



# International Journal of Research in Agronomy

E-ISSN: 2618-0618  
P-ISSN: 2618-060X  
© Agronomy  
NAAS Rating: 5.20  
[www.agronomyjournals.com](http://www.agronomyjournals.com)  
2025; 8(5): 784-789  
Received: 28-03-2025  
Accepted: 30-04-2025

**Ganesh MC**  
Young Professional, Soil Testing  
Lab, Technology Evaluation  
Center, Coffee Board, Gonikoppal,  
Karnataka, India

**SA Nadaf**  
Scientist CRSS, Coffee Board,  
Chettalli, Karnataka, India

**Corresponding Author:**  
**Ganesh MC**  
Young Professional, Soil Testing  
Lab, Technology Evaluation  
Center, Coffee Board, Gonikoppal,  
Karnataka, India

## Climate change and its impact on soil health: Mitigation strategies

**Ganesh MC and SA Nadaf**

**DOI:** <https://www.doi.org/10.33545/2618060X.2025.v8.i5j.3190>

### Abstract

Climate change poses a profound threat to global soil health, disrupting the delicate balance of physical, chemical, and biological properties that sustain terrestrial ecosystems and food systems. Rising temperatures, altered precipitation patterns, increased atmospheric CO<sub>2</sub>, and extreme weather events are accelerating rates of soil degradation, including erosion, compaction, nutrient loss, and microbial imbalance. These changes not only impair soil productivity but also create feedback loops that exacerbate greenhouse gas emissions, making soil both a victim and contributor to climate change. This review explores the multifaceted impact of climate stressors on soil systems and evaluates a range of mitigation strategies aimed at preserving and restoring soil health. Approaches such as conservation agriculture, organic matter management, agroforestry, carbon sequestration, and precision soil monitoring offer scalable solutions to enhance soil resilience and agricultural sustainability. The paper also emphasizes the importance of policy frameworks, community engagement, and interdisciplinary research in achieving long-term climate adaptation. By integrating scientific innovation with traditional land stewardship, soil can be repositioned as a central asset in the fight against climate change.

**Keywords:** Climate change, soil degradation, carbon sequestration, conservation agriculture, soil resilience

### Introduction

Soil is an essential, non-renewable natural resource that serves as the foundation for agricultural productivity, biodiversity, and global biogeochemical cycles. It acts as a buffer, a reservoir, and a living matrix that supports life on land<sup>[1, 2]</sup>. However, this vital resource is increasingly under threat from climate change, which is manifesting through a combination of rising temperatures, erratic rainfall, prolonged droughts, intensified flooding, and increased atmospheric carbon dioxide. These climatic perturbations are reshaping the structure, function, and sustainability of soil systems across the globe. The impact is not uniform; different soil types, agro-ecological zones, and land-use practices respond differently to climatic variables, making this a complex and pressing issue<sup>[3, 4]</sup>.

As climate change accelerates, soils are experiencing degradation at unprecedented rates. The loss of soil organic matter, compaction, acidification, salinization, erosion, and loss of biodiversity are now commonly observed phenomena in both developed and developing regions<sup>[4, 5]</sup>. These changes jeopardize not only crop yields and food security but also the soil's intrinsic ability to act as a carbon sink and regulator of greenhouse gases. Ironically, as soils degrade, they become a net source of emissions, thereby reinforcing the very climate changes that triggered their decline—a classic example of a negative feedback loop<sup>[5, 6]</sup>.

Given the urgency and scale of the problem, this review aims to critically analyse the impacts of climate change on soil health and to explore effective mitigation strategies that can preserve soil function while enhancing resilience<sup>[7, 8]</sup>. By examining changes across physical, chemical, and biological dimensions of soil, and by highlighting both scientific and community-based responses, this article underscores the need for integrated approaches that combine technology, policy, and traditional knowledge. In doing so, it positions soil not merely as a casualty of climate change, but as a powerful instrument for climate mitigation and adaptation<sup>[9, 10]</sup>.

