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THIAGO DERUZA GARCIA

MECHANISMS THAT INFLUENCE THE TROPHIC INTERACTION OF ICHTHYOFAUNA AND FOOD RESOURCES IN NEOTROPICAL RIVERS

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Orientadora: Profa. Dra. Ana Paula Vidotto Magnoni
Coorientadora: Dra. Rosemara Fugi

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BANCA EXAMINADORA

Orientadora: Profa. Dra. Ana Paula Vidotto Magnoni
Universidade Estadual de Londrina - UEL

Prof. Dr. José Luís Olivan Birindelli
Universidade Estadual de Londrina - UEL

Prof. Dr. Fernando Camargo Jerep
Universidade Estadual de Londrina - UEL

Profa. Dra. Rosilene Delariva
Universidade Estadual do Oeste do Paraná - UNIOESTE

Profa. Dra. Bárbara Angélio Quirino
Universidade Estadual de Maringá - UEM

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GARCIA, Thiago Deruza. **Mecanismos que influenciam a interação trófica da ictiofauna e dos recursos alimentares em rios neotropicais**. 2024. 91p. Tese (Doutorado em Ciências Biológicas) – Universidade Estadual de Londrina, Londrina, 2024.

RESUMO GERAL

Considerando que fatores bióticos e abióticos podem influenciar na organização trófica das comunidades de peixes, desempenhando um importante papel no funcionamento dos ecossistemas, o objetivo desta tese foi avaliar os mecanismos que influenciam na ecologia trófica das assembleias de peixes neotropicais. Diante disso, essa tese é composta por três capítulos, a saber: (i) realizou-se uma meta-análise para investigar as mudanças na composição de guildas tróficas entre os trechos montante, reservatório e jusante das barragens; (ii) Analisou-se as métricas de duas redes trófica entre os trechos montante e jusante de uma Pequena Central Hidrelétrica; (iii) Avaliou-se a influência do tamanho corporal na relação predador-presa. De modo geral, constatou-se que houve um aumento na composição dos piscívoros, onívoros, detritívoros e herbívoros no trecho da jusante. Houve diferença significativa entre as redes tróficas de ambos os trechos, destacando um aumento no comportamento generalista dos peixes no trecho jusante. Por fim, ao avaliar a relação predador-presa, observou-se que o tamanho corporal da presa está diretamente relacionado ao tamanho do predador, e que predadores emboscadores têm maior probabilidade de consumir presas de movimento lento-moderado e rápido. Enquanto predadores perseguidores preferem consumir apenas presas rápidas.

Palavras-chave: Dieta de peixes; Ecossistemas aquáticos; Ictiofauna; Organização trófica; Reservatórios neotropicais.

GARCIA, Thiago Deruza. **Mechanisms that influence the trophic interaction of ichthyofauna and food resources in neotropical rivers**. 2024. 91p. Tese (Doutorado em Ciências Biológicas) – Universidade Estadual de Londrina, Londrina, 2024.

GENERAL ABSTRACT

Considering that biotic and abiotic factors can influence the trophic organization of fish communities, playing an important role in the functioning of ecosystems, the objective of this thesis was to assess the mechanisms influencing the trophic ecology of neotropical fish assemblages. Therefore, this thesis comprised three chapters, namely: (i) a meta-analysis was carried out to investigate changes in the composition of trophic guilds between the upstream, reservoir and downstream sections of the dams; (ii) The metrics of two food networks were analyzed between the upstream and downstream sections of a Small Hydroelectric Plant; (iii) The influence of body size on the predator-prey relationship was evaluated. In general, it was found that there was an increase in the composition of piscivorous, omnivorous, detritivorous, and herbivorous in the downstream section. There was a significant difference between the food networks of both stretches, highlighting an increase in the generalist behavior of fish in the downstream stretch. Finally, when evaluating the predator-prey relationship, it was observed that the body size of the prey is directly related to the size of the predator, and that ambushing predators are more likely to consume slow-moderate and fast-moving prey. While stalking predators prefer to consume only fast prey.

Key-words: Aquatic ecosystems; Fish diet; Ichthyofauna; Neotropical reservoirs; Trophic organization.

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LIST OF ABBREVIATIONS AND ACRONYMS

A = Aquatic

AC = *Acestrorhynchus lacustris*

AI = *Apareiodon ibitiensis*

AL = *Astyanax lacustris*

AQU = Aquaculture

BI = *Bryconamericus iheringii*

C = Connectance

CE = *Corydoras ehrhardti*

CK = *Cichla kelberi*

CP = *Cichla piquiti*

DUP = Duplicate studies

EEE = Ecotoxicological effect or experiment

GI = *Geophagus iporangensis*

H’2 = Specialization

H2 = *Hoplias sp*.2

H3 = *Hoplias sp*.3

HA = *Hoplias argentinensis*

HL = *Hypostomus albopunctatus*

HM = *Hoplias mbigua*

HN = Hypostomus *ancistroides*

HP = *Hemisorubim platyrhynchos*

HU = *Hoplerythrinus unitaeniatus*

IAi = Feeding index

IRR = Incidence rate ratio

L = Larvae

M = Modularity

NOD = Does not bring feeding data

NVA = There is no variability in the data

OOR = Other organisms

OSA = Outside the study area (Neotropical region, reservoir, and river)

OUT = larvae, juveniles, parasitism, and migration

PC = *Pseudoplatystoma corruscans*

PELD = Long-Term Ecological Research Program

PP = *Psalidodon paranae*

PS = *Plagioscion squamosissimu*

RSM = Systematic reviews or meta-analyses

RV = *Rhaphiodon vulpinus,*

SB = *Salminus brasiliensis*

SHP = Small Hydroelectric Power Plant

SL = *Sorubim lima*

T = Terrestrial

UEL = Universidade Estadual de Londrina

WNODF = Nesting

Summary

GENERAL INTRODUCTION

The organization of the trophic structure of an ecosystem is directly linked to the composition and availability of food resources that support biological communities, as well as the potential interaction mechanisms between species (Uieda & Motta, 2007). In this scenario, the theory of optimal foraging (MacArthur & Pianka, 1966) is an approach that explores the understanding of these mechanisms, identifying how competition can induce changes in the species' diet, influenced by the predator-prey relationship.

Neotropical aquatic ecosystems, such as rivers, exhibit a high heterogeneity of habitats, with widely varied physicochemical and biological characteristics (Nunes et al., 2020). These characteristics make this region the richest in biodiversity in the world, especially for freshwater fish, which represent 48.35% of global species (Fricke et al., 2024). Furthermore, fish play a crucial role as biological models and bioindicators in aquatic ecosystems (Chovanec et al., 2003; Duarte et al., 2020), proving to be effective in understanding the functioning and health of these ecosystems (Araújo et al., 2018; Authman, 2015; Freitas & Siqueira-Souza, 2009). Biotic and abiotic characteristics can influence the diet of fish in natural ecosystems, resulting in changes in their diet (Hahn & Fugi, 2007). These changes are facilitated by trophic plasticity, a characteristic present in most fish, which, depending on the availability of food resources, begins to consume alternative resources to compensate for the low demand for preferred resources (Abelha et al., 2001).

One of the main mechanisms that influences the trophic structure of fish communities is the construction of dams (Agostinho et al., 2016; Finer & Jenkins, 2012; Pelicice et al., 2015; Winemiller et al., 2016). Dams cause significant changes in watercourses, converting them into semi-silent environments (Agostinho et al., 2016), causing rapid changes in the diet of fish resulting from floods and flow regime flow, which modifies the availability and composition of food resources, benefiting species with high trophic plasticity, but eliminating strictly specialized species (Agostinho et al., 2007; Hahn & Fugi, 2007; Delariva et al., 2013).

