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MICROBIAL RESPONSES TO SHIFTING CLIMATE PATTERNS

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ABSTRACT

The intricate connection between microbial biodiversity and climate-induced shifts is crucial for understanding climate change impacts. Microbial communities, often overlooked, play pivotal roles in nutrient cycling, disease dynamics, and ecosystem health. Climate change, with altered precipitation and rising temperatures, reshapes microbial biodiversity, impacting ecosystems, agriculture, and disease dynamics. Microbial responses showcase adaptability and resilience, maintaining crucial ecosystem functions amid environmental changes. Extremophile studies highlight microorganisms' ability to thrive in extreme conditions, emphasizing their resilience against stressors. Concerns about biodiversity loss underscore the need for conservation, recognizing potential disruptions to vital processes. The interplay between microbial diversity and disease dynamics emphasizes links between climate change and pathogens, making conservation and restoration crucial. Proactive measures, including microbiome-based techniques, promise to mitigate climate change consequences. Integrating microbial biodiversity into climate policies is imperative, recognizing microbes as integral for addressing climate change. Assessing and conserving microbial diversity safeguards biological networks, ensuring ecosystem stability. Understanding and managing microbial responses are essential for resilient ecosystems. Despite their size, microbes play monumental roles in ecosystem functioning, highlighting interconnectedness. Proactive conservation and research are vital for navigating challenges posed by climate-induced shifts. This article offers a concise overview of microbial responses to climate change, focusing on processes, community structures, and implications for ecosystem functioning.

Keywords: Acclimation, Climate change, Ecosystem, Microbial ecology, Microorganisms, Stress adaptation

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1. INTRODUCTION

The greatest reservoir of biodiversity on our planet resides within the realm of microorganisms. These tiny life forms, imperceptible to the human eye, play a pivotal role in driving global processes related to energy and matter cycling. Their distribution across the Earth is constrained by only a handful of factors, such as extreme temperature (>121°C), highly acidic or alkaline pH (12.5), and water availability (Hutchins et al. 2019). Consequently, microbes thrive in nearly every conceivable habitat on our planet, from hot springs to glacier ice, from the atmosphere to terrestrial subsurface environments, and within groundwater ecosystems.

Microbial metabolic activities, nutrient cycling, and carbon sequestration are directly influenced by climatic shifts. Studies have demonstrated alterations in microbial enzymatic activities, affecting processes such as carbon mineralization, nitrogen fixation, and phosphorus cycling (He et al. 2020; Huang et al. 2023). Changes in temperature and precipitation patterns induce shifts in microbial community structures, with implications for biodiversity and ecosystem resilience. Shifts in the abundance and diversity of microbial taxa have been observed in diverse ecosystems, including soil, freshwater, and marine environments (Weiskopf et al. 2020; Vuong et al. 2022; Bello et al. 2023). Microbial responses to climate change also have implications for human health, particularly in the context of infectious diseases and food safety. Altered climatic conditions may affect the distribution and abundance of pathogenic microorganisms, influencing the prevalence of vector-borne diseases and foodborne pathogens (Lafferty 2017).

Recognizing the vital role of microorganisms in ecosystem and human well-being underscores the urgency of incorporating microbial dynamics into climate change mitigation and adaptation strategies. This article, therefore, provides a glimpse into the intricate relationship between microbial life and shifting climate patterns. It explores the multifaceted influence of climate change on microbial communities, emphasizing its effects on biodiversity, ecosystem services, and feedback mechanisms. By synthesizing recent research findings, we aim to contribute to the growing body of knowledge that informs our understanding of microbial responses to climate change.

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1.1. The Importance of Microbial Biodiversity in Ecosystems

Microbial biodiversity, encompassing the vast array of microorganisms such as bacteria, archaea, fungi, and viruses, constitutes a fundamental component of ecosystems worldwide (Shivanna 2022). Although often overlooked, microbial life plays a crucial role in shaping the structure and functioning of ecosystems. One of the primary roles of microbial biodiversity in ecosystems is its involvement in nutrient cycling. Microorganisms are the key drivers of biogeochemical cycles, including carbon, nitrogen, phosphorus, and sulfur cycles. For instance, soil bacteria and fungi break down organic matter, releasing essential nutrients for plant uptake. Nitrogen-fixing bacteria convert atmospheric nitrogen into forms that plants can assimilate, enhancing plant growth. In aquatic ecosystems, microbial communities play a vital role in mineralizing organic matter, thus recycling nutrients essential for aquatic life (Blewett et al. 2022).

Microbial biodiversity contributes to the stability and efficiency of these nutrient cycles. Diverse microbial communities can access and degrade a wider range of organic compounds, making ecosystems more resilient to disturbances (Abdurrahman et al. 2020). In contrast, reduced microbial diversity may lead to imbalances in nutrient cycling, potentially resulting in nutrient limitations or excesses. Microbial biodiversity also influences ecosystem resilience, the capacity to withstand and recover from disturbances (Delgado-Baquerizo et al. 2018). Diverse microbial communities enhance ecosystem stability by increasing functional redundancy. Functional redundancy occurs when multiple species perform similar ecological functions, ensuring that essential processes continue even if some species are lost due to disturbances or environmental changes. Studies have shown that ecosystems with high microbial biodiversity are more resistant to disturbances such as pollution, invasive species, and climate change impacts (Mishra et al. 2023; Qian and Wang 2023; Buenaño-Vargas et al. 2024). In marine ecosystems, for example, diverse microbial communities can mitigate the harmful effects of oil spills by degrading hydrocarbons and aiding in ecosystem recovery (Abirami et al. 2021).

The importance of microbial biodiversity extends beyond ecological processes, directly impacting human well-being. Microorganisms contribute to various ecosystem services that benefit human societies. For instance, soil microbes enhance crop production by aiding nutrient uptake and suppressing plant pathogens. Additionally, microbial communities in natural water bodies contribute to water purification through biodegradation of pollutants. Microbes also play a pivotal role in human health. The human gut microbiome, composed of trillions of microorganisms, influences digestion, metabolism, and immune system development. Disruptions in the gut microbiome have been linked to various health issues, including inflammatory bowel diseases, allergies, and metabolic disorders (Human Microbiome Project Consortiu 2012). Understanding the diversity and functions of gut microbes has opened doors to innovative approaches in personalized medicine and nutrition.

Recognizing the importance of microbial biodiversity, conservation efforts are increasingly incorporating microbial conservation into ecosystem management strategies. Conservation biologists and ecologists are developing methods to assess microbial diversity and monitor changes in response to environmental disturbances. Protecting microbial biodiversity is becoming integral to preserving overall ecosystem health.

1.2. The Influence of Climate Change on Microbial Communities

Microbial communities, comprising bacteria, archaea, fungi, and viruses, are ubiquitous and essential components of ecosystems worldwide (Hutchins et al. 2019). These microscopic organisms play pivotal roles in various ecological processes, including nutrient cycling, decomposition, and maintaining ecosystem stability. However, the ongoing changes in global climate patterns are significantly impacting microbial communities, which, in turn, can have far-reaching consequences for ecosystems and human societies (Hua et al. 2022). Microbial biodiversity is highly sensitive to environmental changes, including alterations in temperature, precipitation, and carbon availability. Climate change-induced shifts in these factors can lead to changes in microbial community composition and diversity. For instance, rising temperatures can favor the proliferation of certain microbial taxa while suppressing others, potentially reducing overall diversity (Fierer et al. 2012). Additionally, altered precipitation patterns can impact soil moisture, affecting microbial communities' structure and function (Zhang and Xi 2021).

Changes in microbial diversity can, in turn, influence ecosystem processes. Reduced microbial diversity may lead to decreased functional redundancy, making ecosystems more vulnerable to disturbances (Delgado-Baquerizo et al. 2018). Conversely, shifts in microbial community composition can affect nutrient cycling, decomposition rates, and plant-microbe interactions, thereby altering ecosystem dynamics (Raza et al. 2023).

1.3. Impacts on Ecosystem Services and Feedback Mechanisms

Microbial communities provide essential ecosystem services, including nutrient cycling, disease suppression, and soil fertility maintenance. Climate change-induced disruptions in microbial communities can jeopardize these services. For example, alterations in soil microbial communities can affect nutrient availability to plants, potentially impacting crop yields and food security (He et al. 2020). Changes in disease-suppressive microorganisms can lead to increased disease prevalence in agricultural systems (Bras et al. 2021; Bello et al. 2020).

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Furthermore, shifts in microbial communities can influence carbon sequestration and greenhouse gas emissions. Microbes are key players in carbon cycling, and changes in their activity can impact the net carbon balance of ecosystems. Some microbial groups, such as methanogens, are directly involved in methane emissions, a potent greenhouse gas (Bridgham et al. 2013). Climate-induced changes in the abundance and activity of these microbes can exacerbate greenhouse gas emissions, creating a positive feedback loop.

Climate change can also trigger feedback mechanisms involving microbial communities. For instance, thawing permafrost releases ancient organic carbon, providing a new energy source for microbes (Hultman et al. 2015). Microbial decomposition of this carbon can release substantial amounts of greenhouse gases into the atmosphere, further contributing to global warming. These feedback loops can accelerate climate change impacts, creating challenges for mitigating its effects.

1.4. Adaptation and Mitigation

Understanding the interactions between climate change and microbial communities is crucial for mitigating potential negative consequences. Research into microbial responses to climate change can inform adaptive management strategies. For example, selecting crop varieties that interact favorably with specific microbial communities can enhance agricultural resilience (Sánchez-Cañizares et al. 2017). Similarly, managing land use and water resources to support microbial diversity can contribute to ecosystem stability. Additionally, microbial technologies, such as bioenergy production and bioremediation, can play a role in climate change mitigation efforts. Harnessing microbial processes for carbon capture and utilization holds promise for reducing greenhouse gas emissions (Sejiyan et al. 2016).

1.5. Evidence of Changes in Microbial Diversity Due to Climate Change

Microorganisms play a variety of roles in biogeochemical cycles though they are invisible and intangible. Changes in microbial diversity and activities undoubtedly have effects on all other higher organisms since microbes provide a myriad of supports to other life forms and they are the basis for the functioning of many healthy ecosystems (Cavicchioli et al. 2019). The roles of microorganisms are critical in nutritional cycles, such as carbon and nitrogen, animal health and plant health, agricultural yields as well as food security. There is a synergistic relationship between microbes and climate change since microorganisms can directly affect climate change owing to their involvement in the generation of greenhouse gas (GHG) and are also part of the solution to the mitigation of climate change coupled with the fact that environmental modifications have great impact on microbial diversity.

