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Influence of climate change on soil microbial community

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Abstract

This study explores how climate change is transforming soil microbial communities, essential drivers of soil health and ecosystem resilience. With rising temperatures, shifting rainfall, elevated CO₂ levels, and changing soil moisture, microbial habitats are under stress, altering community structure, enzyme activity, and nutrient cycles. UV radiation, soil erosion, and increased compaction add to these pressures, affecting soil stability, carbon storage, and fertility. The objective is to understand how these changes impact soil's ability to support agriculture and carbon balance, highlighting the need for adaptive strategies to protect soil ecosystems.

Keywords: Climate change, soil microbes, soil health, Temperature, Soil moisture, enzyme activity, nutrient cycling

Introduction

Climate change has emerged as a significant driver of environmental transformations in recent decades. It is characterized by rise in global temperatures, shifting precipitation patterns and increased frequency of extreme weather events. The present state of climate change is unprecedented, with global temperatures having already increased by about 1.2°C above pre-industrial levels (IPCC, 2021) ^[24]. This warming trend is expected to persist, with forecasts indicating a possible temperature rise of 1.5°C to 4.5°C by the end of the 21st century, depending on future emission scenarios (IPCC, 2021; Gattuso *et al.*, 2021) ^[24, 19]. This increase in temperature is accompanied by prominent shifts in precipitation patterns, resulting in changes in soil moisture levels, which are crucial factors influencing the dynamics of soil microbial communities (Seneviratne *et al.*, 2021) ^[39]. Soil microbial communities, which include fungi, protists, viruses, bacteria, and archaea, play crucial roles in determining the structure and function of terrestrial ecosystems. They do this by participating in biogeochemical cycles and establishing close associations with plant roots. A significant challenge in deepening our understanding of the functional role of soil microbial communities is connecting the changes in their structure and function in response to climate change. Tackling this challenge necessitates a new understanding of the mechanisms that enable soil microbial communities to resist and recover from climate extremes (Bardgett *et al.*, 2020) ^[15].

Historically, Earth's climate has undergone natural fluctuations, but the speed and magnitude of the current changes are unprecedented in modern times. In the pre-industrial era, soil microbial communities evolved under relatively stable climatic conditions, playing key roles in nutrient cycling, organic matter decomposition, and maintaining soil health (Delgado-Baquerizo *et al.*, 2020) ^[41]. Soil microbial communities, comprising bacteria, fungi, archaea, and viruses, are vital for nutrient cycling, organic matter breakdown, and soil structure formation (Delgado-Baquerizo *et al.*, 2020; Singh *et al.*, 2020) ^[41]. The rapid and ongoing changes in climate are now exerting unprecedented pressure on these communities, potentially threatening these essential ecosystem services (Wagg *et al.*, 2021) ^[47]. Over million years, these communities have adapted to natural cycles of warming and cooling. However, the current rate of climate change is much faster, providing these communities with less time to adapt, which could lead to disruptions in critical ecosystem functions.

The future impact of climate change on soil microbial communities raises significant concerns.

As global temperatures rise and changes in precipitation patterns and extreme weather events become more frequent, soil moisture and temperature conditions are likely to shift. These environmental changes can alter the composition, diversity, and function of soil microbial communities, which are crucial for maintaining soil fertility and the capacity for carbon sequestration (Schmidt *et al.*, 2019; Trivedi *et al.*, 2020) ^[38, 45]. Such shifts in microbial communities may disrupt essential ecosystem functions, leading to decreased soil health and productivity. Additionally, the interaction between climate change and soil microbes could create feedback loops that further exacerbate climate change. For instance, changes in microbial activity could result in higher greenhouse gas emissions from soil, such as increased carbon dioxide and methane release, thereby accelerating global warming (Bradford *et al.*, 2020; Crowther *et al.*, 2019) ^[7, 12]. This potential for a feedback loop where soil microbes contribute to the intensification of climate change highlights the importance of understanding and mitigating these impacts to preserve ecosystem stability and function. Addressing these challenges is critical for ensuring the resilience of ecosystems in the face of ongoing climate change.

