

REVIEW ARTICLE

Adapting Soils to Climate Change: Conservation Strategies for a Resilient Future

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ABSTRACT

Soil represents a three-phase system that acts as a medium for agricultural production. Notably, at present, there were abrupt climate changes like an increase in temperature, a drastic shift in rainfall pattern, precipitation, relative humidity, and many more were noticed, which not only affect plant physiological function, but also for soil individual properties (physical, chemical, and biological) which ultimately hinders crop growth and development leads to limited food production. An increase of 1 degree Celsius was found to increase pest population incidence by 20-30%, reducing yield by 6%. Suitable management practices were crucial for mitigating the effects of climate change. Many studies have focused on management practices for crop health, neglecting the physiological functions and soil management processes. This review briefly emphasizes the significance of the changing climate on various soil individual properties and the suitable mitigation strategies, such as system of farming practices, inter-cropping, crop diversification, cover crops, beneficial microbial amendment, conservation tillage, and other precision technologies, which were involved for better crop production and to sustain the agro-ecological system under a changing climate.

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INTRODUCTION

Though some would sensitize the dual role by emphasizing climate change and its effects on agriculture. For the broader sake, it covers every part of agriculture, including crop production, pest populations, yield dynamics, and, finally, soil health.

Climate change has become one of the most crucial terms worldwide, and it has to be addressed with immediate effect. According to the IPCC's 2023 Sixth Assessment Report, the present-day global temperature of 1.1 °C lies above the pre-industrial

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level and is projected to rise to 1.5 °C by 2050, with a projected increase of 1.8 to 4.0 °C by 2100. The primary causes of climate change include burning of fossil fuels, emissions of GHGs, and increases in CO₂ levels in the atmosphere (Kabir *et al.*, 2023). The detrimental effects of climate change have altered ecosystems and environment (Abbass *et al.*, 2022), agriculture (Venkatesan *et al.*, 2024), and, most importantly, the natural resources, including soil health and fertility status (More *et al.*, 2025; Kabato *et al.*, 2025).

The soil system has been functioning to produce various valuable products, such as food, fibre, and timber, by supporting and linking different ecosystem services (Gangadaran *et al.*, 2025; Gangadaran *et al.*, 2025a). Fig. 1 shows how climate change is interlinked with agriculture, food production, and soil health. These factors directly or indirectly influence the agricultural system and soil health.

The effects of climate change have ruined soil health, thereby limiting agricultural production, thereby increasing the risk of food insecurity. The critics' gap between climate change patterns and agricultural production should narrow, and studies should address this. The direct reflection of climate change towards every ecosystem is well noticed, and it should be minimized in future through

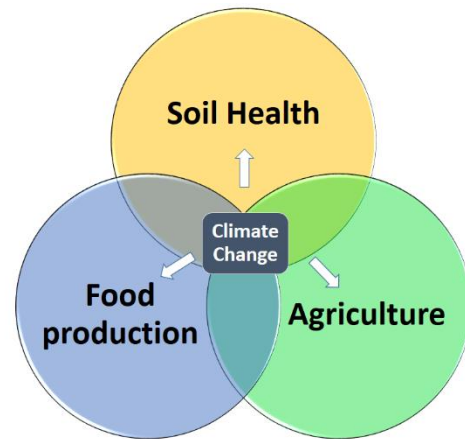


Fig. 1. Triangular perception relating the interrelation of Soil health, food production, and agriculture, and its implications due to climate change

suitable management practices like climate smart agriculture (Zhao *et al.*, 2023), precision farming (Roy and George, 2020), optimisation of resource uses (Erdoğdu *et al.*, 2025), enhancement of crop resilient (Yoselin *et al.*, 2023) and most importantly adjusting date of sowing towards climate. The systematic overview of the effects of climate change on different soil properties was illustrated (Fig. 2). This strongly urges addressing the study gaps represented in this paper.