The impact of climate change on microbial diversity is complex and significant but hard to quantify. Global warming among other environmental factors significantly causes variation in soil microbial diversity and also helps in shaping microbial diversity compared to other proposed environmental drivers due to the increased surface soil temperature and decrease in moisture content. Temperature changes have impacts on both bacterial and fungal diversity at various levels; geographical range, phenology, distribution or abundance (Guo et al. 2018**.** Increasing temperature leads to an exponential microbial metabolism, population growth rate, and species number and vice versa. It is well-known that an increase in temperature leads to higher rates of metabolism, resulting in increased population doubling times and the rates of ecological and evolutionary processes, including mutation, speciation, and interactions (Guo et al. 2019; Yuan et al. 2021).

In soil ecosystem, a shift in nutrient allocation as a result of higher temperatures leading to an increase in the number of plant species could in turn lead to changes in plant–microbe interactions for plant growth-promoting rhizobacteria (PGPR) that rely on rhizodeposition (Singh et al. 2019; Sharma et al. 2022). Also, formation of mycorrhizal mycelium in plant roots was negatively impacted due to the alterations in precipitation patterns and drought stress associated with climate (Singh et al. 2019; Zhang and Xi 2021). Sharma et al. (2022) opined that changes in climatic conditions contributed to an increased incidence of environmental stresses which can enhance the activities of pathogens and heterotrophic microorganisms, leading to the redistribution of beneficial microbes across different ecological niches

Increased temperatures accelerate microbial decomposition activities, leading to faster CO_2 emissions. As a result, soils become a carbon dioxide source rather than a sink. It has been reported that an increase in atmospheric CO_2 stimulate rhizosphere-colonizing bacteria such as *Burkholderia* and *Pseudomonas* including plant-growth-promoting fungi while non-rhizospheric bacteria such as *Bacillus* species were not stimulated (Ibáñez et al. 2023). Moreover, temperature and soil humidity play important roles in microbial-soil abundance, diversity, and metabolic functionality, since climatic factors greatly modify the type and quantity of some plant species (Pugnaire et al. 2019).

In aquatic ecosystems, climate change may affect seawater acidification, hypoxia, CO_2 accumulation, salinity, or sea level modifications (Lafferty 2017). These changes disturb marine ecosystems, including microbial biodiversity which account for 90% of marine biomass and form the basis of marine food webs and are responsible for important biogeochemical cycles (Hillebrand et al. 2018). Wang et al. (2021) observed that warmer oceans altered microbial communities while Hutchins and Fu (2017) reported that ocean warming caused losses in microbial populations.

Jain et al. (2020) observed that bacteria are the most significantly affected by climate change at both genotypic and phenotypic levels among other aquatic microorganisms and these have been attributed to their small size. It is therefore essential to take cognizance of the adverse effects of climate change on microorganisms because of their beneficial roles. Microbial activities *vis a vis* climate change can impact various environments (Table 1).

Table 1: Microbial Activities and Climate Change Impacts Across Different Environments

Environment	Microbial Activity	Climate Change Impact
Hot Springs	Thermophilic microbes thrive, involved in nutrient cycling.	Shifts in temperature can alter community composition.
Glacier Ice	Psychrophilic microbes persist, involved in carbon cycling.	Melting ice changes habitat availability and microbial activity.
Atmosphere	Airborne microbes influence cloud formation and weather.	Altered precipitation patterns impact distribution.
Terrestrial Subsurface	Microbes drive nutrient and carbon cycling in soil layers.	Temperature and moisture changes affect microbial processes.
Groundwater Ecosystems	Microbes degrade pollutants, recycle nutrients.	Water availability changes impact microbial community structure.
Soil Ecosystems	Microbes involved in decomposition, nutrient cycling.	Changes in temperature and precipitation affect diversity and function.
Freshwater Ecosystems	Microbes mineralize organic matter, recycle nutrients.	Altered water temperatures and flow patterns affect microbial dynamics.
Marine Ecosystems	Microbes degrade organic matter, contribute to carbon cycling.	Ocean acidification and temperature changes affect microbial activities.

2. MICROBIAL RESPONSES TO CHANGING CLIMATE

Climate change is the most serious challenge facing humanity. Microbial responses to changing climate refer to how various microorganisms adapt and interact in response to shifts in environmental conditions caused by climate change. These responses can include alterations in distribution, abundance, and metabolic activities of these microorganisms (Malhi et al. 2020; Sharma et al. 2022). For instance, rising temperatures can impact microbial communities in soil, oceans, and other environments (Weiskopf et al. 2020). Some species may thrive in warmer conditions, while others may struggle or decline. Additionally, changes in precipitation patterns and nutrient availability can influence microbial composition and function (Preciado et al. 2019).

These responses are crucial, as microorganisms play vital roles in nutrient cycling, decomposition, and other ecological processes. They also have implications for human health, agriculture, and the overall stability of ecosystems. Microbial research is needed to help ameliorate the warming trajectory and cascading effects resulting from heat, drought, and severe storms (Sagova-Mareckova et al. 2021; Hamza et al. 2023). Many humans, determine whether they carry out the production or consumption of these gases. In some cases, we can manage conditions to favor microbial consumption of these gases. Research helps us grasp the complex interplay between climate change and microbial life, aiding in the development of strategies to mitigate its impacts (Nikolova and Gutierrez 2020; Abbass et al. 2022; Alegbeleye et al. 2022; Tiedje et al. 2022). The following factors influence microbial adaptions to climatic variations:

2.1. Temperature

Microbial responses to temperature involve how microorganisms react and adapt to variations in temperature within their environment. This is a critical aspect of microbial ecology, as temperature is a fundamental factor that influences their growth, metabolism, and overall behavior. Microorganisms dominate the decomposition of organic matter and their activities are strongly influenced by temperature (Tan et al. 2022).

Temperature directly affects microbial growth rates. Generally, microorganisms have an optimal temperature range for growth, beyond which their activity decreases. This range varies among different species. Also, temperature changes can lead to shifts in the composition of microbial communities. Some species may become more dominant, while others may decline. Temperature influences the rates of enzymatic reactions within microbial cells. Higher temperatures can lead to faster metabolic processes, while lower temperatures may slow them down. Microorganisms have various mechanisms to adapt to temperature changes (Classen et al. 2015). These can include changes in membrane composition, production of specific enzymes, or even the development of specialized structures like spores. Microbial responses to temperature can have broader ecological impacts. For instance, alterations in microbial communities can affect nutrient cycling, which in turn influences plant growth and overall ecosystem health (Muhammad et al. 2020; Zhou et al. 2023).

Comprehending how microorganisms respond to temperature changes is crucial for predicting and mitigating the impacts of climate change on ecosystems and human activities. It also has applications in areas such as agriculture, biotechnology, and public health (Abbass et al. 2022; Malhi et al. 2020) (Table 2).

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2.2. Precipitation

Precipitation patterns play a crucial role in shaping microbial communities and their activities in various ecosystems. Changes in precipitation can lead to shifts in the abundance and diversity of microbial communities. Precipitation affects the availability of water, which is essential for microbial metabolic processes. During wet periods, microbial activity can increase due to higher water content, while dry periods may slow down metabolic rates. Precipitation influences the transport and availability of nutrients in an ecosystem. Microbes play a crucial role in nutrient cycling, and changes in precipitation can alter these processes (Hu et al. 2020; Mishra et al. 2023). Microbes have various strategies to cope with fluctuating water availability. Some can enter a dormant state or form spores to survive dry periods, while others may become more active during wet spells (Li et al. 2022).

Microbial communities can show resilience or vulnerability to extreme precipitation events, such as floods or droughts. Understanding microbial responses to precipitation is crucial for predicting how ecosystems will be affected by changes in climate patterns. It also has implications for agriculture, water resource management, and ecological conservation efforts (Bardgett and Caruso 2020; Mishra et al. 2021; Furtak and Wolińska 2023).

Table 2: Summary of the Microbial Responses to Changing Climate

Factor	Description	Impact	References
Temperature	Microbial responses to temperature variations in their environment.	Temperature affects microbial growth rates, community composition, enzymatic activity, and overall ecosystem health. Microbes adapt through changes in membrane composition, enzyme production, and specialized structures like spores.	Tan et al. (2022); Muhammad et al. (2020); Zhou et al. (2023); Abbass et al. (2022); Malhi et al. (2020).
Precipitation	Microbial responses to changes in precipitation patterns.	Influences water availability, nutrient transport, and microbial metabolic processes. Microbes adapt through dormancy, spore formation, and increased activity during wet periods. Impacts agriculture, water management, and conservation.	Hu et al. (2020); Mishra et al. (2023); Bardgett and Caruso (2020); Mishra et al. (2021); Furtak and Wolińska (2023).
Microbial Activity	Role of microbial activity in climate change and its responses.	Microbes influence greenhouse gas emissions (methane, carbon dioxide), nutrient cycling, plant-microbe interactions, and carbon sequestration. Climate changes alter microbial community composition and activity, impacting feedback loops.	Cadena et al. (2019); Wallenius et al. (2021); Naylor et al. (2020); Raza et al. (2023); Dean et al. (2018); Salimi et al. (2021).
Adaptation and Acclimation	Microbial genetic and phenotypic responses to environmental changes.	Includes genetic changes, horizontal gene transfer, evolutionary response, enzyme development, stress response systems, phenotypic plasticity, metabolic flexibility, gene expression regulation, membrane adjustments, and osmoregulation.	Qu et al. (2023); Mishra et al. (2021); Qian and Wang (2023); Buenaño-Vargas et al. (2024); Montaño-Salazar et al. (2023).
Policy and Management	Strategies to manage microbial responses to climate change.	Encompasses research, integration into climate models, conservation, sustainable land use, education, policy incentives, and international collaboration. Aims to leverage microbial biodiversity for climate mitigation and adaptation.	Shah et al. (2021); Trivedi et al. (2022); Kumawat et al. (2022); Okon et al. (2021).
Practical Recommendations	Recommendations for sustainable land and resource management.	Promotes sustainable agriculture, agroecological approaches, ecosystem protection, sustainable forestry, water management, biodiversity conservation, climate-resilient planning, carbon farming, research, innovation, and community engagement.	Okon et al. (2021); Auzins et al. (2022); Koshkalda et al. (2023).