### Effects of Climate Change on Soil Systems

Climate change imposes complex and interlinked pressures on soil systems, altering their structure, fertility, microbial activity, and capacity to support plant life. These changes are primarily driven by four key climate-related stressors: rising temperatures, altered precipitation regimes, elevated atmospheric CO<sub>2</sub> concentrations, and the increased frequency and intensity of extreme weather events. Each of these drivers affects soil differently but synergistically contributes to accelerated degradation and reduced ecological resilience [11, 12].

Rising global temperatures enhance the rate of organic matter decomposition in soils, accelerating microbial respiration and reducing the overall stock of soil organic carbon. While increased microbial activity can temporarily release nutrients, it also leads to higher CO<sub>2</sub> emissions from soils, reducing long-term fertility and exacerbating atmospheric greenhouse gas levels. Moreover, warmer temperatures can alter soil moisture dynamics by increasing evaporation rates, especially in semi-arid and arid zones, leading to desiccation and soil crust formation [13, 14].

Changes in precipitation patterns, including prolonged droughts and sudden heavy rains, severely disrupt soil hydrology. Drought conditions reduce microbial biomass, inhibit enzymatic activity, and weaken soil aggregation, making soil more prone to erosion. Conversely, excessive rainfall leads to waterlogging, nutrient leaching, and reduced oxygen availability in the root zone, thereby impairing plant growth and microbial balance [15, 16].

Elevated levels of atmospheric CO<sub>2</sub> influence plant physiology and root exudation, which in turn affects rhizosphere microbial communities. While increased CO<sub>2</sub> may stimulate biomass production in some plants, it also leads to imbalances in soil carbon inputs and microbial substrate availability. This can result in shifts in microbial community structure and function, further impacting nutrient cycling [17, 18].

Extreme weather events such as storms, floods, and heatwaves cause physical damage to soil by compacting upper layers, washing away topsoil, and destroying vegetative cover. These events intensify soil erosion, disrupt microbial habitats, and undermine natural recovery processes. The cumulative effect of these climatic drivers is a progressive decline in soil quality and ecosystem services, with particularly severe consequences in vulnerable regions such as tropical highlands, coastal zones, and drylands [19, 20].

### Climate Change and Soil Physical Health

Soil physical health refers to the structural integrity and physical functioning of soil, which are crucial for processes such as water infiltration, aeration, root penetration, and resistance to erosion. Climate change, through its multifaceted stressors, significantly alters these physical properties, leading to a cascade of adverse outcomes for both natural and managed ecosystems [21, 22].

One of the most pronounced effects of climate change on soil physical health is the alteration of soil structure. Prolonged dry periods followed by intense rainfall events lead to cycles of shrinking and swelling, which break down soil aggregates and contribute to surface crusting. This degradation reduces pore space, impairs gas exchange, and limits root expansion. As a result, plants experience water stress even when moisture is present, due to poor infiltration and retention capacities [23, 24].

The increased frequency of droughts leads to reduced soil moisture content, which lowers the cohesion of soil particles and makes soils more susceptible to wind erosion. Conversely, extreme rainfall intensifies water erosion, stripping away

nutrient-rich topsoil and leading to sedimentation in water bodies. These processes degrade soil horizons and diminish long-term land productivity. Moreover, heavy rainfall compacts soils, particularly in areas subjected to mechanized farming, thereby decreasing porosity and reducing the soil's ability to retain and transmit water [9, 11].

Another critical concern is the rise in soil bulk density, often associated with repeated wetting and drying cycles and the loss of organic matter. Higher bulk density reduces root permeability and microbial movement, leading to stagnation in nutrient and carbon cycling. Additionally, climate-induced vegetation loss—whether from prolonged heatwaves or pest outbreaks—leaves the soil surface unprotected and vulnerable to raindrop impact and wind deflation [12, 13].

Collectively, these changes compromise the soil's physical resilience and increase its vulnerability to degradation under continued climatic stress. Addressing these physical alterations is a key step in ensuring long-term agricultural viability and ecosystem sustainability under changing climate conditions [14, 15].

