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 in Bünemann et al., 2018). The quality of soils determines agricultural and forestry sustainability, environmental quality and, as a consequence, plant, animal, and human health. Changes in soil quality over time can be due to natural events or, more often, to human use. Assessment of soil quality by the use of indicators is then mandatory to inform policymakers, farmers, and citizens about the impact of human activities on soil and its functions.

From soil quality to soil health

Historically, the term "soil quality" has been strictly related to the concept of land evaluation to support primary production. Indeed, the soil ecosystem service that was first considered by humanity was the production of food, feed and fibers, therefore assessments of the suitability of a soil for crop growth may have been taken into account since the origin of agriculture. Before the introduction of the term soil quality, the concept of "soil fertility" was used to describe the capacity of the soil to provide water and nutrients for plants. The FAO (Food and Agriculture Organization) described soil fertility as "the ability of the soil to supply essential plant nutrients and soil water in adequate amounts and proportions for plant growth and reproduction in the absence of toxic substances which may inhibit plant growth" (http://www.fao.org).

Although soil fertility is a basic concept that refers to the function of biomass production, the soil provides several other functions, important for ecosystems and human well-being. Another term has been then introduced, namely "soil functionality," which means the ability of a soil to provide functions and ensure the provision of the various ecosystem services. The European Commission published the communication "Towards a Thematic Strategy for Soil Protection" (COM 2006.231) where seven soil functions have been defined: (i) production of food and biomass, (ii) storage, filtering and transformation of compounds, (iii) habitats for living creatures and gene pools, (iv) physical and cultural environment, (v) source of raw materials, (vi) carbon pool, and (vii) archive of geological and archeological heritage.

To summarize, soil properties determine the soil functionality, that is the ability to produce functions that grant ecosystem services. The concept of "soil quality" is closely related to functionality, but it emphasizes the multi-functionality behavior of the soil, and it is related to land use. The better is the soil quality, the greater are the functions that the soil can perform optimally.

The need to assess the quality of soils at a certain scale, from continental scale to single farm, is mainly linked to the monitoring of the effects of human activities on soil resources. In the history of humankind, humans have often neglected the soil more than other natural resources, and this lack of awareness resulted in failures and the end of civilizations, namely the Maya in Central America, Vikings in Iceland, Rapa Nui people in Easter Island, and Mesopotamian civilizations. More recently, the catastrophic failures in land management of the 1930s in the United States began with ignorance of the Great Plains' soil resource, which was described as "indestructible and immutable" in the 1909 Bureau of Soils Bulletin.

Efforts to define and assess soil quality can be traced to publications from the 1960s to the 1970s. One of the oldest mentions in the scientific literature is by Klingebiel and Montgomery (1961), who defined soil quality as "an attribute of a soil that cannot be measured directly, but which is deduced from soil properties and soil behavior under defined conditions. Fertility, productivity, and erodibility are examples of soil qualities." Later, Mausel (1971, in Bünemann et al., 2018) when soil mapping in Illinois (United States), defined soil quality as "the ability of soils to yield corn, soybeans, and wheat under conditions of high-level management." It is clear that, historically, the concept of soil quality matched with "land capability," defined as the intrinsic capacity of a soil to contribute to agricultural production. The high-quality soils or "prime farmlands" were the soils of the first two classes of land capability, while the last classes were those only suitable for more or less productive forestry and pasture or just for ecological purposes (Klingebiel and Montgomery, 1961).

Doran and Parkin (1994 in Bünemann et al., 2018) considered the focus on agricultural productivity to be too restrictive and proposed that soil quality should be disconnected from productivity. Besides agricultural productivity, the soil quality concept should include the ability of soils to contribute to environmental quality and to promote plant, animal, and human health. In 1993, the U.S. National Research Council (NRC) published an agenda for U.S. policymakers, titled "Soil and water quality: an agenda for agriculture", which stressed the importance of soil quality and its application in land management. The agenda reported that national policies should not only focus on controlling erosion and conserving agricultural productivity, but they should also consider other threats to soil quality, namely salinization, compaction, acidification, and loss of biological activity. In the same year, the U.S. NRC also established the Soil Quality Institute (SQI), with the mission to develop tools for soil quality assessment. During the 1990s, one of the first methods used to assess soil quality was through the development and use of soil quality scorecards. In 2001, the U.S. Department of Agriculture published the first guidelines for "Soil Quality Assessment in Conservation Planning," where a series of indicators and a field record were proposed.

Sojka et al. (2003) (in Bünemann et al., 2018) criticized the "soil quality" paradigm, expressing dissatisfaction with the idea of a universal soil quality index and with the formal adoption of soil quality evaluation. They also affirmed that soil quality lacks standards and oversimplifies the complex interactions occurring in soil, therefore the concept of "quality of soil management" should be preferred. Although their proposal did not find much support in the scientific society, their criticisms have influenced the development of soil quality evaluation, in which soil management has become central. Soil quality assessment should provide scientific tools to evaluate the management of soil resources, considering not only biomass production but also other ecosystem services provided by the soils (Bünemann et al., 2018).

The original concept of soil quality is continuously evolving and recently has often been replaced by "soil health," to emphasize the behavior of the soil to be a dynamic living resource. Some authors consider the terms "soil health" and "soil quality" to be equivalent and interchangeable, while others differentiate the meaning of the two words. Soil quality is related to soil functions or what it does, while soil health presents a holistic view of the soil as a dynamic living resource (Lehmann et al., 2020). Soil health has also been illustrated as an analogy to the health of an organism or a community. More specifically, soil health has been defined as the "capacity of soil to function as a vital living ecosystem that sustains biological productivity, maintains environmental quality and promotes plant, animal, and human health" (Doran and Zeiss, 2000). Recently, the FAO Technical Group on Soils (ITPS) defined soil health as "the ability to sustain productivity, diversity and environmental services of terrestrial ecosystems" (http://www.fao.org).

