



Soil Quality in Fruit Tree Plantations: Indicators, Assessment Methods, and Land Use Implications

Jay Mark G. Cortado ^{a*} and Sherwin P. De Jesus ^b

^a College of Agroforestry and Forestry, Don Mariano Marcos Memorial State University, Bacnotan, La Union 2515, Philippines.

^b Land and Water Resources Engineering Division, Institute of Agricultural and Biosystems Engineering, College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, Laguna 4030, Philippines.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.9734/ijpss/2025/v37i65525>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://pr.sdiarticle5.com/review-history/138035>

Review Article

Received: 09/04/2025

Accepted: 14/06/2025

Published: 17/06/2025

ABSTRACT

Soil quality is a key concept essential to sustainable land use, agricultural productivity, and environmental protection. It refers to the soil's ability to perform its functions within the limits of a natural ecosystem, encompassing its physical, chemical, and biological properties to sustain productivity, preserve environmental integrity, and support human and animal health. However, soil degradation driven by land use change, deforestation, unsustainable agricultural practices, and climate change has increasingly compromised soil quality worldwide. This emphasizes the urgent need for systematic assessment tools. Soil quality indicators, encompassing physical, chemical, and biological properties, have been developed to capture changes in soil function. These

*Corresponding author: E-mail: jcortado@dmmsu.edu.ph;

indicators are often integrated into soil quality indices (SQIs), such as the additive soil quality index, to simplify and quantify the soil's overall health. Comparative and dynamic assessments using reference conditions and time-series data are crucial for evaluating the effectiveness of land management strategies. Effective soil resource management must balance productivity with environmental protection, particularly in regions with limited resources and vulnerable ecosystems. In Southeast Asia, where forest-to-agriculture conversion is widespread, the soil quality implications of fruit tree plantations remain largely unexamined. This review proposes an integrated conceptual framework for assessing soil quality in fruit tree plantations by consolidating indicators across physical, chemical, and biological domains; contextualizes their use in orchard-based systems; and synthesizes current assessment approaches to support sustainable land management. Such efforts can inform sustainable management practices and policy development. This review underscores the significance of soil quality assessment and the role of SQIs in achieving long-term ecological sustainability, food security, and soil resource conservation.

Keywords: Agricultural productivity; forest conversion; land degradation; soil properties; soil quality index.

1. INTRODUCTION

1.1 Forest Conversion to Tree Plantation

The loss of natural forests is still a significant concern (Altamirano et al., 2020). As reported by the FAO (2020), the global forest area covers around 4.06 billion ha, accounting for 31% of the Earth's total land surface. Since 1990, however, around 178 million ha of forests have been lost. Despite this, the rate of net forest loss has shown a declining trend, dropping from 7.8 million ha annually in the 1990s to 5.2 million ha per year between 2000 and 2010, and further down to 4.7 million ha per year during 2010–2020. This downward trend is projected to continue, with forest loss expected to slow further by 2030 (Annunzio et al., 2015; FAO, 2020).

The major driver of tree cover loss on a worldwide scale is the permanent land-use change for commodity products such as forestry and agriculture, particularly in developing countries, to meet global demand for products such as food, forage, and fuel (Curtis et al., 2018; Gibbs et al., 2010). The ecological effects of land-use expansion on biodiversity and the landscape largely depend on whether these new uses replace forests, degraded forests, or grasslands (Gibbs et al., 2010; Nahuelhual et al., 2012).

According to a study conducted by Curtis et al. (2018), deforestation is responsible for 27% of worldwide forest loss. The yearly rate of deforestation was predicted to be 10 million ha in 2015–2020 (FAO, 2020). It is widely agreed that deforestation occurs predominantly in the tropics and that agricultural expansion is the leading

direct source of deforestation, contributing 70–95% of the total forest loss (Annunzio et al., 2015). Tropek et al. (2014), for example, found that monocultures of oil palm or rubber are expanding at an alarming rate into tropical forest systems. Large-scale industrial plantations of oil palm and pulpwood species, such as *Acacia mangium*, have replaced extensive areas of old-growth forests across Southeast Asia, especially in countries like Malaysia and Indonesia (Gaveau et al., 2018). Gibbs et al. (2010) estimated that as much as 10 billion additional ha of agricultural land will be required to support global demands by 2050.

According to FAO (2020), the definition of “forest” excludes tree stands used in agricultural production systems, including fruit tree plantations, olive orchards, oil palm plantations, and agroforestry systems where crops are cultivated beneath tree cover. As such, these areas are classified by FAO (2020) as “other land use with tree cover,” which mentions that land use is the primary consideration for differentiating forest and other lands with tree cover. By following the FAO (2020) definition of “forest,” tree plantations belonging under agricultural production systems, such as fruit tree plantations, can be regarded as a significant contributor to forest loss if these areas were previously forested and underwent conversion to such present land uses.

Penna (2010) described “tree plantations” as areas predominantly consisting of trees that have been established through planting or intentional seeding and are typically subject to more intensive management compared to natural forests. The borderline between plantations and

agriculture is a challenge for defining the term "tree plantation" (Niskanen & Saastamoinen, 1996). But the use of the term 'tree plantation' considers such unconventional plantation kinds as those with fruit trees and agroforestry (Niskanen & Saastamoinen, 1996).

Tree plantations increasingly meet market demands for timber, food, energy, and carbon storage (Holt et al., 2016). On the other hand, Carle et al. (2002) pointed out that not all plantation projects have favorable environmental, economic, social, or cultural consequences. Plantations may be planted in the wrong places, with the wrong species/provenances, and for inappropriate purposes, if proper planning and management are not in place. If policies encourage the conversion of natural forests to other land uses, negative environmental consequences may occur (Altamirano et al., 2020). As Holt et al. (2016) affirmed, tree plantations frequently endanger native forests for their establishment.

2. TREE CROPS AGRICULTURE / TREE ORCHARD

Tree orchards belong to the sub-category of "other land with tree cover" that mainly comprises trees for producing fruits, olives, or nuts (FAO, 2020). Plieninger (2012) also characterized orchards as a land-use system that consists of open stands of conventional fruit trees in crop fields, meadows, or gardens. The term 'tree crop,' which Yan et al. (2020) defined as a cluster of established tree species with purposes other than timber production, can also be associated. Although primarily focused on trees, tree crop agriculture/cultivation also covers shrubs and perennial herbaceous plants, such as bananas (MacDaniels & Lieberman, 1979).

Smallholders may find tree crops a viable source of income (Yan et al., 2020). Its cultivation has been acknowledged as a prominent and vital element of the agricultural frontier elsewhere (Chomitz & Griffiths, 1996; Kennedy, 2012). It aims to promote national economies, particularly in tropical producing countries (Asubonteng et al., 2018). Throughout Southeast Asia, high-value export-oriented crops have rapidly emerged and expanded over the past decades (Fox & Castella, 2013).

According to MacDaniels & Lieberman (1979), the possible significant contributions of tree crops include erosion management, satisfying energy

demands and increasing energy efficiency, and providing numerous uses in addition to food and forage. Due to minimal to no-tillage activities, there is less disruption of the soil biota and organic matter in the soil (Molnar et al., 2013). Tree crops have several other qualities that can be improved to produce highly effective and sustainable agriculture without requiring heavy mechanization (MacDaniels & Lieberman, 1979; Molnar et al., 2013).

Fruit and multi-purpose trees can help with soil and water management and conservation (Molnar et al., 2013; Temudo & Abrantes, 2014; Plieninger, 2012). Fruit tree orchards can also mitigate global warming by sequestering carbon and supplying biofuels (Aguilera et al., 2015; Plieninger, 2012; Temudo & Abrantes, 2014). Many animal species also benefit because these trees provide food, nesting sites, and physical protection. Furthermore, these can link forests and other semi-natural habitats, which is often vital for the sustainability of wildlife (Plieninger, 2012).

Tree crops could offer options for addressing on-farm labor shortages and creating income for underprivileged rural communities, as well as preserving natural forest integrity through alternative livelihoods (Yan et al., 2020). Fruit trees are low labor-intensive and land-extensive crops, making them a suitable choice in situations where land is ample, but labor is limited (Keys & McConnell, 2005).

