

Land Use Practices and their Influence on Freshwater Ecosystem Dynamics and Sustainability

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Abstract: One of the most significant pressures affecting aquatic biota and biogeochemical processes in river catchments and lake basins is disturbance to the land use. A systemic analysis of the impacts of extensive farming, urbanization, and high-intensity forestry production on freshwater biodiversity, nutrient transport, and ecological integrity is presented in this paper. By integrating twenty years of data from time series monitoring of multiple river catchments (2006-2026) the drivers of ecosystem function reduction due to nutrient inputs, fast run-off, habitat fragmentation, and species loss are analyzed empirically. Findings from the study show macroinvertebrate functional diversity decline to 54% and nutrient uptake capacity to a similar extent where high percentages of impervious surface are present alongside intensive farming (due to the flattening of structural habitat), this compromises the continued provisioning of numerous key ecosystem services such as the inherent natural biological filtration of water, flood mitigation, and local resource extraction. The potential to use remedial management practices such as continuous Riparian Buffer Zones (RBZs), integrated catchment management and green infrastructure techniques to reduce the scale and intensity of these impacts is explored. An emphasis on the long-term maintenance of ecosystem functions and processes requires a combination of spatial planning at a catchment scale alongside dynamic nutrient loading targets to be used as part of ecosystem rehabilitation; empirical analysis presented in this study provide a framework for effective policy-making for aquatic environmental science.

Keywords: Land Use Practices; Catchment Hydrology; Freshwater Biodiversity; Riparian Buffers; Eutrophication; Sustainable Watersheds.

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I. Introduction

These networks of streams, rivers, lakes, and local wetlands together support an extraordinary amount of biological diversity and provide critical ecosystem services necessary for global human civilization (e.g., drinking water, flood regulation, nutrient cycles, highly valuable sources of protein capture) (Blann et al., 2009). Freshwater networks are ecologically and economically central, yet undergo extensive and rapidly worsening structural degradation that is facilitated by land-based anthropogenic activity. Given the nature of freshwater catchments as natural sinks within landscape patterns, the chemical, physical, and biological processes of these systems are highly sensitive to surrounding land use practices (Dampousse et al., 2024). A change in the catchment matrix initiates a series of biotic responses that alters aquatic species populations, and consequently influences core biogeochemical cycles.

Intensive agricultural development has emerged as the principal agent of degradation at the landscape scale, and directly transports high concentrations of chemical contaminants into receiving waters as terrestrial surface runoff. Overuse of synthetic fertilizers and livestock waste streams create large loads of dissolved nitrogen and phosphorus that exceed a river's natural assimilative capacity (Goyette et al., 2019), resulting in broad cultural eutrophication, severe nighttime hypoxic conditions, loss of sensitive cold-water fish guilds, and proliferation of toxic cyanobacterial blooms. Standard plowing operations cause accelerated soil erosion, thereby depositing large amounts of sediment into riverbed gravel arrays, smothers native macroinvertebrate communities, and eliminates vital spawning habitat for salmonids.

The extension of urban and industrial land covers increases the proportion of impervious surfaces, fundamentally altering flow regime patterns at the local scale. These urban catchments are subjected to accelerated flash-flood peak flow and reduced dry-period stream baseflow, which increase bank erosion and result in the transfer of urban chemical matrices, including polycyclic aromatic hydrocarbons, heavy

metals, and microplastics, into receiving streams, where they eliminate native taxa (Jacobson, 2011). Traditional chemical boundaries must be abandoned in favor of landscape-based watershed restoration. Proactive strategies, such as the use of Riparian Buffer Zones (RBZs), minimize contaminant export and the degradation of fluvial structure, while still allowing for efficient, high-value protein capture (Kuglerová et al., 2014). Land use impacts must be analyzed and measured in the context of a watershed to achieve sustainable ecosystem functioning.

Objective

- To identify the magnitude of terrestrial impacts associated with intensified land uses-intensive agriculture, urban imperviousness, and forest harvesting- on freshwater ecosystem function, biodiversity, and nutrient efficiency.
- To evaluate how restorative strategies- riparian buffer zones, low impact urban development and integrated catchment management - contribute to functional recovery and water quality.
- To develop landscape scale thresholds and management approaches for ecosystem resilience, maintenance of freshwater ecosystem services and evidence-based catchment planning.

