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Soil systems and the sustainability nexus: Linking food, water, and climate for global resilience

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Abstract
Soil is a fundamental but often neglected piece of the sustainability equation across the globe the critical link between food production, water resources and climate regulation. This review synthesizes contemporary research on soil systems through the lens of the sustainability nexus acting through the effects of soil properties and management practices on food security, hydrological and greenhouse gas emissions. Drawing from multi-disciplinary perspectives, we study the inter-connections of problems relating to soil degradation, agricultural productivity, and water availability with climate change mitigation. We note new evidence of the potential benefits of sustainable soil management practices which can help to simultaneously improve food production, water quality and availability, and help mitigate climate change by sequestering carbon. Therefore, sustainable soil management is of use in ensuring that food, water and energy are never scarce in the globe particularly at the time when climate change is causing weather to be unpredictable. The most significant component of land- water- food-energy system is soil, and this is the part that links all these regions. It is due to this that the issue of soil degradation is increasingly gaining the attention of policymakers and individuals who operate in such sectors in order to understand its impact on climate control, water availability, and food production. This is because they are in a position to assist in formulating sustainable farming strategies and policies. To achieve this, we must be in control of the rural soils such that we preserve the biodiversity and at the same time ensure that there is sufficient food, water and energy. Furthermore, we address the socio-political dimensions of soil stewardship and the contribution of integrated nexus thinking in the development of (context) specific solutions for achieving the sustainable development goals. This review highlights the importance of putting soil systems at the heart of global sustainability strategies and policy frameworks.

Keywords: Soil Organic Carbon, pH balance, Sustainability, Carbon Cycling, Soil Biodiversity

1. Introduction: The Soil Sustainability Nexus in Context

The twenty-first century is being confronted with an unprecedented convergence of global challenges: climate change rapidly multiplying at an alarming rate, food insecurity threatening the lives of almost 700 million people worldwide, water scarcity exacerbating competition across continents, and environmental degradation driving species extinction at an accelerated pace. These seemingly distinct crises are fundamentally linked by means of a common medium soil. Remarkably, soil is often absent in high-level discussions of policy despite the fact it's very much at the heart of these planetary systems (Wang *et al.*, 2023) [20].
Soil is much more than a dead dirt. It is a living, dynamic ecosystem that is home to billions of microorganisms, the basis for 95% of the world food production, holds twice as much carbon as the atmosphere and moderates the water infiltration and purification processes. The idea of the "nexus" that understanding interconnections as opposed to isolation of issues has gained context among sustainability researchers and policy makers. The food-water-energy nexus framework is based on the understanding that interventions in one sector have inevitable impacts on the others. However, this nexus framework neglects soil's essential mediating role more often (Lal *et al.*, 2017) [10].
The soil is a complex ecosystem in which a great number of species interact, and physicochemical and geological processes occur at various times and locations. Ecological and management processes are also closely related. These processes have a very important

role to play in the biodiversity and sustainability of soil ecosystems, and climate change, which is one of the core pillars of our lives (Lehmann *et al.*, 2020) [11]. As far as we know, healthy soil is relevant to food and water security, but a major issue now is that the quantity of arable land on the planet is slowly dwindling at an increasing pace (Hopmans *et al.*, 2021) [7]. According to the United Nations Environment Programme, an average of 20,000 km 2 of productive land will be destroyed every year due to desertification. The annual loss of fertile soils of up to 75 billion tons is caused by soil degradation and poses a threat to the availability of food and freshwater in the world (Borrelli *et al.*, 2017; Dinar *et al.*, 2019) [2, 3]. Regrettably enough, approximately 30 percent of the global soils have been exhausted because of the unsustainable approach towards its management, and there is a continuing process of the further degradation of arable land under the influence of highly intensive agricultural activities and global change (Nascimento *et al.*, 2021) [14]. In the case of degraded land, the soils emit CO2 and N2O to the atmosphere. This renders land degradation to be among the most significant contributors of climatic change which will only deteriorate unless we move swiftly to correct it. Assuming that this tendency continues, 95 percent of the Earth land cover will be damaged by 2050 (GEF 8, 2022). The decrease in the productivity of the terrestrial areas of the world because of soil degradation is 23 percent and costs more than 10 percent of global annual GDP by the loss of ecosystem services, which negatively impact the lives of 3.2 billion people (IPBES, 2022).