Tree crops may assist farmers in protecting their harvests from year-to-year fluctuations in rainfed annual crop yields (Damatta, 2008; Temudo & Abrantes, 2014). These should be considered a supplement to conventional grain crop cultivation, according to MacDaniels & Lieberman (1979). Agricultural systems containing tree crops exemplifying ecologically appropriate practices have been employed successfully in the production of food and forage in many places of the world for long periods, even though grains will remain the primary source of food globally (MacDaniels & Lieberman, 1979). In fact, several countries, such as China, have pushed tree crops to achieve economic development with environmental rehabilitation (Yan et al., 2020).

Planting the right mix of perennial species in degraded lands would allow for supplemental food or energy while also protecting, building, and improving the soil (Molnar et al., 2013).

Furthermore, tree crops cultivated on rough, marginal lands will not produce yields equivalent to intense cultivation on level land; yet, future food supply concerns may make tree crop production on marginal land feasible (MacDaniels & Lieberman, 1979). According to MacDaniels & Lieberman (1979), there are vast lands generating very little that may support tree crops if adequately managed. However, the ecological benefits provided by tree crops are generally less than those offered by naturally regenerated forests (Yan et al., 2020). Tree crops can enhance soil retention and carbon sequestration when they replace field crops, but their effects can be unfavorable if they compete with forests (Yan et al., 2020). Agriculture commodities like oil palm, cocoa, and coffee are expanding at the expense of biodiversity, water conservation, carbon storage, and other essential ecosystem services (Asubonteng et al., 2018).

Tree crops may result in tradeoffs with natural forest regeneration. However, even if deforestation continues, the state of the remaining forests may improve if earnings from tree crops replace the demand for natural forests (Yan et al., 2020). Enhancing the provision of forest goods and services requires finding a balance between human needs and environmental conservation (Molnar et al., 2013; Peryea, 2001). However, to ensure meaningful benefits for the farmer, crop productivity should also be assessed within the context of naturally evolving environmental conditions. After all, the primary purpose is to improve yield under such circumstances (Damatta, 2008). To ensure sustainability, a clear understanding of what is most appropriate for specific agro-ecological zones and which interventions can be used effectively is required (Dewi et al., 2017).

The orchard floor, particularly the soil, makes up a large part of the orchard agroecosystem. Still, it has gotten less attention in research and management than pest and disease control and tree horticulture (Granatstein & Sanchez, 2009). However, there are opportunities to increase orchard sustainability by manipulating the orchard floor, which could improve tree fruit yield and cut costs (Granatstein & Sanchez, 2009). Aguilera et al. (2015) suggested a need to optimize management in orchards to maximize the quality of the soil.

High-density planting (HDP) systems are increasingly adopted in modern fruit orchards to enhance productivity and land-use efficiency. These systems utilize dwarfing rootstocks, precise canopy management, and closely spaced plantings, often exceeding 1,250 trees per hectare in ultra-high-density configurations and up to 20,000 trees in super-high-density planting (Karishma et al., 2025). While HDP systems offer economic and horticultural benefits, they also pose challenges for soil health, particularly in terms of compaction, nutrient depletion, and soil organic matter maintenance. Increased planting density intensifies below-ground competition for water and nutrients, making tailored soil fertility plans essential, particularly in fertile soils that support denser plantings (Haque & Sakimin, 2022).

Effective orchard-floor management aims to achieve strong tree growth and consistently high yields of quality fruits. Like biodiversity and soil carbon sequestration, other objectives are increasingly garnering more attention (Granatstein & Sanchez, 2009). However, according to Granatstein & Sanchez (2009), improvements in soil quality do not always translate directly to enhanced tree performance, but they reflect changes that are likely to be more valued over time.

3. SOIL QUALITY

Soil is a living, dynamic natural body that performs many vital functions in terrestrial ecosystems essential to life (Doran & Parkin, 1994; Wienhold et al., 2004). It acts as a growing medium for plants, a nutrient reservoir, and a hub for various biological processes such as recycling and decomposition of animal and plant products, as well as pollution management. Soils impact air quality by interacting with the atmosphere and functioning as a reservoir and filtration system for water as it percolates through the soil profile (Obade & Lal, 2016; Wienhold et al., 2004).

The growing recognition of soil as a vital part of the Earth's biosphere, playing roles beyond food and fiber production, including maintaining environmental quality at local, regional, and global scales, has fueled interest in assessing soil quality (Doran & Jones, 1996; Doran & Parkin, 1994; Doran, 2002). It is a complex medium that requires understanding on multiple levels (Karlen et al., 1997).

The soil is not an unlimited resource. It can be lost in a relatively short amount of time if it is misused or mishandled, with minimal possibility for regeneration or replacement (Nortcliff, 2002). Placing a value on soil based on its purpose, function, or use gives rise to the concept of soil quality (Carter et al., 1997). Some people view soil quality as being solely defined by crop yield. Others emphasize the importance of demonstrating how soil quality affects the quality of forage and food, as well as the habitat it provides for a diverse array of organisms (Karlen et al., 1997). Individual priorities in terms of soil function influence insights into what makes a good soil. However, soil quality must be defined to manage and preserve our soils in an acceptable form for future generations. The definition must be comprehensive to capture the numerous dimensions of soil function (Doran & Parkin, 1994).

Soil quality can be generally defined as the ability of living soil to perform effectively within the limits of natural or managed ecosystems, supporting plant and animal productivity, improving or maintaining water and air quality, and fostering the health of both plants and animals (Doran, 2002). According to Karlen et al. (1997), the simplest definition of soil quality is "the capacity of soil to function." A more comprehensive definition describes soil quality as the capacity of a particular soil type to function within the boundaries of natural or managed ecosystems by sustaining plant and animal productivity, preserving or improving water and air quality, and supporting human health and habitation (Karlen et al., 1997).

Doran and Parkin (1994) described soil quality as the soil's capacity to operate within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote the health of plants and animals. Larson and Pierce (1991) defined soil quality in functional terms as the soil's ability to operate effectively within an ecosystem while also interacting beneficially with the surrounding environment. Subsequently, Larson and Pierce (1994) highlighted that soil quality mainly pertains to the soil's ability to facilitate plant growth, control and direct water movement in the environment, and act as a protective buffer against environmental stresses. A common thread across all definitions of soil quality is the emphasis on the soil's ability to perform these functions effectively both now and in the future (Doran & Parkin, 1994).

Soil quality has distinct properties that change through time and space (Karlen et al., 2001). That is why, according to Sojka and Upchurch (1999), soil quality must be described in terms of distinctive environmental and management considerations specific to one soil under particular conditions for a given usage. Biological, economic, social, and other value judgments are among the factors to consider.

Wienhold et al. (2004) stated that the concept of soil quality was introduced to complement soil science research by enhancing our understanding of soil functions and informing the efficient use and allocation of labor, energy, financial resources, and other inputs, especially as agriculture expands and intensifies to meet increasing global demand. Soil quality serves as a unifying idea for educating producers, professionals, and the public about soils' critical functions. It also serves as a tool for assessing current management practices and comparing alternative management approaches (Wienhold et al., 2004). Soil quality is a concept founded on the understanding that management practices can deteriorate, maintain, or enhance the functional capacity of soil ecosystems (Franzluebbers, 2002).

This concept has been recognized as a science-based framework and educational resource for evaluating the sustainability of different soil management practices and land-use strategies (Karlen et al., 2001). It is regarded as a critical indicator of ecosystem sustainability (Carter et al., 1997). Soil quality impacts three crucial aspects of sustainable land management, according to Doran & Jones (1996), namely: agricultural productivity, environmental quality of natural resources, plant, animal, and human health. These are in comparison to what Karlen et al. (2001) enumerated, except with the addition of food safety and quality to the list.