1. Climatic factors affecting soil microbes

Since microorganisms are essential in soil organic matter decomposition and other carbon cycling processes, understanding how they respond to global changes can significantly enhance our knowledge of carbon cycling and its feedback mechanisms related to climate change (Yang *et al.*, 2021) ^[52]. When ecosystems experience disturbances like increased dryness or changes from agricultural practices, the composition and activity of these microbial communities can change significantly. Such shifts may lead to major changes in how soil organic carbon (SOC) is stored or released. These changes in SOC dynamics are crucial because they directly impact the soil's ability to remain productive and sustainable over time (Ramirez *et al.*, 2020). The characteristics of the environment where soil microbes live, such as the long-term climate and the soil's physical and chemical properties, can change the natural traits of soil microbial communities. These traits affect how well these communities can withstand and recover from extreme climate conditions (Bardgett *et al.*, 2020) ^[15].

1.1 Temperature change

Soil is the largest terrestrial reservoir of carbon (C). Warmer temperatures accelerate organic matter decomposition, potentially reducing soil organic carbon (SOC) levels, which are essential for maintaining soil aggregate stability (Six *et al.*, 2000). The decline in SOC content leads to weakened binding agents between soil particles, decreasing the structural integrity of aggregates (Bronick & Lal, 2005) ^[8]. Soil microorganisms drive carbon losses to the atmosphere, but their response to temperature change due to climate warming is often short-lived and unpredictable. Long-term geothermal studies show that microbial activity is inherently sensitive to temperature increases and does not acclimate to warming, causing an initial acceleration in carbon loss. However, this effect is temporary, as substrate depletion reduces microbial biomass, limiting their influence on the ecosystem. A biogeochemical model confirms that warming accelerates microbial processes, but substrate availability ultimately constrains carbon loss from soils (Walker *et al.*, 2018) ^[48]. A global meta-analysis showed that elevated temperature decreases soil microbial biomass nitrogen (N) while

increasing N mineralization, nitrification, and denitrification rates, leading to a significant rise in N₂O emissions. These changes suggest a shift in microbial N cycling from anabolic to catabolic processes, driven by higher temperatures. Increased N cycling processes were closely linked to enhanced microbial carbon metabolism, highlighting the interconnectedness of soil C and N cycles (Dai *et al.*, 2020) ^[13].

1.2 Change in rainfall pattern

Variations in rainfall patterns affect soil water conditions and microbial activity at different depths, influencing plant-soil interactions. An experiment was conducted in which ¹⁸O stable isotope probing (SIP) to examine bacterial and fungal communities at three depths in soil mesocosms exposed to frequent or infrequent watering for 12 weeks. Results revealed that soil depth had a greater impact on microbial response to rewetting than the rainfall pattern (Engelhardt *et al.*, 2018) ^[17]. Reduced rainfall can significantly impact soil microbial communities and affect overall ecosystem processes. This meta-analysis found that less rainfall led to a decrease in total soil microbial biomass and bacterial abundance, while fungal communities remained mostly unchanged. Interestingly, only certain bacterial groups, like Proteobacteria, were affected, indicating that while the overall microbial biomass declined, the composition of microbial communities didn't change much. The study also showed that the size of rainfall reductions mattered more than the duration, with larger reductions in biomass seen in wetter areas. In regions with high rainfall, reductions in soil organic carbon and respiration were closely linked to decreases in microbial biomass, suggesting that these ecosystems may be particularly vulnerable to future droughts (Ren *et al.*, 2018) ^[18].

