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ASSESSMENT OF SOIL QUALITY AND ITS EFFECTS ON PLANT GROWTH AND SOIL FAUNA

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Abstract

Soil is a vital, essentially non-renewable resource that supports the production of food and fibre, regulation of water and nutrients, storage of carbon and provides habitat for an enormous diversity of organisms. Soil quality is a composite property inferred from measurable physical, chemical and biological indicators rather than measured directly and refers to the ability of a soil to function within ecosystem and land-use boundaries. Yet soil quality is under increasing pressure from intensive agriculture, over-fertilization, over-use of pesticides, erosion, heavy metal contamination, salinisation, compaction and climate change. Marginal degradation leads to a 10% reduction of crop yield, moderate degradation to 10–50% and severe degradation to more than 50%. Degradation in the period 1950–2010 is estimated to have reduced soil ecosystem services by 60%. Soil quality is not directly measurable and therefore is assessed through a minimum data set of physical (structure, bulk density, porosity, water-holding capacity), chemical (pH, EC, organic carbon, N, P, K, CEC) and biological (microbial biomass, enzyme activity, faunal diversity) indicators, which are integrated into a Soil Quality Index. Soil quality controls plant growth by controlling root penetration, water and nutrient availability and nutrient mineralisation. Soil fauna, which represent about 23% of all described living organisms, are responsible for organic matter decomposition, nutrient cycling and soil structure formation and are sensitive bioindicators of soil condition. Thus sustainable soil management including organic amendments, diversified cropping, conservation tillage and integrated nutrient and pest management is essential to preserving long-term soil productivity.

2. INTRODUCTION

Soil is a fundamental and almost non-renewable resource of the land ecosystems. It provides food and fibre, regulates water and nutrient cycles, sequesters carbon and provides habitat for a huge diversity of organisms. Thus soil health determines the sustainability of both agricultural and natural systems.

Soil quality is defined as the "capacity of the soil to function" (Karlen et al., 1997). It is the capacity

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of a soil to function within the limits of the ecosystem and land-use boundaries to sustain biological productivity, environmental quality and promote plant, animal and human health in an integrative manner (Lehman et al., 2015; Zornoza et al., 2015). It is a composite attribute that includes physical, chemical and biological characteristics that are not directly measurable but are estimated using measurable indicators (Behairy et al., 2024). Soil quality and soil health are often used interchangeably, although soil health, "the continued capacity of soil to function as a vital living system," more accurately conveys soil as a living, dynamic system (Lehman et al ., 2015). A useful distinction is actual soil health versus inherent soil quality (the capacity of a soil to function) (Bonfante et al, 2020).

Soil is the environment to which plant roots are exposed . Physical properties such as texture, structure, bulk density, porosity, and water retention determine water storage and movement, aeration and mechanical impedance, and therefore dictate where and how roots proliferate (Him et al., 2026). Bulk density and penetration resistance are indicators of compaction and mechanical constraints to root elongation (Paiva et al., 2026). Chemical properties such as pH, electrical conductivity, cation exchange capacity and organic matter determine the availability of nutrients (Hoffland et al., 2020; Jindo et al., 2023). Soil organic matter provides and recycles nitrogen, phosphorus and potassium and maintains phosphorus phytoavailability (Hoffland et al., 2020; Jindo et al., 2023).

The soil fauna component is as important as the soil quality. Soil animals constitute around 23% of all described living organisms and are involved in soil formation, nutrient cycling and regulation of food-webs (Mekonen, 2019). They are regarded ecosystem engineers that enhance aeration and water infiltration, contribute organic matter and stabilise soil aggregates through burrowing and feeding (Mekonen, 2019). Soil arthropods are responsible for organic matter decomposition and translocation, nutrient cycling and bioturbation (Menta & Remelli, 2020). Edaphic macrofauna are among the first organisms to react to environmental disturbance, therefore they are important bioindicators (Guarderas et al., 2022).

Soil degradation is becoming a serious problem world-wide. It is characterised by deterioration of physical, chemical and biological properties of soil resulting in reduced fertility, water retention and crop productivity (T & Rajeswari., 2025) A loss of 10% crop yield can result from marginal degradation, 10-50% from moderate degradation and more than 50% from severe degradation (Gupta, 2019). Over the next 25 years global food production could decline by 12%, food prices could increase by 30% and annual degradation costs are estimated at 3.4 trillion Euros (AbdelRahman, 2023). Degradation between 1950 and 2010 is estimated to have reduced soil ecosystem services by 60% (Osinuga & C.O., 2019).

These pressures lead to the need for soil quality assessment. Soil quality can not be measured directly but it is inferred by a minimum data set of physical, chemical and biological indicators (Bhaduri et al., 2022). Recent work developed minimum data set-based soil quality indices and linked them to crop yield (Tian et al., 2020) and developed integrated frameworks for soil health assessment (Ros et al., 2022). However, despite the increasing recognition of soil biodiversity (Guarderas et al., 2022) the quantification of soil health is still dominated by chemical indicators. The integration of knowledge on soil biodiversity into ecosystem management is low (George et al., 2020) and few approaches offer unambiguous interpretation schemes for measured indicator values (Bünemann et al., 2018).

Research gap: Previous studies generally assess soil quality using either physicochemical or biological indicators and seldom correlate a complete set of physical, chemical and biological properties to both plant growth and soil fauna at the same time. Thus there is no clear framework to link soil quality indicators to these two outcomes.

Aim of the paper: The aim of this paper is to evaluate the soil quality by combining physical, chemical and biological properties and to evaluate the influence of these properties on plant growth and soil faunal communities. The overall study framework is shown in Figure 1.

