Assessing global regionalized impacts of eutrophication on freshwater fish biodiversity

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Citation

Zhou, J. (2024, January 30). *Assessing global regionalized impacts of eutrophication on freshwater fish biodiversity*. Retrieved from https://hdl.handle.net/1887/3715136

Chapter 1

General introduction

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1.1 Challenges in biodiversity worldwide

Biodiversity refers to the variety of life forms on Earth, including ecosystems, species, and genetic diversity (Wilson, 1999). It is essential for the functioning of ecosystems and provides numerous benefits to human well-being (Kumar, 2005; Verma, 2016). For instance, biodiversity plays a crucial role in maintaining the stability and resilience of ecosystems because each species has a unique role within its ecosystem and their interactions contribute to the balance of the ecosystem (Feng et al., 2017; Mori et al., 2017, 2013; Swift et al., 2004). Biodiversity also supports human life through providing ecosystem services, which comprise, among others, the provision of food and fibers, water purification, pollination, nutrient cycling, and the regulation of diseases (Haines-Young and Potschin, 2010; Mori et al., 2017). Furthermore, the diversity of nature is beneficial for the mental well-being of people (Haines-Young and Potschin, 2010).

The Earth is currently facing a biodiversity crisis, marked by ecosystem degradation and unprecedented rates of species loss (Arya, 2021; Díaz et al., 2019; Savage, 1995). This loss of biodiversity can lead to a decline in ecosystem services and the stability of ecosystems, eventually harming human livelihoods and well-being (Corvalan et al., 2005). Specifically, the biodiversity crisis is associated with some practices of human interference (Savage, 1995). One of the human interferences is the conversion of natural lands for agriculture, urbanization, and resource extraction. It leads to habitat loss and fragmentation of ecosystems (Prakash and Verma, 2022). Humans have emitted excessive greenhouse gases and thus causing the rapidly changing climate, which has been found to disrupt ecosystem performance and affect the distribution and behavior of species (IPCC, 2018). Moreover, overexploitation by mankind, such as unsustainable hunting, fishing, logging, and harvesting of wildlife for trade, coupled with illegal activities, even pushes some species to extinction (Prakash and Verma, 2022). Last but not least, pollution from anthropogenic activities, such as industrial production, agricultural practices, and improper waste disposal, can contaminate air, water, and soil (Akhtar et al., 2021; Havugimana et al., 2017; Ogidi and Akpan, 2022). These consequences of human interferences have jeopardized species' survival and reproductive success and thus pose a significant threat to biodiversity (Prakash and Verma, 2022).

Across different ecosystem types, freshwater species are of utmost concern since they are the most endangered overall and decline the fastest compared with terrestrial and marine species (Dudgeon et al., 2006; Harrison et al., 2018). Freshwater species have lost on average 83% of the population since 1970 (Grooten and Almond, 2018). Within freshwater ecosystems, fish biodiversity holds particular significance, serving as an indicator of ecosystem health and contributing to the overall integrity of these fragile habitats (Villéger et al., 2017). Researching fish biodiversity across global freshwater ecoregions is crucial in addressing the challenges posed by environmental threats that further exacerbate the ongoing biodiversity crisis (Whitfield and Elliott, 2002).

Among the anthropogenic drivers, pollution from agriculture is the most prominent driver of freshwater biodiversity loss (Díaz et al., 2019). Pollution overall threatens 49.4% of the threatened fish species and 63% of freshwater fish species (Miranda et al., 2022). It goes without saying that biodiversity conservation from agricultural pollution, particularly fertilizer use is important. Yet to what extent this pollution has contributed to the deterioration of biodiversity is still insufficiently understood, especially for different locations all over the world.

1.2 Global nexus of eutrophication and freshwater fish biodiversity

Agricultural activities, especially fertilizer use, have caused an abundance of contaminants in soil and aquatic systems (Beusen et al., 2016; Bouwman et al., 2009). One of the primary pollutants is nutrients. Excessive nutrient enrichment in aquatic environments characterizes eutrophication, resulting in detrimental effects on the overall biodiversity of ecosystems (Chislock et al., 2013; Müller et al., 2012; Jenny et al., 2016; Vonlanthen et al., 2012; Schindler and Vallentyne, 2008).

