PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–12
https://doi.org/10.14719/pst.5598

HORIZON
e-Publishing Group
HePG

REVIEW ARTICLE

Resilient soils for a changing climate: Navigating the future of sustainable agriculture

Rashmi MR [1], Gopalakrishnan M [1*], Rajeswari R [1], Senthil Kumar M [2], Kavitha M [3], Maragatham S [1]

[1]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Vegetable Science, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: gopalakrishnan.m@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 07 October 2024
Accepted: 06 November 2024
Available online
Version 1.0 : 31 December 2024

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Rashmi MR, Gopalakrishnan M, Rajeswari R, Senthil KM, Kavitha M, Maragatham S. Resilient soils for a changing climate: Navigating the future of sustainable agriculture. Plant Science Today.2024;11 (sp4):01-12. https://doi.org/10.14719/pst.5598

Abstract

Climate change poses a critical threat to global food security and ecosystem sustainability, with soils serving as the backbone of the Earth's ecosystems. This comprehensive review synthesizes the current understanding of how climate change impacts soil health, emphasizing the intricate interactions between soil's physical, chemical, and biological properties. Rising temperatures, altered precipitation patterns, and increasingly frequent extreme weather events severely degrade soil structure, reduce fertility, and disrupt biodiversity. These changes accelerate soil erosion, nutrient depletion, and significantly diminish agricultural productivity. This review explores innovative strategies to enhance soil resilience, with a focus on conservation agriculture, cover cropping, and integrated nutrient management. Conservation agriculture practices improve soil structure and enhance water retention, while cover cropping increases soil organic matter and supports critical nutrient cycling processes. Integrated nutrient management ensures a balanced supply of essential nutrients and promotes beneficial microbial activity, further bolstering soil health and resilience. The importance of adopting a holistic, resilience-based approach to soil management to soil management is vital to mitigate the adverse effects of climate change, preserve vital ecosystem services, and secure sustainable agricultural productivity for future generations. This review provides critical insights for policymakers, researchers, and practitioners, offering practical solutions to safeguard soil health and ensure food security in the face of the challenges posed by a rapidly changing climate.

Keywords

climate change; deforestation; resilience; soil conservation; soil health

Introduction

Climate change significantly impacts soil health, influencing soil formation, structure, and composition. These effects manifests as changes in soil texture, porosity, and its physicochemical and biological components (1). Rising atmospheric carbon dioxide (CO_2) concentrations, global temperatures, and shifting precipitation patterns adversely affect soil's physical and biological properties, thereby disrupting its functioning and biogeochemical cycling processes (2). Furthermore, climate change alters critical soil characteristics such as acidity, sodicity, and salinity, which negatively affects crop production and overall soil health. These changes in soil properties also play a crucial role in the spread and management of neglected tropical diseases and vectors. Additionally, microbial interventions have shown potential for enhancing soil resilience and fertility under changing climate scenarios (3).

Climate change impacts soil health by influencing soil water retention, organic carbon content, erodibility, and long-term processes such as pedogenesis. Soil degradation due to these factors results in reduced crop yields, loss of biodiversity, and increased vulnerability to extreme weather events, such as floods and droughts. These effects pose significant challenges to the sustainable utilization of agricultural land. For instance, rising sea levels, higher temperatures, decreased precipitation, and poor irrigation practices contribute to increased soil salinity, which exacerbates soil degradation caused by climate change (4). Reduced soil organic matter, alterations in soil structure, and increased susceptibility to erosion further amplify these challenges, compromising nutrient cycles, plant growth, and crop quality (Fig. 1) (5).

The drivers of climate change are multifaceted, with the primary factor being the rise in greenhouse gas emissions, leading to global warming. Other contributors include variations in solar activity, such as fluctuations in sunlight intensity (6). Changes in Earth's orbit and volcanic eruptions also influence global climate patterns. Human activities, particularly the release of aerosols, significantly affect the climate system through radiative forcing and interactions with cloud formation. These factors can either amplify or mitigate the Earth's response to climatic influences, with feedback mechanisms playing a crucial role in shaping the overall impact (7). Thus, climate change is a multifaceted phenomenon arising from a combination of natural and human-induced factors.

Impact of climate change on plant health

Rising global temperatures and increased concentrations of greenhouse gases significantly influence crop growth and the spread of phytopathogenic agents. Changes in temperature and precipitation regimes can alter the growth rate and pathogenicity of infectious agents, as well as the resistance of host plants (8) (Fig 2). Furthermore, climate change impacts disease management practices, including the timing, preference, and efficacy of control measures (9).

Temperature and precipitation variations can affect the performance of chemical control methods by changing the dynamics of fungicide, such as residue levels and product degradation rates (10). Additionally, the efficacy of climate chemical pesticides and the persistence of plant protection agents in the phyllosphere are susceptible to climatic changes (11).

To address these changes, it is important to develop new tools and strategies for disease control, including cultural methods, biological control methods, and plant breeding techniques. Encouraging the use of indigenous microbial communities can also play a role in maintaining plant health under changing climatic conditions.

Crop growth, yield and quality

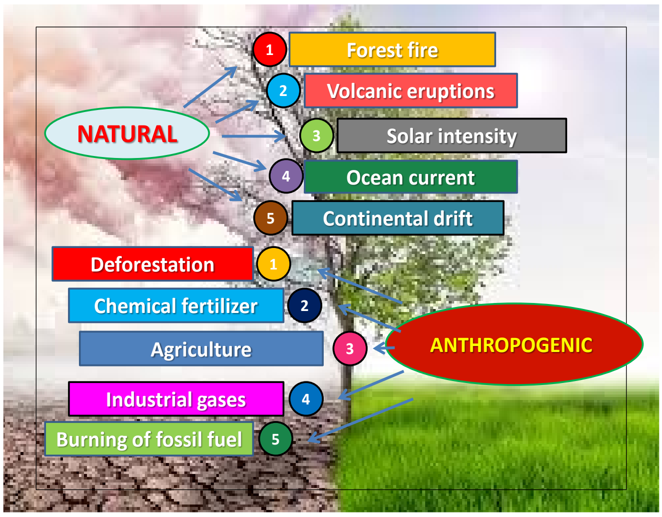

Fig.1. A schematic representation of the both natural and anthropogenic source affecting soil health (This picture is created)

Rising temperatures, reduced water availability, flooding, and salinity are significant factors that restrict the yields of vegetable crops. Climate change also affects the distribution and ecology of insects, their ability to overwinter, and the emergence of pests and diseases, all of which pose significant challenges to the production of vegetables. Ozone pollution and climate change particularly threaten future crop yield, especially in important agricultural regions, which could result in a substantial loss of wheat yield (12).

Abnormal climatic conditions during harvest and post-harvest stages have the potential to diminish the morphological, physiological, and biochemical quality of seeds, ultimately impacting their field performance and planting value. Extreme weather events such as heat waves, droughts, floods, and irregular precipitation patterns have a profound impact on existing agricultural cropping systems, productivity, and global food security. To mitigate these effects, adaptation measures such as breeding climate-resilient crops and implementing agronomic practices are necessary.

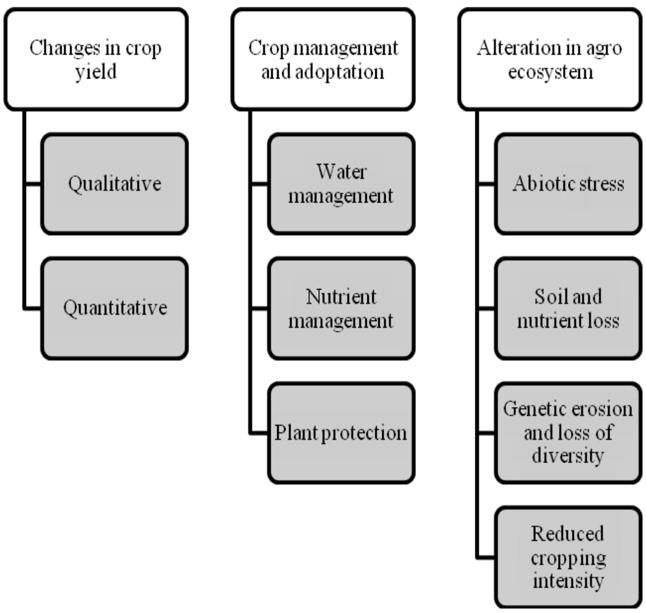

Fig.2. A schematic representation that describes how plant health is affected by climate change

Climate change also exerts a substantial influence on quality of plants, thereby impacting a wide range of crops and their cultivation. For horticultural crops, factors such as rising temperatures, atmospheric CO_2 levels, ozone depletion, UV radiation, heavy metal toxicities, extreme weather events, and changes in precipitation patterns have led to significant physiological and biochemical changes (13). Similarly, in vegetable crops, climatic elements such as light, temperature, drought, salinity, and flooding play pivotal roles in determining the quality and nutritional value of crops. Heat stress, for example, poses a severe threat to cole crops namely cabbage, cauliflower, broccoli, and Brussels sprouts, as it hinders curd setting and compromises product quality.

