# Soil Health Assessment and Management Framework

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## Contents



**Authors:**

Gizaw Desta, Getachew Agegnehu, Mukund Patil, Pushpajeet Choudhari,

Gizachew Legesse, Henok Desalegn, and Lester Botoman

# 1. Background

Soils deliver valuable ecosystem services, such as the release of nutrients from soil organic matter, water storage and transfer (Tahat et al., 2020), water and air quality (Doran and Zeiss, 2000), food security (Lal and Stewart, 2010), cultural heritage, etc. Hence, it is vital to the environment and society that soil functions and its quality are maintained (Blum, 2005). Soil quality and soil health are often used interchangeably, but generally refer to the same concept (Bünemann et al., 2018), i.e., a soil's capacity to function as a dynamic living ecosystem to sustain plant and animal health and environmental quality. Although both terms address the physical, chemical, and biological aspects of soil, soil health is a broader, more holistic concept that encompasses the long-term sustainability and vitality of the soil as a living system, while soil quality sometimes focuses on more specific, land-use-dependent functions and attributes.

Improving the soil quality of marginal lands is critical for improving agricultural productivity and food security (Li et al., 2017). Soil health is defined as "the capacity of a soil to function as a vital living system within ecosystem and land use boundaries to sustain plant and animal production, maintain or enhance water and air quality, and promote plant and animal health (Doran and Zeiss, 2000)."

Soil management can be divided into three overlapping domains. The two widely known soil properties include physical management (e.g., tillage and deep ripping for compaction) and chemical management (e.g., soil amendments and fertility management). The last domain is biological management, which is mostly overlooked in soil management. Soil health is described as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (Kopittke et al., 2024).

A healthy soil is a soil that is multifunctional and is capable of sustaining human and planetary health. It encompasses the interactions between the diverse living organisms in the soil, such as bacteria, fungi, and invertebrates, and their physical and chemical environment, including water, air, and soil structure (Campbell et al., 2025). Improving the biological component of the soil has main advantages, and soil health is shown to impact the ability of soil to support plant health and enhance the yield and quality of crops (Țopa et al., 2025). Yet, most cultivated soils have been influenced by soil compaction, erosion, and nutrient loss. Soil constraints include physical (soil structure, erosion, water deficiency, waterlogging, etc.), chemical constraints (soil pH, soil organic C decline, nutrient depletion, soil acidity, salinization, nutrient imbalance), and biological constraints (conditions that reduce the health, activity, and abundance of beneficial soil organisms like earthworms and arbuscular mycorrhizae, and/or increase harmful pathogens) (Li et al., 2025).

# 2. Why does soil health count?

Healthy soil is the foundation of agriculture. Healthy soil provides physical stability and support for crops to grow stronger roots. It has a big impact on the yield potential of crops; moreover, it improves nutrient availability, nutrient cycling, and enhances water retention, leading to more resilient and productive farms with less reliance on chemical inputs. It also improves water infiltration, reduces runoff, recharges groundwater, and filters and buffers fertilizers and pesticides from polluting rivers and lakes. Healthy soils are the largest terrestrial carbon sink, resulting in more resilient agriculture and agroecosystems to climate impacts like droughts and floods. In terms of economic viability, healthy soil reduces costs for inputs and enhances the long-term value of land by preventing degradation like erosion and nutrient depletion. healthy soil filters and buffers potential pollutants.

# 3. Goal and principles of soil health management

The **goal of soil health management** is to enhance the soil's capacity to function as a vital living ecosystem that sustains plants, animals, and humans. It enhances and sustains agricultural productivity and resilience; improves ecosystem functions and environmental quality beyond the farm field; and supports soil biological diversity and activity to drive chemical and physical processes.