Within the context of freshwater biodiversity, eutrophication presents the critical challenge of algal blooms (Wurtsbaugh et al., 2019). Increased nutrient levels fuel the growth of algae, forming dense layers that block sunlight from reaching lower layers of water and leading to the depletion of oxygen (Chislock et al., 2013; Müller et al., 2012). The shading of light prevents predators such as fish from hunting prey and reduces the chances of survival of predators (Lehtiniemi et al., 2005). Oxygen depletion, creating hypoxic or anoxic conditions in the water, can have severe impacts on fish and other aquatic organisms that rely on adequate oxygen availability for survival (Jenny et al., 2016). Therefore, eutrophication can cause not only the local loss of species and populations but also shifts in species composition, favoring certain algal species over others and altering the intricate balance of the ecosystem (Wang et al., 2021). These consequences can adversely disrupt vital ecological processes within freshwater ecosystems and further cause extinction of species in the long term (Dodds an Smith, 2016). Eventually, it becomes a major threat to fish species richness (Dorgham, 2014).

Understanding the role of eutrophication across global freshwater ecoregions is essential for addressing the threats to freshwater biodiversity. Research efforts aimed at assessing the influence of eutrophication on fish species provide valuable insights into the general impacts of eutrophication on freshwater biodiversity. By studying fish as indicators of ecosystem health, researchers can inform conservation strategies, ecosystem management plans, and policy decisions to mitigate the detrimental effects of eutrophication and preserve the integrity of freshwater ecosystems worldwide.

1.3 Environmental complexity hinders eutrophication assessments

Human activities have nearly doubled the global delivery of nitrogen (N) and phosphorus (P) to freshwater systems and led to a rise in eutrophication worldwide (Beusen et al., 2016). Looking ahead, the trend of nutrient accumulation in freshwater systems is expected to continue due to increased fertilizer use and global population growth (Mogollón et al., 2018b). Additionally, climate change impacts on the hydrological cycle, including increased evaporation and freshwater advection, are likely to exacerbate changes in global nutrient cycles (Bouraoui et al., 2004; Statham, 2012). Consequently, the complex interactions between environmental factors and nutrient cycles make accurate eutrophication predictions challenging (van Vliet et al., 2019).

To effectively address the rising eutrophication trend in global aquatic systems, it is crucial to assess the fate of N and P through global nutrient models. However, current global estimates of nutrient exports vary significantly, highlighting the difficulties in modeling and predicting eutrophication (van Vliet et al., 2019). The discrepancies arise from differences in hydrological data, spatial resolution, and process modeling methods such as retention (van Vliet et al., 2019). Nutrient retention, influenced by various hydrological processes and drivers, plays a crucial role in eutrophication dynamics. Identifying the most effective models for globally predicting nutrient retention can improve our understanding of eutrophication impacts.

In addition, eutrophication impact is reliant on algal blooms (Ansari et al., 2011; Wurtsbaugh et al., 2019). To address the issue of algal blooms, it is crucial to have access to information on the algal distribution and the drivers of their growth. The drivers have been found as nutrient concentrations and bioavailability (Francoeur et al., 1999). The primary focus is usually on managing the concentrations and bioavailability of N and P (McDowell et al., 2020). Therefore, considering the spatial distribution of limiting nutrients can help to disentangle eutrophication impacts.

Given the complex interactions between environmental factors, nutrient cycles, eutrophication processes, and algal growth, the accuracy of the representativeness of nutrient dynamics and nutrient limitation becomes inherently important. The choice of nutrient models and the consideration of nutrient limitations that account for the intricate relationships and feedback mechanisms within aquatic ecosystems are crucial for advancing our understanding of eutrophication and effectively managing its impacts.

1.4 Life cycle impact assessment of freshwater eutrophication

Several methods for assessing the environmental impacts of eutrophication have been developed to quantify the preservation of ecosystem quality. An extensively used approach to evaluate the environmental impacts is life cycle assessment (LCA) (Muralikrishna and Manickam, 2017). Within contemporary economic activities, global environmental impacts are evidently generated in international value chains, encompassing the production, use, and disposal of goods or services. LCA allows for monitoring and evaluating these impacts comprehensively, adopting a system's perspective. LCA aims to pinpoint strategies for enhancement without resorting to the transfer of burdens and can be distinguished into phases (Figure 1.1) (Hellweg and Canals, 2014). The first phase involves outlining the goal and scope, encompassing the definition of research objectives and establishing the system boundaries. In the second phase, inventory analysis gathers inputs and outputs for each life cycle process, consolidating them system-wide. This typically involves quantifying hundreds of emissions and resources. The third phase, known as life-cycle impact assessment (LCIA), assesses the impact of emissions and resources based on their impact categories, which are converted into common impact units to facilitate comparability (Hellweg and Canals, 2014). The final phase is the interpretation of the inventory and impact assessment results to address the aim of the LCA study. The focus of concern in the LCIA method is characterization factors (CFs), as CFs quantitatively represent the relative importance of a specific influence from emissions and resources (Payen et al., 2019). CFs establish a connection between emissions and an environmental impact, such as the loss of biodiversity, through midpoint-level and endpoint-level indicators (Rosenbaum et al., 2007). In the context of eutrophication, midpoint-level indicators represent the fate of nutrients and their exposure to the environment, whilst endpoint-level indicators describe the ultimate effect of eutrophication on species occurrences (Payen et al., 2019).