The implications of climate change extend to seed quality, where factors like temperature and water availability directly influence seed development and germination. This can result in a decline in both the quantity and quality of seeds produced (13).

Wheat production is particularly vulnerable to climate change, with higher temperatures projected to reduce wheat yields by 6% to 23% by 2050. Altered rainfall patterns further exacerbate water availability issues for wheat cultivation. Similarly, rice farming faces significant challenges as increased temperatures and variability in precipitation negatively affect yields, potentially reducing global rice production by 10% to 15% by 2050 (14).

Corn, another globally important crop, is highly susceptible to rising temperatures and extreme weather events like droughts and heat waves, which could lead to a 22% to 49% decrease in corn yields by 2050. This highlights the urgent need for adaptive measures in agriculture. Soybean production is also at risk, with higher temperatures and altered precipitation patterns expected to result in an estimated 3.1% decrease in global soybean yields by 2050 (15). Understanding these effects is crucial for finding ways to reduce the impact of climate change on soybean farming.

Effect of climate change on physiological functions in plants

Climate change substantial influences the physiological functions of plants, encompassing plant growth rate, productivity, and defense mechanisms (16). These effects are evident across various types of crops, including vegetables. Broadly, the impacts of climate change on plants manifest as alterations in metabolic processes, reductions in nitrogen-based defences, imbalances in organic acid levels, weakening of plant defence systems against pests, and disruptions in critical physiological processes.

Furthermore, climate change has the potential to modify plant-microbe interactions, which are vital for essential functions such as nutrient cycling, carbon sequestration, and plant immunity. Such changes can impair the overall health and resilience of plants, affecting their ability to adapt to environmental stressors.

Overall, climate change poses substantial challenges to the physiological functions of plants, influencing their growth, productivity, and interactions with the environment. These challenges necessitate further research and innovative solutions to mitigate the adverse effects of a changing climate on plant systems

(17).

Nutrient uptake and utilization

Elevated levels of greenhouse gases, such as CO_2, nitrous oxide (N_2O) and methane (CH_4), have the potential to alter precipitation patterns and disrupt nutrient cycling, thereby affecting nutrient uptake by plants. The combined effects of increased CO_2 concentration and warming of the plant canopy influence the concentrations and movement of nutrients within plants. Excessive CO_2 levels can reduce the availability of essential nutrients, such as iron (Fe), zinc (Zn), and protein, in vegetable crops, thereby impacting their nutritional quality (18). Additionally, elevated temperatures can alter plant-herbivore interactions, potentially affecting plant chemistry and promoting the growth and nutrition of specific herbivorous species (19).

Climate change significantly affects nutrient dynamics in plants, leading to changes in nutrient concentrations and translocation. Elevated CO_2 levels reduce potassium (K) concentrations in plant shoots and roots, while canopy warming increases nitrogen (N), phosphorus (P), and potassium (K) levels in shoots but decreases these nutrients in roots. Furthermore, higher CO_2 levels are associated with lower Fe, Zn, and protein levels in vegetable crops, raising concerns about food security (20).

Hydrological and temperature changes induced by climate change also impact nutrient dynamics on global scale. Extreme precipitation events increase nutrient leaching and transport through overland flow, which can adversely affect soil fertility and water quality. Overall, climate change alters nutrient availability, plant nutrient uptake, and nutrient cycling processes, thereby influencing plant growth, crop yields, and ecosystem sustainability.

Impact of climate change on soil health

Climate change significantly affects soil health by altering its physical, chemical, and biological properties, which, in turn, influence essential soil processes and functions. Changes in temperature, precipitation, and atmospheric composition, including increased greenhouse gas concentrations and nitrogen deposition, have direct and indirect impacts on soil health. Soil organic matter (SOM) serves as a critical indicator of soil health, with its maintenance being vital for mitigating rising atmospheric CO_2 levels (16). Furthermore, climate change influences soil development, structure, texture, water retention capacity, and its ability to sustain crop productivity (Fig. 3). Understanding the interplay between climate change and soil health is crucial for predicting and managing the spread of soil-associated diseases and vectors. Given the fundamental role of soil health in ensuring food security, crop production, and human well-being, the adoption of climate-smart agricultural practices that enhance soil health and mitigate the adverse effects of climate change is imperative.

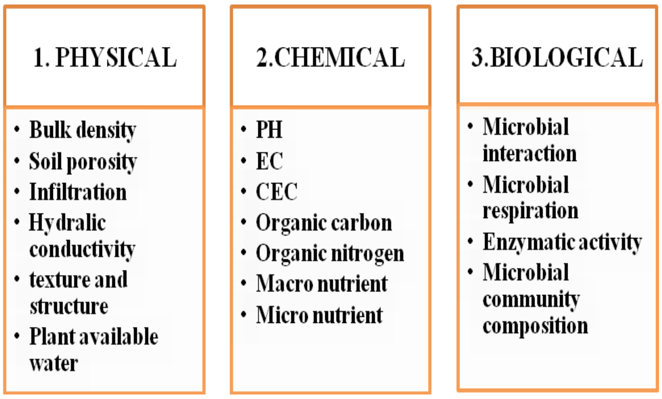

Fig.3. A schematic representation of indicators/properties to assess soil health

Physical properties

Climate change alters precipitation patterns, including changes in rainfall intensity, frequency, and distribution. These shifts affects the temporal and spatial availability of soil water, impacting soil moisture levels and, consequently, the dynamics of soil processes (21). For instance, studies (22) highlight that intensified heavy rainfall events in certain regions increase risks of soil erosion and nutrient leaching. Changes in precipitation patterns directly affect soil water content and infiltration rates. Extreme precipitation events often lead to rapid surface runoff, reducing water infiltration and increasing the risk of soil erosion. These findings underscores the importance of understanding how precipitation changes influence soil water dynamics and the urgent need for sustainable land management practices to mitigate soil erosion risks.

Precipitation variability also impacts soil structure and stability. Drought conditions caused by reduced precipitation can result in soil compaction, decreased porosity, and increased susceptibility to erosion. Research (23) emphasizes the need of adaptive soil management practices to maintain soil structure and prevent degradation under changing precipitation regimes.

Precipitation changes have cascading effects on plant-soil water relations. These alterations influence plant water uptake, affecting plant growth, nutrient availability, and overall ecosystem productivity (Table 1). A study (24) demonstrated how precipitation changes impact eco-hydrological processes, highlighting the interconnected nature of vegetation dynamics and soil water availability. Climate change also affects plant phenology, growth patterns, and distribution, subsequently altering the composition of root exudates and plant litter. These changes impact soil microbial communities and nutrient cycling processes. Disruptions in plant-soil interactions can lead to cascading effects on soil biodiversity and ecosystem functioning. A study explored the intricate links between plant-soil interactions, climate change, and soil biodiversity (25).

Unsustainable land management practices and soil degradation exacerbated by climate change can further modify structure of soil, deplete organic carbon, and diminish soil's capacity to retain water and nutrients (Table 2).

Chemical properties

Climate change significantly influences the chemical properties of soil, altering parameters such as pH, electrical conductivity (EC), and cation exchange capacity (CEC). Rising temperatures, elevated atmospheric CO_2 levels, and changes in rainfall patterns can modify soil pH, disrupt nutrient uptake, and indicate salinity issues through changes in EC, all of which can adversely impact crop productivity. The CEC, which governs the soil's ability to hold and release essential nutrients, is also affected, influencing plant growth and ecosystem stability (26). These alterations can lead to soil acidification, sodicity, and salinization. Moreover, climate change drivers, including elevated CO_2, temperature, nitrogen deposition, and altered rainfall, significantly impact soil processes and nutrient availability (27). Altered soil properties can also impact the diversity and composition of soil organisms, potentially leading to the identification of novel species capable of adapting to climate-induced changes. Collectively, these changes highlights the profound impact of climate change on soil chemical properties and the overall health and productivity of soil ecosystems (28).