**How the goal is achieved**: Improved agricultural productivity and resilience are achieved by improving soil structure for better root growth, increasing water infiltration and holding capacity (making crops more drought-resistant), and efficiently cycling nutrients to reduce the need for synthetic fertilizers. Increasing soil organic matter, which sequesters carbon from the atmosphere (mitigating climate change), improving water filtration to protect groundwater quality, and reducing erosion and runoff to prevent pollution in rivers and lakes, enhances goals on ecosystem functions and environmental health. Soil health is fundamentally linked to improving the soil biological diversity and activity by providing a habitat and substrate, such as through cover crops and organic amendments, for a diverse community of organisms, including earthworms, fungi, and bacteria.

The fundamental principles of soil health management include: 1) **Keep soil covered**: keep the soil covered to maintain a protective layer of residue or living plants on the soil surface at all times for protecting the soil from erosion, conserving soil moisture, managing weeds, and providing feed for microorganisms; 2) **Disturb less**: minimize soil disturbance by reducing tillage and overuse of fertilizers and pesticides; 3) **Diversify**: maximize soil biodiversity above and below ground through diverse crop rotations, cover crops and integrating livestock to stimulate soil biology and nutrient cycles; and 4) **Manage for specific context**: integrate context and adaptive management for effective soil health management tailored to specific context of the land to ensure management decisions are based on the local climate, soil type, topography, and specific resources of the user. By following these principles, the soil becomes a resilient, living system that is more productive, drought-resistant, and better for the environment.

# 4. Soil health functions

An effective soil functions create a resilient and self-sustaining system that supports plant growth, cleans our water, and regulates our climate.

1. **Nutrient cycling**: Healthy soils function to recycle nutrients through the process of storing, transforming, and releasing plant-available nutrients.
2. **Water regulation**: The water regulation function of soil is the ability of soil to absorb, store, and make water available for plants and to recharge groundwater. Good soil structure with stable aggregates and pores allows water to infiltrate rather than run off.
3. **Habitat for soil biodiversity**: Soil provides a physical habitat for a vast array of organisms, from earthworms and insects to bacteria and fungi, that drive the other functions, like nutrient cycling.
4. **Stability and security of the soil**: The soil's structure provides physical support for plant roots and anchors the entire landscape against erosion, where root systems and fungi bind soil particles together, creating stable aggregates that prevent soil from washing.
5. **Filtering and buffering**: The capacity of soil to capture, neutralize, and purify potential contaminants, protecting groundwater and the wider environment. Soil particles, especially clay and organic matter, can adsorb and break down pollutants, while microbes can degrade them.
6. **Carbon sequestration and climate regulation**: The process of pulling carbon dioxide ($CO_2$) from the atmosphere and storing it in the soil as stable organic matter.

# 5. Soil health assessment framework

Soil health is a holistic concept embracing emergence, complexity, and highlighting long-term vitality and resilience. The soil health assessment framework is a structured approach for assessing, managing, and improving the health and resilience of soil (Hannam et al., 2025). It typically involves a set of principles, indicators, and practices designed to maintain or enhance soil quality and function. It moves beyond just measuring nutrients for plants and aims to provide a holistic picture by measuring key indicators that reflect the soil's biological, chemical, and physical properties. It is a framework defined with 1) a key set of measurable indicators (biological, chemical, and physical) that represent soil function, 2) a standardized method of soil sampling and analysis, 3) soil health scoring to compare indicators against optimal ranges or benchmarks for a specific context, 4) providing farmers and land users with tailored advice to improve the soil health constraints. Campbell et al. (2025) identified four distinct frameworks for soil health assessment: 1) Fitness for purpose, 2) free from degradation, 3) external benchmarking, and 4) value assessment, with each possessing a unique role and application.

