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Brief Report

Multiscale controls on ecosystem resilience under global change: Vegetation physiology, mycorrhizal networks and climate feedbacks

Lucas F. Oliveira*

Department of Ecology, University of São Paulo, Brazil

**Corresponding author E-mail: lfoliveira@uorsp.br*

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Ecosystem resilience-the capacity of ecosystems to absorb disturbances while maintaining structure and function-is critical in the context of rapid global change, including climate warming, altered precipitation regimes, land-use modification and biodiversity loss. Resilience emerges from interactions across multiple scales, encompassing physiological processes within individual plants, symbiotic networks such as mycorrhizae and biogeochemical feedbacks that regulate climate. Vegetation physiology influences primary productivity, water and nutrient use and stress tolerance, while mycorrhizal networks mediate resource exchange, soil structure and plant community dynamics. These processes collectively modulate ecosystem-level feedbacks, such as carbon sequestration and albedo effects, shaping the response of ecosystems to global change. This article synthesizes current understanding of multiscale controls on ecosystem resilience, integrating insights from plant physiology, soil–microbe interactions and climate feedback mechanisms. By examining terrestrial ecosystems across spatial and temporal scales, the article highlights how integrating multiscale ecological knowledge can inform conservation, restoration and management strategies under a changing climate.

Keywords: Ecosystem resilience, Global change, Vegetation physiology, Mycorrhizal networks, Climate feedbacks, Carbon cycling, Soil–plant interactions, Ecological adaptation.

Introduction

Ecosystems worldwide are increasingly exposed to multiple, interacting stressors associated with global change. These include rising temperatures, shifts in precipitation patterns, elevated atmospheric CO_2 concentrations, land-use conversion, pollution and invasive species. Maintaining ecosystem resilience under these pressures is essential for sustaining biodiversity, ecosystem services and human well-being. Resilience is a multiscale property emerging from interactions among physiological, ecological and biogeochemical processes. At the plant level, physiological traits-such as photosynthetic capacity, water-use efficiency and nutrient acquisition strategies-determine the capacity of vegetation to withstand stress. At the community and landscape levels, mycorrhizal networks facilitate nutrient and water exchange among plants, enhance soil structure and buffer communities against environmental variability. Collectively, these processes influence ecosystem-level climate feedbacks, including carbon storage, surface energy balance and hydrological regulation (Peng SS., et al. 2014). Understanding the interplay between these multiscale controls is crucial for predicting ecosystem responses to global change and for designing management strategies that maintain or enhance resilience. This explores the mechanisms by which vegetation physiology, mycorrhizal networks and climate feedbacks interact to regulate ecosystem resilience under global change.

Description

Vegetation physiology fundamentally governs ecosystem productivity and resilience. Photosynthetic efficiency, stomatal conductance and leaf area dynamics determine how plants capture carbon and manage water under varying environmental conditions. Traits such as intrinsic water-use efficiency and hydraulic conductivity influence the ability of plants to tolerate drought, heatwaves and fluctuating soil moisture. Elevated atmospheric CO_2 often enhances photosynthesis and WUE, potentially buffering productivity losses under moderate drought (Battipaglia G., et al. 2013). However, physiological gains can be offset by nutrient limitations, heat stress, or altered phenology, emphasizing the need to consider multiple interacting factors in assessing resilience. Root traits-including depth, density and morphology-mediate soil resource acquisition, influencing both plant survival and soil carbon dynamics. Deep-rooted species access groundwater during drought, stabilize soils and facilitate vertical nutrient redistribution (Kjøller R. 2006). Root exudates also shape microbial communities and soil aggregation, creating feedbacks that enhance ecosystem stability.

Mycorrhizal fungi form extensive networks connecting plant roots across spatial scales, facilitating nutrient and water exchange. Arbuscular mycorrhizal fungi are ubiquitous in herbaceous and agricultural systems, while ectomycorrhizal fungi dominate many forested ecosystems. These associations enhance plant nutrient uptake, particularly phosphorus and micronutrients and increase tolerance to abiotic stressors such as drought and soil salinity. Mycorrhizal networks also mediate interspecific interactions. Resource sharing among connected plants can stabilize community composition and support weaker or stress-sensitive individuals, maintaining ecosystem function under environmental perturbations (Bergmark L., et al. 2012). Beyond nutrient exchange, mycorrhizal hyphae contribute to soil aggregation and porosity, improving water infiltration and retention. Hyphal networks also interact with bacteria and other soil organisms, regulating decomposition and nutrient cycling. These belowground interactions propagate resilience from the microbial and plant level to ecosystem scales, particularly under climate extremes.

Vegetation physiology and mycorrhizal activity directly influence carbon dynamics, which feedback to climate systems. High photosynthetic capacity, coupled with efficient mycorrhizal nutrient exchange, promotes net primary productivity and carbon storage in both biomass and soils. Soil aggregation mediated by fungal networks stabilizes carbon in organic matter, reducing microbial decomposition losses. Climate feedbacks are particularly evident in systems vulnerable to drought or temperature extremes, such as drylands and forests. Reduced plant productivity or mycorrhizal activity under stress can trigger carbon release, amplifying atmospheric CO_2 levels and reinforcing climate change pressures. Vegetation and soil microbial interactions also influence hydrological cycles and surface energy balance (Gardes M., et al. 1993). Canopy cover, root architecture and fungal-mediated soil structure affect evapotranspiration, soil moisture retention and albedo. These properties modulate local and regional climate, influencing precipitation patterns, heat fluxes and water availability for ecosystems and human use. Incorporating these biophysical feedbacks into climate models improves predictions of ecosystem vulnerability and the effectiveness of management interventions.

Conclusion

Ecosystem resilience under global change is governed by multiscale interactions among vegetation physiology, mycorrhizal networks and climate feedbacks. Plant traits determine resource acquisition and stress tolerance, mycorrhizal networks facilitate nutrient and water distribution while stabilizing soil structure and ecosystem-level feedbacks regulate carbon dynamics and climate interactions. These interconnected processes enable ecosystems to absorb disturbances while maintaining essential functions and services. Effective conservation and management require a multiscale perspective that integrates above- and belowground processes, recognizes the role of biodiversity and considers biophysical feedbacks to the climate system. By leveraging insights into these mechanisms, we can enhance ecosystem resilience, sustain productivity and support nature-based solutions to the challenges posed by global change. Vegetation and soil microbial interactions also influence hydrological cycles and surface energy balance. Canopy cover, root architecture and fungal-mediated soil structure affect evapotranspiration, soil moisture retention and albedo. These properties modulate local and regional climate, influencing precipitation patterns, heat fluxes and water availability for ecosystems and human use.

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Conflict of Interest

The authors declare no conflict of interest.

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