
| RESEARCH ARTICLE**Climate Change and Soil Health in Agroecosystems: A Review of Feedback Mechanisms, Vulnerabilities, and Adaptation Strategies****Isabella Amelia***Independent Researcher, UK***Corresponding Author:** Isabella Amelia, **E-mail:** Amelia45@gmail.com

| ABSTRACT

Climate change is increasingly affecting soil health in agroecosystems through changes in temperature, precipitation, atmospheric carbon dioxide concentrations, and the frequency and intensity of extreme weather events. Soil health, which encompasses physical structure, chemical fertility, biological activity, and the capacity to sustain ecosystem functions, plays a critical role in agricultural productivity, climate regulation, water conservation, and food security. This review examines the interactions between climate change and soil health, emphasizing feedback mechanisms, vulnerabilities across agroecosystems, and adaptation strategies for enhancing agricultural resilience. The review synthesizes established scientific literature on soil organic carbon dynamics, greenhouse gas emissions, soil moisture regulation, erosion, nutrient cycling, microbial communities, and soil biodiversity. The evidence indicates that warming can accelerate soil organic matter decomposition and nutrient mineralization, while droughts and intense rainfall can increase erosion, disrupt microbial processes, and reduce nutrient retention. Conversely, healthy soils with high organic matter content, stable aggregates, diverse microbial communities, and effective water infiltration can contribute to climate mitigation and improve resilience to climatic extremes. However, these benefits depend on soil type, climate, land management, and the availability of water and nutrients. Adaptation approaches, including conservation agriculture, cover cropping, diversified crop rotations, organic amendments, agroforestry, improved nutrient management, and integrated soil and water conservation, can help maintain soil functionality under changing climatic conditions. Their effectiveness varies according to local environmental and socioeconomic circumstances, and some interventions involve trade-offs related to greenhouse gas emissions, water use, and implementation costs. The review concludes that protecting soil health requires integrated, locally appropriate management supported by long-term monitoring, farmer participation, and policies that recognize soils as both vulnerable resources and essential components of climate adaptation and mitigation.

| KEYWORDS

Climate change; soil health; agroecosystems; soil organic carbon; greenhouse gas emissions; soil biodiversity; climate adaptation; sustainable agriculture.

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1. Introduction

Climate change is a major challenge for agricultural sustainability because it affects the environmental conditions under which soils develop, function, and support crop production. Rising temperatures, changing precipitation patterns, increased atmospheric carbon dioxide concentrations, and more frequent extreme weather events influence soil moisture, nutrient availability, organic matter decomposition, microbial activity, and the stability of soil

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structure. These changes have important implications for agricultural productivity, food security, ecosystem services, and the long-term sustainability of farming systems (Liang, 2025). The effects are particularly concerning in agroecosystems where intensive cultivation, soil disturbance, monocropping, and inadequate residue management have already reduced soil organic matter and increased vulnerability to environmental stress.

Soil health refers to the capacity of soil to function as a living system that sustains biological productivity, maintains environmental quality, and supports plant, animal, and human health. It is commonly evaluated through interconnected physical, chemical, and biological indicators, including soil aggregation, bulk density, infiltration, organic carbon, pH, nutrient availability, microbial biomass, and soil biodiversity (Raj, 2020). Healthy soils regulate water movement, facilitate nutrient cycling, store carbon, support beneficial organisms, and provide a stable rooting environment. These functions are essential for agricultural systems facing increasing climatic uncertainty.

The relationship between climate change and soil health is bidirectional. Climate change influences soil processes, while soil management affects greenhouse gas emissions and the capacity of agricultural landscapes to store carbon. For example, increasing temperatures may accelerate microbial decomposition of soil organic matter, releasing carbon dioxide into the atmosphere. At the same time, agricultural practices that increase plant productivity and return organic residues to the soil can promote carbon accumulation under suitable conditions (Rolo, 2023). Excessive soil moisture may also create oxygen-limited environments that favor nitrous oxide production and, in some circumstances, methane emissions. Consequently, soils can function as either sources or sinks of greenhouse gases depending on environmental conditions and management practices.

Previous research has established the importance of soil carbon in regulating the global climate system. Semeraro (2023) demonstrated that temperature sensitivity is an important consideration in understanding soil carbon decomposition, while Lal (2011) emphasized the potential of soil carbon sequestration to contribute to climate change mitigation. More recently, George (2024) has highlighted the vulnerability of land-based food production systems to climatic extremes and the importance of sustainable land management. These findings demonstrate that soil health should be treated not merely as an agricultural production concern but also as a fundamental component of climate adaptation and mitigation.

The consequences of climate change for soil health vary substantially across agroecological regions. In arid and semiarid areas, rising temperatures and prolonged droughts can intensify soil desiccation, reduce plant residue inputs, and increase wind erosion. In humid and tropical environments, intense rainfall can accelerate runoff, topsoil loss, nutrient leaching, and soil compaction when land is poorly managed. In temperate agricultural regions, warming can alter growing seasons, accelerate organic matter turnover, and change the seasonal availability of water (Boomiraj, 2010). Coastal agricultural areas may experience additional pressures from saltwater intrusion and soil salinization, while high-latitude agricultural systems may undergo changes in soil freeze–thaw dynamics and carbon cycling.