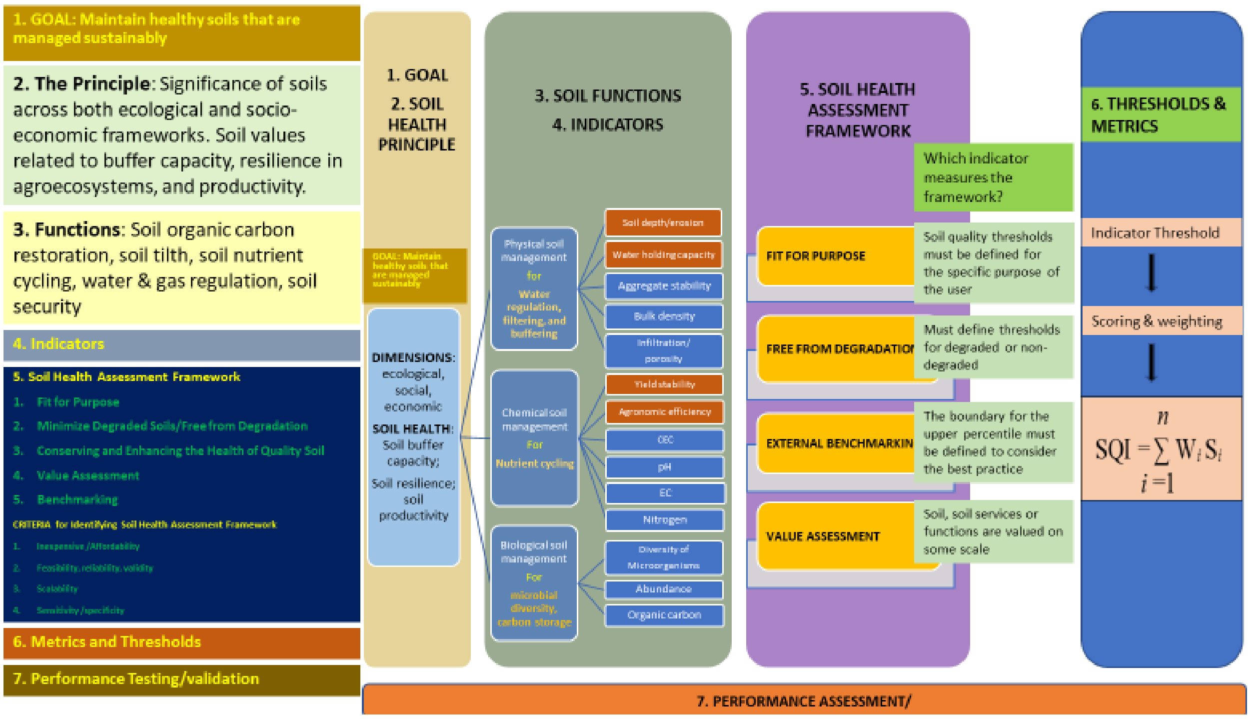


Figure 1. Soil health assessment framework

# 6. Soil health indicators

The concept of soil health is evaluated through indicators, where the choice of framework significantly influences selection and interpretation. However, selecting appropriate soil indicators is challenging due to diverse climate, topography, geology, and soil types, resulting in varied soil processes. Therefore, establishing clear principles and criteria for selecting soil indicators is essential. As there is no single indicator for soil health, a sound framework is needed for selecting indicators (Bone et al., 2014). Recent research has shifted from chemically focused soil fertility assessments toward more integrative frameworks that emphasize soil quality and soil health (Mohkam and Nunes, 2025). A soil health monitoring framework is required to identify targeted and context-specific soil health indicators. There is a need to ensure that these indicators and other subsequent measures are robust for their purpose. Effective soil health indicators must measure both the state and the change of the soil metric over time. A selection criteria framework is presented in Figure 1.