High soil quality serves as the foundation for economic prosperity, environmental stability, and a resilient terrestrial biosphere (Lal, 2015). On the other hand, the general deterioration in soil quality, caused by natural processes and human activities, has strong feedback, resulting in a reduction in ecosystem services and conservation (Lal, 2015). Soil thrives under management and land-use decisions that recognize its multiple functions, rather than focusing exclusively on a single role like crop production (Doran, 2002). For this reason, preserving soil quality is essential to achieving

environmental sustainability (Arshad & Martin, 2002).

The resilience of soil and natural processes to maintain global energy and matter balances has been tested by agricultural and other ecosystem management in the past (Doran, 2002). In the early 21st century, Gibbs & Salmon (2015) reported that global estimates of total degraded land varied widely, ranging from under 1 billion hectares to more than 6 billion hectares. These show how the condition of many soils throughout the world has deteriorated dramatically when the conversion of grasslands and forests to arable agriculture and cultivation began (Doran, 2002). Feeding the world population, which is expected to reach 9.5 billion by 2050, entails approximately a 70% increase in agricultural production between 2005 and 2050, putting greater pressure on soil resources (Lal, 2015; Wienhold et al., 2004). However, soil degradation is a significant hindrance to obtaining the necessary increase in food production (Lal, 2015; Wienhold et al., 2004). It has emerged as a global concern in the 21st century, with particularly severe impacts in tropical and subtropical regions (Lal, 2015). It continues to be one of the most pressing and widespread challenges facing humanity (Karlen et al., 2008).

4. SOIL QUALITY INDICATORS

Soil quality cannot be measured directly (Obade & Lal, 2016). Therefore, it is assessed through physical, chemical, and biological properties, referred to as soil quality indicators, which reflect the soil's functional capacity (Shukla et al., 2006). The soil resource emerges from the distinct balance and interaction of these three components (Karlen et al., 1997). The indicators to be chosen will vary according to the nature of the function under consideration. Nortcliff (2002) has grouped the soil quality indicators into four broad categories, comprising the three common groups of physical, chemical, and biological indicators, along with visible indicators.

Physical Indicators. These indicators primarily relate to the arrangement of soil particles and the spaces (pores) between them. Key physical indicators include soil texture, bulk density (BD), particle density (PD), porosity, and water holding capacity (WHC). Soil texture describes the relative amounts of sand, silt, and clay particles present in the soil (Rai et al., 2017). It significantly influences numerous soil properties and determines the soil's suitability for various

uses (Weil & Brady, 2017). Many regard texture as the most critical soil attribute due to its impact on water retention, aeration, and nutrient availability (Ritchey et al., 2015). BD, another essential property, affects water infiltration, air movement, root penetration, and plant development (Throop et al., 2012). PD represents the mass of solid soil particles per unit volume (Weil & Brady, 2017). Soil porosity refers to the proportion of pore space in the soil, which is vital for transporting water, air, and nutrients (Bizuhoraho et al., 2018; Indoria et al., 2020). WHC indicates how much water a soil can retain against gravity and plays a critical role in supporting plant growth by providing a moisture buffer during dry periods (Deng et al., 2016; Weil & Brady, 2017).

Chemical indicators. The list of possible indicators is rather long in this case, and the final selection will be determined by the soil function being considered. Soil pH, cation exchange capacity (CEC), electrical conductivity (EC), soil nutrient contents, organic matter content, concentrations of potentially toxic elements, and, perhaps most importantly, the soil's ability to buffer against change are all indicators under this group.

Common soil chemical indicators include soil pH, CEC, available phosphorus (P), exchangeable potassium (K), total nitrogen (N), EC, and soil organic matter (SOM). Soil pH reflects the acidity or alkalinity of the soil and is a key factor influencing a wide range of chemical and biological soil properties (Weil & Brady, 2017). CEC measures the soil's ability to retain and exchange essential nutrients such as K, Ca, Mg, and Na (Horneck et al., 2011). It is a vital soil quality indicator influenced by soil characteristics, land use, and management practices (Khaledian et al., 2017). P is a critical nutrient for plant growth and development in terrestrial ecosystems. Since soil P is relatively immobile and often exists in forms that plants cannot readily absorb, P deficiency is a major limiting factor for plant productivity. Therefore, soil P availability is an important indicator of soil fertility and quality (Wang et al., 2021). K is vital for numerous biochemical and physiological processes affecting plant growth and metabolism, and it also helps plants withstand biotic and abiotic stresses (Wang et al., 2013). N is the most crucial nutrient governing plant growth, with its availability in the soil largely determining plant productivity (Saez-Plaza, 2013). Soil EC indicates the soil's salt content (salinity) and serves as a valuable measure of

nutrient availability, soil texture, and water-holding capacity (USDA, 2014). Lastly, SOM is essential for sustaining productivity, especially in tropical soils, as it supplies energy and nutrients while supporting biological diversity that maintains soil quality and ecosystem functions (Guimaraes et al., 2013).

Biological indicators. Biological attributes are generally used for short-term evaluations because they are highly dynamic and susceptible to changes in soil conditions. Macro-, meso-, and micro-organism populations, respiration rate or other markers of microbial activity, and more thorough characterization of SOM are some indicators that could be examined.

Some examples of biological indicators include earthworms, bacteria, and fungi count. Earthworms are often considered keystone species within soil ecosystems due to their significant influence on soil functions (Weil & Brady, 2017). In orchard agroecosystems, earthworms frequently represent the most vital part of the soil macrofauna because of their role in improving soil structure and decomposing SOM. Their activity benefits plant metabolism and crop yields by enhancing nitrogen-fixing processes, increasing the availability of macro- and micronutrients and polysaccharides, and stimulating the biosynthesis of plant growth regulators (Sofo et al., 2020). Meanwhile, bacteria play a dynamic role in nearly all organic processes that define healthy soils (Weil & Brady, 2017). They regulate key soil functions such as decomposition and mineralization, which also involve the release of greenhouse gases. Additionally, many soil bacteria contribute to promoting plant growth and productivity (Kaiser et al., 2016). Lastly, soil fungi are essential to ecosystem diversity and the restoration of functional soil systems, acting as decomposers, symbionts, and pathogens. Fungi are intimately involved in energy flow, nutrient cycling, and the transformation of organic materials within the soil (Wu et al., 2019).

Visible indicators. The observation of visible indicators frequently brings changes in soil quality to our attention. It heightens public awareness and concern; however, in many instances, by the time visible signs of soil quality degradation appear, the decline may have already advanced beyond recovery, making restoration efforts ineffective. Evident indicators include erosion features such as rills and

exposed subsoil, surface runoff, and stunted plant growth.

Wienhold et al. (2004) discussed that soil quality indicators could also be categorized as either inherent or dynamic. The soil-forming variables of climate, topography, parent material, time, and biota determine inherent indicators. The inherent soil qualities and their interpretation concerning potential land use serve as the basis for soil surveying, categorization, and land use recommendations. In contrast, dynamic indicators reflect the present condition of the soil as shaped by recent land use or management activities. They assess the impact of management decisions on soil properties that vary in response to use.

Due to the rising demand for information and the need for rapid interpretation of soil science knowledge, emphasis has been placed on analyzing numerous soil quality indicators to comprehend the positive, negative, and interaction effects on soil properties and processes, as well as the correlations between those parameters, for a variety of land uses and soil management strategies (Karlen et al., 2001). These indicators interact in various ways across space, time, and intensity, and they are interdependent (Gil-Sotres et al., 2005; Karlen et al., 1997).

One way to identify these indicators is by developing an essential list of quantifiable soil attributes that characterize the significant processes operating in soil and guarantee that the measurements being taken accurately represent existing field conditions. The core set of soil quality indicators should meet the following suitability criteria: (a) represent ecosystem processes and be relevant for process-based modeling; (b) integrate physical, chemical, and biological soil properties and processes; (c) be easily accessible to a broad range of users and practical for field application; (d) respond sensitively to changes in management practices and climate; and (e) be included in existing soil databases (Doran & Parkin, 1994). At the same time, it is critical to select indicators that allow for the quantification of soil quality and are appropriate for the task (Nortcliff, 2002; Gil-Sotres et al., 2005). Furthermore, the approach to identifying soil quality indicators must be comprehensive rather than reductionistic (Doran & Parkin, 1994).

