Assessing global regionalized impacts of eutrophication on freshwater fish biodiversity

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Chapter 6

General discussion


My father
闫新亮

6.1 Answers to the research questions

In current eutrophication studies, there exists a notable absence of comprehensive quantification methods to effectively model the loss of biodiversity. It was within this void that my research emerged, weaving a narrative that sought to address two pivotal inquiries: unraveling the extent of influence wielded by phosphorus (P) and nitrogen (N) on biodiversity loss, and discerning the magnitude of impact of these nutrients on fish species. In pursuit of this goal, the narrative of this thesis unfolds as it pioneers the development of comprehensive and regionalized characterization factors (CFs) specifically tailored for the freshwater eutrophication category. This approach is poised to elevate the predictive power and ecoregional precision of life cycle impact assessment (LCIA). Notably, the study meticulously adheres to the guidelines outlined by the Global Life Cycle Impact Assessment Method (GLAM) project, ensuring a methodologically robust and globally applicable framework (Payen et al., 2019; Verones et al., 2019). In detail, by utilizing the Integrated Model to Assess the Global Environment–Global Nutrient Model (IMAGE-GNM, Beusen et al. (2015)), the thesis first established fate factors (FFs) with a spatial resolution of 0.5×0.5 degrees (Chapter 2). It then assessed the performance and role of retention models in IMAGE-GNM to improve nutrient fate predictions (Chapter 3). Thirdly, the research estimated the effects on the species richness at a half-degree resolution based on the relationship between nutrient concentrations and 41-year occurrence records of 13,920 freshwater fish species. This research also estimated robust species sensitivity distributions (SSDs) across global freshwater ecoregions (Chapter 4). Utilizing the aforementioned factors, regionalized CFs were formulated and integrated with global extinction probabilities (GEPs) and nutrient limitation information. Subsequently, global freshwater fish species loss was evaluated based on the CFs and human-generated nutrients, discerned by various emission routes and nutrient types (Chapter 5).

In detail, this thesis achieves the research goal by addressing the four questions mentioned in the first chapter:

Q1: What is the pattern of regionalized nutrient fate, and how do drivers affect the nutrient fate over the global freshwater?

In Chapter 2, we developed a method for regionalized FFs at half-degree resolutions based on the nutrient fate and hydrological parameters modeled by IMAGE-GNM. We took N as an example and analyzed FFs for N over the global freshwater system. Our results reveal that the hydrological conditions can influence the nutrient fate. For instance, low FFs occur in regions characterized by large rivers with high discharge and low residence time, while high FFs occur in water bodies with high residence time, such as lakes and reservoirs. Regarding nutrient removal, high discharge, and low residence time characterize the strong removal by advection, while high residence time and low discharge represent high retention. Advection is the dominant removal process that affects FFs in ~2/3 of global regions. Retention dominates <1/3 of regions, and water consumption only dominates 1.4% of regions that are water-scarce. These results demonstrate the importance of developing site-specific FFs to assess eutrophication impacts since the geographical and hydrological conditions vary spatially. This chapter, therefore, characterizes FFs for N at high spatial resolution and contributes to the improvement of global eutrophication assessment by introducing soil-freshwater N fate to complement existing P-related fates. The same method was used for calculating FFs for P as a component of CFs in Chapter 5.

Q2: How can retention equations improve model performance?

As mentioned above, retention is one of the most crucial processes affecting the accuracy of nutrient fate modeling. in addition to the hydrological input data (governing advection) and the spatial resolution (van Vliet et al., 2019). The hydrological input data rely on the establishment of gauges and stations, and thus more data with better quality is inaccessible at present. Spatial resolution for a model is always fixed when the model is framed. The retention cannot be measured directly and is modeled by empirical equations. Thus, the choice of empirical equations is crucial for characterizing retention and eventually affects the accuracy of nutrient models. Chapter

3 evaluated the performance of retention equations for global nutrient models and analyzed the influence of driving forces, function form, and equation coefficients. We used methods of one-way Analysis of variance (ANOVA) and post hoc tests as well as multiple criteria, including the mean-Normalized Root Mean Square Error (NRMSE), Pearson's r, and relative bias, to validate IMAGE-GNM based on abundant samples from diverse sources.

