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Short Communication

Ecosystem function, microbial dynamics and human-nature interactions under environmental stress

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Ecosystems are complex networks where biotic and abiotic components interact across multiple scales, shaping ecosystem functions and services. Soil microbial communities play a central role in regulating nutrient cycling, carbon sequestration and plant productivity, particularly under environmental stressors such as drought, pollution and land-use change. Simultaneously, human activities-from agriculture to urbanization-interact with these ecological processes, influencing resilience and sustainability. This article synthesizes current knowledge on the interplay between microbial dynamics, ecosystem function and human-nature interactions under environmental stress. Emphasis is placed on multiscale mechanisms, including microbial-plant interactions, hydrological feedbacks and social-ecological determinants of resilience. The discussion highlights strategies for integrating microbial ecology and human dimensions to maintain ecosystem services and adaptive capacity under global environmental change.

Keywords: Ecosystem function, Microbial dynamics, Soil microbiome, Human-nature interactions, Environmental stress, Resilience, Social-ecological systems, Sustainability.

Introduction

Ecosystems function as dynamic networks, where biological communities, physical processes and human interventions coalesce to maintain productivity and resilience. Among biotic components, soil microbes-including bacteria, fungi and archaea-are pivotal mediators of nutrient cycling, organic matter decomposition and carbon storage. Their activities influence plant growth, soil structure and biogeochemical fluxes, making them central to ecosystem function (Craig JM, et al. 2016). Environmental stressors such as drought, flooding, heavy metal pollution and climate extremes can disrupt microbial communities, altering nutrient availability and plant productivity. These stress-induced changes often cascade to affect ecosystem services such as pollination, water purification and climate regulation. Simultaneously, human activities-agriculture, urbanization, land-use change-modulate these ecological processes through management practices, habitat alteration and socio-economic decisions. Understanding ecosystem function under stress therefore requires an integrated perspective linking microbial dynamics, ecosystem processes and human-nature interactions. Recent advances in molecular ecology, functional trait analysis and social-ecological systems research provide opportunities to explore these interactions at multiple scales. This article reviews key mechanisms, feedbacks and management strategies that sustain ecosystem function under environmental stress. Soil microbial communities are central drivers of nutrient cycling and organic matter decomposition (Chen Y, et al. 2022). Bacteria mediate nitrogen fixation, nitrification and denitrification, while fungi contribute to phosphorus solubilization, mycorrhizal symbioses and litter decomposition. These processes regulate soil fertility, plant growth and carbon sequestration.

Description

Environmental stress, however, can reshape microbial communities. Drought, for instance, selects for stress-tolerant taxa that maintain basic nutrient cycling but may reduce overall microbial diversity. Similarly, heavy metal pollution from mining and industrial activities alters microbial community composition, often favoring resistant species while suppressing sensitive taxa, affecting soil function and plant health. Microbial networks, particularly mycorrhizal fungi, form symbiotic associations with plants, facilitating nutrient and water uptake. These networks also connect multiple plants, enabling resource sharing and buffering against environmental stress. Root exudates, which vary with plant species and environmental conditions, shape rhizosphere microbial communities and modulate ecosystem processes (Poulter B, et al. 2014). Under drought or waterlogging, microbial-plant interactions determine the resilience of vegetation. Pre-exposure to stress can enhance microbial resistance, allowing ecosystems to maintain function under recurring stress events. Functional diversity in microbial communities ensures redundancy, promoting ecosystem stability and resilience.

Human land-use activities-deforestation, urbanization and agriculture-directly impact ecosystem function by altering habitat structure, nutrient cycling and hydrological regimes. For example, intensive agriculture can disrupt soil microbial networks through tillage, monoculture and chemical inputs, reducing soil fertility and ecosystem resilience. Conversely, restoration practices, such as reforestation or wetland rehabilitation, can enhance microbial diversity and restore ecosystem function. Social-ecological feedbacks play a critical role. Farmers' adoption of organic or sustainable practices, driven by economic incentives, knowledge systems and participatory approaches, influences microbial-mediated nutrient cycling and plant productivity. Understanding these human drivers is essential for designing interventions that maintain ecosystem services (Xu C, et al. 2021). Environmental pollutants, including air and water contaminants, affect microbial communities and ecosystem functions. Air pollution, for instance, is linked to reduced microbial diversity in soils and aquatic systems, affecting nutrient cycling and crop yields. These changes can have downstream consequences for human health, as reduced ecosystem services compromise food security, water quality and air quality.

Ecosystem function emerges from interactions across microbial, plant, landscape and societal scales. Microbial activity influences plant growth, which modifies soil properties and hydrological patterns. These ecological changes feedback to human land-use decisions, creating complex adaptive systems. For instance, in restored quarries, insect pollination services recover differently depending on active versus spontaneous restoration strategies, demonstrating that human interventions modulate ecological trajectories. Similarly, hydrological modifications affect microbial activity, nutrient cycling and greenhouse gas emissions, with implications for climate regulation (Kale JR, et al. 2009). Ecosystem services-including carbon sequestration, water regulation, soil fertility and biodiversity maintenance-depend on the integrity of microbial-plant-hydrology networks. Stress events, such as droughts or floods, can disrupt these networks, leading to reduced service provision. Maintaining functional redundancy, microbial diversity and habitat connectivity enhances resilience..

Conclusion

Ecosystem function under environmental stress is shaped by the interplay of microbial dynamics, plant traits, hydrological processes and human-nature interactions. Soil microbes mediate nutrient cycling, carbon storage and plant productivity, while plant communities and hydrology modulate microbial activity and ecosystem processes. Human land-use decisions, pollution and management practices feed back into these ecological networks, creating complex adaptive systems. Maintaining ecosystem resilience requires multiscale integration: enhancing microbial and plant diversity, restoring hydrological connectivity and incorporating social-ecological dynamics into management strategies. Adaptive, participatory approaches ensure that ecosystems continue to deliver critical services-such as carbon sequestration, water regulation and biodiversity support-while promoting human well-being. Recognizing the interdependence of microbial, ecological and social systems is essential for sustainable landscape management in the face of global environmental change.

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Conflict of Interest

The authors declare no conflict of interest.

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