Soil health should be maintained, promoted, or recovered through the implementation of sustainable soil management practices. In recent years, several foundations with the mission to promote, safeguard, and enhance soil health through scientific research and advancement have developed in several countries of the world, often supported by their governments. Policymakers have increased awareness of soil health and its importance for the environment and human health. In addition, some major companies are starting soil health programmes to manage their supply chains more sustainably.

In 2012, member countries of the FAO established the Global Soil Partnership (GSP) as a collaborative mechanism to ensure soil governance and promote sustainable soil management (SSM). The GSP is developing technical and policy tools to adapt the principles of sustainable soil management to local needs and stakeholders, as well as to encourage investment in technical cooperation, education, and awareness (http://www.fao.org). After the International Year of Soils 2015 and the revision of the World Soil Charter, the GSP published the Voluntary Guidelines for Sustainable Soil Management (VGSSM). The VGSSM has been aimed at being a reference that provides general technical and policy recommendations on SSM for a wide range of stakeholders, including governments, forest and land managers, agricultural advisors, farmers, civil society and academia. In 2020, FAO-ITPS (http://www.fao.org) published the "Protocol for the Assessment of Sustainable Soil Management," where they reported the recommended indicators and the approaches to evaluate SSM. A farmer-to-farmer training system, called the "Global Soil Doctors programme" was also developed by the GSP in 2020. The programme aims to educate farmers on sustainable soil management and the preservation of soil health through a set of tools including educational material, a soil testing method (STM), and a soil testing kit (STK) for preliminary soil analyzes (http://www.fao.org).

The European Union has also adopted the term soil health. In a recently published document entitled "Taking Care of the Soil is Taking Care of Life" soil health is defined as "the continuous capacity of soils to provide ecological functions for all forms of life." The document puts soil at the center of the actions to be taken to achieve the sustainable development goals set by the European Green Deal (https://ec.europa.eu/info/publications/caring-soil-caring-life_en).

Different approaches on soil indicators: Quantitative and qualitative, field and laboratory analyzes, visual assessments

Assessment of soil quality and health indicators (SQI, SHI), and monitoring the direction of change with time, are fundamental to determine the sustainability of land management and to verify the effectiveness of the strategies for conservation management practices. An important aspect to take into account for soil quality assessment is the identification of a set of indicators or attributes that are sensitive to changes in land management, which influence the capacity of a soil to fulfill its functions. Such indicators can be assessed using qualitative or quantitative techniques and should be easy to measure as well as sensitive to variations in climate and management (Bünemann et al., 2018). Approaches that target farmers and stress the educational aspect usually involve qualitative or semi-quantitative indicators, which can be easily assessed in the field, deliver rapid results, and facilitate communication between farmers and scientists (Fig. 1).

Standardization of the methods to collect and group indicators is also fundamental, although monitoring soil quality is usually planned with specific goals and areas of the study. For example, specific studies on soil quality have been made to evaluate the effects of tillage types in croplands, different types of agricultural management of extensive agricultural areas, land-use change, and urban soils. The reliability of SQIs mainly depends on their ability to represent the spatial and temporal variations within a certain study area. Therefore, it is difficult to find a universal approach to evaluate soil quality worldwide and in all situations. Increasing awareness of soil resources and national regulations have catalyzed a proliferation of various SQI and SHI, guidelines, and scorecards for field surveys. Among the different approaches, qualitative methods based on direct visual assessment of field indicators are the most rapid, easy, and cost-effective. One of the most widely used worldwide is the Visual Soil Assessment (VSA), proposed by the FAO to assess soil quality worldwide, which is based on the visual appraisal of key soil "state" and plant performance indicators. The VSA guidelines have been developed for general land cover categories (annual crops, pastures, orchards) and some specific crops (maize, olive orchards, vineyards, wheat) (http://www.fao.org).

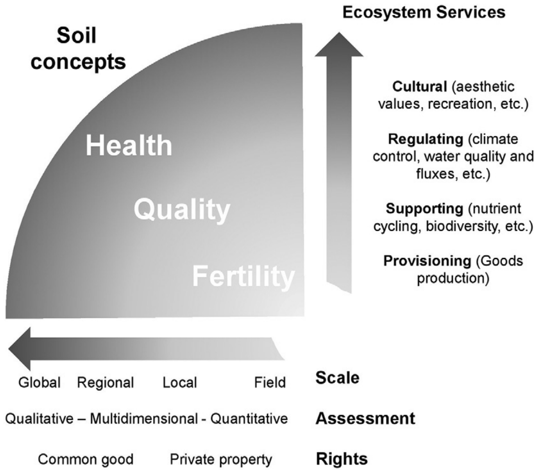

Fig. 1 Graphical sketch to summarize how the different soil concepts, namely soil health, quality, and fertility, are affected by the scale and methods of assessment. On the right, how the different concepts are relevant for soil ecosystem services. The figure was inspired by the sketch of Lehmann et al. (2020).

Another widely used visual method is based only on soil physical characteristics, and it is called Visual Evaluation of Soil Structure (VESS) (Franco et al., 2019). This method is included in the "spade methods" as it involves the sampling of an undisturbed soil slice 0.25-m deep, 0.1-m thick and 0.2-m wide using a straight spade. The VESS scorecard includes the evaluation of structure quality, consistency, aggregate-size distribution, porosity, and roots frequency.

Visual methods are important because they can be included among the techniques of citizen sciences, as they can be executed by non-experts of the soil. On the other hand, visual soil assessment alone cannot fully evaluate the state of ecosystem services driven by biological, chemical, and hydrological soil processes. A combination of visual assessment and low-cost laboratory analysis is needed to improve soil quality determination.

In the United States, the Cornell Soil Health Test offers various soil health testing packages for farmers and policymakers. Furthermore, the U.S. Department of Agriculture developed the "Cropland In-Field Soil Health Assessment Guide" as a qualitative diagnostic tool for field use to help U.S. conservation planners. The guide includes 11 indicators that can be easily monitored in the field to assess the impact of soil management on croplands.