Climate change particularly affects soil pH, temperature, CO_2 levels, and rainfall patterns can change soil pH. Higher temperature and acidic rainfall contributing to soil acidification, while other climate may cause alkalization. Shifts in pH directly impact soil health, productivity and key soil processes (29). Variations in temperature and precipitation influence organic matter formation, soil water regimes, and mineral composition, which, in turn, affect pH levels. Changes in soil pH significantly influence

Table 1. Effect of climate change on soil physical parameters

Soil Physical Parameter	Effect of Climate Change	Reference
Bulk density	Increases due to loss of soil organic matter	(71)
Porosity	Decreases due to compaction from heavy rainfall	(72)
Aggregate stability	Declines due to disruption of soil aggregates from extreme weather events	(73)
Infiltration rate	Reduces because of surface sealing and soil crusting	(17)
Water holding capacity	Decreases owing to loss of organic matter and structural stability	(74)
Hydraulic conductivity	Diminishes due to compaction and poor structure	(75)
Aeration	Lessens due to flooding and water logging	(76)
Texture	Coarser texture over time in some regions because of wind and water erosion	(77)
Depth of topsoil	Shallower due to accelerated erosion processes	(78)
Organic matter content	Declines because of increased mineralization rates and loss through erosion	(79)

Table 2. Effect of soil physical parameters with high and low levels of climatic variations

Factor	High Level	Reference	Low Level	Reference
Temperature	Above 2°C over pre-industrial levels	(80)	Below 1°C over pre-industrial levels	(81)
Precipitation	20% above baseline/average	(82)	20% below baseline/average	(83)
Moisture Content	>30% relative humidity	(84)	<15% relative humidity	(85)
Sea Level	> 3 mm/year rise	(86)	< 1 mm/year rise or fall	(87)
UV Radiation	>295 m W/m^2	(88)	<285 m W/m^2	(89)
Greenhouse Gases	>450 ppm CO_2 equivalent	(90)	<350 ppm CO_2 equivalent	(91)

microbial activity and the cycling rates of carbon and nitrogen, as these processes depend on net primary production and substrate availability. Additionally, climate change exacerbates metal toxicity in polluted soils, particularly in drier regions. Metal toxicity, however, varies among soil types depending on pH and metal concentrations. Changes in climate also affect metal availability and accumulation in soils, influencing plant and soil health (30). Climate change has notable effects on soil electrical conductivity (EC). Altered temperature and precipitation patterns can modify soil organic matter content, which directly impacts EC. Rising temperatures may increase EC, though compost application has been found to mitigate the effects of temperature changes on soil properties (31). Similarly, climate change impacts soil chemical properties such as cation exchange capacity (CEC) and organic matter content, both of which are crucial for maintaining the productivity and environmental quality of cultivated land (32). Increased organic carbon (OC) and higher cation exchange capacity (CEC) levels have been shown to reduce the availability and solubility of heavy metals, such as Pb, in contaminated soils. Climate change has also resulted in the loss of soil organic carbon (SOC) in agricultural topsoils worldwide. The implementation of agro-ecological practices such as conservation agriculture, organic agriculture, and the utilization of organic waste materials holds great potential to enhance SOC stocks and mitigate climate change impacts (33). The response of SOC mineralization to rising temperatures, reduced soil moisture, and drying rewetting cycles emphasizes the need for a comprehensive understanding of SOC dynamics in the context of climate change (34) (Fig.4).

Changes in climate patterns, including surface greening observed in China, have altered SOC dynamics in top soils, where carbon input from vegetation plays a pivotal role in mitigating the effects of climate change on SOC. Additionally, climate warming influences the soil carbon pool by increasing SOC content and affecting components of labile organic carbon.

Heavy rainfall accelerates nutrient leaching, decreases soil pH, and reduces organic matter content, thereby impacting nutrient availability. Soil microorganisms play a vital role in transforming nutrients into forms readily accessible to plants. For instance, microorganisms can convert insoluble forms of phosphorus into soluble forms that plants can absorb. Since nutrient cycles are interdependent, imbalances in one nutrient can affect the availability and absorption of others. Balanced fertilization, influenced by soil pH, organic matter content, microbial activity, and CEC, is essential to ensure optimal nutrient availability and maintain soil health.

Biological properties

Climate change significantly impacts the diversity of soil organisms, potentially revealing new characteristics or species that are capable of adapting to these changes. The diversity and distribution of soil microorganisms play a critical role in regulating the biological properties and processes of soil (35). Variations in climate, such as heightened temperatures and increased greenhouse gas concentrations, can affect the microbial communities residing in the soil (36). Additionally, soil moisture content influences the habitats of microorganisms, particularly fungal communities. By incorporating the dynamics of soil structure into models, more comprehensive predictions can be made regarding the impacts of climate change on the hydrological and biogeochemical cycles of soil.

An increase in soil temperatures directly influences microbial metabolism. Optimal soil temperatures (around 20-30°C) enhance microbial processes such as respiration and nutrient mineralization, while extreme temperatures (above 35°C or below 10°C) can inhibit microbial activity, impacting microbial diversity, nutrient cycling, decomposition, and ultimately soil fertility and plant

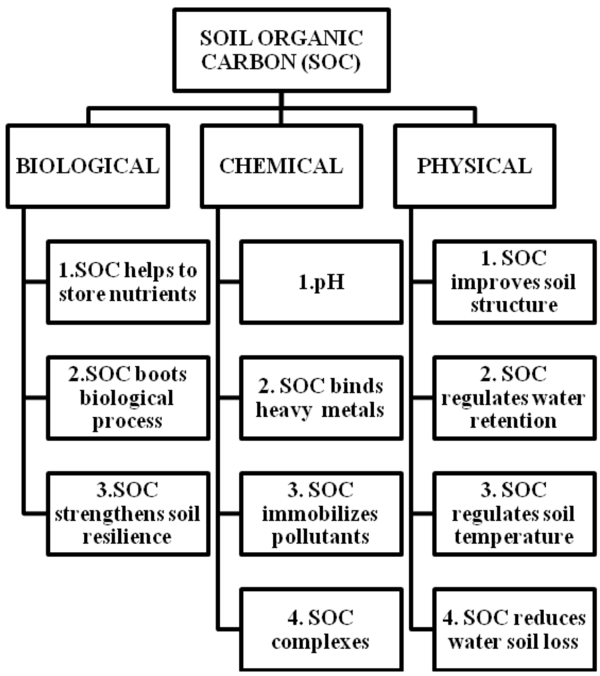

Fig.4. A flowchart representation of soil organic carbon and its significance in agriculture

growth(37).This increased metabolic activity can impact carbon and nitrogen cycling within the soil. Studies have demonstrated a positive correlation between temperature and microbial respiration rates, indicating a heightened release of carbon dioxide as a by- product of microbial activity. The carbon content of microbial biomass in various soil types ranged between 3 and 349 mg/kg of soil (38). Climate change thus modifies the composition and activity of soil microbes.

Temperature, moisture, and carbon dioxide levels significantly affect microbial diversity, abundance, and essential functions such as nutrient cycling and organic matter decomposition. Rising temperatures accelerate microbial metabolism, enhancing these processes, but exceeding optimal temperature ranges may harm beneficial microbes, reducing soil fertility. Changes in precipitation patterns impact soil moisture, with excess rainfall favoring anaerobic microbes and drought limiting microbial diversity and nutrient cycling. Increased CO_2 enhanced plant photosynthesis and microbial activity but may dilute nutrients and alter soil chemistry.

Microbial diversity is essential for ecosystem resilience and functions like nutrient cycling and disease suppression. Climate change poses a threat to this diversity, jeopardizing soil health and ecosystem services, which calls for careful management. Soil microbes are highly sensitive to climate change, leading to shifts in microbial communities with implications for soil functions. Heat-tolerant microbes may become dominant with rising temperatures, altering nutrient cycling and organic matter decomposition. Changes in precipitation and temperature also affect fungal communities, which are essential for nutrient cycling and plant interactions. Climate change thus impacts both fungal communities and overall soil biodiversity (39). Soil fauna, including earthworms and arthropods, are also affected by climate change, influencing nutrient cycling and soil structure. Furthermore, climate change alters biogeochemical processes in soil, such as nutrient availability and greenhouse gas emissions (40). These changes in environmental conditions create feedback loops that amplify the effects of climate change. Soil biodiversity plays a crucial role in soil biogeochemistry and climate change.