Chapter 3 reveals that the specific-runoff-driven equations of Behrendt and Opitz (1999) (q) are the best fit for riverine nutrient retention, and De Klein (2008) performs the best for P retention in lakes. This chapter highlights that 1) the influence of hydraulic drivers in retention models is more important than the function form and coefficients; 2) retention models based on localized coefficients and function forms show better performance globally than those developed at global scales (i.e., the currently used equation of Wollheim et al., 2008, in IMAGE-GNM); 3) the consideration of temperature as a secondary driving force of P retention might increase the accuracy of retention prediction (D'angelo et al., 1991; Jensen and Andersen, 1992; Kim et al., 2003). According to our analysis of the geographical zones, we also find the equation by Behrendt and Opitz (1999) (q) fits well in most regions, while other retention equations perform better than it in some zones. Thus, we suggest applying specific retention equations at the geographical-zone scale rather than the global scale. These conclusions can help to optimize the description of nutrient fate by improving the retention models, and thus further reinforce our understanding of global eutrophication.

Q3: What is the pattern of the regionalized effect on fish species loss across the global freshwater ecosystem?

So far, no existing study developed effect factors (EFs) for N on freshwater species richness (Chapter 4). Chapter 4 regionalized the species sensitivity of freshwater fish against N concentrations at the ecoregion level and provided average and marginal EFs at half-degree resolutions. We used multiple criteria (pseudo R^2 and NRMSE) to evaluate the performance of our SSD equations based on millions of species occurrence observations recorded over 41 years. The results show good fits of SSDs for all the ecoregions with sufficient data. The results underline the high possibility of species loss in the tropical zone and the vulnerability of cold regions. Similar patterns can be seen for average and marginal EFs, while marginal EFs show slightly more areas with high values (>100,000 PDF·m^3·kg^{-1}) than average EFs. High values for marginal and average EFs can be found in regions with a rapid increase of N concentration currently, e.g., Taimyr, Arabian Interior, Baluchistan, Borneo Highlands, and Sangha. In agreement with other studies (Schulte-Uebbing et al., 2022), the regionalization of species sensitivity at finer resolutions in our study is beneficial for reflecting the spatial details in nutrient effects on species richness beyond the existing studies of a few geographical zones (Cosme and Hauschild, 2017). We applied the same method to calculate EFs for P as a component of CFs in Chapter 5, which complements the analysis of the eutrophication of both nutrients.

Q4: What is the impact of eutrophication on global fish species loss in freshwater ecosystems?

In Chapter 5, we connected FFs from Chapter 2 and EFs from Chapter 4 with GEPs to estimate regionalized CFs for P and N at multiple spatial scales: global, country level, and half-degree grid level. We also provided nutrient limitation information to assess when to implement the best CF. Integrating the CFs considering nutrient limitation with nutrient emissions and land use areas, we assessed the nutrient-induced impacts on global freshwater fish biodiversity. Globally, P causes double the potential species loss compared with N. For the nutrient emissions apart from erosion, high CFs are distributed in densely populated regions that encompass either large lakes or the headwater of rivers, most of which occur in tropical and temperate zones. For erosion, high CFs belong to those areas with intensive agriculture and animal husbandry. Our result estimates an impact of eutrophication on global freshwater fish species richness of 0.138 PDF·year, which agrees with the estimation of 15.6% of species affected by water pollution by Miranda et al. (2022). We also find that the dominant contributor is erosion from arable land, which agrees with Scherer and Pfister (2015). These agreements reckon that our CFs are reasonable and able to assess the eutrophication impact. Diffuse emissions occupy over 1/4 of the contribution to the impact. These findings confirm that agriculture is the main driver of eutrophication.

6.2 Limitations and future research

Current studies quantify the human impact on biodiversity by either using biodiversity models or LCIA. For aquatic eutrophication, the most recognized biodiversity model, GLOBIO-Aquatic (Janse et al., 2015), models the impacts on mean relative abundance of inland aquatic species using a meta-analysis of studied information. This model considered diverse drivers (eutrophication, erosion/sedimentation, riparian settlements, and others) by combining local/regional case studies. However, considerable variations in observed effects exist among individual cases across geological scales and between drivers. Combining species composition data raises concerns as the interference with drivers is not interpretable and the correlation between a specific driver and local diversity may not apply at a larger regional level. This model cannot directly be used for the impact assessment of goods because they were designed for estimating biodiversity loss in regions as a whole. Consequently, this model should be viewed as complementary to other approaches and indicators (Janse et al., 2015). LCIA becomes crucial because it can explicitly unlock the cause-effect chain of the fate and transport of nutrients and their impact. The previous limitations of LCIA include the difficulty of quantifying site-specific fate and effect of nutrients and the simplified assumptions about nutrient limitations in ecosystems (P limits marine and N limits freshwater). My studies underscore the consideration of both P and N and the regionalization of both fate and effect.

The data availability, the model accuracy, and the implemented methodology lead to various limitations in this thesis. In detail, we discuss below the research limitations of nutrient fate, its effect on biodiversity, and the assessment of the impact of eutrophication.

