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Brief Report

Multiscale drivers of ecosystem function under environmental change

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Ecosystem functions, including primary productivity, nutrient cycling and carbon sequestration, are shaped by a complex interplay of biotic and abiotic drivers operating across spatial and temporal scales. Environmental change—driven by climate variability, land-use alteration, pollution and biodiversity loss—modulates these drivers, with cascading effects on ecosystem resilience and service provision. This article synthesizes current understanding of the multiscale factors governing ecosystem function, emphasizing the roles of microbial networks, plant physiology, soil properties, hydrological regimes and anthropogenic influences. By integrating insights from molecular biology, landscape ecology and social-ecological systems, we provide a framework for predicting ecosystem responses under environmental stressors and inform strategies for sustainable management and conservation.

Keywords: Ecosystem function, Environmental change, Multiscale drivers, Microbial networks, Land-use change, Hydrology, Resilience, Biodiversity.

Introduction

Ecosystems are dynamic systems in which energy flows, nutrient cycles and biotic interactions collectively maintain functional integrity. The functioning of ecosystems is influenced by drivers operating at multiple scales, from microbial activity in soils to vegetation structure across landscapes and extending to global climate dynamics. Anthropogenic pressures—including deforestation, urban expansion, intensive agriculture and climate change—are rapidly altering these drivers, threatening ecosystem stability and the services that sustain human societies (van Klink R, et al. 2021). Understanding how multiscale drivers interact to influence ecosystem function is critical for predicting ecological responses to environmental change and for designing effective conservation and management strategies. This requires integrating knowledge across ecological scales, from molecular and microbial processes to landscape-level patterns and social-ecological interactions. Such a multiscale perspective allows identification of mechanisms underpinning ecosystem resilience, carbon storage, nutrient dynamics and biodiversity maintenance. This explores key multiscale drivers of ecosystem function, their interactions under environmental change and their implications for ecosystem resilience and management. We highlight the role of microbial networks, plant-soil interactions, hydrological processes, land-use dynamics and socio-ecological factors, drawing examples from terrestrial and aquatic ecosystems. Microbial communities in soils are primary drivers of nutrient cycling, organic matter decomposition and carbon stabilization (Carvalho C, et al. 2022). Bacteria, fungi and archaea form complex networks that mediate soil fertility and influence ecosystem productivity. For instance, mycorrhizal fungi establish symbiotic relationships with plant roots, facilitating nutrient acquisition and promoting plant growth, while also transferring carbon from plants to soil pools.

Description

Environmental stressors such as drought, flooding and pollution can disrupt microbial networks, altering soil processes and carbon fluxes. Studies in dryland ecosystems show that pre-exposure to drought increases microbial resistance, maintaining soil function under extended water stress. Conversely, land-use change and intensive agriculture can reduce microbial diversity, impairing nutrient cycling and soil carbon storage. Therefore, microbial networks act as foundational drivers that modulate ecosystem function across spatial and temporal scales. Vegetation composition and functional traits, including root morphology, leaf physiology and growth strategies, influence primary productivity, water and nutrient uptake and carbon sequestration. Plants integrate environmental signals such as soil moisture, temperature and nutrient availability, adapting their physiology to maintain ecosystem functions under variable conditions (Pohl M, et al. 2011). Land-use changes, such as deforestation, conversion to cropland, or restoration of degraded areas, directly affect plant community structure, with cascading effects on ecosystem processes. For example, restoration of native vegetation increases habitat complexity and supports diverse microbial communities, enhancing nutrient cycling and carbon storage. Similarly, alpine and semi-arid plant species exhibit root adaptations that influence soil stabilization and water retention, shaping local hydrological and carbon dynamics (Nessner Kavamura V, et al. 2018).

Water availability and hydrological regimes are critical determinants of ecosystem function. In wetlands, inundation patterns control microbial-mediated greenhouse gas emissions, nutrient turnover and plant productivity. In semi-arid landscapes, variability in precipitation drives fluctuations in soil moisture, microbial activity and carbon cycling, creating strong interannual variability in ecosystem productivity. Hydrological changes induced by human activities, such as dam construction, irrigation, or urbanization, alter sediment transport, nutrient availability and habitat connectivity, impacting ecosystem resilience. Integrated hydrological and biogeochemical models can predict how these changes interact with plant and microbial processes to influence ecosystem function across scales. Land-use change, including urban expansion, agriculture and mining, modifies habitat structure, alters microclimates and introduces pollutants, all of which affect ecosystem functioning. Fragmentation reduces connectivity, affecting species dispersal and ecosystem resilience. Pollutants such as heavy metals and pesticides alter microbial communities and plant physiology, impacting carbon and nutrient cycles. Participatory management and sustainable land-use practices can mitigate these effects. For example, organic farming, agroforestry and riparian restoration enhance soil microbial diversity, improve nutrient cycling and maintain ecosystem services such as pollination and water regulation (Bouskill NJ, et al. 2013). Understanding the social dimensions of land-use change is essential, as human decisions directly shape landscape patterns and ecosystem drivers.

Biodiversity influences ecosystem function through complementary resource use, trophic interactions and functional redundancy. High species richness stabilizes ecosystem processes under environmental stress, enhancing resilience to climate extremes. Pollinators, herbivores, predators and decomposers form complex interaction networks that mediate productivity, nutrient cycling and pest regulation. Global changes such as habitat loss, climate warming and invasive species disrupt these interactions, affecting ecosystem function at multiple scales. Conservation of biodiversity hotspots, restoration of degraded ecosystems and maintenance of functional connectivity are key strategies to preserve ecosystem function and resilience. Human communities are integral components of ecosystems, influencing and responding to ecological changes.

Conclusion

Ecosystem function is governed by a network of multiscale drivers, including microbial communities, plant physiology, hydrology, biodiversity and human activities. Environmental change—through climate variability, land-use alteration and pollution—modulates these drivers, with cascading effects on ecosystem resilience and services. Recognizing the hierarchical and interactive nature of these drivers is critical for understanding ecosystem responses and for implementing sustainable management strategies. Integrating microbial, plant, landscape and social-ecological perspectives provides a comprehensive framework for predicting and mitigating the impacts of environmental change. Such multiscale approaches are essential to maintain ecosystem productivity, carbon storage, nutrient cycling and biodiversity, ultimately supporting human well-being in a rapidly changing world.

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Conflict of Interest

The authors declare no conflict of interest.

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