1.3 Elevation in CO₂ levels

Prior to the industrial era, atmospheric CO₂ levels were stable at around 280 parts per million (ppm) due to balanced natural processes within the carbon cycle. For nearly 6,000 years, CO₂ levels hovered around this range without significant variation (Nunes *et al.*, 2023) ^[54]. Following the onset of industrialization in the late 18th century, CO₂ levels began a notable rise as fossil fuel combustion, deforestation, and industrial processes released large amounts of CO₂ into the atmosphere. This upward trend continued through the 20th century and has sharply accelerated in recent decades, with current levels exceeding 420 ppm—over 50% higher than pre-industrial levels (Nunes *et al.*, 2023) ^[54]. Higher levels of atmospheric CO₂ can change the way microbial networks are structured. While this hasn't been directly tested, it is possible that these changes could affect how vulnerable microbial communities are to shifting into different states when faced with extreme climate events. This means that increased CO₂ levels might make soil microbes either more or less stable in their response to sudden environmental changes, depending on how their internal networks are altered (Bardgett *et al.*, 2020) ^[15]. Before industrialization, atmospheric CO₂ levels were much lower, but burning fossil fuels and deforestation have significantly raised them. CO₂ capture and storage is a strategy to reduce these levels and fight climate change, but leaks from storage sites can cause rapid acidification, potentially harming soil microbes. On a deeper level, CO₂ influences microbes by altering enzyme activity, electron transfer, and gene expression (Yu *et al.*, 2019) ^[53].

1.4 Soil moisture

Long-term drought experiments revealed that soil microbial communities develop increased resilience to fluctuations in soil

moisture during drying-rewetting (D/RW) cycles, though not resistance to drought itself. Rewetting events, rather than low soil moisture during drought, were key in shaping microbial responses. These cycles promoted efficient recovery, with microbes reducing respiration relative to bacterial growth. Such adaptations to soil moisture changes could help slow down the predicted loss of soil carbon under future drought conditions (EA de *et al.*, 2019) ^[14]

1.5 UV radiation

Ultraviolet (UV) radiation impacts both plants and soil microorganisms, altering their interactions. UV-A (320-400 nm) and UV-B (280-320 nm) influence plant morphogenesis and phototropism, while UV-B and UV-C stimulate secondary metabolite production. Short-wave UV radiation (<350 nm) directly damages pathogens through DNA disruption and increased membrane permeability, with UV-C (100-280 nm) being the most effective but also harmful to plants. UV-B and UV-C also indirectly affect microbes by enhancing plant defence responses, reactive oxygen species (ROS) accumulation, and secondary metabolite production (Vanhaelewyn *et al.*, 2020) ^[46]. Changes in climate and stratospheric ozone dynamics are altering exposure to UV-B radiation, affecting both plants and soil microbes. While ozone recovery may reduce future UV-B levels, climate change introduces new combinations of UV-B with other factors like temperature, water availability, and elevated CO₂ (Bornman *et al.*, 2019) ^[6]. These interactions impact key ecosystem processes such as microbial-driven litter decomposition, pest-pathogen interactions, and species competition. Ozone depletion, particularly in the southern hemisphere, is also contributing to shifts in precipitation, temperature, and fire regimes, influencing microbial activity in terrestrial ecosystems (Bornman *et al.*, 2019) ^[6].

2. Microbial response to climate change

2.1 Shift in microbial habitat

Microbial traits are essential for soil carbon cycling, influencing how microorganisms respond to environmental changes. Climate change, by altering factors like moisture, temperature, and salinity, can push microbes to prioritize maintenance activities such as enzyme production, cellular repair, and defence overgrowth. This shift in microbial focus under stressful conditions affects the balance between carbon decomposition and stabilization in soils. As environmental pressures increase, microbial activity changes, potentially altering soil carbon stocks and contributing to climate change feedback. Understanding these microbial responses is crucial for predicting future ecosystem changes (Malik *et al.*, 2020) ^[28]. Forests play a critical role in combating climate change by storing carbon in their soils, but they are increasingly threatened by rising carbon dioxide levels, warming temperatures, droughts, and nitrogen pollution. These environmental shifts lead to a microbial shift, where the balance of fungi and bacteria that help forests adapt is altered, impacting their ability to support carbon storage and

nutrient cycling. Droughts weaken forest resilience by triggering pathogen outbreaks and wildfires (Baldrian *et al.*, 2023) ^[3].

