Ukrainian Journal of Ecology

Ukrainian Journal of Ecology, 2025, 15(4), 04-06, doi: 10.15421/2025_623

Commentary

Soil fungal diversity as a hidden driver of ecosystem services, productivity and carbon cycling in dryland ecosystems

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Received: *01 July, 2025, Manuscript No: UJE-26-178634,* ***Editor assigned:*** *03 July, 2025, PreQC No: P-178634,* ***Reviewed:*** *16 July, 2025, QC No: Q-178634,* ***Revised:*** *23 July, 2025, Manuscript No: R-178634,* ***Published:*** *31 July, 2025*

Dryland ecosystems, encompassing arid, semi-arid, and dry sub-humid regions, cover more than 40% of the Earth's terrestrial surface and support a large proportion of the global population. Despite their sparse vegetation and harsh climatic conditions, drylands play a disproportionately important role in global carbon cycling, ecosystem productivity, and climate regulation. At the core of these functions lies soil fungal diversity-a largely hidden yet critical driver of ecosystem processes. Soil fungi, including saprotrophs, mycorrhizal fungi, and endophytes, regulate nutrient cycling, organic matter decomposition, plant stress tolerance, and soil structure. Under increasing climate stress, particularly drought and land degradation, fungal communities mediate ecosystem resilience and the capacity of drylands to deliver ecosystem services. This article synthesizes current understanding of soil fungal diversity in dryland ecosystems and its role in sustaining ecosystem services, enhancing productivity, and regulating carbon dynamics. By integrating insights from microbial ecology, plant–soil interactions, and global change biology, the article highlights soil fungi as key, yet often overlooked, agents in dryland sustainability and climate adaptation.

Keywords: Soil fungi, Dryland ecosystems, Ecosystem services, Carbon cycling, Mycorrhizae, Climate change, Soil biodiversity, Ecosystem resilience.

Introduction

Dryland ecosystems are among the most climate-sensitive regions on Earth. Characterized by low and variable precipitation, high evapotranspiration, and frequent disturbances, these systems are often perceived as ecologically simple and low in productivity. However, recent research has revealed that drylands contribute substantially to interannual variability in global carbon uptake and can exhibit rapid productivity responses to climatic fluctuations. Central to these dynamics is the soil microbial community, particularly fungi, which operate largely unseen beneath the soil surface. Soil fungi form extensive networks that link plants, microbes, and soil resources, influencing ecosystem structure and function across spatial and temporal scales. In drylands, where nutrient availability and water are severely limited, fungal-mediated processes are essential for sustaining vegetation and stabilizing ecosystem services (Ihrmark K., et al. 2012). Yet, compared to aboveground biodiversity, soil fungal diversity remains poorly characterized, and its ecological significance is often underestimated. Understanding the role of soil fungal diversity in dryland ecosystems is increasingly urgent as climate change intensifies drought frequency, alters precipitation patterns, and accelerates land degradation. This explores how soil fungal diversity acts as a hidden driver of ecosystem services, productivity, and carbon cycling in dryland ecosystems, emphasizing its importance for resilience and sustainable management.

Description

Soil fungal communities in drylands are taxonomically diverse and functionally heterogeneous. They include saprotrophic fungi responsible for decomposing organic matter, mycorrhizal fungi that form symbiotic associations with plant roots, and endophytic fungi that live within plant tissues and enhance stress tolerance. Despite harsh environmental conditions, dryland soils harbor rich fungal assemblages adapted to extreme temperatures, desiccation, and nutrient scarcity. Mycorrhizal fungi-particularly arbuscular mycorrhizal fungi-are dominant in many dryland systems (Poulter B., et al. 2014). These fungi extend the effective root system of plants, improving water and nutrient uptake, especially phosphorus and micronutrients. Ectomycorrhizal fungi, though less widespread in drylands, play important roles in woody plant-dominated systems. Saprotrophic fungi regulate decomposition rates, influencing soil organic carbon storage and nutrient availability.

One of the most critical ecosystem services provided by soil fungi in drylands is nutrient cycling. Fungi decompose complex organic compounds that are inaccessible to most bacteria, releasing nutrients such as nitrogen and phosphorus into bioavailable forms. This function is particularly important in drylands, where organic inputs are low and nutrient turnover is slow (Wang S., et al. (2023). Mycorrhizal fungi enhance nutrient acquisition by plants, reducing nutrient losses and increasing nutrient-use efficiency. In managed dryland systems, such as rangelands and dryland agriculture, these processes support plant growth and reduce dependence on external inputs, contributing to sustainable productivity. Dryland fungi exhibit remarkable physiological and ecological adaptations to water stress. Many species produce resistant spores, thick-walled hyphae, or melanized structures that enhance survival during prolonged drought. Fungal communities can rapidly resume activity following rainfall, contributing to pulse-driven ecosystem processes typical of drylands. Climate stress shapes fungal community composition, favoring drought-tolerant taxa with efficient resource-use strategies (van Der Heijden MG., et al. 2015). These adaptive traits allow fungi to maintain ecosystem functioning even under extreme conditions, supporting plant survival and productivity during periods of water limitation

Plant productivity in drylands is tightly linked to plant–fungal interactions. Mycorrhizal associations improve plant water relations, nutrient uptake, and resistance to pathogens. Endophytic fungi enhance tolerance to abiotic stress by modulating plant hormone levels and antioxidant responses. Under drought conditions, plants associated with diverse fungal communities often exhibit higher survival and growth rates than non-mycorrhizal plants. Functional diversity among fungi ensures that multiple stress-mitigation strategies are available, enhancing ecosystem resilience (Tedersoo L., et al. 2014). Soil fungal diversity contributes to positive biodiversity–productivity relationships by increasing functional complementarity and redundancy. Diverse fungal communities can exploit a wider range of substrates and environmental niches, stabilizing productivity across variable climatic conditions. In drylands, where productivity is highly sensitive to rainfall variability, fungal diversity buffers ecosystems against climatic extremes, supporting consistent biomass production and forage availability.

Conclusion

Soil fungal diversity is a hidden yet fundamental driver of ecosystem services, productivity, and carbon cycling in dryland ecosystems. Through their roles in nutrient cycling, soil structure formation, plant stress tolerance, and carbon dynamics, fungi underpin the resilience of some of the world’s most climate-sensitive landscapes. As climate change intensifies pressures on drylands, conserving and managing soil fungal diversity becomes increasingly critical for sustaining ecosystem functions and human livelihoods. Integrating soil fungal ecology into dryland research, management, and policy will be essential for advancing sustainable land-use strategies and mitigating climate change impacts in the decades ahead. Recognizing soil fungal diversity as a key driver of ecosystem services has important implications for dryland management and conservation. Land-use practices that disrupt fungal communities-such as overgrazing, intensive tillage, and excessive chemical inputs-can undermine ecosystem resilience. Conversely, practices that support fungal diversity, including reduced disturbance, organic amendments, vegetation diversity, and restoration of native plant communities, can enhance ecosystem services. Incorporating fungal indicators into monitoring and management frameworks can improve the sustainability of dryland ecosystems under climate change.

Acknowledgement

None.

Conflict of Interest

The authors declare no conflict of interest.

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Citation:

Sharma, AK., (2025). Soil fungal diversity as a hidden driver of ecosystem services, productivity and carbon cycling in dryland ecosystems. *Ukrainian Journal of Ecology.* 15:04-06.