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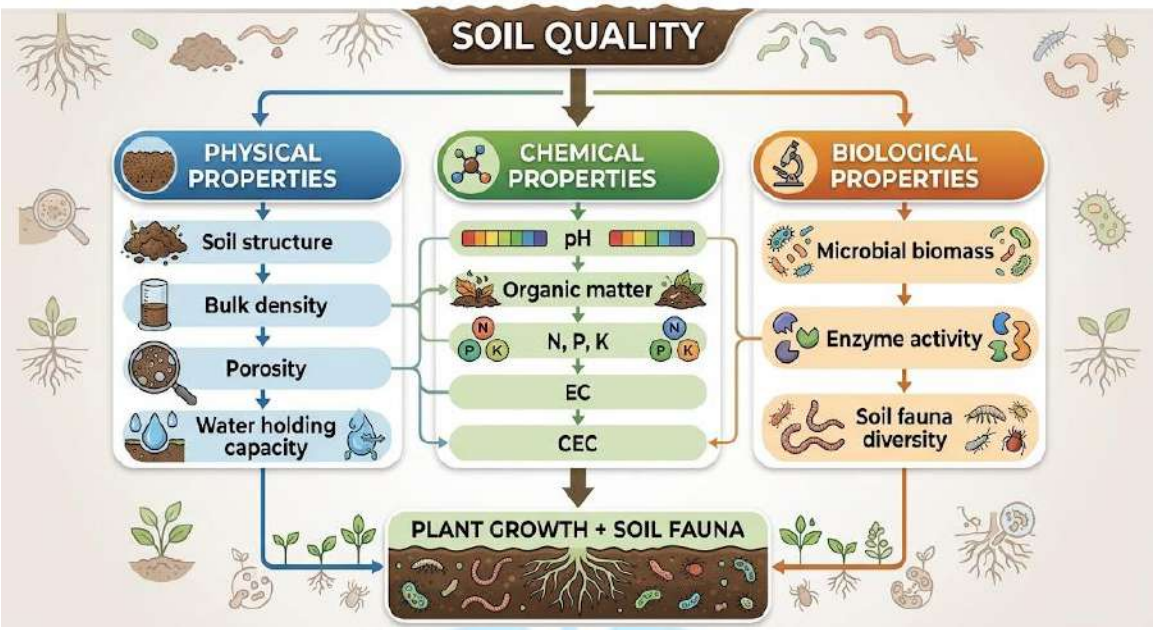


Figure 1: Conceptual Framework of Soil Quality and Its Effects

3. Soil quality concept and elements

Soil quality is a complex concept that cannot be measured directly, but inferred from measurable attributes – soil quality indicators – derived from the physical, chemical and biological properties of the soil (Bhaduri et al., 2022). Because these three dimensions interact and together define function, a complete assessment must take all of them into account.

3.1 Physical quality of the soil

The physical quality of soil is concerned with the structure and behaviour of the solid, liquid and gaseous phases of soil. Soil texture, which refers to the proportions of sand, silt and clay, influences the retention of water and the distribution of pore sizes. A loam texture with 7–27% clay, 28–50% silt and 23–52% sand is best for most crops (Shahane & Shivay, 2021). Soil structure is one of the most important physical indicators for plant growth, and directly affects densification, compaction, crusting, water infiltration and vulnerability to erosion . Bulk density is an indicator of soil compaction and management and controls the pore system, water and oxygen availability and organism activity; 1.33–1.35 g cm^{-3} is considered to be a healthy range for agricultural soils (Shahane & Shivay, 2021). Porosity (macroporosity > 0.05 mm; microporosity < 0.05 mm) regulates the movement of air and water; water is transmitted by macropores or stored in micropores (Soriano, 2013). The pore network serves to retain water and for infiltration; structure degradation and compaction cause reduced porosity and saturated hydraulic conductivity (Pulido-Moncada et al., 2014).

3.2 Soil Quality, Chemical

Chemical indicators measure nutrient availability, toxicity and buffering capacity. Soil pH influences the availability of nutrients to plants. The overall effects are dependent on soil sorption and plant uptake (Barrow & Hartemink, 2023). Electrical Conductivity: This is an estimate of salt content or chemical supply and should be measured along with pH because an acceptable EC range can be found in an acid soil unsuitable for plant growth (Smith & Doran, 1997). Soil organic carbon is one of the most indicative properties related to microbial processes, storage of nutrients, capacity of water available for plants, aggregate stability, cation exchange capacity and presence of invertebrates (Richiedei et al., 2024). Available nitrogen and phosphorus are important macro

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nutrients for plant growth, respiration and reproduction (Richiedei et al., 2024). Soil reaction (pH), EC, P, K and CaCO3 are usually selected as chemical quality measures (Behairy et al., 2024), and CEC is one of the most important factors for the soil quality index (Behairy et al., 2024).

3.3 Soil Quality Biological

Biological soil quality is the living component of the soil. Microbial biomass carbon is a labile fraction of the total soil organic carbon that accounts for a small percentage (1–4%) and is sensitive to carbon availability and management, and it reflects the soil's capacity to store and recycle nutrients and energy (Bhaduri et al., 2022). Microbial diversity and enzyme activity are core biological attributes. Hydrolytic enzymes are sensitive and relatively cheap indicators of the cycling of C, N, P and S (Trasar-Cepeda et al., 2008). The most frequent biological indicators identified in a review of 50 years of research were microbial biomass (118), enzymatic activity (90) and organic matter (78), followed by earthworms, nematodes and springtails (Bonilla-Bedoya et al., 2023). Earthworms are considered indicators of the biological health of soils, with recommended target abundances of >400 ind./m² and at least 25 ind./m² per ecological group (Schon et al., 2022). Nematodes are one of the most abundant multicellular soil organisms and the Maturity Index is based on nematode distribution among functional groups (Ritz et al., 2009). Micro-arthropods are also good indicators because of their sensitivity to management and their role in accumulation of organic matter and nutrient cycling (Sapkota et al., 2012).

Table 1: Major Soil Quality Indicators and Their Ecological Significance

Category	Indicator	What it indicates	Importance
Physical	Bulk density	Soil compaction	Root growth
Physical	Porosity	Air/water movement	Root respiration
Chemical	pH	Soil acidity/alkalinity	Nutrient availability
Chemical	Organic carbon	Soil organic matter	Soil fertility
Chemical	N, P, K	Nutrient status	Plant growth
Biological	Microbial biomass	Biological activity	Nutrient cycling
Biological	Earthworm abundance	Soil biological condition	Soil structure

4. Methods of Soils Quality Assessment

Soil quality assessment comprises a standardised sequence of sampling, laboratory analysis and integration of measured indicators into an interpretable index. This section describes the procedures used for each soil quality dimension, and the framework used to integrate them.