2.2 Change in enzyme activities

Global environmental changes are altering soil extracellular enzyme activities (EEAs), which are critical for carbon and nutrient cycling. Nitrogen addition generally stimulates carbon and phosphorus-acquisition EEAs but suppresses oxidase activity, while phosphorus addition reduces P-acquisition enzymes. Changes in precipitation and warming also affect enzyme activities, with drought dramatically reducing oxidase activity. EEAs are more sensitive to nutrient additions than to climate change, with significant implications for soil carbon storage and plant productivity (Xiao *et al.*, 2018) ^[51]. Climate change-induced thawing of permafrost leads to a shift in microbial communities, where fungal species like ericoid mycorrhizal fungi are replaced by bacteria and archaea that thrive in nitrogen-rich environments, such as ammonia-oxidizing microbes. This transition alters the nitrogen cycle, reducing microbes that support plant growth and potentially accelerating permafrost degradation (Seitz *et al.*, 2022) ^[55]. Changes in soil moisture due to climate shifts, such as more frequent droughts, lead to microbial community changes, favouring species that can tolerate desiccation and produce protective substances like trehalose. On the other hand, wetter conditions promote anaerobic microbes, including methane-producing archaea, which can alter greenhouse gas emissions and soil health (Vicuña *et al.*, 2021) ^[56]. Climate warming significantly increases soil ligninase activity by 21.4%, which is closely linked to higher soil respiration (SR), while cellulase activity remains unaffected (Chen *et al.*, 2018) ^[35]. This increase in ligninase activity suggests that microorganisms are enhancing the breakdown of recalcitrant carbon in response to warming, sustaining long-term rises in SR. The effect of warming on ligninase activity grows over time, indicating that climate change is likely to accelerate carbon decomposition in soils (Chen *et al.*, 2018) ^[35]. Drought, a major consequence of climate change, significantly impacts soil microorganisms by reducing their abundance, altering their structure, and decreasing enzyme production critical for nutrient cycling, such as oxidoreductases and phosphatases. This decline in microbial activity lowers soil fertility, negatively affecting plant productivity. However, organic amendments like compost can enhance soil enzyme activity, while plant growth-promoting microbes (Plant growth promoting Bacteria and plant growth promoting fungi) can help plants cope with drought (Bogati *et al.*, 2022) ^[5]. Climate warming influences soil carbon dynamics by increasing the ratio of ligninase to cellulase activity, which reflects a shift in microbial preference toward decomposing more resistant carbon sources. This enzymatic shift is associated with a reduction in soil carbon stocks, particularly with long-term warming, which decreases the recalcitrant carbon pool by 14% (Chen *et al.*, 2020) ^[13].

Table 1: Changes due to enzymes.

Enzyme	Changes	Reference
Phosphatase	Rapid Phosphorous mobilisation	Martinez <i>et al.</i> , 2022 ^[29]
Dehydrogenase	Increase Microbial respiration.	Wang <i>et al.</i> , 2021 ^[52]
B-Glucosidase	Improves Carbon cycling.	Smith <i>et al.</i> , 2019 ^[43]
Phosphatase	Increase Phosphorous mobilisation.	Garcia <i>et al.</i> , 2018
Ligninase	Increase Microbial Respiration.	Chen <i>et al.</i> , 2018 ^[35]