2. Soil as a Living System: Understanding Structure and Function

Soil is much more than weathered rock and accumulated organic matter, however. Modern soil science regards soil as a living ecosystem, where physical, chemical and biological processes interact complex and harmoniously to make conditions that support growth of plants, water cycles and transformations of nutrients (Lal *et al.*, 2017) [10]. The soil structure, properties of the aggregates are some of the factors that influence the health and functionality of soil. Experimental system Liu *et al.*, (2023) [13] discovered that the addition of polymer γ-PGA would increase the mean weight diameter (MWD) and the quantity of large aggregates (particles bigger than 0.25 mm) in the sandy and the loam soils that have undergone wetting-drying (WD) cycles. Besides, the greater the wetting-drying cycles, the more porous the soil was normally. Another significant measure to enhance the structure of the soil is to use organic amendments. Xuan *et al.*, (2022) [24] measured the features of the pore structures of soil using a field experiment with the use of several organic substances, such as maize straw, cattle manure, biochar, woody peat, and polyacrylamide, using a three-dimensional digital image analysis technique. They found out that there was a general reduction of the bulk density of the fluvoaquic soil by the use of organic amendments alongside the increase in field water capacity and the amount of water-stable macroaggregates. Ye *et al.*, (2023) [25] found out that the concomitant use of straw and charred straw would inhibit the emission of N2O in the soils when compared to manure of straw alone regardless of nitrogen (N) management since straw would immobilize the N in combination with pH increment of the charred straw. In addition, the late nitrogen fertilization produced by a great effect on the decrease of N2O emission after straw incorporation with the pH of soils being the most important factor that defined the production of N2O emissions in diverse straw application procedures as well as nitrogen treatments. The study conducted by Fu *et al.*, (2022) [5] revealed that the use of water-based spent drilling mud (WBSM), which is one of the proposed solutions to structural problems in coarse-textured soils, reduced the proportion of soil pore sizes larger than 30 μm, and increased the proportion of medium pore sizes (≥30-50 μm), micro pore sizes (5003-5 μm) and extremely micro pore sizes (<0.3 800 3m), which is explained by the clog Also, the soil was more water retentive with the use of WBSM and less water to evaporation. This comes in handy in dealing with coarse text soils with an obvious water shortage in delicate ecosystems. According to the field reclamation experiments which were carried out in coastal China, including a period of less than 7 years up to more than 30 years, Wang *et al.*, (2022) [21] found that the long-term reclamation significantly improved the soil unsaturated shear strength. Besides, further analysis showed that two major components (PC1 and PC2) would effectively explain most of the soil variables, PC1 was an explanatory of the soil texture and PC2 an explanatory of the soil salinity features and structure. The issue of salinization of soil is one of the largest challenges of the sustainable agriculture, particularly in dry and semi dry regions.

2.1 Physical Properties and Water-Holding Capacity

The domain of soil assessment has been transformed permanently as it is no longer concerned with the growing crops, but with an extensive range of functions and processes that includes biodiversity, water quality, climate change, and human health. Nevertheless, there is also limited information on the extent to which these processes and functions are related to each other (Banerjee and Heijden, 2023; Lehmann *et al.*, 2020; Steffan *et al.*, 2018) [1, 11, 15]. The stakeholders and decision makers are also forced to pay attention to land protection, food production, and control and provision of water resources as a part of their agricultural practices and policies. Land-water-and-plants interrelationships, in terms of ecosystem productivity, as well as environmental services, often lead to a set of mutually incompatible elements that impede sustainable ecosystems. Sustainable ecosystem for global land, water, food, and energy security, as well as, biodiversity preservation requires compromises: that is, trade-offs between resource capacities, environmental constraints, and demands, and management policies and practices (Watson *et al.*, 2014) [22]. Effective measures are always needed in the whole chain of the agri-food. This involves better comprehension of the physical, chemical and biological operations that occur in soil and their association with farming, land preservation, biodiversity conservation, element cycle and global change. There are also policies and management plans that are aimed at soil health (Toor *et al.*, 2021) [18]. Agroecosystems may be described as spatiotemporal processes that are based on the interactions of hydrological, biological, physicochemical, economic, sociological, and environmental processes on diverse landscapes on the Earth, where soil physics, specifically, the structural features of soils, is one of the underlying foundations of the functioning of the entire ecosystem (Hartmann and Six, 2023) [6]. The thing is that to learn how complex agroecosystems operate, you should know much about biogeochemical processes. Sustainable development requires the land-water-food-climate nexus, and soil is a key connection between these key areas of concern (Keith *et al.*, 2016) [8]. This special issue was assembled with the aim of highlighting research on the topic of soil-land- water-food-climate nexus and its implications on sustainable development.

