SPJP JOURNAL OF MULTIDISCIPLINARY SCIENCES

Visit Us: https://spjpjms.com



Mini Review

Climate Change Impacts on Microbial Ecosystems and Global Biogeochemical Cycles

[1]Aman Shukla

[1]Department of Environmental Science, SGT University, Gurugram, India

ABSTRACT

Background: Microbial ecosystems play a central role in regulating Earth's biogeochemical cycles by mediating the transformation of carbon, nitrogen, sulfur, and phosphorus. Ongoing climate change—characterized by rising temperatures, altered precipitation patterns, ocean acidification, and permafrost thaw—is increasingly disrupting microbial community structure and metabolic functioning. These alterations have significant implications for greenhouse gas emissions and global climate feedback mechanisms.
Objectives: This study aims to synthesize current scientific evidence on climate-driven changes in microbial ecosystems and to evaluate their impacts on global biogeochemical cycles, with emphasis on carbon and nitrogen dynamics across terrestrial and marine environments.
Methods: A narrative review approach was employed, integrating peer-reviewed literature from major scientific databases. Studies involving field observations, experimental warming, molecular microbial analyses, and Earth system modeling were critically evaluated. Comparative assessment across ecosystems was conducted to identify consistent microbial responses and feedback patterns.
Results: Climate warming significantly enhances microbial respiration and organic matter decomposition, leading to increased carbon dioxide emissions from soils. Hydrological variability alters nitrogen cycling pathways, promoting denitrification and nitrous oxide release. In marine systems, ocean warming and acidification reduce primary productivity and weaken biological carbon sequestration. Permafrost thaw mobilizes large carbon reservoirs, stimulating microbial methane production. Collectively, these responses intensify positive climate feedbacks and modify global elemental cycling.
Conclusion: Microbial ecosystems are highly sensitive to climate change and actively regulate biogeochemical feedbacks that influence future climate trajectories. Incorporating microbial processes into Earth system models is essential for improving climate predictions. Long-term monitoring and integrated molecular–biogeochemical approaches are required to better understand microbial adaptation and to inform effective mitigation and ecosystem management strategies.

Keywords: Climate change, Microbial ecosystems, Biogeochemical cycles, Greenhouse gas feedbacks

***Corresponding author:** Aman Shukla, Department of Environmental Sciences, SGT University, Gurugram, India

Email:
Shukla_aman9034@yahoo.com

DOI: 10.62502/spjpjms/v1i2art3

Received: 20/06/2025
Accepted: 28/08/2025
Published: 20/09/2025

Copyright © 2025. The Author (s)

This is an open-access article distributed under the terms of the Creative Commons Attribution, Non-Commercial- 4.0 International License (CC BY-NC-4.0), which permits non-commercial use, sharing, adaptation, and reproduction in any medium, provided the original work is properly cited and any derivative works are distributed under the same license.

INTRODUCTION

Microbial ecosystems are fundamental drivers of Earth's biogeochemical processes, regulating the transformation and movement of carbon, nitrogen, sulfur, and phosphorus across terrestrial and aquatic environments. [1] These microorganisms act as primary decomposers of organic matter, facilitators of nutrient cycling, and regulators of atmospheric greenhouse gases. Their metabolic activities influence soil fertility, ocean productivity, and climate stability. Climate change, characterized by rising global temperatures, altered precipitation patterns, ocean acidification, and permafrost thaw, is rapidly modifying microbial habitats worldwide. [2] Such environmental changes directly affect microbial physiology and community composition, resulting in shifts in ecosystem functioning. Soil warming experiments demonstrate enhanced microbial respiration and carbon loss, reinforcing atmospheric CO_2 concentrations and accelerating global warming [3] Microorganisms respond rapidly to environmental stress due to short generation times and high genetic adaptability. [4] Consequently, microbial communities often act as early indicators of ecosystem change. Recent research highlights the vulnerability of microbial diversity to climate perturbations, with implications for nutrient cycling efficiency and greenhouse gas emissions [5] Despite growing recognition of microbial importance, their integration into climate prediction models remains limited. Understanding how climate change alters microbial-mediated biogeochemical cycles is critical for

accurate assessment of future climate trajectories. This study synthesizes current evidence on climate-driven microbial responses and evaluates their impacts on global elemental cycles.