Impact on soil organic matter decomposition

The decomposition of soil organic matter is a critical process for nutrient cycling and carbon sequestration. Elevated temperatures can influence the rates of organic matter decomposition, with potential consequences for soil fertility (41) (Fig.5). Studies by (42) have observed an acceleration in the decomposition of soil organic matter under elevated temperature conditions, suggesting the potential release of stored carbon into the atmosphere. Soil microorganisms play a crucial role in regulating soil moisture dynamics, and changes in precipitation patterns significantly influence microbial activity, which in turns affects nutrient cycling and organic matter decomposition. Specific microorganisms, such as *Pseudomonas* and *Bacillus* bacteria, as well as *Aspergillus* and *Trichoderma* fungi, are particularly sensitive to variations in temperature and moisture. *Pseudomonas* bacteria enhance nutrient cycling by breaking down complex organic compounds, while *Bacillus* bacteria solubilize nutrients like phosphorus, making them available for plant uptake. Fungi like *Aspergillus* decompose lignocellulosic materials in wet conditions, facilitating nutrient release, and *Trichoderma* promotes plant growth by enhancing organic matter decomposition(43). It is important to emphasize the significance of understanding microbial responses to changing moisture conditions for predicting soil carbon dynamics and nutrient cycling in a changing climate.

Soil Resilience

Soil resilience plays a crucial role in addressing the effects of climate change on agriculture. Studies have demonstrated that high quality soils can mitigate the sensitivity of crop yield to climate variability, resulting in increased average crop yields and greater yield stability (44) (Table 3). Climate change impacts, such assoil erosion and alterations to environmental conditions, further complicate these challenges. Therefore, developing innovative and feasible solutions is imperative for fostering resilient landscapes amidst climate change (45).

Microbial interventions have shown promise in enhancing soil resilience and promoting crop growth under changing

Table 3. The impact of soil health and its resilience by parameters of climate change

Parameters	Impact on soil health	Building resilience	Reference
Higher temperatures	Loss of organic matter, altered biology	Increase carbon inputs to soils, promote soil biological buffering of temperature increase	(92)
Changing precipitation	Increased erosion, nutrient leaching, runoff	Improve water infiltration, storage and cover crops	(93)
Rising co_2 levels	Some positive impacts on C storage, but unbalanced nutrients, toxins may accumulate	Nutrient management plans, controlled drainage	(94)
Increase in extreme weather events	Reduced soil structure, stability, loss of topsoil	Cover crops, no/low till, soil organic matter management	(95)
Differential drying & wetting	Disruption of soil aggregates, flow paths	Controlled drainage, frequent organic matter additions	(96)
Salinization in some regions	Lower water infiltration, retention and nutrient imbalance	Improved irrigation management, gypsum, organic amendments	(97)
Acidification in some areas	Aluminium toxicity, nutrient deficiencies	Liming, reduced acid rain deposits	(98)
Land use changes	Massive soil disruption, loss of C stocks	Retention of natural areas, integrate buffer zones and field borders	(99)

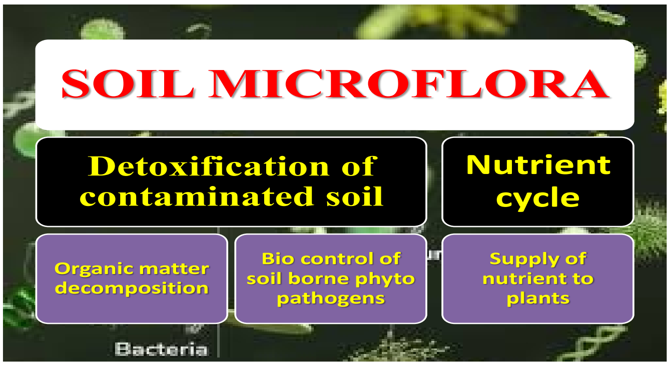

Fig.5. A schematic representation of soil micro flora as a biological indicator

climate scenarios. For example, biofertilizers containing *Rhizobium* and *Azospirillum* improved nitrogen fixation, resulting in a 15-20% yield increase in wheat during drought conditions in India. Mycorrhizal fungi like *Glomus* enhanced drought tolerance, boosting crop growth by 30% in arid Australia, while plant growth-promoting rhizobacteria (PGPR) led to a 25% yield increase in soybeans under climatic stress in Brazil. These cases highlight the potential of microbial interventions to improve soil health and agricultural productivity amidst climate change(46).

Soil quality is of utmost importance in agriculture under the influence of climate change, and enhancing soil quality can serve as a buffer against the adverse effects of climate change on crop yields (Fig.6).

Carbon sequestration

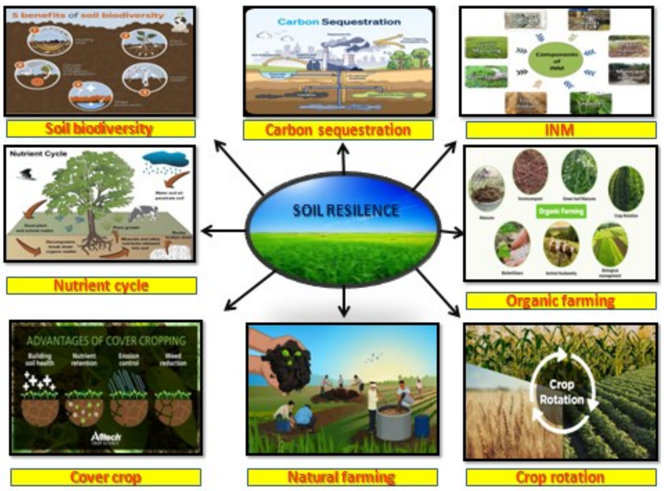

Fig.6. A schematic representation of soil resilience strategies to reduce the effects of climate change on soil health

Carbon sequestration is essential for enhancing soil's ability to withstand the impacts of climate change. It supports the preservation and augmentation of SOC stocks, which are indispensable for soil health and productivity. The effects of afforestation and reforestation on SOC stocks may vary depending on the soil type and tree species (47). Practices such as conservation tillage, agroforestry, residue management, and crop rotation also contribute to soil carbon sequestration. Biochar, a stable carbon source, can be administered to the soil to enhance long-term carbon sequestration and reduce greenhouse gas emissions (48). Increasing soil carbon content through carbon sequestration ameliorates soil structure, fertility, and nutrient availability, thus making the soil more resilient to climatic extremes and disturbances (49). These practices hold the potential to mitigate global warming, enhance environmental sustainability, and strengthen the overall resilience of agricultural systems in the face of climate change (50).

Cover cropping

Planting cover crops between main crops is sustainable agronomic practice that contributes to enhancing soil resilience in the face of climate change. During unproductive periods, such as fallow periods, farmers can cultivate cover crops to provide ecosystem services that aid in climate change mitigation and improve soil health (51). Cover crops can increase soil organic carbon levels, which plays a role in mitigating climate change by sequestering carbon dioxide from the atmosphere. Moreover, cover crops can enhance soil fertility, nutrient cycling, and water regulation all of which are crucial for the maintenance of soil health and productivity (52). Another benefit of cover crops is their ability to improve soil porosity and permeability, resulting in increased water infiltration and decreased runoff during periods of rainfall. This, in turn can help reduce the risk of flooding and improve water management in agricultural systems. Cover cropping is an essential practice that supports sustainable cropping systems, enhances soil resilience and contributes to global food security.

Organic farming

Organic farming is an effective strategy for enhancing soil resilience in the face of climate change. It helps conserve soil fertility and health, improves crop yield and quality, and reduces carbon concentrations in the atmosphere. Organic farming practices, such as the use of organic manures and amendments, crop rotations, mulching, non-synthetic fertilizers, zero tillage, and integrated nutrient and pest management, contribute to the development of resilient soils. These practices enhance soil organic matter, which is crucial for improving soil fertility and crop productivity (53). SOC plays a key role in soil quality and resilience against climate change (54). Additionally, organic farming also promotes the activity of soil microorganisms, which are vital for nutrient cycling and other ecological processes in the soil. By adopting organic farming practices, farmers can build and maintain soil organic carbon stocks, leading to more resilient agricultural systems in the face of climate changes Traditional farming practices, such as biodiversity management, soil management, and water harvesting, can increase resilience and economic benefits in small-scale agriculture, while mitigating global warming. A farm transitioning to organic practices achieved improved food security and resilience while maintaining greenhouse gas intensity similar to regional averages, demonstrating global responsibility as biosphere stewards (55).

