Soil health in a nutshell

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Soil is the upper layer of the earth's crust. It consists of a mixture of mineral particles, organic material, organisms and liquids, and has various physical, chemical, biological and morphological properties. It sustains plant life, which in turn sustains the lives of animals and humans.

Since we rely on soil to supply food, feed and fibre to the world, it is an essential natural resource. Furthermore, it is not merely a substrate for the growth and proliferation of plants, but it also maintains environmental quality through services like the decontamination of water, sustaining biodiversity, maintaining ecosystems, and serving as a carbon sink.

Despite its significance to the survival of life, soil is constantly degraded mainly through agricultural processes. More than 50% of agricultural soils are moderately to highly degraded. Soil degradation is the result of erosion, pollution, extensive cultivation, overgrazing, and land clearing. Moreover, the growing human population increases the demand for feed, fibre and food, and puts immense pressure on all natural resources, including soil.

What are soil health and quality?

Soil health is associated with the fitness of the soil to function as a system to sustain biological productivity, environmental quality, and animal and plant health. Soil health considers the soil as a living system, which delivers services. The functioning of this system is mostly carried out by a myriad living organisms that require management and conservation.

Healthy soils are synonymous with sustainability, whereas life cannot thrive in unhealthy soil. Soil health is, therefore, a major contributor to agricultural productivity and sustainability, and indirectly affects human, animal, and plant health. Soil health varies according to the soil characteristics and properties and currently, mainly due to the complex nature of the soil, there is no consensus on what the exact requirement for healthy soil is.

Soil quality refers to the inherent properties of soil, including chemical and physical properties that are intertwined with regional ecosystems and climate. Practices such as mechanical soil cultivation and repeated production of crops on the same soil over many years can cause physical loss of soil through soil erosion. These farming methods also cause loss of organic matter in the soil and the release of CO_2 into the atmosphere.

The conservation and maintenance of soil quality are non-negotiable in the quest for sustainable plant production systems, yet it can be a major challenge to develop agricultural systems that sustain high levels of plant production while conserving the land.

Soil health and quality assessment

Soil health and quality vary across environments, climates and land use management types and can be measured in several ways. Soil organisms are surrogates for soil health and quality because the abundance, diversity and functions of these organisms strongly correlate with the health and quality status of the soil. As the environment and soil properties change, so does soil biology. These biological measures link directly with the abiotic environment in which the organisms live.

Soil organisms also respond to anthropogenic disruption and are indicators of soil ecosystem services. They live in soil and respond sensitively to climate and land management practices. These ecosystem services include contributions to water-holding capacity, decomposition of organic materials, recycling of nutrients, detoxifying toxins and promoting plant health by suppressing pathogenic organisms.

In addition, the organisms that live in the soil also reflect the properties of the soil – their abundance, diversity, community stability, and food web structure are indicators of the status of the soil. As a surrogate for soil health and quality, organisms that live in soil are relatively inexpensive and easy to measure.

For example, earthworms have for many years been used to measure soil health, but the diversity and abundance of nematodes, mites, bacteria and fungi also provide information on soil health, quality and functions. Thus, the measurement of soil organisms is sensitive to disturbance and is correlated with soil function and a reliable indicator of soil health and quality; however, the measurement of soil organisms must follow well-developed sampling protocols and the relevant soil organism's identification processes.

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These organisms reflect land management decisions and ultimately the productivity and health of the plants and animals living off that soil. Indicators of soil health should be easy to understand for those who manage the land and are stewards of soil quality and health.

Assessments of soil health and quality are essential to sustainably manage land. These assessments help identify problems in production areas and help farmers and other land managers link science and practice when assessing the sustainability of their soils. Generally, soil health and quality indicators should assess both the biological (*Table 1*) and physiochemical (or abiotic) (*Table 2*) factors that contribute to high-quality and healthy soil.

The list of factors that contribute to soil health (*Table 1* and *2*) is not all-inclusive and other factors can also contribute to soil health and quality. Yet, this list gives an insight into the requirements of healthy soils and the factors that can be measured to assess whether a given soil is healthy or not.

Need for holistic approaches

Holistic management approaches that conserve soil as a resource to optimise

Table 1: Biological measures of soil health.

Parameters	
Ecosystem services	These are functions delivered by soil and include the storage and release of water, decomposition of organic materials, transforming and cycling of nutrients, detoxifying and sequestration of toxins, and the promotion of plant health by suppression of pathogens and phytophagous organisms. Many of the soil ecosystem services are delivered by microbes and other living organisms.
Soil microbial community	Microbes colonise the whole soil profile, but they are more abundant on the surface, in areas surrounding the rhizosphere, and around macropores in the soil. The soil microbial community refers to different groups of microbes that share a common living space. This community is influenced by biotic and abiotic elements in the soil which include available nutrients and minerals, soil type, texture, moisture, and oxygen availability as well as the resident plant diversity.
Soil microbial diversity	Taxonomic and functional microbial diversity in the soil refers to the array of different microbial organisms present in the soil. A high diversity means there are many different kinds of organisms present, which may also be reflected in the variety of services they provide, including decomposition of organic material and nutrient cycling. The importance of microbial diversity in the soil is recognised, but there is not a full understanding of the processes that drive diversity in soil.
Soil microbial structure	Microbial community structure refers to the composition of the community and the abundance of particular members of the community. It is influenced by land use, as well as biotic and abiotic factors. When these factors alter soil properties, the microbes in the soil will respond to the changing conditions. Soil type, pH, mineral composition, soil texture, soil moisture, available nutrients and oxygen are drivers of the microbial community structure. Additionally, climate change affects soil microbial communities through direct impacts on soil temperatures and indirect impacts such as a shift in plant communities.
Enzymatic activity	The microbial inhabitants of the soil produce a wide variety of enzymes that act on soil organic matter and mineral compounds. Some enzymes play a role in the release of nutrients and energy that microbes need for survival and growth. The lipids, sugars, peptides, amino acids, and other compounds liberated by enzymatic activity are competed for by the soil microbial community, as well as the plants and other soil biota. Microbial enzymes also degrade complex substrates like cellulose and lignin.
Soil fauna	Soil mesofauna includes protists, nematodes, tardigrades and arthropods. These organisms deliver ecosystem services that include the decomposition of animal and plant residues. The presence of mesofauna, both number and diversity, their reproduction rates and structure reveal information on the state of the soil.
Genomic diversity	Genomic diversity refers to how diverse the soil biota (living things) is, and the extent to which the organisms can deliver ecosystem services.