Condition	Enzyme activity	Enzyme	Change in activity (%)	Reference
Temperature increase	Increase in mass-specific enzyme activity	Nitrogen, Phosphorus, Carbon degrading enzymes.	10-30% increase in activity.	Steinweg <i>et al.</i> , (2013) ^[57]
Drought	Reduction in microbial biomass	Dehydrogenase, Phosphatase	21% reduction in heterotrophic respiration.	Chen <i>et al.</i> , (2018) ^[35]
Precipitation increase.	Increase in enzyme production and microbial biomass.	Phosphatase	15-25% increase in activity.	Allison <i>et al.</i> , (2005) ^[58]
Seasonal changes like Temperature & moisture	Strong seasonal variation.	Nitrogen, Phosphorus, Carbon acquiring enzymes.	Seasonal variation up to 40%.	Sinsabaugh <i>et al.</i> , (2009) ^[59]

2.3 Impact on respiration

Repeated cycles of drying and wetting can cause long-lasting changes in the functional state of soils, which can be measured through soil respiration - the process by which microbes break down organic matter and release carbon dioxide (CO₂). The way soil respiration responds to these cycles depends on how the land has been used in the past. Soils that were previously used for farming (arable agriculture) are more likely to undergo a sudden change in their respiration rates compared to soils that have a history of being grasslands, which tend to be more stable in their respiration response. This suggests that land use history plays a significant role in determining how soil respiration and

overall soil function respond to environmental stress (Bardgett *et al.*, 2020) ^[15]. The temperature response of soil microbial respiration (Rh) is crucial for understanding how these microorganisms will react to climate change, especially as temperatures rise. A recent study that analysed 25 soil samples from various forests, ranging from tropical to cold-temperate regions, found that the optimum temperature (for Rh) is much higher than previously thought between 38.5 and 46.0 °C, compared to the old benchmark of 35 °C. This discovery highlights that varies significantly across different climates, with northern regions potentially releasing more CO₂ as temperatures rise (Liu *et al.*, 2018) ^[27].

Table 3: Respiration rate of different microbes.

Microbes	Examples	Rate of Respiration (μmol CO ₂ /g soil/ha)	Reference
Fungi	Aspergillus, Penicillium	0.5-3.5	Smith <i>et al.</i> , (2023) ^[44]
Bacteria	Bacillus, Pseudomonas	0.3-4.0	Auffret <i>et al.</i> , (2016) ^[1]
Archaea	Archaea Methanobacteria	0.02-1.0	Schindlbacher <i>et al.</i> , (2012) ^[36]
Actinobacteria	Streptomyces	0.5-2.0	Smith <i>et al.</i> , (2023) ^[44]

3. Impact on soil health and functions

3.1 Soil structure & aggregate stability

The breakdown of soil structure and weakening of aggregate stability due to climate change has significant consequences for both soil health and agricultural productivity. When soil aggregates weaken, they easily break apart, which increases the risk of erosion, strips away valuable topsoil, and reduces the soil's ability to absorb water. As a result, soils become less effective at holding onto essential nutrients and moisture, directly impacting crop yields. This issue is particularly pressing in arid and semi-arid regions, where water is already scarce. In these areas, declining soil quality can further threaten food

production, compounding the challenges faced by farmers (Schlesinger & Andrews, 2000) ^[37]. Soil microbiomes play a crucial role in agroecosystems, driving soil fertility, crop productivity, and stress resilience. Their functions are closely tied to soil structure, including aggregation and pore connectivity, which regulate water, oxygen, and nutrient flow. Agricultural practices can alter soil structure, impacting microbial processes and leading to issues like soil erosion and reduced fertility. Sustainable practices like integrated soil fertility management aim to improve soil structure and enhance microbial biodiversity (Hartmann *et al.*, 2023) ^[21].

Table 4: Parameters to measure aggregate stability.