Integrated Nutrient Management (INM)

INM involves the utilization of a combination of all available sources of nutrients for plants in a holistic package for crop nutrition (56). Research has shown that

INM significantly improves soil health and crop yields while reducing greenhouse gases emissions. It has been found that the application of INM significantly improves the overall health of the soil, as evidenced by decreased bulk density, increased porosity, and enhanced water-holding capacity. INM can improve soil aggregates and microbiota by integrating organic manure and retaining residue, which further increase soil resilience (57). Soils plays a prominent role in driving global change, and the establishment of a global program for soil resilience is necessary to safeguard soil fertility and ecosystem services while acknowledging their pivotal role in supporting ecosystems and sustainable development (58). Integrated systems for managing plant nutrients that involve beneficial microorganisms enhance crop productivity, increase fertilizer efficiency, and improve resilience to environmental constraints.

Nutrient cycle

Climate change factors such as rising temperature, altered precipitation patterns, and intense rainfall events can significantly impact soil nutrient cycling processes. These changes also affect microbial communities, including soil bacteria and arbuscular mycorrhizal (AM) fungi, which play a significant role in nutrient cycling. Research has demonstrated that warming of soils during the winter seasons can accelerate nutrient cycling, resulting in greater nutrient availability and leaching (59). Moreover, climate change drivers can influence soil microbial communities, which, in turn, can affect nutrient storage, soil properties, and other ecosystem processes. It has been found that AM fungi reduce nutrient losses through leaching, improving soils' capacity to absorb nutrients and lessening the detrimental effects of increased precipitation on nutrient losses (60). While global change factors do impact soil biodiversity and nitrogen cycling in terrestrial ecosystems, there is limited evidence linking species richness to nutrient cycling efficiency (61). Advanced techniques, such as stable isotopes and tree ring analysis, enhance our understanding of carbon and nutrient cycling in forest ecosystems, addressing the long-term impacts of climate change.

Biodiversity

Soil biodiversity is vital for maintaining ecosystem services such as organic matter breakdown and nutrient cycling. The various microbial populations present in soil, including bacteria, fungi, and viruses, are impacted by attributes such as pH, temperature, and organic carbon. Key soil bacteria like *Pseudomonas* aid plant growth and nutrient cycling, *Bacillus* enhances soil fertility and suppresses pathogens, and *Rhizobium* is known for nitrogen fixation in legumes. Fungi such as *Aspergillus* decompose organic matter, while *Trichoderma* promotes plant growth and suppresses soil-borne pathogens. Mycorrhizal fungi like *Glomus* improve nutrient and water uptake through symbiosis with plants, and viruses, such as bacteriophages, regulate bacterial populations and influence nutrient cycling(62). Changes in soil biodiversity can impact how plant communities respond to disturbances brought about by climate change. A decline in soil biodiversity can hinder the recovery of legumes and reduce plant diversity(63). Soil microorganisms, including biota, respond to changes in soil conditions and vegetation caused by climate change. Maintaining soil biodiversity is critical to mitigating climate change's impact on plant diversity and ecosystem function, especially in grasslands. Soil biodiversity, particularly through the involvement of mycorrhizal soil mutualism, is critical for the persistence of legumes and the maintenance of plant diversity in grasslands during environmental changes. Climate change has a significant impact on soil biodiversity and the services it provides, with the potential for intensified seasonal disturbances and an increase in extreme events.

Crop rotation

Crop rotation enhances soil durability by diversifying crops and reducing the depletion of soil nutrients. Conventional farming systems that heavily depend on excessive amounts of fertilizers and pesticides have a negative impact on the environment. Conversely, diversified crop rotations have been shown to increase system resilience, enhance carbon storage, strengthen resistance against pests and diseases, improve the efficiency of water and fertilizer use, and optimize the health of the soil (64). The incorporation of pastures and crops, along with other ecologically-based practices, significantly enhances the content of organic carbon and nitrogen in the soil, leading to improved soil quality and environmental sustainability (65). The excessive use of mineral fertilizers and pesticides in modern agriculture has deteriorated the health and sustainability of soils, highlighting the need to provide fresh energy sources for soil biota to reduce reliance on mineral fertilizers. Sustainable and resilient management of organic matter in the soil is indispensable for viable agricultural development (66).

Natural farming

Soil resilience is a critically important aspect of sustainable agriculture within the framework of natural farming. The primary objective of natural farming practices is to preserve and enhance soil health, which is of utmost importance for the growth of plants and the stability of ecosystems. The conservation of soil and water resources, as well as the promotion of biodiversity, are fundamental components of natural farming (67). It is important to note that the health and nutrient cycling of soil are heavily dependent on the presence of healthy soil microbial communities, whose functional diversity is influenced by the management practices employed on farms (68). In achieve agricultural sustainability, it is crucial to adopt an integrative approach to the management of soil and water resources. Nature-based solutions can serve as effective means of improving soil resilience and mitigating the adverse effects of climate change. Soil resilience, in the context of natural farming, offers farmers valuable guidance for implementing practices that enhance the long-term productivity and sustainability of their agricultural systems.

Future perspective

Land degradation, as highlighted by the Intergovernmental Panel on Climate Change (IPCC), ranks among the most urgent issues faced by humanity (69). Rising atmospheric CO_2 levels are expected to reduce crop yields and degrade the nutritional quality of food. Addressing climate change requires not only a shift away from fossil fuels but also a focus on carbon sequestration. SCO, which consists of carbon-based substances such as leaves, roots, and living organisms, plays a crucial role in this regard. Unfortunately, modern agricultural practices have led to soil degradation and a loss of organic carbon content. Globally, cropland soils have lost 20-60% of their original organic carbon content, with North American farmland losing approximately half of its natural soil carbon. This degradation is primarily driven by tillage and heavy fertilizer use, both of which release more carbon into the atmosphere. Investing in soil regeneration offers multiple benefits.

Firstly, healthy soils sequester carbon, and by improving soil organic matter, their capacity to hold water is enhanced, allowing more rainfall to penetrate the ground. This facilitates crop sustenance, especially during drought-stressed years, and reduces downstream flooding (70). Secondly, conventionally tilled soils erode over 100 times faster than they form, but restoring soil health through practices like cover cropping can significantly reduce erosion. For instance, farmers in the Midwest United States who implemented cover crops such as clover and rye reduced soil erosion by up to 50% compared to conventional tillage. These cover crops improve soil structure, enhance organic matter content, and increase biodiversity, contributing to better soil health and lower erosion rates.

Thirdly, changes in forestry and agriculture can contribute significantly to climate solutions by reducing global emissions by 5% to 20%, thereby aiding in climate mitigation. Lastly, healthy soils improve resilience to extreme weather events such as hurricanes, floods, and droughts. Additionally, improved soil health supports biodiversity by providing a thriving habitat for various microorganisms, plants, and animals, contributing to ecosystem stability and resilience in the face of environmental stressors.

While it is important to note that soil restoration alone will not solve the entire climate crises, it is a significant step towards addressing climate change. It is crucial to recognize that soil health is not only an agricultural concern but also a climate imperative.

Conclusion

As climate challenges intensify, resilient soils are vital for sustainable agriculture and ecological stability. Healthy soils not only support food systems but also play a crucial role in combating climate change, as soil degradation leads to declining crop yields and biodiversity loss. The intricate connections between soil health, nutrient dynamics, and microbial communities highlight the need for proactive soil management. Practices such as integrated nutrient management, organic farming, and cover cropping can revitalize soils, increase organic carbon content, and improve nutrient availability, thereby boosting agricultural productivity and ecological health. Continued research is essential to identify innovative soil management practices that can adapt to changing climate conditions, helping to understand the best techniques for restoring soil health and improving resilience. Additionally, investigating the long-term effects of various restoration practices will provide valuable insights into enhancing soil biodiversity and overall functionality. Prioritizing soil health today ensures resilient ecosystems and secures food systems for future generations.

Acknowledgements

Authors wish to thanks to anonymous reviewers for their feedback on the manuscript, which helped to improve the quality of the manuscript, and the Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University for their constant support.

