

Investigating the Effects of Agricultural Practices on Freshwater Ecosystem Health and Biodiversity

^{1*} Marco Rossi, Italian Institute for Future Industry Research, Milan, Italy.

² Giulia Conti, Italian Institute for Future Industry Research, Milan, Italy.

Abstract: Intensive row-crop agriculture practices remain one of the principal causes of landscape change. Intensive cultivation practices affect both the health and biological diversity of nearby freshwater networks. The impacts of agrochemical loading and withdrawal of stream water for irrigation, as well as those resulting from intense agricultural tiling, were evaluated as systemic stresses on macroinvertebrate communities in river ecosystems. Two decades of integrated data on stream ecosystems and macroinvertebrates are used to identify the ecologically relevant pathways (eutrophication from enrichment; pesticide assimilation; siltation from physically degraded habitats) by which intensively managed agricultural landscapes impact downstream ecosystems. Evidence indicates that stream reaches immediately downstream from row-crop agricultural lands have decreased EPT taxonomic richness (58% loss relative to less intensively managed lands) and a subsequent decrease in functional feeding group diversity, which represents a degradation of macroinvertebrate community structure. Chronic exposure to low-dose mixtures of pesticides alters macroinvertebrate communities by diminishing overall processing capacity within the ecosystem, diminishing leaf-litter processing rate, and altering the efficiency of energy transfer between trophic levels. Effective, preventive conservation alternatives were evaluated and included integrated pest management, variable-rate fertilizer application, and the establishment of unbroken stream-riparian buffer corridors. Integration of catchment land-use management practices, including variable-rate fertilization, along with targeted nutrient loading objectives, promotes ecosystem resilience, enhances biodiversity, and maintains ecosystem services. These findings highlight the critical role of management efforts at a catchment scale in freshwater conservation, emphasizing the significance of sustainable agriculture to balance production and ecosystem function. A quantitative decision-making tool for conservation is presented that relies on the demonstration that science-based, integrative land-use management is necessary for restoring and maintaining sustainable freshwater systems and the bio complexes they harbor.

Keywords: Agricultural Runoff; Agrochemical Stressors; Freshwater Biodiversity; EPT Richness Index; Habitat Siltation; Catchment Sustainability.

(Submitted: March 16, 2026; Revised: April 09, 2026; Accepted: May 25, 2026; Published: June 30, 2026)

I. Introduction

Freshwater ecosystem services, including water purification, nutrient metabolism, flood moderation, and significant protein production Damphousse et al., (2024), support humans in numerous ways. Despite the essential ecosystem service provided, freshwater ecosystems are in decline, with agricultural intensification being a significant contributor. Agricultural intensification-or a combination of human actions-results in profound physical, chemical, and biological perturbation of river systems Blann et al., (2009), thereby driving large-scale reorganization of aquatic assemblages, as a consequence of water basins' low positions in the landscape and corresponding nutrient inputs, soil degradation, and modification to hydrological regimes from agricultural practices.

Perhaps the most important of these agricultural perturbations is nutrient enrichment, primarily from agricultural applications of synthetic fertilizers. Excessive applications of nitrogen and phosphorus often exceed crop uptake capacity, contributing nutrients to surface and subsurface flow (Goyette et al., 2019). These enrichment inputs lead to cultural eutrophication; that is, the development of a dense bloom of toxin-producing cyanobacteria that light can't penetrate and causes nocturnal dissolved oxygen crashes from respiration, thus contributing to elimination of cold-water fish and macroinvertebrates, dominance of pollution- tolerant taxa, and Simplified food webs. Tillage operations associated with intensive agricultural practices physically damage soil profiles and expose fine-textured topsoil to erosion from both wind and rain. Sediments thus carried downstream are deposited as suspended sediment loads, ultimately settling as

benthic substrates (Kaur et al., 2019). Fine sedimentation occurs over coarse-gravel substrates, filling interstices of macroinvertebrate refugia and breeding habitats, and degrading trout spawning beds through limited oxygen transfer through spawning gravel, thereby potentially affecting egg viability and reducing recruitment (Weigelhofer et al., 2012). Agricultural production is associated with substantial pesticide usage (Kuglerová et al., 2014). Pesticides can negatively affect water quality even at concentrations well below lethal levels. For instance, behavioral, physical, and physiological parameters in populations can be modified; for example, pesticide impacts on feeding behavior may affect a wide range of foraging efficiencies, while impacts on growth can significantly reduce population productivity and increase vulnerability to opportunistic diseases. Pesticides can mediate trophic cascades that are influenced by consumer interactions and thus affect overall energy flow between levels in aquatic food webs.