4.1 Sampling of Soil

Sampling should be representative of the study area and be done prior to fertilisation or recent tillage so that results reflect the prevailing condition. The most frequent sampling depth is the plough layer, 0-20 cm, although 0-10 cm, 10-20 cm or 0-30 cm increments are used where depth-related stratification is of interest. Sampling locations are selected using random, grid or stratified random designs and the coordinates of each point are recorded with a GPS unit to allow repeat monitoring. At each location, a composite sample is made by taking 8 to 15 subsamples from within a small radius, mixing the subsamples thoroughly in a clean bucket and quartering the mix to get a representative working sample. For statistical purposes a minimum of three to four replicated composite samples per land-use unit is required. Samples are air-dried in the shade, crushed and sieved at 2 mm for physical and chemical analysis; for biological and microbial analyses, field-moist samples are stored at 4 °C and processed within a few days, because air-drying affects microbial biomass and enzyme activity.

4.2 Physical measurements

Bulk density is measured using the undisturbed core method: a known volume of soil is forced into a metal cylinder and oven dried at 105 °C and weighed, thus providing a mass per unit volume.

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Soil texture is determined by the hydrometer or pipette method after dispersion of the sample and the percentages of sand, silt and clay are read from the rates of settling. Total porosity is calculated indirectly from bulk density and particle density (generally assumed to be 2.65 g cm -3). Water-retention is determined gravimetrically or on pressure plates after saturation and drainage. Aggregate stability is determined by wet sieving, with the percentage of stable aggregates remaining after immersion and agitation showing resistance to slaking and erosion.

4.3 Chemical Indicators

Soil pH is determined potentiometrically in a 1:2.5 soil to water suspension or in a 1:1 or 0.01 M $CaCl_2$ suspension for a more stable reading. Electrical conductivity in a 1:5 soil-water extract was determined using a conductivity meter and expressed as dS m-1. Soil organic carbon is measured either by wet oxidation (Walkley–Black) or by dry combustion in a CHN analyser, the latter method being preferred where complete oxidation is required. Total nitrogen is determined by Kjeldahl digestion and distillation. Depending on the pH of the soil, available phosphorus is extracted with sodium bicarbonate or dilute acid and measured colorimetrically. Exchangeable potassium is extracted with neutral ammonium acetate and measured by flame photometry. Cation exchange capacity is determined as follows: saturation with ammonium acetate, pH 7, displacement and titration.

4.4 Biological Indicators

Microbial biomass carbon was determined by chloroform fumigation-extraction or substrate-induced respiration. Soil respiration is determined as CO 2 evolution trapped in alkali or continuously recorded by an infra-red gas analyser. Enzyme activities (usually urease, phosphatase, dehydrogenase and β-glucosidase) are measured colourimetrically by the release of product from a buffered substrate. Earthworm abundance is assessed by hand-sorting of standard soil monoliths (typically 25 × 25 × 25 cm) and mustard or formalin extraction. Nematode diversity was assessed through extraction of nematodes from soil, nematode identification to genus and assignment of functional groups for computation of ecological indices. The diversity of soil arthropods is sampled using Berlese-Tullgren funnels for micro-arthropods or pitfall traps for surface-active groups, and then identified and analysed for diversity.

4.5 Index of Soil Quality

Each indicator is assigned a weight, representing the contribution of the indicator to soil function. Linear or non-linear scoring functions transform individual indicators, measured on different scales, to dimensionless scores. Weights are either from a principal component analysis with the weight of each component proportional to the variance explained by it or from expert judgement. The scores and weights are then aggregated into a single Soil Quality Index:

SQI = Sum of (Indicator score x Weight)

The higher the index value, the better the soil condition. The calculated values are interpreted using critical limits or in relation to the reference soil.

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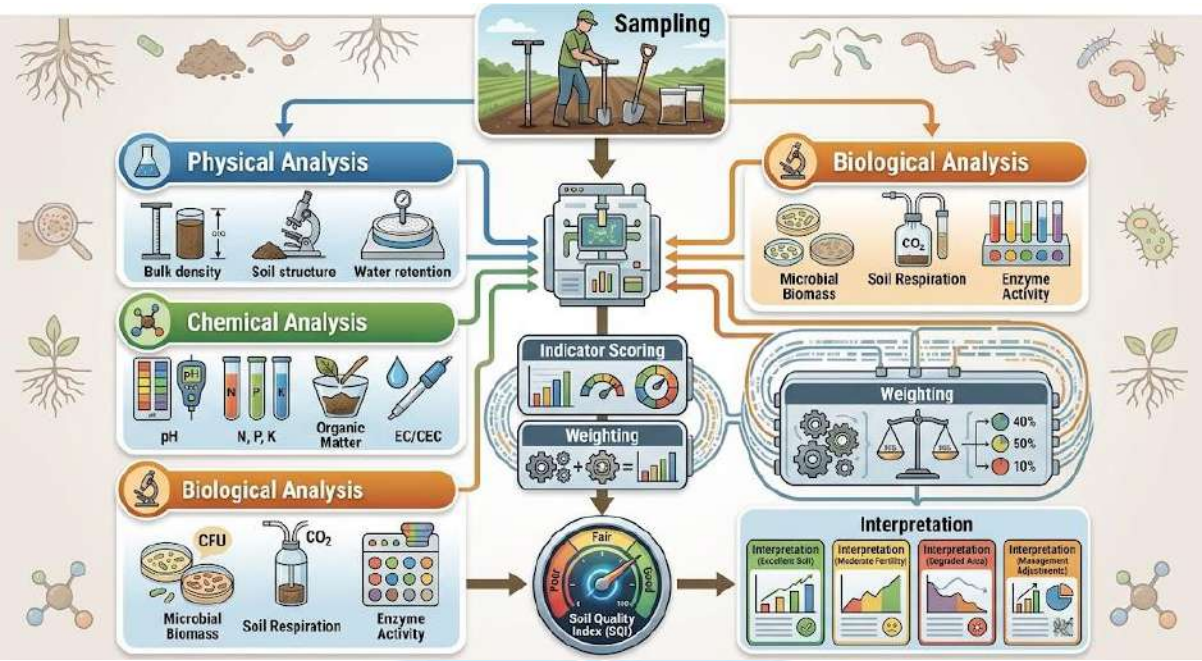