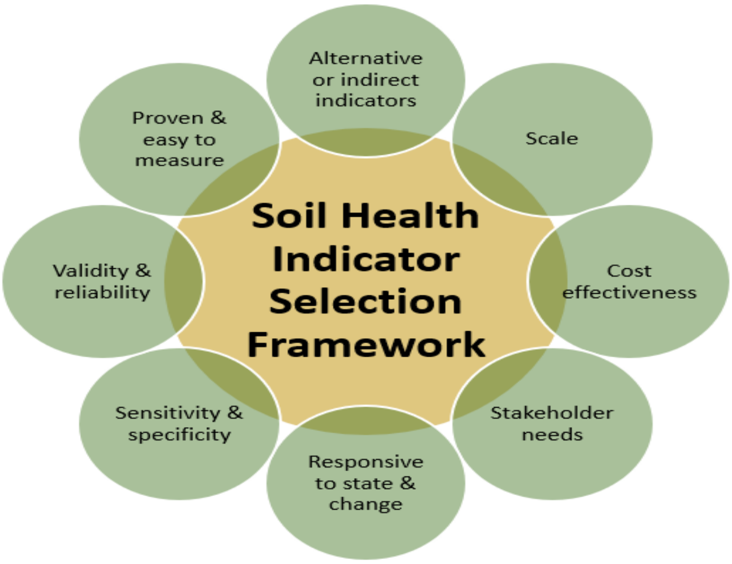


Figure 2. Soil health indicator selection framework (extracted from different sources: Campbell et al., 2025; Hannam et al., 2025)

## 6.1. Chemical, physical, and biological soil properties

Soil health indicators refer to measurable soil attributes that influence the capacity of soil to perform crop production or environmental functions. Attributes that are most sensitive to management are most desirable as indicators. Soil health should be considered in three spheres, including chemical, physical, and biological. Sometimes, only one component is affected and needs support. A Soil Health Assessment Framework uses indicators (physical, chemical, and biological) to evaluate the soil's ability to perform vital functions. In some cases, soil management practices like tillage can impact all three domains at the same time. In an agroecosystem, soils are continuously influenced as a result of the addition of inputs, the removal of nutrients, changes in water balance, and microorganisms. These processes affect physical, chemical, and biological properties. In a given agro-climatic region, the measurable soil quality attributes that are primarily considered as s**oil health indicators** are nutrient availability, nutrient retention capacity, clay fraction, acidity/toxicity, salinity, soil moisture retention capacity and infiltration, microbial activity, organic matter/carbon stock, soil depth, bulk density, and soil aggregates, yield stability, and agronomic efficiency. Indicators like soil carbon, aggregate stability, and pH are commonly used to assess physical, chemical, and biological health.

There is no ideal or magic index value; soil health assessments can be made using a framework that prioritizes management goals, identifies critical soil functions necessary for achieving those goals, and selects indicators that provide useful information regarding how a specific soil is functioning (Hannam et al., 2025). Soil health can be assessed based on its intended use. For example, Li et al. (2017) identified slope, soil erosion, soil organic carbon (SOC), texture, pH, cation exchange capacity (CEC), soil depth, and drainage to map agricultural land suitability and identify the distribution of marginal land in Malawi. Likewise, Hannam et al. (2025) identified 47 key soil physical, chemical, and biological properties directly relevant for soil health and ecosystem service delivery. The top-ranked scores included a variety of common soil physical, chemical, and biological properties (Fig. 3).