The new environments formed by reservoirs, both upstream and downstream, can influence the quality of food resources in different ways, with the downstream stretch having a more pronounced impact on resources, resulting in an increase in the biomass of piscivorous (Delariva et al., 2013) and a predominance of generalist species (Gerkin, 1994; Oliveira et al., 2018). On the other hand, although the upstream region presents conditions similar to those of the river's natural course, especially at the beginning of the reservoir's operation, changes were also reported, mainly associated with populations that could migrate from the reservoir (Dias et al., 2020). Small Hydroelectric Power Plants (SHPs), designed for their reduced size reservoirs, with a maximum of 13 km², and operation under a daily regulation regime or "run of water" (Garcia et. al., 2020), are specifically interested in the electricity sector, due to its relative ease of approval, implementation, and operation, compared to large reservoirs (Borges & Meira, 2017). Although SHPs do not present a strong longitudinal gradient like large reservoirs, their impacts are expected on fish assemblages, influencing the variation in the structure of ichthyofauna over time, and this appears to be related to variations in water level of the reservoir (Baumgartner et al., 2018).

Although changes in food resources promoted by dams can directly affect ichthyofauna (Delariva et al., 2013; Dias et al., 2020; Fráguas & Pompeu 2021), changes in trophic interaction networks can have effects on local energy dynamics, affecting the entire ecosystem (Hairston & Hairston, 1993). The trophic structure of a community can be represented by networks of trophic interactions, considered an antagonistic network, revealing how species are organized in an ecosystem (Dunne et al., 2002; Dallas & Cornelius, 2015). The ability of a network to resist perturbations is determined by its structure, and network analysis metrics have been extensively used in investigating biological interactions (Dormann et al., 2009; Kondoh et al., 2010; Dátillo et al., 2014; Rosa et al., 2022). A highly relevant metric in ecological networks is connectance, which indicates the proportion of effective connections in relation to potential connections between network participants (Dormann et al., 2009). Furthermore, trophic interaction networks enable simulations of species extinction over time, resulting from human activities, indicating the potential decline of biodiversity after an environmental impact (Dormann et al., 2009; Peipoch et al., 2015).

The predator-prey dynamic of fish is a biological mechanism that can influence the trophic structure of the community, especially when it comes to predation, which is considered one of the main forces that affect the abundance and distribution of fish assemblages in aquatic ecosystems (Angermeier, 1992; Hixon et al., 2002; Nilsson, 2006). Variations in predator-prey dynamics in the environment can be caused by different hunting strategies of predators, foraging, and swimming modes of prey (Klecka & Boukal, 2013; Schmitz, 2010; Pawar & Savage, 2012; Miller et al., 2014). For example, predators that adopt ambush strategies demonstrate greater efficiency in capturing fast-swimming prey, while pursue predators tend to have better efficiency in capturing slow-swimming prey (Schmitz, 2010). On the other hand, from the prey's point of view, the predator-prey interaction can be influenced by the prey's defense mechanisms, exhibiting anti-predatory behavior (Gervasi et al., 2015).

Therefore, with the aim of evaluating the different mechanisms that influence the trophic ecology of fish assemblages in the Neotropical region, the thesis is organized into three chapters.

In the first chapter, we performed meta-analysis to quantitatively evaluate the effect of Neotropical dams on the composition of trophic guilds of fish assemblages. In this study, we calculated 72 effect sizes, across 18 studies included in the meta-analysis and a total of 1270 analyzed. In the second chapter we used the trophic network approach to evaluate network analysis metrics, such as connectance, modularity, nesting, specialization, extinction simulations and robustness in order to evaluate whether the areas upstream and downstream of a Small Hydroelectric Power Plant (SHP) in the Jaguariaíva River spatially influence the structure of the trophic networks of local fish assemblages. Finally, in the third chapter we seek to understand whether the body size of prey is a determining factor in the predation behavior of piscivorous predatory fish. Furthermore, we also seek to understand how the prey selection mechanisms exhibited by predators relate to their foraging mode in the floodplain of the upper Paraná River.

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2 CHAPTER 1

This manuscript was prepared according to *Environmental Monitoring and Assessment* journal standards, in compliance with the Postgraduate Program in Biological Sciences.

VARIATION IN THE COMPOSITION OF FISH TROPHIC GUILDS OF NEOTROPICAL DAMS: A SYSTEMATIC META-ANALYTIC REVIEW

ABSTRACT

The dams and the consequent formation of reservoirs promote pronounced biotic and abiotic changes not only in the reservoir but also in the stretches immediately upstream and downstream of the dam. In fish communities, the structure and composition of trophic guilds can be affected by environmental changes driven by damming. Thus, the objective of this study was to evaluate the effect of neotropical reservoirs, through a meta-analysis, in fish trophic guilds. We calculated 72 effect sizes, in 18 studies that were included in the meta-analysis, in which positive, negative, and neutral. were found, which correspond to high, low, and similar trophic guilds when stretches are compared. We also evaluated whether variables (Age, Area, and Latitude) influence trophic guilds. We observed that neotropical reservoirs promote changes in trophic structure in the fish assemblage. Specifically, we found increased of detritivorous, herbivorous, omnivorous, and piscivorous fish in the reservoir and downstream the dams. Furthermore, there was no evidence that latitude influenced the trophic guilds. On the other hand, age and reservoir area were relevant variables to explain differences found in the effect size. Finally, we highlight the importance of investigating the impacts of small, medium, and large reservoirs on the trophic structures of fish assemblages, seeking to create management and conservation measures for the rich neotropical biodiversity.

Keywords: Dam, Trophic Ecology, Freshwater fish, Meta-analysis, Spatial variation

2.1 INTRODUCTION

The Neotropical region is home to the greatest biodiversity fish in the world, reaching 9,000 species of fish in the coming decades, considering the number of species not yet described (Birindelli & Sidlauskas, 2018; Castro & Polaz, 2020), which corresponds to 48.35% of the world's freshwater species (Fricke et al., 2023). In this region there are two important river basins, due to their large extension and high diversity of specimens, namely the Amazon basin and the La Plata basin (Galves et al., 2009; Lowe-McConnell, 1999). Neotropical rivers have suffered constant human influences, being fragmented by dam installations to generate electricity (Carvajal-Quintero et al., 2017; Winemiller et al., 2016). Although these constructions are quite common in the Neotropical region, their distribution is not homogeneous (Agostinho et al., 2008), with a large number of small to large dams concentrated in the upper Paraná River basin, considered one of the most impacted basins in the world.

Biodiversity is threatened by habitat conversion worldwide, and dams' construction is one of the most common types of habitat conversion in freshwater ecosystems. The damming and the consequent formation of reservoirs promote marked changes not only in the reservoir area but also in the stretches upstream and downstream the dam (Agostinho et al., 1999; 2007). One of the most pronounced effects on the trophic structure of fish assemblages is changes in the river's natural flow regime (Gandini et al., 2014). In undammed rivers, the natural flow regime promotes increased environmental heterogeneity and maintains the species composition of the community. However, the changes in the river flow regime caused by damming causes changes in the availability and quality of food resources (Abujanra et al., 2009).