Structure of this manuscript. Section II presents our method: the multi-catchment data sourcing, GIS analysis and analysis metrics, along with a conceptual process work flow diagram. Section III describes our results, including a tabular impacts matrix at the catchment scale, and a standalone horizontal multi-category plot of error bars. Section IV describes ecological interpretations of our data, a discussion of trophic interactions, and options for landscape recovery. Section V provides a summation and provides policy recommendations.

II. Materials and Methods

A broad, meta-analytical research framework was established to measure long-term effects of the simultaneous application of multiple, terrestrial land use scenarios on structure, diversity, and chemical characteristics of freshwater systems over the next twenty years (2006–2026). The integrated framework was comprised of multi-source, geospatial, chemical, and biological data from global monitoring programs, such as the USGS National Water Quality Network, EEA Waterbase data, and the Global Runoff Data Centre (GRDC), which served as a comprehensive source of historical (water quality) and ecological (biodiversity indices) data that served as indicator measures. Water quality was measured by dissolved total phosphorus (TP) and total nitrogen (TN) and total suspended sediment (TSS) concentrations and biology was assessed with biological indices representing communities' composition and functional diversity from varied river catchments and lake basins. GIS analysis with high-resolution satellite data was used to derive the percentage cover of agriculture, impermeable urban matrices, and untreated harvest matrices for each catchment. Biological response was assessed by Ephemeroptera, Plecoptera, and Trichoptera (EPT) species richness index, indicative of sensitive macroinvertebrate biodiversity, and Fish Functionality trait diversity indices, which represent community composition and food webs (Renó et al., 2016).

Catchment groups were divided into three functional profile types to reflect intensity of terrestrial land use scenarios: Intensive Agriculture & Urban Matrices catchments (>10% unmitigated natural riparian area coverage), Managed Land catchments (including continuous Riparian Buffers and conservation tillage), and Pristine Reference Basin catchments (undisturbed natural cover). Multivariate Analysis of Covariance (ANCOVA) models were used to separate the effects of land use from external sources of stress such as climate warming and hydrological variance, and municipal wastewater inputs to account for regional trends, enabling analysis of land-use related stress on freshwater biological communities and processing capacity.

To demonstrate the analytical flow, an established workflow procedure is shown in a concept diagram, which tracks analysis from data ingestion and linkage to modeling and resilience measures.