Authors' Contributions

RMR carried out the works such as collection of literature, structuring the manuscript, preparation and drafting of the manuscript. GM contributed to the manuscript through his guidance, preparation of the framework, correction and revision of the manuscript. RR participated in visualization, re-drafting and editing of the draft. SM, KM, and MS participated in correcting the final version of the manuscript. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Chat GPT, Quillbot in order to improve language quality. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Wasan, et al. Effects of climate change on soil health resulting in an increased global spread of neglected tropical diseases. PLOS Neglected Tropical Diseases. 2023;17(6):e0011378. https://doi.org/10.1371/journal.pntd.0011378
2. Patil A, Lamnganbi M. Impact of climate change on soil health: A review. Int J Chem Stud. 2018;6(3):2399-404.
3. Brinkman R, Sombroek WG. The effects of global change on soil conditions in relation to plant growth and food production. Global Climate Change and Agricultural Production. 1996;49-63.
4. Eswar D, Karuppusamy R, Chellamuthu S. Drivers of soil salinity and their correlation with climate change. Current Opinion in

Environmental Sustainability. 2021;50:310-18. http://dx.doi.org/10.1016/j.cosust.2020.10.015

5. Lal, et al. Soil health and climate change: an overview. Soil Health and Climate Change. 2011;3-24. http://dx.doi.org/10.1016/B978-0-12-818032-7.00026-6

6. Song J, Ma M. Climate change: Linear and nonlinear causality analysis. Stats. 2023;6(2):626-42. http://dx.doi.org/10.3390/stats6020040

7. Myhre G, Myhre CL, Samset B, Storelvmo T. Aerosols and their relation to global climate and climate sensitivity. Nature Education Knowledge. 2013;4(5):7.

8. Ghini R, Hamada E, Bettiol W. Climate change and plant diseases. Scientia Agricola. 2008;65:98-107. http://dx.doi.org/10.1590/S0103-90162008000700015

9. Priyanka M, Varma S, Kumar V, Sharma R. Impact of climate change on plant diseases and management strategies: A review. Int J Chem Stud. 2020;8:2968-73. http://dx.doi.org/10.22271/chemi.2020.v8.i2at.9203

10. Gautam H, Bhardwaj M, Kumar R. Climate change and its impact on plant diseases. Current Science. 2013;1685-91.

11. Kumar A, Kumar S, Kumar R, Kumar R, Imran M. Impact of climate change on plant diseases and their management strategies. Journal of Pharmacognosy and Phytochemistry. 2017;6(6S):779-81.

12. Spaldon S, Samnotra R, Chopra S. Climate resilient technologies to meet the challenges in vegetable production. International Research on Current and Academic Review. 2015;3(2):28-47.

13. Saqib M, Anjum MA, Ali M, Ahmad R, Sohail M, Zakir I, et al. Horticultural crops as affected by climate change. Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective. 2022;95-109. http://dx.doi.org/10.1007/978-3-030-79408-8_7

14. Zhao M, Lin Y, Chen H. Improving nutritional quality of rice for human health. Theoretical and Applied Genetics. 2020;133:1397-413. https://link.springer.com/article/10.1007/s00122-019-03530-x

15. Thomasz EO, Pérez-Franco I, García-García A. Assessing the impact of climate change on soybean production in Argentina. Climate Services. 2024;34:100458. http://dx.doi.org/10.1016/j.cliser.2024.100458

16. Kumar SS, Wani OA, Krishna JR, Hussain N. Impact of climate change on soil health. Int J Environ Sci. 2022;7:70-90.

17. Singh S, Naresh R, Kumar S, Kumar V, Mahajan N, Mrunalini K, et al. Conservation agriculture effects on aggregates carbon storage potential and soil microbial community dynamics in the face of climate change under semi-arid conditions: A review. Journal of Pharmacognosy and Phytochemistry. 2019;8(2):59-69.

18. Nisa KU, Tarfeen N, Nisa Q, Wani S. Climate change and plant nutrient availability: challenges and assessment strategies. Sustainable Plant Nutrition: Elsevier. 2023;p. 71-86. http://dx.doi.org/10.1016/B978-0-443-18675-2.00015-8

19. Shen X, Ma J, Li Y, Li Y, Xia X. The Effects of multiple global change factors on soil nutrients across China: A meta-analysis. International Journal of Environmental Research and Public Health. 2022;19(22):15230. http://dx.doi.org/10.3390/ijerph192215230

20. Kumari M, Solankey SS, Singh D, Rajiv. Impact of climate change on nutraceutical properties of vegetables. Advances in Research on Vegetable Production Under a Changing Climate. Springer. 2023; 2: p. 71-84. http://dx.doi.org/10.1007/978-3-031-20840-9_3

21. Legg, et al. IPCC, 2021: Climate change 2021-the physical science basis. Interaction. 2021;49(4):44-45.

22. Seneviratne S, Nicholls N, Easterling D, Goodess C, Kanae S, Kossin J, et al. Changes in climate extremes and their impacts on the natural physical environment. 2012. https://doi.org/10.1017/CBO9781139177245.006

23. Gleeson D, Mathes F, Farrell M, Leopold M. Environmental drivers of soil microbial community structure and function at the Avon river critical zone observatory. Science of the Total Environment. 2016;571:1407-18. http://dx.doi.org/10.1016/j.scitotenv.2016.05.185

24. Bardgett RD, Manning P, Morriën E, De Vries FT. Hierarchical responses of plant–soil interactions to climate change: consequences for the global carbon cycle. Journal of Ecology. 2013;101(2):334-43. http://dx.doi.org/10.1111/1365-2745.12043

25. Kirkham, et al. Principles of soil and plant water relations. Elsevier; 2023. http://dx.doi.org/10.1016/B978-0-12-409751-3.X5000-2

26. Anjali M, Dhananjaya B. Effect of climate change on soil chemical and biological properties–a review. Int J Curr Microbiol App Sci. 2019;8(2):1502-12. http://dx.doi.org/10.20546/ijcmas.2019.802.174

27. Niwas R, Khichar M, Kumar A. Study of climate change impact on crops and soil health in India: A review. Agricultural Reviews. 2023;44(3):357-63. https://link.springer.com/article/10.1007/s00704-016-1991-7

28. Bhat MA, Yousuf A, Sandhu PS. Soil quality vis-à-vis climatic upheaval. Climate Change Alleviation for Sustainable Progression: Floristic Prospects and Arboreal Avenues as a Viable Sequestration Tool. 2022;151. http://dx.doi.org/10.1201/9781003106982

29. Houle D, Marty C, Augustin F, Dermont G, Gagnon C. Impact of climate change on soil hydro-climatic conditions and base cations weathering rates in forested watersheds in Eastern Canada. Frontiers in Forests and Global Change. 2020;3:535397. http://dx.doi.org/10.3389/ffgc.2020.535397

30. Alcaraz MN, Gestel CA. Climate change effects on enchytraeid performance in metal-polluted soils explained from changes in metal bioavailability and bioaccumulation. Environmental Research. 2015;142:177-84. http://dx.doi.org/10.1016/j.envres.2015.06.027

31. Khursheed, et al. Soil biodiversity and climate change. Adv Plants Agric Res. 2016;3(5):00113. https://doi.org/10.15406/apar.2016.03.00113

32. Gelybó G, Tóth E, Farkas C, Horel Á, Kása I, Bakacsi Z. Potential impacts of climate change on soil properties. Agrokémia és Talajtan. 2018;67(1):121-41. http://dx.doi.org/10.1556/0088.2018.67.1.9

33. Kpemoua TP, Leclerc S, Barré P, Houot S, Pouteau V, Plessis C, et al. Are carbon-storing soils more sensitive to climate change? A laboratory evaluation for agricultural temperate soils. Soil Biology and Biochemistry. 2023;183:109043. http://dx.doi.org/10.2139/ssrn.4292994

34. Puche N, Kirschbaum M, Viovy N, Chabbi A. Potential impacts of climate change on the productivity and soil carbon stocks of managed grasslands. Plos One. 2023;18(4):e0283370. https://doi.org/10.1371/journal.pone.0283370

35. Leung A, Feng S, Vitali D, Ma L, Karimzadeh AA. Temperature effects on the hydraulic properties of unsaturated sand and their influences on water-vapor heat transport. Journal of Geotechnical and Geoenvironmental Engineering. 2020;146(4):06020003. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0002227

36. Biswal, et al. Climate change and its impact on soil fertility and life forms. Research Anthology on Environmental and Societal Impacts of Climate Change: IGI Global. 2022; p. 1229-55. http://dx.doi.org/10.4018/978-1-6684-3686-8.ch060