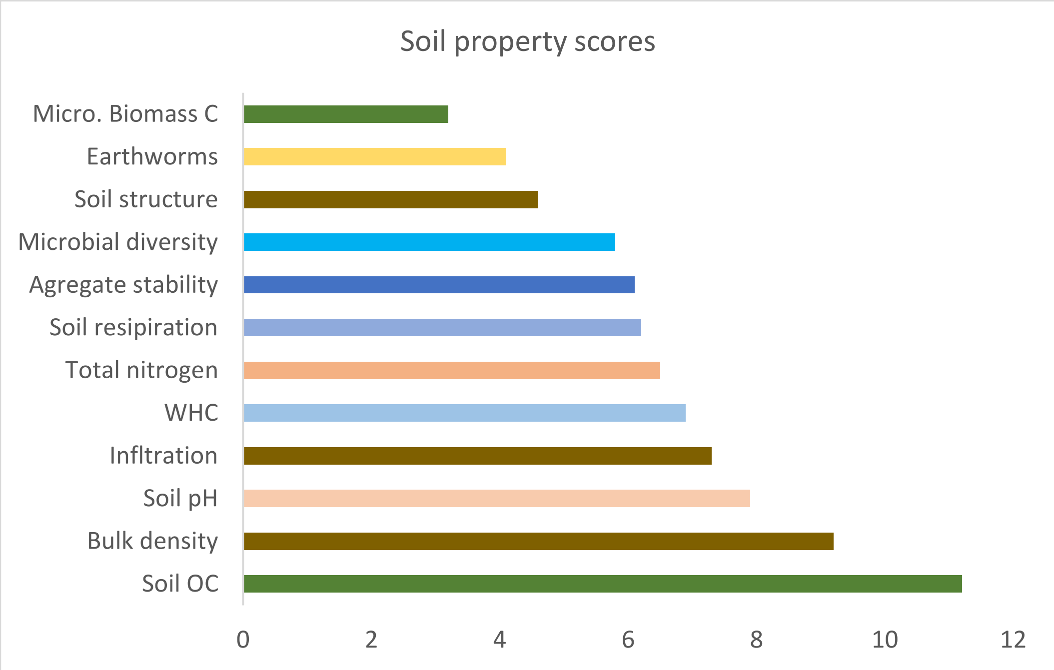


Figure 3. Soil property relevance and significance to soil health and ecosystem service delivery (scores). (adapted from Hannam et al., 2025)

## 6.2. Thresholds for indicators

Knowledge and assessment of changes (positive or negative) in soil status with time is needed to evaluate the impact of different management practices. Selection of key indicators and their critical limits (threshold values), which must be maintained for normal functioning of the soil, are required to monitor changes and determine trends in improvement or deterioration in soil health for various agro-ecological zones for use at district, national, and global levels. Many soil indicators interact with each other, and thus, the value of one is affected by one or more of the selected parameters. Thresholds for soil health indicators are context-specific, varying by soil-, site-, management-, and climate-specific, not universally fixed; they define **critical values for soil degradation or desirable conditions to achieve ecosystem services.** Thresholds often appear in soil quality indices (SQIs) or soil health scores, categorized into levels like "poor," "fair," "good," and "excellent" to interpret measured indicator values. Table 1 presents threshold values for key soil health indicators.