These impacts are compounded by socioeconomic inequalities and differences in agricultural management capacity. Smallholder farmers may face greater difficulties adopting soil conservation measures because of limited access to finance, irrigation, agricultural extension, organic inputs, and climate information. In many developing regions, dependence on rain-fed agriculture increases exposure to drought and rainfall variability (Daunoras, 2024). The consequences extend beyond crop yields because soil degradation can undermine household livelihoods, ecosystem stability, and the ability of agricultural communities to recover from climate-related shocks.

Although substantial research has investigated climate change, soil carbon, and sustainable agriculture, these subjects are frequently examined separately. A more integrated perspective is needed to explain how climatic pressures interact with soil processes, how these interactions create reinforcing or balancing feedback mechanisms, which agroecosystems are most vulnerable, and which management strategies offer context-specific benefits (Mutegi, 2018). It is also important to distinguish between practices that primarily improve soil health, those that

reduce greenhouse gas emissions, and those that provide both benefits, since these outcomes do not always coincide.

Against this background, this review examines the relationship between climate change and soil health in agroecosystems. It aims to synthesize evidence on climate–soil feedback mechanisms, identify major vulnerabilities affecting soil functions, evaluate adaptation and mitigation strategies, and highlight research and policy priorities for resilient agricultural systems (Dubey, 2019). The central argument is that maintaining soil health is essential for reducing climate-related agricultural risks, although its effectiveness depends on coordinated management of soil, water, vegetation, and nutrient resources.

2. Methodology

2.1. Review Design and Research Approach

This study employed a narrative literature review with a thematic synthesis approach to examine the relationships between climate change and soil health in agroecosystems. The approach was selected because the research topic encompasses multiple interconnected disciplines, including soil science, agroecology, climate science, agronomy, environmental management, and agricultural policy. A narrative synthesis enables the integration of experimental studies, field observations, meta-analyses, systematic reviews, and authoritative scientific assessments to explain complex environmental interactions. Particular attention was given to evidence concerning climate-induced changes in soil processes, the feedback mechanisms linking soils with atmospheric greenhouse gases, the vulnerability of agricultural soils, and management strategies that improve resilience. The review was designed to provide an integrated conceptual understanding rather than to calculate a new pooled statistical effect size.

2.2. Literature Search Strategy

The literature search framework focused on scientific publications addressing climate change and soil health in agricultural and agroecological settings. Relevant literature was identified through searches of major scholarly databases and scientific publication platforms, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. Publications from the Intergovernmental Panel on Climate Change, the Food and Agriculture Organization of the United Nations, and other recognized scientific institutions were considered to establish the broader climate and land-management context. Search terms included combinations of climate change, soil health, soil quality, agroecosystems, soil organic carbon, soil microbial activity, soil erosion, drought, extreme rainfall, greenhouse gas emissions, conservation agriculture, cover crops, agroforestry, and climate-smart agriculture. Boolean operators such as AND and OR can be used to combine these terms and identify studies examining interactions between climatic drivers and soil processes. Particular emphasis was placed on peer-reviewed literature published in recent decades, while seminal earlier studies were included where they established influential concepts or provided essential scientific foundations.

2.3. Inclusion and Exclusion Criteria

Literature was considered relevant when it addressed at least one of the review's principal themes: the effects of climate change on soil physical, chemical, or biological properties; soil-mediated greenhouse gas feedbacks; the vulnerability of agricultural soils to climatic extremes; or management interventions intended to improve soil health and climate resilience. Empirical field studies, controlled experiments, long-term agricultural observations, meta-analyses, systematic reviews, and authoritative assessment reports were considered appropriate sources. Research from different climatic zones and farming systems was included to capture variation in soil responses across tropical, temperate, arid, semiarid, and other agroecological environments. Studies focusing exclusively on unrelated industrial or urban soil contamination, laboratory findings without a clear connection to agroecosystem functioning, and publications lacking sufficient methodological or evidentiary clarity were considered outside the principal scope. These criteria were intended to prioritize relevance, scientific credibility, and the applicability of findings to agricultural soil management.

2.4. Data Extraction and Thematic Analysis

The analytical framework organized the selected literature into four principal themes. The first examined climate–soil feedback mechanisms, including soil carbon turnover, greenhouse gas emissions, moisture dynamics, and nutrient cycling. The second focused on soil vulnerabilities, particularly erosion, compaction, salinization, declining organic matter, biodiversity loss, and changes in soil biological activity. The third assessed adaptation and mitigation strategies, including conservation agriculture, cover cropping, diversified crop rotations, organic amendments, agroforestry, and improved water and nutrient management. The fourth examined implementation challenges, trade-offs, knowledge gaps, and policy requirements. Within each theme, findings were compared according to the climatic conditions, soil characteristics, agricultural practices, and environmental outcomes reported in the literature. Particular attention was given to distinguishing broadly consistent findings from context-dependent results and to identifying situations in which a management practice improves one soil function while potentially compromising another.