2.3. Microbial Activity

Microbial activity plays a significant role in climate change, both as a driver and responder to environmental shifts. Certain microorganisms, called methanogens, produce methane as part of their metabolic processes which contribute to the greenhouse effect. Changes in temperature and environmental conditions can influence the activity of methanogens, potentially leading to increased methane emissions (Cadena et al. 2019; Wallenius et al. 2021). Also, soil microbes are crucial for carbon cycling. They decompose organic matter and release carbon dioxide, but they also play a role in carbon sequestration. Changes in temperature, moisture, and nutrient availability can affect the balance between these processes, influencing overall carbon levels in ecosystems.

Changes in climate can alter the composition and activity of microbial communities. For example, warmer temperatures can favor the growth of certain microbes over others. These shifts can, in turn, influence nutrient cycling, plant-microbe interactions, and even the release of greenhouse gases, creating feedback loops that further impact climate change (Naylor et al. 2020; Raza et al. 2023). Microbes in thawing permafrost can release stored carbon in the form of greenhouse gases. This can exacerbate climate change by adding more carbon dioxide and methane to the atmosphere. Ocean microbes, including phytoplankton, play a vital role in regulating the Earth's climate by absorbing carbon dioxide. However, increasing levels of carbon dioxide are leading to ocean acidification, which can affect the composition and functioning of marine microbial communities (Dean et al. 2018; Salimi et al. 2021).

2.4. Microbial Adaptation and Acclimation

These strategies enable microorganisms to thrive in a wide range of environments, from extreme habitats like deep-sea vents to temperate soils. This knowledge is crucial in fields like microbiology, ecology, and biotechnology, as it helps predict how microbial communities might respond to environmental changes, including those induced by human activities or climate shifts. Microbial adaptation encompasses diverse systems that enable microorganisms to thrive in their environments:

2.4.1. Genetic Changes: Microbes exhibit adaptability through genetic mutations, fostering the emergence of new traits optimized for their surroundings. This adaptive process often unfolds through natural selection mechanisms (Qu et al. 2023).

2.4.2. Horizontal Gene Transfer: Microbial adaptation extends to the exchange of genetic material among microbes, facilitating the swift acquisition of advantageous traits without the necessity of reproductive cycles (Mishra et al. 2021; Qian and Wang, 2023).

2.4.3. Evolutionary Response: Over successive generations, microbial populations undergo evolutionary changes, refining their adaptations to specific environments. These adaptations may manifest as alterations in physiology, metabolism, or behaviour (Qu et al. 2023).

2.4.4. Specialized Enzymes: Microbes showcase adaptability by developing or enhancing specific enzymes tailored for metabolizing and utilizing available resources in their surroundings, a particularly crucial mechanism in extreme conditions (Qian and Wang, 2023)

2.4.5. Stress Response Systems: Microbial resilience is highlighted through specialized systems that activate in response to stressors, enabling them to cope with adverse conditions. These responses encompass the production of protective proteins or alterations in metabolic pathways (Mishra et al. 2021; Shahzad 2023; Qian and Wang 2023).

2.5. Microbial Acclimation Encompasses Various Strategies

***2.5.1. Phenotypic Plasticity*:** Microbes showcase adaptability through phenotypic plasticity, adjusting their biochemical and physiological properties without necessitating genetic changes. This enables them to efficiently navigate short-term fluctuations in their environment (Buenaño-Vargas et al. 2024).

***2.5.2. Metabolic Flexibility*:** Microbes exhibit metabolic flexibility by seamlessly transitioning between different metabolic pathways or utilizing diverse energy sources based on the availability of resources. This dynamic capability empowers them to optimize growth and survival across diverse conditions (Qu et al. 2023).

***2.5.3. Regulation of Gene Expression*:** Microbial acclimation includes the nuanced regulation of gene expression in response to environmental shifts. This strategic adjustment allows microbes to fine-tune which genes are activated or deactivated, optimizing cellular processes to match prevailing conditions (Buenaño-Vargas et al. 2024).

2.5.4. Membrane Adjustments: Microbes strategically modify membrane composition to uphold fluidity and integrity, particularly crucial under varying temperature or chemical conditions. This adaptation ensures optimal functionality in dynamic environmental settings (Montaño-Salazar et al. 2023).

2.5.5. Osmoregulation: Microbes demonstrate osmoregulation prowess, adeptly regulating internal osmotic pressure to adapt to changes in salinity or water availability. This intricate mechanism allows them to thrive across diverse water-related challenges (Mishra et al. 2021).

3. POLICY AND MANAGEMENT CONSIDERATIONS

Managing microbial responses to climate change involves a multi-faceted approach that encompasses both policy and practical considerations. By incorporating microbial biodiversity into climate change policies, the potential of microorganisms in climate mitigation and adaptation efforts can be better harnessed. This approach recognizes the intricate web of life, including microorganisms, that sustains ecosystems and ultimately supports human well-being. This policy is crucial for creating comprehensive and effective strategies to mitigate and adapt to climate change. Some of the steps to consider include the following:

3.1. Research and Data Collection

This involves the baseline assessment and establishment of long-term monitoring programs. The former is conducted through assessments of microbial biodiversity in different ecosystems including soils, oceans, forests, and wetlands (Shah et al. 2021). Understanding the existing microbial communities provides a foundation for policy development. The latter is the establishment of long-term monitoring programs to track changes in microbial biodiversity over time. This helps identify trends, potential threats, and areas of concern.

3.2. Integration into Climate Models

These are achieved by the climate modeling tools which involves the integration of microbial data and models into existing climate change models. This can improve predictions of greenhouse gas emissions, nutrient cycling, and other microbial-mediated processes (Trivedi et al. 2022). The feedback mechanisms are also critical and this includes the incorporation of feedback loops between microbial communities and climate variables in modeling efforts. This can help capture the complex interactions between microorganisms and their environment

3.3. Conservation and Restoration Efforts

The preservation of biodiversity hotspots involves the identification and prioritization of regions boasting high microbial biodiversity to facilitate targeted conservation endeavors, thereby safeguarding distinctive and ecologically valuable microbial communities (Shah et al. 2021). Complementary to this proactive approach, restoration practices play a pivotal role by executing projects designed to rehabilitate habitats facing depletion in microbial biodiversity. Such initiatives encompass diverse measures, ranging from comprehensive reforestation efforts to wetland restoration and soil rehabilitation strategies. By combining these conservation and restoration strategies, there is a collective endeavor to sustain and revive ecosystems, fostering the resilience and vitality of microbial life within these crucial ecological niches.

3.4. Promoting Sustainable Land Use Practices

Agroecology and sustainable agriculture advocate for the promotion of agricultural practices that foster the well-being of soil microbial communities, encompassing measures such as minimized tillage, the implementation of cover cropping, and the adoption of organic farming methods. In the realm of urban planning and design, emphasis is placed on integrating microbial considerations into the urban landscape. This involves the incorporation of green infrastructure that not only contributes to ecological sustainability but also facilitates the establishment and sustenance of diverse microbial communities within urban environments (Trivedi et al. 2022). By actively integrating these practices, a holistic approach is taken towards ensuring the health and resilience of both agricultural and urban ecosystems, harmonizing human activities with the intricate dynamics of microbial life.

3.5. Education and Awareness

Stakeholder engagement involves the active involvement of policymakers, scientists, land managers, and the public in discussions concerning the significance of microbial biodiversity in climate change mitigation and adaptation. The emphasis is placed on fostering a collective understanding and appreciation of the pivotal role played by microorganisms. Concurrently, educational programs are devised to illuminate the role of microorganisms in enhancing ecosystem health and fortifying resilience against climate change impacts (Kumawat et al. 2022). These educational initiatives are strategically tailored for dissemination across schools, communities, and professionals in pertinent fields, aiming to cultivate a widespread awareness and informed discourse about the indispensable contribution of microbial biodiversity in the face of climate challenges.

3.6. Policy Incentives

Financial incentives are offered to landowners, farmers, and businesses to encourage the adoption of practices that foster microbial biodiversity, encompassing measures such as the provision of tax breaks, grants, or subsidies. Simultaneously, regulatory support entails the incorporation of microbial biodiversity considerations into prevailing environmental regulations and land use policies (Shah et al. 2021). By aligning financial incentives and regulatory frameworks with the promotion of microbial biodiversity, a comprehensive approach is undertaken to stimulate widespread adoption of ecologically sustainable practices, thereby contributing to the preservation and enhancement of microbial diversity within diverse ecosystems.

3.7. International Collaboration

In the pursuit of safeguarding microbial biodiversity amidst the challenges posed by global climate change, international cooperation is actively fostered in the realms of data sharing, research collaboration, and the exchange of best practices. A collective effort is made to promote a passive but robust framework that encourages the sharing of data and insights on microbial biodiversity preservation across borders (Kumawat et al. 2022). Through this collaborative approach, a global network emerges wherein nations actively contribute to the collective understanding and implementation of effective strategies for the preservation of microbial diversity in the face of the changing climate.

4. PRACTICAL RECOMMENDATIONS FOR LAND AND RESOURCE MANAGEMENT

Implementing this practical recommendation can work towards more resilient and sustainable land and resource management practices that address the challenges posed by climate change. Some practical recommendations for land and resource management in the context of climate change include the following:

4.1. Promotion of Sustainable Agriculture

Strategic promotion of sustainable agriculture is pivotal for effective land and resource management. This involves advocacy for progressive practices such as no-till farming, crop rotation, and agroforestry, which collectively contribute to bolstering soil health, carbon sequestration, and the mitigation of greenhouse gas emissions (Okon et al. 2021). Additionally, endorsing organic farming methods emerges as a crucial facet, emphasizing biodiversity preservation, minimizing reliance on chemical inputs, and fostering natural nutrient cycling. By embracing these sustainable agricultural approaches, we can not only fortify the resilience of ecosystems but also advance toward a harmonious coexistence between agricultural productivity and environmental stewardship.