In addition to the qualitative methods described above, quantitative methods to assess soil quality have also been proposed. To capture the overall state of the soil, quantitative methods usually have complex and multivariate approaches, such as "least square regression" models. In some cases, the measurement of a specific soil feature can be relatively time-consuming and becomes impractical to analyze in the laboratory. In that case, the literature has reported several pedotransfer functions (PTFs) to estimate some soil parameters through the measurement of basic soil properties, which are easier to analyze and are often available in the soil databases. The PTFs are frequently used to estimate the hydrological properties of soils, in particular, saturated permeability (K_{sat}) and available water capacity (AWC), but others have been developed to estimate many other properties, like oxygen diffusion coefficient and cation exchange capacity (CEC).

Importantly, the soil classification and taxonomic systems, such as the World Reference Base (IUSS Working Group WRB, 2014), and Soil Taxonomy (Soil Survey Staff, 1999) are not only based on soil genetic processes but also characteristics related to soil fertility and quality. Soil evaluation based on soil classification has been conducted for many purposes, such as assessment of soil productivity (Eswaran et al., 1997, see Bünemann et al., 2018), cadastral quality and value of soils (Sapozhnikov and Granina, 2021), as well as soil quality in urban environments (Makki et al., 2021). Therefore, the type of soil can be used as an indicator of soil quality, with different possible interpretations according to the detail of the taxonomic level. Soil classification systems usually focus on the subsurface horizons in addition to the topsoil, therefore, soil types are better indicators of slowly changing environmental conditions.

Selecting indicators

Many frameworks exist for soil quality and health assessments, and they are characterized by various indicators and their aggregation. Such indicator frameworks can be divided into three groups concerning their main focus: (i) assessing soil quality of a certain territory, based on detailed field measurements or by soil database and associated models; (ii) comparing the impact of different soil management systems; (iii) elaborating on the status of specific soil threats. In addition, the selection of indicators should be made based on the type of land of interest: croplands, forests, polluted soil, etc. A review by Bünemann et al. (2018) reported the frequency of the indicators used in the literature. The most commonly used to assess soil quality and health are soil organic carbon/matter, pH, available phosphorus and potassium, total nitrogen, water storage, and bulk density. Other indicators are less commonly used because of the difficulty and/or costs of the measurement, for example, labile organic carbon, soil respiration, microbial biomass, earthworms, and micronutrient availability. Further indicators are used to assess the state of specific threats, for example, sodicity–salinity for salinization processes, or presence of contaminants. The technical literature reports a long list of possible soil indicators, and there is no general agreement about the ones to use in the different national legislations and policies. In some cases, indicators are grouped in a comprehensive soil quality index equation, after the application of weight factors provided by the experts.

A possible strategy is the setting of a minimum dataset to overcome problems like costs of measurements, collinearity, as well as excessive complexity of the relationships between indicators and management options (Bünemann et al., 2018). Selection can be carried out through a statistical data reduction by multivariate techniques such as principal component analysis (PCA), redundancy analysis (RDA), and discriminant analysis. A selection of a minimum dataset of soil indicators is also recommended by the FAO, the Soil Quality Institute, and the EU expert panel, while larger datasets are advised for specific purposes.

Interestingly, some methodological approaches include features of soil health indicators that are not directly related to soil characteristics. For example, the FAO protocol includes the evaluation of soil productivity through the weight of the total biomass or an estimate of the dry biomass per unit area. The EU expert panel includes vegetation cover and soil sealing in the minimum dataset, because of their direct impact on soil health in farmland, forestry, and urban settings. The Implementation Plan of the Soil Deal for Europe also considers landscape heterogeneity and forest cover (https://ec.europa.eu/). The inclusion of landscape features within soil indicators shows the attempt to use indirect traits of soil health that can be monitored through remote sensing, such as satellite images. A recent approach in assessing the effectiveness of management strategies is by combining analysis of the spatial pattern of vegetation with qualitative soil surface indicators. This simplified but effective methodology allows the monitoring of variation in landscape functioning in space and time, and it is particularly suitable for the assessments carried out at intermediate territorial scales (Costantini et al., 2016).

Soil indicators across spatial and temporal scales

The soil information needed to assess and monitor soil quality and health depends on the spatial and temporal scales. The area of consideration can be punctual like a site on a landscape, a small research plot, etc., or as large as a nation or a continent. The reliability of broader-scale assessment will depend strongly on the quality of the database in terms of the spatial distribution of observations and quality of the data, as well as on the efficiency of models to interpolate the data in the area of interest. Two approaches that deal with spatial scale have usually been used by researchers (Fig. 2). The first is based on the selection of the most sensitive set of indicators, the method of their aggregation, and the spatial distribution, for the geographic scale for which soil quality assessment is performed. In general, broader scales will include easier, more economic, and less precise indicators than detailed scales. In this approach, the quantity of data is more important than the quality, because the interpolation is data-driven. The second approach is based on precise and detailed punctiform measurements that can be expanded to a larger area of investigation by combining interpolation and extrapolation models. This approach is more costly but provides more detail on the investigation at the monitoring sites. In this case, the extrapolation is model-driven, therefore the selection and calibration of the model to spatialize the information are fundamental to obtain reliable soil quality assessment of a certain area.

The selection of monitoring time frames is also fundamental for soil quality assessment because the effect of climate, soil moisture conditions, stage of plant growth, and human factors can cause great temporal variability in indicator status. Biological and biochemical indicators, in particular, show strong temporal variability, mainly due to fluctuations of soil temperature and moisture. The response time for an individual indicator to change, as a result of management, determines the appropriate time interval for monitoring indicator changes.

