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Opinion

Linking soil microbial dynamics, wetland ecosystem function and social-ecological health: Multiscale perspectives in ecology

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Soil microbial communities underpin fundamental ecosystem processes, including nutrient cycling, carbon sequestration and stress resilience, yet their role in linking ecological function with human health remains underexplored. Wetlands, as critical transitional ecosystems, amplify the influence of microbial dynamics on ecosystem services such as flood mitigation, water purification and greenhouse gas regulation. Concurrently, human activities and social-ecological systems interact with microbial-mediated processes, creating feedback loops that shape both environmental and societal outcomes. This article synthesizes multiscale perspectives on soil microbial ecology, wetland function and SES integration. Drawing upon terrestrial, coastal and agricultural case studies, we highlight the mechanisms through which microbial communities influence ecosystem resilience and human well-being, offering insights for sustainable management under global environmental change.

Keywords: Soil microbial dynamics, Wetland ecosystems, Social-ecological systems, Ecosystem services, Carbon cycling, Nutrient cycling, Resilience, Climate adaptation, Human-environment health, Multiscale ecology.

Introduction

Ecosystem function emerges from intricate interactions across biological, physical and social scales. Microorganisms—bacteria, fungi, archaea—serve as invisible engineers of ecosystems, mediating decomposition, nutrient turnover and plant productivity. Wetlands, including coastal, riparian and inland systems, exemplify the amplification of microbial effects, where soil and water microbial communities regulate key biogeochemical cycles that support ecosystem services and human health. Parallel to these ecological processes, human societies influence ecosystems through land-use decisions, urbanization, agriculture and resource exploitation. Social-ecological systems frameworks offer a holistic approach to understanding these feedbacks, emphasizing the co-dependence of ecological integrity and societal resilience. Integrating microbial ecology with SES perspectives is essential for predicting ecosystem responses to global change and for guiding adaptive management strategies that sustain both biodiversity and human well-being. Soil microbes are central to ecosystem processes (van Klink R, et al. 2021). Bacteria drive nitrogen fixation, nitrification and denitrification, while fungi, particularly mycorrhizal symbionts, enhance plant nutrient acquisition and stress tolerance. Functional diversity within microbial communities provides redundancy, ensuring ecosystem stability under environmental fluctuations such as drought, flooding, or nutrient limitation. Vegetation type, inundation frequency and hydrological regimes shape microbial composition and activity, demonstrating that microbial-mediated processes are tightly linked to both biotic and abiotic ecosystem components.

Description

Microbial communities also mediate soil carbon dynamics. Decomposer fungi and bacteria regulate organic matter turnover, while interactions with plants influence carbon allocation belowground. These processes directly affect soil fertility, plant productivity and carbon sequestration, linking microbial function to ecosystem-level resilience. Environmental perturbations such as hydrological extremes, salinity, or pollution can restructure microbial communities, affecting ecosystem services. Pre-exposure to stress often induces microbial "memory," enhancing resistance and recovery during subsequent disturbances (Carvalho C, et al. 2022). These feedbacks are critical in drylands, coastal wetlands and agricultural soils, where microbial mediation sustains ecosystem productivity under fluctuating environmental conditions. Wetlands are hotspots of microbial activity, influencing nutrient cycling, carbon fluxes and greenhouse gas emissions. Microbial communities in inundated soils modulate the transformation of nitrogen and phosphorus, control methane and nitrous oxide emissions and drive organic matter decomposition. Vegetation type, water regime and soil chemistry shape these microbial communities, demonstrating the tight coupling between microbial dynamics and wetland function.

Wetland ecosystem services, including flood mitigation, water purification and climate regulation, are directly linked to microbial processes. For example, microbial denitrification reduces nitrogen loading, preventing eutrophication downstream. Similarly, soil microbes regulate greenhouse gas emissions, contributing to climate change mitigation (Pohl M, et al. 2011). Maintaining diverse and functional microbial communities is therefore essential for wetland resilience and service provision. Restoration of degraded wetlands requires consideration of microbial-mediated processes. Reestablishing native vegetation, restoring hydrological regimes and minimizing anthropogenic disturbance promote microbial diversity, enhancing ecosystem resilience and ecosystem service delivery. Adaptive management guided by microbial monitoring ensures the long-term sustainability of restored wetlands. Human activities such as agriculture, urbanization and pollution alter microbial community composition and function (Liu X, et al. 2022). Soil compaction, chemical inputs and hydrological modification reduce microbial diversity, impair nutrient cycling and weaken ecosystem resilience. These changes have cascading effects on ecosystem services that humans rely upon, including food production, water quality and climate regulation.

SES frameworks emphasize the feedback loops between human actions and ecosystem processes. Policies, governance and community engagement shape land-use decisions, which in turn influence microbial-mediated functions. Participatory approaches in conservation and land management allow communities to align human needs with ecological integrity, promoting sustainable resource use and enhancing social resilience. The health of social-ecological systems is intimately connected to microbial dynamics. Wetlands that efficiently filter pollutants reduce exposure to waterborne pathogens and harmful chemicals. Productive soils with diverse microbial communities enhance food security and nutrition. Recognizing these links provides a foundation for ecosystem-based health interventions and climate adaptation strategies. Studies in southern Australia have demonstrated that inundation patterns and vegetation composition strongly influence microbial community structure and greenhouse gas fluxes. Restoration strategies that mimic natural hydrology and promote native plant communities support microbial-mediated services such as carbon sequestration, nutrient cycling and flood mitigation (Craig JM, et al. 2016). Drylands, often considered marginal landscapes, contribute disproportionately to global productivity due to specialized microbial communities. Biological soil crusts and symbiotic mycorrhizal fungi stabilize soils, enhance water retention and promote nitrogen availability, illustrating the importance of microbial mediation in sustaining ecosystem services under arid conditions.

Conclusion

Soil microbial dynamics are central to ecosystem function, influencing nutrient cycling, carbon sequestration and resilience across biomes. Wetlands serve as amplifiers of microbial-mediated processes, providing critical ecosystem services that support human health and societal resilience. Human activities and social-ecological systems, in turn, shape microbial composition and function, creating feedbacks that influence both ecological and social outcomes. Multiscale integration of microbial ecology with SES frameworks enables adaptive management strategies that sustain ecosystem services, biodiversity and human well-being under global environmental change. Future research should focus on linking high-resolution microbial monitoring with participatory governance and policy development to achieve resilient, multifunctional landscapes.

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Conflict of Interest

The authors declare no conflict of interest.

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