- **Soil structure:** The arrangement of soil particles into aggregates is of fundamental importance to hydrological and mechanical properties. Well aggregated soils have higher porosity which both enables water to infiltrate during rain events and also enables the soils to have adequate pore space for plant root swelling and oxygen availability (Lal *et al.*, 2017) [10]. On the other hand, poor soils with low structure compact, leading to decreased infiltration and increased surface runoff and erosion.
- **The vadose zone:** The zone between the soil surface and groundwater is an important filter and storage reservoir. Soil texture (proportion of sand, silt, and clay) and structure influence the water holding capacity: soils high in clay hold more water, but sometimes restrict the extent of root penetration, while sandy soils drain quickly but hold less water (Lal *et al.*, 2017) [10]. Optimum management of soil structure maintains stability and pore size distribution favourable both for water availability for plants and for gravitational drainage avoiding waterlogging.

2.2 Biological Processes and Soil Organic Carbon

Soil organic carbon (SOC) is the sum of all the plant and animal remains that have broken down in different ways. This small percentage of the total soil mass, which is usually 1-5% by weight, has a big effect on soil fertility, structure stability, water retention, and carbon storage. (Wang *et al.*, 2023; Lal *et al.*, 2017) [20, 10]. Microbial communities breaking down organic matter at the same time: (1) release nutrients in forms that plants can use; (2) make substances that hold soil particles together in stable aggregates; (3) control greenhouse gas emissions; and (4) make secondary compounds that make plants more resistant to disease. The connection between SOC and soil health is not always straightforward. As SOC rises from severely degraded levels (0.5%), incremental additions lead to significant enhancements in soil structure, water retention, nutrient availability, and biological activity. But SOC levels off at higher levels, and the benefits grow at a slower rate (Wang *et al.*, 2023) [20]. This nonlinearity has significant implications for restoration targeting, as prioritizing initial efforts on the most degraded soils yields the highest return on investment.

2.3 Nutrient Cycling and Ecosystem Services

Soil is the link between the global cycles of nitrogen, phosphorus, sulfur, and other elements that plants need to grow and ecosystems to work. For instance, nitrogen cycling involves a lot of complicated changes in microbes: nitrogen fixation (changing atmospheric N_2 into forms that plants can use), nitrification (changing organic N into nitrate), denitrification (changing nitrate into atmospheric N_2), and immobilization (microbes taking up nutrients) (Lal *et al.*, 2017) [10]. When these cycles are broken by soil degradation or intensive management, nutrients become less available, which hurts productivity and pollutes the environment when nutrients escape into waterways.

Table 1: Key soil properties and their interconnected impacts across the food-water-climate nexus

Soil Property	Impact on Food Security	Impact on Water Management	Impact on Climate
Soil Organic Carbon	↑ Nutrient availability; ↑ Yield	↑ Water retention; ↓ Runoff	↑ Carbon storage; ↓ GHG
Soil Structure	↑ Root penetration; ↑ Yield	↑ Infiltration; ↓ Erosion	↑ Porosity; ↓ Compaction
Soil Biodiversity	↑ Disease suppression; ↑ Nutrient cycling	↑ Water purification	↑ Resilience; ↓ Sensitivity
pH Balance	↑ Nutrient availability	↑ Contaminant immobilization	Neutral response
Water-Holding Capacity	↑ Drought resilience; ↑ Yield stability	↑ Groundwater recharge	↓ Surface runoff

3. Soil Degradation: Mechanisms, Extent, and Cascading Consequences

One of the most important but least talked about environmental problems is global soil degradation. About 33% of the world's soils are now degraded, which affects the lives of more than 1.3 billion people (Wang *et al.*, 2023) [20]. Degradation occurs via various mechanisms, each yielding unique implications for the sustainability nexus.