4.2. Implementation of Agroecological Approaches

Efficient land management hinges on the adoption of agroecological approaches, wherein agricultural systems are harmoniously integrated with ecological knowledge. This encompasses the implementation of natural pest management strategies, the cultivation of diverse crop varieties, and the practice of conservation tillage (Auzins et al. 2022). By embracing these agroecological principles, we not only foster a more sustainable and resilient agricultural ecosystem but also cultivate a balanced and environmentally conscious approach to farming that emphasizes the synergy between ecological health and productive agricultural practices.

4.3. Protection and Restoration of Ecosystems

Central to effective land and resource management is the prioritization of conserving and restoring natural ecosystems, including wetlands, forests, grasslands, and coastal areas. These habitats, essential for carbon sequestration, also serve as indispensable reservoirs of critical biodiversity (Koshkalda et al. 2023). By focusing on the preservation and restoration of these ecosystems, we not only contribute to mitigating climate change through enhanced carbon sequestration but also safeguard and promote the invaluable biodiversity that underpins the ecological balance of our planet. This holistic approach ensures the long-term health and resilience of these ecosystems, playing a pivotal role in sustainable land management practices.

4.4. Promotion of Sustainable Forestry Practices

Advance sustainable forestry practices by advocating for logging methods that prioritize forest regeneration, diversity, and resilience. This proactive approach ensures the maintenance of robust and thriving forest ecosystems, contributing not only to carbon sequestration but also to the provision of crucial ecological services (Fawzy et al. 2020). By endorsing sustainable logging practices, we foster a harmonious coexistence between human activities and forest vitality, thereby fortifying the ecological integrity of these invaluable habitats. This strategic emphasis on sustainability forms a cornerstone for responsible land and resource management, promoting the longevity and well-being of forested ecosystems.

4.5. Implementation of Water Management Strategies

Water management strategies are actively implemented through the adoption of water-saving technologies and practices in agriculture, including drip irrigation, rainwater harvesting, and the cultivation of water-efficient crop choices. Additionally, watershed management approaches are promoted to guarantee a sustainable water supply and safeguard aquatic ecosystems (Auzins et al. 2022). By emphasizing these measures, a comprehensive and passive framework is established, ensuring the efficient use of water resources in agriculture while simultaneously fostering the long-term health and resilience of watershed ecosystems.

4.6. Supporting Biodiversity Conservation

Biodiversity conservation is actively supported through the establishment of protected areas and wildlife corridors aimed at safeguarding diverse ecosystems. Additionally, the encouragement of habitat restoration initiatives and the creation of green spaces within urban areas are actively pursued to enhance ecological balance. Measures are also implemented to passively control invasive species, mitigating their potential to disrupt ecosystems and displace native flora and fauna (Okon et al. 2021). By prioritizing these efforts, a holistic approach is fostered, ensuring the sustained preservation of biodiversity while promoting the coexistence of diverse species within their respective habitats.

4.7. Integration of Climate-Resilient Land Use Planning

Climate-resilient land use planning is actively integrated by incorporating climate considerations into the planning process, encompassing factors such as sea-level rise, extreme weather events, and evolving precipitation patterns. Zoning regulations are passively developed to account for climate vulnerabilities, prioritizing sustainable development practices (Koshkalda et al. 2023). By embracing these measures, a comprehensive and passive approach is taken to ensure that land use planning is adaptable to the challenges posed by climate change, promoting resilience and sustainability in the face of shifting environmental conditions.

4.8. Promotion of Carbon Farming and Reforestation

Carbon farming and reforestation practices are actively promoted through the encouragement of afforestation (planting trees on previously non-forested land) and reforestation (replanting trees in previously deforested areas) to actively sequester carbon and enhance biodiversity. Additionally, carbon farming techniques, such as cover cropping and rotational grazing, are passively supported to enhance soil carbon levels (Okon et al. 2021). By prioritizing these initiatives, a comprehensive and passive approach is undertaken to ensure the active sequestration of carbon and the fostering of biodiversity, contributing to sustainable land management practices.

4.9. Facilitation of Research and Innovation

Research and innovation facilitation is actively pursued through the provision of funding and resources for investigations into sustainable land and resource management practices. This proactive support aims to cultivate the development of innovative technologies and approaches that can significantly contribute to the enhancement of sustainable practices (Koshkalda et al. 2023). By prioritizing these initiatives, a comprehensive and passive framework is established, encouraging the exploration of cutting-edge solutions and advancements that align with the evolving needs of sustainable land and resource management.

4.10. Engagement of Community and Education

Community engagement and education are actively prioritized by involving local communities, stakeholders, and landowners in decision-making processes. Efforts are made to foster passive awareness and education regarding sustainable land management practices and their associated benefits (Okon et al. 2021). Through these initiatives, a comprehensive and proactive approach is taken to empower communities with knowledge and promote understanding, cultivating a shared commitment to sustainable practices and the long-term well-being of the land.

5. BIODIVERSITY LOSS AND MICROBIAL EXTINCTION

5.1. The Threat of Climate-Induced Microbial Extinctions

Climate change alters the environmental conditions that microorganisms depend on for survival. Rising temperatures, changing precipitation patterns, and shifts in pH levels can significantly impact microbial communities. Temperature variations will hurt the organization of microbial communities because they are strongly dependent on it (Abirami et al. 2021). Some microorganisms may thrive under these new conditions, while others may face extinction. Climate-induced microbial extinctions are becoming increasingly common, affecting the balance of microbial communities in diverse ecosystems.

Several mechanisms contribute to climate-induced microbial extinctions. Habitat loss and fragmentation, driven by climate change-related events such as wildfires and extreme weather events, can disrupt microbial communities (McLaughlin et al. 2002). Additionally, the introduction of pollutants and invasive species can exacerbate the vulnerability of microbial populations. Interactions like competition and predation can also influence microbial community dynamics, further complicating the picture. Changes in microbial communities can trigger ecological cascades, affecting higher trophic levels in ecosystems. Warming temperatures due to climate change are likely to result in a mass homogenization of global soil microbial communities, leading to an overall loss of microbial biodiversity (Guerra et al. 2021).

Modifications in climate factors place natural populations under intense selective pressure. Certain species, for instance, may be able to adapt to changes in the climate, while others would suffer if they are unable to do so. There have been significant changes in the range and geographical distributions of species and ecosystems due to climate change (Muluneh, 2021). According to Muluneh (2021), long-term weather fluctuations have a substantial impact on food security, availability, accessibility, and utilisation. Similarly, differences in mean temperatures and rainfall will have an impact on the suitability of land for agriculture, pasture, and the productivity of marine resources. These changes will also increase the occurrence of pests and illnesses, degrade ecosystem functioning, reduce biodiversity, and lower the amount of water available for crop, livestock, and inland fish production. Ladau et al. (2018)

demonstrated that soil prokaryotes followed soil characteristics in exhibiting a significant lagged response to a changing climate over several decades. This pattern was observed in both the Tibetan Plateau and northern North America. They also showed that their models predicted widespread increases in diversity and changes in community composition if bacteria and archaea could equilibrate to the current climate change.

Many microbial species' distributions and abundances are projected to shift as a result of climate change. Geographic range shifts that correlate to climatic warming support predictions of climate-induced population extinctions, but few extinctions have been mechanistically connected to climate change (McLaughlin et al. 2002). Thomas et al. (2004) described the potential impact of climate change on various species and their risk of extinction. Based on mid-range climate-warming scenarios, the study forecasts that 15-37% of species in its sample of areas and taxa will be "committed to extinction" by 2050. The estimates vary depending on the approach employed, but minimal climate-warming scenarios result in lower projected extinction rates (less than 18%) than mid-range (24%) and maximum-change (35%). The study emphasises the importance of developing carbon-sequestration technologies and techniques to reduce the impact of climate change on species.

5.2. Consequences for Ecosystems and Biogeochemical Cycles

Microbial diversity is a hallmark of healthy ecosystems. Microorganisms are involved in various ecological processes, such as nutrient cycling, organic matter decomposition, and symbiotic relationships with plants. They are responsible for converting organic matter into forms that plants can use, making nutrients available to higher trophic levels. Microbes also regulate soil structure, water retention, and disease suppression. Any disruption in microbial diversity can have cascading effects throughout an ecosystem (Vuong et al. 2022).

The consequences of climate-induced microbial extinctions are far-reaching. Disruptions in microbial communities can lead to decreased soil fertility, increased vulnerability to pathogens, and reduced plant productivity (Bukar et al. 2019). These changes ultimately threaten food security and biodiversity. Moreover, microbial extinctions can exacerbate climate change by altering greenhouse gas emissions, contributing to a feedback loop that further exacerbates global warming. Microbes play crucial roles in nutrient acquisition and stress tolerance for plants. Changes in microbial communities can affect plant-microbe interactions, potentially reducing crop yields and ecosystem stability. Microbes are part of complex food webs. Their decline can ripple through ecosystems, affecting higher trophic levels and biodiversity (Vuong et al. 2022).

Microbes play a pivotal role in biogeochemical cycles, including the carbon, nitrogen, and phosphorus cycles (Vanwonterghem and Webster, 2020; Abirami et al. 2021; Cui et al. 2023). According to Falkowski et al. (2008), microorganisms found in the ocean are in charge of all primary and most secondary production, which drives important biogeochemical cycles and environmental processes. Climate-induced microbial extinctions disrupt these cycles, potentially leading to imbalances in nutrient availability and greenhouse gas concentrations. For example, reduced microbial activity can hinder organic matter decomposition, leading to carbon accumulation in ecosystems (Allison and Martiny, 2008). The loss of microbial biodiversity due to climate change and other environmental perturbations can lead to disruptions of food webs due to nutrient cycling changes and increased greenhouse gas production due to alterations of the carbon cycle. These consequences may result in further biodiversity loss along the ecological chain. Biodiversity drives ecological and environmental processes, so its decline across the globe threatens the vital ecosystem services that all life relies upon (Vuong et al. 2022).

The threat of climate-induced microbial extinctions is an often-overlooked consequence of climate change, with profound implications for ecosystems and biogeochemical cycles. Protecting microbial diversity and understanding its importance in maintaining ecosystem stability and global biogeochemical cycles is crucial to combating climate change and safeguarding the health of our planet.

6. CONSERVATION AND RESTORATION STRATEGIES

6.1. Preservation of Microbial diversity

The loss of biodiversity is usually seen as unfavorable to the proper functioning of an ecosystem. Microorganisms made up of fungi, archea, protozoans and bacteria as a major part of the total biomass of the organisms inhabiting the earth and also make up the largest source of biodiversity. They also make a substantial contribution to wastewater treatment, bioreactors and agricultural fields (Table 3).

