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Soil and water management perspectives for tropical and dryland areas of Africa

Suleiman Usmani[1]*

[1]Department of Soil Science, Faculty of Agriculture, Federal University Dutse, Nigeria

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***Corresponding Author**
Tel.: +234 703 423 32 41
E-mail: labboallugu@yahoo.com

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Abstract

Soil and water are two natural resources that deliver various functional services to humanity. Advanced soil and water management is highly needed in the tropics. This revision focused on soil and water management issues in the tropics, soil and water management linkages to major soil functional groups (soil health, soil quality, soil fertility, water quality, and soil function), soil quality management and rehabilitation, and soil quality assessment. This study revealed that soil indictors are physical, chemical and biological, reflecting a better understanding of the major soil functional groups in an integrated soil water assessment for better soil and water management in the tropics. Regular checks and balances of comprehensive soil water management can lead to reduced soil erosion, increased water use efficiency, enhanced soil nutritional content, improved infiltration and water holding capacity, minimized runoff and surface soil leaching of pesticides and inorganic chemicals to groundwater reservoirs, increased decomposition and soil organic matter, enhanced soil biodiversity, and increased plant health and food security. To make this viable, an integrated assessment of soil water indicators and the application of sustainable soil water management approaches are needed. Regular checks and balances of the current status of soil and water quality and soil fertility must be given permanent priority.

Introduction

Soil is a natural resource that delivers various functional services to humans (Brady and Weil, 2021). In tropical and dryland areas of Africa, soil plays a key role for the management of various organic and inorganic materials and the overall systems that take place between the atmosphere (air), lithosphere (rocks), biosphere (organisms), and hydrosphere (water) (Harnung and Johnson, 2012). This role is not only limited to food production and diverse natural materials for industrial development (USDA-NRCS, 2008). However, there is increasing acknowledgement that the array of other soil functional services (nutrients supply, erosion control, soil quality etc), which are much broader, received significant recognition from various soil conservation and soil management studies (Andrews et al., 2004; Bekunda et al. 1997; Delgado et al., 2020; Greenland and Lal, 1977; Jat et al., 2023; Karlen and Peterson, 2014; Pierce, 2020; Ssali et al., 1986). Tropical and dryland areas of Africa were regarded as important regions that require regular adaptation of soil and water management (Usman and Kundiri, 2016). This is essential because of the fact that the extent of soil degradation in these areas was reported to have accounted for 37.5% severity, 4.3% moderate, 26.3% high, and 27.9% very high (FAO, 2005). Human population is increasing on daily basis and the need for food security is become a challenge (Global Center on Adaptation, 2021). Soil erosion and nutrient depletion are soaring due to deforestation, poor vegetation cover, poverty and climate change impact (Usman et al., 2024). The use of pesticide chemicals had caused many contamination problems, which also affected soil and water quality in tropical and dryland areas of Africa (Usman, 2024). These problems, demanded for advanced innovative development to help ensure adequate soil and water management in the regions (Hillel, 2008; Lal, 2010). This innovative development is driven by a comprehensive soil conservation package that provides integrated support for ensuring functional services within the soil medium (Kassam et al., 2014). This puts soil and water management at the core of food security and sustainable livelihoods in the tropics (Panda, 2022). Soil and water are vital resources that deserve to be managed in all aspects, including the environment, agriculture, and human development (Huang et al., 2022). Managing soils and water to address food security issues of the twenty-first century in Africa has been emphasized and is necessary for all aspects of agronomic and environmental resource production (Lal, 2010).

In African tropical and dryland regions, soil and water qualities have been affected, and their potential support for ensuring food security and economic development has declined (Hartemink, 2006a). According to Delgado et al. (2020), soil and water management practices, which have evolved since the 1930s and have been adopted around the world, are responsible for the decline in soil and water quality in tropical and dryland environments. Many studies have focused on providing better protection to soil and water in the tropics (Oweis and Hachum, 2003; Usman, 2013; Piemontese et al., 2020; Wolka et al., 2018). Similarly, issues of high concern regarding the management and rehabilitation of soil and water resources have been covered in many recent studies (Jamaluddin et al., 2013; Mahajan et al., 2021; Panda, 2022). Therefore, this paper addressed soil and water management issues for the benefits of tropical and dryland soils in Africa. This paper also covered other important issues related to soil quality assessment and soil rehabilitation, the design and management of soil and water conservation practices, the management of nutrient-depleted lands, soil water management approaches, and water quality improvement.

