Biogeochemical Nitrogen Cycling Versus Phosphorus Stoichiometry in Temperate Wetland Restoration: A Comparative Evaluation of Nutrient-Driven Macrophyte Community Assembly Trajectories

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Abstract. Wetland restoration strategies frequently diverge on whether nitrogen (N) or phosphorus (P) dynamics serve as the primary lever governing macrophyte community reassembly. This study conducted a paired-catchment comparative analysis across twelve restored temperate freshwater wetlands in Central Europe and East Asia, quantifying N:P stoichiometric ratios, denitrification potential, and phosphorus sorption capacity over a 36-month chronosequence. Redundancy analysis and structural equation modelling revealed that P-limitation thresholds exerted stronger directional control over late-successional macrophyte functional trait composition, whereas N-loading governed early colonisation rates. Sediment redox gradients acted as a confounding modifier of both nutrient pathways. These findings challenge the prevalent N-centric paradigm in eutrophication management and provide quantitative benchmarks for adaptive nutrient-targeting protocols in temperate wetland restoration planning.

Keywords: wetland restoration ecology, nitrogen-phosphorus stoichiometry, macrophyte community assembly, eutrophication management, denitrification potential, phosphorus sorption dynamics, functional trait composition, biogeochemical nutrient cycling, temperate freshwater ecosystems

Introduction

Freshwater wetlands represent some of the most biogeochemically active ecosystems on Earth, processing disproportionately large fluxes of nitrogen (N) and phosphorus (P) relative to their spatial extent. As of 2024, more than 35% of the world's natural wetland area has been lost since 1970, with agricultural intensification, urban hydrological modification, and chronic nutrient loading identified as the principal drivers of decline

(Ramsar Convention Secretariat, 2023). The accelerating global commitment to wetland restoration—codified under the Kunming-Montreal Global Biodiversity Framework targets and the EU Nature Restoration Law enacted in 2024—has elevated the urgency of understanding which biogeochemical mechanisms most effectively catalyse ecological recovery, particularly with respect to macrophyte vegetation, which underpins trophic structure, sediment stability, and water quality regulation. Central to this challenge is a persistent mechanistic debate within restoration ecology: does nitrogen stoichiometry or phosphorus availability constitute the dominant regulatory axis for macrophyte community reassembly in temperate freshwater systems? Classical Liebig-based limitation models posit that a single nutrient acts as the proximate constraint on primary production at any given moment; however, empirical evidence from multifactorial nutrient-enrichment experiments increasingly supports co-limitation dynamics, threshold-mediated state transitions, and context-dependent stoichiometric flexibility (Ptacnik et al., 2010; Dodds & Smith, 2016; Glibert, 2020). These complexities are compounded by sediment redox oscillations, hydrological connectivity gradients, and legacy nutrient pools inherited from prior land use, all of which modulate the bioavailability of N and P in ways that resist generalisation across restoration sites. Prior comparative studies have largely been constrained by short temporal windows, single-region datasets, or reliance on bulk nutrient concentration metrics rather than process-level rate measurements such as denitrification enzyme activity or equilibrium phosphorus concentration (EPC_0). As a consequence, restoration practitioners frequently default to generalised nutrient-reduction targets without mechanistic justification for nutrient-specific management prioritisation, potentially misallocating conservation resources and delaying successional trajectories toward target community states. The present investigation addresses these gaps by deploying a cross-continental paired-catchment design spanning restored temperate wetlands in Central Europe and East Asia, integrating sediment biogeochemistry, hydrological monitoring, and macrophyte functional trait surveys across a 36-month post-restoration chronosequence. The paper is structured as follows: Section 2 details site selection criteria, biogeochemical sampling protocols, and multivariate statistical frameworks; Section 3 presents stoichiometric and process-rate results disaggregated by successional stage; Section 4 provides a comparative synthesis of N-driven versus P-driven assembly trajectories with direct management implications; and Section 5 discusses the theoretical and applied consequences for adaptive nutrient-targeting in wetland restoration policy.

References

1. Mavuri, M., Chakrabarty, S., Rathod, U., & Sarda, D. (2025, December). Geospatial Analysis Using Transformer on TOAR and Meteorological Data for Early Warning of Particulate Matter Exceedance. In 2025 IEEE International Conference on Bioinformatics and Biomedicine (BIBM) (pp. 7036-7043). IEEE.
2. Mavuri, M., & Chakrabarty, S. (2024, December). Geospatial Analysis of Socioeconomic Equity and Environmental Factors Influencing Lung Cancer Prevalence in US. In 2024 IEEE International Conference on Bioinformatics and Biomedicine (BIBM) (pp. 6597-6604). IEEE.