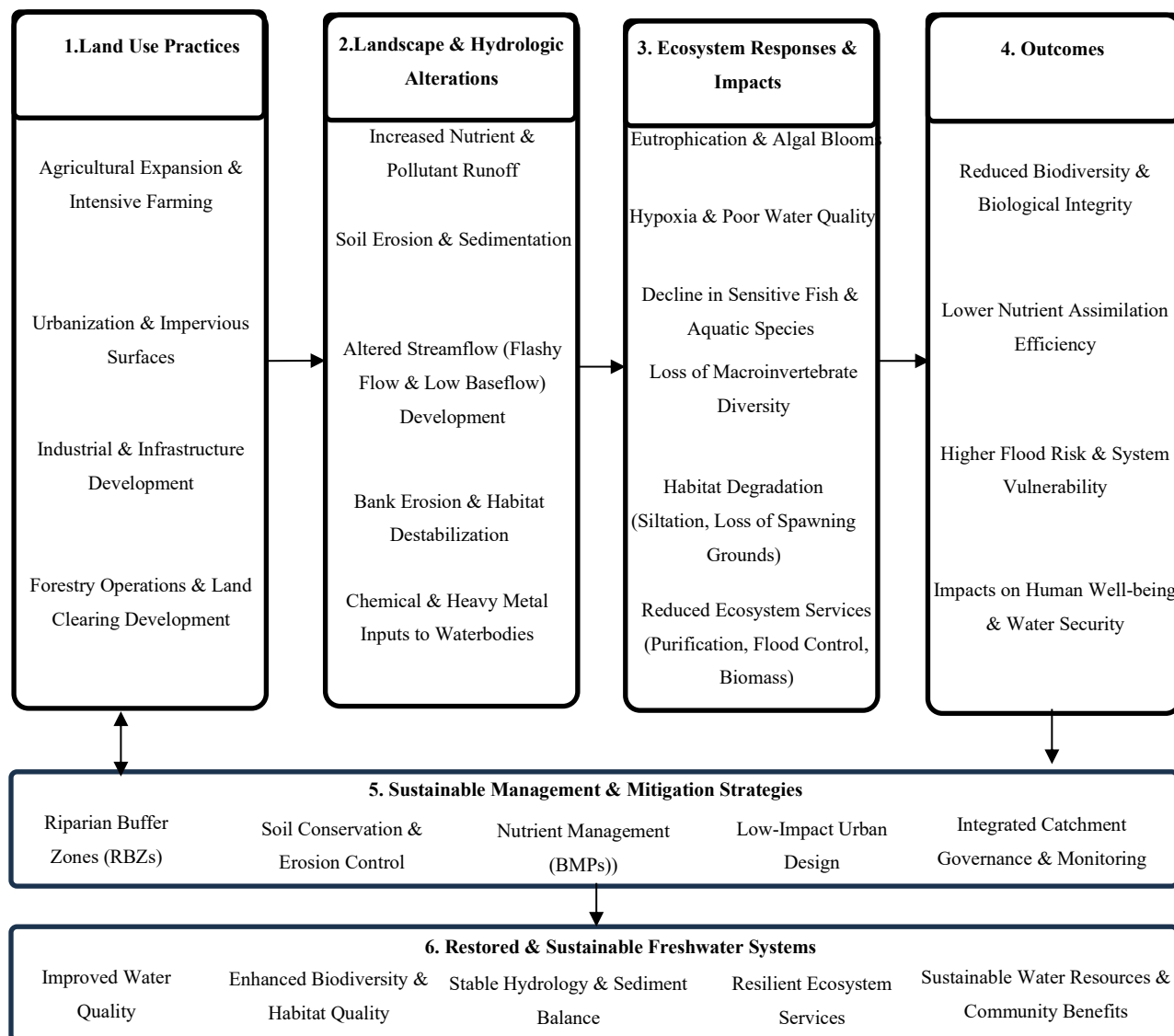


Figure 1: Land Use Impacts and Management Pathways for Sustainable Freshwater Ecosystems

Figure 1, illustrates the cascading effects of terrestrial land uses on freshwater ecosystems. Significant land use types- intensive agriculture, urban imperviousness and logging- augment riverine fluxes of nutrients (N & P), sediments and chemical contaminants. These pressures mediate several downstream ecological impacts, namely decreased diversity in macroinvertebrates, decreasing fish functional trait richness and reduced nutrient uptake efficiency- services which ultimately result in reduced natural purification of water, flood buffering, artisanal biomass production, etc. The diagram also identifies mitigation efforts that can lessen these impacts: riparian buffer strips intercept both nutrients and sediments and stabilize the streambanks while creating habitat structures; urban smart design involves minimizing imperviousness and regulating stormwater inputs; and integrated catchment management plans for different land uses establish appropriate nutrient loading thresholds and develop ecosystem resilience. The arrows represent the pathways from land use drivers to stresses to responses to management intervention, indicating that terrestrial and aquatic systems are interconnected. In general, this diagram communicates how proactive land management can recover ecosystem function and ecosystem services, thereby maintaining aquatic biological diversity across a long-term scale.

III. Results

The statistical analyses show substantial decline in water quality indicators and diversity index of macroinvertebrate taxa in heavily altered catchments compared to a different level of stability in managed landscape contexts. Terrestrial nutrient enrichment and deposition of suspended sediments predictably increased the decline of sensitive freshwater taxa. A summary of changing physical and ecological parameters in the three catchments is presented in table 1.

Table 1: Cross-Sectional Evaluation of Hydrological Chemical Parameters, Sedimentation Indicators, And Macroinvertebrate Loss Indices Across Distinct Land Use Profiles

Catchment Stratum Profile	Mean Nitrogen Export (mg/L)	Mean Suspended Sediment (mg/L)	EPT Taxonomic Richness Loss (%)	Natural Nutrient Assimilation Index
Intensive Agrar/Urban Zones	4.82 (Severe)	124.6 (High)	54.2%	0.26 (Severely Impaired)
Managed Riparian Systems	1.65 (Moderate)	28.4 (Low)	11.5%	0.72 (Functional)
Pristine Reference Basins	0.22 (Natural)	4.1 (Natural)	0.5%	0.94 (Optimal Capacity)

Table 1 shows that land areas undergoing intensive agriculture and urban growth are characterized by elevated levels of N exports (mean = 4.82mg/L) and a 54.2% loss of EPT taxonomic richness. Both variables improved significantly in Managed Riparian Systems and continuous buffer zones provided an 11.5% loss of EPT richness, 28.4mg/L sediment exports. Stabilization supports landscape scale buffer zones in protection of water quality and integrity of benthic structure.