### Climate Change and Soil Chemical Properties

Climate change significantly alters the chemical composition and functioning of soil systems, with far-reaching implications for plant nutrition, contaminant mobility, and biogeochemical cycling. The soil chemical environment, including pH, nutrient availability, cation exchange capacity, and redox potential, is highly sensitive to shifts in temperature, moisture regimes, and atmospheric composition each of which is being destabilized by ongoing climatic changes [16, 17].

One of the most notable impacts is the alteration of soil pH, driven by increased acid deposition, enhanced organic matter decomposition, and changes in vegetation type. Higher temperatures and frequent rainfall extremes promote the leaching of base-forming cations such as calcium and magnesium, resulting in acidification. In contrast, arid and semi-arid regions often experience alkalization due to evaporation-driven accumulation of soluble salts, especially under conditions of poor drainage [18, 19].

Nutrient availability is also deeply affected by climate variability. For instance, prolonged flooding or waterlogging—linked to erratic rainfall patterns creates anaerobic conditions that shift the redox potential of the soil. These changes alter the solubility and mobility of key nutrients like iron, manganese, and phosphorus. Similarly, nitrogen transformations are disrupted, with increased volatilization of ammonia under heat stress and enhanced denitrification leading to greater losses of nitrogen in the form of nitrous oxide, a potent greenhouse gas [20, 21].

Climate-induced changes in soil moisture also accelerate leaching of nutrients, particularly nitrates and potassium, thereby reducing fertility and increasing the risk of groundwater contamination. Concurrently, drought conditions slow microbial-mediated nutrient mineralization, leading to nutrient immobilization and reduced crop uptake. Such imbalances may necessitate increased fertilizer inputs, which, if poorly managed, can further exacerbate soil and water pollution [17, 22].

Moreover, the mobilization of heavy metals and toxic elements is intensified under shifting redox and pH conditions. For example, acidic conditions can enhance the bioavailability of aluminum and cadmium, leading to toxicities that impair root development and microbial activity. These emerging chemical stresses not only compromise crop productivity but also pose long-term risks to environmental and human health [23, 24].

Understanding and managing these chemical disruptions is essential for developing climate-resilient soil management strategies. It requires integrated monitoring of soil chemistry and proactive adaptation of nutrient management practices tailored to shifting environmental baselines [26, 27].

## 6. Climate Change and Soil Biological Health

Soil biological health encompasses the diversity, abundance, and functional capacity of living organisms within the soil, including bacteria, fungi, archaea, protozoa, nematodes, and macrofauna such as earthworms and insects. These organisms play vital roles in organic matter decomposition, nutrient cycling, disease suppression, and the maintenance of soil structure. However, climate change is increasingly destabilizing these biological communities, leading to reduced soil vitality and diminished ecosystem services [17, 27].

Temperature fluctuations, altered precipitation, and elevated CO<sub>2</sub> levels exert direct and indirect effects on soil biota. Prolonged drought and heat stress reduce microbial biomass and diversity, particularly affecting moisture-sensitive groups such as mycorrhizal fungi and nitrogen-fixing bacteria. These losses can lead to a breakdown in microbial-mediated processes, such as nitrification, cellulose degradation, and phosphorus solubilization, which are essential for plant growth and soil fertility. In contrast, warming in cold regions may temporarily stimulate microbial activity, increasing respiration rates and organic matter turnover—though at the expense of long-term soil carbon stocks [18, 25].

Climate-driven changes in vegetation and root exudation also reshape rhizosphere dynamics, influencing which microbial communities dominate and how they function. Shifts in root architecture and chemistry can either enhance or suppress microbial interactions, with implications for both mutualistic relationships (e.g., mycorrhizae) and pathogenic outbreaks. Elevated atmospheric CO<sub>2</sub> can initially boost plant growth and microbial abundance by increasing belowground carbon inputs, but the benefits are often short-lived, as nutrient limitations and water stress eventually constrain productivity [26, 27].