Due to the absence of bio geographical restrictions in distribution of microorganisms, short doubling time and plasticity of their genome, it is believed that communities of microorganisms do not face limits in their biodiversity. It is important to note that different microorganisms do not have equal ability to adapt to changes in their environment, and also face the risk of extinction due to disturbances in their natural environment and thus, it is important to preserve and maintain microbial biodiversity (Paramithiotis and Dimopoulou, 2023). Compared to the world of plants and animals, the microbial world remains the largest reservoir of biodiversity on planet earth (Singh et al. 2019). Microorganisms are ubiquitous and essential for life, with a profound influence on any functioning ecosystem.

Microbes are important to understanding metabolic pathways, thus the preservation of microbial diversity is essential to maintain natural ecosystems, development of applications in industries, and for research purposes.

Table 3: Impacts of Climate Change on Microbial Biodiversity and Conservation Strategies

Activities	Impacts	References
Biodiversity Loss and Microbial Extinction	Climate change impacts microbial communities through temperature rise, precipitation changes, and pH shifts. It leads to extinctions and alters community dynamics, affecting ecosystem balance.	Abirami et al. (2021); McLaughlin et al. (2002); Guerra et al. (2021); Muluneh (2021); Ladau et al. (2018); Thomas et al. (2004)
The Threat of Climate-Induced Microbial Extinctions	Climate changes disrupt habitats via wildfires, extreme weather, pollutants, and invasive species, triggering extinctions and ecological cascades.	McLaughlin et al. (2002)
	Climate variations exert selective pressures, with some species adapting while others face extinction risks.	Muluneh (2021); Ladau et al. (2018)
	Shifts in species distributions due to climate warming suggest potential extinctions, albeit few directly linked to climate.	McLaughlin et al. (2002); Thomas et al. (2004)
Consequences for Ecosystems and Biogeochemical Cycles	Microbial diversity loss decreases soil fertility, increases pathogen vulnerability, and reduces plant productivity, threatening food security and biodiversity.	Vuong et al. (2022); Bukar et al. (2019)
	Microbial extinctions alter greenhouse gas emissions, exacerbating climate change through nutrient cycle disruptions.	Allison and Martiny (2008); Vuong et al. (2022)
	Microbes drive carbon, nitrogen, and phosphorus cycles; their loss disrupts nutrient availability and alters carbon sequestration.	Falkowski et al. (2008); Vanwonterghem and Webster (2020); Cui et al. (2023)
Conservation and Restoration Strategies	Importance of preserving microbial biodiversity through global repositories and diverse preservation techniques.	Paramithiotis and Dimopoulou (2023); Singh et al. (2019); Maron et al. (2018); Prakash et al. (2020)
	Techniques include ex-situ and in-situ conservation, focusing on gene banks, culture collections, and habitat preservation.	Onen et al. (2020); Sharma et al. (2016); Kerckhof et al. (2014); Rappuoli et al. (2023)
Preservation of Microbial diversity	Microbes contribute significantly to ecosystem functions and are crucial for maintaining biodiversity and ecological balance.	Schnecker et al. (2023)
	Various preservation methods (e.g., cryopreservation, lyophilization) ensure genetic and functional integrity of microbial strains.	Srivastava et al. (2022); Prakash et al. (2020)
Restoration of disturbed ecosystems	Inoculation of soil with beneficial microbes aids in ecosystem restoration, enhancing soil fertility and plant health.	Farrell et al. (2020); Asmelash et al. (2016); Huang et al. (2023)
	Difficulty in restoring original microbial species due to climate-induced extinctions; use of organic fertilizers aids recovery.	

In the current global change context that is assumed to impact soil biodiversity, the preservation of microbial diversity is highly relevant. Although the relationship between microbial diversity and soil functioning remains controversial, numerous studies have established that microbial communities respond rapidly to environmental changes (Maron et al. 2018). The United Nations proclaimed the year 2010 as the International Year of Biodiversity, to direct attention on hopes to establish strategies to prevent biodiversity loss, with a key step being to mitigate the loss of biodiversity and the degradation of ecosystem function (Schnecker et al. 2023) (Table 3).

Microbial Resource Centers (MRCs), or microbial depositories, are of immense importance in research. Organizations such as the American Society for Microbiology, Society for General Microbiology and Federation of European Microbiological Societies should promote the concept of microbial diversity and highlight the role of MRCs. It is necessary to have adequate preservation of microbes without changes in morphological, physiological and genetic traits, in addition to the isolation and cultivation of pure strains.

Srivastava et al. (2022) reported that the World Data Centre for Microorganisms (WDCM) currently lists 820 culture collections, in 78 countries, holding more than 3,348,121 microbial strains, registered with the World Data Centre for Microbes. At present, WDCM database of culture collections encompasses 1,521,992 bacteria, 952,933 fungi, 32,839 viruses and some of them are cell lines. Due to the enormous diversity of microorganisms, there are different methods of conservation or preservation ex- situ. Different preservation methods used include slant, stab, mineral oil stock, cryopreservation, lyophilization and drying in an inert material. Some of the microbes can survive in sterile water (e.g. *Ralstonia*). Prakash et al. (2020) described different methods that can be used to preserve intact samples of microbiomes which includes:

The Cell Alive System (CAS) from Japan: CAS freezing technology has been approved as a well optimized tool for long term preservation of deep sea sediment samples for geo-microbiological studies. Researchers might be able to achieve increased storage period and viability of microorganisms in a microbiome according to Gopal and Gupta (2016).

Cryopreservation and lyophilization are well known methods for long term preservation of microbial cultures. The use of ultra-low temperature with different cryoprotectants for preservation of microorganisms is a traditional practice in every microbiological laboratory. Cryoprotectants, for example Glycerol and Dimethyl Sulphoxide

(DMSO) are a group of chemicals, which prevent the formation of lattice from water molecules during preservation. Other cryoprotectants include Amino acids for *Lactobacillus* and galacto-oligosaccharides (GSO).

Cellular immobilization or entrapment in the gelling matrix is another alternative of long-term preservation of microbial viability and functionality. These methods can be explored for consortium and mixed microbiome preservation when the protocol is optimized.

Electrospinning and electrospraying (Microencapsulation): These are novel microencapsulation techniques used to maintain the viability and functionality of microorganisms. Generally, these technologies are known as "sister technologies" because the way of working of both technologies are almost similar with only difference in viscosity of the polymer solution.

Another approach to conservation of microbial diversity is the application of specialized techniques to reclaim degraded habitats. Onen et al. (2020) suggested the *ex situ* and *in situ* techniques. In the *ex-situ*, repositories like gene bank, culture collections and microbial resources centers are used as key repositories of biodiversity and important resources for the future. The is-situ technique concentrates on the on-site conservation of microbial flora. It is the conservation of natural habitats, ecosystems, and maintenance and recovery of viable populations in their natural habitat. All these can be archived by encouraging tree planting while discouraging deforestation to prevent soil erosion and loss of diver's micro flora. Water bodies can also be protected by controlling pollution which will in turn protect and preserve zooplanktons, phytoplanktons and other floating microbes.

The "*in situ*", "*ex situ*" and "in-factory" form of preservation was also proposed by Sharma et al. 2016 where "*in situ*" ('on site', 'in place') conservation links the microbes in their natural habitats and is the most appropriate way of conserving viable populations in their ecosystem and natural habitats, "*ex situ*" (off-site) conservation preserves and maintains the distinct wild/isolated/cultivated species and their genetic resources in artificial media and are taxonomically well described and "*in-factory*" form of conservation is an intermediate form of conservation and mainly used by the agro-industrial sectors.

Kerckhof et al. (2014) evaluated a cryopreservation protocol that succeeded in preserving both community structure and functionality of value-added microbiomes at -80 ^{o}C for three months. Rappuoli et al. (2023) concluded that to preserve microbial diversity on earth, we should focus on vaccines while reducing the use of broad-spectrum antibiotics, and also reduce the overuse of antibiotics in agriculture to prevent the emergence of resistant bacteria, which will go a long way to mitigate against destroying the delicate balance of the microbial world.

6.2. Restoration of Disturbed Ecosystems and Microbial Communities

In order to promote restoration of disturbed ecosystems, biotic soil conditions have been manipulated by inoculating soil with soil microbes, to promote outcomes leading to the creation of conditions that promotes the establishment of desirable plant communities and ecosystem with the services these microorganisms provide (Farrell et al. 2020). It is generally assumed that microbial diversity and function in revegetated areas will without intervention, revert to the formal level before the disturbance of the ecosystem. In order to achieve targeted reintroductions aimed at improving the health of plants: Inoculation of single species of non-native Arbuscular Mycorrhizal Fungi (AMF) is a common restoration practice. Non-native AMF are used to help revegetated plants establish and grow, but this practice ignores all other components of soil biota. However, it has been argued that AMF inoculations could be improved by incorporating whole native communities rather than using single non-native species (Asmelash et al. 2016).

It may be impossible to reestablish the species of microorganisms found in a particular geographical location in the past because they may have become extinct either locally or totally due to climate change. The application of organic fertilizers has been found to reverse the negative effect of fumigants (especially broad-spectrum nematicides and fungicides) that kill non-targeted microbes, and restore microbial community structure and function (Huang et al. 2023).

7. CONCLUSION

Microbial biodiversity is fundamental to ecosystem functioning, affecting nutrient cycling, ecosystem resilience, and human well-being. Conserving and managing microbial biodiversity is crucial for safeguarding ecosystems and ensuring long-term human well-being. Climate change profoundly impacts microbial communities, leading to biodiversity alterations, ecosystem service disruptions, and feedback mechanisms, highlighting the intricate relationship between climate change and microorganisms. Managing microbial responses to climate change is essential for building resilient and sustainable ecosystems. Climate-induced shifts in microbial biodiversity reveal significant insights and potential research pathways. Evidence from various ecosystems shows microbial diversity changes due to climate change, underscoring the delicate equilibrium governing microbial life and their critical role in ecosystem functioning. Case studies, such as melting Arctic permafrost and coral reefs battling ocean warming, demonstrate how microbial communities act as both sentinels and drivers of change, influencing nutrient cycling, biogeochemical processes, and overall ecosystem health. These examples emphasize the urgency of protecting these ecosystems from further damage.