The stretches formed by the dams (upstream, reservoir and downstream) have a great influence on the availability and diversity of food resources, directly affecting the composition of species that make up the trophic guilds (Dias et al., 2020a). The stretch downstream of the dam has a more pronounced effect on resources compared to the upstream, as its availability of food resources is influenced by the water retention time in the reservoir, the amount of nutrients and the flow regime (Dias et al. 2020a; Fráguas & Pompeu 2021). Specifically, there are reduction in the levels of solid particles in the water column, leading to the impoverishment of water quality, since nutrients are retained by the dam in the reservoirs, arriving in smaller quantities downstream and blocking of the migratory routes of migratory species (Agostinho et al., 2007; Oliveira et al., 2018)

In addition, the reservoir stretch also influences the trophic structure of fish, through lentic water flow, which allows the deposition of solid particles, nutrient retention, and thermal stratification, according to the depth of water column (Agostinho, 1992). In the deeper region of the reservoir, benthic macroinvertebrates, such as crustaceans and mollusks, can be harmed in newly formed reservoirs due, for example, to the lack of oxygen at the bottom (de Mérona et al., 2001; Hahn & Fugi, 2007), leading to a reduction in invertivorous fish due to the lack of these resources (Hahn & Fugi, 2007; Luz-Agostinho et al., 2006; Novakowski et al., 2007).With the aging of the reservoir, the increase in the number of individuals of many small and medium-sized species is expected due to the increase in primary productivity, mainly in the transition zones between upstream and reservoir (Kimmel et al., 1990; Agostinho et al., 2008). With the filling of a reservoir, a period characterized by intense ecological changes (Agostinho et al., 1999), and consequently the flooding of large areas, terrestrial resources are incorporated into the aquatic environment and become rapidly available to the aquatic organisms (Hahn & Fugi, 2007). Among the resources available in this new environment are terrestrial invertebrates and plants (Loureiro-Crippa & Hahn, 2006), as well as fish species capable of exploiting these resources, mainly generalist and opportunistic species (Dias et al., 2020a). Therefore, considering the great importance of these new resources for insectivorous, herbivorous, and omnivorous fish, these fish groups are favored at the beginning of the reservoir formation, increasing their density (Agostinho et al., 1999).

Due to the large number of dams installed on the main neotropical rivers and the importance of conserving fish communities, the aim of this study was to quantitatively evaluate, through a meta-analysis, the effect of neotropical dams on the composition of trophic guilds in fish communities. In this way, we seek to answer two hypotheses, the first is that the effect size of trophic guilds will be greater in the intervention area (reservoir and downstream) than in the upstream area. Thus, we expect an increase in the composition of piscivore, detritivore and omnivore guilds. Piscivorous benefit from water transparency and a greater density of small prey (Luz-Agostinho et al., 2008; Pereira et al., 2016; Santos et al., 2017), in addition to the increase in non-native species. Omnivorous because food resources are more limited in environments with a greater degree of disturbance, causing fish species to consume different resources, increasing generalist behavior; finally, detritivorous due to the greater availability of decomposing material, especially after the filling the reservoirs. The second hypothesis is that the area and age of dams influence the effect size of the composition of trophic guilds, that is, larger and older dams will present a lower composition of trophic guilds, since in larger dams the concentration of food resources is more dispersed and older dams present a reduction in species, influencing the composition of trophic guilds.

2.2 MATERIAL AND METHODS

2.2.1 Study area

The meta-analysis was carried out with data obtained from scientific articles on dams located in the Neotropical region (Table 1). This region has a rich biodiversity of fish, in addition to being home to one of the largest concentrations of hydroelectric plants in operation in the world. Although most of the studies included in the meta-analysis focus on Brazilian rivers and one study on the Uruguay river, the search was carried out for the entire neotropical region (see Supplementary Information 1).

Table 1 - Studies included in the meta-analysis, with their respective reservoirs and their characteristics such as Age, Area, and Latitude. SHP = Small Hydroelectric Plant.

Author	Dam	Age	Area (km²)	Latitude (decimal)
Bennemann et al. (2011)	Escola Mackenzie Reservoir	34	576	22.65694444
Brandão et al. (2009)	Salto Grande Reservoir	64	12.2	22.90416667
Cassemiro et al. (2005)	Salto Caxias Reservoir	23	144.2	25.54305556
Corrêa et al. (2015)	Chasqueiro Reservoir	32	248.42	32.16194444
Delariva et al. (2013)	Salto Caxia Reservoir	23	144.2	25.54305556
Esguícero & Arcifa (2011)	Gavião Peixoto Reservoir	17	77	21.84805556
Galindo et al. (2020)	Corredeira SHP	70	0.35	23.29708333
Garcia et al. (2020)	Nova Jaguariaíva SHP	71	753	24.30197222
Lima et al. (2016)	Peixe Angical Reservoir	15	294	14.23527778
López-Rodríguez et al. (2019)	Salto Grande Reservoir	40	224	31.27416667
Oliveira et al. (2020)	Jamari SHP	6	656	9.9375
Pereira & Agostinho (2019)	Salto Caxias Reservoir	23	144.2	25.54416667
Pereira et al. (2016)	Salto Caxias Reservoir	22	144.2	25.54416667
Sá-Oliveira (2015)	Coaracy Nunes Reservoir	45	23.5	0.903277778
Sa-Oliveira et al. (2014)	Coaracy Nunes Reservoir	46	565	0.902777778
Silva et al. (2008)	Balbina Reservoir	34	2360	1.915833333
Terra et al. (2010)	Funil Reservoir	52	38.3	22.5
Vidotto-Magnoni (2009)	Chavantes Reservoir	50	400	23.12722222

2.2.2 Search protocol

The search was conducted systematically in three online databases (Web of Science, Scielo and Scopus) in October 2021. To increase the number of articles for review, we performed additional searches such as gray literature (Google Scholar). We used Boolean search operators in English, Portuguese, and Spanish: (‘diet*’ OR ‘food*’ OR ‘guild*’) AND (‘fish*’ OR ‘ichthyofauna*’) AND (‘neotropic*’) AND (‘reservoir*’ OR ‘dam*’). We used this keyword combination because it is comprehensive enough concerning trophic ecology in Neotropical dams and has returned a viable number of studies for screening. We entered these keywords and operators in "topic" for Web of Science, "all fields" for Scopus and Scielo, and "advanced search" in Google Scholar. We used no restriction by year or area filters.

We found 1270 studies during the database searches (Supplementary Information 1), and the inclusion and exclusion criteria for studies in our systematic search were carried out based on the PRISMA model (Moher et al. 2009). We removed 14 studies that were duplicated between different databases. We excluded 836 studies because they were out of scope after screening the abstracts (e.g., outside the Neotropics, ecotoxicological studies or experimental studies). We evaluated the full text of 420 articles. We removed a total of 402 studies because they did not have enough information to be included in the meta-analysis, were out-of-scope (see Figure 1). Furthermore, the small number of articles is due to the low number of studies focusing on the variation in fish trophic guild composition between dam areas, highlighting that there is still a lack of studies in many dams and standardization of variables to facilitate future meta-analyses.