Theory of tropical and dryland soils

Tropical and dryland areas of Africa are home to over 525 million people (Global Center on Adaptation, 2021). However, when considering soil and water management in the tropical and dryland areas of Africa, it is important to embrace the theory of tropical and dryland soils and how they related well to soil and water management. The tropics are low-latitude sand seas (ergs) that are considered extensive areas of sand dunes located in the tropical and subtropical deserts of the world (Lancaster, 2013). Tropical regions receive greater amounts of solar radiation per unit area and per unit time than any other ecosystem in the world, primarily due to a spherical Earth, where light energy at higher latitudes intercepts the Earth's surface at a more oblique angle (Roxburgh and Noble, 2001). The landscapes in regions with a tropical climate are typically characterized by deeper regolith mantles influenced by the local rock composition and structure couple with chemical and physical properties of the weathering products, the type and intensity of the soil processes, and the slope gradient (Dewitte et al., 2022). The farming systems are characterized by an enormous disparity of crops such as cereals (millet, sorghum, rice, and maize), groundnuts, soybeans, sugarcane, cocoa, coffee, oils, and fruit, which are cultivated year-round, providing the possibility for several harvests per year (Pröhl et al., 2012). The tropics contain dryland areas, which play key roles in global agricultural production (Peterson 2018). However, the name dryland was derived from the word arid, which implies prolonged dryness (Usman, 2017). According to the United Nations Convention to Combat Desertification (UNCCD, 1997), drylands include arid, semiarid, and sub-humid zones, which cover approximately 54 million km^2 of the globe. The African drylands occupied significant part of this land area, estimated to be around 19.6 million km^2 (46% approximately) (FAO, 2019). This means that drylands cover approximately 41% of the terrestrial land and are inhabited by more than one-third of the global population, supporting mainly grazing, crop cultivation, and natural forests (Biazin et al., 2023).

Drylands are characterized by a scarcity of water, which affects both natural and managed ecosystems and constrains the production of livestock as well as crops, wood, forage and other plants, affecting the delivery of environmental services (FAO, 2023). They have been shaped by a combination of low precipitation, droughts and heat waves, as well as human activities such as fire use, livestock grazing, the collection of wood and non-wood forest products, and soil cultivation (FAO, 2023). These areas are home to more than a quarter of the global population, including millions of biological organisms and their biodiversity, with over a quarter of the world's forest area accommodating various farming activities called ‘dryland farming’ (Usman, 2017; FAO, 2023). Dryland farming is a crop production practice in dryland areas with less than 500 mm of annual precipitation and where the annual potential water evaporation exceeds the annual precipitation (Peterson, 2018). Tropical and dryland soils tend to be vulnerable to wind and water erosion, subject to intensive mineral weathering, and have low fertility due to the low content of organic matter in the topsoil (FAO, 2023). They are also susceptible to various degradation processes (e.g. physical, chemical) as a result of frequent deforestation, desertification, lack of awareness, and poverty (Usman et al., 2017).

Soil and water management issues in the tropics and drylands of Africa

Tropical and dryland soils are vulnerable to soil erosion and nutrient depletion (FAO, 2023). They are also susceptible to various types of soil degradation (Usman et al., 2017). The impact of climate change has amplified the soil degradation to cause more damage to soil quality and soil fertility in the tropics and drylands (Usman et al., 2024). Soil cover and surface land quality are affected by combination of environmental problems (Mishra et al., 2021). These problems include mismanagement of vegetation and forest areas, untenable land use practices, deforestation and poverty (Usman et al., 2016). These problems are factors, which put the tropical and dryland soils at a very high risk of soil erosion and nutrient depletion (Abbass et al., 2020). The nature and condition of the soil are deteriorating (Ezeh et al., 2024). This soil condition in the tropics and drylands of Africa, require appropriate adaptation of soil management to ensure food security for the growing population (FAO, 2019; Yang et al., 2020). Soil and water management is a general concept applicable to the administration and supervision of soil water resources for optimum utilization for agricultural and non-agricultural purposes. Loiskand and Kammerer (2014) defined soil water management as active involvement in controlling soil water content at an optimal state for all given purposes, including environmental needs. This optimal state involves regular cooperation between competing uses and needs to account for the long-term sustainability of soil water management (Loiskand and Kammerer, 2014). This is important for all the terrestrial ecosystems of the biosphere and hydrosphere (Gusev and Novak, 2007). This means that the management of these spheres depends on how well the soil (pedosphere) is conserved to improve soil properties and biodiversity. This entails the importance of soil water management in agriculture (Usman, 2013). According to the Soil Science Society of America (SSSA), soil management is defined as the sum of all tillage and planting operations; cropping practices; fertilizer, lime, herbicide and insecticide applications, and irrigation and other treatments conducted on or applied to a soil for the production of plants (Karlen and Peterson, 2014). Baumhardt and Blanco-Canqui (2014) noted that farming operations and management strategies could be conducted with the goal of controlling soil erosion by preventing or limiting soil particle detachment and transport in water or air. The Twelve definitions describe the position of a comprehensive soil and water conservation package that always focuses on ensuring better soil and water quality. However, regarding 'soil quality', Doran and Parkin (1994) noted that it is the capacity of a soil to function within the ecosystem and land use boundaries to sustain productivity, maintain environmental quality, and promote plant and animal health. In 'water quality', Delgado et al., (2020) reported that advances during the last 75 years in soil and water conservation have contributed greatly to protecting water quality and purity for both soil and human health. This confirmed that the concept of soil and water management broadly includes all activities at the local level that maintain or enhance the productive capacity of the land in areas affected by or prone to degradation (WOCAT, 1992). Lal (1990) suggested that these soil and water management activities are based on six attributes: (a) soil erosion control, (b) improvement in soil organic matter content, (c) enhancement of soil structure, (e) increase in soil biodiversity, (f) strengthening of nutrient cycling mechanisms, and (g) increase in soil resilience.