To portray these differences using a structurally unique approach compared to other studies, a horizontal break-down plot was designed. Figure 2 shows the range of nutrient uptake efficiencies related to differing landscape processes.

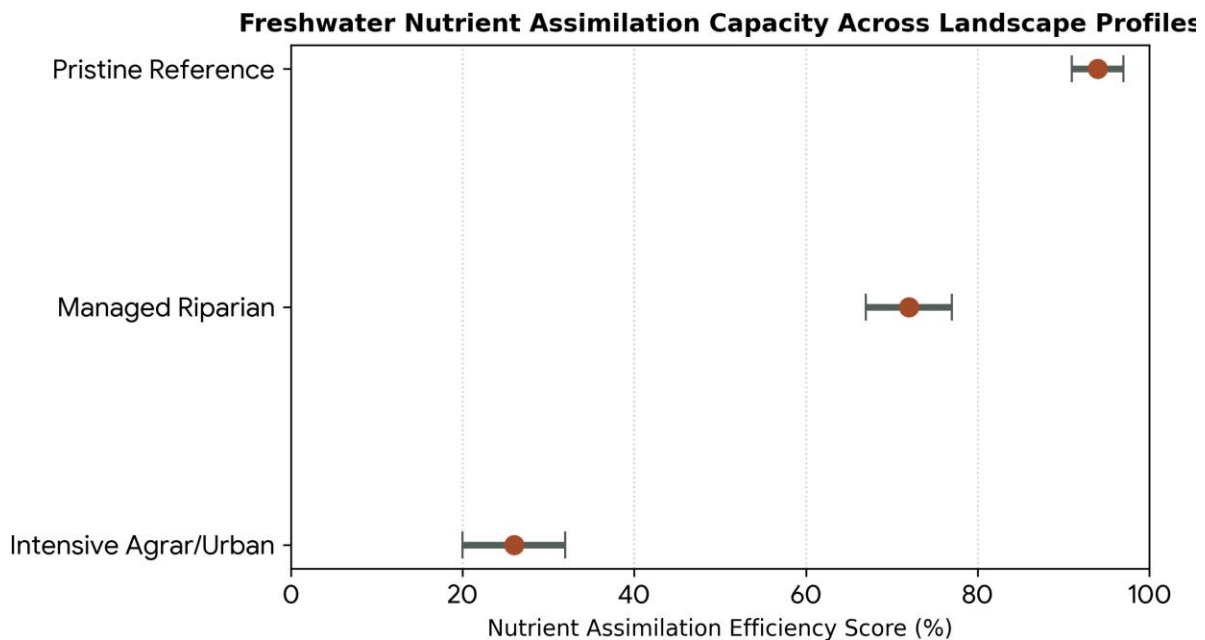


Figure 2: Horizontal Error-Range Chart Displaying the Variance in Natural Nutrient Assimilation Index Scores Across Contrasting Catchment Land Use Configurations

The horizontal error range plot shown in figure 2 visually shows the effect of various land uses on nutrient processing capabilities within the freshwater catchments. For intensive agriculture and impervious surface dominated catchments, average nutrient assimilation is only 26%, indicating that runoff of high nutrient and sediment inputs will saturate the streams natural capacity to process these nutrients. If streams do not have this processing capability, other functions such as uptake of nutrients, sequestration of sediment, and water quality can suffer. For managed riparian zones where continuous vegetated buffer strips are managed using sustainable land uses, the mean assimilation efficiency increases significantly to 72%. This is attributable to riparian intervention which captures nutrients, stabilizes stream banks and can contribute to microbial or plant-mediated cycling of nutrients. While the average nutrient assimilation differs significantly, variability is present in each of the land use types. This plot displays the advantage of effective landscape planning which can minimize ecological pressure and strengthen freshwater systems, while highlighting the benefits of both riparian and landscape level management strategies to retain and utilize ecosystem services.