37. Alvarez R, Santanatoglia OJ, Garcîa R. Effect of temperature on soil microbial biomass and its metabolic quotient in situ under different tillage systems. Biology and Fertility of Soils. 1995;19:227-30. http://dx.doi.org/10.1071/EA97142

38. Minnikova T, Kolesnikov S, Khoroshaev D, Tsepina N, Evstegneeva N, Timoshenko A. Assessment of the health of soils contaminated with Ag, Bi, Tl and Te by the intensity of

microbiological activity. Life. 2023;13(7):1592. http://dx.doi.org/10.3390/life13071592

39. Classen AT, Sundqvist MK, Henning JA, Newman GS, Moore JA, Cregger MA, et al. Direct and indirect effects of climate change on soil microbial and soil microbial plant interactions: What lies ahead? Ecosphere. 2015;6(8):1-21. http://dx.doi.org/10.17503/agrivita.v46i1.4215

40. Crowther TW, Glick HB, Covey KR, Bettigole C, Maynard DS, Thomas SM, et al. Mapping tree density at a global scale. Nature. 2015;525(7568):201-05. http://dx.doi.org/10.1038/nature14967

41. Conant RT, Ryan MG, Ågren GI, Birge HE, Davidson EA, Eliasson PE, et al. Temperature and soil organic matter decomposition rates–synthesis of current knowledge and a way forward. Global Change Biology. 2011;17(11):3392-404. http://dx.doi.org/10.1111/j.1365-2486.2011.02496.x

42. Luo J, Xie Z, Lam JW, Cheng L, Chen H, Qiu C, et al. Aggregation-induced emission of 1-methyl-1, 2, 3, 4, 5-pentaphenylsilole. Chemical Communications. 2001;(18):1740-41. http://dx.doi.org/10.1039/B105159H

43. Hu Y, Wang S, Niu B, Chen Q, Wang J, Zhao J, et al. Effect of increasing precipitation and warming on microbial community in Tibetan alpine steppe. Environmental Research. 2020;189:109917. http://dx.doi.org/10.1016/j.envres.2020.109917

44. Yuan Y, Ton BL, Thomas WJ, Batley J, Edwards D. Supporting crop plant resilience during climate change. Crop Science. 2023;63(4):1816-28. http://dx.doi.org/10.1002/csc2.21019

45. Qiao L, Wang X, Smith P, Fan J, Lu Y, Emmett B, et al. Soil quality both increases crop production and improves resilience to climate change. Nat Clim Chang. 2022;12:574-80. http://dx.doi.org/10.1038/s41558-022-01376-8

46. Iqbal B, Li G, Alabbosh KF, Hussain H, Khan I, Tariq M, et al. Advancing environmental sustainability through microbial reprogramming in growth improvement, stress alleviation and phytoremediation. Plant Stress. 2023;100283. http://dx.doi.org/10.1016/j.stress.2023.100283

47. Schindlbacher A, Mayer M, Jandl R, Zimmermann S, Hagedorn F. Optimizing forest management for soil carbon sequestration. 2022. http://dx.doi.org/10.19103/AS.2022.0106.18

48. Shahzad K, Sintim H, Ahmad F, Abid M, Nasim W. Importance of carbon sequestration in the context of climate change. Building Climate Resilience in Agriculture: Theory, Practice and Future Perspective. 2022;385-401. http://dx.doi.org/10.1007/978-3-030-79408-8_23

49. Devi S, Singh S. Soil organic carbon sequestration in dryland soils to alleviate impacts of climate change. Enhancing Resilience of Dryland Agriculture Under Changing Climate: Interdisciplinary and Convergence Approaches: Springer; 2023. p. 221-45. http://dx.doi.org/10.1007/978-981-19-9159-2_13

50. Purakayastha T, Bhaduri D, Singh P. Role of biochar on greenhouse gas emissions and carbon sequestration in soil: Opportunities for mitigating climate change. Soil Science: Fundamentals to Recent Advances. 2021;237-60. http://dx.doi.org/10.1007/978-981-16-0917-6_11

51. Ma J, Anthoni P, Olin S, Rabin S, Bayer A, Arneth A. Integrating cover crops with no-tillage benefits crop yields, increases soil carbon storage while reducing nitrogen leaching in global croplands. Copernicus Meetings; 2023. DOI: 10.1029/2022EF003142

52. Quintarelli V, Radicetti E, Allevato E, Stazi SR, Haider G, Abideen Z, et al. Cover crops for sustainable cropping systems: A review. Agriculture. 2022;12(12):2076. DOI: 10.3390/agriculture12122076

53. Adil M, Riaz M, Riaz F, Jehangir K, Ashraf MA, Ali S, et al. Organic amendments for sustainable crop production, soil carbon sequestration and climate smart agriculture. Climate Change Alleviation for Sustainable Progression: Floristic Prospects and Arboreal Avenues as a Viable Sequestration Tool. 2022;202. DOI: 10.3390/su131910966

54. Taylor A, Wynants M, Munishi L, Kelly C, Mtei K, Mkilema F, et al. Building climate change adaptation and resilience through soil organic carbon restoration in Sub-Saharan rural communities: challenges and opportunities. Sustainability. 2021;13(19):10966. DOI: 10.3390/su131910966

55. Röös E, Bajzelj B, Weil C, Andersson E, Bossio D, Gordon LJ. Moving beyond organic–A food system approach to assessing sustainable and resilient farming. Global Food Security. 2021;28:100487. DOI: 10.1016/j.gfs.2020.100487

56. Paramesh V, Kumar RM, Rajanna G, Gowda S, Nath AJ, Madival Y, et al. Integrated nutrient management for improving crop yields, soil properties and reducing greenhouse gas emissions. Front Sustain Food Syst. 2023;7(10.3389). DOI:10.3389/fsufs.2023.1173258

57. Anantha K, Garg KK, Dixit S. Building resilience to climate change in agriculture: integrated natural resource management and institutional measures. Global Climate Change: Resilient and Smart Agriculture. 2020;109-36. DOI: 10.3390/plants11010138

58. Urmi TA, Rahman MM, Islam MM, Islam MA, Jahan NA, Mia MAB, et al. Integrated nutrient management for rice yield, soil fertility and carbon sequestration. Plants. 2022;11(1):138. DOI: 10.3390/plants11010138

59. Kaštovská E, Choma M, Čapek P, Kaňa J, Tahovská K, Kopáček J. Soil warming during winter period enhanced soil N and P availability and leaching in alpine grasslands: A transplant study. Plos One. 2022;17(8):e0272143. DOI: 10.1371/journal.pone.0272143

60. Yuan Z, Jiao F, Shi X, Sardans J, Maestre FT, Delgado-Baquerizo M, et al. Experimental and observational studies find contrasting responses of soil nutrients to climate change. elife. 2017;6:e23255. DOI: 10.7554/eLife.23255

61. Swift M, Andren O, Brussaard L, Briones M, Couteaux MM, Ekschmitt K, et al. Global change, soil biodiversity and nitrogen cycling in terrestrial ecosystems: three case studies. Global Change Biology. 1998;4(7):729-43. DOI: 10.1046/j.1365-2486.1998.00207.x

62. Prabhakaran A, Meenatchi R, Pal S, Hassan S, Bramhachari PV, Kiran GS, et al. Soil microbiome: Characteristics, impact of climate change and resilience. Understanding the Microbiome Interactions in Agriculture and the Environment: Springer; 2022. p. 285-313. DOI:10.1007/978-981-19-3696-8_15

63. Yang G, Roy J, Veresoglou SD, Rillig MC. Soil biodiversity enhances the persistence of legumes under climate change. New Phytologist. 2021;229(5):2945-56. DOI: 10.1111/nph.17065

64. Liu C, Plaza-Bonilla D, Coulter JA, Kutcher HR, Beckie HJ, Wang L, et al. Diversifying crop rotations enhances agroecosystem services and resilience. Advances in Agronomy. 2022;173:299-335. DOI: 10.1016/bs.agron.2022.02.007

65. Franzluebbers AJ, Gastal F. Building agricultural resilience with conservation pasture-crop rotations. Agroecosystem Diversity: Elsevier; 2019. p. 109-21. DOI: 10.1016/B978-0-12-811050-8.00007-8

66. Leah T. Soil protection of Republic Moldova in the context of sustainable development. Present Environment and Sustainable Development. 2012;(1):47-57

67. Turek ME, Prasuhn V, Holzkämper A, editors. Agro-hydrological modeling of soil water retention measures to increase crop system resilience to extreme events. EGU General Assembly Conference Abstracts; 2022. DOI: 10.5194/egusphere-egu22-2919

68. Neher DA, Harris JM, Horner CE, Scarborough MJ, Badireddy AR, Faulkner JW, et al. Resilient soils for resilient farms: An integrative approach to assess, promote and value soil health for small-and medium-size farms. Phytobiomes Journal. 2022;6(3):201-06. DOI: 10.1094/PBIOMES-10-21-0060-P

69. Hulme M, Mahony M. Climate change: What do we know about the IPCC? Progress in Physical Geography. 2010;34(5):705-18. DOI: 10.1177/0309133310373719

70. Stockmann U, Padarian J, McBratney A, Minasny B, de Brogniez D, Montanarella L, et al. Global soil organic carbon assessment. Global Food Security. 2015;6:9-16. DOI: 10.1016/j.gfs.2015.07.001.