Soil and water conservation has recently celebrated 75 years in history (Delgado et al., 2020). In a detailed compilation, Delgado and his co-workers deliberated on key issues of soil and water management throughout these 75 years of history. They covered the major subject areas that summarized what soil conservation/management entails and the kinds of contributions it has made to global agricultural and environmental development. They discussed the concept of soil and water conservation with respect to the evolution of soil and water conservation, the importance of social and economic factors influencing conservation practices, managing water quantity and quality challenges, advancing assessments of erosion and implementation of soil and water conservation on the ground, climate change creating new challenges in soil and water conservation for food security, the future of conservation, mitigating soil losses to adapt to climate change will provide billions of dollars in returns, forecasting future conservation developments, and a bright future in soil and water conservation (Delgado et al., 2020). According to their overall observations, conservation management of soil and water needs to be at the center of land use to develop sustainable agricultural systems for food security, and history shows that when we develop or implement new agricultural advances, we must conserve soil, water, and biological resources to provide solutions for wise land use (Delgado et al., 2020). In this regard, there is a need for cooperation and reassurance from all bodies involved, and this entails that local, national and international institutions at high levels, such as the UN and its research bodies (FAO, IPCC, IAEA), must come together to help achieve the combined goals of the UN: ending poverty, achieving zero hunger, clean water, and sanitation (Lal, 2020). Therefore, as stressed by Delgado et al. (2020), all working in the conservation of soil and water needs to be mindful to develop systems to maximize productivity and reduce environmental impacts in the future. This advice may help achieve the UN goals and will ensure best management practices in conserving and managing soil water for food security, environmental health and human development in the tropics (Jat et al., 2023).

Developments and challenges

There have been significant developments in technological efforts to conserve soil and water in tropical dryland's areas (Gusev and Novak, 2007; Loiskand and Kammerer, 2014; Oweis and Hachum, 2003; Piemontese et al., 2020; Wolka et al., 2018). The tropical dryland and farming systems require a sustainable framework for long-term management of soil and water (Usman, 2017). Improving the water use efficiency of dryland soils is also needed on a regular basis (Stroosnijder et al., 2012) and has been regarded as an important way to conserve water (Delgado et al., 2020). Advancements have been made in many areas of agriculture and non- agriculture to enhance the potential of soil and water through conservation techniques (Pierce, 2020). Numerous studies have contributed to these advancements. These studies include those of Pratt (1994) and Singletary (2009) on water banking (a new tool for water management), Wolka et al. (2018) on the effects of soil and water conservation techniques on crop yield, runoff and soil loss in sub-Saharan Africa, Biazin et al. (2023) on tackling crop water stress through soil water conservation by the integrated use of organic and chemical fertilizers, Morton (2020) on agricultural management and conservation of soil and water resources, and Mahajan et al. (2021) on soil and water conservation measures to improve soil carbon sequestration and soil quality. These various landscape-scale soil and water management studies are vital for soil security and for meeting increasing global demands for food, feed, fiber, and fuel (Karlen and Peterson, 2014).

The most important developments and influences determining soil and water management in tropical and dryland soils for the last 50 years have been covered by many researchers. One of the outstanding works in this field has been the effort of Pierce (2020), an author of 'Advances in Soil and Water Conservation'. His work addressed many fundamental aspects of the subject matter and addressed the technological developments of erosion processes, methods for their control, policy and social forces shaping the research agenda, and future directions. It covered key issues related to the processes of soil and water degradation, control practices and soil quality enhancement, conservation tillage, the connection between soil and water conservation and sustainable agriculture, and the effects of technology and social influences on soil and water conservation in the tropics (Pierce, 2020). Global achievements in soil and water conservation are another effort made by Kassam et al. (2014). This work provided an overview of achievements in soil and water conservation on agricultural lands through experience derived from the adoption and spread of conservation agriculture globally. They considered conservation agriculture an agro-ecological approach to sustainable production intensification that involved the application of locally formulated practices, mainly permanent no or minimum mechanical soil disturbance (direct seeding through mulch into no-till soils), maintenance of soil shields with crop residues and green manure crops (legumes), and diversified cropping systems involving annuals and perennials in rotations (sequences and associations) (Kassam et al., 2014). According to these authors, conservation agriculture offers environmental, economic and social advantages that are not fully possible with tillage-based production systems, as well as improved productivity and resilience and improved ecosystem services while minimizing the excessive us of agrochemicals, energy and heavy machinery (Kassam et al., 2014).

However, complex challenges are facing tropical and dryland areas in Africa, which are more or less due to natural and anthropogenic causes affecting sustainable livelihoods, environmental resources and social resilience (Biazin et al., 2023). These challenges have put the management of soil and water into many setbacks (Bouwer, 2000; Karlen and Peterson, 2014). Factors that threaten the conservation and management of tropical and dryland soils and water resources include persistent drought and water scarcity exacerbated by climate variability and changes, land and soil degradation caused by deforestation, loss of organic matter resulting from inappropriate land use practices and mismanagement, and soil erosion caused by the combined effect of water and wind, which is worsened by the degree of desertification (Ahmed Hayat et al., 2022; Bouwer, 2000; Davies et al., 2015; James and Reynolds, 2007; Marques et al., 2016). Poverty, deforestation and multiple land use practices are also challenges facing better adaptation of soil and water management in the tropics, and these have been understood long time ago in the history of soil and water conservation (Greenland and Lal, 1977).Lack of adequate soil testing prior to the application of a given conservation approach (Usman et al., 2024), soil and land pressures (Toor et al., 2021), are also factors diminishing the effectiveness of soil water management in the tropics.

