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Short Communication

Ecosystem memory under water stress: Microbial resistance, plant–soil feedbacks and climate extremes

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Ecosystem memory—the capacity of ecological systems to retain the effects of past disturbances—plays a pivotal role in mediating resilience under water stress and climate extremes. Droughts, altered precipitation and heatwaves increasingly affect terrestrial ecosystems, influencing microbial communities, plant–soil interactions and overall ecosystem functioning. This article synthesizes evidence on microbial resistance and resilience, plant–soil feedbacks and the emergent properties of ecosystem memory under hydrological stress. It explores how past exposure to water limitation shapes microbial community composition, nutrient cycling and plant growth, influencing ecosystem recovery and productivity. Emphasis is placed on drylands, grasslands, forests and agroecosystems, integrating experimental, observational and modeling studies. Understanding ecosystem memory mechanisms is essential for predicting ecosystem responses to climate variability, managing landscapes for resilience and sustaining ecosystem services under a changing climate.

Keywords: Ecosystem memory, Water stress, Microbial resistance, Plant–soil feedbacks, Climate extremes, Drought resilience, Ecosystem recovery, Drylands.

Introduction

Terrestrial ecosystems are increasingly challenged by water stress driven by climate variability and human-induced land-use changes. Droughts, irregular rainfall and heatwaves influence plant physiology, soil microbial communities and biogeochemical cycles, with cascading effects on productivity, nutrient cycling and ecosystem services. Ecosystem memory—the imprint of past conditions on current ecological responses—has emerged as a critical concept for understanding how ecosystems withstand and recover from stress events. Microbial communities, which drive nutrient cycling and soil fertility, often retain adaptive traits shaped by prior exposure to drought or heat, influencing ecosystem resistance and recovery (Zhang W, et al. 2022). Similarly, plant–soil feedbacks, through root exudates, litter inputs and symbiotic interactions, mediate resource availability, water retention and resilience to environmental fluctuations. These multiscale interactions determine the trajectory of ecosystem function under recurrent climate extremes. This examines ecosystem memory under water stress, focusing on microbial resistance, plant–soil feedbacks and the broader implications for ecosystem productivity and resilience. By integrating empirical studies and conceptual frameworks, we highlight strategies to harness ecosystem memory for climate adaptation and sustainable management of terrestrial landscapes. Soil microbial communities are central to ecosystem memory, influencing nutrient cycling, organic matter decomposition and plant productivity. Drought and water limitation impose selective pressures, favoring drought-tolerant taxa and altering community composition (Chen Y, et al. 2022). Studies in drylands and grasslands indicate that pre-exposure to moderate drought increases the resistance of microbial communities to subsequent stress events, maintaining key functional processes such as nitrogen mineralization and carbon turnover.

Description

Microbial resistance arises from physiological acclimation, shifts in community structure and the persistence of drought-adapted functional groups. Soil microbial extracellular polymeric substances, osmolyte production and spore formation enhance survival during water limitation. Legacy effects, where prior drought exposure modifies microbial enzymatic activity and functional gene expression, contribute to ecosystem memory, sustaining nutrient availability and facilitating plant recovery. Microbial memory affects ecosystem productivity by maintaining decomposition rates and nutrient cycling under repeated stress. Resistant microbial communities enhance soil organic matter stabilization, influence greenhouse gas fluxes and regulate plant growth through symbiotic associations (Nessner Kavamura V, et al. 2013). Disruptions to microbial community structure—such as those caused by intensive land-use or repeated extreme droughts—can compromise ecosystem memory, reducing resilience and productivity. Plants actively shape soil microbial communities through root exudates, which provide substrates for microbial metabolism and signaling. Under water stress, changes in exudate composition alter microbial activity, nutrient mobilization and soil structure. Positive plant–soil feedbacks enhance water-use efficiency, improve nutrient uptake and stabilize soil aggregates, contributing to ecosystem resistance and recovery.

Mycorrhizal fungi and nitrogen-fixing bacteria play critical roles in mediating plant–soil feedbacks under drought. Mycorrhizal networks enhance water and nutrient acquisition, while symbiotic bacteria support stress tolerance and promote root growth. Functional complementarity among microbial taxa and plant species buffers ecosystems against environmental variability, reinforcing the memory effect of previous stress exposure. Plant–soil feedbacks create legacy effects that influence future ecosystem responses. For example, prior drought events can induce shifts in species composition, favoring drought-tolerant plants, which in turn shape soil microbial communities and nutrient cycling (Bouskill NJ, et al. 2013). These feedbacks modulate ecosystem productivity, carbon storage and resilience, illustrating the multiscale nature of ecosystem memory. Climate extremes disrupt water availability, alter plant physiology and stress microbial communities. Ecosystem memory determines how past exposure influences current responses. Systems with established drought memory—through adapted microbial communities and plant functional traits—exhibit greater resistance to extreme events, maintaining primary productivity and soil nutrient cycling.

Ecosystem memory operates across scales, from microbial microsites to landscape-level patterns. Spatial heterogeneity in soil properties, vegetation cover and water availability modulates the persistence of memory effects. Temporally, short-term memory involves physiological acclimation, while long-term memory encompasses shifts in community composition and ecosystem structure. Recognizing these scales is crucial for predicting ecosystem responses to recurrent stress. Management practices influence ecosystem memory (Adebiyi JA, et al. 2022). Irrigation, organic amendments and vegetation restoration can enhance microbial resistance and positive plant–soil feedbacks, while intensive tillage, monoculture and chemical inputs may disrupt memory, reducing resilience. Landscape-level planning that integrates hydrological management, biodiversity conservation and soil health supports the development of ecosystem memory, improving resistance to future extremes.

Conclusion

Ecosystem memory under water stress is a central determinant of resilience, productivity and carbon cycling in terrestrial landscapes. Microbial resistance, plant–soil feedbacks and legacy effects of past stress events interact across spatial and temporal scales, shaping ecosystem responses to recurrent droughts and climate extremes. Functional diversity, habitat heterogeneity and sustainable land management reinforce these memory effects, supporting ecosystem services and human well-being. Understanding the mechanisms and scales of ecosystem memory is essential for predicting ecosystem responses to climate variability and designing management strategies that sustain productivity, biodiversity and carbon storage. By harnessing microbial resistance and positive plant–soil feedbacks, land managers and policymakers can enhance ecosystem resilience, mitigating the impacts of water stress and climate change while ensuring the long-term sustainability of natural and managed landscapes. Functional diversity within plant and microbial communities reinforces ecosystem memory. Redundant species provide stability in nutrient cycling and productivity, ensuring that ecosystem functions persist despite extreme events. Conservation of biodiversity, combined with restoration of degraded landscapes, enhances the capacity of ecosystems to retain memory and resist the impacts of water stress.

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Conflict of Interest

The authors declare no conflict of interest.

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