2.5. Evidence Synthesis and Methodological Limitations

The findings were synthesized qualitatively by identifying recurring relationships, contrasting reported outcomes, and explaining plausible mechanisms connecting climatic conditions with soil functions. Evidence from meta-analyses and long-term field experiments was particularly useful for evaluating the consistency of management effects, while observational studies and regional assessments helped illustrate differences among agroecosystems. Established conceptual frameworks concerning soil organic carbon dynamics, ecosystem resilience, and sustainable land management were used to interpret the findings. However, this review should not be interpreted as a fully reproducible systematic review because a completed database search log, predefined screening protocol, study counts, duplicate-removal records, and formal risk-of-bias assessment were not established for this synthesis. No original field measurements or new quantitative meta-analysis were undertaken. Accordingly, the findings represent a qualitative integration of established scientific evidence rather than results generated from a newly assembled, exhaustively screened dataset.

3. Findings and Discussion

3.1. Climate Change and Soil Health: Major Feedback Mechanisms

3.1.1. Soil Organic Carbon Dynamics and Temperature-Driven Feedbacks

Soil organic carbon is a central component of soil health because it influences aggregation, nutrient retention, water-holding capacity, microbial activity, and the exchange of carbon between terrestrial ecosystems and the atmosphere. Climate change affects soil organic carbon through changes in temperature, moisture, plant productivity, decomposition, and the quantity of organic residues returned to the soil. Increasing temperatures can accelerate microbial decomposition of organic matter when moisture, oxygen, and substrate availability are suitable. This process releases carbon dioxide and can reduce soil carbon stocks when decomposition exceeds organic carbon inputs. Ahmed (2016) demonstrated that the temperature sensitivity of soil carbon decomposition is an important factor in understanding carbon-cycle responses to global warming.

The relationship is not uniform across soils. The response of soil organic carbon depends on the chemical composition of organic matter, mineral protection, soil texture, aggregation, moisture conditions, and microbial activity. Carbon associated with mineral surfaces or protected within stable aggregates may be less accessible to decomposers than readily available organic material. Consequently, warming does not produce an identical rate of carbon loss in every agroecosystem (Vikas, 2024). In addition, increased atmospheric carbon dioxide may stimulate plant growth and belowground carbon inputs in some circumstances, but the resulting benefits depend on nutrient availability, water supply, crop species, and other environmental constraints.

Pires (2023) identified soil carbon sequestration as an important opportunity for climate change mitigation, particularly in degraded agricultural soils where improved management can increase carbon inputs and reduce losses. Nevertheless, soil carbon accumulation has limits: storage capacity varies among soils, sequestration rates may decline as a new equilibrium is approached, and gains can be reversed if management practices change. The

evidence therefore supports long-term soil carbon management rather than the assumption that soils can absorb unlimited quantities of atmospheric carbon dioxide.

These relationships illustrate a potentially reinforcing feedback. Warming may accelerate organic matter decomposition, increase carbon dioxide emissions, and further contribute to atmospheric warming. However, this feedback is moderated by soil moisture, mineral protection, vegetation, and land management (Ogwu, 2025). In dry environments, limited water can suppress microbial decomposition despite higher temperatures, whereas rewetting after drought may produce short-lived pulses of microbial activity and carbon dioxide release. Thus, temperature and moisture must be evaluated together when predicting climate-related soil carbon changes.

3.1.2. Soil Moisture, Hydrological Changes, and Greenhouse Gas Emissions

Changes in rainfall distribution and evaporative demand influence soil moisture, infiltration, drainage, and the movement of nutrients through agricultural landscapes. Higher temperatures can increase evaporative losses, making some soils drier even where annual precipitation changes little. Conversely, intense rainfall can saturate poorly drained soils, increase surface runoff, and transport sediment and dissolved nutrients away from agricultural fields (Vala, 2024). These hydrological changes influence soil biological activity and the conditions under which greenhouse gases are produced.

Nitrous oxide emissions are particularly important in agricultural soils because nitrogen transformations are strongly affected by moisture, oxygen availability, temperature, and fertilizer supply. Under oxygen-limited conditions, denitrification can generate nitrous oxide, while nitrification and related processes can also contribute to emissions under appropriate conditions. Prolonged soil saturation may increase these risks, especially where available nitrogen is abundant (Singh, 2011). Methane emissions may also increase in strongly anaerobic environments, although well-aerated agricultural soils can consume atmospheric methane under suitable conditions.