Approaches for soil and water management

Many approaches have been used for soil and water management in the tropics (Doran and Michael, 2000; Jatet et al., 2023; Lal 2000, 2017). These approaches are considered physical, chemical and biological soil water management approaches (Usman, 2013). These soil and water management approaches are noted to improve soil texture, soil structure, soil colour, soil organic matter, macro (e.g. nitrogen, potassium, phosphorus) and micro nutrients (e.g. calcium, magnesium, sodium), and overall soil biota and biodiversity (Bünemann et al., 2018). In this regards, the physical soil conservation was regarded as methods, which involved the management of soil aggregate and soil structural formation; the biological approaches enhance the activities of soil biota and biodiversity; and chemical approaches improve the nutrient content of the soil (Usman, 2013). Physical conservation methods such as manure application, surface terracing, planting shelter belts, contour farming, land ridges, planting cover crops, and mixed cropping, are noted to have significant positive impact on soil properties and food security (Usman, 2017; Lal, 2017). The biological conservation methods build soil organic matter, enhances aggregate stability, binds soil particles, and control soil erosion (Simpson and Simpson, 2017). The chemical conservation methods include the addition of organic and inorganic fertilizers, which are considered useful for soil fertility development and soil carbon cycling. The broad benefits of these conservation methods have been described as reservoir for soil productivity, plant growth, animal production, and sustainable human development.

Largely, there have been significant advancements regarding the physical, biological and chemical conservation approaches in recent years (Delgado et al., 2020). The primary aim of these set of approaches, was to improve and enhance soil quality, soil fertility and control soil erosion and nutrient depletion in the tropics and drylands (Toor et al., 2021). The global achievements with respect to soil and water management are much clear (Kassam et al., 2014). Practically, approaches such as manure application, surface soil terracing, planting shelter belts, afforestation, forest regeneration, drainages, contour farming, surface land ridges, planting cover crops, and inter- and mixed cropping systems are considered vital for soil and water management in the tropics (Usman, 2017). Hence, the adaptation of these conservation techniques in the tropics and drylands of Africa would help protect soil against erosion, increase food security and enhance agricultural economic development. For example, Huang et al. (2022) studied soil and water management techniques in the tropics and subtropics and reported that compared with other land use practices, contour tillage, ridge farming, and reduced tillage are more efficient at reducing soil loss. Their observation noted that the combination of engineering and biological techniques could be more effective in reducing soil and water loss than the application of contour tillage, ridge farming, or reduced tillage (Huang et al., 2022). Liang et al. (2023) studied four different tillage practices (longitudinal ridge tillage, cross ridge tillage, flat tillage and hole sowing) under three rainfall intensities (60–90–120 mm/h). Their study investigated the changes in hydrodynamic parameters and the response of purple soil slope cropland to erosion to reveal the soil and water conservation benefits of different tillage practices. They reported that longitudinal ridge tillage is more effective than flat tillage, followed by hole-sowing and cross-ridge tillage (Liang et al., 2023).

Advances in soil and water management are crucial for farming systems, and they can be used to improve soil quality and soil fertility in tropics and drylands of Africa. These farming systems are driving economy in many rural areas of Africa and have been challenged by complex environmental problems, such as erosion, fertility decline, and water scarcity (Usman, 2013). Measures to control erosion, enhance soil fertility, and ensure sustainable water use efficiency through soil water management are needed. Hillel (2008) noted that improving soil quality and water-use efficiency in dryland farming requires measures to increase infiltration, avoid runoff losses, and prevent water losses. He highlighted that the following measures should be taken into consideration (Hillel, 2008):

a. Well-structured, aggregated, and porous topsoil was maintained to prevent surface crusting and runoff.

b. The mulch cover (consisting of plant residues) on the soil surface was maintained to shield the soil surface against the aggregate-slaking impact of striking raindrops.

c. Terracing and contouring cultivation to facilitate absorption of rainfall and prevention of runoff.

d. Avoiding mechanical compaction to enhance infiltration and prevent runoff losses.

e. The land was periodically frozen to collect rainwater, which was then stored in the soil for subsequent use.

f. Minimizing surface evaporation of soil moisture by judicious tillage and especially by means of maintaining a diffusion barrier over the surface, e.g., straw mulch.

g. Transpiring weeds were removed to prevent losses of moisture from deeper layers of the soil.

h. Enhancing the rainwater supply by means of water harvesting, i.e., inducing and collecting runoff from adjacent slopes and directing it to planted plots.

i. Suitable (drought resistant, high yield potential) crops should be planted and fertilized at optimal times to ensure germination and establishment and to utilize seasonal rains.

j. Cultured shelter belts or mechanical barriers (perpendicular to the prevailing wind direction) should be established to reduce the wind speed and thereby lower potential evaporation