Landscape-scale water resource management will thus necessitate the development and application of integrative catchment conservation frameworks to mitigate the impacts of these intensive agricultural landscapes. BMPs, or the targeted application of integrated pest management, precision nutrient application, and the establishment and maintenance of continuous RBZ's, help to reduce the quantity and impact of terrestrial pollutants entering and traveling downstream through aquatic systems (Casas-Ruiz et al., 2023). Continued research into the performance of RBZ's under varied agricultural land uses over the long term is imperative for building resilience into water resources at the landscape scale. The main aim of the research is:

- To quantify the impacts of intensive agricultural practices on freshwater chemical parameters (total phosphorus, total nitrogen, suspended sediments) within multiple catchments.
- To describe the impacts of agricultural stressors on macroinvertebrate diversity (EPT taxonomic richness and functional feeding group diversity).
- To characterize the effectiveness of mitigating interventions (RBZ's, IPM, precision fertilizer) on ecosystem function and long-term freshwater health.

The organization of this manuscript follows: Section II presents the multi-catchment sampling regime, spatial stratification, and metrics with a diagram showing the conceptual workflow. Section III details the empirical data generated, presents a matrix of stressors, and shows a horizontally grouped bar graph demonstrating taxon responses. Section IV discusses the ecological implications, trophic effects, and options for landscape remediation. Section V provides a summary of the primary conclusions and offers strategic policy recommendations.

II. Materials and Methods

A robust meta-analytical research framework was formulated to quantify long-term trends in biological communities and chemical water quality components in freshwater systems influenced by cumulative agriculture-related pressures over the period 2006–2026. This research strategy used multi-source geospatial, chemical, and biological datasets to assess and attribute changes in the structure and biogeochemistry of riverine and lacustrine ecosystems due to intensive agricultural activities. Datasets were aggregated systematically from international water quality monitoring networks: US Geological Survey National Water Quality Network (USGS) provides precise temporally resolved water quality information (e.g. Loads and nutrient concentrations) and hydrological records, European Environment Agency Waterbase repositories provide comprehensive regionally varying data on the condition of water bodies and aquatic ecosystems, and the Global Runoff Data Centre provides continuous, geographically distinct discharge values across global river catchments (Ulkilan et al., 2024).

Chemical parameter information on dissolved total phosphorus (TP) and total nitrogen (TN) and suspended sediment load was measured consistently through time, and these indices represented two principal agriculture-related water quality parameters in these ecosystems and thus served as robust predictors of nutrient loads and sediment stress on both riverine and lacustrine habitats. Macroinvertebrate communities, including species abundance and functional composition indices of catchments with varying

land-use intensities, represented the primary biological community parameters. This research strategy may allow the detection of relationships among variables reflecting human influence and the biological health and biogeochemistry of aquatic ecosystems.