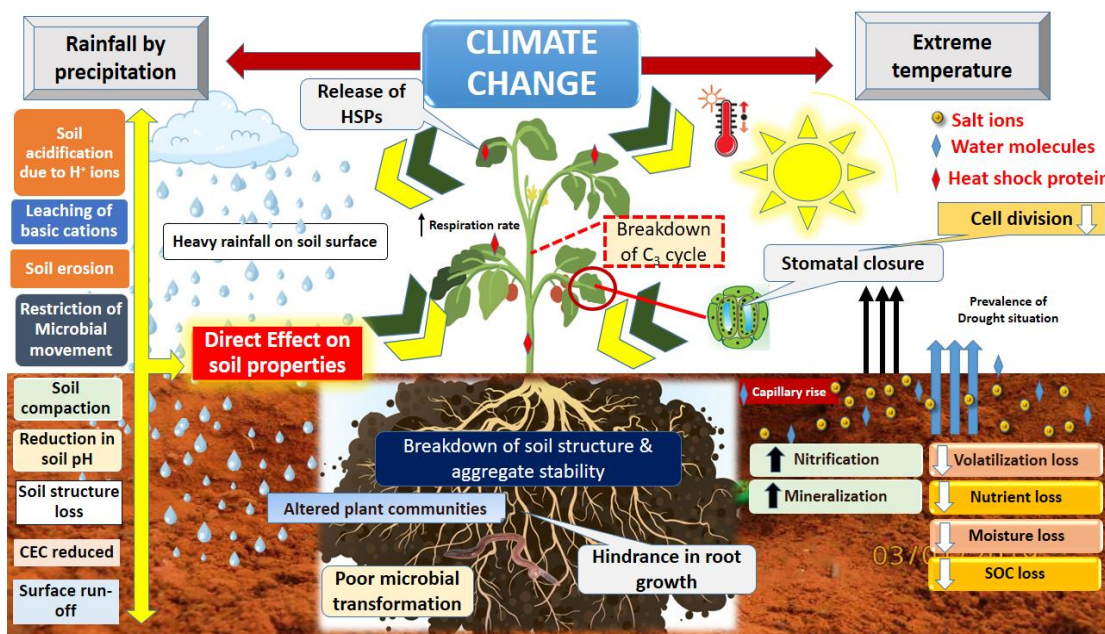


Fig. 2. Overall effect of climate change scenario towards soil physical, chemical, and biological properties and its implication on soil health and crop response

[H⁺ - Hydrogen ions; pH - soil reaction; CEC - cation exchange capacity; HSP - Heat shock protein; C3 - Calvin cycle; SOC - soil organic carbon; Temperature and Rainfall alter soil properties. Due to high temperature, the surface soil moisture gets evaporated at faster rate which influence other nutrient losses like volatilization loss, nutrient loss, and biological property of SOC loss; Due to capillary rise of water, the salt remain to present in soil itself; Other properties also gets reduces due to heavy rainfall of intense pattern and causes compaction, acidic pH, structural loss, CEC gets reduced, surface run-off. Moreover, biological properties of microbial activity are restricted, basic cations are reduced, and surface soil erosion occurs. In the plant system, the C3 cycle gets broken down]

Effect of climate change on soil physical properties

The physical state or properties are a key factor in other soil properties. The majority of research studies focus on soil health, including the application of remote sensing, which serves as a keystone tool for understanding how basic soil formation and physical structure are disturbed by climate change (Diaz-Gonzalez *et al.*, 2022). The effect of climate change had a direct impact on soil due to changes in temperature

(John *et al.*, 2019), precipitation patterns, and, most importantly, intensified weather events within a short span of time (Mondal, 2021). One of the critical factors is moisture content dynamics. Since it was strongly hampered by changes in climate, precipitation, and temperature fluctuations. Both adverse temperatures and severe rainfall can affect and disturb the microbial population and its regular activities in the Rhizosphere. Due to erratic, continuous rainfall, the soil undergoes a reduced condition, thereby all pores (macro and micro) are filled with water, which affects gaseous flow and heat exchange for both the soil and microorganisms. This affects the aggregate stability of the soil system (Zhu and Zhao, 2023). Although, due to the effect of climate change, which has a direct effect on soil compaction (Hamidov *et al.*, 2018).