MATERIALS AND METHODS

This research adopts a narrative review methodology integrating peer-reviewed literature from international scientific databases including Web of Science, PubMed, and Scopus. Studies published between 2000 and 2024 were considered, focusing on experimental warming studies, field observations, molecular microbial analyses, and Earth system modeling. Key search terms included climate change, microbial ecosystems, carbon cycling, nitrogen dynamics, permafrost thaw, and marine microbial ecology. Selected articles were screened based on relevance, methodological rigor, and contribution to understanding microbial-climate interactions.

Data synthesis emphasized:

- Microbial responses to temperature and moisture variability
- Greenhouse gas fluxes mediated by microbes
- Alterations in carbon and nitrogen cycling
- Ecosystem-scale feedback mechanisms

Comparative analysis was performed across terrestrial, freshwater, and marine environments to identify consistent trends and divergent responses.

RESULTS AND DISCUSSION

Temperature-Driven Shifts in Microbial Metabolism and Community Structure: Across terrestrial ecosystems, elevated temperatures consistently increased microbial metabolic activity, particularly heterotrophic respiration. Experimental warming studies demonstrated a 10–40% rise in soil CO_2 efflux during initial warming phases, reflecting enhanced enzymatic degradation of soil organic matter. [6,7] This response follows classical metabolic scaling theory, where enzymatic reaction rates accelerate with temperature until substrate limitation occurs. However, long-term observations reveal a progressive attenuation of respiration rates due to depletion of labile carbon pools and microbial acclimation [7] Community-level shifts were also observed, with thermophilic and copiotrophic taxa becoming dominant under sustained warming, while oligotrophic and cold-adapted organisms declined. These compositional changes altered functional gene abundance related to carbon degradation pathways, indicating restructuring of microbial metabolic networks. Importantly, warming-induced increases in microbial respiration represent a positive climate feedback, as additional CO_2 released from soils amplifies atmospheric greenhouse forcing [12] Yet, the magnitude of this feedback varies with soil type, vegetation cover, and historical climate conditions, highlighting strong ecosystem-specific responses.

Effects of Hydrological Variability on Carbon and Nitrogen Cycling: Changes in precipitation regimes exerted significant control over microbial-mediated biogeochemical processes. Drought conditions suppressed overall microbial activity due to reduced substrate diffusion and osmotic stress. In contrast, rewetting events produced pronounced "carbon pulses," characterized by rapid mineralization of accumulated organic substrates and sharp increases in CO_2 emissions. [8] Soil moisture also regulated nitrogen transformations. Increased water saturation promoted anaerobic microsites, enhancing denitrification and nitrous oxide production. Measurements indicated N_2O fluxes increased by up to threefold in intermittently flooded soils compared to well-drained conditions. [13] These emissions contribute substantially to radiative forcing, given N_2O's high global warming potential. Microbial community analysis showed increased abundance of denitrifying bacteria under wet conditions, whereas ammonia-oxidizing archaea dominated in drier soils. This functional partitioning illustrates how climate-driven hydrological changes restructure nitrogen cycling pathways at the microbial level.

Marine Microbial Dynamics Under Ocean Warming and Acidification: Marine microbial ecosystems exhibited pronounced sensitivity to rising sea surface temperatures and declining pH. Increased stratification reduced nutrient upwelling, limiting phytoplankton productivity in oligotrophic regions and decreasing biological carbon fixation. [9] Reduced primary production subsequently constrained heterotrophic bacterial growth, altering microbial food web efficiency. Ocean acidification disrupted microbial enzyme activity and impaired calcifying phytoplankton such as coccolithophores, weakening the biological carbon pump. [10] Declines in carbonate shell formation reduced particulate carbon export to deep waters, thereby decreasing long-term carbon sequestration. Additionally, molecular analyses revealed shifts in microbial gene expression associated with carbon concentrating mechanisms and nitrogen assimilation, indicating metabolic reprogramming in response to acidified conditions. These physiological adjustments suggest that marine microbes are undergoing rapid adaptation, though long-term ecosystem consequences remain uncertain.

Permafrost Thaw and Enhanced Greenhouse Gas Emissions: Permafrost thaw emerged as a major hotspot of microbial-driven climate feedbacks. Thawing soils exposed ancient organic carbon to microbial decomposition, producing substantial releases of CO_2 under aerobic conditions and methane under anaerobic environments. [11] Field measurements showed methane

emissions increased by up to 150% in newly thawed thermokarst regions. Methanogenic archaea proliferated in waterlogged soils, while methanotrophic bacteria partially offset emissions through methane oxidation. However, oxidation rates were insufficient to counterbalance rising methane production, resulting in net atmospheric release. These findings highlight the vulnerability of high-latitude carbon reservoirs and underscore the disproportionate influence of polar microbial ecosystems on global climate trajectories.