Many authors have presented different key soil indicators for soil quality assessment (Arshad & Martin, 2002; Bunemann et al., 2018; Doran & Parkin, 1994; Karlen et al., 2008; Wienhold et al., 2004). For example, in a review of 65 different soil quality assessment methodologies undertaken by Bunemann et al. (2018), total organic matter/carbon and pH were identified as the most often proposed soil quality indicators, followed by exchangeable phosphorus, various indicators of water storage, and bulk density. Texture, available P, and total N were also commonly employed. Furthermore, the average number of proposed indicators is 11, which is likely more than is practicable and financially feasible under most conditions, and at least one indicator from each group (physical, chemical, and biological) is included in most of the publications reviewed.

According to Shukla et al. (2006), the most dominant soil quality indicator is soil organic carbon (SOC). They proposed that if only one soil characteristic were to be utilized to track changes in soil quality every 3–5 years, SOC should be chosen. Lal (2015) additionally stated that the SOC pool is not only a significant measure of soil quality but also a key driver of agricultural sustainability. Without clear guidance on selecting indicators, assessing soil quality may be misdirected and of little value. Indicators are important because they (a) provide reference points for tracking trends and patterns; (b) connect soil quality to other system components; and (c) allow soil quality to be evaluated against established trigger or precautionary thresholds (Nortcliff, 2002).

Doran and Zeiss (2000) stated that to assist farmers, foresters, ranchers, conservationists, and other land managers in identifying suitable interventions, a soil quality indicator must do more than simply predict whether a soil would serve a good function. The indicator should additionally explain why the soil will or will not perform as expected. Indicators are required to assist land managers in understanding the chain of cause and effect that connects land management decisions to the health and productivity of plants and animals.

5. SOIL QUALITY ASSESSMENT

The capacity to define and evaluate soil quality is crucial for the development, implementation, and assessment of sustainable land and soil management practices (Doran & Parkin, 1994).

Due to growing land-use pressures, soil quality assessments are in increasing demand, which can be done at a small research plot or at the landscape level (Armenise et al., 2013; Bolinder et al., 1999).

Various authors have emphasized that the main objectives for assessing soil quality appeared to be as an instrument for evaluating the effectiveness and sustainability of the different soil and land use management practices, farming systems, policies, and technologies, to determine how soil properties and processes are responding to anthropogenic decisions and actions over time, and ensure ecological balance; delivering further the recommendations which may translate into improved soil function (Arshad & Martin, 2002; Karlen et al., 2001; Monsalud et al., 2021; Nakajima et al., 2015; Wienhold et al., 2004). Bunemann et al. (2018) emphasized that the primary purpose of evaluating soil quality is to provide farmers and land managers with insights into how soil management affects soil functionality. Therefore, it is crucial that any soil quality assessment starts with a clear understanding of the soil's functions, both natural and user-defined, and the measurable soil properties that reflect quality in relation to these functions (Nortcliff, 2002).

Quantifying the important relationships of soil quality indicators, linking them to various management approaches, and establishing tradeoffs among these factors are all instances of how soil quality assessments could be employed (Karlen et al., 1997). A farming system or practices that have a negative impact on any of the chosen indicators may be considered unsustainable and consequently discouraged or modified. To ensure sustainability, systems that increase indicator performance can be promoted and enhanced (Arshad & Martin, 2002).

It is essential to highlight that meaningful comparisons in soil quality assessment can only be made among soil series within a specific location and with a well-documented management history when establishing a baseline. Because of variations in the inherent soil-forming factors, comparisons across different soils are often irrelevant (Karlen et al., 2008). As noted by Karlen et al. (2001), soils formed under different conditions possess fundamentally distinct characteristics, making direct comparisons of soil health or human impact assessments impractical. However, such soils can be meaningfully compared based on their

inherent productivity and their natural capacity to support specific land uses without human interference.

The conceptual framework of a soil quality assessment of a fruit tree plantation is presented in Fig. 1. It shows that a reference site must be included in addition to the selected fruit tree plantation in the soil quality assessment. The reference site should be close by, have similar parent material and topography, and be in the same ecosystem as the site was originally under, as best as can be determined (Sarrantonio et al., 1996). The inclusion of the reference site is necessary to have a basis for comparison to assess whether there has been a relative soil improvement or deterioration (Sarrantonio et al., 1996). The framework shows that there must be a determined and uniform soil depth where the soil samples will be gathered. Tolessa & Senbetta (2018) have stated that many studies generally accept that there are differences that can be observed at various soil depths. There are also selected soil physical, chemical, and biological indicators for soil quality assessment. After measuring the soil quality indicators, soil quality index computation needs to be done to determine the overall soil quality, leading to the identification of management implications and recommendations to improve soil quality.

5.1 Soil Sampling

A sampling area of one hectare is to be established for the collection of soil samples in fruit tree plantations with an area of at least one hectare. The number of sampling areas may be increased as deemed necessary. Soil subsamples will be collected throughout each designated sampling area using a zigzag pattern, maintaining a distance of 10 meters between subsamples. This approach ensures comprehensive representation of the entire field. Soil samples shall be taken directly below the rim of the crown of the fruit tree. At least 15 subsamples shall be collected to form one composite sample for each soil depth per sampling area.

Each subsample belonging to the same soil depth observation for each sampling area or fruit tree plantation shall be thoroughly mixed, using a trowel, to form a homogenous mixture as a composite sample. The composite samples shall be removed from unnecessary debris such as roots and stones and shall undergo air drying for seven days. Afterwards, at least one kilogram shall be taken as a representative sample from the composite sample, which shall be placed into a sample bag printed with proper labeling, ready for transport to the laboratory for physicochemical analyses.

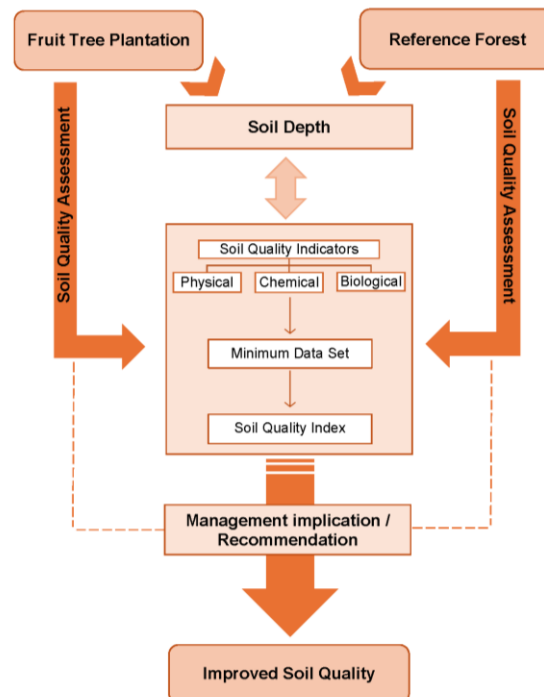


Fig. 1. Conceptual framework of a soil quality assessment of a fruit tree plantation

For soil sample collection intended for microbial analysis, soil samples collected shall be packed immediately into a sample bag and placed in an ice box to cool, which will then be transported immediately to the laboratory for analysis. Meanwhile, the recommended procedure in determining earthworm population count in fruit tree plantations shall be conducted by selecting three random soil samples (25 x 25 x 60 cm) from a 1 m² area that will be sieved to separate and then count the average number of earthworms in each sampling area or fruit tree plantation.

5.2 Minimum Data Set

Increasing the number of indicators can enhance collinearity and add complexity to the interactions between indicators and management practices. However, measurement costs can quickly escalate, particularly when precise soil biological parameters are added (O'Sullivan et al., 2017). Therefore, the number of soil quality indicators assessed for a specific set of samples should be confined to a minimum dataset, carefully selected to produce meaningful and relevant soil quality evaluations (Arshad & Martin, 2002; Bunemann et al., 2018).