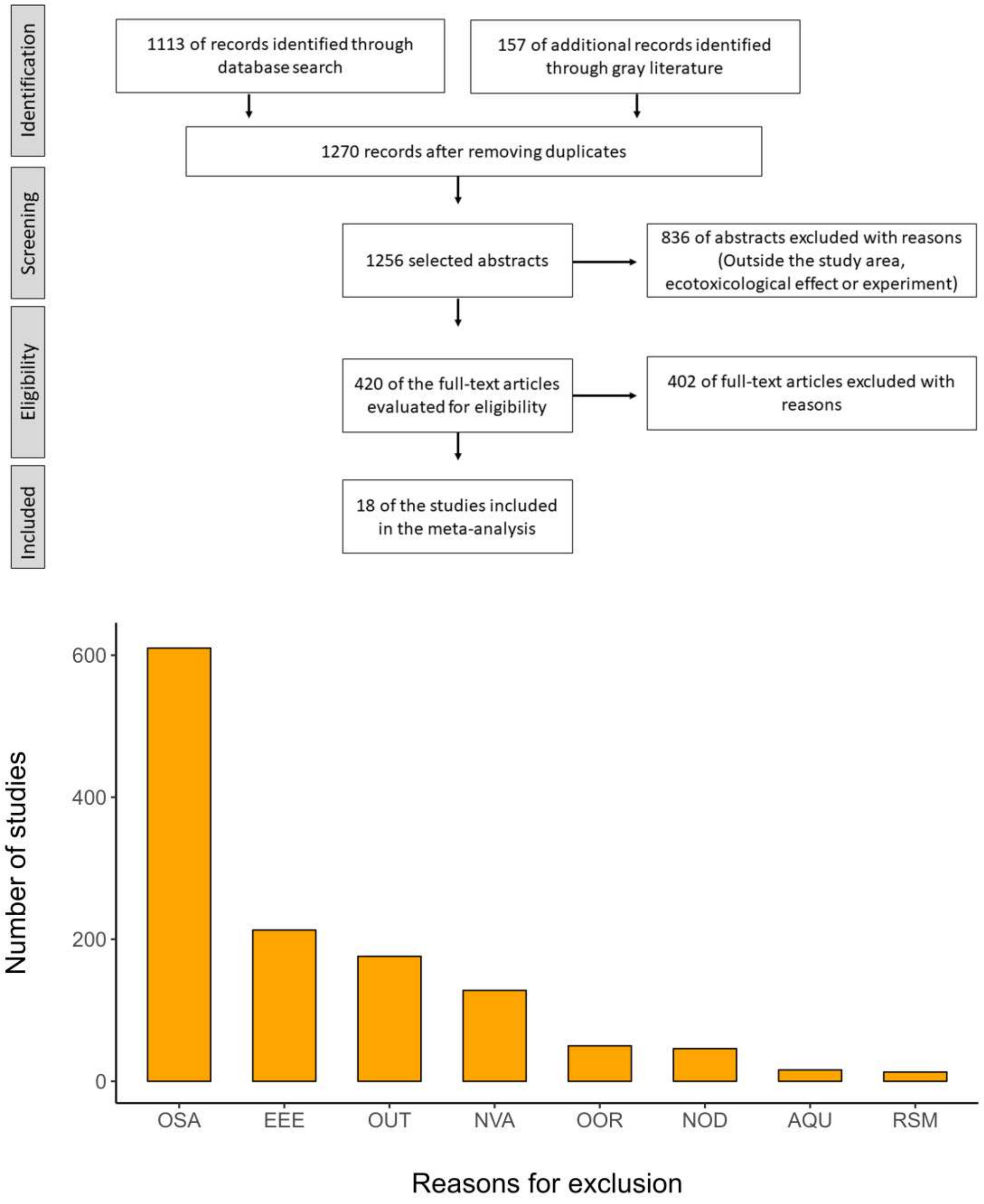

Figure 1 - Inclusion and exclusion criteria for studies in our systematic search (PRISMA; Moher et al. 2009). OSA = Outside the study area (Neotropical region, reservoir, and river); EEE = Ecotoxicological effect or experiment; OUT = larvae, juveniles, parasitism, and migration; NVA = There is no variability in the data; OOR = Other organisms; NOD = Does not bring feeding data; AQU = Aquaculture; DUP = Duplicate studies; RSM = Systematic reviews or meta-analyses.

In addition, we emphasize that comparing the stretches before and after the dam operation would be a better approach. However, information about dams is rare, mainly due to the lack of studies of older dams.

2.2.3 Data extraction and meta-analysis

From the studies selected for the meta-analysis, we extracted the sample size, mean and standard deviation of the composition of trophic guilds for the upstream stretch, the intervention stretches. For the checklist studies in dams, where there were no classifications of fish trophic guilds, we classified the guilds based on Lima et al. (2018) and Dias et al. (2020a). We also obtained information regarding the age, area, and latitude of the dams, which were used as response variables.

2.2.4 Data analysis

2.2.4.1 Effect size

To perform the meta-analysis, we calculated the effect size of the reservoir and downstream were coded as “intervention”, because we seek to answer whether there is a reservoir effect and not which stretches have a greater or lesser effect. As we deal with studies of differences between means, we estimated the log response ratio (ln RR) to measure effect size (Borenstein et al., 2009; Lajeunesse, 2011). The ln RR consists of a natural logarithm of a ratio between the mean *beta* diversity from the intervention (numerator; reservoir and downstream) and control (denominator; upstream) (Borenstein et al., 2009). Effect sizes with positive values indicate an increase in species composition belonging to a specific trophic guild in the intervention stretch of the dam, and effect sizes with negative values indicate an increase in species composition in the upstream stretch.

We calculated a cumulative effect size using a random effects model, which assumes that effect sizes vary across studies (Borenstein et al., 2009; Nakagawa & Santos, 2012). We weighted each effect size by the inverse of its variance and estimated the parameters by maximum likelihood. We performed a sensitivity analysis, in which we reported the T^2, Q, and I^2 statistics as measures of heterogeneity because of the complementary description of heterogeneity these statistics provide (Borenstein et al., 2009). T^2 expresses, in absolute terms, how much the effect size varies from one study to another, Q is a measure of heterogeneity on a standardized scale and I^2 is a proportional measure, representing the proportion of T^2 that can be explained by moderating variables (Borenstein et al., 2009).

Multiple effect sizes were estimated for a single study because most papers contained data from two or more levels (Supplementary Information 1). This causes multiplicity in effect size estimates for the studies included in the meta-analysis (López-López et al., 2018). Using all these effect sizes as independent information would bias our estimates, artificially increasing our sample size and the accuracy of parameter estimation (López-López et al., 2018; Noble et al., 2017), consequently inflating error rates type I (Song et al., 2020). To control the effect of multiplicity, we considered two hierarchical levels describing heterogeneity (T^2) with a variance between studies ($T^2{}_{\text{Between studies}}$) and at study level ($T^2{}_{\text{Studies}}$) in multilevel meta-analysis models (Nakagawa & Santos, 2012) in all analyses.

2.2.4.2 Meta-regression

We tested the influence of age, area, and latitude of Neotropical dams on effect sizes with meta-regressions (Borenstein et al., 2009; Gurevitch et al., 2018; Rosenberg, 2013) as the response variables. We transformed the variables by $\log_{10}$ to increase the linearity of relationships and reduce differences in scale. We also reported a pseudo coefficient of determination (pseudo-R^2), which indicates the proportion of variance explained by the variables (Borenstein et al., 2009).

2.2.4.3 Subgroup analysis

We performed a subgroup analysis (Borenstein et al., 2009) to assess how effect sizes varied between levels of each trophic guild. We also used the multilevel meta-analysis in the subgroup analyses to control for the multiplicity between effect sizes. We removed the intercept from these subgroup models. Thus, the model coefficients were estimates of mean effect sizes for each subgroup level (Stein et al., 2014).

2.2.4.4 Publication bias

We assessed possible publication bias with Orwin's fail-safe number (Orwin 1983). We estimated the number of studies needed to reduce the weighted mean effect size to 25, 50 and 75% of the observed value. We also applied the trim-and-fill method, an iterative procedure that estimates the number of studies possibly omitted due to publication bias and corrects the estimate of the cumulative effect size considering the possible publication bias (Borenstein et al., 2009; Duval & Tweedie, 2000). We used to mean effect sizes and variances per study to avoid multiplicity in the publication bias analysis. We performed all analyses in the R software (R Core Team, 2022), with the 'metafor' (Viechtbauer, 2010) and 'meta' (Balduzzi et al., 2019) packages.

2.3 RESULTS

We calculated 72 effect sizes from 18 studies included in our meta-analysis. Each study reported 1 to 8 effect sizes, ranging from 0.16 to 0.68 (mean ± SD = 0.25 ± 0.72). We observed that the effect sizes were significantly different between the sampled stretches of the dam (ln RR ± CI95 = 0.42 ± 0.26; $z = 3.18$, $p = 0.001$), with 15 effect sizes positive, indicating an increase in trophic guild composition in the intervention reaches, three negative effect sizes, indicating that there was greater composition in the upstream reach, and 54 null effect sizes, indicating similar guild composition between the stretches (Figure 2).