3.1 Primary Degradation Processes

Erosion is the most common way that things get worse. In many farming areas, water and wind erosion take away topsoil at rates that are 10 to 40 times faster than natural formation (Wang *et al.*, 2023) [20]. Erosion not only decreases productivity on-site, but it also has effects off-site, such as sediment pollution of waterways, nutrient loss from aquatic ecosystems, and damage to infrastructure. Erosion takes away more fine particles (silt and clay) and organic matter than anything else, which are the things that make soil fertile and hold water (Wang *et al.*, 2023) [20]. Salinization and alkalinization happen when salt build up in the soil, making it hard for most crops to grow. Salt-induced degradation affects about 1.5 billion hectares around the world, and most of it is caused by irrigation that doesn't have enough drainage (Zanella *et al.*, 2015) [26]. Salinized soils have less water available even though they are very wet because dissolved salts lower the water potential. Heavy machinery traffic, especially when it's wet, causes compaction. Compacted soils make it harder for roots to grow, lower their porosity, make it harder for water to get in, and make it harder for plants to grow. Compaction, unlike other types of degradation, can last for decades because soil organisms need time to rebuild structure (Wang *et al.*, 2023) [20]. Nutrient depletion happens when the amount of nutrients taken out of the soil by harvesting is greater than the amount of nutrients put back into the soil by atmospheric deposition, biological fixation, or fertilizer application. Nutrient depletion is the main thing that keeps agriculture from being more productive in sub-Saharan Africa. It is estimated that each year, the region loses 4 to 8 million tonnes of nitrogen, phosphorus, and potassium (Zanella *et al.*, 2015) [26]. Intensive farming speeds up the loss of organic matter by increasing microbial decomposition and lowering the amount of residue that is added. When soils lose organic matter, they also lose their ability to hold water, their structural stability, and their biological diversity. This starts a chain reaction of degradation.

3.2 Cascading Effects Across the Nexus

Soil degradation is not confined to agricultural fields. Instead, it sets off a chain reaction of effects throughout the sustainability nexus:

- **Consequences for Food Security:** Degraded soils cut crop yields by 20 to 50%, with the biggest effects seen in developing countries that rely on rain-fed farming (Wang *et al.,* 2023) [20]. Decreasing yields make food insecurity worse, especially for people who can't afford to buy other types of food. Also, degraded soils often grow crops that don't have enough nutrients, which affects billions of people who are hungry but don't realize it, even though they eat enough calories (Zanella *et al.,* 2015) [26].
- **Disruption of the Water Cycle:** Soils that are compacted and eroded don't let water in as easily, which makes surface runoff worse. When groundwater recharge goes down, groundwater tables go down too. This makes streams less likely to flow during dry seasons and makes droughts worse (Lal *et al.,* 2017) [10]. At the same time, more runoff concentrates nutrients and pesticides, which pollutes surface waters and harms aquatic ecosystems.
- **Climate Feedback Loops:** As soil organic carbon breaks down and erodes, CO_2 levels in the air rise. Instead of being sinks for greenhouse gases, degraded soils become sources of them. Also, less vegetation cover because of low productivity makes the surface albedo higher, which could make the area warmer (Wang *et al.,* 2023) [20].

4. Soil and Food Security: Nutrition, Productivity, and Resilience

Food security encompasses not merely caloric availability but nutritional adequacy, access equity, and system stability. Soil health influences each dimension.

4.1 Soil-Driven Agricultural Productivity

In the past, increasing the amount of land used for farming was the main way to increase agricultural productivity. But almost all of the land that can be farmed is now being farmed, so existing farmland needs to be more productive. Soil quality is a major factor that limits such intensification. Applying fertilizers to degraded soils often doesn't work because the poor structure makes it hard for roots to get through, the lack of organic matter stops microbes from cycling nutrients, and the low biological diversity doesn't stop plant diseases (Lal *et al.,* 2017) [10].

On the other hand, investments in soil restoration often pay off in terms of productivity. Research conducted in East Africa indicates that the integration of enhanced soil water management, via conservation agriculture, with organic amendments can elevate maize yields by 50-200%, particularly on soils that were initially degraded (Zanella *et al.,* 2015) [26]. These changes are good for farmers with few resources because they lower input costs (less chemical fertilizers needed) and make up for the small amount of work needed.

4.2 Soil Health and Crop Nutritional Quality

Soil affects more than just how much food it can grow; it also affects how nutritious it is. Plants that grow on soils rich in micronutrients take in more iron, zinc, selenium, and other minerals that are important for human growth, brain function, and immune system health (Zanella *et al.,* 2015) [26]. On the other hand, crops grown in soils that lack micronutrients pass these deficiencies on to people who eat them. Addressing the status of soil micronutrients at the same time improves both farmer profits (through stable yields) and consumer nutrition, which is a rare case of interests aligning.