Larson and Pierce (1991) recommended the use of a minimum data set (MDS) as a standardized approach for evaluating the health of soils globally. A vital feature of a MDS is that it must comprise soil attributes that can be measured quantitatively in a short amount of time and are valuable in land use or management decisions. The components of a MDS are chosen for their convenience of measurement, reproducibility, and how well they represent critical soil quality characteristics. It is crucial to note that any MDS represents the least number of attributes that must be measured to determine soil quality. Additional attributes may be included in a more extensive data set intended for other analyses (Larson & Pierce, 1994).

The method for determining the minimum data set can also differ significantly. Two often used techniques are expert opinion (EO) and principal component analysis (PCA). The EO approach works best when a diverse team of scientists, landowners, land operators, and other interested stakeholders collaborate to identify soil quality goals, essential functions, relevant indicators, scoring methodologies, and preferences among each factor. In contrast, PCA is a statistical technique for determining the indicators that best

represent variability in a broad set of available data (Andrews et al., 2002; Karlen et al., 2001). Tesfahunegn (2014) noted that while the EO method for selecting a MDS is often supported due to its alignment with sustainable management objectives, many researchers prefer statistical approaches like PCA. His findings indicated that PCA can help minimize the potential for expert bias compared to the EO method.

5.3 Soil Quality Indices

SQIs that synthesize key soil attributes, which were developed in response to a need for a science-based tool to assess soil quality, provide land managers with the vital integration of information to assist them in making informed decisions about complex issues like management of agroecosystems (Andrews & Carroll, 2001; Armenise et al., 2013; Obade & Lal, 2016). The SQI is a metric that evaluates a soil's fitness to carry out one or more functions by integrating various physical, chemical, and biological attributes. A lower SQI value indicates reduced functional capacity of the soil. Therefore, the interpretation of overall "soil health" or "fitness for purpose" becomes more straightforward (Armenise et al., 2013). An effective SQI should meet the following criteria: (a) sensitivity to soil management practices, (b) responsiveness to shifts in soil function(s), and (c) ease of measurement (Armenise et al., 2013).

An example of an effective soil quality index approach is the additive soil quality index which was based on the approach of Andrews et al. (2003). In the index, each selected indicator was transformed using a nonlinear scoring function ranging from 0 to 1. After transformation, the indicator scores for each observation were combined by calculating the sum of all individual indicator scores and dividing it by the total number of indicators. A higher index value was interpreted as indicating enhanced soil function performance or improved soil health (Andrews et al., 2003). The Additive soil quality index is a useful tool to evaluate soil quality in a relatively easy and user-friendly manner (AbdelRahman et al., 2018). This indexing method is a straightforward approach that has already been used worldwide under various soil types, land uses, and geographical locations, as many authors have employed this index in their soil quality assessment studies (AbdelRahman et al., 2018; Chaudhary et al., 2021; Mukherjee & Lal, 2014; Santos-Frances et al., 2022; Tesfahunegn,

2014). In the recent study of Santos-Frances et al. (2022), they revealed that the Additive soil quality index can best reflect the state of the quality of the soil. They also found that this index could provide a better estimate of soil quality than other indices, such as the Nemerlo Soil Quality Index, and was also found to be comparable with the Weighted Additive Soil Quality Index, which involves a more complicated method of index computation.

Moreover, a nonlinear scoring function can also be used as the scoring method in soil quality studies, which is necessary for the calculation of the SQI. This scoring function is a relatively easier way of obtaining the indicator scores compared to the linear scoring function (LSF), due to the fact that many studies have confirmed that it represents system function better than the linear scores, have resulted in higher SQI values than LSF, and also showed maximum response to the land use system impacts on soil quality changes (Andrews et al., 2002; Askari & Holden, 2014; Masto et al., 2008; Sinha et al., 2013).

The most crucial point about soil quality indexing is that there are no "magic" scores or ideal ratings because inherent and dynamic features and processes are involved. The scores on the SQI are always relative, not absolute. The comparisons must be rational (e.g., temporal changes or comparisons of practices on soils with similar inherent soil quality features) and defensible to be meaningful and valuable (Karlen et al., 2001).

5.4 Comparative Assessment and Reference Condition

There is no absolute soil health standard against which an individual soil's condition can be measured. However, it is still necessary to have a basis for comparison to assess whether there has been a relative soil improvement or deterioration (Sarrantonio et al., 1996). A comparison can be made by gathering data from two or more systems (Larson & Pierce 1994). It is a useful tool for detecting differences in soil properties and functions across long-standing management practices (Wienhold et al., 2004).

Identifying reference values is one stage that will likely benefit from and draw on the knowledge base of traditional soil morphology and genesis, particularly concerning inherent chemical and physical indicators (Karlen et al., 2001). Although it is unlikely for agricultural fields to fully revert to

their original undisturbed state, comparing them with natural ecosystems or undisturbed sites can help establish natural benchmarks, such as the maximum attainable organic matter content for similar soil types and climatic conditions. Ideally, the reference site should be nearby, share the same parent material and topography, and belong to the same original ecosystem as the managed site, to the extent that this can be determined. In certain cases, a native forest may serve as the ideal reference, though an undisturbed fencerow could also provide a suitable comparison (Sarrantonio et al., 1996).

5.5 Dynamic Assessment

A dynamic assessment is possible when data from a system is collected over time. A dynamic assessment is necessary to evaluate both the extent and the trajectory of changes resulting from management practices (Wienhold et al., 2004). Changes and trends over time are the only sensible approach to project the impacts of soil management or land use on the long-term viability of a dynamic, living, and ever-changing natural resource (Karlen et al., 2001).

There is no way to go back in time and establish a baseline state for assessing soil quality. Hence, Karlen et al. (2008) proposed that evaluating long-term trends for the same soil within the same management unit requires repeated assessments over time. The critical baseline is the state or quality of the soil resource at the time of the initial measurements, whereas the assessment is the trend in response to subsequent soil management actions. Measurements taken over time, often every 3 to 5 years, will reveal if the methods implemented are causing the indicators to improve, decline, or remain steady at all scales - from the smallest cultivated field or the whole planet.

6. SOIL RESOURCE MANAGEMENT

Soil management that degrades the quality of the soil decreases the soil's functional abilities, whereas stewardship safeguards them (Franzluebbers, 2002). A soil management system can be considered sustainable only if it maintains or enhances soil quality (Larson & Pierce, 1994). Soil quality assessment provides a valuable opportunity to restructure soil and land management practices to promote sustainability (Doran & Parkin, 1994).

We are challenged to establish management strategies that balance food and fiber production needs with environmental conservation since soil quality involves both a soil's productive and environmental capacities (Doran & Zeiss, 2000; Lal, 2015; Wander et al., 2002). Farmers need strategies or frameworks to help them maintain soil quality because a mere focus on productivity might have adverse environmental repercussions, and a sole focus on ecological concerns could jeopardize food and fiber supplies (Wander et al., 2002).

The prudent management of our finite soil resources is essential for achieving sustainable development and ensuring food security for the growing global population (Arshad & Martin, 2002). Thus, a basic lack of understanding will lead to unfavorable resource management decisions (Karlen et al., 2001). Making informed decisions grounded in a deeper understanding of various soil properties and processes would be more beneficial for all stakeholders than overlooking the unintended environmental and social impacts of poor soil management or land-use choices (Karlen et al., 2001).

Soil resources are limited in quantity, unevenly disbursed geographically, and vulnerable to degradation due to land mismanagement and misuse, but they are critical to all terrestrial life and human well-being (Lal, 2015). Without healthy and secure soil, we cannot guarantee sufficient food and fiber supplies, access to safe and clean water, or the preservation of diverse landscapes. Additionally, this compromises the soil's role as a carbon sink and removes a crucial foundation for producing renewable energy sources (McBratney et al., 2014). Soil security can only be accomplished by preserving and improving the global soil resource, which necessitates reversing existing degradation processes (Bouma, 2015). The aim of soil resource management should be to adopt a holistic and integrated approach. The finite nature of soil resources must always be recognized, ensuring they are used wisely, improved, and replenished (Lal, 2015). Given the limited resources and access to inputs, soil quality management is critical for strengthening and sustaining ecosystem services (Lal, 2015) and building economic success, particularly in rapidly developing regions (Qi et al., 2009).