Table 2: Abiotic or physiochemical measures of soil health.

Parameters	
Soil nutrient levels	Since the decomposition of organic material takes place in the soil, nutrients are mobilised as a result of the decomposition process. Atmospheric nitrogen (N) is also fixated by symbionts. Specific microbial communities drive nutrient cycling and mineralise carbon and nutrients. The presence of nutrients in the soil can thus indicate which functional groups are present and how fast nutrients are released for uptake.
Soil carbon cycling	Microbes in soil are crucial to the cycling of carbon. Carbon is the key constituent of all living things. Plants, as primary producers, fix carbon from carbon dioxide and convert it into organic material. Other living organisms, which are not primary producers, rely on the carbon fixed by plants as a source of organic material. Mineralisation of organic compounds occurs during degradation and results in inorganic products such as carbon dioxide, ammonia and water. Fungi are the main contributors to organic matter decomposition and constitute the majority of soil biomass.
Soil nitrogen cycling	Nitrogen is an essential element, and all organisms need N as it is a building block of proteins and nucleic acids. Animals receive N from organic sources, mainly from plants, while plants use inorganic N, including ammonium and nitrate. Soil microbes are important in the N cycle. They fix N by the reduction of atmospheric N gas to ammonium. This function is only performed by bacteria, and it is the only process through which new N enters the biosphere.
Soil structure	Soil structure refers to the natural arrangement of soil particles into aggregates as initiated by the chemical and physical interaction of organic matter (from various sources) with soil particles. Soil aggregates are fundamental to biological processes in the soil because they determine the sizes of pores in the soil through which air and water will move. Both the availability of moisture and air, as well as the movement thereof through the soil profile determine the levels of microbial activity. In turn, the microbial products affect soil aggregation. Soil structure greatly affects the functioning of soil since the bonding between soil minerals and organic matter results in micro-aggregate formation. Well-developed soil pore systems and aggregates are crucial for healthy soil.
Soil aggregation	Soil aggregates are clusters of soil particles that attach to one another with greater strength than they attach to adjacent soil particles. The spaces between soil aggregates provide pore space for retention and the exchange of air and water. Soil aggregate formation is associated with soil structure, soil organic matter and soil stability. The arrangement of soil particle fractions to micro- and macro-aggregates affects soil functioning. The bonds between minerals in the soil and organic matter result in the formation and stabilisation of micro-aggregates. The higher the soil aggregation, the higher the water-holding capacity. High soil aggregates reduce chances for erosion and increase soil productivity. Aggregates are grouped into large (>2 mm), macro (2 to 0.5 mm), small (0.5 to 0.25 mm) and micro-aggregates (0.25 to 0.053 mm).
Water-holding capacity	Soil water-holding capacity refers to the amount of water the soil can retain for crops to use. Good soil structures result in higher water-holding capacities, since there is a larger surface area for the water to hold on to.
Soil erosion	Soil erosion refers to the wearing of topsoil through water, wind, and mechanical processes such as tilling.
Soil contamination	The accumulation of soil contaminants, which can include pesticides, fertilisers or toxins from atmospheric deposition or nearby industrial activities.
Soil pH	While soil pH drives bacterial communities, it does not have such a strong effect on soil fungi. In the case of soil fungi, the nutrient status is a driver for their occurrence.

Soil quality refers to the inherent properties of soil, including chemical and physical properties that are intertwined with regional ecosystems and climate.

its multiple functions are needed in support of soil health and quality. Soil health and quality indicators still vary throughout the world and different soil management systems, and the indicators are useful to researchers, but not always to land managers. Consensus on the measurements is needed and the availability of quick, reliable and cost-effective measures of soil health parameters will support farmers and land managers to better manage soils in future.

Strategies for the sustainable management of soil include the conservation of organic matter. This can be achieved through reduced tilling, the use of animal manure, increasing plant diversity and the use of cover crops. Cover crops can also minimise soil erosion. The use of integrated pest and pathogen management strategies, which reduce the reliance on fossil fuels and petrochemicals, will also support biological diversity in soils, which in turn will contribute to healthy and high-quality soil.

Overall, it seems that the challenge of developing comprehensive sustainable soil management systems that will safeguard the health of the soil remains. A better understanding of what soil health and quality are will support decision-makers in the way forward.

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