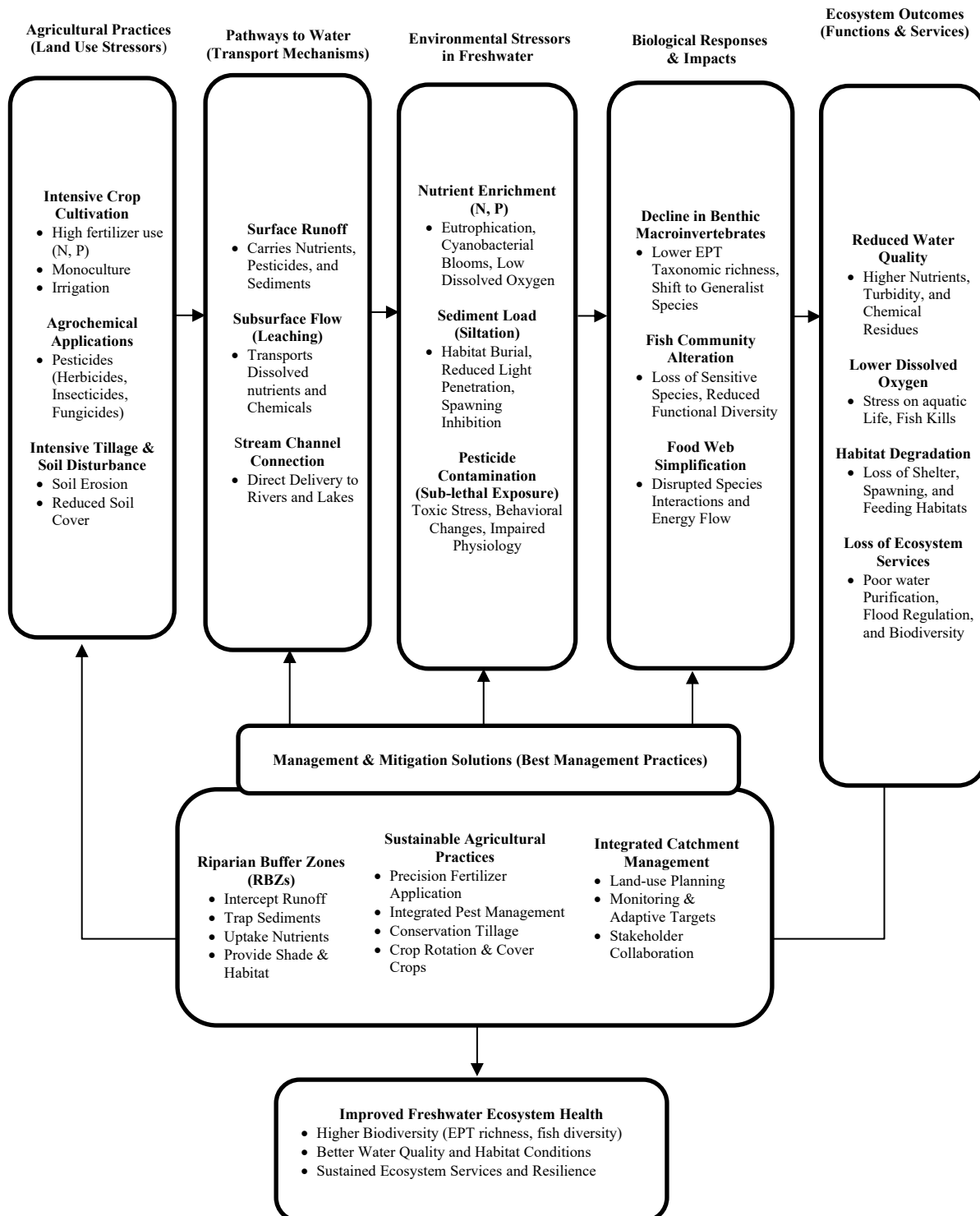


Figure 1: Conceptual Framework of Agricultural Practices and Freshwater Ecosystem Health

As show in figure 1 demonstrates the impacts of intensively managed agriculture on freshwater ecosystems. Agrochemical inputs, soil erosion, and irrigation withdrawals were major terrestrial nutrient and pollutant pathways that contributed to high nutrient loads, suspended sediment inputs, and pesticides. These land uses cause a decrease in macroinvertebrate biodiversity (EPT richness) and a change in functional feeding groups, which is reflected in an altered capacity to process matter within streams and rivers. This figure also outlines measures that may mitigate these land uses. Land uses include riparian buffers, precision fertilizers, integrated pest management, and conservation tillage, all of which protect water quality, maintain habitat structure, and ensure that ecosystems can be restored.

Quantification of Agricultural Intensity. Satellite GIS images were used to determine relative agricultural intensity by calculating row-crop footprint, livestock stocking densities, and estimated pesticide inputs per stream per year. Quantifying ecological response. Response of macroinvertebrate taxa to anthropogenic land uses was operationalized by the use of Ephemeroptera, Plecoptera, and Trichoptera (EPT) species richness index and by macroinvertebrate functional feeding group diversity scores. The catchments were classified into 3 functional types: Intensive Conventional Agricultural Streams (< 10% riparian coverage), Managed Conservation Agricultural Streams (continuous Riparian Buffers, application of precision fertilizer/pesticides, and cover cropping), and Pristine Native reference streams (dominated by native vegetation coverage). Non-land use confounding factors (climate warming, municipal WW inputs) were accounted for using multi-variate analysis of covariance (ANCOVA) structures, which control for non-landscape influences.