7. CONCLUSION

Soil plays a pivotal role in supporting environmental productivity, ecosystem services,

and sustainable land use. Despite its importance, systematic efforts to assess soil quality, particularly through integrated frameworks, remain limited in Southeast Asia. The widespread conversion of forests to agricultural and forestry plantations, driven by commodity production, has significantly reduced forest cover and led to concerns about soil degradation. Studies indicate that many forest plantations do not maintain the original soil fertility of natural forests. Yet, the specific impacts of fruit tree plantations on soil quality remain poorly understood.

This review underscores the value of evaluating soil quality using a comprehensive approach that incorporates physical, chemical, and biological indicators synthesized into SQIs. Tools such as the additive soil quality index offer a practical, science-based method for assessing soil "fitness" and guiding sustainable land management. Comparative and dynamic assessments, referencing baseline conditions and tracking changes over time, are essential for evaluating the sustainability of land use practices.

Given the finite nature of soil resources, there is a pressing need to prioritize soil quality assessment in fruit tree plantations, particularly in the context of ongoing land use changes in Southeast Asia. Establishing a soil quality knowledge base for these systems is critical for developing informed management strategies that balance productivity with ecological sustainability. Future research should adopt integrated SQI frameworks to inform policy, guide land use planning, and ensure the long-term viability of soil functions essential for both human and environmental well-being.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript. All work presented is entirely the original effort of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Abdelrahman, M. A. E., Shalaby, A., & Mohamed, E. S. (2018). Comparison of

- two soil quality indices using two methods based on geographic information system. *The Egyptian Journal of Remote Sensing and Space Sciences*, 22(2), 127–136. <https://doi.org/10.1016/j.ejrs.2018.03.001>
- Aguilera, E., Guzman, G., & Alonso, A. (2015). Greenhouse gas emissions from conventional and organic cropping systems in Spain. II. Fruit tree orchards. *Agronomy for Sustainable Development*, 35(2), 725–737. <https://doi.org/10.1007/s13593-014-0265-y>
- Altamirano, A., Miranda, A., Aplin, P., Carrasco, J., Catalan, G., Cayuela, L., Fuentes-Castillo, T., Hernandez, A., Martinez-Harms, M., Peluso, F., Prado, M., Reyes-Riveros, R., Holt, T., Vergara, C., Zamorano-Elgueta, C., & Bella, C. (2020). Natural forests loss and tree plantations: Large-scale tree cover loss differentiation in a threatened biodiversity hotspot. *Environmental Research Letters*, 15, 124055. <https://doi.org/10.1088/1748-9326/abca64>
- Andrews, S., & Carroll, R. (2001). Designing a soil quality assessment tool for sustainable agroecosystem management. *Ecological Applications*, 11(6), 1573–1585. [https://doi.org/10.1890/1051-0761\(2001\)011\[1573:DASQAT\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2001)011[1573:DASQAT]2.0.CO;2)
- Andrews, S., Karlen, D., & Mitchell, J. (2002). A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agriculture, Ecosystems and Environment*, 90(1), 25–45. [https://doi.org/10.1016/S0167-8809\(01\)00174-8](https://doi.org/10.1016/S0167-8809(01)00174-8)
- Anunzio, R., Sandker, M., Finegold, Y., & Min, Z. (2015). Projecting global forest area towards 2030. *Forest Ecology and Management*, 352, 124–133. <https://doi.org/10.1016/j.foreco.2015.03.014>
- Armenise, E., Redmile-Gordon, M. A., Stellacci, A. M., Ciccacese, A., & Rubino, P. (2013). Developing a soil quality index to compare soil fitness for agricultural use under different managements in the Mediterranean environment. *Soil & Tillage Research*, 130, 91–98. <https://doi.org/10.1016/j.still.2013.02.013>
- Arshad, M. A., & Martin, S. (2002). Identifying critical limits for soil quality indicators in agro-ecosystems. *Agriculture, Ecosystems and Environment*, 88(2), 153–160. [https://doi.org/10.1016/S0167-8809\(01\)00252-3](https://doi.org/10.1016/S0167-8809(01)00252-3)
- Askari, M. S., & Holden, N. (2014). Indices for quantitative evaluation of soil quality under grassland management. *Geoderma*, 230–231, 131–142. <https://doi.org/10.1016/j.geoderma.2014.04.019>
- Asubonteng, K., Pfeffer, K., Ros-Tonen, M., Verbesselt, J., & Baud, I. (2018). Effects of tree-crop farming on land-cover transitions in a mosaic landscape in the Eastern Region of Ghana. *Environmental Management*. <https://doi.org/10.1007/s00267-018-1060-3>
- Bizuhoraho, T., Kayiranga, A., Manirakiza, N., & Mourad, K. A. (2018). The effect of land use systems on soil properties; A case study from Rwanda. *Sustainable Agriculture Research*, 7(2). <https://doi.org/10.5539/sar.v7n2p30>
- Bolinder, M. A., Angers, D. A., Gregorich, E. G., & Carter, M. R. (1999). The response of soil quality indicators to conservation management. *Canadian Journal of Soil Science*, 79(1), 37–45. <https://doi.org/10.4141/S97-099>
- Bouma, J. (2015). Reaching out from the soil-box in pursuit of soil security. *Soil Science and Plant Nutrition*, 61, 556–565. <https://doi.org/10.1080/00380768.2015.1045403>
- Bünemann, E., Bongiorno, G., Bai, Z., Creamer, R., de Deyn, G., Geode, R., Fleskens, L., Geissen, V., Kuyper, T., Mäder, P., Pulleman, M., Sukkel, W., van Groeningen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, 120, 105–125. <https://doi.org/10.1016/j.soilbio.2018.01.030>
- Carle, J., Vuorinen, P., & Del Lungo, A. (2002). Status and trends in global forest plantation development. *Baltic Forestry*, 8(1), 71–78.
- Carter, M. R., Gregorich, E. G., Anderson, D. W., Doran, J. W., Janzen, H. H., & Pierce, F. J. (1997). Concepts of soil quality and their significance. *Developments in Soil Science*, 25, 1–19. [https://doi.org/10.1016/S0166-2481\(97\)80028-1](https://doi.org/10.1016/S0166-2481(97)80028-1)
- Chaudhary, R. S., Jayaraman, S., Sinha, N. K., Lakaria, B. L., Mohanty, S. R., Singh, A. B., Mohanty, M., Hati, K. M., Singh, R. K., & Patra, A. K. (2021). Participatory soil quality assessment using low-cost tools under contrasting management practices in a vertisol. *Agricultural Research*, 11,