Figure 2: Soil Quality Assessment Workflow

Table 2: Common Methods Used for Soil Quality Assessment

Indicator	Measurement Method	Unit	Interpretation
Bulk density	Undisturbed core, oven-dry	g cm^{-3}	Higher values indicate compaction, restricting root growth
Soil texture	Hydrometer / pipette	% sand, silt, clay	Determines pore space and water retention
Porosity	Calculated from bulk and particle density	%	Higher porosity favours aeration and infiltration
Water-holding capacity	Pressure plate / gravimetric	% (w/w)	Higher values indicate greater water storage
Aggregate stability	Wet sieving	% stable aggregates	Higher values indicate resistance to erosion
pH	Potentiometry, 1:2.5 soil:water	pH units	Near-neutral range favours nutrient availability
Electrical conductivity	Conductivity meter, 1:5 extract	dS m^{-1}	Higher values indicate salinity stress
Soil organic carbon	Walkley–Black / dry combustion	% or g kg^{-1}	Higher values indicate better fertility and structure
Total nitrogen	Kjeldahl digestion	% or g kg^{-1}	Indicates nitrogen reserve for plant growth
Available phosphorus	Olsen / Bray-1 extraction	mg kg^{-1}	Indicates plant-available P status
Exchangeable potassium	Ammonium acetate, flame photometry	mg kg^{-1}	Indicates K availability for plant growth

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CEC	Ammonium acetate saturation, pH 7	cmol(+) kg^{-1}	Higher values indicate greater nutrient retention
Microbial biomass C	Fumigation–extraction / SIR	mg C kg^{-1}	Higher values indicate active microbial community
Soil respiration	CO_2 evolution (alkali trap / IRGA)	mg CO_2 kg^{-1} day^{-1}	Higher values indicate greater biological activity
Enzyme activity	Colorimetric substrate assays	µmol product g^{-1} h^{-1}	Higher values indicate active nutrient cycling
Earthworm abundance	Hand-sorting / extraction	ind. m^{-2}	Higher values indicate favourable soil biological condition
Nematode diversity	Extraction and identification to genus	Indices / ind. 100 g^{-1}	Higher maturity index indicates stable, undisturbed community
Arthropod diversity	Berlese–Tullgren / pitfall traps	Ind./sample, diversity indices	Higher diversity indicates a healthy, undisturbed habitat

5. How Soil Quality Impacts Plant Growth

The growth of plants depends on the physical, chemical and biological processes of the soil, which are closely linked together. Each dimension affects a different but overlapping portion of the soil–plant system and together they ultimately determine germination, biomass accumulation and yield.

5.1 Physical Properties of Soil and Plant Growth

The environment that roots have to explore is defined by the physical properties. Compaction, indicated by increased bulk density, reduces total porosity and removes macropores, so that root elongation is mechanically inhibited and roots become shallow, thickened and clustered. As the roots are restricted in their growth the volume of soil that can be exploited for water and nutrients is limited and the plant is more vulnerable to drought. The pore-size distribution directly controls the water availability: micropores retain water against drainage, macropores conduct excess water and prevent waterlogging. In poorly drained soils prolonged saturation displaces oxygen, aeration becomes limiting, root respiration declines and anaerobic conditions favour denitrification and the accumulation of reduced, phytotoxic compounds. By contrast, a well-structured soil with stable aggregates offers a continuous pore network, extensive root development, increased rooting depth and a root system able to cope with transient moisture deficits.

5.2 Soil Chemical Characteristics and Plant Growth

The availability of nutrients to plants depends on chemical properties. The most important single factor influencing nutrient availability is soil pH: strongly acidic conditions reduce the availability of phosphorus, calcium and magnesium and increase the solubility of aluminium and manganese to potentially toxic levels, whereas strongly alkaline conditions reduce the availability of phosphorus and micronutrients such as iron, zinc and manganese. High electrical conductivity (salinity) reduces the osmotic potential of the soil solution and inhibits water uptake causing physiological drought and poor germination. Chemical fertility is supported by the organic matter in the soil, which provides and cycles nutrients, increases the cation exchange capacity and buffers the pH. Nitrogen is the most common limiting nutrient for vegetative growth. Deficiency results in stunted plants with pale, chlorotic leaves. Phosphorus is required for root growth, energy transfer and reproductive growth. Its deficiency limits root proliferation. Potassium regulates the water relations, enzyme activation and transport and its deficiency decreases the drought tolerance and grain filling. The availability of nitrogen, phosphorus and potassium is relative and thus determines the growth rate and quality of plants.

5.3 Soil Biological Properties and Plant Growth

The biological component of soil quality is involved in the transformation of nutrients into

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plant available forms. Rhizosphere microorganisms – bacteria and fungi that colonise the root zone – decompose organic residues and mineralise nitrogen, phosphorus and sulphur, i.e. convert them from organic to inorganic forms that can be absorbed by the roots. Thus the key biological process linking organic matter inputs to plant nutrition is nutrient mineralisation. Mycorrhizal associations, especially arbuscular mycorrhizal fungi, increase the effective absorbing surface of the root system beyond the depletion zone and improve the uptake of phosphorus, zinc and water and in many crops improve drought tolerance and seedling establishment. Plant-microbe interactions include the plant growth-promoting rhizobacteria producing phytohormones, enhancing root branching and suppressing soil-borne pathogens, free-living nitrogen fixers and symbiotic rhizobia. Thus, the diversity and activity of these organisms regulate the efficiency of conversion of soil nutrient reserves into plant tissue.

5.4 Soil quality and crop production

The enhanced soil quality is demonstrated at the level of the whole plant in successive growth stages. In soils with good moisture retention, suitable pH and low salinity, germination and seedling establishment are more reliable. In the absence of compaction, water and nutrients are available throughout the profile and root biomass increases . The larger root system in turn supports greater nutrient uptake . The increased supply of nitrogen and phosphorus associated with higher organic matter and biological activity affects shoot biomass, plant height and leaf development. Photosynthetic capacity, which drives biomass production, is determined by leaf area expansion and chlorophyll content. These effects build up over the growing season and the ultimate expression of soil quality is crop yield. Soils with a higher soil quality index value produce greater above-ground biomass and a higher grain or fruit yield. Degraded soils with low organic matter, high bulk density and poor structure produce consistently lower yields.