Existing FF studies, including the one presented in Chapter 2, do not reproduce seasonal information on nutrient fate. Studies such as de Andrade et al. (2021) reckoned that FFs intensely vary spatially but are not highly temporally dependent. Thus, it is more important to regionalize FFs. However, temporal variability on a global scale still requires further study, since nutrient fate relies on hydrological conditions that are sensitive to the seasonal dynamics in climate (Chapter 2).

In the estimation of FFs, limitations in hydrological data restrict the reproduction of the advection and retention process. Due to a lack of data such as water volume, water depth, and damming information, the assumptions in the hydrological model and retention model integrated into IMAGE-GNM introduce uncertainty in the prediction of nutrient fate (Chapter 2). For instance, river damming can lead to a decrease in the hydraulic load, thus causing sediment trapping. This results in a decrease in advection and an increase in nutrient retention (Maavara et al., 2015). In addition, empirical retention equations used in IMAGE-GNM can only characterize the effects of changing hydrological parameters but cannot capture biogeochemical mechanisms for P and N. Apart from biogeochemical mechanisms, the nutrient model has limitations due to the absence of including interactions among nutrient forms, interactions with other elements, and release of P into water bodies from long-term accumulation of anthropogenic P retention in sediments. This ignorance of P release also leads to a larger uncertainty in the representativeness of P than of N in the nutrient model (Chapter 3).

As such, future work in process-based biogeochemical dynamics, especially in the modeling of retention, is needed to better reproduce P and N fate. Such a model would allow us to distinguish the specific forms and to capture the interaction among different nutrient species. For instance, the predictions of nutrient fate and concentrations can be upgraded by using a mechanistic model, IMAGE-DGNM (Vilmin et al., 2020). IMAGE-DGNM can simulate the interactive processes between nutrient species and capture the monthly variability of nutrient fate. The research scope of the current version of IMAGE-DGNM is restricted to specific watersheds, whilst a future version of global scope can substitute IMAGE-GNM to better support the research on P and N fate and their impact on fish biodiversity (Vilmin et al., 2020) (chapter 2, 3, 4, 5).

In the assessment of EFs, limitations relate to an underlying assumption that fish species loss is caused by P or N increase. However, the occurrence of fish species may be affected by other stressors as well. Despite the major stressor of nutrient enrichment, the decrease in fish occurrence may also be affected by land-use change interactions (Comte et al., 2021), global warming (Barbarossa et al., 2021; Comte et al., 2021), and overuse of water (Pierrat et al., 2022). We thus suggest future studies on EFs to encompass other biodiversity threats concurrently. Such comprehensive consideration will reinforce the understanding of the way nutrient effects and other human pressures interact (chapter 4).

Moreover, the SSDs are limited by the quality of species observations. Uncertainty exists in potential sampling bias for our underlying point occurrence dataset. The issue of lack of observational data in cold regions is particularly prevalent, as pointed out in previous studies (Azevedo et al., 2013; Cosme and Hauschild, 2017). The accessibility to more species occurrence records in the future can reduce such uncertainty for some ecoregions (Chapter 4).

Our CFs on eutrophication impact for N may also include the influence of ecotoxicity (Kroupova et al., 2018), mixing in a different impact category to eutrophication (Chislock et al., 2013; Dodds and Smith, 2016; Payen et al., 2019; Smith et al., 2006). However, we believe this impact is limited because eutrophication is regarded as the predominant impact of N in aquatic ecosystems (Chislock et al., 2013; Dodds and Smith, 2016; Wang et al., 2021), as direct toxicity by certain forms of N at high concentrations, such as ammonia and nitrite, exerts little influence (Jones et al., 2014; Kroupova et al., 2018; Thurston et al., 1981). On the other hand, eutrophication and ecotoxicity are inseparable from N and should be considered comprehensively in their impact on the ecosystem. While previous studies only consider hypoxia (Cosme and Hauschild, 2017), our method covers the comprehensive impact of N. However, disentangling the eutrophication and ecotoxicity of N is an important work in the future since it matches the standard impact categories (Chapter 5).

Within this thesis, I utilized freshwater fish species richness as a focal point to illustrate the biodiversity challenges influenced by eutrophication. However, relying solely on this metric may be insufficient to fully comprehend the broader impact on freshwater biodiversity. As previously highlighted, freshwater fish hold particular ecological significance, acting as indicators of ecosystem health and contributing to the overall integrity of habitats (Villéger et al., 2017). While species richness is a vital initial step in unraveling the complexities of the biodiversity issue, it represents just one facet of a broader spectrum. Biodiversity encompasses not only a variety of life forms but also involves factors such as cross-taxon congruence and other indicators that contribute to ecosystem health. Future research could delve further into the exploration of more comprehensive indicators associated with biodiversity to gain a more nuanced understanding of its intricacies.