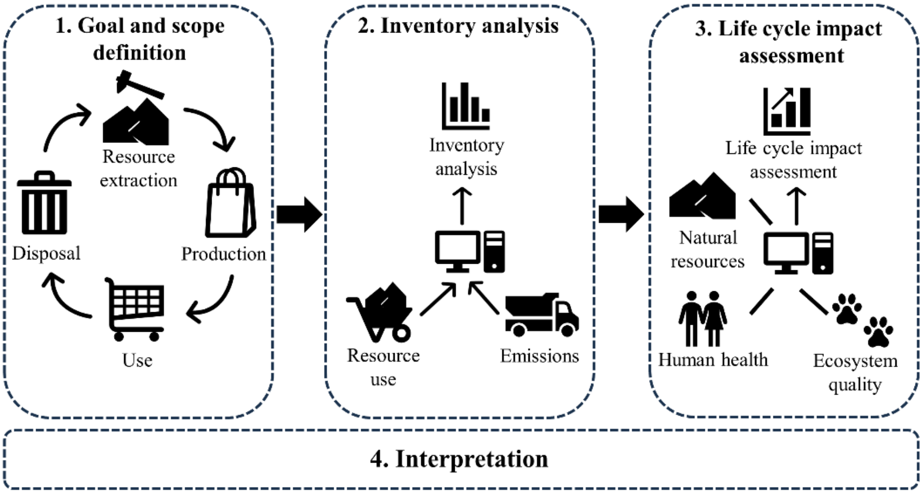

Figure 1.1 Four phases of life cycle assessment (LCA), modified from Hellweg and Canals (2014)

In freshwater ecosystems, impacts on fish biodiversity have been widely explored by LCA studies given its importance to ecosystem health (Villéger et al., 2017; Whitfield and Elliott, 2002). Various environmental stressors to freshwater fish biodiversity loss have been quantified and converted to CFs, including climate change (de Visser et al., 2023; Hanafiah et al., 2011), water consumption (Hanafiah et al., 2011; Pierrat et al., 2022), and hydropower (Turgeon et al., 2021). All these studies focus on the global scale. These global studies use different degrees of regionalization from biomes to the grid level to capture variation in environmental impacts. Also in the case of freshwater eutrophication, regionalization is essential to account for the influence of diverse environmental conditions on the relationship between eutrophication and biodiversity loss. This influence encompasses spatial variations in phosphorus (P) and nitrogen (N) impacts due to varying nutrient limitations and species compositions. Current studies on CFs solely focus on either P-related freshwater eutrophication (e.g., LC-IMPACT (Azevedo et al., 2020), ReCiPe2016 (Huijbregts et al., 2017), and Jwaideh et al. (2022)) or N-related marine eutrophication in CFs (e.g., (Cosme and Hauschild, 2017)). Yet as we mentioned, it is crucial to consider both P and N to decide which nutrient restricts algal growth, as it characterizes the regionalized impact of eutrophication on freshwater ecosystems. Additionally, the spatial representation of these studies is insufficient as these studies only specify the species loss relating to P and N for four or five geographical zones globally, which is too few for characterizing the global variation in impacts.