Indicators with a strong sensitivity to rapid changes (Table 1) may be used as either an "early warning system" of degradation, or to assess the effectiveness of soil management changes at the field scale. Different management practices affect different aspects of soil functionality, especially indicators associated with labile organic carbon, enzymatic activity, and biodiversity. For instance, changes in tillage intensity appear to have greater effects than organic vs. conventional practices (van Es and Karlen, 2019).

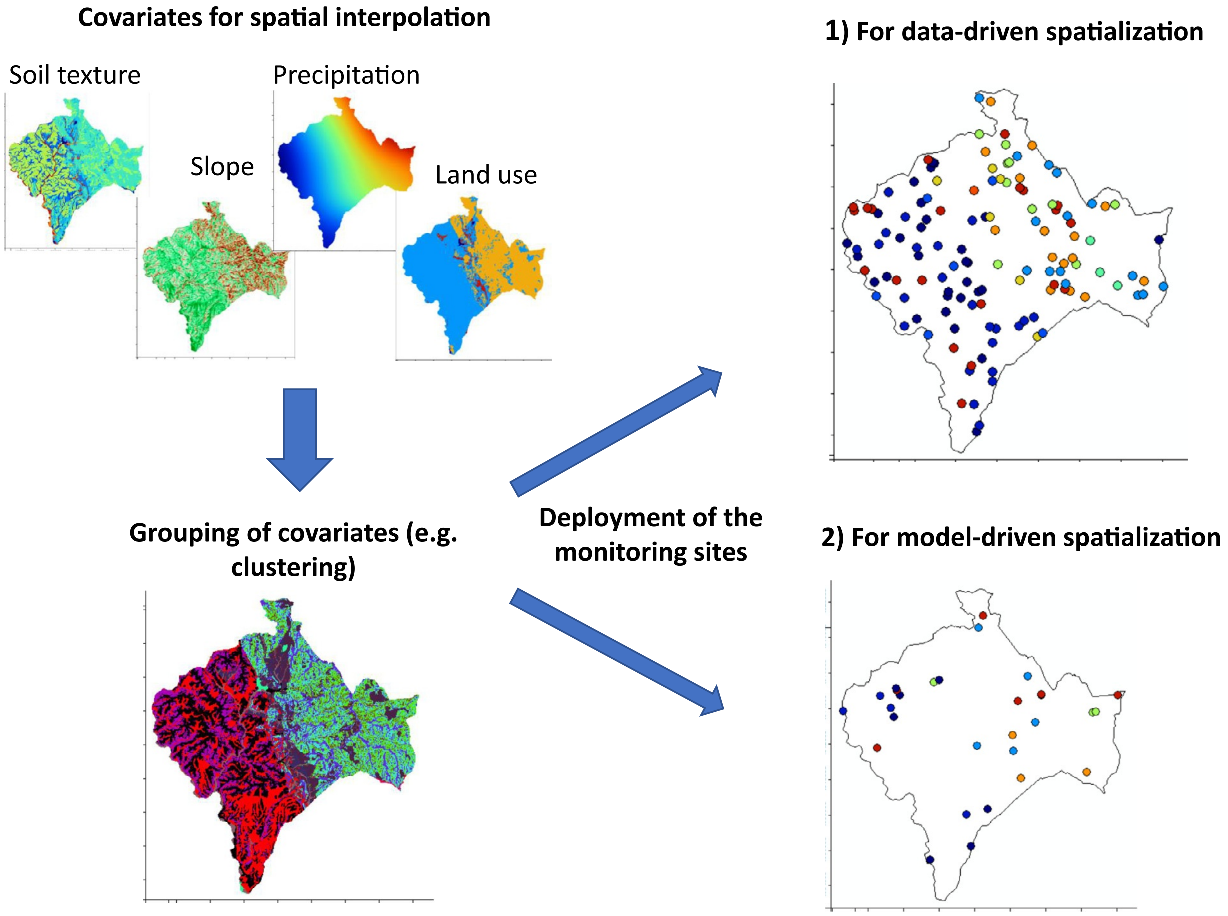

Fig. 2 Deployment of the monitoring sites. After the selection of the covariates for spatial interpolation, they are grouped and used for the deployment of the monitoring sites. The spatialization can then follow two alternative ways: data or model-driven. The first one is more suitable for a large number of easy to measure and cheap indicators, representative of the territory. The second way is for precise and sensitive (e.g., biological) indicators, when they are strongly related to one or more covariates of interpolation (e.g., land use).

It must be also considered that for the soil system many natural or anthropic interventions can be seen as "catastrophic events," in the sense that they largely disturb and disrupt soil characteristics and functionalities. Exceptional events, like flooding and consequent accumulation of sediment, aeolian erosion and deposition, slumps, earth slides, or gully erosion, can result in truncation of the soil profile or its burial. Similarly, anthropic activities such as land leveling, slope reshaping, and deep ploughing can profoundly modify the soil profile and its quality (Costantini et al., 2018). In these cases, which are increasingly frequent in both space and time, there is little value in considering the sensitivity of soil quality indicators because they might all change abruptly. On the other hand, at the landscape spatial scale, it is critical to consider indicators that focus on long-term changes, to overcome the short-term variation in land use and management. Soil indicators that change slowly are more related to inherent soil qualities and can reflect the impacts of climate and long-term management changes (Pellegrini et al., 2018).

The placement of monitoring sites should reflect the soil spatial and temporal variability of the indicators used. This is perhaps the most delicate and professional part of the work. The areas selected must be representative of both the soil and management practice to be assessed. A more accurate delimitation of the study area within a management type can take place based on the characterization of soil through proximal sensing by, for example, geoelectric, spectrophotometric and radiometric sensors. It is crucial to make comparisons within the same type of soil. The great variety of soil properties, even within a limited territory, means that the values of soil indicators cannot be compared with those at a different soil site. The risk is that of arriving at wrong or approximate evaluations, as a consequence of inadequate sampling. Correct use of the indicators passes from a comparison with the measurements carried out on the same area before starting the testing of the management practice, or on similar and nearby areas that have not received the treatment studied but have the same soil type.