6.3 Implications

This thesis offers practical indicators that can assist economic actors in evaluating the impacts of P and N on the global freshwater ecosystem and incorporate recommendations from GLAM (Payen et al., 2019). The research marks a crucial first step in untangling the intricacies of the biodiversity challenges stemming from human-induced P and N excess. It can serve as a prototype, laying a foundation for future impact assessments of eutrophication in both terrestrial and marine ecosystems as well as other biodiversity indicators. This work also underscores the imperative of aligning with the United Nations' Sustainable Development Goals (SDGs) 6.3[1] and 15.1[2] (SDGs, 2015), alongside Kunming-Montreal Global Biodiversity Framework target 7[3] (Joly, 2023), focusing on the conservation of freshwater ecosystems, biodiversity, and the mitigation of excessive nutrient levels. This research contributes to the pursuit of these targets by evaluating the repercussions of curbing nutrient excess as pollutants on freshwater biodiversity in diverse pathways. Consequently, the findings of the thesis offer valuable insights for decision-makers across nations, aiding them in formulating environmental strategies that adhere to international agreements and obligations.

Specifically, the inclusion of fate and effect for N complements the current P-related studies on freshwater environments. The findings highlight the connections between nutrient fate and the physical processes that rely on the hydrological and geographical conditions. This finding emphasizes the importance of regionalization at a fine resolution due to the large spatial variability of hydrological and geographical conditions. With a half-degree resolution, our FFs can be consolidated to any chosen

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[1] By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.

[2] By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements.

[3] Reduce pollution risks and the negative impact of pollution from all sources, by 2030, to levels that are not harmful to biodiversity and ecosystem functions and services, considering cumulative effects, including: reducing excess nutrients lost to the environment by at least half including through more efficient nutrient cycling and use; reducing the overall risk from pesticides and highly hazardous chemicals by at least half including through integrated pest management, based on science, taking into account food security and livelihoods; and also preventing, reducing, and working towards eliminating plastic pollution.

regional scale, taking into account the nutrient emissions or, in the case of erosion, utilizing the land use distribution. This approach enables life cycle assessment (LCA) practitioners to gain insights into the spatial distribution of nutrient fate resulting from production activities across the globe, aligning with their inventory data.

My comprehensive evaluation of retention equations on a global scale can serve as a valuable tool for evaluating the performance of any process in modeling nutrient fate. Employing ANOVA and post hoc tests shows an effective way to reveal the role of diverse components in empirical equations, such as driving forces, function form, and equation coefficients. My findings of the best-fit retention equation can be utilized for elevating the accuracy of FFs by improving the performance of IMAGE-GNM. The geographical assessment of retention equations also facilitates model developers to integrate spatial variability of process functions into global nutrient simulations. Overall, the retention research can potentially contribute to the development of empirical retention equations and the accurate reproduction of nutrient fate in future modeling works.

The selection approach for determining effects provides not only the findings of robust correlations between N content and freshwater fish species richness across 425 ecoregions but also an approach for assessing such relationships for other environmental impacts, as I verified the replicability of the method for P effect in Chapter 5. The regionalization of freshwater-ecoregion-level SSDs underscores the spatial variability of sensitivities of ecosystems to nutrients. It goes beyond previous studies that assessed marine N in five geographical zones and freshwater P in four geographical zones and promotes geographical precision of effect by refining the resolution. My approach also offers a contrasting insight to existing linear EFs that rely on a generic point (Verones et al., 2020), as I calculated the average and marginal EFs that consider current background concentrations on SSDs. These EFs illustrate variations in species richness resulting from both long-term and instantaneous nutrient changes. The EFs can be implemented in LCA research and consequently aid the formulation of sustainable strategies, such as considering the high sensitivity of species richness in tropical regions and the vulnerability of cold regions.

My research further underscores the benefits of utilizing regionalized indicators with enhanced spatial resolution. With regionalization, I innovate a method to incorporate nutrient limitation into CFs, in contrast to the focus solely on P in previous freshwater studies (Azevedo et al., 2020). My findings therefore recognize that N can contribute ~1/3 to freshwater eutrophication. The insights into nutrient limitation provided by our study offer guidance to LCA practitioners in selecting the most suitable nutrient CF for a specific location.

The global assessment of eutrophication impact conducted in our study not only identifies primary contributors but also sheds light on the severity of human pressures contributing to eutrophication-related biodiversity loss. The consideration of the comprehensive impacts of nutrients on species can be extended to assess eutrophication impact in both terrestrial and marine ecosystems, providing a holistic perspective on the environmental implications of nutrient-related disturbances. Our CFs are harmonized with other indicators considered under GLAM, which might improve the ease of application for LCA practitioners.