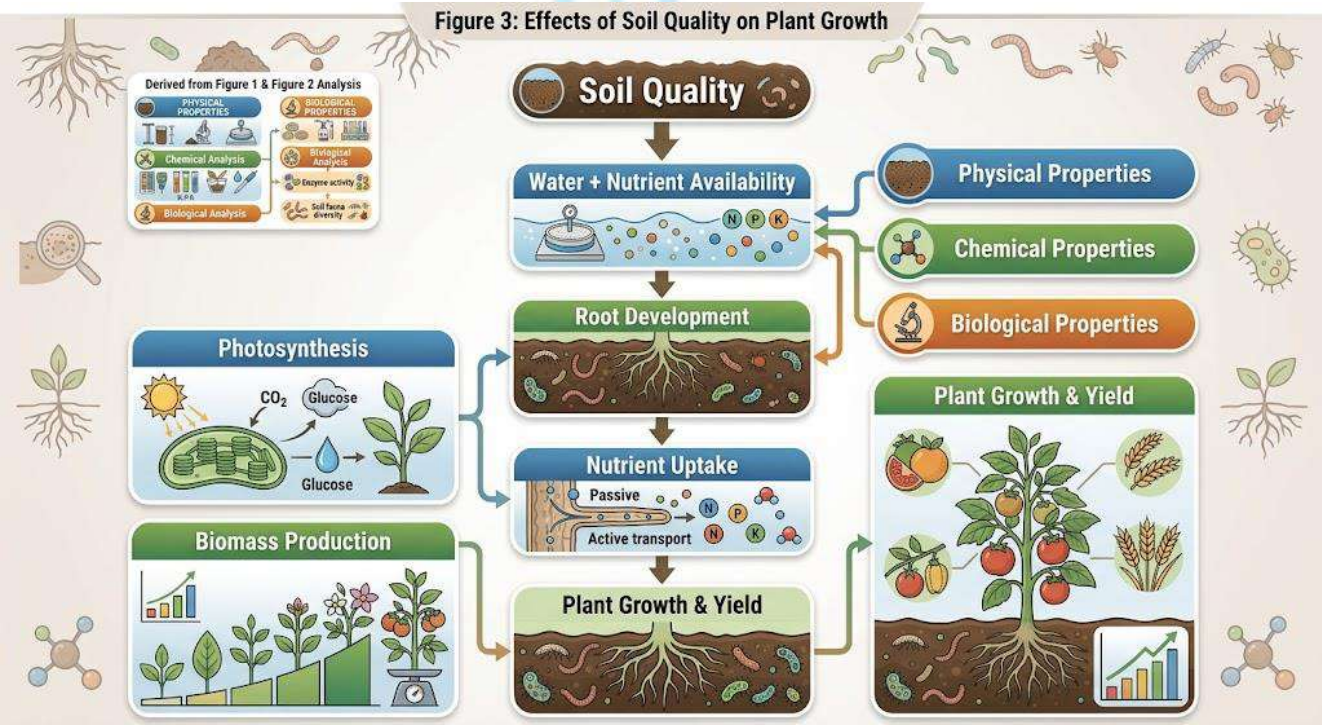


Figure 3: Effects of Soil Quality on Plant Growth

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Table 3: Effects of Different Soil Quality Indicators on Plant Growth

Soil indicator	Poor condition	Effect on plant
pH	Highly acidic/alkaline	Reduced nutrient availability
Bulk density	High	Restricted root growth
Organic matter	Low	Reduced fertility
Nitrogen	Deficient	Poor vegetative growth
Water holding capacity	Low	Water stress

6. Influence of Soil Quality on Soil Fauna

6.1 Major Soil Faunal Groups

Soil fauna show a high diversity in body sizes and functions. Macrofauna (2–20 mm) are large soil invertebrates such as earthworms, woodlice, ants, termites, beetles, arachnids, myriapods and insect larvae. They include litter transformers, predators, some plant herbivores and ecosystem engineers that move through the soil, perturbing it and increasing water permeability and aeration whilst creating new habitats for smaller organisms (George et al., 2020). Mesofauna, mainly springtails and mites, speed up the breakdown of litter and improve nutrient cycling and availability, especially of nitrogen, and they also feed on smaller soil organisms (George et al., 2020). The most abundant multicellular animals in soil are microfauna, mainly nematodes. Soil arthropods alone comprise at least five classes, Arachnida (spiders, mites), Chilopoda, Diplopoda, Crustacea (isopods) and Hexapoda (insects, collembolans) (Lehman et al., 2015).

6.2 Soil Quality and Earthworms

Among the macrofauna, the earthworms are the most influential members. Social insects, through their foraging and burrowing behaviour and their nest-building activity, have a strong influence on the dynamics of soil structure and consequently on the dynamics of water and soil quality (George et al., 2020). They change the porosity of the soil and the movement of water and gas, and their casts and burrows bind the particles of the soil into stable aggregates that hold the soil in place and reduce erosion (George et al., 2020). Invertebrate communities are more abundant and diverse in soils with high soil organic matter and water content and low metal concentrations (Zornoza et al., 2015), and earthworm populations are sensitive to the organic matter, moisture and contamination status in the soil. Earthworms are widely considered as indicators of the biological condition of soil, since they integrate organic matter inputs, moisture regime, pH and habitat quality. However, they have been included as indicators in only about 40% of the literature consulted, despite responding sensitively to land management (Zornoza et al., 2015).

6.3 Soil Health and Nematodes

Nematodes occur in several particularly informative trophic positions. Bacterial- and fungal-feeding nematodes regulate microbial populations and release nitrogen and other nutrients through grazing activities, predatory nematodes occupy higher trophic levels, and plant-parasitic nematodes feed on roots and have the potential to reduce crop performance . Different groups react differently to disturbance and pollution, which changes the community structure of nematodes: the abundance of sensitive species decreases under light to moderate pollution, while tolerant species are unaffected, but even tolerant species decline in heavily polluted soils, due to toxic effects or a reduction in microbial activity (Bhaduri et al., 2022). Thus, the species composition of the nematode assemblage gives a graded signal of the soil biological quality.