Soil and water management: its linkage to major soil functional groups

The linkage between soil and water management and other soil functional groups is a relationship that needs to be understood in the 21st century. This relationship is used in this review to explain how connected soil water management is to overall soil rehabilitation and soil functionalities for achieving food security and sustainable livelihoods for the growing population in Africa. Tropical and dryland soils of Africa offered various functions to human development and environmental habitat (Usman and Kundiri, 2016). Management of these soils requires detail understanding of the major soil functional groups, which determine the practical aspects of soil and water management in the tropics (Hillel, 2008). By definition however, soil functional group is a compound term used in this assessment to include combined soil water management terms, such as soil health, soil quality, soil fertility, soil productivity, water quality, and water efficiency. Therefore, to illustrate how advanced soil and water management has played a key role in African agricultural and environmental development over the last 75 years, since the emergence of soil conservation in history (Delgado et al., 2020), some important soil functional groups are taken into consideration. This is in addition to their relevance to crop production, biodiversity, and animal health for diverse economic development in Africa. In this overview, soil functional groups can be defined as the potential stage of soil that receives adequate management to support biological living organisms, manage water efficiency, control soil erosion, enhance nutrient cycles, and ensure food security over a long period of time without decline. The concept described in this definition captured the concept and future prospects of soil health, soil quality, soil fertility and water resources quality (Lehmann et al., 2020).

Soil health is considered the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans" (USDA-NRCS, 2023). This definition emphasizes that soil and water management are necessary because of their vital role in sustaining plants, animals, and humans (Mandal et al., 2016). This suggests that soil health is a system within the soil medium that can be enhanced only through proper soil water management. Karlen (2020) provided an advanced review on the subject of 'the evolution, assessment of, and future opportunities of soil health' and proposed that a focus on soil health evolution and management will improve the potential of soil water management and can help ensure sustainable soil fertility and food security, among other many benefits, such as animal feeds, fiber, and fuel. This entails that soil health and conservation management are interlinked and must be observed on a regular basis. The benefits of this conservation relationship include long-term soil health sustainability for managing the biotic component of soil quality (Doran and Michael, 2000; Lehmann et al., 2020; Toor et al., 2021), which is vital for enhancing dryland and humid tropical soils (Greenland and Lal, 1977). It is also vital for agricultural conservation and for restoring soil health and mitigating climate change (Jat et al., 2023). The management of soil health can be achieved through integrated ideas where various conservation approaches work together to achieve better soil health (Manter et al., 2018). However, Costantini and Mocali (2022) highlighted that soil health has different connotations depending on the environmental setting, as it may show high spatial and temporal dynamics. Their study noted that surface and deep soil genetic horizons are important interpretative tools for soil functional biodiversity and soil health (Costantini and Mocali, 2022). This emphasizes that assessments of soil health should focus on different components of soil, more importantly, on the basis of soil genetic horizons. This is because the loss of natural self-organization of these genetic horizons affects soil health stability (Usman, 2013).

Soil quality is a concept that directly affects the persistence of soil and water management. Doran and Parkin (1994) defined soil quality as "the capacity of a soil to function, within the ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health". This definition suggests that any technique that can be used for soil water management has one or more supportive benefits to the empowerment of soil quality to function within the ecosystem to sustain crop production and animal health. For example, organic matter binds soil particles, improves aggregate stability, and enhances water efficiency (Reeves, 1997). The functional services offered to the soil by organic matter rehabilitate the potential quality of the soil and enhance the long-term benefits to soil quality and the soil organic matter relationship (Martins et al., 2017; Simpson and Simpson, 2017). The benefits also extended to the proper management of soil erosion, particularly in the tropics (Lal, 1990).

A fertile soil has been described as a soil with a good supply of available plant nutrients to be drawn upon by plants throughout their growth period (Usman, 2017). This suggests that for a soil to be considered a ‘fertile soil’, it must contain all the essential nutrients, which could be available in both equitable amounts and an appropriate balance, such that plants can take them from mineral and organic soil fractions and must be located in a climatic zone that provides sufficient moisture, light and heat for the needs of the plants under consideration (Miller, 1963). Soil fertility decline is perceived to be widespread in the upland soils of the tropics, particularly in sub-Saharan Africa (Hartemink, 2006). The pedogenesis processes affecting soil fertility decline include the addition, removal, transformation, and transfer of materials within the soil medium (Brady and Weil, 2021). Addition (input) includes dust, nutrients in the rainfall, symbiotic and asymbiotic N-fixation, and sedimentation; removal (output) includes leaching, volatilization, denitrification, and erosion; transformation includes mineral weathering, organic matter, decomposition, and fixation; and transfer includes deep uptake, clay eluviation and illuviation (Hartemink, 2006a). Many studies have noted that a decrease in soil fertility is a serious threat to soil and water resources in the tropics (Ahn, 1970; Hartemink, 2002, 2003, 2006b; Huang et al., 2022; Kant and Ghosh, 2012; Lucas, 1982; Sanchez, 1976; Ssali et al., 1986). Assessing the soil fertility status of degraded soils will help establish advanced soil and water management practices in the tropics (Bekunda et al., 1997; Jamaluddin et al., 2013).