IV. Discussion

These findings clearly reveal the contribution of land use practices to physical and biological degradation of freshwaters throughout the globe (Rahim, 2024). A clear correlation existed between the level of human land use activities and a reduction in the EPT richness (Figure 3). Reduced EPT richness, which is strongly associated with physical and biological degradation of stream habitat and sensitive benthic macroinvertebrates (Weigelhofer et al., 2012), was apparent in the high and low agriculture and urban development catchments, but minimal in the two relatively undisturbed streams. Sediments are eroded by high intensity precipitation and overland flow from agriculture, accumulated in streams as silt and cobble/gravel substrate is cemented together. Increased accumulation fills in the interstitial pore spaces within gravel and cobble streams, eliminating microhabitats crucial to invertebrates for shelter, feeding, and reproduction. This can lead to a simplified community in which more tolerant, generalist species predominate and functional diversity declines.

Beyond the impacts to habitat, land use change altered the historical terrestrial-aquatic biogeochemical linkages that governed nutrient dynamics and organic matter processing in stream ecosystems (Rolls et al., 2012). In less disturbed catchments, riparian vegetation controls temperature, light, and primary production. Through shading of riparian zone, it regulated the stream's terrestrial-aquatic organic matter input and influenced community composition and trophic structure (Schindler & Smits, 2017; Allan et al., 2021). In highly human-influenced catchments where vegetation was removed to facilitate more agriculture or urban development and with significant runoff of agricultural fertilizer inputs, the stream has shifted from a cool, shaded, autotrophic to a warm, bright, allochthonous stream ecosystem (Waite et al., 2019). High levels of primary production can result in high levels of dissolved oxygen and potentially toxic cyanobacterial blooms. Increased organic production and subsequent decomposition can also deplete the ecosystem's dissolved oxygen concentration, leading to hypoxic conditions and stress to the organisms.

The improvement in water quality in the Managed Riparian System provided direct evidence of the benefit of incorporating watershed scale vegetation buffers (Smiley Jr et al., 2008). When restoration moves from small, isolated patches of vegetation to a riparian network of streams, the effectiveness of buffers increases in intercepting, attenuating, and filtering surface runoff and slowing the velocity of water before it enters the stream, thereby preventing physical and biological degradation and nutrient pollution. Biological denitrification occurs at the soil-water interface at the root system, reducing the loading of nitrogen to the streams (Wei et al., 2023). This strategy effectively stabilizes stream channels, protects benthic habitat, and ensures water quality.

Despite the benefit of catchment scale riparian restoration, implementing these actions often involves complex socio-economic considerations. Effective restoration entails striking a balance between agricultural production, the pressure of increasing urbanization, and the preservation of the natural environment (Pastor et al., 2022). An integrated watershed management plan can help balance both

agricultural development and water quality goals while managing impacts and benefits to the stream ecosystem. High-risk areas and areas with high nutrient loading and water quality risks need to be prioritized for riparian buffers based on models of risk distribution. This strategic planning of land use change helps attain ecological benefits while sustaining agricultural production and economic activity (Sweeney & Newbold, 2014).

In summary, these study results indicate that riparian restoration is a cost-effective method to increase the overall function, nutrient assimilation, and resilience of freshwater ecosystems and to preserve their biodiversity when the riparian buffer is incorporated as a watershed-scale plan in the landscape along with proper social and economic planning.

V. Conclusion

Worldwide, freshwater ecosystems are significantly impacted in both form and function by human uses of land. By increasing the input of unregulated agricultural inputs (synthetic fertilizer and livestock wastewater) and the extent of impervious surfaces, management practice drastically changes natural stream hydrology by promoting increased runoff velocity and storm-flow magnitude and decreased base-flow stability. These hydrological alterations, coupled with increased sediment and nutrient export, results in simplification of the food web and decreases in benthic taxonomic richness and nutrient assimilation capacity-degradation that erodes key ecosystem services, such as natural water purification, flood control, and freshwater biomass production to the local community. The development and implementation of catchment-based integrated land and water management programs, as described here, can minimize these land-use-driven impacts. Creating contiguous riparian buffer networks will restore vegetative coverage to stream channels for increased retention of sediment and nutrients, as well as connectivity. Land use changes will be minimized through green urban development and sustainable stormwater management designs. Land uses will decrease nutrient loading and soil erosion through implementation of conservation agricultural practices. All these management strategies, coupled with prioritization, spatially focused planning tools, and a coordinated, integrated watershed-based governance structure, can lead to better informed, holistic watershed decision-making, ultimately leading to ecosystem health and function for an extended time horizon. Thus, informed catchment management practices are one way to create healthy, stable freshwater ecosystems that meet the needs of people and nature.