4.3 Agroecological Approaches to Soil-Mediated Food Security

Agroecology applies ecological principles to agriculture and sees soil as a living system that needs to be cared for rather than controlled (Zanella *et al.,* 2015) [26]. Some of the main agroecological practices are: Crop diversification lowers the number of pests and diseases by spreading them out across different types of crops. It also increases income and nutrition. Compared to monocultures, diversified cropping systems create more diverse soil microbial communities. This makes the soil more resilient and less likely to spread diseases (Zanella *et al.,* 2015) [26].

Conservation and less tillage Agriculture minimizes soil disturbance, thereby maintaining structure and aggregate stability. Less tillage helps microbial communities recover, organic matter build up, and the water-holding properties of the soil get better (Wang *et al.,* 2023) [20]. But conservation agriculture needs to be managed carefully so that weeds and pests don't spread without chemicals. Instead of sending crop residues and livestock manures away, organic amendments and composting put them back into the soil to rebuild its organic matter. Adding compost to soil makes it hold more water, gives plants nutrients that are slowly released, and helps microbial communities grow. But the benefits of compost only stay in one place unless production goes up a lot (Zanella *et al.,* 2015) [26]. Agroforestry and perennial systems mix trees and shrubs with yearly crops or animals, which makes the soil more complicated. Trees grow deeper roots that reach water and nutrients below the surface. They then spread these nutrients through leaf litter. Perennial root systems keep giving soil microbes organic material all the time, which stops the biological crashes that happen every year when crops are grown.

5. Soil and Water: The Hydrological Nexus

About 2 billion people around the world don't have enough water. This number is expected to rise as climate change makes rainfall less predictable and groundwater runs out faster. Soil is the main way that water is made available by letting it seep in, storing it, cleaning it, and releasing it.

5.1 What Soil Does in the Water Cycle

When it rains, there are three ways for the water to get to the ground: (1) it can soak into the soil, (2) it can flow over the surface along the topography, or (3) it can be caught by plants. This partitioning is based on the properties of the soil. In well-aggregated soils with enough organic matter, more than 80% of rainfall may soak into the ground, which helps recharge groundwater and make moisture available to plant roots. On compacted, eroded soils, infiltration may drop below 10%, and 70-80% may turn into runoff (Lal *et al.,* 2017) [10].

This split between infiltration and runoff creates a basic problem in managing water. Increasing infiltration makes groundwater reserves bigger and makes more water available to plants, which makes droughts less severe. But if water quickly seeps through permeable soils, it may skip over soil layers that trap pollutants and carry them to groundwater. On the other hand, less infiltration protects groundwater but makes surface runoff more concentrated, which can cause floods and erosion. The best way to manage these conflicting needs is to find a balance between them (Lal *et al.*, 2017) [10].

5.2 Soil as a Water Filter and Aquifer Mediator

The vadose zone filters water that seeps in by physically straining it, chemically adsorbing it, and breaking it down by microbes. Compared to sandy soils, soils that are rich in organic matter and clay are better at keeping potential contaminants (like pesticides, heavy metals, and nitrate) from moving around. As agriculture becomes more intensive, the amount of contaminants in the soil exceeds its ability to filter them out, which leads to more pollution in groundwater (Lal *et al.*, 2017) [10].

Changes in soil-mediated infiltration quickly affect shallow groundwater tables. When soil conservation makes it easier for water to soak into the ground, groundwater levels rise, which makes streams flow more during dry seasons. On the other hand, soil degradation that makes it harder for water to soak into the ground leads to less groundwater and less stream flow, which makes droughts worse (Lal *et al.*, 2017) [10].

5.3 How soil holds water and how the climate changes

A significant finding from recent research pertains to the soil's capacity to mitigate climate variability. As the global climate shows more extreme rainfall (heavy rain after dry spells), the ability of soil to hold water becomes very important for stable agriculture. Soils that have a lot of organic matter, a stable structure, and biological activity hold more water that plants can use during dry periods and let water drain away during heavy rains, which helps both droughts and floods (Wang *et al.*, 2023; Lal *et al.*, 2017) [20, 10]. When the amount of organic carbon in the soil goes up by 1%, the soil's ability to hold water goes up by about 0.2%. This is a big improvement in how much water is available during dry seasons (Lal *et al.*, 2017) [10]. This relationship indicates that soil carbon sequestration initiatives concurrently tackle climate change mitigation and adaptation by enhancing agricultural resilience to precipitation variability.

