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Commentary

Multiscale ecological interactions governing ecosystem services in natural and managed landscapes under climate stress

Ananya Mukherjee*

Department of Ecology and Environmental Sciences, Jadavpur University, Kolkata, India

**Corresponding author E-mail: ananya.mukherjee@durunac.in*

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Ecosystem services-ranging from food production and climate regulation to water purification and cultural well-being-are sustained by complex ecological interactions operating across multiple biological, spatial, and temporal scales. Climate change intensifies pressures on these interactions through rising temperatures, altered precipitation regimes, extreme climatic events, and accelerating land-use change. Both natural and managed landscapes respond to climate stress through interconnected processes involving plants, soil organisms, animals, hydrological systems, and human decision-making. This article synthesizes current understanding of how multiscale ecological interactions govern ecosystem services under climate stress. It highlights the roles of belowground microbial networks, plant functional traits, landscape connectivity, biodiversity dynamics, and socio-ecological feedbacks. By integrating evidence from terrestrial, agricultural, forest, dryland, and coastal ecosystems, the article underscores the need for holistic, multiscale management strategies to sustain ecosystem services and enhance resilience in a rapidly changing climate.

Keywords: Ecosystem services, Climate change, Multiscale ecology, Soil microbiome, Biodiversity, Socio-ecological systems, Landscape management, Resilience.

Introduction

Ecosystem services form the ecological foundation of human well-being and economic development. These services-provisioning (e.g., food, fiber, medicinal resources), regulating (e.g., climate regulation, flood control, pollination), supporting (e.g., nutrient cycling, soil formation), and cultural (e.g., recreation, spiritual value)-emerge from interactions among organisms and their physical environment. However, global climate change is profoundly altering the conditions under which ecosystems function, challenging the capacity of landscapes to deliver these services reliably. Climate stressors rarely act uniformly across ecosystems. Instead, their impacts cascade across scales, from molecular and microbial processes to landscape patterns and global biogeochemical cycles. Natural ecosystems such as forests, grasslands, wetlands, and drylands respond differently to climate stress compared to managed systems like agricultural fields, plantations, and urban landscapes (Huang H., et al. 2024) Yet, these systems are increasingly interconnected through land-use change, hydrological flows, species movements, and human governance. Understanding ecosystem services under climate stress therefore requires a multiscale ecological perspective that integrates biological interactions, spatial heterogeneity, and socio-economic drivers.

Description

At the smallest ecological scales, soil microorganisms-bacteria, fungi, archaea, and microfauna-regulate critical ecosystem services by controlling nutrient availability, carbon sequestration, and soil structure. Mycorrhizal fungi enhance plant access to nutrients and water, while decomposer microbes drive organic matter turnover (Li M., et al. 2021) Climate stress, particularly drought and flooding, alters soil moisture and temperature, reshaping microbial community composition and function. Drought stress often reduces microbial activity but may also select for drought-tolerant taxa, increasing ecosystem resistance through ecological "memory." Root exudates released by plants under stress can modify rhizosphere microbial communities, influencing nutrient cycling and pathogen suppression. These belowground interactions directly affect provisioning services such as crop productivity and regulating services such as carbon storage. In managed landscapes, agricultural practices-including irrigation, fertilization, pesticide use, and crop rotation-further modify soil microbial dynamics. Sustainable management that supports soil biodiversity can buffer climate impacts and enhance ecosystem service stability (Tiemann LK., et al. 2015).

Traits determine how plants acquire resources, tolerate stress, and interact with other organisms. For instance, deep-rooted species can access water during droughts, contributing to ecosystem stability and hydrological regulation. Climate stress alters plant physiological processes such as photosynthesis, transpiration, and phenology (Li X., et al. 2019). Elevated atmospheric CO_2 can enhance water-use efficiency, but this benefit may be offset by heat stress or nutrient limitations. In forests and grasslands, shifts in species composition driven by climate change can modify ecosystem services such as carbon sequestration, forage production, and habitat provision. In managed systems, crop and tree selection based on functional traits is increasingly recognized as a climate adaptation strategy. Diversified systems with functionally complementary species often show greater resilience and sustained service delivery.

At landscape scales, biodiversity and spatial configuration play critical roles in regulating ecosystem services. Species diversity enhances functional redundancy, increasing ecosystem resilience to climate extremes. Landscape connectivity allows species movement, genetic exchange, and recolonization after disturbances, supporting long-term service provision. Climate stress interacts with habitat fragmentation caused by infrastructure development, urbanization, and agricultural expansion. Fragmented landscapes often show reduced pollination services, impaired water regulation, and diminished carbon storage. Mitigation measures such as ecological corridors, wildlife crossings, and restored habitats can partially restore connectivity and ecosystem function (Menkis A., et al. 2014). Pollinators illustrate the importance of landscape-scale interactions. Climate-driven changes in temperature and precipitation affect pollinator phenology and distribution, while land-use practices influence habitat availability. The resulting effects on pollination services have direct implications for food security.

Conclusion

Multiscale ecological interactions are fundamental to the generation and maintenance of ecosystem services in both natural and managed landscapes. Climate stress disrupts these interactions across biological, spatial, and social dimensions, challenging the resilience of ecosystems and the benefits they provide to humanity. From soil microbes and plant traits to landscape connectivity and human governance, ecosystem services emerge from dynamic, interconnected processes that cannot be understood or managed in isolation. A multiscale ecological perspective reveals that enhancing ecosystem service resilience requires protecting biodiversity, maintaining functional diversity, restoring degraded systems, and fostering adaptive socio-ecological relationships. As climate change accelerates, integrating ecological science with participatory management and policy innovation will be crucial for sustaining ecosystem services and supporting human well-being in a changing world. Policy frameworks that recognize ecosystem services as coupled human–natural systems are essential. Cross-sectoral collaboration, adaptive management, and evidence-based decision-making can help reconcile competing land-use demands while maintaining ecological integrity.

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Conflict of Interest

The authors declare no conflict of interest.

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