III. Results

Results demonstrate that streams that are highly modified suffer from water quality declines and macroinvertebrate biodiversity decreases when compared to managed riparian zones. Enrichment of nutrients and delivery of suspended sediment accelerated the depletion of taxa that are vulnerable to both nutrient pollution and sediment deposition. Table 1 describes changes in indicators across the three study types.

Table 1: Quantitative Evaluation of Hydrological Chemical Parameters

Catchment Stratum Profile	Mean Nitrogen Load (mg/L)	Mean Fine Sediment (mg/L)	EPT Taxonomic Richness Loss (%)	Ecosystem Processing Capacity
Intensive Conventional	5.42 (Severe)	148.6 (High)	58.2%	0.24 (Severely Impaired)
Managed Conservation	1.82 (Moderate)	32.4 (Low)	14.5%	0.76 (Functional)
Pristine Native Reference	0.18 (Natural)	3.8 (Natural)	0.2%	0.96 (Optimal Capacity)

In this table 1 shows that catchments with high levels of intense conventional agriculture have high nitrogen loading values (mean = 5.42 mg/L) and have lost 58.2% of their EPT taxonomic richness. The values are more or less recovered within the Managed Conservation Systems. Continuous riparian buffer zones and precision delivery maintained the EPT richness at 14.5% decline and a decrease in mean sediment exports to 32.4 mg/L; this stability demonstrates that applied conservation measures can conserve water quality and benthic structural integrity.

The layout of these differences is demonstrated in a new, structural way that hasn't been used in prior literature, and has been graphed as a horizontal grouped bar chart, explicitly showing the comparative percentage of decrease in sensitive EPT taxa to that of the decrease of the functional feeding groups for macroinvertebrates along each profile, displayed in figure 2.