Water resources are dynamically influenced by several factors, such as human, agricultural, and industrial activities (Quevedo-Castro et al., 2019). The water quality needs to be standardized for a variety of functions. According to the US-EPA (2023), water quality standards consist of three core components, which include the designated uses of a water body, criteria to protect designated uses, and anti-degradation requirements to protect existing uses and high-quality/high-value waters. The designated uses are protection and propagation of water animals and wildlife, recreation, public drinking water supply, and agricultural, industrial, navigational and other purposes, whereas the criteria can be numeric (e.g., the maximum pollutant concentration levels permitted in a water body) or narrative (e.g., a criterion that describes the desired conditions of a water body being “free from” certain negative conditions); additionally, the anti-degradation maintains the chemical, physical and biological integrity of the Nation's waters, and the requirements provide a framework for maintaining and protecting water quality that has already been achieved (US-EPA, 2023). Soil and water contaminated with various concentrated agrochemicals, upstream mining leachates, herbicides, domestic waste, and wastewater discharge may easily lose quality because of toxicity and pollutants (Usman, 2020; Wu et al., 2018). Ensuring water quality is important in the propagation of healthy soil and crop production because when water is in defaces, the biological component of the soil is affected (Usman et al., 2017). Advanced soil and water management approaches are highly needed to maintain the quality of water resources and to ensure sufficient availability of water for crop utilization (Lal, 2010; Panda, 2022). The monitoring and evaluation of water quality involving an analysis of various parameters that indicate the degree of alteration of natural variations in a water body is an advanced method useful for improving the standard quality of water (Quevedo-Castro et al., 2019). Wu et al. (2018) noted that advancement in the analysis of water quality could be achieved through various indicators that quantify water quality for a given use from a complete viewpoint. Reducing the use of highly toxic chemicals such as pesticides and chemical fertilizers can help improve water quality and maintain soil health (Hillel, 2008; Manteret al., 2018).

From the general overviews of how advanced soil and water management support real soil functional services, which are useful for ensuring better soil health, soil quality, soil fertility, water quality and water efficiency, one may agree that efforts to maintain this relationship must be permanent. This will help achieve the United Nations Sustainable Development Goal (SDG 15) for ensuring food security. According to Panda (2022), this SDG 15 for sustainable food security can be assured by plot-wise management of soil erosion, soil organic matter, soil moisture, irrigation water, soil salinity, mulching application, growing cover crops and agro-forestry on each farm. Panda (2022) is optimistic that such combined farming practices would result in regional as well as country-level cumulative impacts on good outcomes of application of plot-level soil water conservation measures in each crop field.

Soil quality assessment and rehabilitation

The concept of soil quality and its assessment and rehabilitation is sometimes challenging for a few reasons, including the issues of climate change and its adaptation policies, the diversification of soil types and definitions of surrounding biomass resources, the complex environmental and social issues in the tropics and drylands, and the limited scientific understanding of the best integrated principles with regard to soil and water management in the tropics and subtropics (Bünemann et al., 2018). This challenge is a knowledge gap (Hopmans et al., 2021) and needs urgent explanation to help address advanced measures and approaches that are more convenient for achieving better soil quality assessment and rehabilitation globally. This would help researchers discover some of the methods of soil quality assessment and management and then describe promising principles for receiving a sustainable set of management packages that could target soil erosion problems, soil quality decline, soil fertility depletion, and water use inefficiency in drylands and other tropical soils (Andrews et al., 2004). If this discovery becomes achievable, it could provide a promising guide towards understanding soil quality as the capacity of a soil to function within the ecosystem and land use boundaries to sustain productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994).

At this junction, soil quality assessments must focus on monitoring and observing soil properties and components via both visual and quantitative concepts (Ball et al., 2007; Basak et al., 2016; Doran and Parkin, 1996; Jamaluddin et al., 2013; Martins et al., 2017; Seybold et al., 1998). This will entail more about what Karlen et al. (1997) considered to be soil quality, which is the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. The capacity of a specific soil to function reflects overall inherent soil properties and dynamic characteristics, which change very little or not at all with management as a result of single or combined effects of soil-forming factors (climate, topography, parent material, biota, and time) (USDA-NRCS, 2008). Andrews et al. (2002) described this function as a medium that affects overall environmental quality. They understood that the major components of soil quality are physical, chemical and biological factors, which have effects on soil, air and water, reflecting directly on agricultural sustainability in terms of economic and social viability. In this regard, soil can provide physical stability and support for plants and serves as an engineering medium to support buildings and roads, human development and economic empowerment (USDA-NRCS, 2008).

Soil indicators: a key component of soil quality assessment

To this end, soil quality assessment considers various soil indicators, some of which are physical or biological, while others are chemical or ecological (Table I). These soil quality indicators under assessment are dynamic soil properties used to describe soil function and can help determine how well a soil performs essential ecological functional services to humans and the environment (USDA-NRCS, 2008). Although it is often difficult to clearly separate soil functions into chemical, physical, and biological processes because of the dynamic, interactive nature of these processes (Schoenholtza et al., 2000), some methods of visual soil structure examination enable varieties of semi-quantitative information for use in soil biological and chemical quality assessments, monitoring and modelling soil functions in a quick and reliable manner (Mueller et al., 2010).