Parameter	Interpretation	Assessment method	References
Mean weight diameter	Average diameter of soil aggregates.	Dry or wet sieving technique.	Zhang <i>et al.</i> , 2023 ^[26]
Soil organic carbon	Carbon within soil aggregates, related to stability.	Dry combustion	Zhang <i>et al.</i> , 2023 ^[26]
Bulk Density	Indicates Soil compaction.	Core sampling.	Phefadu & Munjonji, ^[33] 2024
Aggregate size distribution	Distribution of aggregate sizes which shows stability across different sizes.	Image analysis and sieving.	Phefadu & Munjonji, 2024 ^[33]

3.2 Soil erosion & compaction

Soils are essential for food security and providing various ecosystem services, but climate change poses significant challenges to their health. It affects soils directly through shifts in temperature, rainfall, and moisture levels, and indirectly through adaptations like irrigation and changes in crop rotation. A review of 20 case studies across Europe revealed that while many adaptation strategies can help reduce soil erosion and boost soil organic carbon, they might also lead to increased compaction in some areas (Hamidov *et al.*, 2018) ^[20]. Climate

and land use changes significantly impact soil erosion and land degradation. A study focused on a critical dam watershed near the Strait of Hormuz examined how these factors affect soil erosion now and, in the future (Azimi *et al.*, 2019) ^[2]. Using advanced modelling techniques, the study found that rainfall erosivity is expected to increase under various climate scenarios, with the highest erosivity projected for 2030. Future land use changes are likely to convert rangelands into agricultural areas, resulting in decreased vegetation cover and increased soil erosion, which could reach up to 14.5/ha/year. Among the

various factors contributing to soil erosion, the soil cover (C factor) is one that watershed managers can actively manage to help reduce soil loss and mitigate the adverse effects of climate change (Azimi *et al.*, 2019)^[2].

3.3 Rate of decomposition

Microbial decomposition of soil organic matter (SOM) plays a significant role in the carbon cycle by releasing up to 60 peta-

grams (Pg) of carbon as CO₂ from soils into the atmosphere each year. This amount is about six times greater than the current annual rate of human-caused (anthropogenic) carbon emissions, making microbial decomposition a crucial part of the global carbon cycle. Studies have shown that microbial decomposition of SOM generally increases exponentially with temperature (Moinet *et al.*, 2021)^[31].

Table 5: Rate of decomposition of different soil organic matter.

Soil organic matter	Rate of decomposition	Reference
Polysaccharides	Fast to moderate. Usually fast because microbes prefer carbohydrates.	Rong <i>et al.</i> , 2024
Protein	Moderate to slow.	Shen <i>et al.</i> , 2024
Fats	Slowest because of hydrophobic property and microbial attack resistance.	Zhang <i>et al.</i> , 2024

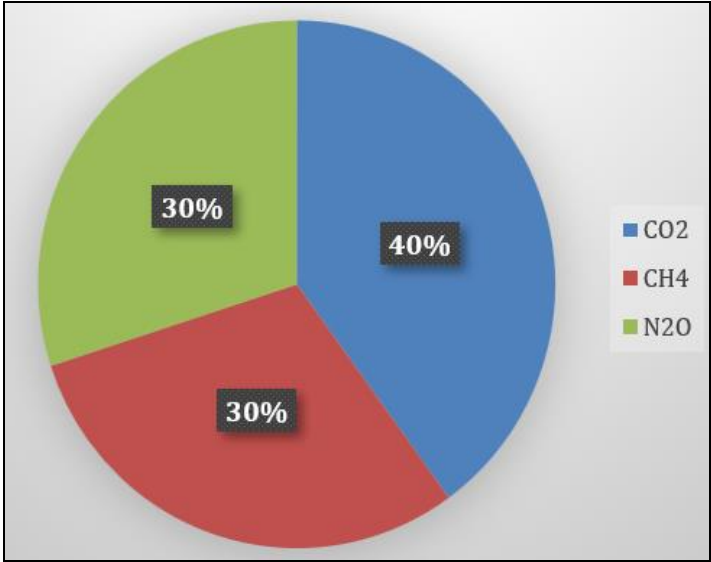


Fig 1: Percentage share of Greenhouse gases impacting nutrient cycling.