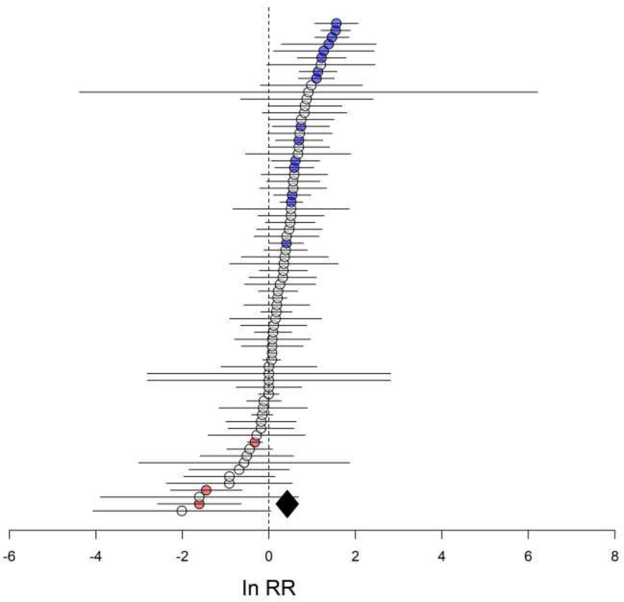

Figure 2 - Variation of the composition of trophic guilds between dam regions (effect sizes, ln RR) of Neotropical dams. Circles and horizontal lines represent effect sizes and their 95% confidence interval (CI_{95}). The closed diamond indicates the weighted mean effect size and estimated CI_{95} based on a multilevel random-effects model. The dashed line indicates an effect equal to zero. Effect sizes with upper bounds of CI95 lower than zero are in red; effect sizes with lower bounds of CI_{95} greater than zero are in blue, and effect sizes with a CI_{95} that includes zero are in white.

As multiple effect sizes were estimated for a single study (T^2 $_{\text{Studies}}$), we performed a heterogeneity analysis that indicated a significant difference in effect sizes ($Q = 335.09$; $df = 72$, $p < 0.001$) within the same study (T^2 $_{\text{Studies}}$) and between different studies (T^2 $_{\text{Between-studies}}$). On the other hand, the variance was low both at the study level ($T^2_{\text{Studies}} = 0.069$) and between studies ($T^2_{\text{Between-studies}} = 0.048$). Because of this, the I^2 measure was calculated, indicating that the variation in effect size can be explained by the response variables (age, area, and latitude) between studies ($I^2_{\text{Between-studies}} = 18.64\%$) and heterogeneity at study level ($I^2_{\text{Studies}} = 65.82\%$).

In general, the meta-regression model indicated that the inclusion of response variables was able to significantly explain the variation in differences in the composition of fish trophic guilds between the intervention and upstream stretches ($Q = 23.48$; $df = 3$; $k = 18$; $p < 0.001$). Regardless of the stretches, we observed that age and area showed significant correlations (z = 3.15; p = 0.001 and z = 4.16; p < 0.001, respectively), indicating that the older the age and the size of the dams, the greater will be the composition of trophic guilds. On the other hand, latitude was not considered an explanatory variable (z = -1.66; p = 0.095) (Table 2; Figure 3). Regarding heterogeneity, the model had no explanatory power for the variance between studies (pseudo-R2 between studies = 0). However, it explained a small amount of heterogeneity at the study level (pseudo-R2 studies = 0.079).

Table 2 - Relationships between age, area, latitude (moderator variables) and the difference in trophic guild diversity between Control (upstream) and Treatment (reservoir and downstream) (In RR; response variable) evaluated by meta-regression. The moderator variables were transformed by log10. SE: Standard error; CI_{95}: 95% Confidence Interval.

Variables	**Estimate**	**SE**	**CI_{95} low**	**CI_{95} up**	**Z**	**p**
Intercept	-1.54	0.61	-2.76	-0.33	-2.50	**0.012**
Age	0.39	0.12	0.14	0.63	3.15	**0.001**
Area	0.20	0.04	0.10	0.29	4.16	**<0.001**
Latitude	-0.12	0.07	-0.26	0.02	-1.66	0.095

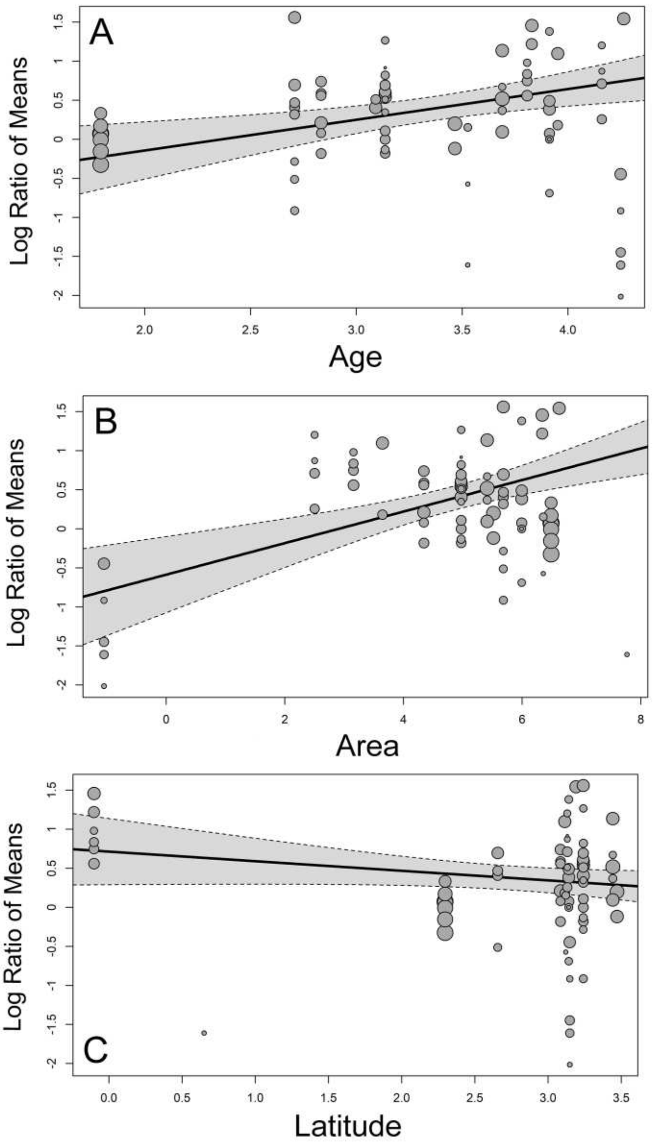

Figure 3 - Relationship between logarithmic response ratio of fish trophic guilds in Neotropical dams in relation to Age (A), Area (B) and Latitude (C) of the dams. Points are scaled by the weight assigned in the regression. The solid line and the gray band indicate fitted values and its 95% Confidence Interval

When evaluating the effect of the dam on trophic guilds individually, the subgroup analysis showed positive and significant values for trophic guilds detritivorous (ln RR ± CI_{95} = 0.18 ± 0.0.82; z = 3.1, p = 0.001), herbivorous (ln RR ± CI_{95} = 0.07 ± 0.89; z = 2.33, p = 0.019), omnivorous (ln RR ± CI_{95} = 0.09 ± 0.70; z = 2.58, p = 0.009), and piscivorous (ln RR ± CI_{95} = 0.23 ± 0.86; z = 3.42, $p < 0.001$), indicating that in the intervention stretch of the dam the effect is greater, that is, there is an increase in species composition belonging to these guilds in these stretches. The trophic guilds algivorous, carnivorous, insectivorous, invertivorous and planktivorous did not present significant values, indicating that these guilds are similar between the intervention and upstream stretches (Figure 4).