Moreover, extreme weather events—including floods and wildfires—can abruptly alter microbial habitats. Flooding leads to anaerobic conditions that promote the proliferation of denitrifying and methanogenic bacteria, resulting in greenhouse gas emissions and nutrient losses. Wildfires sterilize surface soils and eliminate organic substrates, leading to declines in microbial biomass and delayed recolonization. These disturbances not only affect microbial diversity but also disrupt soil food webs, weakening the biological resilience of the soil ecosystem [28, 29].

Macrofaunal organisms, including earthworms, termites, and arthropods, are similarly affected. Many of these organisms have narrow tolerance ranges and are highly sensitive to soil moisture and temperature changes. Their decline leads to reduced bioturbation, poor aeration, and impaired organic matter incorporation—further diminishing soil structure and fertility.

As the foundation of soil health, biological communities must be protected and promoted through climate-adaptive practices. Restoring microbial diversity, maintaining organic inputs, and minimizing physical and chemical disturbances are critical to ensuring the continued functionality of these life-sustaining processes [30, 31].

## Feedback Loops - Soil as a Source and Sink of Greenhouse Gases

Soils play a dual role in the context of climate change—they act

both as a significant source and a vital sink of greenhouse gases (GHGs), including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). This duality creates powerful feedback loops that either exacerbate or help mitigate climate impacts. Understanding and managing these feedback mechanisms is essential for leveraging soils as allies in climate change mitigation [32, 33].

Under natural conditions, soils store more carbon than the atmosphere and terrestrial vegetation combined, largely in the form of soil organic carbon (SOC). However, climate-induced degradation—such as erosion, loss of vegetation, and increased microbial respiration—can convert these carbon-rich soils into net emitters of CO<sub>2</sub>. Rising temperatures accelerate the breakdown of organic matter, especially in temperate and boreal regions where large carbon stocks are held in peatlands and permafrost. As these soils warm, vast quantities of carbon are released, reinforcing atmospheric warming in a positive feedback loop [34, 35].

Similarly, altered precipitation regimes affect soil moisture conditions, influencing microbial pathways that govern CH<sub>4</sub> and N<sub>2</sub>O emissions. Waterlogged soils, particularly in rice paddies or wetlands, foster anaerobic environments conducive to methanogenesis, resulting in CH<sub>4</sub> emissions. On the other hand, dry and compacted soils are often hotspots for denitrification processes that emit N<sub>2</sub>O a greenhouse gas nearly 300 times more potent than CO<sub>2</sub> over a 100-year timescale [36, 37].

Soil management practices and land-use changes can also tip the balance toward either sequestration or emission. For instance, intensive tillage, monoculture farming, and overuse of nitrogen fertilizers can all increase GHG emissions from soils. In contrast, well-managed soils enriched with organic inputs and maintained under cover vegetation can act as carbon sinks, drawing down atmospheric CO<sub>2</sub> through enhanced biomass production and carbon stabilization in aggregates and humic substances [38, 39].

Moreover, the capacity of soils to sequester carbon is finite and varies across ecosystems. Factors such as clay content, mineralogy, microbial community structure, and land-use history determine how long carbon remains sequestered. Therefore, it is not just the quantity but also the stability of sequestered carbon that defines a soil's long-term climate benefit [40, 41].

In essence, soils can either serve as a buffer against climate change or amplify its effects, depending on how they are managed. Enhancing the soil's role as a GHG sink requires a nuanced understanding of these feedback loops and a commitment to practices that minimize emissions while promoting long-term carbon storage [42, 43].

## Mitigation Strategies for Soil Health under Climate Stress

To counter the escalating threat climate change poses to soil systems, a suite of mitigation strategies has emerged—ranging from regenerative farming practices to technological innovations and nature-based solutions. These strategies aim to restore the physical, chemical, and biological integrity of soil while enhancing its capacity to adapt to and mitigate climate impacts. Successful implementation not only preserves soil productivity but also positions soil as a key player in the global climate solution framework [31, 35].