Intensified rainfall is prone to heavy runoff, which triggers soil erosion, thereby washing away the top-layer of fertile soil; hence, crops are set back in nutrient uptake. Sometimes, strong winds can remove the top 5cm of dry soil and minimize vegetative land cover, which leads to poor soil productivity (Du *et al.*, 2019). Normally, climate change imposes significant constraints on soil physical health, which are further multi-linked with other soil factors like chemical and

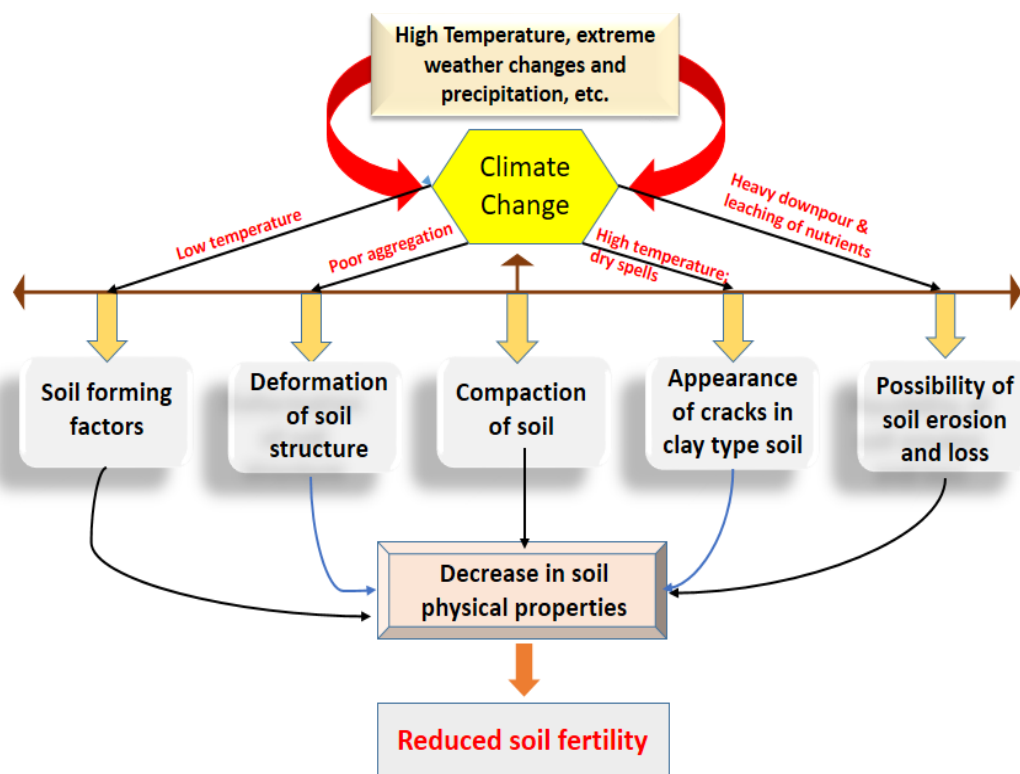


Fig. 2. Different pathways involving climate change affecting soil physical properties and fertility

biological properties. (Adimassu *et al.*, 2018) also suggested that research using traditional methods following tillage practices will lead to surface runoff and erosion of the top soil. Overcoming climate change will be more effective through the effective utilisation of conservation tillage or zero tillage, thereby minimizing negative effects and maintaining soil and crop productivity.