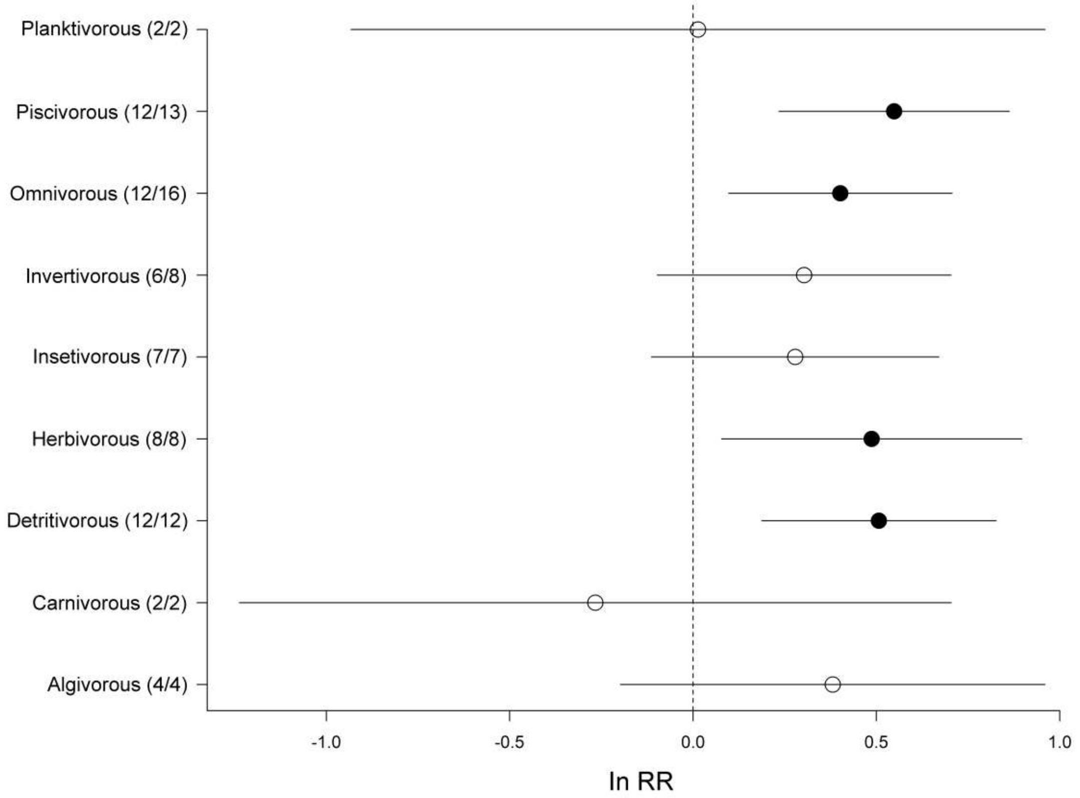

Figure 4 - Variation in the difference of species diversity between dams stretch (ln RR) between the trophic guilds. Circles and horizontal lines represent the weighted mean effect size for each trophic guild and its 95% confidence interval (CI95).

Regarding publication bias, according to Orwin's fail-safe number it would be necessary to 54, 18 and 6 studies with zero effect to reduce the unweighted mean effect size to 25, 50 and 75% of the observed mean effect size. The trim-and-fill method indicated that six studies were potentially omitted due to publication bias. However, the cumulative effect size accounting for potential publication bias is positive. Its CI_{95} includes the observed value and remains statistically significant (ln RR, weighted effect size ± CI_{95} = 0.73 ± 0.64; $p < 0.001$). Therefore, our results are robust to publication bias (Supplementary Information 2). Furthermore, although many articles were excluded, the robustness of the results and confidence in interpretation were ensured.

2.4 DISCUSSION

We systematically showed that the dams lead to changes in the trophic structure of fish assemblages in Neotropics, varying according to the trophic guild considered between the upstream and intervention stretches. Specifically, we found an increase in the species composition of the guilds piscivorous, herbivorous, omnivorous, and detritivorous guild species in the intervention stretch. Although the results have shown a positive effect with the increase of certain trophic guilds, it is essential to note that this positive effect characterizes a form of dam's impact, disrupting the trophic structure of the fish assemblages. We also observed that this effect is higher in older and larger dams but did does not depend on the latitude.

The grouping of fish into trophic guilds is a strong indication of changes in diet occurring along the longitudinal dams stretches (Cassemiro et al., 2005). In addition to changes in the hydrological flow regime due to the retention time of water in reservoirs and water quality, damming also causes changes in the quantity of nutrients in the channel in the downstream stretches (Brandt 2000; Stevaux et al., 2009). Such factors promote changes in the proportion of food resources available in these stretches, leading to many species, over those morphologically adapted to a certain type of resources, to change their diet, and consequently changing their trophic guild, which explains the results obtained in our meta-analysis.

In the upstream stretches we recorded a uniformity of trophic guilds, indicating the low variation of species belonging to specific guilds, which is expected since this stretch presents characteristics, such as flow and greater turbidity, similar to the natural conditions of the river before the dam, promoting a less pronounced effect on food resources, with slight variation in their proportions expected (Dias et al, 2020a; but see Fráguas & Pompeu, 2021). These conditions allow for a more uniform distribution of the numerical proportion of trophic guilds compared to other stretches, as observed in studies carried out in the Salto Caxias reservoir, Rio Iguaçu (Cassemiro et al., 2005; Santos et al., 2017).

Response variables evaluated in this study played a fundamental role in explaining the difference in effect size found in our meta-analysis, such as age and reservoir area. For example, in old and small dams, a greater consumption of allochthonous resources is expected due to the high input of these resources into the environment (Dias et al., 2020b). In the medium to large old dams, the fish are mainly maintained by autochthonous resources (Abelha et al., 2005; Bennemann et al., 2011; Ribeiro et al., 2014; Souto et al., 2016). In addition, we observed that in the literature, only some studies provide information on the diet of fish associated with the time of formation and operation of the dams. Most of the time, the studies only outline perspectives on the effects of dams on the food composition of fish communities (Lima et al., 2018). On the other hand, the latitude of the dams was not related to differences in guild species composition between the stretches. This would be expected within the dams evaluated in this study, which show less variation in latitude.

When we evaluate the guilds individually, we observe an increase in the composition of piscivorous, omnivorous, detritivorous and herbivorous trophic guilds. Of all the guilds evaluated, piscivorous had the largest positive effect size recorded, indicating greater species composition in the intervention stretches compared to upstream. This result can be explained mainly by the introduction of other non-native piscivorous and the intense stocking of fish (Pelicice & Agostinho, 2008) and the lowering of the water level in the dams, as with the reduction, there is a greater concentration of prey fish, being used as resources for piscivorous (Nordhaus, 1989; Ploskey, 1986; Sutela & Vehanen, 2008), Delariva et al. (2013) observed that near 70% of the biomass and 50% of the numerical abundance was composed by piscivorous fish close to the dam area of the Salto Caxias reservoir (Rio Iguaçu, Brazil).

The omnivorous guild also presented greater species composition in the intervention stretches. This increase in omnivorous species composition has been reported as the increase in the proportion of generalist species after impoundment in a recent meta-analysis (Turgeon et al., 2019), and for primary studies conducted in reservoirs (Bem et al., 2021; Fráguas & Pompeu, 2021; Oliveira et al., 2018; Wootton, 2017). The increase of this guild occurs mainly downstream of the dam, favored by their more generalist feeding, consuming different food resources ranging from algae to fish, according to the availability of specific food resources in the river (Gerkin, 1994; Oliveira et al., 2018).