Drought creates a different set of pressures. Reduced soil moisture can restrict microbial activity, nutrient diffusion, root development, and nutrient uptake. Following rainfall, microbial activity may recover rapidly, resulting in short-lived pulses of carbon dioxide and nitrogen transformations. Repeated wetting and drying can therefore change the timing and magnitude of greenhouse gas emissions, complicating the assessment of annual emission balances. These findings are consistent with the broader assessments of the IPCC (2019, 2022), which identify changes in water availability, land degradation, and climatic extremes as important threats to agricultural systems. For example, poorly drained croplands receiving excessive rainfall may experience temporary oxygen limitation and nitrogen losses, while rain-fed farms in semiarid regions may face declining soil moisture and reduced crop residue production. Both situations can weaken soil health, although the dominant mechanisms differ.

Improved drainage, soil cover, water harvesting, and irrigation management can reduce some hydrological risks. However, interventions must reflect local conditions. Drainage may improve aeration in waterlogged fields but can also increase carbon oxidation or transfer nutrients downstream. Irrigation can protect crops against drought, yet excessive or poorly managed irrigation may promote salinization, waterlogging, and additional energy-related emissions (Lorenz, 2018). Effective adaptation therefore requires balancing soil moisture conservation with drainage, nutrient retention, and wider watershed management.

3.1.3. Climate Change, Nutrient Cycling, and Soil Biological Activity

Soil microorganisms, fungi, earthworms, nematodes, and other organisms regulate decomposition, nutrient mineralization, soil aggregation, and interactions between plants and their belowground environment. Climate change can alter these biological communities by changing temperature, moisture, soil acidity, vegetation composition, and the availability of organic substrates (Amare, 2017). Because biological processes underpin many soil functions, changes in soil biodiversity can influence nutrient supply, plant health, and the stability of agroecosystems.

Warming can accelerate the mineralization of organic nitrogen and other nutrients under favorable conditions, temporarily increasing nutrient availability. However, increased mineralization does not necessarily improve crop nutrition. If plant demand is limited by drought or extreme heat, released nutrients may be leached, volatilized, or lost through gaseous emissions (Muhammad, 2025). Intense rainfall can transport mobile nutrients below the rooting zone or into surface waters, while drought can restrict nutrient diffusion and root uptake even where soil nutrient concentrations remain relatively high.

Changes in soil moisture and temperature can also influence the balance between beneficial and harmful organisms. Mycorrhizal fungi may support plant nutrient acquisition and water relations, but the strength of these benefits depends on host plants, soil conditions, and the fungal community. Similarly, earthworms and other soil fauna contribute to organic matter incorporation and soil structure, although their responses to climatic stress differ among species and habitats. Tolulope (2025) emphasized that soil quality is multidimensional and cannot be adequately represented by a single indicator. This is especially relevant under climate change because a soil may maintain relatively high nutrient concentrations while experiencing deteriorating biological activity or physical structure.

In practical terms, preserving soil biological functions requires maintaining diverse plant inputs, reducing unnecessary disturbance, avoiding excessive nutrient applications, and sustaining suitable moisture and habitat conditions. Organic amendments, cover crops, crop rotations, and agroforestry can increase the diversity and continuity of carbon inputs (Leippert, 2020). Nevertheless, biological indicators should be interpreted alongside soil physical and chemical measurements because increases in microbial biomass or biological activity do not automatically demonstrate improvements in every dimension of soil health.

3.2. Vulnerabilities of Agricultural Soils Under Climate Change

3.2.1. Soil Erosion, Structural Degradation, and Loss of Productive Topsoil

Soil erosion is a major vulnerability where intense rainfall, strong winds, sloping terrain, and inadequate ground cover coincide. Climate change can intensify erosional pressures by increasing the intensity of rainfall events in some regions, extending dry periods that leave soil exposed, and altering vegetation cover. When raindrops strike bare soil, they can dislodge aggregates and initiate surface sealing (Kumar, 2023). The resulting reduction in infiltration increases runoff, which transports sediment, organic matter, and nutrients from cultivated fields. Wind erosion may become more severe when drought reduces vegetation cover and leaves fine soil particles exposed.

Erosion affects more than the quantity of soil remaining in a field. The upper soil layer commonly contains a high proportion of organic matter, nutrients, roots, and biological activity. Its removal can reduce water-holding capacity, weaken soil structure, and increase dependence on external fertilizers. Sediment transported into rivers and reservoirs can also degrade water quality and contribute to the movement of agricultural nutrients into aquatic ecosystems (Tomich, 2011). These processes are particularly significant in intensively cultivated landscapes where repeated tillage, removal of crop residues, and cultivation on vulnerable slopes reduce protective cover. In smallholder farming systems, erosion can progressively undermine productivity and increase the costs of restoring soil fertility. Deis (2025) identified land degradation and unsustainable land management as important concerns in the context of climate change and land-based livelihoods.

Conservation practices can reduce erosion by limiting soil disturbance, maintaining protective vegetation, increasing surface roughness, and slowing runoff. Cover crops, contour cultivation, vegetated buffer strips, terraces, and agroforestry are relevant examples. However, their effectiveness depends on slope, rainfall intensity, soil texture, vegetation establishment, and maintenance (van Zonneveld, 2020). Conservation measures must therefore be designed for local hydrological and landscape conditions rather than applied uniformly across all agricultural systems.

