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*Opinion*

# Land-use change, drought adaptation and microbial mediation: Integrating carbon, pollination and soil ecosystem services

**Jun Wu***

*Department of Plant Sciences, Zhejiang University, China*

**Corresponding author E-mail: junwu@zjdu.cn*

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Land-use change and climate-induced droughts increasingly threaten ecosystem services by altering soil microbial communities, vegetation dynamics and pollination networks. Microbial mediation plays a pivotal role in sustaining soil fertility, carbon cycling and plant productivity under these stressors, yet the integrative understanding of microbial, ecological and human dimensions remains limited. This article synthesizes current knowledge on how land-use transformations and drought interact to influence microbial function, carbon sequestration and pollination services. Drawing on case studies from agricultural landscapes, drylands and restored ecosystems, we demonstrate how microbial diversity and plant-microbe-pollinator interactions buffer ecosystem services against environmental stress. By integrating microbial ecology with land management and adaptive strategies, this framework informs sustainable conservation and climate adaptation practices that preserve soil health, biodiversity and ecosystem resilience.

**Keywords:** Land-use change, Drought adaptation, Soil microbial dynamics, Carbon cycling, Pollination services, Ecosystem resilience, Soil fertility, Climate adaptation, Ecosystem services, Dryland ecosystems.

## Introduction

Global environmental change, characterized by rapid land-use modification and increased frequency of droughts, exerts significant pressures on ecosystems and the services they provide. Agricultural expansion, urbanization and deforestation disrupt soil microbial communities, impair pollination networks and reduce carbon storage, thereby threatening food security and climate regulation. Microorganisms—bacteria, fungi and archaea—serve as the foundation for ecosystem function by driving nutrient cycling, organic matter decomposition and symbiotic plant interactions. Drought further exacerbates ecosystem vulnerability, particularly in semi-arid and dryland regions, where water scarcity limits plant growth, reduces soil microbial activity and destabilizes pollination services. Integrating microbial ecology with land-use and drought adaptation frameworks provides a pathway to maintain ecosystem services under environmental stress. This article explores the interplay between land-use change, drought, microbial mediation, carbon dynamics and pollination, offering a multiscale perspective for sustainable management and climate adaptation. Soil microorganisms are central to ecosystem function, facilitating nitrogen fixation, phosphorus solubilization, organic matter decomposition and symbiotic interactions with plants. Mycorrhizal fungi and nitrogen-fixing bacteria enhance plant nutrient uptake, improve drought tolerance and contribute to soil carbon stabilization (Houghton RA, et al. 1999). Functional diversity and redundancy within microbial communities buffer ecosystems against environmental perturbations, ensuring the continuity of critical ecosystem services.

## Description

Microbial communities respond dynamically to water stress. While prolonged drought can reduce microbial biomass and activity, pre-exposure to moderate water limitation often enhances microbial resistance, creating an "ecosystem memory" that promotes resilience upon rewetting (Gallant AL, et al. 2014). These microbial responses regulate soil fertility, nutrient availability and carbon cycling, influencing plant productivity and ecosystem recovery during drought events. Conversion of natural habitats into agricultural land alters microbial diversity, disrupts soil food webs and reduces ecosystem resilience. Monoculture, overfertilization and soil compaction negatively impact microbial-mediated nutrient cycling, leading to decreased soil fertility and productivity. Incorporating organic amendments, crop rotations and biofertilizers can restore microbial function and enhance soil ecosystem services. Urban expansion fragments habitats, reduces plant diversity and modifies hydrological regimes, affecting microbial communities and pollinator networks (Chen Y, et al. 2022). Soil sealing and chemical pollution impair microbial-mediated decomposition and nutrient cycling, leading to reduced carbon storage and diminished ecosystem services. Green infrastructure, urban wetlands and habitat corridors can mitigate these impacts by supporting microbial diversity and ecosystem connectivity.

Microbial communities regulate the decomposition of organic matter and soil carbon stabilization. Mycorrhizal fungi enhance plant carbon allocation to soils, while decomposer bacteria facilitate nutrient turnover. Land-use change and drought alter microbial activity, potentially shifting carbon fluxes and reducing sequestration. Maintaining microbial diversity through sustainable land management ensures continued carbon storage and climate regulation. Microbial communities indirectly influence pollination by affecting plant health and floral traits. Healthy soils, enriched by microbial activity, promote plant growth and flower production, supporting pollinator abundance and diversity. Disruptions to microbial communities through land-use change or drought can cascade into reduced pollination services, affecting crop yields, seed set and overall ecosystem productivity. Drought-adapted plants often rely on symbiotic microbial interactions for nutrient acquisition and stress tolerance (Nessner Kavamura V, et al. 2013). Root exudates shape microbial communities, which in turn enhance soil structure, water retention and nutrient cycling. These feedbacks stabilize ecosystem function during water scarcity, demonstrating the importance of microbial mediation in drought adaptation.

Microbial functional redundancy allows ecosystems to maintain key services under environmental stress. Communities with diverse metabolic capabilities can compensate for the loss of sensitive taxa, maintaining nutrient cycling and carbon fluxes. Ecosystem memory, shaped by historical exposure to drought or disturbance, enhances resilience and facilitates rapid recovery following environmental perturbations. Land management strategies that integrate microbial ecology, drought adaptation and ecosystem services can sustain soil fertility, carbon storage and pollination networks (Bouskill NJ, et al. 2013). Agroecological practices, including intercropping, reduced tillage and organic amendments, promote microbial diversity and functional resilience. Landscape restoration, reforestation and wetland conservation further enhance ecosystem services and biodiversity. Incorporating social-ecological perspectives ensures that ecosystem management aligns with human needs and community participation. Stakeholder engagement, participatory planning and adaptive governance facilitate locally relevant strategies that enhance microbial-mediated services, food security and climate resilience. Integrating microbial monitoring with SES frameworks supports evidence-based decision-making and sustainable resource management.

## Conclusion

Land-use change and drought are major drivers of ecological stress, altering soil microbial dynamics, carbon cycling and pollination networks. Microbial communities mediate critical ecosystem services, buffering ecosystems against environmental perturbations and enhancing resilience. Sustainable land management, restoration practices and social-ecological integration can maintain microbial diversity and ecosystem function, ensuring continued carbon storage, soil fertility and pollination services. By linking microbial ecology with land-use strategies and SES frameworks, policymakers, scientists and communities can foster resilient, multifunctional landscapes capable of sustaining biodiversity, productivity and human well-being under global environmental change. Restoration of hydrological regimes and native vegetation promotes microbial function and ecosystem resilience.

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## Conflict of Interest

The authors declare no conflict of interest.

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