Most common soil quality and health indicators

The main soil indicators can be grouped according to their relevance to provide specific functions. In this chapter, we focus on the soil indicators that are related to soil quality and health, are affected by management, and sensitive to variations. The indicators related to soil functions that are not directly related to soil management, namely the ability of the soil cover to support human activities and infrastructures (bearing capacity) or to be used as a source of raw materials, the role of an archive of geological and archeological heritage, its cultural and esthetic values, are omitted. Among the indicators described below, those that are most relevant and commonly used in monitoring programmes are reported in Table 1.

Water supply

One of the most important soil functions is to provide and regulate the water uptake by plants and other organisms that live in the soil. Soil degradation very often goes together with the impairment of this paramount function. The potential water supply can be assessed and monitored in different ways, but the most common soil indicators are available water capacity, rooting depth and volume, bulk density, and soil salinity.

The most common indicator used to estimate the amount of potentially available soil water for plants is the so-called "available water capacity" (AWC), which refers to the water held in the soil between "field capacity" (matrix potential of fine earth (<2 mm) at -33, -10 kPa for sandy soils) and "permanent wilting point" (matrix potential of -1500 kPa). The easily available water is the fraction of AWC held between -10 and -200 kPa, which is more affected by temporal variation and soil physical conditions, in particular macroporosity and structure. In addition, the study of the relationship between water tension and volume (water retention curve) can provide useful indicators of the soil structural quality. Many times, AWC is estimated through particle size distribution.

The amount of water that is potentially available for plants depends on the soil volume that can be explored by roots. Rooting volume is based on multiple factors. First, rooting depth, the distance between the soil surface and a horizon or layer preventing root penetration, such as a consolidated substrate, a cemented pedogenetic horizon, a layer very rich in salts, or a water table. Second, there is the need to subtract the volume of soil that cannot be penetrated by roots, namely the quantity of unaltered skeleton, very firm clods, and the parts of the soil profile volume that show very marked compaction (Priori et al., 2021).

Soil penetration resistance can be useful for estimating the compaction of soil horizons. It indicates root-impeding layers, such as hardpans or dense soil layers, and can be used to compare relative strengths among similar soil types. Moreover, field observation of soil consistence and root growth pattern can give useful hints on where to place the measurements.

Soil bulk density is an indicator of the porosity of the soil mass, therefore of the maximum volume that can be occupied by water and air. It is also called apparent volumetric mass, to differentiate it from the real volumetric mass, or the real density, which depends on the densities of the soil minerals and organic components. It is calculated as the dry weight of the soil divided by its volume, including both the volume of soil particles and the pores. Particular care must be taken to exclude gravels from the computation. Bulk density not only reports the quantity of voids in the soil mass but also reflects the degree of aggregation of the soil particles (the soil structure). Therefore, it is strictly related to the ability of plant roots to penetrate into the soil mass, and also of the soil to function for structural support, water and solute movement, and gas exchanges.

Soil salinity is the accumulation of water-soluble salts in the soil profile, mainly chloride, sulfate, carbonate and bicarbonate of sodium, magnesium, calcium, and potassium. Salinity increases the osmotic potential of the soil water solution, which limits the plant's capacity to absorb water. Salinity can be estimated using electrical conductivity (EC).

Oxygen supply

Most of the organisms living in soil and plant roots need good aeration and the presence of oxygen in the soil atmosphere. Good soil health and functionality go together with a large presence of interconnected macropores, letting the soil atmosphere, which is richer in carbon dioxide, to be oxygenated with atmospheric air. The kind of macropores that ensure an effective diffusion of oxygen within the soil mass are those produced by the biological activity of soil fauna, flora, and roots. The soil indicators used to assess potential oxygen supply are mainly related to soil structure. Apart from wet aggregate stability, particle size, bulk density, and air capacity are among the most utilized. Soil porosity can also be estimated by visual assessment or by the micromorphometric method.

Oxygen supply is also related to sodicity because excess sodium can lead to the destruction of soil structure through the swelling and dispersion of clay particles and the formation of low permeability layers that restrict root growth. Clay dispersion also reduces water infiltration throughout the soil profile and causes waterlogging, clogs drainage pipes, reduces the bearing capacity of the soil (restricting the use of machinery to work the soil), and enhances surface and subsurface soil erosion.

There are also good macro- and micro-morphological methods to assess the state of soil oxygenation. In particular, the field assessment of soil structure and consistence, as well as the study in the field and under the microscope of porosity and redoximorphic features, are considered in the most important soil classification schemes. In the WRB classification system (IUSS Working Group WRB, 2014), in particular, the presence of more or less expressed stagnic properties indicates that the infiltrated water cannot be drained at depth and saturates the soil profile. Gleyic properties, instead, refer to the presence of shallow groundwater for most of the year when soil temperatures permit biological activity.

Nutrient supply

Plants need nutrients in different supply ranges, which are usually higher for productive crops. Among basic macronutrients (nitrogen (N), phosphorus (P), potassium (K), sulfur (S), magnesium (Mg) and calcium (Ca)), total nitrogen and available phosphorus are the most frequently suggested in soil quality and health monitoring schemes (EJP-SOIL, 2021). Plant available phosphorus, in particular, is often the most limiting nutrient for crop and forage production. It is used to monitor chemical soil fertility as it is a stable element, and its mobility in the soil is limited. In addition, potentially mineralizable nitrogen, which represents the fraction of nitrogen that can be easily decomposed by soil microorganisms, is considered in monitoring the effects of soil management on nitrogen availability during the growing season and as an indirect measure of biological activity.

Minor nutrients (molybdenum (Mo), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), nickel (Ni), boron (Bo), selenium (Se), and chlorine (Cl)), although essential for plant growth, are only considered when symptoms of deficiency in plants have been recognized.