Table 1. Soil health indicators and thresholds

| Soil health dimension | Soil health indicators | Thresholds | References |
|---|---|---|---|
| **Physical** | Soil aggregates | Water stable aggregate: >66.1% very high, 50.1% to 66.0% high , 34.1% to 50% medium, 18.1 to 34% low, <18% very low | Bartlova et al. 2015 |
| | Bulk density | Sandy soils: Ideal <1.60 g/cm3, restriction above 1.80 $g/cm3$<br>Silty soils: Ideal <1.40 g/cm3, restriction above 1.65 g/cm3<br>Clayey soils: Ideal <1.10 g/cm3, restriction above 1.47 $g/cm3$ | USDA, 2008 |
| | Porosity | Very compact when the total porosity is < 5%<br>Compact when the total porosity is 5-10%<br>Moderately porous when total porosity is 10-25%<br>Highly porous when the total porosity is 25-40%<br>Extremely porous when total porosity is >40% | Pagliai 1988 |
| | Water holding capacity | Total Available Water: Loam 12%; Silt loam 13%; Sandy clay loam 11%; Clay loam % | Datta et al. 2017 |
| | Soil depth (cm) | Very shallow < 25cm; Shallow 25-50 cm; 50-75 moderately deep; ≥ 75 deep | Rai et al. 2017 |
| | Clay fraction | < 10% very low; 10-25% low; 25-40 moderate; 40-50 high; > 50 very high | Hazelton and Murphy, 2025 |
| **Chemical** | pH | 3-4 very strongly acidic; 4-5.5 strongly acidic; 5.5-6.0 moderately acidic; 6-7 slightly acidic; 7-8 slightly alkaline; 8-9 moderately alkaline; 9-10 strongly alkaline; 10-11 very strongly alkaline | Hazelton and Murphy, 2025 |
| | EC | All textures: 0-2 non-saline; 2.1-4 slightly saline; 4.1-8 moderately saline; 8.1-16 strongly saline; >16.1 very strongly saline | Smith and Doran, 1996 |
| | CEC | < 6 cmol/kg very low; 6-12 cmol/kg low; 12-25 cmol/kg moderate; 25-40 cmol/kg high; > 40 cmol/kg very high | Hazelton and Murphy, 2025 |
| | Total nitrogen (%) | Very low < 0.05%; low 0.05–0.15; medium 0.15–0.25; high 0.25–0.50%; very high >0.5% | Bruce and Rayment (1982); Hazelton and Murphy, 2025 |
| | Nitrate ($NO_3$) (mg/kg) | >30 Adequate, no response; < 8 deficient, good chance of response | |
| | C:N ratio | < 25 Decomposition may proceed at the maximum rate possible; >25 Decomposition slows unless nitrogen is added. | |
| | Phosphorus | Bray P1 (mg/kg):<br>Very low 1-9; low 10-17; medium 18-25; high 26-35; very high >35<br>Olsen P (mg/kg):<br>Very low 1-5; low 6-10; medium 11-16; high 16-20; very high >20 | Jones, 2002 |
| | Extractable Al in CaCl2 solution above which yield declines: Critical exchangeable Al levels for crops as a percentage of CEC | For EC <0.07 (infertile soils, low CEC):<br>Very sensitive plants 9-16%; sensitive plants 17-20%; tolerant plants 21-32%; very tolerant plants 33-43%<br>EC 0.07–0.23 (most fertile soils):<br>Very sensitive plants 2-8%; sensitive plants 9-12%; tolerant plants 13-21%; very tolerant plants 22-30%<br>EC >0.23 (fertilizer bands, saline soils):<br>Very sensitive plants 0.5-2%; sensitive plants 3-6%; tolerant plants 7-10%; very tolerant plants 11-16% | Fenton and Helyar, 2007; Hazelton and Murphy, 2025; Upjohn *et al.*, 2005 |
| **Biological** | Organic carbon (%) | Soil health: Very low 0.40–0.59%; low 0.60–0.99; moderate 1.00-1.59; high 1.60-1.99; very high 2.00-2.99<br>Crop nutrient uptake and yield: > 2% no increase<br>Aggregate stability: < 2% unstable; 2-2.5% stable; > 2.5% very stable | Hazelton and Murphy, 2025; Janzen, 1987; Carter, 1992 |
| | Biological activity | A common threshold is around **1.5% to 2% soil organic carbon (SOC) for optimal biological activity in the soil.** | Schloter et al., 2018 |

| | | | |
|---|---|---|---|
| | Microbial abundance | Soil pH plays a pivotal role in shaping microbial diversity and community composition. Optimal soil pH conditions for bacterial and fungal abundance in acidic and alkaline soils occur at values of ~5.5 and ~8.3, respectively. | Shi et al., 2021 |
| | Agronomic efficiency | Typical agronomic efficiency of nitrogen (AEN) values range from 10 to 30 kg grain $kg^{-1}$ N fertilizer applied.<br>The average agronomic efficiency of phosphorus (AEP) across all crops typically falls within the range of **10 to 45 kg grain per kg P applied.** | Brouder and Volenec, 2023; Fageria et al. 2013 |

# 7. Metrics for soil quality index

Developing a quantitative soil quality index involves a systematic approach encompassing three crucial steps: (1) identifying relevant indicators; (2) scoring these indicators based on their attributes; and (3) amalgamating these indicators into a comprehensive index (Karlen *et al.,* 2003). The process begins with pinpointing indicators—key physical, chemical, and biological properties of soil that are responsive to both natural and human-induced changes (Doran and Parkin,1994). To select these indicators, methodologies such as the Minimum Data Set (MDS) have been extensively employed to assess soil quality (Doran and Parkin, 1994).

The steps to create a soil quality index after establishing management objectives are: (1) selecting suitable indicators for the MDS; (2) converting these indicators into scores; and (3) integrating these scores to form the overall index. The principle of using a minimum set of indicators that mirrors the objectives of sustainable management is well-regarded, although the selection of the MDS components has traditionally depended on expert opinions (Doran and Parkin, 1994; Karlen et al., 2003). Nonetheless, the challenge of determining which variables to include in a soil quality index can be streamlined through statistical techniques.