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Microbes play fundamental roles in ecosystem services, mediating nutrient cycles, sustaining soil fertility, and supporting plant health. Climate change poses a serious threat to these services, with far-reaching consequences for ecosystems and agriculture. Recognizing the significance of microbial contributions to ecosystem services is both a scientific and ethical imperative. Agriculture faces the challenge of adapting to shifting microbial populations to maintain food security. The impact on microbial biogeography highlights the evolving landscape of microbial communities in response to climate change. As temperatures rise, some microbes expand into new regions, while others face extinction due to their inability to adapt quickly enough. These changes in microbial distribution patterns have significant consequences for broader ecosystems, impacting nutrient cycling, disease dynamics, and overall health. This underscores the vulnerability of these minuscule yet mighty life forms, whose roles in ecosystem functioning are monumental.

Microbial responses to changing climates demonstrate their extraordinary adaptability. Microbes fine-tune their activity in response to temperature fluctuations, showcasing their resilience in maintaining critical functions within ecosystems. Microbial communities in extreme environments, such as polar regions and deserts, serve as models for studying the impacts of climate-induced changes, revealing how life persists against all odds. Concerns about biodiversity loss and potential extinction of microorganisms due to climate change highlight the precarious state of microbial diversity. Microbial extinctions can disrupt vital processes like nutrient cycling and disease dynamics, compromising ecosystem stability. Conservation efforts must include these often-overlooked life forms. Understanding microbial interactions in a changing climate, including competition and mutualism, provides valuable insights into the dynamic nature of ecological systems. The interplay between microbial diversity and disease dynamics underscores the connections between climate change and microbial pathogens. Alterations in temperature and humidity patterns affect disease dynamics, impacting the health of human populations and wildlife. Thorough comprehension of these shifts is paramount as we grapple with their far-reaching consequences.

Adaptation strategies for microbial conservation are crucial to fortifying microbial resilience in the face of climate change. Pioneering approaches, such as microbiome-based techniques, hold promise for mitigating the consequences of climate change. Policy and management considerations must integrate microbial biodiversity into climate change policies. Recognizing microbes as integral components of strategies designed to ameliorate climate change consequences is imperative. Exploring future research directions involves addressing knowledge gaps concerning climate-microbe interactions. Developing innovative research methodologies and technologies to assess and conserve microbial diversity is pivotal for the stability of ecosystems and the health and well-being of all species, including humans.

REFERENCES

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., and Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, *29*(28), 42539–42559. https://doi.org/10.1007/S11356-022-19718-6

Abdurrahman, M. I., Chaki, S., and Saini, G. (2020). Stubble burning: Effects on health and environment, regulations and management practices. *Environmental Advances*, 2, 100011, https://doi.org/10.1016/j.envadv.2020.100011.

Abirami, B., Radhakrishnan, M., Kumaran, S., and Wilson, A. (2021). Impacts of global warming on marine microbial communities. *Science of the Total Environment*, *791*, 147905. https://doi.org/10.1016/j.scitotenv.2021.147905

Alegbeleye, O., Odeyemi, O. A., Strateva, M., and Stratev, D. (2022). Microbial spoilage of vegetables, fruits and cereals. *Applied Food Research*, 2(1). https://doi.org/10.1016/j.afres.2022. 100122

Allison, S. D., and Martiny, J. B. (2008). Resistance, resilience, and redundancy in microbial communities. *Proceedings of the National Academy of Sciences*, *105*(supplement_1), 11512-11519. https://doi.org/10.1073/pnas.0801925105

Asmelash, F., Bekele, T., and Birhane, E. (2016). The potential role of arbuscular mycorrhizal fungi in the restoration of degraded lands. *Frontiers in Microbiology*, 7, 1–15. https://doi.org/10. 3389/fmicb.2016.01095

Auzins, A., Brokking, P., Jürgenson, E., Lakovskis, P., Paulsson, J., Romanovs, A., Valčiukienė, J., Viesturs, J., and Weninger K. (2022). Land Resource Management Policy in Selected European Countries. *Land*, *11*(12), 2280. https://doi.org/10. 3390/land11122280

Bardgett, R. D., and Caruso, T. (2020). Soil microbial community responses to climate extremes: Resistance, resilience and transitions to alternative states. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794). https://doi.org/10.1098/RSTB.2019.0112

Bello, O. O, Bello, T. K., Babalola O. O., and Olu-Aderoumu, W. O. (2020). Antibiogram of bacterial flora of public health significance associated with postharvest *Irvingia gabonensis* seeds. *Proceedings of the Nigerian Academy of Science*, *13*(2), 13-29.

Bello, O. O., Akinpeloye, B. O., Bello, T. K., Oluwafemi, Y. D., and Osungbemiro, B. W. (2023). Physicochemical constituents and bacterial diversity in river waters in Ondo State, Nigeria. *Iranian Journal of Microbiology*, *15*(6), 788-795.

Blewett, T. A., Binning, S. A., Weinrauch, A. M., Ivy, C. M., Rossi, G. S., Borowiec, B. G., Lau, G. Y., Overduin, S. L., Aragao, I., and Norin, T. (2022). Physiological and behavioural strategies of aquatic animals living in fluctuating environments. *Journal of Experimental Biology*, *225* (9), jeb242503. https://doi.org/10.1242/jeb.242503

Bras, T. A., Seixas, J., Nuno, C., and Jonas, J. (2021). Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environmental Research Letters*, *16*(5), 065012. doi: 10.1088/1748-9326/abf004.

Bridgham, S. D., Cadillo-Quiroz, H., Keller, J. K., and Zhuang, Q. (2013). Methane emissions from wetlands: biogeochemical, microbial, and modeling perspectives from local to global scales. *Global Change Biology*, *19*(5), 1325-1346. https://doi.org/10.1111/gcb.12131

Buenaño-Vargas, C., Gagliano, M. C., Paulo, L. M., Bartle, A., Graham, A., van Veelen, H. P. J., and O'Flaherty, V. (2024). Acclimation of microbial communities to low and moderate salinities in anaerobic digestion. *Science of The Total Environment*, *906*, 167470, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.167470.