The soil quality indicators can be considered basic soil indicators or hazard soil indicators (Figure 1), depending on the nature or objectives of the assessment. However, Nortcliff (2002) suggested that the overall selection of soil indicator attributes, as outlined in Table 1, should be based on key issues relevant to soil and water management, particularly in the tropics. These relevant issues are land use, soil function, measurement reliability, spatial and temporal variability, sensitivity to changes in soil management, comparability in monitoring systems, and skills required for use and interpretation (Nortcliff, 2002). Regardless of the indicator(s) used for a given soil quality assessment, they end in describing soil function and its potential to sustain biological diversity and productivity in soil; regulate and screen water and solute flow; filter and buffer; and degrade, immobilize, and detoxify organic and inorganic materials, including industrial and municipal byproducts and atmospheric deposition (Seybold et al., 1998). They also help to store and cycle nutrients and carbon within the Earth's biosphere, provide physical stability and support for plants, and protect archaeological treasures associated with human habitation (Seybold et al., 1998).

Advanced developments have been made in recent years in soil–water quality assessment and rehabilitation using various soil quality indicators for a particular purpose, although challenges and opportunities are noted (Schoenholtza et al., 2000). These developments include the work of Andrews and

Table I: Grouping type, soil indicators and key indicators

Grouping type	Soil indicators	Key indicators[1]
Physical attributes	Soil texture	**
	Stoniness	
	Soil structure	
	Bulk density	**
	Porosity	
	Aggregate strength and stability	**
	Soil crusting	
	Soil compaction	**
	Drainage	
	Water retention	
	Infiltration	**
	Hydraulic conductivity	
	Topsoil depth	**
Chemical attributes	Color Reaction (pH)	
	Carbonate content	**
	Salinity	
	Sodium saturation	**
	Cation exchange capacity	
	Plant nutrients	
	Toxic elements	**
Biological attributes	Organic matter content	
	Populations of organisms	**
	Fractions of organic matter	
	Microbial biomass	
	Respiration rate	**
	Mycorrhizal associations	
	Nematode communities	
	Enzyme activities	
	Fatty acid profiles	
	Bioavailability of contaminants	

[1]Key indicators according to USDA (2006)

Carroll (2001), who provided an overview of the design of a soil quality assessment tool for sustainable agro-ecosystem management; Hartemink (2006a), who assessed soil fertility decline in the tropics using soil chemical data; Ding et al. (2021), who investigated the use of vermicompost and deep tillage systems to improve saline-sodic soil quality and wheat productivity; Grigget al. (2006), who investigated the effect of organic mulch amendments on physical and chemical properties and re-vegetation; Hafez et al. (2015), who investigated the effect of gypsum application and irrigation intervals on clay saline-sodic soil characterization, rice water use efficiency, growth, and yield; and Meena et al. (2016), who investigated the effects of municipal solid waste compost, rice-straw compost and mineral fertilizers on the biological and chemical properties of saline soil and yields in a mustard–pearl millet cropping system. There are also many comprehensive and critical reviews regarding soil quality assessment and rehabilitation (e.g., Bünemann et al., 2018; Basak et al., 2022) that have focused on multifunctional services of soil management and food security. These studies have provided an advanced understanding of conservation practices, which are involved in the design and management of soil and water in the tropics (Andrew, 2001). They also guided towards better management of sloping lands, especially those that are affected by erosion and surface damage (Andualem et al., 2023).

The methods and techniques involved in soil quality assessments have yielded vital resource information for diverse agricultural and non-agricultural references. Quentin et al. (2018) assessed derelict soil quality using abiotic, biotic and functional approaches, and their results showed that derelict soils may provide a biodiversity ecosystem service and are functional for high decomposition. The method they used assessed the functional parameters (i.e., the macro-decomposer proportion, enzyme activity, average mineralization capacity, and microbial polycyclic aromatic hydrocarbon degraders) by combining abiotic and biotic parameters. The method used by Quentin et al. (2018) can be very useful in tropical dryland soils where the need for high decomposition machinery is increasing due to low