- 642–651. <https://doi.org/10.1007/s40003-021-00598-0>
- Chomitz, K., & Griffiths, C. (1996). *Deforestation, shifting cultivation, and tree crops in Indonesia: Nationwide patterns of smallholder agriculture at the forest frontier*. World Bank. Washington DC 20433.
- Curtis, P., Slay, C., Harris, N., Tyukavina, A., & Hansen, M. (2018). Classifying drivers of global forest loss. *Science*, 361(6407), 1108–1111. <https://doi.org/10.1126/science.aau3445>
- Damatta, F. M. (2008). Ecophysiology of tropical tree crops: An introduction. *Brazilian Journal of Plant Physiology*, 19(4), 239–244. <https://doi.org/10.1590/S1677-04202007000400001>
- Deng, Y., Xia, D., Cai, C., & Ding, S. (2016). Effects of land uses on soil physico-chemical properties and erodibility in collapsing-gully alluvial fan of Anxi County, China. *Journal of Integrative Agriculture*, 15(8), 1863–1873. [https://doi.org/10.1016/S2095-3119\(15\)61223-0](https://doi.org/10.1016/S2095-3119(15)61223-0)
- Dewi, S., van Noordwijk, M., Zulkarnain, M. T., Dwiputra, A., Hyman, G., Prabhu, R., Gitz, V., & Nasi, R. (2017). Tropical forest-transition landscapes: A portfolio for studying people, tree crops and agro-ecological change in context. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 13(1), 312–329. <https://doi.org/10.1080/21513732.2017.1360394>
- Doran, J. W. (2002). Soil health and global sustainability: Translating science into practice. *Agriculture, Ecosystems and Environment*, 88(2), 119–127. [https://doi.org/10.1016/S0167-8809\(01\)00246-8](https://doi.org/10.1016/S0167-8809(01)00246-8)
- Doran, J. W., & Jones, A. J. (1996). *Methods for assessing soil quality* (SSSA Publication No. 49). Soil Science Society of America. <https://doi.org/10.2136/sssaspecpub49>
- Doran, J. W., & Parkin, T. B. (1994). Defining and assessing soil quality. In *Defining soil quality for a sustainable environment* (SSSA Special Publication No. 35). Soil Science Society of America.
- FAO. (2020). *Global Forest Resources Assessment 2020: Main report*. Rome. <https://doi.org/10.4060/ca9825en>
- Fox, J., & Castella, J. (2013). Expansion of rubber (*Hevea brasiliensis*) in Mainland Southeast Asia: What are the prospects for smallholders? *The Journal of Peasant Studies*, 40(1), 155–170. <https://doi.org/10.1080/03066150.2012.750605>
- Franzluebbers, A. J. (2002). Soil organic matter stratification ratio as an indicator of soil quality. *Soil and Tillage Research*, 66(2), 95–106. [https://doi.org/10.1016/S0167-1987\(02\)00018-1](https://doi.org/10.1016/S0167-1987(02)00018-1)
- Gaveau, D., Locatelli, B., Mohammad, S., Husna, Y., Pacheco, P., & Sheil, D. (2018). Rise and fall of forest loss and industrial plantations in Borneo (2000–2017). *Conservation Letters*, 12(3). <https://doi.org/10.1111/conl.12622>
- Gibbs, H. K., & Salmon, J. M. (2015). Mapping the world's degraded lands. *Applied Geography*, 57, 12–21. <https://doi.org/10.1016/j.apgeog.2014.11.024>
- Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., & Foley, J. A. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *PNAS*, 107(38). <https://doi.org/10.1073/pnas.0910275107>
- Gil-Sotres, F., Trasar-Cepada, C., Leirós, M. C., & Seoane, S. (2005). Different approaches to evaluating soil quality using biochemical properties. *Soil Biology & Biochemistry*, 37, 877–887. <https://doi.org/10.1016/j.soilbio.2004.10.003>
- Granatstein, D., & Sanchez, E. (2009). Research knowledge and needs for orchard floor management in organic tree fruit systems. *International Journal of Fruit Science*, 9(3), 257–281. <https://doi.org/10.1080/15538360903245212>
- Guimaraes, D. V., Gonzaga, M. I. S., Da Silva, T. O., Da Silva, T. L., Dias, N. S., & Matias, M. I. S. (2013). Soil organic matter pools and carbon fractions in soil under different land uses. *Soil & Tillage Research*, 126, 177–182. <https://doi.org/10.1016/j.still.2012.07.010>
- Haque, M. A., & Sakimin, S. Z. (2022). Planting arrangement and effects of planting density on tropical fruit crops—A review. *Horticulturae*, 8(6), 485. <https://doi.org/10.3390/horticulturae8060485>
- Holt, T., Binford, M., Portier, K., & Vergara, R. (2016). A stand of trees does not a forest make: Tree plantations and forest

- transitions. *Land Use Policy*, 56, 147–157. <https://doi.org/10.1016/j.landusepol.2016.04.015>
- Horneck, D. A., Sullivan, D. M., Owen, J. S., & Hart, J. M. (2011). *Soil test interpretation guide*. Oregon State University – Extension Service.
- Indoria, A. K., Sharma, K. L., & Reddy, K. S. (2020). Hydraulic properties of soil under warming climate. In *Climate change and soil interactions* (pp. 473–508). <https://doi.org/10.1016/B978-0-12-818032-7.00018-7>
- Kaiser, K., Wemheuer, B., Korolkow, V., Wemheuer, F., Nacke, H., Schöning, I., Schrumpf, M., & Daniel, R. (2016). Driving forces of soil bacterial community structure, diversity, and function in temperate grasslands and forests. *Scientific Reports*, 6, 33696. <https://doi.org/10.1038/srep33696>
- Karishma, N. A., Simi, S., Manju, P. R., & Rafeekher, M. (2025). A comprehensive review on high-density planting in fruit crops and its outcomes. *Journal of Advances in Biology & Biotechnology*, 28(5), 360–374. <https://doi.org/10.9734/jabb/2025/v28i52298>
- Karlen, D. L., Andrews, S. S., & Doran, J. W. (2001). Soil quality: Current concepts and applications. *Advances in Agronomy*, 74, 1–40. [https://doi.org/10.1016/S0065-2113\(01\)74029-1](https://doi.org/10.1016/S0065-2113(01)74029-1)
- Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., & Schuman, G. E. (1997). Soil quality: A concept, definition, and framework for evaluation (A guest editorial). *Soil Science Society of America Journal*, 61(1), 4–10. <https://doi.org/10.2136/sssaj1997.03615995006100010001x>
- Karlen, D., Andrews, S., Wienhold, B., & Zobeck, T. (2008). Soil quality assessment: Past, present and future. *Publications from USDA-ARS / UNL Faculty*, 1203. <https://digitalcommons.unl.edu/usdaarsfacpub/1203>
- Kennedy, J. (2012). Agricultural systems in the tropical forest: A critique framed by tree crops of Papua New Guinea. *Quaternary International*, 249, 140–150. <https://doi.org/10.1016/j.quaint.2011.06.020>
- Keys, E., & McConnell, W. (2005). Global change and the intensification of agriculture in the tropics. *Global Environmental Change*, 15, 320–337. <https://doi.org/10.1016/j.gloenvcha.2005.04.004>
- Khaledian, Y., Brevik, E. C., Pereira, P., Cerdà, A., Fattah, M. A., & Tazikeh, H. (2017). Modeling soil cation exchange capacity in multiple countries. *Catena*, 158, 194–200. <https://doi.org/10.1016/j.catena.2017.07.002>
- Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7, 5875–5895. <https://doi.org/10.3390/su7055875>
- Larson, W. E., & Pierce, F. J. (1991). Conservation and enhancement of soil quality. In *Evaluation for Sustainable Land Management in the Developing World* (pp. 175–203). International Board for Soil Research and Management, Bangkok.
- Larson, W. E., & Pierce, F. J. (1994). The dynamics of soil quality as a measure of sustainable management. In *Defining Soil Quality for a Sustainable Environment* (SSSA Special Publication no. 35). Soil Science Society of America, 677 S. Segoe Rd., Madison, WI 53711, USA.
- Macdaniels, L. H., & Lieberman, A. S. (1979). Tree crops: A neglected source of food and forage from marginal lands. *BioScience*, 29(3), 173–175.
- Masto, R. E., Chhonkar, P. K., Singh, D., & Patra, A. K. (2008). Alternative soil quality indices for evaluating the effect of intensive cropping, fertilisation and manuring for 31 years in the semi-arid soils of India. *Environmental Monitoring and Assessment*, 136, 419–435. <https://doi.org/10.1007/s10661-007-9697-z>
- McBratney, A., Field, D. J., & Koch, A. (2014). The dimensions of soil security. *Geoderma*, 213, 203–213. <https://doi.org/10.1016/j.geoderma.2013.08.013>
- Molnar, T., Kahn, P., Ford, T., Funk, C. J., & Funk, C. R. (2013). Tree crops, a permanent agriculture: Concepts from the past for a sustainable future. *Resources*, 2, 457–488. <https://doi.org/10.3390/resources2040457>
- Monsalud, R. G., Arguelles, E., Brown, M. B., Pedro, M. S., Nepomuceno, R. A., Villadiego, S. A., & Monsalud, F. C. (2021). Relationship between microbial soil quality indicators and soil productivity under cassava-based farming systems in various sites in the Philippines. *Journal of the International Society for Southeast*