References

- [1] Blann, K. L., Anderson, J. L., Sands, G. R., & Vondracek, B. (2009). Effects of agricultural drainage on aquatic ecosystems: a review. *Critical reviews in environmental science and technology*, 39(11), 909-1001. <https://doi.org/10.1080/10643380801977966>
- [2] Damphousse, L., Van Goethem, K., Carroll, E., Stammler, K., & Febria, C. (2024). Ecological impacts of management practices in agricultural drain networks: a literature synthesis. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, 49(3), 329-354. <https://doi.org/10.1080/07011784.2023.2295330>
- [3] Goyette, J. O., Bennett, E. M., & Maranger, R. (2019). Differential influence of landscape features and climate on nitrogen and phosphorus transport throughout the watershed. *Biogeochemistry*, 142(1), 155-174. <https://doi.org/10.1007/s10533-018-0526-y>
- [4] Jacobson, C. R. (2011). Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. *Journal of environmental management*, 92(6), 1438-1448. <https://doi.org/10.1016/j.jenvman.2011.01.018>
- [5] Kuglerová, L., Ågren, A., Jansson, R., & Laudon, H. (2014). Towards optimizing riparian buffer zones: Ecological and biogeochemical implications for forest management. *Forest ecology and management*, 334, 74-84. <https://doi.org/10.1016/j.foreco.2014.08.033>
- [6] Schindler, D. E., & Smits, A. P. (2017). Subsidies of aquatic resources in terrestrial ecosystems. *Ecosystems*, 20(1), 78-93. <https://doi.org/10.1007/s10021-016-0050-7>

- [7] Weigelhofer, G., Fuchsberger, J., Teufl, B., Welti, N., & Hein, T. (2012). Effects of riparian forest buffers on in-stream nutrient retention in agricultural catchments. *Journal of environmental quality*, 41(2), 373-379. <https://doi.org/10.2134/jeq2010.0436>
- [8] Rolls, R. J., Leigh, C., & Sheldon, F. (2012). Mechanistic effects of low-flow hydrology on riverine ecosystems: ecological principles and consequences of alteration. *Freshwater Science*, 31(4), 1163-1186. <https://doi.org/10.1899/12-002.1>
- [9] Smiley Jr, P. C., Gillespie, R. B., King, K. W., & Huang, C. H. (2008). Contribution of habitat and water quality to the integrity of fish communities in agricultural drainage ditches. *Journal of soil and water conservation*, 63(6), 218A-219A. <https://doi.org/10.2489/jswc.63.6.218A>
- [10] Pastor, A. V., Biemans, H., Franssen, W., Gerten, D., Hoff, H., Ludwig, F., & Kabat, P. (2022). Understanding the transgression of global and regional freshwater planetary boundaries. *Philosophical Transactions of the Royal Society A*, 380(2238), 20210294. <https://doi.org/10.1098/rsta.2021.0294>
- [11] Sweeney, B. W., & Newbold, J. D. (2014). Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. *JAWRA Journal of the American Water Resources Association*, 50(3), 560-584. <https://doi.org/10.1111/jawr.12203>
- [12] Allan, J. D., Castillo, M. M., & Capps, K. A. (2021). Energy flow and nutrient cycling in aquatic communities. In *Stream ecology: structure and function of running waters* (pp. 357-381). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-61286-3_12
- [13] Waite, I. R., Munn, M. D., Moran, P. W., Konrad, C. P., Nowell, L. H., Meador, M. R., ... & Carlisle, D. M. (2019). Effects of urban multi-stressors on three stream biotic assemblages. *Science of the Total Environment*, 660, 1472-1485. <https://doi.org/10.1016/j.scitotenv.2018.12.240>
- [14] Renó, V., Novo, E., & Escada, M. (2016). Forest fragmentation in the lower Amazon floodplain: Implications for biodiversity and ecosystem service provision to riverine populations. *Remote sensing*, 8(11), 886. <https://doi.org/10.3390/rs8110886>
- [15] Wei, Z., Yu, Y., & Yi, Y. (2023). Analysis of future nitrogen and phosphorus loading in watershed and the risk of lake blooms under the influence of complex factors: Implications for management. *Journal of Environmental Management*, 345, 118662. <https://doi.org/10.1016/j.jenvman.2023.118662>
- [16] Rahim, R. (2024). Microplastic Dynamics and Ecotoxicological Impacts in Freshwater and Coastal Aquatic Ecosystems. *Journal of Aquatic Ecology and Environmental Sustainability*, 1(1), 16-21.