Effect of climate change on soil chemical properties

Soil chemical properties, which are affected by climate change and weather, are setbacks to soil fertility. Most chemical properties, i.e., soil reaction, are governed by soil moisture and temperature. Thermodynamics plays a critical role in the completion of every reaction. During intense rainfall, all the basic cations are washed and leached from the soil (Fig. 3), leading to soil nutrient loss. Through changes in temperature and precipitation patterns, which directly affect and alter soil reaction (pH) and nutrient availability. The anticipated effect of temperature directly influences different soil factors, including soil temperature, soil moisture content, and, most importantly, soil organic matter decomposition (Hamidov *et al.*, 2018). Due to high temperatures amid climate change, rapid decomposition of organic matter

occurs, thereby facilitating the release of organic acids such as nitric acid, oxalic acid, and formic acid, leading to increased soil acidification (Barros *et al.*, 2021; Zhang *et al.*, 2023). Both adverse climatic conditions, such as extreme drought, and long-term precipitation patterns would simultaneously affect soil salinization and soil acidification (Molin *et al.*, 2020). According to (Sun *et al.*, 2023), a study conducted at grassland regions on the Tibetan Plateau revealed that under climate condition, the percent of 45.52%, 44.49% and 21.43% of the study area at three different depth of 0–10, 10–20 and 20–30 cm were recorded acidic situation and this might be due to both climate change scenario and anthropogenic activity. Soil electrical conductivity is the total dissolved salts present in the soil solution and also serves as a biological indicator of where microorganisms thrive (Muhilan *et al.*, 2025). But due to climate change, with increased temperatures and altered precipitation patterns (Gangadaran *et al.*, 2025b), the range of soil EC increases, and over time, higher temperatures cause water molecules to evaporate, leaving salt in the soil, which hampers crop production. CEC is the second most important chemical reaction in the plant system, following to photosynthesis, as it exchanges cations like (Ca^{2+} , Mg^{2+} , Na^+ , K^+) to the plant outer surface

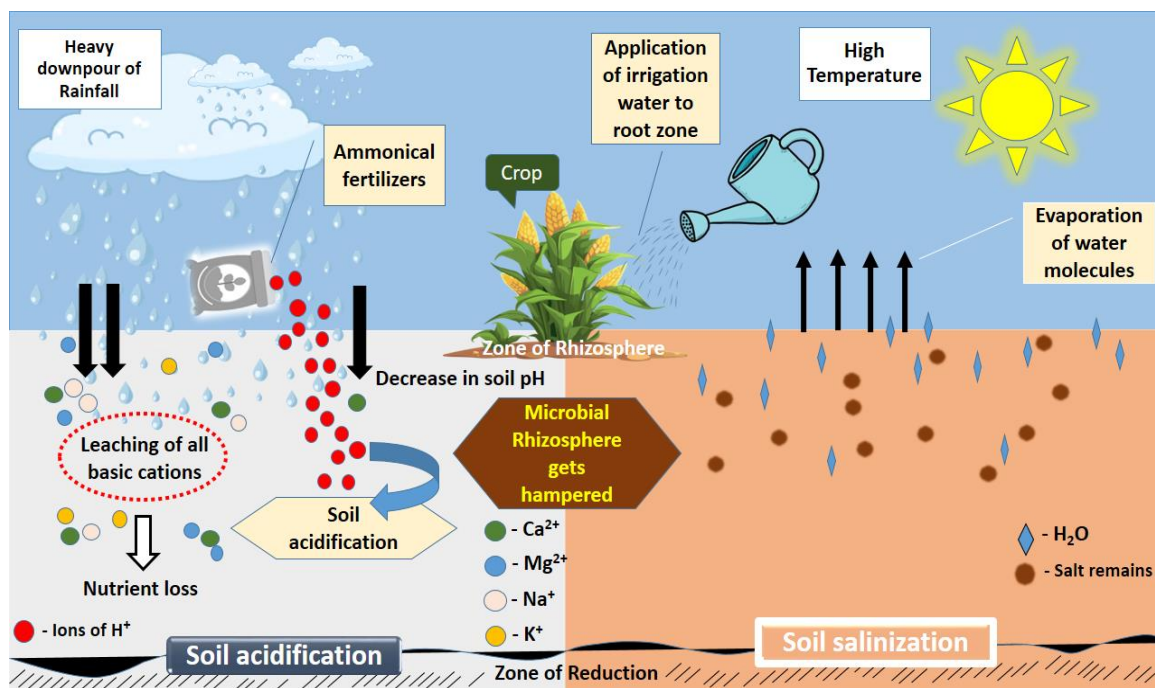


Fig. 3. Effect of Climate change dynamics on soil chemical properties and its implications for soil health and productivity