Other main soil indicators of nutrient supply are pH, cation exchange capacity, base saturation, and soil mineralogy. Soil pH gives an important indication of the availability of plant nutrients, and different crops thrive at different pH values. Soil pH may change in response to management activities such as liming, fertilizer addition, irrigation that leads to the accumulation of salts, and some forms of soil pollution. Soil pH controls the solubility and mobility of heavy metals, such as Al (aluminum), Fe, Mn, Cu, and Zn, and nutrients, such as phosphorus. It also controls the toxicity of many heavy metals.

The CEC of soil represents its capacity to hold and exchange positively charged cations, in particular, H, Al, Ca, Mg, K, and Na. The CEC is a characteristic of the soil that is influenced by both very stable (soil mineralogy) and dynamic (organic carbon) properties and affects the soil's retention of fertilizers and other ameliorants. The base saturation of the CEC depends on the presence of Ca, Mg, K, and Na, in contrast to the acidic saturation of H and Al, and it is the basis for cation availability and the buffering capacity of soil pH.

Some indicators highlight the proportion of different cations on the exchange complex (e.g., K/Mg, Ca/Mg). This is particularly important for Na^+, as an excess of it can negatively alter cell morphology, plant photosynthesis, and chlorophyll production. The exchangeable sodium percentage (ESP) is the amount of Na^+ adsorbed on the surfaces of the soil particle as a proportion of the CEC, while the sodium absorption ratio (SAR) is the relative concentration of Na^+ to Ca^{2+} and Mg^{2+}.

The contents of total and active calcium carbonate are important in regulating the supply of nutrients for plants and microorganisms, and their abundance may decrease the iron uptake, but can also interfere with the supply of water and oxygen. The quantity and activity of carbonates can vary according to soil management, in particular the quality and quantity of irrigation water. Degraded soils may show higher values of carbonates (Costantini et al., 2018).

Regulation of runoff

Soil surface characteristics regulate water runoff and soil in good health can limit runoff by increasing infiltration, while degraded soils on slopes show increased runoff. Soil indicators related to runoff are particle size, surface stoniness, infiltration capacity, and crusting susceptibility. The presence on the surface of gravel and stones acts as a mulch, protecting the surface aggregates from raindrop impact, favoring water infiltration, and reducing runoff. Soil infiltration rate is a measure of how fast water enters the soil under saturated or non-saturated conditions. Water entering too slowly can produce ponding conditions and reflect soil compaction, thus enhancing surface runoff and water erosion. The susceptibility of soil crusting depends on the soil characteristics, such as fine and coarse silt, clay, and organic matter content. Both soil infiltration and crusting susceptibility are strongly influenced by porosity and aggregate stability.

Sediment production

Soil characteristics regulate the production of sediments through erosion. Soil erosion can be caused by wind, water, or anthropogenic activities such as soil tillage. The volume of sediments detached from the soil can be measured in the field with various tools and methods, or by observing visible evidence of soil losses, or can be estimated through laboratory experiments or models that consider soil, climate, morphology, land use and management.

Soils regulate the production of sediments delivered to water bodies through the susceptibility to erosion. The main indicator is soil erodibility. Soil erodibility is the degree of resistance to the impact of raindrops on the soil surface and the shearing action of runoff water. Similar to crusting susceptibility, it can be considered a soil property that depends on soil texture, organic matter content, and aggregation. Other soil indicators related to erosion risk are surface roughness and stoniness, hydrophobicity, but also the content of soluble salts and sodicity in the soil profile, which can cause the formation of erosion tunnels under the soil surface.

Groundwater recharge

An important soil function is the ability to allow the infiltrating water to replenish the groundwater. The process is regulated by the capacity of the soil to infiltrate and hold water and let it percolate throughout the entire profile. Key factors are the depth of groundwater table and the presence of soil horizons that impede vertical movement (e.g., massive clayey layers, thick petrocalcic and petroferric horizons), or create preferential subvertical (e.g., horizons with vertic properties) or subhorizontal flows (e.g., fragic horizons).

The main soil indicators to be considered are infiltration capacity, AWC and hydraulic conductivity of the most limiting horizon of the soil profile.

Purifying capacity and regulation of contaminants

Soils in good condition are an essential filter for clean water and are low in contaminants. Water that moves through the soil is cleaned by physical, chemical, and biological processes. Small pores mechanically filter pollutants and, within pores, the negatively charged soil components, mainly organic matter and clays, capture chemicals with a positive charge, such as many toxic chemicals and ammonium. The bases held on the exchange complex contribute to neutralizing the soil solution, while pH regulates the chemical behavior of toxic elements. Soil organic matter can also have positive charges able to capture some negatively charged chemicals, such as nitrate. Soil bacteria and fungi may transform the pollutants into non-toxic substances such as carbon dioxide and water.

Although the purifying capacity of soil is a complex process, the main indicators used are cation exchange capacity, base saturation, pH, organic matter content, and rooting depth and volume. Indicators of the biodiversity pool are also relevant, but since it is difficult to relate them directly to purifying capacity, they are only used indirectly, or in specific cases of bioremediation.

Any substance that exceeds naturally occurring levels in the soil and poses health risks to life forms, in particular humans, is a contaminant. Soil indicators refer to the presence of contaminants whose nature, location, or quantity produces undesirable effects on the environment or human health. They can be very variable, such as heavy metals, different types of pesticides, excess nutrients, hydrocarbons, microplastics, etc. In Europe, the pollutants most frequently monitored are Cd (cadmium), Co (cobalt), Cr (chromium), Cu, Ni, Pb (lead), Zn, among the potentially toxic elements, while there are organochlorine pesticides, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls, among organic pollutants (EJP-SOIL, 2021).

Carbon sequestration

Soils support vegetation that photosynthetically captures carbon dioxide and host soil organisms responsible for its storage and recycling. Soil organic matter has long been the most widely used quality indicator.