6.4 Soil Quality and Soil Arthropods

Mites, springtails, and other arthropods are drivers of decomposition and food web function. Generally, Acari are the most abundant group of microarthropods, followed by Collembola and Hymenoptera (Sapkota et al ., 2012). They are highly sensitive to soil quality. In no-tillage, the abundance and diversity of micro-arthropods were also higher and Simpson's diversity index was about 40% higher than in conventional tillage, with soil organic matter increased to 3.31% from

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2.19% in conventional tillage and microbial biomass increased by 71% (Sapkota et al., 2012). Surface residues in no-till systems provide food supplies and physical protection for micro-arthropods and this management has been reported to increase numbers and biomass of meso- and macrofauna (Sapkota et al., 2012). They link the microbial food web to higher trophic levels, and control decomposition and nutrient cycling (George et al., 2020).

6.5 Bioindicators: Soil Fauna

Soil fauna are now commonly used as soil quality bioindicators . Because they are sedentary, they are present each year, they are easy to measure, they are highly sensitive and respond quickly to environmental stress (Guarderas et al., 2022), making them suitable for this task. Soil invertebrates are also reported to be useful indicators to monitor qualitative and quantitative environmental changes caused by anthropogenic activities (Bhaduri et al., 2022). Biological indicators include multi-dimensional phenomena such as the delivery of key soil processes and thus capture information that cannot be captured by physico-chemical indicators alone (Ritz et al., 2009). For example, ants are sensitive to environmental disturbance and are functionally important as ecosystem engineers, making them useful monitoring tools in restoration programs (George et al., 2020). However, careful selection is required for the conversion of faunal data into operational monitoring tools: a systematic framework surveyed 183 candidate biological indicators and resulted in a ranked list of 21, covering genotypic-, phenotypic- and functional-based indicators for different trophic groups (Ritz et al., 2009).

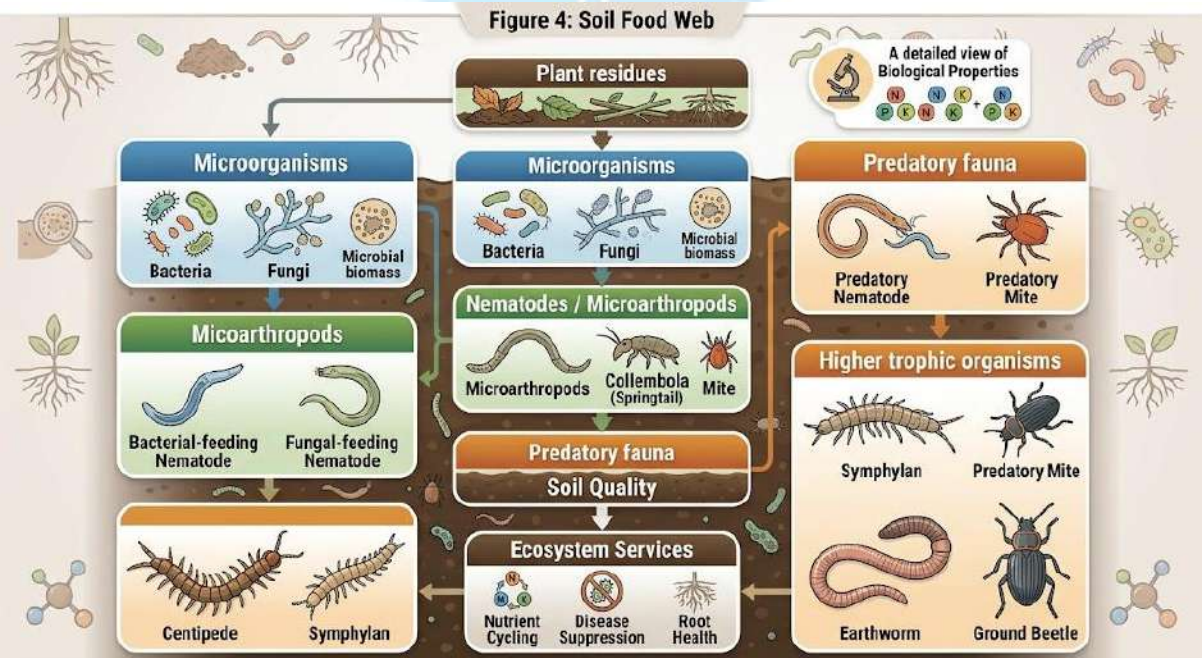


Figure 4: Soil Food Web

Table 4: Major Soil Fauna Groups and Their Functions

Soil fauna	Major function	Soil quality relationship
Earthworms	Organic matter decomposition	Soil structure
Nematodes	Nutrient cycling	Biological quality
Mites	Decomposition	Organic matter
Springtails	Fungal feeding	Decomposition
Predatory arthropods	Food-web regulation	Ecosystem stability

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7. Relationship of soil quality, plant growth and soil fauna

Soil quality, plant growth and soil fauna are not separate compartments of the soil system. They are one self-reinforcing cycle, each component determining the conditions of the others. This section pulls together the preceding discussion by tracing that cycle through its productive and degraded manifestations.

In good soil quality the cycle begins with organic matter. High organic matter content provides substrate and habitat for the biological community, supporting greater microbial biomass and more diverse enzymatic activity. The higher microbial activity then supports a larger and more functionally complete soil fauna, more earthworms, nematodes, mites and springtails, because microorganisms are the main food resource for the lower trophic levels of the soil food web. The fauna then speed up nutrient cycling. Earthworms fragment and mix litter, nematodes graze microbial populations and release nitrogen and arthropods regulate fungal and bacterial biomass. Organic nutrients are mineralised into plant available forms more rapidly and completely than microbial decomposition alone could achieve. Improved porosity, infiltration and water retention, together with the physical benefits of faunal burrowing and aggregation, enhance nutrient availability and create a more favourable rooting environment. Roots grow more extensively, take up more water and nutrients and sustain greater canopy development and photosynthesis leading to higher plant productivity. The cycle closes when plant residues and root exudates return to the soil as fresh organic matter, feeding the microbial and faunal communities that started the cycle.

The same cycle runs in reverse with poor soil quality. Compaction, contamination, salinity or nutrient deficiency suppresses microbial activity and the lower food base and degraded habitat leads to lower faunal abundance and diversity, often with a shift toward tolerant or plant-parasitic groups. Thus the rate of nutrient cycling is reduced, organic residues build up without being decomposed, mineralisation is retarded and nutrients are retained in forms that are unavailable to plants. Poor root growth is caused by a combination of mechanical impedance, water stress and nutrient shortage. Reduced root systems supply less water and nutrients to the shoot, thus reducing biomass accumulation and yield. The reduced input of plant residues and exudates further weakens the biological community so that degradation becomes self-perpetuating unless management intervenes.

