Ukrainian Journal of Ecology

Ukrainian Journal of Ecology, 2025, 15(6),15-17, doi: 10.15421/2025_644

Commentary

Linking microbial networks, carbon dynamics and human health in natural and managed landscapes

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Received: *01 November, 2025, Manuscript No: UJE-26-178654,* ***Editor assigned:*** *03 November, 2025, PreQC No: P-178654,* ***Reviewed:*** *15 November, 2025, QC No: Q-178654,* ***Revised:*** *21 November, 2025, Manuscript No: R-178654,* ***Published:*** *27 November, 2025*

Microbial communities are fundamental drivers of ecosystem processes, shaping carbon cycling, nutrient availability and soil fertility. Their interactions with plants, soil and environmental conditions influence ecosystem productivity and resilience, with cascading effects on human health and well-being. In both natural and managed landscapes, understanding the connections among microbial networks, carbon dynamics and health outcomes is critical for sustainable ecosystem management. This review synthesizes evidence on the role of microbial networks in carbon sequestration, greenhouse gas flux regulation and soil-plant interactions and explores how these processes link to human health via ecosystem services, air quality and nutrition. We discuss the implications for natural ecosystems, agricultural lands and urban landscapes, emphasizing multiscale integration from microbial to societal levels. The article underscores the need for interdisciplinary approaches combining microbial ecology, ecosystem science and public health to inform landscape management and climate adaptation strategies.

Keywords: Microbial networks, Carbon dynamics, Ecosystem services, Human health, Natural and managed landscapes, Soil-plant interactions, Climate adaptation.

Introduction

Global landscapes are increasingly shaped by human activities, including urbanization, intensive agriculture and industrial development, which alter ecosystem processes and services. Among these, microbial communities play a central yet often underappreciated role. Soil and root-associated microbiomes regulate carbon cycling, influence greenhouse gas emissions and drive plant growth and productivity (Poulter B, et al. 2014). These microbial-mediated processes not only determine ecosystem functioning but also affect human health by modulating air and water quality, food security and exposure to pathogens. Managed landscapes, including farmlands, urban green spaces and restored ecosystems, present opportunities to leverage microbial functions for sustainable outcomes. However, land-use change, pollution and climate extremes can disrupt microbial networks, impair carbon dynamics and compromise ecosystem services, ultimately impacting human well-being. Integrating microbial ecology with ecosystem carbon modeling and health considerations is therefore essential for designing resilient and sustainable landscapes. This explores the interplay between microbial networks, carbon dynamics and human health, highlighting evidence from natural and managed landscapes. We examine mechanisms linking microbial activity to carbon cycling, the influence of land management and environmental stressors and the consequences for ecosystem services relevant to human health (Xu C, et al. 2021). By connecting micro-scale processes to landscape-level outcomes, this review provides insights into sustainable management strategies in the Anthropocene.

Description

Soil microbial communities, including bacteria, fungi and archaea, orchestrate carbon storage and turnover through decomposition, mineralization and soil organic matter stabilization. Mycorrhizal fungi, for instance, form symbiotic associations with plant roots, enhancing nutrient acquisition and facilitating carbon transfer from plants to soil. These networks modulate the balance between carbon sequestration and greenhouse gas emissions, influencing both local ecosystem productivity and global carbon budgets. Semi-arid ecosystems and drylands, although often overlooked, contribute disproportionately to interannual variability in the global carbon cycle. Microbial activity in these regions mediates carbon fluxes under fluctuating moisture conditions, enhancing ecosystem resilience to drought (Kjøller R. 2006). Similarly, wetlands act as critical carbon sinks, where microbial communities regulate methane and nitrous oxide emissions depending on vegetation type, inundation regimes and nutrient availability. Understanding these microbial-mediated processes is key to managing carbon dynamics in natural and managed landscapes.

Land-use practices directly shape microbial composition and activity, with cascading effects on carbon dynamics. Intensive agriculture, monocultures and chemical inputs can reduce microbial diversity and functional redundancy, impairing soil carbon storage. Conversely, organic farming, agroforestry and restoration initiatives promote diverse microbial networks, enhancing nutrient cycling, soil aggregation and carbon sequestration. For example, crop rotations and cover cropping can stimulate beneficial soil microbes, increasing microbial biomass and carbon retention. Restoration of degraded lands, such as reforestation or wetland rehabilitation, fosters microbial community recovery, contributing to carbon storage and ecosystem resilience. Integrating microbial indicators into land management practices provides a mechanistic basis for optimizing carbon dynamics while maintaining soil fertility and ecosystem services (Stokols D. 1992). Microbial networks influence human health both directly and indirectly. Direct pathways include interactions with environmental pathogens, allergenic organisms and probiotic soil microbes that contribute to immune system regulation. Exposure to diverse environmental microbiomes in natural and semi-natural landscapes is associated with lower incidence of allergies, asthma and inflammatory diseases, highlighting the concept of the "microbial-mediated health effect."

Indirectly, microbial activity shapes ecosystem services that support human health. By regulating carbon storage and greenhouse gas emissions, microbial networks influence climate stability, air quality and food production. Soil microbial communities enhance nutrient availability for crops, improving nutritional quality and food security. In wetlands and riparian zones, microbes contribute to water purification, reducing exposure to contaminants and pathogens. Recognizing these linkages is essential for integrating public health objectives into landscape and conservation planning. Microbial networks operate at micro-scale (soil aggregates, root surfaces) but influence processes at landscape and regional scales. Spatial heterogeneity in soil type, vegetation cover and land-use intensity drives variability in microbial composition and function. Remote sensing, GIS modeling and metagenomic approaches enable the mapping of microbial-mediated processes across landscapes, linking microbial ecology to ecosystem service provision and human health outcomes (Stokols D. 1996). For instance, mapping wetland vegetation types alongside microbial-mediated greenhouse gas fluxes informs conservation strategies that optimize carbon sequestration and flood regulation. In agricultural landscapes, integrating pollinator habitat suitability with soil microbial diversity models can enhance crop productivity, resilience and ecosystem service delivery. This multiscale integration facilitates targeted interventions that maximize ecological and societal benefits.

Conclusion

Microbial networks are central to ecosystem functioning, influencing carbon dynamics, soil fertility and ecosystem service provision. In natural and managed landscapes, these microbial-mediated processes directly and indirectly impact human health, shaping resilience to environmental stressors and climate variability. Integrating microbial ecology with carbon management, habitat prioritization and public health considerations provides a comprehensive framework for sustainable landscape management. Future strategies should adopt multiscale, interdisciplinary approaches that bridge soil microbiology, ecosystem science and social-ecological systems.

Acknowledgement

None.

Conflict of Interest

The authors declare no conflict of interest.

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Citation:

Kale, AR., (2025). Linking microbial networks, carbon dynamics and human health in natural and managed landscapes. *Ukrainian Journal of Ecology.* 15: 15-17.