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Perspective

Land-use change as a central regulator of carbon budgets and ecosystem productivity in a changing climate

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Land-Use Change (LUC) is a primary driver of alterations in ecosystem productivity, carbon storage and global biogeochemical cycles. The conversion of forests, grasslands and wetlands for agriculture, urban development, or other anthropogenic purposes significantly impacts terrestrial carbon budgets, greenhouse gas fluxes and ecosystem resilience under climate change. This article synthesizes current understanding of how LUC influences carbon dynamics and ecosystem productivity across spatial and temporal scales. We examine mechanisms including deforestation, afforestation, agricultural intensification and urbanization and their effects on carbon sequestration, net primary productivity and soil health. We also explore feedbacks between LUC, climate variability and ecosystem services, emphasizing strategies for sustainable land management that mitigate carbon emissions and enhance ecosystem productivity. Understanding these interactions is crucial for climate adaptation, biodiversity conservation and global carbon management.

Keywords: Land-use change, Carbon budget, Ecosystem productivity, Climate change, Deforestation, Afforestation, Soil carbon, Ecosystem services.

Introduction

Land-use change is a dominant anthropogenic force altering the Earth's surface, with profound implications for carbon dynamics and ecosystem productivity. Terrestrial ecosystems act as both carbon sinks and sources, mediating the exchange of carbon dioxide (CO_2) and other greenhouse gases with the atmosphere. Conversion of natural landscapes to croplands, pastures, or urban areas reduces carbon storage, disrupts nutrient cycling and alters primary productivity. Conversely, restoration and afforestation can enhance carbon sequestration, soil fertility and ecosystem resilience. Global climate change exacerbates the impacts of LUC, influencing precipitation patterns, temperature regimes and disturbance frequencies such as droughts, fires and storms. These interactions create complex feedbacks, affecting both carbon budgets and the productivity of terrestrial ecosystems. Understanding the mechanisms and outcomes of LUC across scales—from local to global—is essential for developing mitigation strategies, conserving biodiversity and maintaining ecosystem services critical for human well-being (Houghton RA, et al. 1999). This explores the role of land-use change as a central regulator of carbon budgets and ecosystem productivity, examining the ecological processes, biogeochemical feedbacks and management strategies that shape terrestrial ecosystems in a changing climate.

Description

Deforestation, particularly in tropical and boreal forests, is a major driver of carbon emissions. Forest conversion to cropland or pasture releases large quantities of stored carbon from biomass and soils into the atmosphere. Tree removal reduces photosynthetic capacity, limiting carbon uptake, while soil disturbance accelerates decomposition and CO_2 release. The loss of forest canopy also alters microclimates, hydrological cycles and soil moisture, further impacting productivity and carbon retention. Afforestation and reforestation initiatives can partially offset carbon losses by restoring forest cover and enhancing net primary productivity. Trees act as carbon sinks, sequestering CO_2 in woody biomass, leaves and roots (Gallant AL, et al. 2014). The rate of carbon accumulation depends on species selection, planting density, soil quality and climate conditions. Mixed-species plantations and restoration of native vegetation often provide greater carbon storage and ecosystem resilience compared to monocultures.

Agricultural expansion and intensification influence carbon dynamics through tillage, fertilizer use and crop selection. Conventional tillage increases soil respiration and organic matter loss, while reduced-tillage and conservation agriculture promote carbon retention (Guo X, et al. 2023). Crop rotations, cover crops and agroforestry enhance soil fertility, water retention and ecosystem productivity, creating opportunities to mitigate LUC-driven carbon emissions while sustaining food production. Urban expansion converts vegetated landscapes into impervious surfaces, reducing carbon sequestration and altering local microclimates. Urban soils store less carbon than natural ecosystems and vegetation removal diminishes primary productivity. Urban green infrastructure, including parks, street trees and green roofs, can partially compensate by sequestering carbon, moderating temperatures and improving ecosystem service provision. Land-use change modifies the global carbon budget by altering carbon fluxes between the biosphere and atmosphere. Deforestation and soil degradation increase atmospheric CO_2 concentrations, enhancing greenhouse warming (Porcar-Castell A, et al. 2014). Conversely, carbon sequestration through afforestation and sustainable land management can mitigate climate change. These feedbacks are amplified by climate-sensitive processes such as fire regimes, droughts and pest outbreaks, which further influence carbon storage and ecosystem productivity.

Soil represents a major carbon reservoir and LUC significantly affects soil carbon stocks and turnover rates. Conversion of forests to agriculture reduces organic carbon content, while urbanization often leads to compaction and reduced microbial activity. Restoration practices, including afforestation, cover cropping and organic amendments, increase soil carbon sequestration and improve soil health, supporting ecosystem productivity. Soil microbial communities mediate decomposition, nutrient cycling and carbon stabilization. Land-use change disrupts microbial diversity and function, altering carbon mineralization rates. Restoration and conservation practices that maintain microbial diversity enhance soil fertility, carbon sequestration and resilience to environmental stress. Biodiversity influences ecosystem productivity and carbon dynamics. Diverse plant communities exhibit complementary resource use, stabilizing productivity and enhancing carbon sequestration (Houghton RA, et al. 1999). LUC often reduces biodiversity, weakening ecosystem function and resilience. Restoration of native species and maintenance of habitat heterogeneity promote both biodiversity and carbon storage, creating synergistic benefits for climate mitigation and ecosystem services.

Conclusion

Land-use change is a central regulator of carbon budgets and ecosystem productivity, influencing both biophysical processes and climate feedbacks. Deforestation, agricultural intensification and urbanization reduce carbon sequestration, disrupt nutrient cycling and impair ecosystem function, while restoration, afforestation and sustainable land management enhance productivity, soil health and carbon storage. Biodiversity plays a key role in stabilizing ecosystem services and ensuring resilience under climate stress. Understanding the multiscale interactions among land-use, carbon dynamics and ecosystem productivity is essential for mitigating climate change, conserving biodiversity and supporting human well-being. Integrating ecological, socio-economic and policy perspectives enables effective strategies for land management that balance development needs with environmental sustainability. In a rapidly changing climate, addressing land-use impacts is critical for sustaining both ecosystem function and global carbon balance. Restoration of degraded lands enhances carbon sequestration, biodiversity and hydrological function. Native species restoration, afforestation and riparian buffer establishment improve ecosystem productivity and carbon storage while supporting local livelihoods and climate adaptation.

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Conflict of Interest

The authors declare no conflict of interest.

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