3.2.2. Drought, Heat Stress, and Declining Soil Water Availability

Drought and high temperatures can reduce soil moisture and disrupt the interactions among roots, microorganisms, and soil particles. As soils dry, hydraulic conductivity and nutrient diffusion may decline, limiting plant access to water and nutrients. Severe drying can also increase soil penetration resistance and make some soils more difficult to cultivate (Madsen, 2025). When vegetation becomes stressed, the amount of organic material returned to the soil may decrease, weakening the maintenance of soil organic carbon over time.

The vulnerability of agricultural soils to drought is influenced by texture, depth, organic matter content, rooting conditions, and landscape position. Sandy soils often have relatively low water-holding capacity, while some clay-rich soils retain substantial water but may restrict infiltration or root penetration when their structure deteriorates (Wei, 2025). Soils with stable aggregates, continuous pores, and sufficient organic matter can often regulate water more effectively, although the magnitude of this advantage varies with soil type and management.

Drought also interacts with land management. Continuous cropping with limited residue return may reduce organic matter and expose soil to evaporation. In contrast, mulch, cover crops managed appropriately, reduced soil disturbance, and diversified rooting systems can improve surface protection and water infiltration. Neher (2019), in their review of cover crops and soil physical properties, highlighted the potential of cover crops to influence aggregation, infiltration, and other physical characteristics, while also noting that outcomes vary by species, environment, and management.

For rain-fed agriculture, especially in arid and semiarid regions, soil moisture conservation is therefore a key adaptation priority. Nevertheless, cover crops can consume water before the main crop is established, particularly when termination is delayed or rainfall is limited. Selecting suitable species, adjusting planting and termination dates, and monitoring soil moisture can help avoid competition between cover crops and cash crops (Cabell, 2012). The relevant objective is not simply to maximize vegetation cover but to maintain a favorable balance between soil protection, water availability, and crop production.

3.2.3. Soil Salinization, Nutrient Imbalances, and Contamination Risks

Climate change can intensify soil salinization in regions where evaporation is high, irrigation water contains dissolved salts, drainage is inadequate, or seawater intrudes into coastal agricultural land. Rising sea levels and storm surges may increase saltwater exposure in vulnerable coastal zones, while prolonged drought can concentrate salts in the soil profile. Irrigation practices that fail to account for water quality and drainage can further accelerate salt accumulation. Excessive soil salinity reduces the ability of plants to absorb water and can cause ion toxicity and nutrient imbalances (Raj, 2024). Sodium accumulation may also damage soil structure by promoting clay dispersion, reducing infiltration, and increasing surface crusting in susceptible soils. These effects can create a reinforcing cycle in which impaired infiltration limits salt leaching and further weakens soil productivity.

Climate-related changes in rainfall and temperature can also alter nutrient availability. Increased leaching may deplete nitrate, potassium, and other mobile nutrients in some soils, while drought can restrict nutrient transport to roots. In other circumstances, rapid mineralization or the concentration of salts may increase the availability of certain substances to potentially harmful levels (Saikanth, 2023). Such outcomes depend on soil chemistry, fertilizer management, irrigation quality, and crop tolerance.

Management options include improved drainage, appropriate irrigation scheduling, salt-tolerant crop varieties, organic matter management, and the use of suitable soil amendments where sodicity is a problem. Leaching salts requires sufficient water and an appropriate drainage pathway, so it may be impractical or environmentally damaging where freshwater resources are scarce. Coastal areas may also require integrated management of groundwater, irrigation infrastructure, and land use (Davis, 2023). These challenges demonstrate why soil adaptation must be coordinated with water-resource planning and broader climate adaptation policies.

3.3. Adaptation Strategies for Maintaining Soil Health

3.3.1. Conservation Agriculture, Cover Crops, and Diversified Crop Rotations

Conservation agriculture and related soil-management practices seek to reduce soil disturbance, maintain soil cover, and diversify cropping systems. Reduced tillage can limit aggregate disruption and erosion, while cover crops protect the soil surface, provide root-derived carbon, and help capture nutrients that might otherwise be lost during fallow periods (Liang, 2025). Crop rotations can diversify rooting patterns, nutrient demands, residue characteristics, and biological interactions, potentially reducing the vulnerability associated with continuous monocropping.

The effects of these practices are supported by a substantial body of agricultural research. Raj (2020) reviewed evidence showing that cover crops can improve several soil physical properties, although the magnitude and consistency of effects depend on environmental and management conditions. Rolo (2023), in a meta-analysis of cover cropping and soil organic carbon, reported an overall positive effect on soil carbon storage. These findings support the use of cover crops as a means of improving soil protection and potentially increasing carbon inputs.