and exchanges other cations. Most of the soil under alluvium is highly correlated to soil organic matter. Hence, increased atmospheric temperature increases the rate of decomposition, thereby accelerating the CEC reaction in soil (Muhilan *et al.*, 2026). Also, every cycle involving C, N, P, S, and water was thus adversely affected by climate change and global temperature. Hence, as a holistic behaviour, climate change behaviour hampers chemical reactions and thus adversely affects the soil ecosystem.

Effect of climate change on soil biological properties

These climate change patterns modify the cycles of hydrology (water), nitrogen, phosphorus, sulphur, etc. The microorganisms were the active living bodies responsible for various nutrient transformations, carbon sequestration, and cycling in the soil system (Cavicchioli *et al.*, 2019). Drastic fluctuations in soil pH due to climate change and precipitation patterns hampers microbial activity across a wide range, and each organism requires a particular pH at which it can thrive and participate in nutrient transformation without loss (Sun *et al.*, 2023). Several model-based simulation studies were recently used to predict the effect of climate change on crop performance (Muhilan and Bagavathi Ammal, 2025), which predict linear stream flow generation by minimizing human error and prolonged surveys, thereby determining in a faster way (Ansari *et al.*, 2023). Emphasizing simulation modelling in climate change, which helps in dispelling through climate-based modelling, which involves calibration, validation, weather parameter conversion, and generation of data without involving manpower (Giorgi, 2019; Tsujimoto *et al.*, 2022; Masud *et al.*, 2018; Ahrens and Dobler, 2015; Challinor *et al.*, 2009). The prevalence of top fertile soil is characterized by higher humus content, where microbial activity is more abundant, but amid leaching of top fertile soil due to heavy rainfall patterns and intensification, the fertile soil gets washed away, thereby limiting crop growth and development. Repeated and unfavourable conditions of short, hot days and long, humid days affect microbial respiration rates. Since microbial respiration is essential for the carbon cycle, this cycle favours soil organic carbon and stock determination. Due to changing weather, intensified rainfall, heat stress, and wind speed, soil organic carbon stocks can change. There are two main types of soil organic carbon in the soil system. It includes mineral-associated organic carbon (MAOC) and particulate organic carbon (POC),

which drive soil structure, water retention, and nutrient availability. But altered atmospheric temperatures and global warming hinder activity, thus delimiting the soil system and crop function. A critical examination study conducted by Rocci *et al.* (2021) revealed that atmospheric CO₂ emissions and increased input of nitrogenous fertilizers from farmers might be the major reasons affecting soil SOC stocks, and that the change in POC was more responsive to global climate change, he supposed.