6. Soil and Climate: Carbon Cycling and Greenhouse Gas Emissions

Soils are the largest carbon storage area on Earth, holding about 2,400 gigatonnes of carbon, which is three times the amount in the atmosphere and four times the amount in living things (Wang *et al.*, 2023) [20]. Soil's role in the climate goes beyond just storing carbon; it also actively cycles greenhouse gases.

6.1 Soil Organic Carbon Dynamics and Sequestration Potential

Soil carbon comes in different forms. Some are labile organic compounds that cycle every year, some are intermediate compounds that cycle every ten years, and some are stable mineral-associated compounds that last for hundreds of years (Wang *et al.*, 2023) [20]. The rates at which carbon cycles depend on the moisture, temperature, texture, microbial community composition, and management intensity of the soil. Soils that are warm, wet, and cultivated lose carbon quickly. Soils that are cool, dry, and undisturbed gain carbon slowly. Carbon sequestration is the process of managing soil in a way that increases the amount of carbon it holds. Globally, agricultural soils have 25-50% less carbon than they did before farming, which means they could be restored to a large extent (Wang *et al.*, 2023) [20]. To get soils back to higher carbon levels, you can either (1) reduce decomposition by tilling less, (2) increase organic inputs by planting cover crops, managing pasture, or agroforestry, or (3) do both at the same time. As carbon markets put a price on cutting greenhouse gas emissions, the economic case for storing carbon in agriculture gets stronger. But there are a few things you should keep in mind. First, carbon sequestration rates level off after 20 to 30 years, so stocks need to be managed all the time to stay high. Second, sequestered carbon can be released quickly by extreme drought or fires. Third, carbon benefits are still site-specific, with tropical soils and soils that have lost organic matter recently having the most potential for sequestration (Wang *et al.*, 2023) [20].

6.2 Greenhouse Gas Emissions: Nitrous Oxide and Methane

Soils also release nitrous oxide (N_2O) and methane (CH_4), both of which are strong greenhouse gases. Nitrous oxide, which is made during nitrification and denitrification, has a radiative forcing effect that is 298 times stronger than CO_2 per molecule. Agricultural soils are now the biggest man-made source of N2O (Wang *et al.*, 2023) [20]. Emissions are related to how much nitrogen fertilizer is used, how wet the soil is, and how much organic matter it has. Too much nitrogen fertilizer raises both yields and N_2O emissions at the same time, which has a climate cost that partially cancels out the benefits to productivity. On a per-area basis, methane emissions from agricultural soils are still lower than N2O emissions. However, they do happen in certain systems, such as rice paddies with flooded conditions and soil microbes that make methane. As the demand for rice around the world grows, it becomes more and more important to reduce methane emissions by better managing water (for example, by letting the soil dry out from time to time).

6.3 Integrating Soil Carbon and Water Management

Recent studies increasingly acknowledge the complementarity between soil carbon management and the enhancement of water-holding capacity. Conservative estimates suggest that restoring agricultural soils globally to preagricultural carbon levels while maintaining productivity would sequester 1-2 gigatonnes of carbon annually representing 10-15% of current fossil fuel emissions (Wang *et al.*, 2023) [20]. This carbon sequestration does four things at once: (1) it slows down climate change; (2) it makes farming more productive by cycling nutrients; (3) it makes water retention better; and (4) it makes people more resilient to changes in the weather.

7. Integrated Nexus Management: Multifunctional Soil Systems

The most promising ways to manage soil take into account how food, water, and climate are all connected, rather than trying to maximize one goal at a time. The goal of multifunctional soil management is to get synergistic results from all of the nexus components. A field study of an area in Xinjiang Province, China, a typical oasis area of farming, indicated that the addition of biochar to salty soils had the potential to reduce soil pH, increase the content of soil organic carbon (SOC) and water retention capacity of the soil, and increase the amount of water available in the soil. It demonstrated that biochar addition is potentially one of the methods of managing agriculture in an oasis land to make it environmentally friendly. Bacteria and phages interactions influence the lives of the microbes in the soil and soil nutrient cycling. The study by Wu *et al.,* (2022) [23] evidences the impacts of a single soil phage on bacterial lysis and subsequent necromass generation at different nutrient levels using a laboratory incubation microcosm model system, and also controls the carbon and nitrogen cycles. They found that the bacterial lysis caused by phages enhanced the content of carbon and nitrogen in necromass, and the eutrophic environment favors phage-induced bacterial lysis; on the other hand, the rate of bacterial lysis of the phage decreases in the presence of oligotrophs.