Bukar, M., Sodipo, O., Dawkins, K., Ramirez, R., Kaldapa, J. T., Tarfa, M., and Esiobu, N. (2019). Microbiomes of Top and Sub-Layers of Semi-Arid Soils in North-Eastern Nigeria are Rich in Firmicutes and Proteobacteria with Surprisingly High Diversity of Rare Species. *Advances in Microbiology*, *9*(1), 102–118. https://doi.org/10.4236/aim.2019.91008
Cadena, S., Cervantes, F. J., Falcón, L. I., and García-Maldonado, J. Q. (2019). The Role of Microorganisms in the Methane Cycle. *Frontiers for Young Minds*, *7*, 00133. https://doi.org/10.3389/FRYM.2019.00133
Cavicchioli, R., Ripple, W. J., Timmis, K. N., Azam, F., Bakken, L. R., Baylis, M., Behrenfeld, M. J., Boetius, A., Boyd, P. W., Classen, A. T. et al. (2019). Scientists' warning to humanity: Microorganisms and climate change. *Nature Reviews Microbiology*, *17*, 569–586. https://doi.org/10.1038/s41579-019-0222-5
Classen, A. T., Sundqvist, M. K., Henning, J. A., Newman, G. S., Moore, J. A. M., Cregger, M. A., Moorhead, L. C., and Patterson, C. M. (2015). Direct and indirect effects of climate change on soil microbial and soil microbial-plant interactions: What lies ahead? *Ecosphere*, *6*(8), 1-21. https://doi.org/10.1890/ES15-00217.1
Cui, L., Xin, Y., Yang, K., Li, H., Tan, F., Zhang, Y., Li, X., Zhu, Z., Yang, J., Kao, S. J., Ren, B., Zhu, Y. G., Musat, F., and Musat, N. (2023). Live tracking metabolic networks and physiological responses within microbial assemblages at single-cell level. *PNAS Nexus*, *2*(3), pgad006. https://doi.org/10.1093/pnasnexus/pgad006
Dean, J. F., Middelburg, J. J., Röckmann, T., Aerts, R., Blauw, L. G., Egger, M., Jetten, M. S. M., de Jong, A. E. E., Meisel, O. H., Rasigraf, O., Slomp, C. P., in't Zandt, M. H., and Dolman, A. J. (2018). Methane Feedbacks to the Global Climate System in a Warmer World. *Reviews of Geophysics*, *56*(1), 207–250. https://doi.org/10.1002/2017RG000559
Delgado-Baquerizo, M., Oliverio, A. M., Brewer, T. E., Benavent-González, A., Eldridge, D. J., Bardgett, R. D., and Fierer, N. (2018). A global atlas of the dominant bacteria found in soil. *Science*, *359*(6373), 320-325. https://doi.org/10.1126/science.aap9516
Falkowski, P. G., Fenchel, T., and Delong, E. F. (2008). The microbial engines that drive Earth's biogeochemical cycles. *Science*, *320*(5879), 1034-1039. https://doi.org/10.1126/science.1153213
Farrell, H. L., Léger, A., Breed, M. F., and Gornish, E. S. (2020). Restoration, soil organisms, and soil processes: Emerging approaches. *Restoration Ecology*, *28* (S4), S307–S310. doi: 10.1111/rec.13237
Fawzy, S., Osman, A. I., Doran, J., and Rooney, D. W. (2020). Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters*, *18*(6), 2069–2094. https://doi.org/10.1007/S10311-020-01059-W
Fierer, N., Lauber, C. L., Ramirez, K. S., Zaneveld, J., Bradford, M. A., and Knight, R. (2012). Comparative metagenomic, phylogenetic, and physiological analyses of soil microbial communities across nitrogen gradients. *The ISME Journal*, *6*(5), 1007-1017. https://doi.org/10.1038/ismej.2011.159
Furtak, K., and Wolińska, A. (2023). The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture – A review. *Catena*, *231*, 107378. https://doi.org/10.1016/j.catena.2023.107378
Gopal, M., and Gupta, A. (2016). Building plant microbiome vault: a future biotechnological resource. *Symbiosis*. *77*, 1–8. doi: 10.1007/s13199-018-0574-z.
Guerra, C. A., Delgado-Baquerizo, M., Duarte, E., Marigliano, O., Görgen, C., Maestre, F. T., and Eisenhauer, N. (2021). Global projections of the soil microbiome in the Anthropocene. *Global Ecology and Biogeography*, *30*(5), 987-999. https://doi.org/10.1111/geb.13273
Guo, X., Feng, J., Shi, Z., Zhou, X., Yuan, M., Tao, X., Hale, L., Yuan, T., Wang, J., Qin, Y., et al. (2018). Climate warming leads to divergent succession of grassland microbial communities. *Nature Climate Change*, *8*(9), 813–818. https://doi.org/10.1038/s41558-018-0254-2
Guo, X., Zhou, X., Hale, L., Yuan, M., Ning, D., Feng, J., Shi, Z., Li, Z., Feng, B., Gao, Q., et al. (2019). Climate warming accelerates temporal scaling of grassland soil microbial biodiversity. *Nature Ecology Evolution*, *3*(4), 612–619.
Hamza, R.M.A., Aslam, H., Aleem, K., Bukhari, M.A., Farooq, H., Akbar, M., Manzoor, M., and Ashraf, H. (2023). The genetics of insecticide resistance in relation to climate change. *Agrobiological Records, 12*, 92-98. https://doi.org/10.47278/ journal.abr/2023.019
He, H., Liu, Y., Hu, Y., Zhang, M., Wang, G., and Shen, W. (2020). Soil Microbial Community and Its Interaction with Soil Carbon Dynamics Following a Wetland Drying Process in Mu Us Sandy Land. *International Journal of Environmental Research* and *Public Health, 17*(12), 4199. https://doi.org/10.3390%2Fijerph17124199
Hillebrand, H., Brey, T., Gutt, J., Hagen, W., Metfies, K., Meyer, B., and Lewandowska, A. (2018). Climate Change: Warming Impacts on Marine Biodiversity. In *Handbook on Marine Environment Protection*; Springer International Publishing: Cham, Switzerland, pp. 353–373.
Hu, Y., Wang, S., Niu, B., Chen, Q., Wang, J., Zhao, J., Luo, T., and Zhang, G. (2020). Effect of increasing precipitation and warming on microbial community in Tibetan alpine steppe. *Environmental Research*, *189*. https://doi.org/10.1016/j.envres .2020.109917
Hua, F., Bruijnzeel, L. A., Meli, P., Martin, P. A., Zhang, J., Nakagawa, S., Miao, X., Wang, W., McEvoy, C., Peña-Arancibia, J. L., Brancalion, P. H. S., Smith, P., Edwards, D. P., and Balmford, A. (2022). The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science*. *20*, 376(6595), 839-844. doi: 10.1126/science.abl4649.
Huang, B., Chen, Y., Pei, Z., Jiang, L., Zhang, Y., Wang, J., and Wang, J. (2023) Application of microbial organic fertilizers promotes the utilization of nutrients and restoration of microbial community structure and function in rhizosphere soils after dazomet fumigation. *Frontiers in Microbiology*. *13*, 1122611. doi: 10.3389/fmicb.2022.1122611
Hultman, J., Waldrop, M. P., Mackelprang, R., David, M. M., McFarland, J., Blazewicz, S. J., and Jansson, J. K. (2015). Multi-omics of permafrost, active layer and thermokarst bog soil microbiomes. *Nature*, *521*(7551), 208-212. https://doi.org/10.1038/nature14238
Human Microbiome Project Consortium, (2012). Structure, function, and diversity of the healthy human microbiome. *Nature*, *486*(7402), 207-214.
Hutchins, D. A., and Fu, F. (2017). Microorganisms and ocean global change. *Nature Microbiology*, *2*, 17058.
Hutchins, D. A., Jansson, J. K., Remais, J. V., Rich, V. I., Singh, B. K., and Trivedi, P. (2019). Climate change microbiology - problems and perspectives. *Nature Review Microbiology*, *17*(6), 391-396. doi: 10.1038/s41579-019-0178-5.
Ibáñez, A., Garrido-Chamorro, S., and Barreiro, C. (2023). Microorganisms and Climate Change: A Not So Invisible Effect. *Microbiology Research*. *14*(3), 918-947. https://doi.org/10.3390/microbiolres14030064
Jain, P. K., Purkayastha, S. D., Surajit De Mandal S. D. Passari, A. K., and Govindarajan, R. K. (2020). Effect of climate change on microbial diversity and its functional attributes. *Recent Advances in Microbial Ecology*, 315- 331.
Kerckhof, F. M., Courtens, E. N., Geirnaert, A., Hoefman, S., Ho, A., Vilchez-Vargas, R., Pieper, D. H., Jauregui, R., Vlaeminck, S. E., Van de Wiele, T., Vandamme, P., Heylen, K., and Boon, N. (2014). Optimized cryopreservation of mixed microbial communities for conserved functionality and diversity. *PloS One*, *9*(6), e99517. https://doi.org/10.1371/journal.pone. 0099517
Koshkalda, I., Dombrovska, O., Stoiko, N., and Riasnianska, A. (2023). Land resource management system in the sustainable development context: scientific and practical approaches. IOP Conf. Series: *Earth and Environmental Science*, *1254*, 012129. doi:10.1088/1755-1315/1254/1/012129
Kumawat, K. C., Razdan, N., and Saharan, K. (2022). Rhizospheric microbiome: Bio-based emerging strategies for sustainable agriculture development and future perspectives. *Microbiological Research*, *254*, 126901. https://doi.org/10. 1016/j.micres.2021.126901

Ladau, J., Shi, Y., Jing, X., He, J. S., Chen, L., Lin, X., Fierer, N., Gilbert, J. A., Pollard, K. S., and Chu, H. (2018). Existing climate change will lead to pronounced shifts in the diversity of soil prokaryotes. *mSystems*, *3*(5), e00167-18. https://doi.org/10. 1128/mSystems.00167-18
Lafferty, K. D. (2017). Marine Infectious Disease Ecology. *Annual Review of Ecology, Evolution and Systematics*, *48*,473–496.
Li, X., Yan, Y., Lu, X., Fu, L., and Liu, Y. (2022). Responses of soil bacterial communities to precipitation change in the semi-arid alpine grassland of Northern Tibet. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/FPLS.2022.1036369
Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M. G., Field, C. B., and Knowlton, N. (2020). Climate change and ecosystems: Threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794). https://doi.org/10.1098/RSTB.2019.0104
Maron, P., Amadou Sarr A., Aurore Kaisermann , A., Jean Lévêque, J., Mathieu, O., Julien Guigue J., Karimi , B., Bernard L., Dequiedt S., Terrat S., Chabbi A., & Ranjard, L. (2018). High microbial diversity promotes soil ecosystem functioning. *Applied Environmental Microbiology*, *84*(9), e02738-17. https://doi.org/10.1128/AEM.02738-17
McLaughlin, J. F., Hellmann, J. J., Boggs, C. L., and Ehrlich, P. R. (2002). Climate change hastens population extinctions. *Proceedings of the National Academy of Sciences*, *99*(9), 6070–6074. https://doi.org/10.1073/pnas.052131199
Mishra, A., Alnahit, A., and Campbell, B. (2021). Impact of land uses, drought, flood, wildfire, and cascading events on water quality and microbial communities: A review and analysis. *Journal of Hydrology*, *596*. https://doi.org/10.1016/j.jhydrol. 2020.125707
Mishra, A., Singh, L., and Singh, D. (2023). Unboxing the black box—one step forward to understand the soil microbiome: A systematic review. *Microbial Ecology*, *85*(2), 669–683. https://doi.org/10.1007/S00248-022-01962-5
Montaño-Salazar, S., Quintanilla, E., and Sánchez, J. A. (2023). Microbial shifts associated to ENSO-derived thermal anomalies reveal coral acclimation at holobiont level. *Scientific Reports*, *13*, 22049. https://doi.org/10.1038/ s41598-023-49049-6
Muhammad, M. H., Idris, A. L., Fan, X., Guo, Y., Yu, Y., Jin, X., Qiu, J., Guan, X., and Huang, T. (2020). Beyond Risk: Bacterial Biofilms and Their Regulating Approaches. *Frontiers in Microbiology*, *11*. https://doi.org/10.3389/FMICB.2020.00928
Muluneh, M. G. (2021). Impact of climate change on biodiversity and food security: A global perspective—a review article. *Agriculture and Food Security*, *10*(1), 36. https://doi.org/10.1186/s40066-021-00318-5
Naylor, D., Sadler, N., Bhattacharjee, A., Graham, E. B., Anderton, C. R., McClure, R., Lipton, M., Hofmockel, K. S., and Jansson, J. K. (2020). Soil microbiomes under climate change and implications for carbon cycling. *Annual Review of Environment and Resources*, *45*, 29–59. https://doi.org/10. 1146/annurev-environ-012320-082720
Nikolova, C., and Gutierrez, T. (2020). Use of Microorganisms in the Recovery of Oil From Recalcitrant Oil Reservoirs: Current State of Knowledge, Technological Advances and Future Perspectives. *Frontiers in Microbiology*, *10*. https://doi.org/10.3389/fmicb.2019.02996
Okon, E. M., Falana, B. M., Solaja, S. O., Yakubu, S. O., Alabi, O. O., Okikiola, B. T., Awe, T. E., Adesina, B. T., Tokula, B. E., Kipchumba, A. K., and Edeme, A. B. (2021). Systematic review of climate change impact research in Nigeria: implication for sustainable development. *Heliyon*, *7*(9), e07841. https://doi.org/10.1016/j.heliyon.2021.e07941
Onen, O. I., Aboh, A. A., Mfam, A. N., Akor, M. O., Nweke, C. N. and Osuagwu, A. N. (2020). Microbial Diversity: Values and Roles in Ecosystems *Asian Journal of Biology* 9(1), 10-22, http://dx.doi.org/10.9734/ajob/2020/v9i130075
Paramithiotis, S., and Dimopoulou, M. (2023). Preserving Microbial Biodiversity: The Case of Food-Associated Microorganisms. *Ecologies*, *4*(3), 521–534. MDPI AG. Retrieved from http://dx.doi.org/10.3390/ecologies4030034
Prakash, O., Nimonkar, Y., and Desai, D. (2020). A Recent Overview of Microbes and Microbiome Preservation. *Indian Journal of Microbiology*, *60*(3), 297–309. https://doi.org/10.1007/s12088 -020-00880-9
Preciado, C. C., Boxall, J., Soria-Carrasco, V., and Douterelo, I. (2019). Effect of temperature increase in bacterial and fungal communities of chlorinated drinking water distribution systems. *Access Microbiology*, *1*(1A). https://doi.org/10.1099/ acmi.ac2019.po0304
Pugnaire, F. I., Morillo, J. A., Peñuelas, J., Reich, P. B., Bardgett, R. D., Gaxiola, A., Wardle, D. A., and van der Putten, W. H. (2019). Climate change effects on plant-soil feedbacks and consequences for biodiversity and functioning of terrestrial ecosystems. *Science Advances*, *5*(11), eaaz1834.
Qian, H., and Wang, Y. (2023). Predicting microbial adaptability to climate change in the Anthropocene. *Global Change Biology*, *30*, e17122. https://doi.org/10.1111/gcb.17122
Qu, Q., Xu, J., Kang, W., Feng, R., and Hu, X. (2023). Ensemble learning model identifies adaptation classification and turning points of river microbial communities in response to heatwaves. *Global Change Biology*, *29*, 6988–7000. https://doi.org/10.1111/gcb.16985
Ramasamy, K. P., Mahawar, L., Rajasabapathy, R., Rajeshwari, K., Miceli, C., and Pucciarelli, S. (2023). Comprehensive insights on environmental adaptation strategies in Antarctic bacteria and biotechnological applications of cold adapted molecules. *Frontiers in Microbiology*, *14*, 1197797. doi: 10.3389/fmicb.2023.1197797
Rappuoli, R., Young, P., Ron, E., Pecetta, S., and Pizza, M. (2023). Save the microbes to save the planet. A call to action of the International Union of the Microbiological Societies *(IUMS). One Health Outlook, 5*, 5. https://doi.org/10.1186/ s42522-023-00077-2
Raza, T., Qadir, M. F., Khan, K. S., Eash, N. S., Yousuf, M., Chatterjee, S., Manzoor, R., Rehman, S. ur, and Oetting, J. N. (2023). Unrevealing the potential of microbes in decomposition of organic matter and release of carbon in the ecosystem. *Journal of Environmental Management*, *344,* 118529. https://doi.org/10.1016/j.jenvman.2023.118529
Rodgers, E. M. (2021). Adding climate change to the mix: Responses of aquatic ectotherms to the combined effects of eutrophication and warming. *Biology Letters*, *17,* 20210442 https://doi.org/10.1098/rsbl.2021.0442
Sagova-Mareckova, M., Boenigk, J., Bouchez, A., Cermakova, K., Chonova, T., Cordier, T., Eisendle, U., Elersek, T., Fazi, S., Fleituch, T., Frühe, L., Gajdosova, M., Graupner, N., Haegerbaeumer, A., Kelly, A. M., Kopecky, J., Leese, F., Nõges, P., Orlic, S., and Stoeck, T. (2021). Expanding ecological assessment by integrating microorganisms into routine freshwater biomonitoring. *Water Research*, *191*, 116767. https://doi.org/10.1016/j.watres.2020.116767
Salimi, S., Almuktar, S. A. A. A. N., and Scholz, M. (2021). Impact of climate change on wetland ecosystems: A critical review of experimental wetlands. *Journal of Environmental Management*, *286*, 112160. https://doi.org/10.1016/j. jenvman.2021.112160
Sánchez-Cañizares, C., Jorrín, B., Poole, P. S., and Tkacz, A. (2017). Understanding the holobiont: the interdependence of plants and their microbiome. *Current Opinion in Microbiology*, 38, 188-196. https://doi.or/10.1016/j.mib.2017.07.001.
Schnecker, J., Spiegel, F., Li, Y., Richter, A., Sanden, T., Spiegel, H., Zechmeister-Boltenstern, S., and Fuchslueger, L. (2023). Microbial responses to soil cooling might explain increases in microbial biomass in winter. *Biogeochemistry*, *164*, 521–535. https://doi.org/10.1007/s10533-023-01050-x
Sejiyan, V., Bhatta, R., Malik, P. K., Madiajagan, B., Al-Hosni, Y. A. S., and Gaughan, J. B. (2016). Livestock as sources of greenhouse gases and its significance to climate change. In: Moya B. L., Pous, J., et al. editors. *Greenhouse gases.* London: IntechOpen.
Shah, A., Nazari, M., Antar, M., Msimbira, L. A., Naamala, J., Lyu, D., Rabileh, M., Zajonc, J., and Smith, D. L. (2021). PGPR in Agriculture: A Sustainable Approach to Increasing Climate Change Resilience. *Frontiers in Sustainable Food Systems*, *5*, 667546. https://doi.org/10.3389/fsufs.2021.667546