71. Smith P, Soussana JF, Angers D, Schipper L, Chenu C, Rasse DP, et al. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology. 2020;26(1):219-41.DOI: 10.1111/gcb.14815.

72. Kannan P, Krishnaveni D, Ponmani S. Biochars and its implications on soil health and crop productivity in semi-arid environment. Biochar Applications in Agriculture and Environment Management. 2020;99-122. DOI:10.1007/978-3-030-40997-5_5.

73. Ma N, Zhang L, Zhang Y, Yang L, Yu C, Yin G, et al. Biochar improves soil aggregate stability and water availability in a mollisol after three years of field application. PloS One. 2016;11(5):e0154091. DOI: 10.1371/journal.pone.0154091.

74. Kane DA, Bradford MA, Fuller E, Oldfield EE, Wood SA. Soil organic matter protects US maize yields and lowers crop insurance payouts under drought. Environmental Research Letters. 2021;16(4):044018. DOI: 10.1088/1748-9326/abe492.

75. Singh VK, Panda KC, Sagar A, Al-Ansari N, Duan H-F, Paramaguru PK, et al. Novel Genetic Algorithm (GA) based hybrid machine learning-pedotransfer function (ML-PTF) for prediction of spatial pattern of saturated hydraulic conductivity. Engineering Applications of Computational Fluid Mechanics. 2022;16(1):1082-99. DOI: 10.1080/19942060.2022.2071994.

76. Lee EH, Kim JH. Development of resilience index based on flooding damage in urban areas. Water. 2017;9(6):428. DOI: 10.3390/w9060428.

77. Hook PB, Burke IC. Biogeochemistry in a shortgrass landscape: control by topography, soil texture and microclimate. Ecology. 2000;81(10):2686-703. DOI: 10.2307/177334.

78. Meena RS, Lal R, Yadav GS. Long-term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in central Ohio, USA. Geoderma. 2020;363:114164. DOI: 10.1016/j.geoderma.2019.114164.

79. Laurion I, Massicotte P, Mazoyer F, Negandhi K, Mladenov N. Weak mineralization despite strong processing of dissolved organic matter in Eastern Arctic tundra ponds. Limnology and Oceanography. 2021;66:S47-S63. DOI: 10.1002/lno.11634.

80. Kuyper J, Schroeder H, Linnér B-O. The Evolution of the UNFCCC. Annual Review of Environment and Resources. 2018;43:343-68. DOI: 1 0.1146/annurev-environ-102017-030119.

81. Ogunbode CA, Doran R, Böhm G. Exposure to the IPCC special report on 1.5 C global warming is linked to perceived threat and increased concern about climate change. Climatic Change. 2020;158:361-75. DOI: 10.1007/s10584-019-02609-0.

82. Sheet EF. The Growth in greenhouse gas emissions from commercial aviation. URL: https://www eesi org/files/FactSheet_Climate_Impacts_ Aviation_1019 pdf.

83. Bennett B. The Fourth National Climate Assessment. 2021.

84. Aboelkhair H, Morsy M, El Afandi G. Assessment of agroclimatology NASA POWER reanalysis datasets for temperature types and relative humidity at 2 m against ground observations over Egypt. Advances in Space Research. 2019;64(1):129-42. DOI: 10.1016/j.asr.2019.03.032.

85. Garrett K, Liu H, Ide K, Hoffman RN, Lukens KE. Optimization and impact assessment of Aeolus HLOS wind assimilation in NOAA's global forecast system. Quarterly Journal of the Royal Meteorological Society. 2022;148(747):2703-16. DOI:10.1002/qj.4331.

86. Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, et al. Global and regional sea level rise scenarios for the United States. 2017. DOI: 10.7289/v5/tr-nos-coops-083.

87. Cazenave A, Hamlington B, Horwath M, Barletta VR, Benveniste J, Chambers D, et al. Observational requirements for long-term monitoring of the global mean sea level and its components over the altimetry era. Frontiers in Marine Science. 2019;6:582. DOI: 10.3389/fmars.2019.00582.

88. Trummer C, Pandis M, Verheyen N, Grübler MR, Gaksch M, Obermayer-Pietsch B, et al. Beneficial effects of UV-radiation: vitamin D and beyond. International Journal of Environmental Research and Public Health. 2016;13(10):1028. DOI: 10.3390/ijerph13101028.

89. Petrescu RV, Aversa R, Apicella A, Petrescu FI. NASA sees first in 2018 the direct proof of ozone hole recovery. Journal of Aircraft and Spacecraft Technology. 2018;2(1):53-64. DOI: 10.3844/jastsp.2018.53.64.

90. Allan RP, Arias PA, Berger S, Canadell JG, Cassou C, Chen D, et al. Intergovernmental Panel on Climate Change (IPCC). Summary for policymakers. Climate change 2021: The physical science basis Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change: Cambridge University Press; 2023. p. 3-32. https://doi.org/10.1017/9781009157896.001.

91. Svensen HH, Bjærke MR, Kverndokk K. The past as a mirror: deep time climate change exemplarity in the Anthropocene. Culture Unbound. 2019;11(3-4):330-52. DOI: 10.3384/cu.2000.1525.1909301.

92. Fang C, Smith P, Moncrieff JB, Smith JU. Similar response of labile and resistant soil organic matter pools to changes in temperature. Nature. 2005;433(7021):57-59. DOI: 10.1038/nature03138.

93. Rao KK, Kulkarni A, Patwardhan S, Kumar BV, Kumar TL. Future changes in precipitation extremes during northeast monsoon over south peninsular India. Theoretical and Applied Climatology. 2020;142:205-17. DOI: 10.1007/s00704-020-03308-y.

94. El-Ramady H, Hajdú P, Törős G, Badgar K, Llanaj X, Kiss A, et al. Plant nutrition for human health: A pictorial review on plant bioactive compounds for sustainable agriculture. Sustainability. 2022;14(14):8329. DOI: 10.3390/su14148329.

95. Lehman RM, Ducey TF, Jin VL, Acosta-Martinez V, Ahlschwede CM, Jeske ES, et al. Soil microbial community response to corn stover harvesting under rain-fed, no-till conditions at multiple US locations. Bioenergy Research. 2014;7:540-50. DOI: 10.1007/s12155-014-9417-9.

96. Zhu K, Li W, Yang S, Ran Y, Lei X, Ma M, et al. Intense wet-dry cycles weakened the carbon sequestration of soil aggregates in the riparian zone. Catena. 2022;212:106117. DOI: 10.1016/j.catena.2022.106117.

97. Hansen MS, Madsen K, Price M, Søe K, Omata Y, Zaiss MM, et al. Transcriptional reprogramming during human osteoclast differentiation identifies regulators of osteoclast activity. Bone Research. 2024;12(1):5. DOI: 10.1038/s41413-023-00312-6.

98. Butterly CR, Amado TJC, Tang C. Soil acidity and acidification. Subsoil Constraints for Crop Production: Springer; 2022. p. 53-81. https://doi.org/10.1007/978-3-031-00317-2_3.

99. Cetin M, Isik Pekkan O, Bilge Ozturk G, Cabuk SN, Senyel Kurkcuoglu MA, Cabuk A. Determination of the impacts of mining activities on land cover and soil organic carbon: Altintepe gold mine case, Turkey. Water, Air and Soil Pollution. 2023;234(4):272. DOI: 10.1007/s11270-023-06274-z.