The main source of soil organic matter (SOM) is the above- and below-ground residues of vegetation. The humification and decomposition of these organic materials sustain the soil food chain, as SOM is used as a source of energy for the soil micro-and meso-fauna and fungi. At the same time, mineralization of the plant residues releases nutrients into the soil solution, where they become accessible for uptake by the vegetation's root system. Soil organic matter is subjected to microbial degradation and its persistence can vary depending on both chemical recalcitrance and physical protection.

The main soil indicator is the organic carbon content, also called the organic carbon density. Derived from it is the carbon stock, which refers to the organic mass of the soil, calculated at the reference depth, considering bulk density and stoniness. Other derived indicators are the temporal changes in organic carbon and/or stock and the stratification throughout the soil profile. The stratification ratio is calculated by the SOC concentration at a shallow depth divided by that at a deeper depth. The stratification ratio is higher in soils that have stored more carbon in the topsoil, whereas it is lower when for example, water or wind erosion has occurred, there is compaction, fertility is poor, carbon input was limited or could not accumulate.

The thickness of the Ah horizon (topsoil mineral horizon with humus accumulation) is another useful indicator to monitor carbon sequestration and the variation in soil health.

Soil organic matter is composed of different functional fractions, which are defined according to their persistence capacity vs. decomposability. There are soil indicators used for monitoring the labile organic carbon fraction or "active" pool, which encompasses only very few per cent of the overall carbon pool and represent the most readily decomposable fraction. Among the most used, there are the hot water extractable carbon (Ghani et al., 2003 in Bünemann et al., 2018), the particulate organic matter (POM) (Cambardella and Elliott, 1992 in Bünemann et al., 2018), and the active carbon (Weil et al., 2003 in Bünemann et al., 2018). The POM, in particular, is the fraction of total organic matter which does not pass through a filter and that typically ranges in size from 0.053 and 2 mm, while active carbon is extracted with dilute, instead of concentrated, potassium permanganate to react with only the most readily oxidizable (active) forms of soil C. The labile organic carbon is responsive to land-use change and management practices, therefore, it has often been considered in monitoring soil health.

Biological activity and cycling of organic matter and nutrients

It is the activity of soil organisms that recycle dead organic matter and mineral inputs, producing mineral forms that plants and microflora can use for vegetative growth, and is at the basis of the soil food web. Several biological indicators have been widely used to monitor soil life in space and time. The most commonly used are the C:N ratio, microbial biomass carbon, microbial respiration rate, and enzymatic activity.

Biological properties are very sensitive to external conditions, as microorganisms require only a brief time to reproduce (from hours to days), allowing them to react to pressure and to transfer genetic modifications swiftly at population levels. This makes these indicators very sensitive to changes, but also increases the relevance of proper sampling. The cycle of organic matter and nutrients is usually evaluated in the laboratory as potential activity, because routine methods for open field measurements have not been standardized (e.g., Tea Bag Index, earthworm test). Potential activity means metabolic activity, including enzymatic activities that soil microbes are capable of developing under optimal laboratory conditions. The decomposition of SOM is carried out by microorganisms through the enzymatic attack of SOM and microbial respiration: extracellular enzymes degrade SOM through hydrolytic or oxidative processes, producing assimilable dissolved organic matter that can be rapidly incorporated by microbes.

Biologically active forms of SOM can function as short-term indicators of longer-term changes in SOM. Autoclaved-citrate extractable protein is an indicator of organically bound nitrogen that is easily mineralized by microbes (Hurisso et al., 2018).

Biodiversity pool

Healthy soils are capable of hosting great biodiversity. The term "soil biodiversity" is used in a genetic sense and denotes the number of distinct species (richness) in an ecosystem, and their proportional abundance (evenness), but can be extended to encompass phenotypic, functional, structural, or trophic diversity (Benedetti and Mocali, 2010).

Soil biodiversity plays an important role in supporting the sustainable productivity of ecosystems and regulating multiple other ecosystem services, including nutrient cycling, organic matter decomposition, pollutant degradation, and pathogen control in terrestrial ecosystems. However, the linkages between diverse soil organisms and ecosystem functions remain unclear, and the roles played by bacteria, fungi, protists, and invertebrates for multiple types of ecosystem functions remain largely unresolved. Soil biological diversity reflects the variability among living organisms including microorganisms (e.g., bacteria, fungi, protozoa) and mesofauna (e.g., nematodes, acari, and springtails), as well as the macro-fauna (e.g., earthworms, ants and termites).

Indicators for soil biodiversity include the collection of macro- and meso-organisms in the field by pitfall trapping, their identification and counting by a trained person, following extractions in the laboratory. Regular genomic analysis can also assess biodiversity more accurately at the microbial level. Currently, many methods are available to assess soil microbial diversity. The use of molecular techniques to investigate the microbial diversity of soil communities continues to provide a new understanding of soil properties and quality. Analysis of the soil-extracted nucleic acid sequences (DNA and RNA profiling) provides a powerful tool for characterization of the entire microbial community. The metagenomic approach is another method to assess simultaneously both soil microbial diversity and function (Benedetti and Mocali, 2010).

The analysis of types and amounts of different phospholipid fatty acids (PLFA) is a biochemical approach that offers an alternative to molecular techniques because it reflects both microbial taxonomic and functional diversity. The amount of total PLFA can be used as an indicator of viable microbial biomass; further characterization can be done based on the specific signature of biomarker fatty acids (Quideau et al., 2016).

Soil mesofauna composition (microarthropods <2 mm) has been proposed for the evaluation of soil ecosystem services, in particular, biodiversity pools. Soil-dwelling animals play a significant role in the colonization and restoration of degraded biological habitats. Their role includes litter fragmentation, soil aggregation and porosity formation, water infiltration, and the distribution of organic matter in soil horizons. The greater the number of different mesofauna groups adapted to the soil habitat, the better is the soil functionality. Healthy soil systems show a set of ecosystem niches and related organisms, while stressed soils are poorer, both in species and individuals. The QBS-ar index has been developed to overcome difficulties related to identification at the species level, by focusing on the evaluation of adaptability to hypogeal life. Higher values correspond to more complex and soil-adapted communities.