- Asian Agricultural Sciences*, 27(1), 87–105.
- Mukherjee, A., & Lal, R. (2014). Comparison of soil quality index using three methods. *PLOS ONE*, 9(8). <https://doi.org/10.1371/journal.pone.0105981>
- Nahuelhual, L., Carmona, A., Lara, A., Echeverria, C., & Gonzalez, M. (2012). Land-cover change to forest plantations: Proximate causes and implications for the landscape in south-central Chile. *Landscape and Urban Planning*, 107, 12–20. <https://doi.org/10.1016/j.landurbplan.2012.04.006>
- Nakajima, T., Lal, R., & Jiang, S. (2015). Soil quality index of a Crosby silt loam in central Ohio. *Soil & Tillage Research*, 146, 323–328. <https://doi.org/10.1016/j.still.2014.10.001>
- Niskanen, A., & Saastamoinen, O. (1996). *Tree plantations in the Philippines and Thailand: Economic, social and environmental evaluation*. UNU World Institute for Development Economics Research (UNU/WIDER). ISSN 1239-6761.
- Nortcliff, S. (2002). Standardisation of soil quality attributes. *Agriculture, Ecosystems & Environment*, 88(2), 161–168. [https://doi.org/10.1016/S0167-8809\(01\)00253-5](https://doi.org/10.1016/S0167-8809(01)00253-5)
- Obade, V., & Lal, R. (2016). Towards a standard technique for soil quality assessment. *Geoderma*, 265, 96–102. <https://doi.org/10.1016/j.geoderma.2015.11.023>
- O'Sullivan, L., Bampa, F., Knights, K., & Creamer, R. E. (2017). Soil protection for a sustainable future: Options for a soil monitoring network for Ireland. *Soil Use and Management*. <https://doi.org/10.1111/sum.12351>
- Penna, I. (2010). *Understanding the FAO's 'Wood supply from planted forests' projections*. Series Editor A. J. J. Lynch, University of Ballarat Centre for Environmental Management Monograph Series No. 2010/01. University of Ballarat, Victoria.
- Peryea, F. (2001). Heavy metal contamination in deciduous tree fruit orchards: Implications for mineral nutrient management. *Acta Horticulturae*, 564, 31–39. <https://doi.org/10.17660/ActaHortic.2001.564.2>
- Plieninger, T. (2012). Monitoring directions and rates of change in trees outside forests through multitemporal analysis of map sequences. *Applied Geography*, 32, 566–576. <https://doi.org/10.1016/j.apgeog.2011.06.015>
- Qi, Y., Darilek, J., Huang, B., Zhao, Y., Sun, W., & Gu, Z. (2009). Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. *Geoderma*, 149, 325–334. <https://doi.org/10.1016/j.geoderma.2008.12.015>
- Rai, R. K., Singh, V. J., & Upadhyay, A. (2017). Soil analysis. In *Planning and Evaluation of Irrigation Projects* (pp. 505–523). <https://doi.org/10.1016/B978-0-12-811748-4.00017-0>
- Ritchey, E. L., McGrath, J. M., & Gehring, D. (2015). Determining soil texture by feel. *Agriculture and Natural Resources Publications*, 139. https://uknowledge.uky.edu/anr_reports/139
- Saez-Plaza, P., Navas, M. J., Wybraniec, S., Michałowski, T., & Asuero, A. (2013). An overview of the Kjeldahl method of nitrogen determination. Part II. Sample preparation, working scale, instrumental finish, and quality control. *Critical Reviews in Analytical Chemistry*, 43, 224–272. <https://doi.org/10.1080/10408347.2012.751787>
- Santos-Francés, F., Martínez-Graña, A., Ávila-Zarza, C., Criado, M., & Sánchez-Sánchez, Y. (2022). Soil quality and evaluation of spatial variability in a semi-arid ecosystem in a region of the southeastern Iberian Peninsula (Spain). *Land*, 11(5). <https://doi.org/10.3390/land11010005>
- Sarrantonio, M., Doran, J. W., Liebig, M. A., & Halvorson, J. J. (1996). On-farm assessment of soil quality and health. In *Methods for Assessing Soil Quality*, SSSA Special Publication 49. Soil Science Society of America, 677 S. Segoe Rd., Madison, WI 53711, USA.
- Shukla, M. K., Lal, R., & Ebinger, M. (2006). Determining soil quality indicators by factor analysis. *Soil & Tillage Research*, 87, 194–204. <https://doi.org/10.1016/j.still.2005.03.011>
- Sinha, N. K., Chopra, U. K., & Singh, A. K. (2013). Cropping system effects on soil quality for three agro-ecosystems in India.

- Experimental Agriculture*, 50(3), 321–342. <https://doi.org/10.1017/S001447971300046X>
- Sofo, A., Mininni, A. N., & Ricciuti, P. (2020). Soil macrofauna: A key factor for increasing soil fertility and promoting sustainable soil use in fruit orchard agrosystems. *Agronomy*, 10, 456. <https://doi.org/10.3390/agronomy10040456>
- Sojka, R. E., & Upchurch, D. R. (1999). Reservations regarding the soil quality concept. *Soil Science Society of America Journal*, 63(5), 1039–1054.
- Temudo, M., & Abrantes, M. (2014). The cashew frontier in Guinea-Bissau, West Africa: Changing landscapes and livelihoods. *Human Ecology*, 42, 217–230. <https://doi.org/10.1007/s10745-014-9641-0>
- Tesfahunegn, G. B. (2014). Soil quality assessment strategies for evaluating soil degradation in Northern Ethiopia. *Applied and Environmental Soil Science*, 2014, 1–14. <https://doi.org/10.1155/2014/646502>
- Throop, H. L., Archer, S. R., Monger, H. C., & Waltman, S. (2012). When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. *Journal of Arid Environments*, 77, 66–71.
- Tolessa, T., & Senbeta, F. (2018). The extent of soil organic carbon and total nitrogen in forest fragments of the central highlands of Ethiopia. *Journal of Ecology and Environment*, 42(20). <https://doi.org/10.1186/s41610-018-0081-4>
- Tropek, R., Sedlacek, O., Beck, J., Musilova, Z., Simova, I., & Storch, D. (2014). Comment on “High-resolution global maps of 21st-century forest cover change”. *Science*, 344, 981. <https://doi.org/10.1126/science.1248753>
- USDA – Natural Resources Conservation Service. (2014). *Soil electrical conductivity (Soil health – Guide for educators)*.
- Wander, M., Walter, G., Nissen, T., Bollero, G., Andrews, S., & Cavanaugh-Grant, D. (2002). Soil quality: Science and process. *Agronomy Journal*, 94(1), 23–32. <https://doi.org/10.2134/agronj2002.2300>
- Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The critical role of potassium in plant stress response. *International Journal of Molecular Sciences*, 14, 7370–7390. <https://doi.org/10.3390/ijms14047370>
- Wang, Y., Huang, Q., Gao, H., Zhang, R., Yang, L., Guo, Y., Li, H., Awasthi, M. K., & Li, G. (2021). Long-term cover crops improved soil phosphorus availability in a rain-fed apple orchard. *Chemosphere*, 275, 130093. <https://doi.org/10.1016/j.chemosphere.2021.130093>
- Weil, R. R., & Brady, N. C. (2017). *The nature and properties of soils* (15th ed.). Pearson Education Limited. ISBN 10: 1-292-16223-6
- Wienhold, B. J., Andrews, S. S., & Karlen, D. L. (2004). Soil quality: A review of the science and experiences in the USA. *Environmental Geochemistry and Health*, 26, 89–95. <https://doi.org/10.1023/b:egah.0000039571.59640.3c>
- Wu, D., Zhang, M., Peng, M., Sui, X., Li, W., & Sun, G. (2019). Variations in soil functional fungal community structure associated with pure and mixed plantations in typical temperate forests of China. *Frontiers in Microbiology*, 10, 1636. <https://doi.org/10.3389/fmicb.2019.01636>
- Yan, R., Zinda, J. A., & Ke, S. (2020). Designating tree crops as forest: Land competition and livelihood effects mediate tree crops impact on natural forest cover in South China. *Land Use Policy*, 96, 104702. <https://doi.org/10.1016/j.landusepol.2020.104702>

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2025): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

The peer review history for this paper can be accessed here:

<https://pr.sdiarticle5.com/review-history/138035>