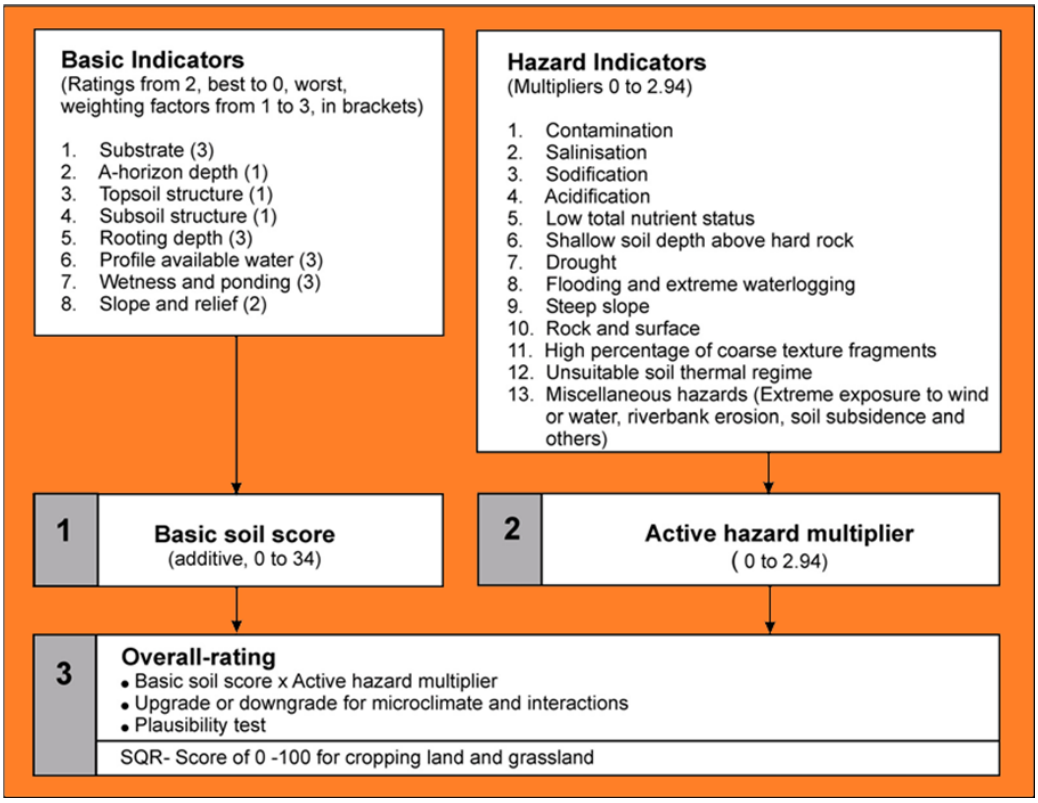

Figure I: Basic and hazard indicators of the soil quality assessment. Indicator system of the Muencheberg Soil Quality Rating (Mueller et al., 2007)

nutrient and organic matter contents (Hartemink, 2006b).

Muñoz-Rojas et al. (2016) used soil quality indicators to assess soil functionality in restored semiarid ecosystems, and the results revealed that biological indicators (microbial diversity and activity in particular), organic C and the C:N ratio are the most sensitive indicators for detecting differences among reconstructed soils and analogous undisturbed soils in semiarid areas. Theresults revealed a positive effect of vegetation on reconstructed soils and a recovery of soil functionality in waste material to levels similar to those of topsoil once vegetation was established (Muñoz-Rojas et al., 2016). The methodology used in this study involved the collection of soil samples collected from two subareas with different soil materials used as growth media: topsoil retrieved from nearby stockpiles and a lateritic waste material utilized for its erosive stability and physical competence. In their narrative, an undisturbed natural shrub-grassland ecosystem dominated by Triodia spp. and Acacia spp. representative of the restored area was selected as the analogue reference site, whereas soil physicochemical analysis was undertaken according to standard methods. Soil microbial activity was measured with a 1-day CO_2 test, a cost-effective and rapid method to determine the soil microbial respiration rate based on the measurement of the CO_2 burst produced after moistening dry soil; at the same time, the soil microbial abundance of specific groups was measured by phospholipid fatty acid analysis. This technique is multifunctional and can be applied effectively in a broad range of restoration projects in arid and semiarid tropics (Muñoz-Rojas et al., 2016).

Johannes and Boivin (2017) studied soil structural quality assessment for soil protection regulation, and the results showed that the relationships between the physical properties and the soil constituents were linear and highly determined, representing the reference properties of the corresponding soils. Their observation also allowed us to define the most discriminant parameters that depart from the different structural qualities and their threshold limits. The method they used employed two steps. In the first step, the structural quality was assessed with field expertise and visual evaluation of the soil structure (VESS), and the physical properties were assessed via shrinkage analysis. In the second step, the properties of the physically degraded soils were analysed and compared to the reference properties. This study can be useful for farmers in the tropics because it provides vital resource information for soil–water quality protection. There are many other studies with similar or closely related approaches. These include the study of soil invertebrates as bioindicators of urban soil quality (Santorufo et al., 2012), which are considered among the most appropriate for soil quality assessment, and the assessment of soil quality indicators under different land uses and soil erosion conditions using multivariate statistical techniques (Nosrati, 2012), which suggests that dehydrogenase and silt are the most sensitive to land use and soil erosion management. However, for the integrated soil quality assessment approach, the development of relationships between all the soil-quality indicators and the various soil functions may be an enormous assessment (Zalidis et al., 2002), although it is very useful in determining the effective quality of soil and water resource management (Bouwer, 2000).

Conclusion

Tropical and drylands soils required management application to support growing population in Africa. This management is important for soil quality improvement and ensuring food security in the region. Despite the vast developments in soil water conservation studies over the last 75 years, the advanced soil and water management requires considerable effort because of the combine environmental challenges, which include climate change impact, poverty, deforestation and contamination. Soil quality, soil health, soil function, and water quality are soil functional groups, which have various linkages to soil and water management in the tropics and drylands. Assessment of soil quality indicators (physical, biological and chemical) is a valuable tool for understanding the management approach suitable for soil and water improvement. This revision demonstrated that soil and water management in the tropics and drylands, are directly related to inherent and dynamic soil properties (physical, biological and chemical attributes), and can be measured and explained through soil quality assessment. The maintenance of soil quality, soil health, and soil fertility depend largely on soil and water management adaptation in the tropical and dryland areas of Africa. This study recommends that soil assessment is needed for sustainable agriculture and for soil and food security in Africa.

Ethics approval and consent to participate

The paper was part of Kebbi Dryland and Fadama research project works approved by the Department of Agronomy, Faculty of Agriculture Nasarawa State University Keffi, and Nigeria. The work is under the supervision of Professor James O. Jayeba – the Director Amina Muhammand Centre of Climate Change NSUK, Nigeria

Conflicts of Interest

The authors declare no conflict of interest.

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