The interdependence of these components has practical implications for assessment. Soil fauna respond rapidly to changes in organic matter, structure and contamination, providing an early signal of decline that precedes visible loss of plant productivity, while plant performance provides the integrated, longer-term expression of the same underlying soil condition. Soil quality, soil fauna and plant growth should therefore be seen as indicators of each other rather than as independent outcomes.

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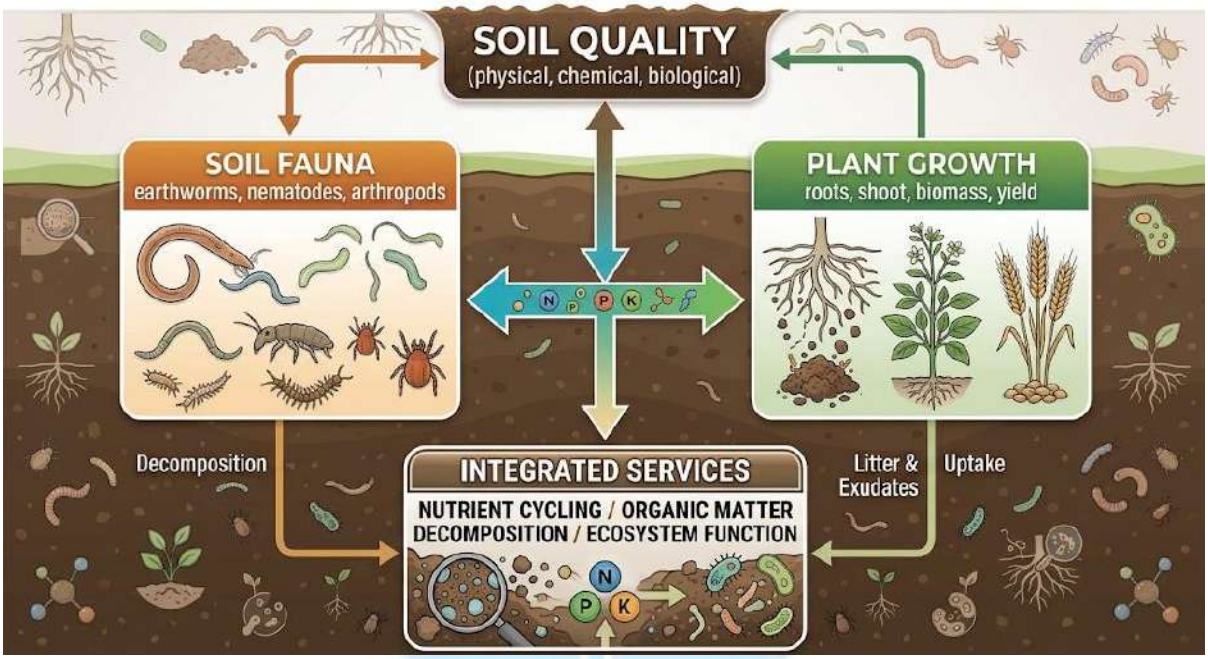


Figure 5: Integrated Relationship Among Soil Quality, Soil Fauna and Plant Growth

8. Factors Responsible for Soil Quality Degradation

Soil quality degradation results from a combination of land-use and environmental pressures that act on the physical, chemical and biological dimensions of the soil simultaneously.

8.1 Intensive Agriculture. Continuous cultivation, monocropping and removal of crop residues deplete soil organic matter and disrupt aggregate stability. Reduced residue return lowers the substrate available to the microbial community and diminishes faunal habitat, while repeated tillage breaks down the structure that sustains porosity and infiltration.

8.2 Excessive Fertilizer Use. Imbalanced or excessive application of mineral fertilizers causes chemical imbalance in the soil solution, accumulation of unused nutrients and nutrient toxicity, and can suppress microbial and faunal diversity through altered soil chemistry. Excess nitrogen and phosphorus may also be lost to leaching and runoff.

8.3 Pesticides. Herbicides, insecticides and fungicides disturb soil biology directly by causing mortality of non-target fauna and indirectly by removing the plant and microbial food resources on which faunal communities depend. Some compounds may also be phytotoxic to crops.

8.4 Soil Erosion. Water and wind erosion remove the nutrient-rich topsoil, reducing fertility and rooting depth. Loss of topsoil also destroys the surface habitat and organic matter layer that supports litter-dwelling fauna, causing habitat loss and declining biological activity.

8.5 Heavy Metal Contamination. Accumulation of metals such as cadmium, lead, copper and zinc contaminates the soil, inhibits root and shoot growth, and is toxic to soil fauna and microorganisms. Faunal communities typically lose sensitive species first, so that abundance and diversity decline.

8.6 Salinization. Rising salt concentration increases electrical conductivity, raises osmotic stress and impairs water uptake by roots. Salinity also alters microbial activity and restricts the faunal groups able to persist, reducing biological diversity.

8.7 Soil Compaction. Traffic and tillage at high moisture content increase bulk density and reduce porosity, restricting root penetration, limiting aeration and infiltration, and destroying the pore

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network that serves as habitat for meso- and macrofauna.

8.8 Climate Change. Altered rainfall, higher temperatures and more frequent extreme events accelerate organic matter decomposition, increase erosion and salinization risk, and shift faunal communities beyond their tolerance ranges.

Table 5: Major Causes of Soil Quality Degradation and Their Effects

Factor	Soil effect	Plant effect	Fauna effect
Excessive fertilizer	Chemical imbalance	Nutrient toxicity	Reduced diversity
Pesticides	Biological disturbance	Possible phytotoxicity	Fauna mortality
Heavy metals	Soil contamination	Growth inhibition	Toxicity
Compaction	Reduced porosity	Poor roots	Reduced habitat
Erosion	Loss of topsoil	Low fertility	Habitat loss

9. Soil Quality Management and Improvement Strategies

Restoring and maintaining soil quality requires a combination of organic inputs, diversified cropping, reduced disturbance and balanced nutrient and pest management, applied together rather than in isolation.