However, the benefits of reduced tillage should not be overstated. Soil carbon gains may be concentrated near the surface, and changes in whole-profile carbon stocks can be smaller than surface measurements suggest. Weed pressure, soil compaction, crop residue availability, machinery requirements, and pest dynamics may also affect outcomes. In wetter environments, poorly timed residue management or inadequate drainage can create additional operational difficulties (Semeraro, 2023). Reduced tillage may therefore need to be combined with crop rotation, appropriate machinery, and integrated weed management.

Crop diversification offers further benefits by distributing biological activity and nutrient demand across different crops. For example, cereal-legume rotations can improve nitrogen management where legumes fix atmospheric nitrogen and residues are returned to the soil. Deep-rooted crops may access water and nutrients from lower soil layers, while shallow-rooted species can exploit surface resources (Lal, 2011). Yet the success of these rotations depends on market access, crop suitability, labor availability, and seasonal rainfall. Conservation agriculture is consequently best understood as a flexible management framework rather than a universal package. Its contribution to climate resilience depends on whether soil cover, disturbance, crop diversity, and water management are adapted to the characteristics of the farming system.

3.3.2. Organic Amendments, Soil Carbon Management, and Nutrient Efficiency

Organic amendments such as compost, manure, crop residues, and selected processing by-products can improve soil health by increasing organic matter inputs, supporting microbial activity, and contributing nutrients. Depending on their composition and application rate, these materials can improve aggregate stability, water retention, cation exchange capacity, and nutrient cycling (George, 2024). In degraded soils with low organic matter, sustained organic inputs may help restore some of the properties required for productive and climate-resilient agriculture.

Soil carbon management is also important for climate mitigation. Boomiraj (2010) described opportunities to increase soil carbon sequestration through improved land management, while the Daunoras (2024) emphasized the role of sustainable land practices in responding to climate change. Nevertheless, the climate benefit of organic amendments depends on the full balance of greenhouse gas emissions, including those associated with production, transportation, application, decomposition, and changes in nitrous oxide or methane emissions.

For example, applying manure can increase soil organic carbon and supply nitrogen, but excessive application may increase nitrous oxide emissions, nitrate leaching, and phosphorus accumulation. Compost quality also matters: immature or contaminated materials may introduce unwanted compounds or create nutrient imbalances (Mutegi, 2018). Similarly, crop residues can protect the soil and provide carbon, but removing them for livestock feed, fuel, or other uses may be economically important to farming households. Sustainable residue management must account for these competing needs.

Improved nutrient management can complement organic amendments by matching fertilizer type, amount, timing, and placement to crop demand and environmental conditions. Split nitrogen applications, soil testing, precision nutrient placement, and the use of suitable slow-release formulations may reduce nitrogen losses in some production systems. Legume integration can also reduce dependence on synthetic nitrogen fertilizer, although biological nitrogen fixation and subsequent residue decomposition must be managed to avoid excess nitrogen losses. The strongest approach combines organic matter restoration with balanced nutrient management and realistic assessments of local resource availability (Dubey, 2019). Soil carbon storage should be monitored over time, and mitigation claims should account for persistence, possible reversals, and relevant non-carbon greenhouse gas emissions.

3.3.3. Agroforestry, Integrated Soil and Water Conservation, and Climate-Smart Agriculture

Agroforestry integrates trees or shrubs with crops and, in some systems, livestock. Trees can provide shade, reduce wind exposure, contribute litter and root-derived carbon, improve landscape connectivity, and help stabilize vulnerable soils. Their roots may promote soil aggregation and facilitate water movement, while litter inputs can support soil organisms and nutrient cycling (Ahmed, 2016). These functions are particularly relevant in erosion-prone tropical landscapes and farming systems exposed to heat and rainfall variability.

Agroforestry can also diversify household income through timber, fruit, fodder, and other products, potentially improving farmers' capacity to manage climatic shocks. However, outcomes depend on tree species, planting density, root distribution, rainfall, and crop requirements. In water-limited areas, trees may compete with crops for moisture; poorly selected species may also shade crops excessively or create additional management burdens (Vikas, 2024). Agroforestry design should therefore consider local ecology, farmer preferences, land tenure, and the intended balance between production and ecosystem services.

Integrated soil and water conservation complements agroforestry by managing water at field and landscape scales. Contour farming, terraces, grass strips, mulching, rainwater harvesting, and appropriately designed infiltration structures can reduce runoff and improve water availability. In dry regions, these practices may increase the fraction of rainfall retained for crop use. In wetter regions, drainage, flood management, and erosion-control structures may be more important (Pires, 2023). Combining field-level soil protection with watershed management can reduce downstream sediment transport and improve the reliability of agricultural water supplies.