One of the most widely endorsed approaches is conservation agriculture, which emphasizes minimal soil disturbance (no-till or reduced tillage), continuous soil cover through cover cropping or mulching, and crop diversification via rotation or intercropping. These practices improve soil structure, reduce

erosion, enhance water retention, and foster microbial activity, all of which build long-term resilience against climate variability [21, 23].

Organic matter management plays a central role in rebuilding soil health. The application of compost, farmyard manure, and crop residues enriches soil organic carbon, boosts microbial biodiversity, and improves nutrient cycling. Such amendments also buffer temperature extremes and enhance the soil's water-holding capacity—critical attributes in both drought and flood conditions [23, 26].

Agroforestry systems, which integrate trees and shrubs with crops or livestock, offer multifunctional benefits including erosion control, microclimate regulation, biodiversity conservation, and increased carbon sequestration. Perennial root systems improve soil stability and reduce nutrient leaching, while aboveground biomass contributes organic matter over time. Agroforestry is particularly effective in semi-arid and degraded landscapes vulnerable to desertification [27,28].

To further enhance carbon capture, soil carbon sequestration techniques such as biochar application are being explored. Biochar a stable form of charcoal produced from biomass pyrolysis—can persist in soils for decades, improve nutrient retention, and act as a habitat for beneficial microbes. It also helps mitigate nitrous oxide emissions from fertilized soils [29, 30]. Water conservation practices are essential in regions experiencing erratic rainfall or water scarcity. Techniques like contour bunding, swales, mulching, and micro-irrigation help maintain soil moisture, reduce runoff, and prevent erosion. These methods also contribute to temperature moderation and reduce the vulnerability of microbial and root systems to stress [30, 31].

Precision agriculture leveraging GPS, drones, and soil sensors enables real-time monitoring and site-specific management of soil conditions. These tools optimize input use, prevent over-fertilization, and reduce emissions while maintaining or improving yields. Additionally, decision-support systems powered by AI and satellite data can guide farmers toward climate-smart soil management practices [33, 35].

Each of these mitigation strategies can be adapted to regional contexts and integrated into a broader sustainable land management framework. Their success, however, hinges on access to knowledge, technology, financial resources, and supportive institutional and policy environments [38, 39].

### **Policy, Governance, and Community-Based Approaches**

Effective mitigation of climate change impacts on soil health cannot be achieved through technical innovations alone; it requires robust policy frameworks, institutional support, and community engagement at multiple levels. Policies that recognize soil as a vital ecological asset—integral to both climate mitigation and adaptation—are essential for scaling up sustainable practices, incentivizing behavioural change, and coordinating action across sectors and borders [41, 42].

At the international level, agreements such as the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement, and the 4 per 1000 Initiative have placed soil carbon management at the center of climate action. These frameworks promote the sequestration of carbon in agricultural soils as a means of reducing global CO<sub>2</sub> concentrations, while simultaneously improving food security and ecosystem resilience. Other initiatives, such as the UN Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land), emphasize the conservation and restoration of soil health

through integrated land-use strategies [44, 45].

National governments have also begun to respond by launching soil-focused missions and programs. For example, India's Soil Health Card Scheme, the United States' Healthy Soils Program, and the European Union's Soil Strategy for 2030 aim to promote best practices in soil management, provide soil monitoring tools, and financially support farmers who adopt sustainable techniques. However, implementation gaps persist due to inadequate funding, weak enforcement mechanisms, and limited farmer outreach [46, 47].

Community-based and participatory governance models offer powerful mechanisms for localized soil stewardship. Traditional knowledge systems, such as India's Zai pits or Ethiopia's community terracing, have long demonstrated the viability of soil conservation through collective action. When combined with scientific insights and modern technologies, these indigenous approaches can yield context-specific solutions that are both effective and culturally relevant [48, 49].