Plant root and soil complexes are significant soil components that influence soil structure and its functions. Using a Dicranopteris linearis fern root-soil system and a direct shear measurement methodology, Zhou *et al.,* (2022) [28] found out that roots could increase the shear strength of collapsing-wall soil, especially in the layer of the lateritic soil, compared to the sandy and detritus layers. They also derived new shear strength equations of root-soil complexes of D. linearis using the modified Wu-Waldron model and the Coulomb formula. Wang, Zhang, *et al.,* (2022) [27] applied experimental data to establish a mathematical equation to describe the kinetics of different air-filled porosity (AFP) in the process of soil shrinkage. They also demonstrated that the variations in porosity as the soil shrink is usually large enough to influence the AFP prediction hence is not insignificant. The nature of the water movement at the hillslope critical zone, especially the nature of the water flowing during extreme rainfalls is critical to the water management. Based on the hydrometric and the use of 18O isotopes, Zhang *et al.,* (2022) [27] performed an experiment on the mechanism of rainwater infiltration and the output of runoff in karst hillslopes of deep and relatively shallow soil cover. They found out that in slopes with thicker soil layers, there is higher susceptibility with flooding in the karst region with considerably high surface run offs in extreme rain conditions compared with the normal rain events where infiltration excess process dominates the surface run off. In addition, soil moisture beforehand is a considerable characteristic which influences the nature of runoff. Su *et al.,* (2022) [16] suggested another method of determining soil saturated hydraulic conductivity (Ksat) as a factor of the void ratio and the arithmetic mean diameter of soil particles. They found that the model with Sauter mean diameter (dS) obtained with the moments of the PSD function is more effective in the estimation of Ksat as compared to that of Hazen equation and that of PTF-based. Liu *et al.,* (2022) [12] conducted a study to determine the hectometre-scale soil water content (θv) in a cosmic-ray neutron sensing (CRNS) to continuously measure the θv of the soil in the Loess Plateau in China and found that the θv of the shrubland was higher than that of the grassland. They also found out that the CRNS was able to accurately measure hectometre-scale 3v in ecosystems with complex terrains, it was more sensitive to precipitation than EC-5 sensors. On most soils, physical crusts of soil occur when it rains or when it is watered. This impacts greatly on hydrological and erosion processes since it alters the structure of the soil pores.

7.1 Conservation Agriculture as a Nexus Integration Strategy

- Conservation agriculture, which minimizes soil disturbance, keeps crop residues, and rotates crops, is an example of multifunctional management. The nexus has many benefits that add up:
  Food Security: Less erosion keeps soil depth and productivity; more organic matter makes nutrients more available; and different cropping systems lower the risk of production failure (Wang *et al.,* 2023; Zanella *et al.,* 2015) [20, 26].
- **Water:** Better infiltration recharges groundwater; less runoff reduces erosion and water pollution downstream; better water retention makes it easier for plants to get water during the dry season (Lal *et al.,* 2017) [10].
- **Climate:** Less disturbance means less carbon dioxide is released from the soil; more organic matter means more carbon is stored; and more vegetation cover means more carbon dioxide is taken up. (Wang *et al.,* 2023) [20].

There are problems with implementing conservation agriculture, such as what farmers need to know, how to deal with weeds, and how to get used to new yields. However, when farmers are given training and incentives, adoption spreads quickly because they see the many benefits. (Zanella *et al.,* 2015) [26].

7.2 Agroforestry Systems: Multi-Product Multifunctional Approaches

Agroforestry, which combines trees with crops or livestock, makes soils that are complex and have many useful properties. Roots of trees create deeper soil zones that get water and nutrients that annual crops can't get. Leaf litter brings back organic matter, which adds carbon to the soil. Shade keeps soil temperatures from getting too hot or too cold. Trees that fix nitrogen add nitrogen that plants can use. Fruits, nuts, and wood are all different ways for farmers to make money. This makes them less likely to lose money when the price of one crop goes up or down.

Water impacts are very important. Agroforestry systems boost the amount of water that goes into the ground compared to deforested areas but less than intact forests. At the same time, they grow crops. Carbon sequestration rates are higher than those of single-crop monocultures, but they are still lower than those of forests (Wang *et al.,* 2023; Zanella *et al.,* 2015) [20, 26].