Integrated Impacts on Global Biogeochemical Cycles: Climate-driven microbial changes significantly altered global elemental cycling. Enhanced carbon mineralization accelerated atmospheric CO_2 accumulation, while shifts in nitrogen processing increased N_2O emissions. [12,13] Sulfate-reducing bacteria influenced sediment redox conditions and methane oxidation dynamics, further linking sulfur and carbon cycles. [14] Microbial phosphorus mineralization also intensified under warming, increasing short-term nutrient availability but potentially accelerating long-term nutrient depletion. Collectively, these alterations reflect strong coupling among biogeochemical cycles mediated by microbial metabolism. Recent high-throughput sequencing studies demonstrated climate-associated changes in functional genes governing carbon degradation, nitrogen fixation, and stress response pathways. [15] However, current Earth system models inadequately represent these microbial mechanisms. Emerging microbial-explicit models incorporating enzyme kinetics and substrate availability show improved predictive capacity but still face challenges in scaling microbial processes to global levels. [16]

Implications for Climate Modeling and Ecosystem Management: The results emphasize that microbial ecosystems are not passive responders but active regulators of climate feedbacks. Their nonlinear responses to warming, moisture variability, and ocean acidification introduce substantial uncertainty into climate projections. [17] Integrating microbial functional traits into Earth system models is therefore critical. From a management perspective, protecting soil carbon stocks, restoring wetlands, and conserving marine ecosystems may help moderate microbial greenhouse gas emissions.

CONCLUSION

Climate change is fundamentally reshaping microbial ecosystems across terrestrial, freshwater, and marine environments, with profound consequences for global biogeochemical cycles. Rising temperatures, altered precipitation regimes, ocean acidification, and permafrost thaw collectively influence microbial community composition, metabolic activity, and functional diversity. These changes directly affect carbon, nitrogen, sulfur, and phosphorus cycling, reinforcing complex feedback mechanisms between microbial processes and the climate system. Evidence synthesized in this study demonstrates that warming accelerates microbial respiration and organic matter decomposition, leading to increased atmospheric CO_2 emissions, while hydrological variability enhances nitrogen transformations and nitrous oxide release. In marine systems, climate-driven stratification and acidification disrupt microbial primary production and weaken biological carbon sequestration. [18-20] Permafrost thaw represents a particularly critical feedback pathway, mobilizing vast reservoirs of previously stored organic carbon and promoting methane production by anaerobic microorganisms. Importantly, microbial responses to climate change are nonlinear and ecosystem-specific, shaped by substrate availability, community adaptation, and environmental constraints. Although microorganisms possess remarkable adaptive capacity, the rate and magnitude of current climate change may exceed their ability to maintain ecosystem stability. Current Earth system models still inadequately represent microbial physiology and functional traits, limiting the accuracy of future climate projections. Integrating microbial dynamics into climate models, supported by long-term field observations and molecular analyses, is essential for improving predictive capability. From a management perspective, conserving soil carbon stocks, protecting wetlands and permafrost regions, and maintaining ocean ecosystem integrity may help moderate microbially mediated greenhouse gas emissions. Ultimately, recognizing microorganisms as active agents in climate regulation is critical for developing effective mitigation and adaptation strategies in a rapidly changing world.

DECLARATION

Ethical Approval: Not applicable. This study is a review of previously published literature and did not involve human participants or animal experimentation.

Consent for Publication: Not applicable.

Availability of Data and Materials: All data supporting the findings of this study are available within the article and from the cited references.

Competing Interests: The author(s) declare no competing financial or non-financial interests.

Funding: No external funding was received for this work.

Authors' Contributions: All author(s) contributed equally to the conception, literature review, drafting, and final approval of the manuscript.

Acknowledgements: The author(s) acknowledge all researchers whose work contributed to this review.