Land tenure security is another critical governance issue. Farmers are less likely to invest in long-term soil health improvements when they lack ownership rights or face land-use instability. Strengthening legal frameworks for land access and use, especially for marginalized groups such as women and smallholders, can empower more sustainable soil practices and enhance community resilience [50, 52].

Finally, education and awareness campaigns at the grassroots level are indispensable. Extension services, farmer cooperatives, and non-governmental organizations (NGOs) must play a central role in disseminating information, facilitating capacity-building, and fostering behavioural shifts toward sustainable land management [53, 54].

### **Future Perspectives and Research Needs**

As the climate crisis deepens and its impact on soil health becomes increasingly evident, there is an urgent need to chart a forward-looking research and innovation agenda that bridges scientific knowledge, technological innovation, and practical implementation. The dynamic nature of soil systems under changing climatic conditions demands a deeper and more holistic understanding—one that integrates physical, chemical, biological, and socio-economic dimensions in both time and space [33, 35].

A critical future need lies in the development of region-specific soil-climate models capable of predicting the impact of localized climate stressors on soil health. These models should integrate high-resolution data on soil types, land use, cropping patterns, and weather variability to inform adaptive management practices. Coupled with this, there is a growing need for long-term experimental sites and observatories to monitor the cumulative impacts of climate variability on soil properties, microbial communities, carbon dynamics, and nutrient cycles [42, 43].

Another frontier is the integration of traditional ecological knowledge with cutting-edge technologies such as artificial intelligence, remote sensing, and metagenomics. Indigenous land-use systems, often overlooked by mainstream science, have demonstrated time-tested approaches to soil and water conservation under extreme climates. When synergized with modern tools, they can offer hybrid solutions that are both ecologically sound and socio-culturally acceptable [34, 37].

The scaling of nature-based solutions, such as agroforestry, regenerative farming, and organic amendments, requires deeper investigation into their long-term effectiveness under diverse agro-climatic zones. Research must also address potential trade-

offs such as water competition in tree-crop systems or nutrient imbalances from excessive organic inputs that may emerge when scaling up these practices [36, 37].

Another emerging area is the role of soil biodiversity and microbiomes in climate resilience. Advances in molecular biology and systems ecology can unravel the functional roles of microbial communities under stress, opening avenues for bioengineering resilient soil ecosystems or developing microbial inoculants that enhance stress tolerance and carbon storage [31, 38].

Lastly, transdisciplinary collaboration is paramount. Soil science must intersect with climate science, economics, social studies, and policymaking to develop integrated frameworks that guide sustainable soil management at farm, landscape, and global levels. Such collaboration should also prioritize capacity building and youth engagement, ensuring that the next generation of researchers and practitioners is equipped to steward soil resources in a rapidly changing world [39, 41].

## Conclusion

Soil health is both a casualty and a key determinant in the global climate narrative. As climate change accelerates through rising temperatures, erratic precipitation, and intensified extreme weather events, the very foundation of terrestrial life—soil—is undergoing profound transformations. These changes manifest across physical, chemical, and biological domains, undermining soil structure, fertility, biodiversity, and ecosystem services. Left unaddressed, soil degradation under climate stress will compromise food security, water regulation, carbon sequestration, and resilience against environmental shocks.

Yet, within this crisis lies opportunity. Soils, when managed with foresight and care, hold immense potential to buffer the impacts of climate change and contribute meaningfully to mitigation efforts. A diverse array of practices—from conservation agriculture and agroforestry to organic matter management and precision monitoring—offer tangible pathways to restore soil function and enhance resilience. Likewise, science-backed policy frameworks, participatory governance, and the integration of indigenous wisdom can translate innovation into widespread impact.

The future of soil health in a warming world will depend not only on technological advances, but on our collective capacity to foster cross-sector collaboration, long-term stewardship, and inclusive action. By treating soil not merely as a substrate for production, but as a living, dynamic ally in climate adaptation, we can protect this vital resource for future generations. Investing in soils today is an investment in tomorrow's climate stability, ecological integrity, and human well-being.

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