7.3 Landscape-Scale Nexus Integration

Managing individual fields by themselves won't solve systemic problems. Landscape-scale approaches coordinate soil management across farms, take into account how water flows from upland sources to downstream users, and find a balance between farming productivity and ecosystem conservation (Lal *et al.,* 2017; Zanella *et al.,* 2015) [10, 26]. For instance, the use of conservation agriculture in upland areas helps both soil health and water quality for downstream users by reducing erosion and sediment pollution that affects irrigation systems. In the same way, keeping riparian plants on stream banks that aren't used for farming or are completely wild provides ecosystem services like stability for the streambank, filtering water, providing habitat for wildlife, and keeping stream temperatures from getting too hot or too cold (Lal *et al.*, 2017) [10].

8. Technologies and Innovations in Soil Monitoring and Management

Technological advancements increasingly facilitate soil monitoring and adaptive management at scales and resolutions that were previously unattainable.

8.1 Soil Remote Sensing and Real-Time Monitoring

Multispectral satellite imagery makes it easy to quickly check the health of large areas of soil and plants, which helps find droughts early and manage irrigation more effectively. Soil spectroscopy looks at how soil samples absorb light and quickly predicts soil properties like organic carbon, texture, and nutrient content. It costs less than traditional lab analysis (Lal *et al.*, 2017) [10]. Recently, new technologies have come out, such as wireless soil sensor networks that send real-time data on moisture and temperature, unmanned aerial vehicles that take high-resolution surveys of soil and vegetation conditions, and spectral-spatial image analysis that makes detailed soil property maps (Lal *et al.*, 2017) [10].

8.2 Soil Amendment Innovations: Biochar and Other Options

Biochar charcoal made from biomass pyrolysis looks like it could help degraded tropical soils. When biochar is added to soil, it holds more water, has more nutrients available, and has a wider range of microbes (Wang *et al.*, 2023) [20]. Indigenous Amazonian people made terra preta (Amazonian dark earth) soils thousands of years ago by adding biochar. These soils stayed very fertile even though they were exposed to tropical weather. Modern biochar application aims to replicate these results on a larger scale. Biochar is still expensive on a large scale, and its effects depend on the type of soil and how much is used. Compost, manure, and green manure crops are other ways to improve soil that cost less but need more work and management knowledge (Zanella *et al.*, 2015) [26].

8.3 Digital Agriculture and Decision Support Systems

Decision support systems that use satellite data, weather forecasts, soil information, crop models, and economic data can give farmers advice that is specific to their situation. Machine learning algorithms are getting better at figuring out the best times to plant, how much fertilizer to use, and how to deal with pests based on the weather and the farmer's situation (Lal *et al.*, 2017) [10].

9. Conclusion

The evidence presented in this review leads to a single conclusion: soil health is a key part of global sustainability. Soil system functionality is what makes the connections between food production, water resources, and climate regulation possible. Soil degradation affects all of these areas: eroded soils make less food, let less water in, and store less carbon. On the other hand, restoring soil has many benefits that go beyond just one area. The size of the problem is scary. About 1.3 billion hectares are currently degrading, and this is happening faster because of climate change and population growth but the potential for restoration is just as impressive: restoring degraded soils around the world to healthy productivity all at once would improve food security for about 1 billion people, recharge groundwater reserves in areas with low water availability, and store carbon from the atmosphere equal to 10-15% of current fossil fuel emissions. To make this change happen, people need to work together in many areas:

Technological innovation must expedite the development and scaling of suitable soil amendments (biochar, compost, cover crop integration), monitoring systems that facilitate real-time adaptive management, and mechanical innovations (handheld tools, draught animal power) tailored for smallholder contexts. Policy integration needs to include soil conservation in policies about food security, water management, and climate change, instead of keeping institutions separate. Programs that pay for ecosystem services need to go beyond carbon sequestration to include restoring the water cycle and protecting biodiversity. To protect soil better, governance reform needs to make land tenure more secure, create environmental rules that stop harmful practices, and include farmers and community members in decisions about soil policy. The soil-sustainability connection is not just a theory; it is a real thing that affects the health of people and ecosystems. In the next few decades, the only way to reach sustainable development goals is to make soil systems the main focus of global sustainability strategies. The science is clear, the technologies are available, and the knowledge has been gathered. What is left is the group's desire to put these solutions into action at the speed and scale that the moment calls for.

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