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

Shahzad, A. (2023). Effect of heat stress on wheat (Triticum aestivum) and strategies to cope with this stress. *Agrobiological Records, 14*, 1-6. https://doi.org/10.47278/ journal.abr/2023.031

Sharma, B., Singh, B. N., Dwivedi, P., and Rajawat, M. V. S. (2022). Interference of Climate Change on Plant-Microbe Interaction: Present and Future Prospects. *Frontiers in Agronomy*, *3*, 725804. https://doi.org/10.3389/FAGRO.2021.725804

Sharma, S. K., Gupta, A. K., Shukla, A. K., Ahmad, E., Sharma, M. P., and Ramesh, A. (2016). Microbial Conservation strategies: Status and Challenges. *Indian Journal of Plant Genetic Resourses. 29*(3), 340-342. https://doi.org/10.5958/0976-1926.2016.00062.0

Shivanna, K. R. (2022). Climate change and its impact on biodiversity and human welfare. *Proceedings of* the *Indian National* Science *Academy, 88*(2), 160–71. doi: 10.1007/s43538-022-00073-6.

Singh, V. K., Shukla, A. K., and Singh, A. K. (2019). Impact of Climate Change on Plant–Microbe Interactions under Agroecosystems. In *Climate Change and Agricultural Ecosystems*; Elsevier: Amsterdam, the Netherlands, pp. 153–179. https://doi.org/10.1016/B978-0-12-816483-9.00007-4

Srivastava, A. K., Chakdar, H., Sahu, P. K., and Kumar, M. (2022). Conserving Microbial Diversity: Practices, Trends and Beyond. *Indian Journal of Plant Genetic Resources*, *35*(3), 338–342. https://doi.org/10.5958/0976-1926.2022.00095.X

Tan, Y. S., Zhang, R. K., Liu, Z. H., Li, B. Z., and Yuan, Y. J. (2022). Microbial Adaptation to Enhance Stress Tolerance. *Frontiers in Microbiology*, *13*, 888746 https://doi.org/10.3389/FMICB. 2022.888746

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., Erasmus, B. F. N., de Siqueira, M. F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A. S., Midgley, G. F., Miles, L., Ortega-Huerta, M. A., Peterson, A. T., Phillips, O. L., and Williams, S. E. (2004). Extinction risk from climate change. *Nature*, *427*(6970), 145-148. https://doi.org/10.1038/nature02121

Tiedje, J. M., Bruns, M. A., Casadevall, A., Criddle, C. S., Eloe-Fadrosh, E., Karl, D. M., Nguyen, N. K., and Zhou, J. (2022). Microbes and Climate Change: a Research Prospectus for the Future. *MBio*, *13*(3). https://doi.org/10.1128/MBIO.00800-22

Trivedi, P., Batista, B. D., Bazany, K. E., and Singh, B. K. (2022). Plant–microbiome interactions under a changing world: responses, consequences and perspectives. *New Phytologist*, *234*(6), 1951–1959. https://doi.org/10.1111/NPH.18016

Vanwonterghem, I., and Webster, N. S. (2020). Coral Reef Microorganisms in a Changing Climate. *iScience*, *23*(4), 100972. https://doi.org/10.1016/j.isci.2020.100972

Vuong, P., Chong, S., and Kaur, P. (2022). The little things that matter: How bioprospecting microbial biodiversity can build towards the realization of United Nations Sustainable Development Goals. *Npj Biodiversity*, *1*(1), 4. https://doi.org/10.1038/s44185-022-00006-y

Wallenius, A. J., Dalcin Martins, P., Slomp, C. P., and Jetten, M. S. M. (2021). Anthropogenic and Environmental Constraints on the Microbial Methane Cycle in Coastal Sediments. *Frontiers in Microbiology*, *12*, 631621. https://doi.org/10.3389/fmicb.2021. 631621

Wang, Z., Tsementzi, D., Williams, T. C., Juarez, D. L., Blinebry, S. K., Garcia, N. S., Sienkiewicz, B. K., Konstantinidis, K. T., Johnson, Z. I., and Hunt, D. E. (2021). Environmental stability impacts the differential sensitivity of marine microbiomes to increases in temperature and acidity. *ISME Journal*, *15*, 19–28.

Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., Hyde, K. J. W., Morelli, T. L., Morisette, J. T., Muñoz, R. C., Pershing, A. J., Peterson, D. L., Poudel, R., Staudinger, M. D., Sutton-Grier, A. E., Thompson, L., Vose, J., Weltzin, J. F., and Whyte, K. P. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of the Total Environment*, *733*, 137782. https://doi.org/10.1016/j. scitotenv.2020.137782

Yuan, M. M., Guo, X., Wu, L., Zhang, Y., Xiao, N., Ning, D., Shi, Z., Zhou, X., Wu, L., Yang, Y., Tiedje, J. M., and Zhou, J. (2021). Climate warming enhances microbial network complexity and stability. *Nature Climate Change*, *11*, 343–348. https://doi.org/10.1038/s41558-021-00989-9

Zhang, C., and Xi, N. (2021). Precipitation Changes Regulate Plant and Soil Microbial Biomass *Via* Plasticity in Plant Biomass Allocation in Grasslands: A Meta-Analysis. *Frontiers in Plant Science*, 12, 614968. https://doi.org/10.3389/fpls.2021.614968

Zhou, X., Chen, X., Qi, X., Zeng, Y., Guo, X., Zhuang, G., and Ma, A. (2023). Soil bacterial communities associated with multi-nutrient cycling under long-term warming in the alpine meadow. *Frontiers in Microbiology*, *14*, 1136187. https://doi.org/10.3389/fmicb.2023.1136187