The increase in the composition of detritivorous and herbivorous is mainly associated with the accumulation of sediment and nutrients in older dams (Kautz 1980; Yurk & Ney 1989; Persson et al., 1991; Bachmann et al., 1996; Jeppesen et al., 2000; Vanni et al., 2005), mainly through the replacement of coarse particles by fine particles, leading to many fish species to change their diet by consuming more of these resources. Santos et al. (2020) in their study in the São Francisco River basin with cascade reservoirs, in which the retention of nutrients between reservoirs affects the quality of sediments in downstream reservoirs, which favors changes in the consumption of fine particles. The increase in herbivorous occurs in addition to the accumulation of nutrients of plant origin, due to the increase in aquatic macrophytes in the reservoirs. In addition, smaller dams tend to have more area of riparian vegetation, being an important route for allochthonous plant material. In newly formed reservoirs there tends to have an increase in herbivorous due to the decomposition of flooded vegetation, increasing primary production (Agostinho et al., 2016; Kimmel et al., 1990). Souto et al. (2016), recorded in their study at the Jurumirim dam (Paranapanema River - Brazil) the great importance of allochthonous plants as food resources for fish, promoting the maintenance of the trophic structure in these environments.

2.5 CONCLUSION

Neotropical reservoirs increase relative the composition of piscivorous, omnivorous, herbivorous, and detritivorous. This is a problem for local fish assemblages, causing an imbalance in the food chain. We also showed that dams age and size influence the species composition of trophic guilds of fish assemblages in a dam. Furthermore, we recognize that the effects analyzed only consider the composition dimension of trophic guilds, and that it is still necessary to understand other aspects of the trophic structure, such as numerical abundance. We also highlight the importance of investigating the impacts of small, medium, and large dams on the trophic structure of fish assemblages, seeking to create management and conservation measures for this rich neotropical biodiversity.

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3 CHAPTER 2

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EFFECT OF SPATIAL VARIATION ON THE NETWEORK STRUCTURE OF NEOTROPICAL FISH IN A SMALL HYDROPOWER PLANT

ABSTRACT

Based an increase in the construction of small and medium-sized dams in Brazil, food web analyses are essential tools that can provide insights into the way in which biological communities interact spatially and understand the magnitude of impacts on biological communities. Therefore, we sought to evaluate whether the structure of fish trophic networks is affected by spatial variation between the upstream and downstream stretches of the Nova Jaguariaíva Small Hydroelectric Power Plant (SHP). Fish were collected quarterly between March/2013 and December/2014 at two points in each stretch of the SHP, and had their gastrointestinal tracts removed and analyzed in the laboratory. Network metrics such as connectance, modularity, nesting, specialization, species extinction and robustness were evaluated. The results obtained show differences between the food webs in the upstream and downstream stretches, with the downstream network being more sensitive in practically all metrics evaluated, with greater connectance, more modular and nested, but less specialization. Simulations of the loss of food resources indicated that, although the upstream food network is more robust compared to the downstream food network, it is also more susceptible to fish extinctions, that is, it has a greater capacity to resist and adapt to these extinctions. maintaining its structure and functionality.

Keywords: Ecological networks; Freshwater fish; Ichthyofauna; Neotropical Dam; Trophic Ecology.

INTRODUCTION

Extensive and large rivers receive several tributaries along their course, contributing to the maintenance and support of aquatic ecosystems through the supply of organic and inorganic matter, as well as to the transport of propagules from different biological communities (Bomfim et al., 2017). For decades, the conservation of these ecosystems has been a major challenge for the scientific community, as these environments have been exploited by countless human activities, including as the construction of dams (Agostinho et al., 2007; Winemiller et al., 2016). One of the main effects of dam construction is to alter the natural flow pattern of the river, changing and lotic into lentic stretches (Agostinho et al., 2007; Pelicice et al., 2015; Winemiller et al., 2016). These modifications into the environments cause changes in the composition and availability of food resources, leading to disruptions between trophic levels, directly affecting the organization of aquatic communities (Poff et al., 1997; Dias et al., 2020; Garcia et al., 2023).

Neotropical freshwater fish exhibit a wide variety of foraging behaviors, and many species have high trophic plasticity, enabling them to consume a variety of food resources. This is due to their ability to modify their diet in response to the availability of resources provided by the environment (Abelha et al., 2001; Hahn & Fugi, 2007). In this case, changes of intense magnitude in the environment, such as dams, favor the increase and dominance of generalist species, due to their greater capacity to deal with environmental stress, while strictly specialist species, have their abundance reduced (Hahn & Fugi, 2007; Dias et al., 2020).

Negative impacts resulting from damming vary depending on the specific characteristics of the river environment and the aquatic community, with impacts varying in intensity depending on the distance from the dam (Agostinho, et al., 2007). In the downstream stretch, the effects of damming are more pronounced on the trophic structure of fish compared to the upstream stretch, because the availability of resources is determined by the water retention time in the reservoir, the amount of nutrients and the water flow regime (Ferreira, 1984; Agostinho & Zalewski, 1995; Araujo-Lima et al., 1995; Dias et al., 2020; Fráguas & Pompeu, 2021). Furthermore, these effects can be even more pronounced when the river has cascade or series reservoirs, since these systems tend to amplify the impacts and environmental changes in river systems (Ganassin et al., 2021). This is due to the cumulative or synergistic impacts caused by these projects, which have the capacity to propagate throughout the entire length of the river system (Barbosa et al., 1999; Santos et al., 2018; Ganassin et al., 2021). These systems tend to reduce habitat heterogeneity, inducing alterations and changes in the structure and distribution of fish fauna (Barbosa et al., 1999; Loures and Pompeu, 2018; Santos et al., 2016).

In the current scenario, Small Hydroelectric Power Plants (SHPs), designed for their reduced size reservoirs, with a maximum of 13 km², and operation under a daily regulation regime or "run of water" (Garcia et. al., 2020), are specifically interested in the electricity sector, due to its relative ease of approval, implementation, and operation, compared to large reservoirs (Borges & Meira, 2017). Although SHPs do not present a strong longitudinal gradient like large reservoirs, their impacts are expected on fish assemblages, influencing the variation in the structure of ichthyofauna over time, and this appears to be related to variations in water level of the reservoir (Baumgartner et al., 2018).

Ecological networks are valuable tools that demonstrate how species interact with each other. These interactions can be mutualistic, in the case of fish, joint foraging, or schooling for defense, or as antagonistic, as seen in trophic and host-parasite networks (Dunne et al., 2002; Kaiser -Bunbury et al., 2010; Dallas & Cornelius, 2015).

The resistance of a network to perturbations is determined by its structure, and network analysis metrics are commonly used to study biological interactions (Dormann et al., 2009; Kondoh et al., 2010; Rosa et al., 2022). Connectance is a crucial metric in ecological networks as it represents the proportion of connections made relative to the putative connections between network participants. (Dormann et al., 2009). In addition, nesting indicates specialized organisms that interact with a subset of these organisms from a more generalized participant (Dormann et al., 2009; Ulrich & Almeida-Neto, 2012). In this sense, food networks offer insights into spatial interactions and the magnitude of impacts on biological communities (Dormann et al., 2017; Tylianakis & Morris, 2017; Agostinho et al., 2008). In addition, network analyzes provide simulations of species extinction over time due to human activities, suggesting a possible decline in biodiversity following environmental impacts (Dormann et al., 2009; Peipoch et al., 2015).