There are standardizations and guidelines that can be used for the evaluation of the impact. In 2020, the United Nations Environment Programme (UNEP) initiated the third phase of the Global Life Cycle Impact Assessment Method (GLAM) project as part of the broader "Life Cycle Initiative", whose primary objective is to establish global standardization and harmonization of LCIA methods (Verones et al., 2019). GLAM advocates for the adoption of spatially explicit models with global coverage for the midpoint and endpoint levels (Payen et al., 2019). For the midpoint-level indicators, GLAM recommends to use global nutrient models with a fine resolution to develop the fate of environmental drivers and emphasizes capturing physical and biogeochemical processes in assessment models. When it comes to the endpoint level, GLAM recommends summarizing the assessment of impacts on species richness of fish as has previously been employed in LCIA studies. However, historical studies hamper the characterization of the fine spatial variability in both the nutrient fate and its effect on species. As a result, developing spatially explicit fate factors (FFs), effect factors (EFs), and CFs at a finer resolution is essential for accurate impact assessment.

Considering global species loss can offer a broader insight into the interactions of nutrient inputs and the impacts on freshwater ecosystems than when restricting the analysis solely to local or regional species loss. As a consequence, global extinction probabilities (GEPs) have recently been developed within the framework of GLAM (Verones et al., 2022). GEPs can translate the regional species loss to global species loss by a simple multiplication with CFs.

In summary, the objective of achieving a more comprehensive assessment of eutrophication impacts on global freshwater biodiversity requires improvements in the spatial representation of nutrient fate, understanding the relationship between nutrients and their effects on species richness, and quantitatively evaluating CFs for the current state. Drawing upon previous research, these enhancements can be achieved by prioritizing the regionalization of fate and effect, encompassing both P and N impacts, integrating GEPs, and acknowledging nutrient limitations.

1.5 Aims and research questions

The overall aim of this thesis is to disentangle the impact of eutrophication from other anthropogenic impacts on global freshwater fish biodiversity. I therefore developed region-specific and inclusive indicators for nutrient fate and effects, followed by improving nutrient retention predictions, and subsequently quantified the impacts on freshwater fish species richness. These indicators can be integrated into LCIA methods, thereby enhancing their predictive power and ecoregional precision. To achieve this aim, this research can be subdivided into several questions (Q):

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

As mentioned above, fate factors are the midpoint-level components of CFs. Historically, studies on fate factors for freshwater systems focus on P but lack a view on N. To better represent nutrient fate in LCIA methods, the fate factors not only need to be regionalized to reproduce the transport of N, but also should characterize N fate from the direct emissions, diffuse emissions, and erosions. It is also important to explore the role of drivers in nutrient fate to know the contributors to freshwater eutrophication. The same method can be used for assessing P fate.

Q2: How can retention equations improve model performance?

fate factors are based on the simulation of P and N dynamics, which is achieved by using a global nutrient model. In the process of nutrient modeling, retention is of utmost importance. Assessing the performance of retention models in the global nutrient model helps to optimize the simulation of nutrient fate.

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

Current LCIA indicators only characterize the effect of P on species in four geographical zones for freshwater and the effect of N in five geographical zones for marine globally. However, due to a large variation in hydro-climatic conditions and human stressors over the world, the response of fish species differs across the freshwater ecoregions. Nutrients are such drivers that are affected by hydrological conditions and human emissions. Thus, the effects of nutrients on fish species richness need to be assessed more site-specifically.

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

Characterization factors can reflect the hotspots of impact from P and N emissions per unit of inventory on species. However, so far, characterization-factor-related studies lack the regionalization of both P and N and the knowledge of which nutrient influences fish biodiversity where. As discussed in the above sections, such innovative work is necessary to be done for evaluating the eutrophication impact on global ecosystems, such as freshwater systems.

1.6 Thesis outline

This thesis is composed of six chapters (Figure 1.2). The first chapter, the general introduction, gives an overview of the background, motivation, and the outline of the thesis. To realize the objectives, the thesis focuses on deriving spatially explicit fate factors (FFs), effect factors (EFs), and resulting characterization factors (CFs) for N and P to use in life cycle impact assessments by employing IMAGE-GNM. This thesis reproduces the major processes of nutrient inputs, eutrophication, and the impacts (Figure 1.3). This is done in Chapter 2 for fate factors of N, in Chapter 3 by assessing the importance of alternative descriptions of nutrient retention on fate factors, in Chapter 4 for effect factors of N (linking N concentrations to fish species loss) and finally for CFs in Chapter 5 by linking fate and effect factors Finally, the last chapter of the general discussion encompasses the limitations and implementation of the thesis. The narrative of Chapters 2 – 6 is further expanded upon below.