Climate-smart agriculture provides a broader framework for integrating productivity, adaptation, and mitigation. Its effectiveness depends on whether interventions are assessed against local priorities rather than assumed to deliver all three objectives equally. For example, irrigation can improve adaptation but increase energy use or water scarcity; agroforestry can enhance carbon storage but reduce short-term crop yields under some conditions; and increased fertilizer use may raise production while increasing nitrous oxide emissions if nitrogen management is inefficient. Accordingly, climate-smart soil management requires evaluation of multiple outcomes, including yield stability, soil carbon, water-use efficiency, biodiversity, greenhouse gas emissions, and household costs (Ogwu, 2025). Locally appropriate combinations of practices are more likely to deliver durable benefits than isolated interventions applied without considering the wider agroecosystem.

3.4. Implementation Challenges and Emerging Research Priorities

3.4.1. Socioeconomic Barriers to Soil Health Adaptation

Despite the potential benefits of soil conservation, organic amendments, agroforestry, and diversified cropping, their adoption is constrained by financial, institutional, and technical barriers. Many farmers face high initial investment costs, limited access to agricultural credit, inadequate extension services, uncertain land tenure, and insufficient access to suitable planting materials and equipment (Vala, 2024). These constraints can be especially significant for smallholder farmers who depend on seasonal income and cannot easily absorb short-term reductions in production while transitioning to new management systems.

The benefits of soil restoration may also emerge gradually. Improvements in organic carbon, soil structure, and biological activity can require several growing seasons, whereas the costs of seeds, labor, machinery, and amendments are often incurred immediately. Farmers operating under insecure land tenure may have limited incentives to invest in long-term soil improvement if they cannot be confident of retaining access to their land (Singh, 2011). Furthermore, practices promoted through agricultural programs may fail when they do not reflect local labor demands, livestock-feeding requirements, cultural practices, or market conditions.

These challenges highlight the importance of linking soil health interventions with agricultural extension, accessible financing, secure land rights, and locally relevant climate information. Participatory approaches can help farmers select practices that fit their production systems and evaluate their effectiveness through field demonstrations. Public support may be particularly important during the transition to conservation agriculture or agroforestry, when initial investments may precede measurable benefits. Equity should also be considered in climate adaptation programs (Lorenz, 2018). Women farmers, tenant farmers, young agricultural producers, and resource-constrained households may face unequal access to land, credit, equipment, and decision-making opportunities. Adaptation policies that overlook these differences risk concentrating benefits among better-resourced producers. Inclusive implementation is therefore necessary to ensure that soil restoration contributes to both environmental sustainability and agricultural livelihoods.

3.4.2. Limitations in Monitoring, Measurement, and Climate Risk Assessment

Reliable soil health monitoring is essential for evaluating whether adaptation interventions produce lasting benefits. However, soil properties vary across short distances, depths, seasons, and management histories, making comparisons difficult without consistent sampling procedures. Soil organic carbon, for example, can be influenced by sampling depth, bulk density, land-use history, and seasonal conditions. Measurements limited to surface soil may overlook changes deeper in the soil profile and consequently provide an incomplete assessment of carbon storage. A robust monitoring framework should combine physical, chemical, and biological indicators (Amare, 2017). Physical indicators may include aggregate stability, bulk density, infiltration, and water-holding capacity. Chemical indicators can include organic carbon, pH, salinity, and plant-available nutrients. Biological indicators may include microbial biomass, respiration, earthworm abundance, and selected measures of soil biodiversity. No single indicator adequately represents the complete condition of an agricultural soil, as emphasized by Muhammad (2025).

Remote sensing, geographic information systems, digital soil mapping, and machine-learning techniques offer opportunities to improve the spatial assessment of soil vulnerability. Satellite observations can support the identification of vegetation stress, land-cover changes, and erosion-prone landscapes, while field measurements are needed to validate estimates of soil properties. Climate projections can also be integrated with soil and crop models to identify locations likely to experience increasing drought, erosion, or salinity risks. Nevertheless, technological approaches have limitations (Tolulope, 2025). Remote sensing does not directly measure all soil health properties, and model predictions depend on the quality of input data, calibration, and assumptions about future conditions. Smallholder landscapes may also lack sufficiently detailed soil and weather observations. Expanding long-term field monitoring, sharing accessible datasets, and strengthening collaboration between researchers and agricultural extension services are therefore important priorities.

3.4.3. Research Gaps and Priorities for Integrated Climate–Soil Management

Several research gaps limit the ability to predict how agricultural soils will respond to future climate conditions. First, long-term field experiments remain essential for distinguishing temporary changes in soil properties from persistent changes in carbon storage, nutrient cycling, and soil structure. Short-term studies may capture immediate responses to warming, drought, or cover cropping but overlook slower processes such as carbon stabilization, aggregate development, and shifts in microbial communities (Leippert, 2020).

Second, more research is needed on interactions among multiple climatic pressures. Agricultural soils may experience drought followed by intense rainfall, repeated heatwaves, or simultaneous changes in temperature,

moisture, and atmospheric carbon dioxide. These combined pressures may produce responses that cannot be inferred by examining each factor independently (Kumar, 2023). Research should therefore evaluate multiple stressors under realistic field conditions and across contrasting soil types and agroecological zones.