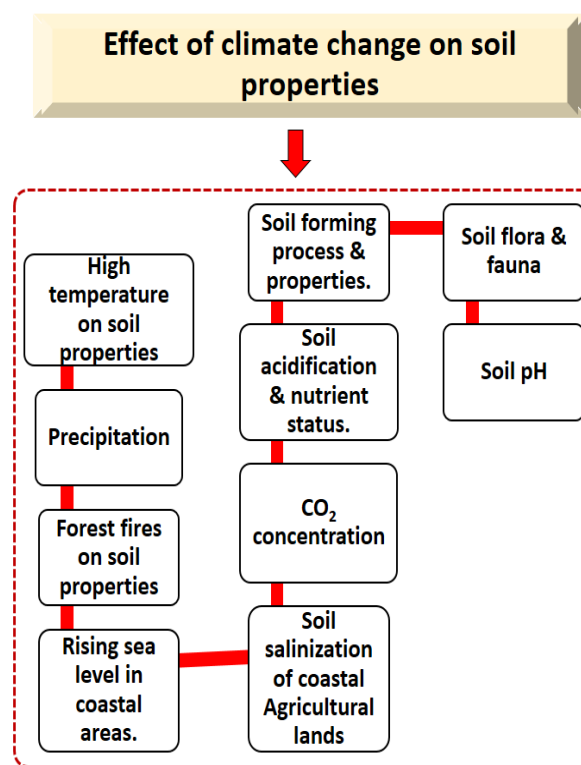


Fig. 4. Overall effect of Climate change on soil properties

Mitigation strategies

Various management practices, including farming practices, intercropping, crop diversification, cover crops, beneficial microbial amendment, conservation tillage, and other precision technologies, were adopted to improve soil-plant response in the face of climate change. The various aspects of the management schedule were given in Table 1.

Conclusion

Healthy soil provides healthy food, which in turn supports ecological diversity, nutrient recycling, decomposition of soil organic matter, sequestering of organic carbon, and resilience against natural pests



Table 1. Various aspects of the management process for soil sustainability and crop production

SI. No	Methodology employed	Main benefits	Output about sustainability	References
1	Precision irrigation management	Potential use of water	Optimizing water-use-efficiency, minimizing water waste, reducing nutrient leaching and soil erosion, and improving soil structure	Kaur <i>et al.</i> (2025)
2	Optimising fertilizer application (Site-specific nutrient management)	Reducing the over-addition of inorganic fertilizers	Precisely adjusting fertilizer doses based on soil tests to meet a specific crop yield target, thus optimizing fertilizer use, increasing yield, and minimizing environmental impact.	Sakthi Priyanka <i>et al.</i> (2024)
3	Atmospheric carbon dioxide level monitoring sensor using low-cost NDIR (Non-Dispersive Infrared) sensors	Monitor soil carbon dynamics.	Understand soil health, carbon turnover, and the impact of agricultural practices.	Ko <i>et al.</i> , (2020)
4	Nutrient management by STCR-IPNS	Enhances nutrient use efficiency and eliminates overdosing on the on-field application	Optimizing fertilizer use for targeted crop yields, which improves soil health and nutrient cycling, and promotes integrated nutrient management with organic amendments	(Koushal <i>et al.</i> , 2025)
5	Hyper-spectral drone sensors	Availing soil data at a faster rate without manpower.	Enabling precision agriculture through detailed soil property monitoring (e.g., moisture, nutrients) and crop health assessment	Vahidi <i>et al.</i> (2025)

and diseases. Increasing anthropogenic activity is a crucial driver of abrupt change, and if this trend continues, the world's agricultural production will face a food shortage in the near future. The management practices not only support agricultural production, but should also promote long-term sustainability. Hence, soil, as a system, functions better through interactions among its physical, chemical, and biological properties. Better agronomic practices like crop rotation, intercropping, cover cropping, no-till farming, and precision farming were employed to boost production, and neglecting any one of these factors will suppress the system. Future studies must rely on soil development, emphasizing holistic approaches that encompass climate change, weather pattern prediction, crop timing, crop patterns, and soil amendment using microsensors for better prediction. Simulation studies through empirical models like DNDC, Random Forest, Cubist, Info Crop, RothC were effectively help understand the prediction of climate change and offers potential solution for soil system in decomposition, effect of temperature, precipitation change etc., thus, a holistic modelling approach along with soil properties will aims to mitigate climate change thus improves soil health and ecosystem sustenance.

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Data Availability Statement

Data sharing does not apply to this article

Conflict of Interest or Declaration of Competing Interest

The authors declare that there is no conflict of interest with the present publication.

Consent for Publication

All authors have agreed to the publication of this content.

Credit Authorship Contribution Statement

G. Muhilan: Investigation, formal analysis, writing - original draft. U. Bagavathi Ammal: Validation, methodology, writing-reviewing. Elavarasi P: Resources, investigation writing - reviewing. V. G. Venkatesan - Investigation, writing - reviewing. A. Akash: Investigation, writing - reviewing,

Ethics Statement

No humans or animals was used in our study

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