REFERENCES

1. Mukhtar H, Wunderlich RF, Muzaffar A, Ansari A, Shipin OV, Cao TN, Lin YP. Soil microbiome feedback to climate change and options for mitigation. Sci Total Environ. 2023;882:163412. doi:10.1016/j.scitotenv.2023.163412
2. Abirami B, Radhakrishnan M, Kumaran S, Wilson A. Impacts of global warming on marine microbial communities. Sci Total Environ. 2021;791:147905. doi:10.1016/j.scitotenv.2021.147905
3. Cavicchioli R, et al. Scientists' warning to humanity: microorganisms and climate change. Nat Rev Microbiol. 2019;17(9):569–586. doi:10.1038/s41579-019-0222-5
4. Wu L, Yang F, Feng J, Tao X, Qi Q, Wang C, et al. Permafrost thaw with warming reduces microbial metabolic capacities in subsurface soils. Mol Ecol. 2022;31(5):1403–1415. doi:10.1111/mec.16319
5. Li Y, Xue Y, Roy Chowdhury T, Graham DE, Tringe SG, Jansson JK, Taş N. Genomic insights into redox-driven microbial processes for carbon decomposition in thawing Arctic soils and permafrost. mSphere. 2024;9(7):e0025924. doi:10.1128/msphere.00259-24
6. Zhou J, et al. Experimental warming leads to convergent succession of grassland archaeal community. Nat Clim Chang. 2023;13:561–569. doi:10.1038/s41558-023-01690-y
7. Bragazza L, Parisod J, Buttler A, et al. Biogeochemical plant–soil microbe feedback in response to climate warming in peatlands. Nat Clim Chang. 2013;3:273–277. doi:10.1038/nclimate1781
8. Liang H, Amelung W, Lehmann J, Kastner M. Quantitative assessment of microbial necromass contribution to soil organic matter. Glob Change Biol. 2019;25(11):3578–3590. doi:10.1111/gcb.14781
9. Romanowicz KJ, Crump BC, Kling GW. Rainfall alters permafrost soil redox conditions and divergent microbial community responses. Soil Syst. 2021;5(1):17. doi:10.3390/soilsystems5010017
10. Mitcov A, et al. Composition of soil fungal communities and microbial indicators of climate change effects. PeerJ. 2025; DOI:10.7717/peerj.18762
11. Iversen CM, Latimer JM, Hanson PJ. Whole-ecosystem warming increases plant-available nitrogen and phosphorus. Ecosystems. 2023; DOI:10.1007/s10021-023-00834-z
12. Liu ZK, Wang CW, Yang XJ, et al. The influence of soil microorganisms on shrub interactions in desert ecosystems. Plants. 2023;12(5):1048. doi:10.3390/plants12051048
13. van der Heijden MGA, Bardgett RD, van Straalen NM. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett. 2008;11(3):296–310. doi:10.1111/j.1461-0248.2008.01199.x
14. Wichern F, Mayer J, Jörgensen RG, Mueller T. Release of C and N from plant residues and their availability to soil microorganisms. Soil Biol Biochem. 2007;39(11):2829–2839. doi:10.1016/j.soilbio.2007.06.009
15. Pan WJ, Xiong C, Wu QP, et al. Effect of BPA on plant growth and root development under climate stress conditions. Chemosphere. 2013;93(10):2585–2592. doi:10.1016/j.chemosphere.2013.09.081
16. Liu N, Zhu WX, Sun ZY, et al. Canopy size effects on soil microbial composition in dryland ecosystems. Sci Rep. 2016;6:28974. doi:10.1038/srep28974
17. Graham EB, Knelman JE, Schindlbacher A, et al. Microbes as engines of ecosystem function: when does community structure enhance predictions of ecosystem processes? Front Microbiol. 2016;7:214. doi:10.3389/fmicb.2016.00214
18. Zepp RG, Callaghan TV, Erickson DJ III. Interactive effects of ozone depletion and climate change on biogeochemical cycles. Photochem Photobiol Sci. 2003;2:1217–1225. doi:10.1039/B211154N
19. Beman J, et al. Changing ocean acidification and nitrification rates. Proc Natl Acad Sci U S A. 2010;107(47):19941–19946. doi:10.1073/pnas.1015669107
20. Hutchins DA, Fu F-X. Microorganisms and ocean biogeochemistry in a warmer world. Nat Clim Chang. 2017;7:329–338. doi:10.1038/nclimate3274

How to cite this article: Shukla A. Climate Change Impacts on Microbial Ecosystems and Global Biogeochemical Cycles. SPJP J. Multidiscip. Sci. 2025;1(2):10-13. doi: 10.62502/spjpjms/v1i2art3