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Perspective

Linking hydrology, soil-microbiome interactions and socio-environmental drivers for resilient and sustainable landscapes

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Sustainable landscape management requires an integrative understanding of hydrological processes, soil-microbiome interactions and socio-environmental drivers that collectively determine ecosystem resilience. Hydrology influences nutrient cycling, water availability and plant productivity, while soil microbial communities mediate carbon sequestration, soil fertility and ecosystem recovery under environmental stress. Human land use, governance and socio-economic practices further modulate these ecological processes, shaping both ecosystem service provision and societal well-being. This review synthesizes recent findings on the interconnections among hydrological dynamics, microbial ecology and social-ecological systems, emphasizing multiscale mechanisms that support resilient landscapes. Through the integration of ecological modeling, microbial studies and participatory management approaches, we highlight strategies for mitigating environmental stressors, enhancing ecosystem function and promoting sustainable landscape management in the context of global change.

Keywords: Hydrology, Soil microbiome, Ecosystem resilience, Landscape sustainability, Socio-ecological drivers, Carbon cycling, Water regulation, Land management.

Introduction

Landscapes are dynamic systems shaped by the interaction of physical, biological and social processes. Hydrology governs water availability, nutrient transport and flood or drought dynamics, influencing plant growth and ecosystem functioning. Simultaneously, soil microbial communities, including bacteria, fungi and archaea, play central roles in nutrient cycling, organic matter decomposition and plant-soil feedbacks that sustain ecosystem services. Human activities—ranging from agriculture, urban development, to forest management—intersect with these ecological processes, producing complex socio-environmental feedbacks that can either reinforce resilience or exacerbate vulnerability. Environmental change, including climate variability and land-use transformation, increasingly threatens the stability of these coupled systems. Droughts, floods and soil degradation not only reduce ecosystem productivity but also compromise services such as water purification, carbon sequestration and food production, with direct implications for human health and livelihoods (Fashola MO, et al. 2016). Understanding how hydrological regimes, soil-microbiome interactions and socio-environmental drivers jointly determine landscape resilience is essential for developing sustainable management strategies (Maestri E, et al. 2002). Recent studies have explored these interactions across multiple scales. For instance, flood control modeling using spatial decision support systems highlights how hydrological management can mitigate disaster risks, while investigations into drought effects on root exudates reveal how microbial communities enhance soil and plant resilience.

Description

Hydrology is a key determinant of ecosystem resilience. Water availability affects plant productivity, soil moisture regimes and nutrient transport. In wetlands and riparian zones, inundation patterns control microbial activity, greenhouse gas fluxes and sediment deposition. Research in temperate coastal wetlands in southern Australia demonstrates that varying vegetation types influence soil carbon dynamics under inundation, highlighting the coupled effects of hydrology and plant-microbial interactions. Flood management and water conservation strategies also depend on understanding hydrological variability. Spatial-temporal sensitivity analyses, such as those using MADM-GIS models, identify areas most susceptible to flooding and help prioritize interventions to maintain landscape functionality (Stokols D. 1992). By managing hydrological regimes strategically, landscapes can better buffer against climate extremes while sustaining essential ecosystem services such as water regulation, habitat provision and soil stabilization.

Soil microbial communities are central to ecosystem function and resilience. Bacteria and fungi mediate nutrient cycling, organic matter decomposition and carbon storage, forming intricate networks that support plant growth and ecosystem recovery. Ectomycorrhizal fungi, for instance, influence nutrient uptake and plant stress tolerance, while bacterial consortia can enhance soil structure and water retention under drought conditions. Drought and other environmental stressors alter root exudation patterns, which in turn modify microbial community composition and activity (Poulter B, et al. 2014). Studies on crop rhizospheres show that pre-exposure to water stress can increase microbial resistance to subsequent drought events, providing a buffering effect for plant productivity. These findings underscore the importance of integrating soil microbial dynamics into landscape management, particularly in regions experiencing increased climate variability.

Human activities shape the structure, function and resilience of ecosystems. Land-use change, urbanization and agricultural intensification influence hydrological connectivity, soil quality and biodiversity. Incentive structures, governance systems and participatory management approaches determine the adoption of sustainable practices, such as organic farming, conservation agriculture and wetland restoration. Participatory causal loop mapping, as applied in Nigerian organic farming systems, illustrates how stakeholder engagement, local knowledge and policy support can drive sustainable land-use adoption. Social-ecological frameworks emphasize the need to consider human behavior, institutional capacity and socio-economic constraints alongside ecological processes. These socio-environmental drivers interact with hydrology and microbial networks to produce emergent outcomes in ecosystem function and resilience. Effective landscape management requires integrating hydrological, microbial and socio-environmental processes across scales (Wang S, et al. 2023). Local-scale interventions, such as enhancing soil microbial diversity or restoring riparian vegetation, must be linked to landscape-level planning for flood control, biodiversity conservation and water resource management. Regional and national policies can provide the regulatory framework and incentives necessary for implementing these strategies at scale.

Conclusion

Integrating hydrology and soil microbiome management directly influences ecosystem services that underpin human health and livelihoods. Water regulation, flood mitigation, carbon sequestration, soil fertility and pollination are all mediated by these processes. Disruptions to hydrology or microbial networks can exacerbate risks such as soil degradation, crop failure and waterborne diseases. Air quality and public health are also connected to landscape management. Vegetation cover, wetland integrity and soil microbial activity influence pollutant filtering and greenhouse gas dynamics. Time-series studies in urban regions demonstrate that poor ecosystem management increases exposure to harmful pollutants, leading to elevated morbidity and mortality. By aligning hydrological management and microbial resilience with socio-environmental governance, landscapes can maintain ecosystem services that support both ecological integrity and human health. Resilient and sustainable landscapes emerge from the intricate interplay of hydrological processes, soil-microbiome interactions and socio-environmental drivers.

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Conflict of Interest

The authors declare no conflict of interest.

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