3.4 Nutrient cycling

Soil microbiomes consist of a wide variety of microorganisms, including bacteria, fungi, archaea, viruses, and protozoa. These microbes are crucial for cycling nutrients in the soil, which means they help break down and recycle essential elements. This process is important for keeping the soil healthy, supporting plant growth, and even influencing the climate. As microbes cycle nutrients, they can either release or absorb greenhouse gases like carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). This happens because different microbes have different roles and capabilities. Some microbes may release these gases into the atmosphere, while others might help reduce their levels. This diversity in microbial functions helps regulate not only soil health and plant growth but also

impacts the climate by controlling the levels of greenhouse gases (B Mohanty *et al.*, 2021)^[30]

3.5 Impact on chemical properties

Climate change significantly impacts carbon sequestration by altering key factors such as temperature, CO₂ levels, and precipitation, which influence nutrient cycles like mineralization, decomposition, and leaching in soils. These changes affect soil fertility and plant nutrient availability. Enhancing soil carbon sequestration through effective management practices is critical not only for mitigating climate change but also for improving plant nutrition and boosting agricultural productivity, particularly in developing regions facing food security challenges (Elbasiouny *et al.*, 2022)^[16].

Table 6: Rate of carbon sequestration.

Ecosystem	Rate of carbon sequestration	Reference
Forests	2-10 Mg C/ha/yr	Lal, R. 2020
Grasslands	0.3-3 Mg C/ha/yr	Conant <i>et al.</i> , 2001 ^[11]
Wetlands	3-12 Mg C/ha/yr	Mitsch <i>et al.</i> , 2000
Agriculture practices	0.1-1 Mg C/ha/yr	Lal, R. 2004 ^[25]

4. Resistance of soil microbes to climate change

4.1 Resistance to drought & water stress.

Soil properties, like the amount of organic matter and texture, can influence how well soil microbial communities resist and recover from climate extremes. For example, these properties

can affect the impact of environmental changes by determining how much water the soil can hold, which influences moisture availability during droughts. Repeated droughts can help microbial communities become more tolerant to future cycles of dry and wet conditions (Bardgett *et al.*, 2020)^[15]. This increased

tolerance mainly happens because the community reorganizes itself, favouring microbial groups that are better able to survive during droughts. As the environment changes, these drought-resistant microbes become more dominant, making the entire community more resilient to similar stress in the future. They can also shape the inherent characteristics of soil microbial communities. A global meta-analysis found that soils with high organic carbon content and a balanced pH had less variation or instability in microbial biomass over time, suggesting that these factors help reduce stress and enhance the stability of soil microbial communities (Bardgett *et al.*, 2020)^[15].

4.2 Role of mutualistic relationships.

In a microbial community, the overall abilities and functions of the microbiome go beyond just the individual microbes present. This is because different microbial species interact with each other in complex ways and with the host plants in various types of relationships: mutualistic, synergistic, commensalistic, amensalistic, or parasitic. These interactions affect each microbe's survival, growth, and reproduction. When focusing on mutualistic relationships, where both the microbes and plants benefit from each other, these interactions become especially important in resisting climate change. For example, mutualistic soil microbes can help plants better absorb nutrients and water, making them more resilient to environmental stresses like drought or extreme temperatures. This improved plant health supports soil fertility, which in turn creates a healthier environment for the microbes, reinforcing the entire system's ability to cope with climate change impacts (Suman *et al.*, 2022).

Conclusion

The impact of climate change on soil microbial communities is complex and transformative, affecting both soil health and its role in supporting ecosystems. As temperatures rise and rainfall patterns shift, microbial habitats change, altering the balance of species and the activity of key enzymes. Elevated CO₂ and fluctuations in soil moisture also influence microbial respiration, nutrient cycles, and decomposition rates. Increased UV exposure further disrupts microbial functions, while soil structure and stability weaken, leading to erosion and compaction issues. Climate-driven stresses like drought test microbes' resilience, affecting their ability to support plant growth and maintain essential mutualistic relationships with plants. Together, these changes reshape the intricate web of life belowground, ultimately impacting soil fertility, carbon storage, and agricultural productivity.

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