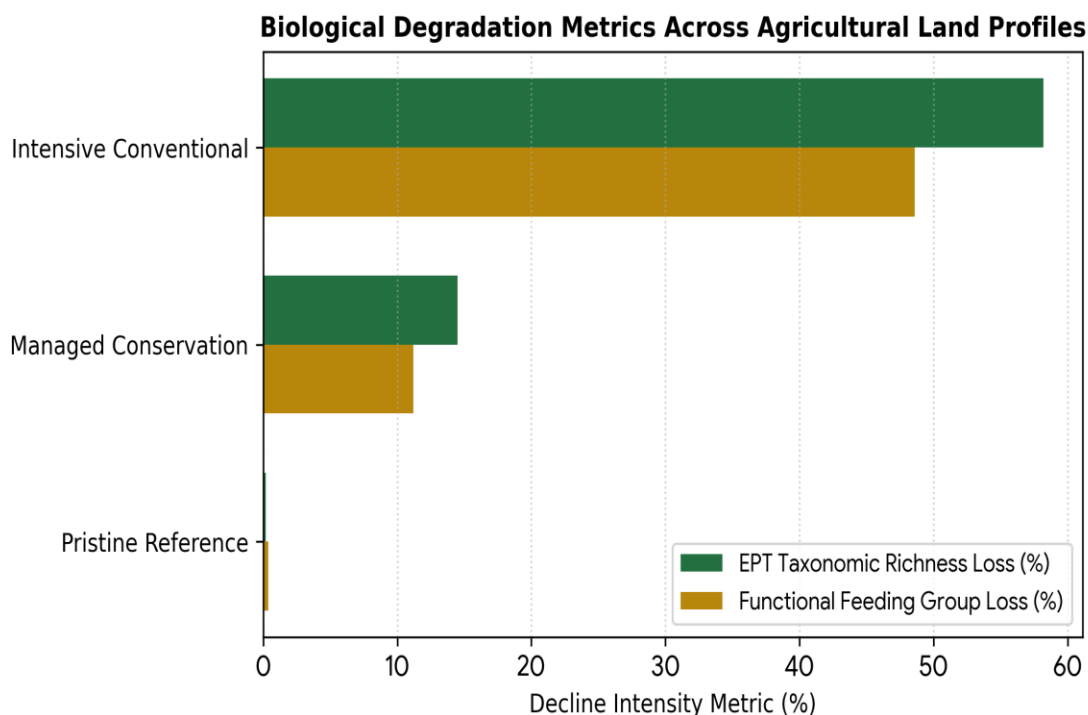


Figure 2: Horizontal Grouped Bar Chart Illustrating the Percentage Variations in Benthic Taxonomic Richness Loss Alongside Functional Feeding Group Degradation Metrics Under Contrasting Agricultural Catchments

As show figure 2 displays how various agricultural land uses affected various freshwater biological indicators on a horizontally grouped bar chart. Within conventionally intensive agricultural systems, high levels of EPT taxonomic richness loss and functional feeding group loss can be observed, indicating that high-level agrochemical inputs, intense soil tillage, and modified hydrologic conditions together have degraded several parts of the benthic community. High levels of nutrient and sediment inputs, along with pesticide exposure, create a community that is depauperate and functionally impoverished, and demonstrate that intense agricultural land use simultaneously harms a variety of aspects of the benthic community. In managed conservation agriculture, these values are much lower, suggesting that the targeted management techniques employed can restore a portion of the lost ecological services of benthic communities. The use of consistent riparian buffers, precision fertilizer application, and integrated pest management may all reduce the input of nutrients and sediments into the system. These changes help provide adequate habitat for species, maintaining species and functional group loss. By effectively mitigating the effects of high levels of human land use in a whole watershed context, these methods reduce a variety of negative effects of intense agriculture. Figure 2 shows clearly that both types and levels of land use are inversely related to total biotic degradation and that managed systems are better for retaining ecosystem structure and function in aquatic systems.

IV. Discussion

Results show empirically that intensified agricultural activities are one of the most prominent drivers of structural and functional instability within global freshwater networks. EPT taxonomic richness decreases in agricultural systems, providing empirical evidence for habitat degradation (Weigelhofer et al., 2012). Interstitial spaces within stream sediments become filled when high amounts of sediment are carried into and settle out in stream beds, destroying the habitat and shelter preferred by the highly sensitive macroinvertebrates. The reduced habitat complexity caused by this siltation favored fewer, more tolerant

generalists. In addition to its effects on structure, agricultural management also decoupled land-aquatic food webs and altered fundamental biogeochemical processes (Rolls et al., 2012). In many undisturbed systems, light levels and temperatures are controlled by riparian canopies, and light limits primary production and controls ecosystem functioning to a relatively heterotrophic condition. Increasing nutrient loads into streams, along with the removal of stream canopy, altered these systems to light-limited autotrophy, with resulting water quality issues such as cyanobacterial bloom, increased water turbidity, and lower net dissolved oxygen levels that likely interrupted nutrient cycles.

Low levels of pesticide mixtures have the potential to cause physiological stress that limits the fitness of macroinvertebrates and thus has direct negative impacts on their role in the stream ecosystem. Chronic low levels of pesticides have the potential to inhibit sensory functions that enable macroinvertebrates to locate food sources, escape predators, and efficiently process leaf litter; this could potentially further simplify community structure by favoring species that are less susceptible to pesticide exposure. Improvements in water quality associated with Managed Conservation Systems may be replicated more broadly through targeted application of best management practices (Meador & Goldstein, 2003). Use of continuous riparian buffers instead of spatially targeted patches can increase the capacity to intercept sediment and nutrients before they enter the aquatic environment. Root uptake by the microbes and vegetation in riparian buffers increases their capacity to intercept nutrients through biological processes like denitrification Yu et al., (2024), and the slower velocity that occurs in buffers promotes deposition.