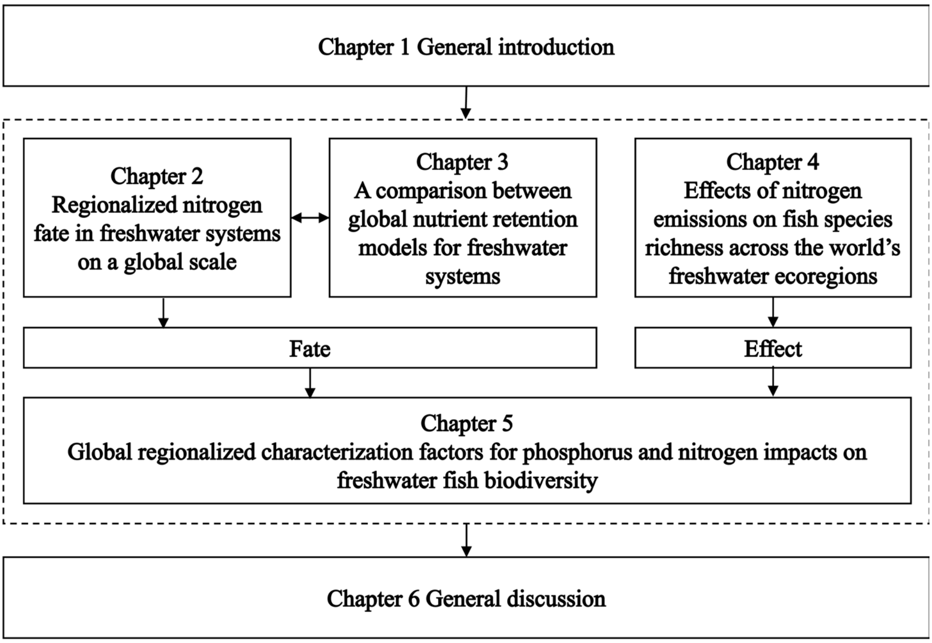

Figure 1.2 Outline of the thesis

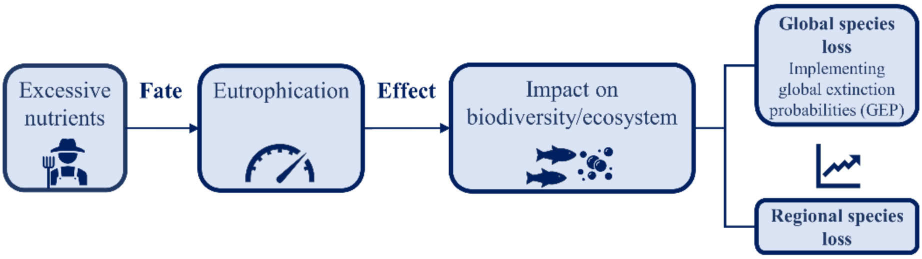

Figure 1.3 A schematic diagram of the major processes and interactions of nutrient inputs, eutrophication, and the impacts

Chapter 2 addresses the first research question. It provides regionalized FFs for N in global freshwater at half-degree resolution and at the country level. These FFs specify N fate from the direct and diffuse emissions, as well as erosion. This chapter complements current analyses of freshwater eutrophication about P. It presents a quantitative analysis of N fate against hydrological parameters and illustrates their spatial heterogeneity, highlighting the importance of regionalization in LCIA indicators.

Chapter 3 answers the second research question. It assesses the performance of the global nutrient model that was used in the calculation of FFs in Chapter 2. This research quantifies the improvement of model performance in the best-fit retention equation compared to the currently used one. The results present the importance of retention in the prediction of nutrient fate.

Chapter 4 answers the third research question. This chapter regionalizes the effect of eutrophication on species richness by establishing the relationship between nutrient concentration (the stressor) and the potentially disappeared fraction (PDF) of species richness. This research regress the curve of how PDF changes due to N concentration across hundreds of freshwater ecoregions based on observed data and calculate the EFs at half-degree resolution. The method can also be applied to P and used for calculating CFs.

Chapter 5 addresses the fourth research question. This chapter calculates regionalized CFs at half-degree resolution and at the country level based on the fate and effect research in this thesis. It provides both views of eutrophication CFs on regional species loss and global species loss (by integrating regional species loss with GEP, Figure 1.3). This research also gives nutrient limitation at the same resolution, which can guide the users of life cycle assessment to determine whether P or N should be considered in the use of CFs.

Chapter 6 provides a general discussion on Chapters 2-5. This chapter summarizes the answers to the questions, the limitations of the research, and the implications of this thesis.