The soil quality evaluation involved three basic steps: a) selection of appropriate soil properties, b) transformation into unit-less scores and c) aggregation into an index (Andrews *et al.,* 2002).

## 7.1. Indicator selection

Two methods for indicator selection were employed *viz.,* principal component analysis (PCA) and expert opinion (EO)

**Principal component analysis:** Principal Component Analysis (PCA) is applied, with the aim of reducing data dimensionality while preserving as much information as possible (Armenise *et al.,* 2013). The selection of principal components for further analysis is based on their eigenvalues, with those equal to or greater than 1 identified for inclusion in the minimum data set (MDS). Components with eigenvalues less than 1 will be considered to capture less variance than a single variable and is therefore excluded. To improve the clarity and interpretability of these components, a Varimax rotation can be applied to the selected principal components. Within each principal component, variables exhibiting high factor loadings will be considered for inclusion in the soil quality index (SQI). If a principal component comprised multiple highly loaded variables, a correlation test will be performed to determine potential redundancy among them. Variables that are not significantly correlated are all deemed important and included in the SQI. In cases where correlated variables are found, only the one with the highest factor loading will be selected for inclusion in the SQI, ensuring that the index is both comprehensive and efficient in capturing the essential aspects of soil quality.

**Expert opinion:** PCA, though widely accepted, is a method of data reduction which simplifies the procedure of indicator selection. However, expert opinion is necessary to consider specific contexts. Indicators will be scored as ‘higher is better’ up to a threshold value and then scored as ‘lower is better’ above the threshold (Andrews *et al.,* 2002).

## 7.2. Indicator transformation or scoring

Selected indicators in MDS will be scored into dimension less values ranging from 0 to 1 using linear scoring method (Liebig *et al.,* 2001). Indicators will be ranked in ascending or descending order depending on whether a higher value was considered "good" or "bad" in terms of soil function. For 'higher is better' indicators, each value of indicator will be divided by the highest value such that the highest value received a score of 1. For 'less is better' indicators, the lowest value was divided by each data value such that the lowest value received a score of 1.

## 7.3. Weighted index

The given indicator data will be adjusted in accordance with the results of principal component analysis (PCA). Each principal component (PC) represent a certain percentage of the total dataset's variation. To determine the weightage of each PC, the percentage of variance explained by each PC will be divided by the cumulative variance percentage, as described by Vasu *et al.* in 2016. This weightage factor will then be applied to the chosen variables (indicators) from their respective PCs. These weighted variables will be added together to calculate an index value for all soil horizons. For the indicators selected using the expert opinion (EO) method, the weight assignment was based on the relative importance of each indicator in determining soil function. Weightage factors will be assigned in such a way that the sum of all factors equaled one.

## 7.4. Soil quality index (SQI)

Soil properties throughout the control section (both PCA and EO) will be considered for SQI calculation as they represent inherent soil quality. Finally, after all the selected indicators were scored and weighted as mentioned in above process and further SQIs will be calculated using the equation (Vasu et al, 2016):

$$\mathrm{SQI} = \sum_{i=1}^{n} \mathrm{W}_i \, \mathrm{S}_i$$

Where, $W_i$ is the weighing value of each indicator, $S_i$ is the indicator score, and n is the number of indicators included in the MDS. After calculating the S-values for all soil quality parameters, each variable will be weighted using the results of PCA.

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This research was conducted as part of the CGIAR Sustainable Farming Science Program. This research is being implemented by CGIAR researchers from ICRISAT. CGIAR is a global research partnership for a food-secure future. Its science is carried out by 15 Research Centers in close collaboration with hundreds of global partners. www.cgiar.org

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**Key Words:**

Soil health, indicators and metrics, soil quality index

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The CGIAR Sustainable Farming Science Program will address key challenges in agrifood systems by fostering efficient production of nutritious foods and safeguarding the environment to create fair employment opportunities, as we simultaneously tackle climate change, soil degradation, pests, diseases, and desertification.

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