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Editorial

Progress and Prospects in Assessing the Multidimensional Environmental Impacts of Global Vegetation Restoration

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The restoration of degraded vegetation and ecosystems is a critical tool for mitigating biodiversity losses, stabilizing soils, improving water quality, sequestering carbon, and providing other ecosystem services. The goals of vegetation restoration include reestablishing native plant communities, restoring ecological processes and functions, and repairing human impacts to the landscape [1]. However, the environmental impacts of vegetation restoration practices remain inadequately understood. Recent research has aimed to elucidate restoration outcomes across multiple ecological indicators and provide guidance for maximizing benefits while minimizing unintended consequences.

The significance of vegetation restoration stems primarily from widespread ecosystem degradation and biodiversity declines worldwide [2]. Up to 2 billion hectares globally may be suitable for restoration [2], presenting major opportunities for ecological enhancement. Degradation reduces the ability of ecosystems to provide services that are foundational for human wellbeing, such as climate regulation, water provisioning, and nutrient cycling [3]. Restoration goals thus center on increasing vegetation cover, richness, structural complexity, and native species abundances to recover these ecosystem functions [4]. Successful restoration can generate numerous ecosystem service benefits, including enhanced carbon storage, soil development, hydrologic regulation, nutrient cycling, habitat provisioning, and resilience to climate change [3,5,6]. However, restoration practices may also have unintended environmental tradeoffs that require careful evaluation [4]. Environmental impacts may also change over time as restored systems develop along ecological successional trajectories [7].

Considerable research in recent years has examined the environmental impacts of vegetation restoration across various biomes and ecological indicators. Multiple meta-analyses indicate that restoration effectively increases species diversity and richness on average, but long-term trajectories may continue diverging from reference ecosystems even after decades [8,9]. A closer examination reveals that biodiversity responses vary across biomes, with larger gains seen in wetland and forest restoration compared to grassland and shrubland projects [8]. Nevertheless, specific geographic regions within these biomes, such as tropical forests in Sub-Saharan Africa and Southeast Asia, remain understudied [9,10]. Focused research expanding across these tropical regions could provide new insights into restoration outcomes and context dependencies. Temporal studies tracking soil nutrients, microbial communities, and enzymatic activities demonstrate successional changes during restoration [11–13], but more long-term data are needed [7,14].

Soil carbon accumulation is commonly enhanced by restoration, but the magnitude depends on climate, soil type, previous land use, and restoration methods [3,15]. Modeling studies project continuing soil carbon accrual over decades to centuries as restored systems aggrade [16,17]. Potential tradeoffs exist between increased water yield from reforestation and reduced storm flow buffers [18]. Assessments using multiple ecosystem service indicators highlight both synergies and tradeoffs among hydrologic regulation, biodiversity enhancement, carbon storage, and sustainability outcomes [9,19].

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Several reviews synthesize the state of knowledge on vegetation restoration outcomes. Brudvig et al. [4] emphasize the need to embrace variability and context dependency in judging restoration success across multidimensional ecological indicators. They highlight major knowledge gaps regarding long-term trajectories, landscape factors, and integrating socioeconomic considerations. A global meta-analysis by Crouzeilles et al. [9] determines key biophysical and anthropogenic factors influencing restoration success for forests, including climate, previous land use intensity, and herbivory. Wortley et al. [19] review the criteria for evaluating restoration outcomes and call for standardized indicators encompassing ecosystem services.

Recent studies also elucidate factors influencing restoration outcomes across habitat types and biome boundaries. In tropical forests, passive restoration has proven more effective than tree planting for biodiversity recovery [6,9]. However, active interventions may still be needed in certain contexts and cost-effective techniques require further research [9]. For riparian zones, revegetation success depends on climate, topography, channel dynamics, and flooding regimes [20,21]. Outcomes also vary with landscape factors like adjacent land use and connectivity [9]. Studies clarifying how biotic and abiotic controls interact across spatial scales are lacking.

Several key knowledge gaps persist regarding vegetation restoration. Plant and animal colonization dynamics during restoration are poorly characterized, limiting understanding of community assembly patterns [4]. Long-term studies tracking soil development trajectories are scarce, precluding assessment of time lags [7]. Landscape context effects on local restoration outcomes need elaboration, including edge influence, fragmentation, and metapopulation source-sink dynamics [9]. Integrating socioeconomic factors into planning remains a challenge, such as cost–benefit analysis and stakeholder participation [19]. Developing standardized criteria and indicators for systematic evaluation across sites and ecosystem types is also essential [19].

To address these knowledge gaps, a global network of coordinated, long-term, interdisciplinary studies is critically needed to elucidate restoration outcomes across contexts. By linking restoration practices to multivariate ecological responses over decades, this research network could provide integrated guidelines to maximize restoration success. It is crucial to continue focusing on the connection between restoration practices, environmental factors, and multivariate outcomes in order to understand the dependencies on context [4]. Conducting systematic experiments that test different restoration methods across various biomes can help unveil general principles while taking into account landscape variation [9]. Additionally, it is essential to extend monitoring efforts to capture slower responses such as plant colonization and soil development, but this will require sustained funding [7,9]. Techniques such as remote sensing, geospatial modeling, and simulation approaches can shed light on the effects of scale on restoration outcomes [9]. When planning and assessing restoration efforts, it is important to incorporate socioeconomic factors and standardize criteria for evaluating success [19,22].

The priorities of different research directions can be ranked in the following order of importance:

(1) Standardize criteria and indicators for systematic meta-analysis across diverse studies: Standardizing criteria and indicators is crucial for conducting robust meta-analysis and synthesis of restoration research. By establishing consistent guidelines, researchers can clarify general principles and enhance the reliability of their findings. This will facilitate the integration of diverse studies and provide a stronger evidence base for restoration practices. (Top Priority)

(2) Establish coordinated research networks for long-term, interdisciplinary studies linking practices to ecological outcomes: Coordinated research networks are essential for managing long-term studies and fostering interdisciplinary collaborations. These networks can help establish a framework for monitoring and evaluating the ecological outcomes of restoration practices. Linking practices with multiple ecological

responses will fill key knowledge gaps and provide valuable insights for future restoration efforts. (Second Highest Priority)

(3) Incorporate socioeconomic factors into participatory planning and development of success metrics: Considering socioeconomic factors and involving local communities in the planning and implementation of restoration initiatives is crucial for their success. By integrating social and economic aspects into the decision-making process, researchers can ensure that restoration efforts are relevant and impactful. Furthermore, developing success metrics that are locally relevant will provide a more meaningful evaluation of restoration outcomes. (Third Highest Priority)

(4) Test different restoration methods through replicated experiments across regions and biomes: Conducting replicated experiments across different regions and biomes is important for understanding the efficacy of restoration methods across contexts. This approach allows researchers to account for variability and identify methods that are most effective in specific circumstances. By conducting rigorous experiments, valuable insights can be gained regarding the best practices for restoration. (Fourth Highest Priority)

(5) Harness remote sensing, geospatial modeling, and simulation approaches to clarify scale dependencies: While remote sensing, geospatial modeling, and simulation approaches can provide valuable insights on scaling effects in restoration, field studies should take priority. These methods should be used in conjunction with on-the-ground research to verify and validate their findings. Field studies provide a more direct and accurate understanding of ecological processes and should be the primary focus when investigating scale dependencies in restoration. (Lowest Priority)

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