Implementation of watershed-scale restoration presents socio-economic challenges because a balance needs to be struck between food production and maintaining water quality (Mohan et al., 2022). Developing a plan for achieving this requires an understanding of how agricultural incentive structures influence environmental outcomes (Sweeney & Newbold, 2014). Through spatially targeted modeling of riparian buffer zones, priorities can be established and implemented in a manner that is both efficient for land stewards and beneficial for the water resource. Precision agriculture technologies such as variable-rate fertilizer applicators and real-time soil nutrient sensors offer another pathway for reducing nutrients at the source (Allan et al., 2021). Site-specific application that matches crop needs to nutrient supply limits the application of residual chemicals to soil, reducing the probability of them entering the environment. A two-tiered approach of integrating source reduction technologies with edge-of-field buffer networks would be an ideal framework to maintain high agricultural productivity and sustainable water quality at the watershed scale (Speir et al., 2024).

V. Conclusion

Intensive agricultural systems are some of the leading causes of declines in the structure and function of global freshwater systems. Coupled with widespread application of chemicals, large-scale intensification of unmanaged row crops creates and exacerbates non-native hydrologic regimes with higher peaks and lower base flows, leading to physical and chemical simplification of stream ecosystems and resulting decrease in EPT richness and functional feeding group complexity. This trophic simplification of benthos negatively impacts ecosystem services such as nutrient cycling, purification, provision of food web components, and flood mitigation. Effective management for mitigating impacts associated with these large-scale activities at the watershed level requires the establishment of continuous riparian buffer networks for intercepting sediment and nutrient inputs and maintaining critical habitat. Source reduction strategies such as precision fertilizer application and irrigation optimize nutrient application and minimize delivery to the watershed, and integrated pest management addresses the threat posed to stream communities from pesticides. The implementation of an integrated watershed management strategy that prioritizes spatial allocation of resources and addresses agricultural, residential, and natural land use elements will ensure a robust freshwater ecosystem that supports both societal needs and natural ecosystem processes.

References

- [1] Damphousse, L., Van Goethem, K., Carroll, E., Stammer, 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>
- [2] 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>
- [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] Kaur, L., Rishi, M. S., Sharma, S., & Khosla, A. (2019). Impervious surfaces an indicator of hydrological changes in urban watershed: A review. *Journal of Environmental and Soil Sciences*, 4(1), 469-473. <http://dx.doi.org/10.32474/OAJESS.2019.04.000180>
- [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] Casas-Ruiz, J. P., Bodmer, P., Bona, K. A., Butman, D., Couturier, M., Emilson, E. J., ... & Del Giorgio, P. A. (2023). Integrating terrestrial and aquatic ecosystems to constrain estimates of land-atmosphere carbon exchange. *Nature Communications*, 14(1), 1571. <https://doi.org/10.1038/s41467-023-37232-2>
- [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] Meador, M. R., & Goldstein, R. M. (2003). Assessing water quality at large geographic scales: relations among land use, water physicochemistry, riparian condition, and fish community structure. *Environmental management*, 31(4), 0504-0517. <https://doi.org/10.1007/s00267-002-2805-5>
- [10] Yu, R., Wu, Q., Li, F., Zhan, A., Zhou, J., & Li, S. (2024). Risk screening of invasive aquatic species and a survey of fish diversity using environmental DNA metabarcoding analysis in Shanghai. *Diversity*, 16(1), 29. <https://doi.org/10.3390/d16010029>
- [11] Mohan, C., Gleeson, T., Famiglietti, J. S., Virkki, V., Kumm, M., Porkka, M., ... & Jähnig, S. C. (2022). Poor correlation between large-scale environmental flow violations and freshwater biodiversity: implications for water resource management and the freshwater planetary boundary. *Hydrology and Earth System Sciences*, 26(23), 6247-6262. <https://doi.org/10.5194/hess-26-6247-2022>, 2022
- [12] 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>
- [13] 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
- [14] Speir, S. L., Rose, L. A., Blaszcak, J. R., Kincaid, D. W., Fazekas, H. M., Webster, A. J., ... & Wymore, A. S. (2024). Catchment concentration–discharge relationships across temporal scales: A review. *Wiley Interdisciplinary Reviews: Water*, 11(2), e1702. <https://doi.org/10.1002/wat2.1702>

- [15] Ulkilan, A., Mara, G. R., & Aleem, F. M. (2024). Modeling Sediment Transport and Nutrient Runoff in Aquaculture Watersheds Using RUSLE–GIS Framework. *National Journal of Smart Fisheries and Aquaculture Innovation*, 2(2), 16-23.