Table 1 Key soil functionality indicators.

Soil indicator	*Sensitivity to changes*[a]	*Method of evaluation and analysis*	*References*	*Cost of sampling and analysis*[b]
Available water capacity	Low	Sandbox and pressure-plate extractors	Cassel and Nielsen (1986)	Medium
Rooting depth and volume	Low	Visual assessment, bulk density, penetration resistance	Priori et al. (2021)	Low
Bulk density	Medium	The core method	Arshad et al. (1997)	Low
Penetration resistance	Medium	Penetrometer	Herrick and Jones (2002)	Low
Wet aggregate stability	Medium	Wet sieve procedure	Le Bissonnais (1996)	Medium
Hydraulic conductivity	Medium	Two-ponding head method; disc permeameter; pedotransfer functions	Reynolds et al. (2000)	Medium
Infiltration capacity	Medium	Double ring infiltrometer; disc permeameter	Lowery et al. (1997)	Medium
Crusting susceptibility	Medium	Cone penetrometer; pedotransfer functions	ASAE (1994)	Low
Erodibility	Low	Pedotransfer function	Torri et al. (1997)	Low
Total nitrogen	High	Micro-Kjeldahl determination; dry combustion	FAO-GSP-GLOSOLAN (2021)	Medium
Potentially mineralizable nitrogen	High	Anaerobic incubation	Drinkwater et al. (1997)	Medium
Available phosphorus	Medium	Olsen, Bray, and Mehlich methods using sodium bicarbonate or other extractants	FAO-GSP-GLOSOLAN (2021)	Medium
pH	Low	Electrode system	FAO-GSP-GLOSOLAN (2021)	Low
Cation exchange capacity (CEC)	Low	Sum of cations on the exchange complex	Sikora and Moore (2014)	Medium
Base saturation of the CEC complex	Low	Calculation—percentage of sodium on the total exchangeable cations	Sikora and Moore (2014)	Low
Sodicity—Exchangeable Sodium Percentage (ESP) of the CEC	Low	Calculation—percentage of sodium on the total exchangeable cations	Sikora and Moore (2014)	Low
Salinity—Soil Electrical Conductivity (EC)	Medium	Standard electrical conductivity meter system on saturated paste of different soil: water ratios	FAO-GSP-GLOSOLAN (2021)	Low
Total carbonate content	Low	Gas-volumetric method using Dietrich-Fruhling Calcimeter	Sparks (1996)	Medium
Thickness of the Ah horizon	Low	Visual assessment	Jahn et al. (2006)	Low
Organic carbon	Medium	Walkley-Black titration and colorimetric method; dry combustion	FAO-GSP-GLOSOLAN (2021)	Medium
Labile organic carbon	High	Hot-water extractable carbon; particulate organic matter; active carbon	Weil et al. (2003 in Bünemann et al., 2018)	Medium
C:N ratio	Medium	The ratio between organic carbon and total nitrogen		Medium
Microbial biomass carbon	High	Substrate induced respiration (SIR); chloroform fumigation extraction (CFE)	Alef and Nannipieri (1995)	High
Microbial respiration rate	Medium	Laboratory-based soil respiration measurement (static or dynamic)	Bastida et al. (2008 in Bünemann et al., 2018)	High
Enzymatic activity: *N*-acetyl-β-glucosaminidase, β-glucosidase, butyrate esterase, acid phosphatase, arylsulphatase, β-xylosidase, cellulose and acetate esterase	High	Incubation and fluorescence	Marx et al. (2001)	High
DNA and RNA profiling	High	RNA genes amplified via Polymerase Chain Reaction (PCR), analyzed by Denaturing Gradient Gel Electrophoresis (DGGE)	Kowalchuk (2004)	High
Phospholipid fatty acids	High	Solid-phase extraction and chromatography	Quideau et al. (2016)	High
QBS-ar index	Medium	Berlese–Tullgren extractor	Parisi et al. (2005 in Bünemann et al., 2018)	Medium

[a] Excluding intense soil perturbation, such as anthropic earthworks, strong manuring, liming and additions of other materials. High = day and single management variations; medium = seasonal and main year management variations; low = long term variations, land-use changes.

[b] High = specialistic analysis with skilled personnel and/or high costs; medium = routine wet laboratory analysis; low = low-cost laboratory analysis, field assessment.

Conclusions

The selection of appropriate indicators for the scope of soil quality and health assessment and monitoring, the methods of analysis, the elaboration and interpretation of results, their reporting and the guidelines given to farmers, policymakers and the general public, are still the object of great debate and a wealth of studies. In general, the list of suggested indicators is never exclusive, leaving room for the use of further indicators. Similarly, the choice of a minimum dataset should have sufficient degrees of freedom to meet the aims of the assessment and the availability of resources. However, the inclusion of at least one or two indicators for each of the physical, chemical, and biological properties of the soil is always recommended to arrive at a proper evaluation of soil functions.

When databases are incomplete for some important soil characteristics, measured data may be substituted by information derived from pedofunctions or rules, based on local, benchmark soils. On the other hand, if the datasets are limited or we make use of many derived characteristics, the benchmark sites are particularly important for validating the results given by the indicators.

The relevance of trained and specific competencies in the use of soil indicators cannot be overemphasized. The selection of indicators and methods of analysis, knowledge of the local soil types and their variability, interpretation and use of the results all require close cooperation of professionals with different and specific expertise.

Future developments should go towards increasing integration between field observations and measurements, use of proximal and remote sensors, and laboratory analysis. It should always be kept in mind that soil is a complex system where processes act throughout the whole profile, not only in the topsoil, and that simplification (use of few indicators or synthetic indicators) and approximations (derivative indicators, pedofunctions) can easily lead to incorrect, incomplete or biased results.

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