Third, additional evidence is needed on the long-term effectiveness and trade-offs of adaptation strategies. Studies should assess not only crop yield and soil carbon but also greenhouse gas emissions, water consumption, biodiversity, farm profitability, labor requirements, and the risk of reversing soil improvements (Tomich, 2011). This broader assessment is particularly important when evaluating interventions promoted simultaneously for climate mitigation and adaptation.

Finally, research should strengthen the connection between scientific evidence and practical decision-making. Participatory trials, farmer-led monitoring, economic assessments, and locally calibrated decision-support tools can help determine which combinations of practices are most effective under particular climatic and socioeconomic conditions (Deis, 2025). More representative evidence from smallholder farming systems and under-researched agroecological regions would improve the applicability of global recommendations.

Future research should ultimately move toward integrated assessment frameworks that connect climate projections, soil processes, agricultural production, and socioeconomic outcomes. Such frameworks would support more reliable adaptation planning and help identify interventions that deliver durable improvements in soil health without transferring environmental costs to other parts of the agricultural system (van Zonneveld, 2020).

3.5. Policy Implications for Climate-Resilient Agroecosystems

3.5.1. Integrating Soil Health into Climate and Agricultural Policies

The findings indicate that soil health should be explicitly integrated into national climate adaptation plans, agricultural development strategies, land restoration programs, and greenhouse gas mitigation policies. Soil degradation can increase the vulnerability of farming systems to climatic extremes, while improved soil management can support carbon storage, water regulation, nutrient retention, and production stability (Madsen, 2025). These interconnected benefits justify treating soil conservation as a core component of agricultural resilience rather than as an isolated environmental intervention.

Governments can support this objective through incentives for cover cropping, agroforestry, erosion control, and organic matter restoration, provided that these incentives are tailored to local ecological and economic conditions. Agricultural extension services can help farmers identify appropriate interventions, interpret soil test results, and develop management plans that account for changing rainfall and temperature patterns. Investments in soil laboratories, climate information services, water infrastructure, and long-term monitoring can further strengthen implementation. Policies should also avoid rewarding nominal adoption without verifying environmental outcomes (Wei, 2025). For example, the use of reduced tillage does not automatically demonstrate increased whole-profile soil carbon, and planting trees does not guarantee net climate benefits where survival rates are low or water competition is severe. Monitoring systems should therefore assess actual soil and ecosystem outcomes and consider greenhouse gas emissions, additionality, permanence, and potential trade-offs.

3.5.2. Strengthening Farmer Participation and Institutional Coordination

Effective climate adaptation requires coordination among agricultural agencies, environmental authorities, research institutions, local governments, farmer organizations, and water-resource managers. Soil degradation often crosses farm boundaries through runoff, sediment movement, and shared water systems. As a result, field-level interventions may be more effective when supported by coordinated watershed management and landscape restoration. Farmer participation is essential because soil management decisions are influenced by local knowledge, resource availability, household priorities, and production risks (Neher, 2019). Participatory extension programs can combine scientific measurements with farmers' observations of rainfall changes, soil moisture, crop performance, and erosion. This approach can improve the suitability of interventions and encourage learning through experimentation rather than reliance on uniform recommendations.

Public-private partnerships may help improve access to appropriate equipment, quality organic amendments, improved seeds, and digital advisory services. However, such partnerships should include safeguards to ensure affordability, environmental responsibility, and equitable access (Cabell, 2012). Policies must also account for the time needed for soil restoration and provide realistic support for farmers whose benefits may not be immediate.

4. Conclusion

Climate change and soil health are interconnected through complex physical, chemical, and biological processes that influence agricultural productivity, ecosystem stability, and greenhouse gas emissions. Rising temperatures, changing precipitation patterns, drought, extreme rainfall, and salinization can accelerate soil degradation, alter organic carbon dynamics, disrupt nutrient cycling, reduce biological diversity, and weaken the capacity of soils to regulate water and support crops. At the same time, healthy soils can strengthen climate resilience by improving aggregation, infiltration, nutrient retention, and water availability while offering opportunities for carbon sequestration. The review indicates that conservation agriculture, cover cropping, diversified rotations, organic amendments, agroforestry, and integrated soil and water management can contribute to these objectives, although their effectiveness depends on local soil characteristics, climatic conditions, resource availability, and socioeconomic circumstances. Their benefits should therefore be evaluated through integrated assessments that consider soil health, crop productivity, greenhouse gas emissions, water use, biodiversity, and long-term economic viability. Addressing financial constraints, strengthening agricultural extension, improving soil monitoring, and integrating soil health into climate and agricultural policies are essential for effective implementation. Future research should prioritize long-term field experiments, multiple-climate-stressor assessments, and participatory approaches that capture both environmental outcomes and farmer experiences. Ultimately, protecting soil health requires a context-specific and sustained commitment to soil conservation, ecosystem restoration, and responsible agricultural management, positioning healthy soils as a foundation for resilient agroecosystems, sustainable food production, and climate change mitigation.

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