9.1 Organic Amendments. Compost, farmyard manure and biochar are the primary means of rebuilding soil organic matter. They supply carbon and nutrients, increase cation exchange capacity and water-holding capacity, stimulate microbial biomass and enzyme activity, and improve aggregate stability. Biochar additionally provides stable carbon and porous surfaces that increase microbial habitat and nutrient retention. Organic amendments also constitute the food base for earthworms and mesofauna, so they directly support faunal recovery.

9.2 Crop Rotation. Rotating crops with different rooting depths and nutrient demands interrupts pest and pathogen cycles, diversifies root exudates and residue quality, and prevents the selective depletion of nutrients associated with monocropping. Greater residue diversity supports a more diverse microbial and faunal community.

9.3 Cover Cropping. Cover crops protect the soil surface from erosion, reduce nutrient leaching, add organic matter and, through their root systems, maintain continuous pore networks and root channels. Leguminous cover crops fix nitrogen, while their surface residues provide food and physical protection for soil arthropods.

9.4 Reduced/Conservation Tillage. Minimum or no-tillage limits the physical disruption of aggregates, preserves pore continuity and stratification of organic matter, and reduces compaction from repeated passes. Residue retention on the surface favours earthworms and micro-arthropods and improves infiltration and water storage.

9.5 Integrated Nutrient Management. Combining organic sources with mineral fertilizers in balanced proportions, guided by soil testing and crop requirement, avoids both nutrient deficiency and excess. This maintains favourable pH and salinity levels and sustains microbial activity without the chemical imbalance caused by over-fertilization.

9.6 Integrated Pest Management. Combining cultural, biological and minimal chemical control reduces the pesticide load reaching the soil, protecting non-target fauna while maintaining pest suppression through natural predators and parasitoids.

9.7 Soil Fauna Conservation. Practices that maintain organic matter, minimise tillage, avoid contamination and preserve habitat connectivity allow earthworm, nematode and arthropod communities to persist and function, which in turn sustains decomposition, nutrient cycling and structure formation.

9.8 Sustainable Water Management. Efficient irrigation, drainage and moisture conservation maintain optimal soil moisture, avoid salinization from over-irrigation and prevent waterlogging, preserving aeration for roots and soil organisms.

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Figure 6: Sustainable Soil Quality Management Framework

Table 6: Soil Management Practices and Expected Benefits

Practice	Mechanism	Expected benefit
Organic amendments (compost, manure, biochar)	Adds carbon, nutrients and microbial habitat	Improved structure, fertility and faunal food base
Crop rotation	Diversifies roots, residues and nutrient demand	Reduced pest pressure, balanced nutrient use
Cover cropping	Protects surface, fixes N, maintains root channels	Less erosion and leaching, more organic matter
Reduced/conservation tillage	Limits aggregate disruption, retains residues	Better porosity, infiltration and faunal habitat
Integrated nutrient management	Balances organic and mineral inputs	Avoids nutrient excess and chemical imbalance
Integrated pest management	Minimises chemical inputs, uses natural control	Protects non-target soil fauna
Soil fauna conservation	Maintains habitat, moisture and organic matter	Sustained decomposition and nutrient cycling
Sustainable water management	Controls irrigation, drainage and moisture	Avoids salinization, waterlogging and water stress

10. Gaps in Research and Future Perspectives

Soil quality research has advanced considerably but there are multiple gaps limiting scientific understanding and practical application.

The core gap is a lack of a standard set of indicators. Different studies select different physical, chemical and biological properties, apply different scoring functions and weight them by different procedures, so that values of the soil quality index are rarely comparable between regions or studies. Before soil quality can be monitored consistently on a national or global

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scale, a consensus minimum data set is required with agreed analytical protocols and interpretation thresholds.

The second gap is the poor integration of the three dimensions of the indicators. Chemical properties are still the major focus of assessment, and biological indicators, particularly soil fauna, are under-represented despite their sensitivity and rapid response to disturbance. Soil fauna need to be more systematically developed as bioindicators with a standardised sampling effort, taxonomic resolution and reference values defined for different land uses.

Third, most of the evidence comes from short-term trials. Long term field experiments are needed to separate real trends from seasonal and interannual variation, and to quantify the response of soil quality to management on decadal scales. Such experiments are also needed to detect the effects of climate change - altered rainfall, warming and extreme events - on organic matter dynamics, erosion and faunal communities which are still poorly quantified.

Fourth, methodological opportunities are not fully exploited. Remote sensing and GIS offer large-area, spatially explicit monitoring of soil and vegetation properties. Machine learning and AI-based methods can integrate heterogeneous datasets to predict soil quality and identify degradation hotspots. Methods such as metabarcoding and high-throughput sequencing enable a far more complete characterisation of soil biodiversity than morphological identification.

Finally, it is unlikely that a single universal index will be sufficient, given the differences in soil forming factors, land use and faunal assemblages between regions. The most promising direction for future research is the development of region-specific and ecosystem-specific Soil Quality Indices, calibrated to local reference soils and management systems.

11. Conclusion

Soil quality is fundamental to ecosystem productivity and to the sustainability of agricultural systems. It is a composite attribute that cannot be measured directly, but is inferred from its physical, chemical and biological properties, and these three dimensions should be assessed together rather than in isolation, since each influences soil function through its interaction with the others.

Soil quality directly affects plant growth. Physical conditions such as structure, bulk density and porosity determine root penetration, water availability and aeration; chemical conditions including pH, salinity and nutrient status govern the supply of nutrients in plant-available form; and biological processes such as mineralisation and mycorrhizal association determine how efficiently those nutrients are delivered. Plant productivity, from germination and root and shoot biomass through to final yield, is therefore an integrated expression of the underlying soil condition.

Soil fauna are equally central to soil function. Earthworms, nematodes, mites, springtails and other arthropods drive organic matter decomposition, regulate the soil food web and accelerate nutrient cycling, and their abundance and diversity respond rapidly to changes in soil quality, making them valuable bioindicators.

These components operate as a single cycle: healthy soil supports diverse soil fauna, diverse fauna enhance nutrient cycling, and improved nutrient cycling promotes better plant growth, which in turn returns organic matter to the soil. Sustainable soil management — through organic amendments, diversified cropping, reduced tillage and balanced nutrient and pest management — is therefore essential to preserve long-term soil productivity.

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