Considering the importance of studies on food webs to understand how species are behaving along the stretches of the reservoir, the aim of this study was to evaluate the structure of fish food webs and how it is affected by spatial variation between upstream and downstream stretches of a Small Hydroelectric Plant (SHP). Our hypothesis is that there are differences in food network metrics between the upstream and downstream stretches. We expected that greater connectivity, modularity and nesting, and less specialization, due to the increased impact of the dam on the downstream section, reducing the abundance of food resources, leading species to consume what is available, reducing selectivity and increasing the consumption of resources in a more generalist way (Wootton, 2017). We also expected an increase in the local extinction of fish species downstream, since the impact of the dam in this stretch is relatively greater, influencing the availability of food resources, leading to changes in the trophic structure of the species (Agostinho et al., 2007; Oliveira et al., 2018).

MATERIAL E METHODS

3.1.1 Study area

The Jaguariaíva River extends for 130 km from its headwaters (24°37'55.22" S; 49°35'35.49" W) to its mouth at the Itararé River (Figure 1). The relief of the area of direct influence is characterized by the presence of a deep canyon that is up to 100 meters high. The slope on its edges is quite steep, favoring the occurrence of high walls that reach vertically the reservoir margin (Garcia et al., 2020).

The SHP Nova Jaguariaíva is located on the Jaguariaíva River (24°16’48.93” S and 49°41’41.30” W), Paranapanema River basin, Brazil (Figure 1). It has a drainage area of 753 km² and its reservoir forms a lake measuring approximately 44 hectares (Garcia et al., 2020). The most preserved portion of the marginal vegetation is on the banks of the reservoir with great slope and difficult to access. The most degraded area is the stretch between the powerhouse (S4) and the dam. This area displays typical Cerrado vegetation.

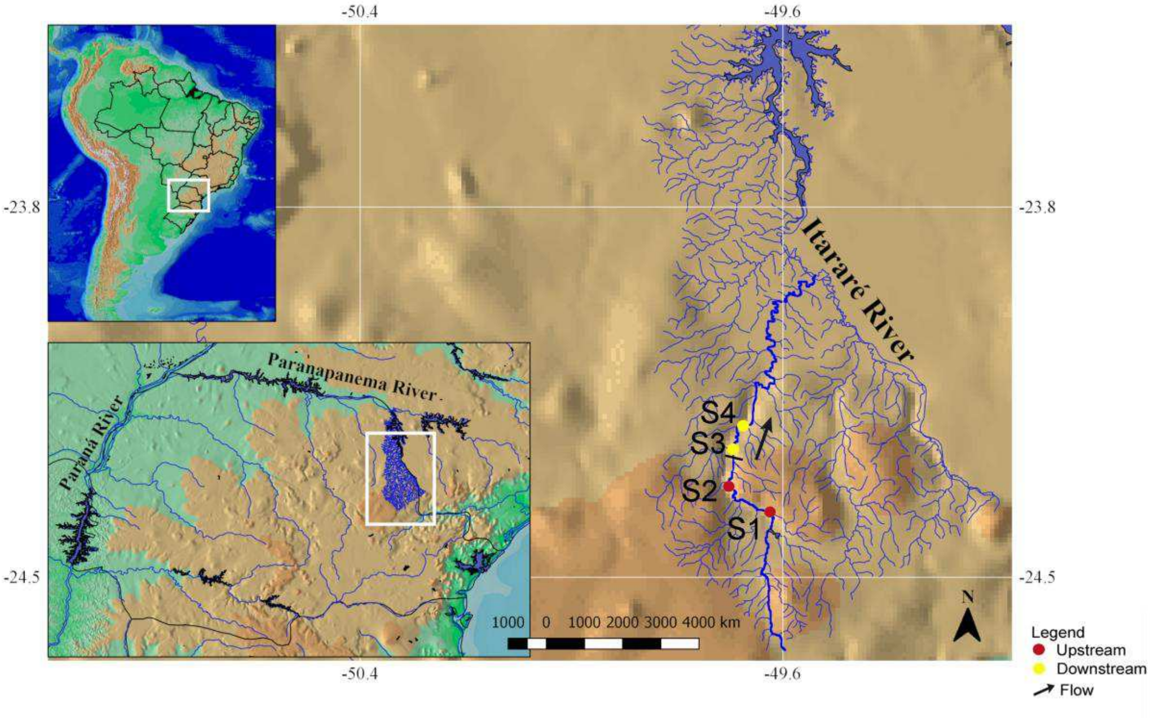

Figure 1 – Location of sampling points on the Jaguariaíva River, Paranapanema River basin, Paraná state, Brazil.

3.1.2 Data collection

Sampling was carried out quarterly, between March 2013 and December 2014, at two points on the upstream and downstream stretches of SHP Nova Jaguariaíva (Figure 1; Table 1). The upstream stretches S1 (24º19'37.33” S and 49º42'7.66” W) and S2 (24º18'7.1” S and 49º41'40.4" W) are located above the SHP reservoir, is a lotic and shallow stretch, with substrate composed of sand, presence of riparian forest at the margins and with a high density of aquatic macrophytes on the banks. The downstream stretches S3 (24º16'49.2"S and 49º41'40.4" W) and S4 (24º15'28.5” S and 49º41'39.03” W) are located below the SHP reservoir, with lotic water flow and rocky substrate, with depths that vary in the different compartments, and may have deeper wells, but the majority are shallow areas with low macrophyte density.

The fish were captured in a standardized way with the aid of gillnets of different mesh sizes (ranging from 2.0 to 18.0 cm between adjacent nodes), which were exposed for 24 hours and checked every 6 hours. To increase the sample effort, 20 castnet throws (with a 2.0 cm mesh between adjacent nodes) and 30 minutes of trawl net (10 m long, 2 m high and mesh size from 4 to 16 cm) and sieve were also employed.

The captured fish were anesthetized by immersion in an aqueous solution of Eugenol, until death was confirmed by checking respiratory movement. Then, the fish were fixed in 10% formalin and preserved in 70% ethanol. In the laboratory, fish were identified to species level following Ota et al. (2018). The ichthyofauna samplings were carried out with authorization (MMA/ICMBio/SISBIO nº 38202-1), and the test specimens were deposited at the Zoology Museum of the Universidade Estadual de Londrina (MZUEL).

3.1.3 Diet analyses

In the laboratory, the fish had their stomachs removed and the stomach contents analyzed under a stereoscopic microscope and identified to the lowest possible taxonomic level, based on Hamada et al. (2014). In the case of *H. albopunctatus* and *H. ancistroides*, the first third of the intestine was analyzed. The volume of stomachs contents was estimated using two methods, pending on its volume. In cases in which volume was greater than 0.1 ml, the estimation was carried out by displacing the water column in graduated cylinders. For cases in which volumes was less than 0.1 ml, it was estimated with the aid of millimeter plates, expressing the volume in mm^3, which was later converted to ml (Hellawell & Abell, 1971).

3.1.4 Data analyses

We characterized the structure of the food network by recording the stomach contents of the fish community and their food resources for the upstream and downstream stretches of SHP Nova Jaguariaíva, based on two adjacency matrices. The first matrix included 25 food items and 8 fish species in the upstream stretch, and the second matrix 30 and 8 for the downstream stretch, respectively. From these matrices, the metrics connectance (C), modularity (M), specialization (H'_2), nesting (WNODF), extinction simulation, and robustness (R) were calculated.

Connectance was calculated using the numbers of connections in relation to the total number of possible interactions in the food network (Dunne et al., 2002). This metric reflects the strength of internal connections and their interactions with external influences (Holling & Gunderson, 2002). Modularity is a measure of the extent to which species are connected in subgroups or semi-independent modules in which the density of interactions is greater within than between subgroups (Dormann & Strauss, 2014). Nesting quantifies whether interactions involving species with few connections represent a subset of interactions involving highly connected species (Bascompte et al., 2003), which was assessed by weighted nesting based on overlap and decreasing fill (Almeida-Neto & Ulrich 2011). Specialization considers all species in the network, presenting values close to 0, indicating low specialization (mainly generalists), and close to 1, indicating high levels of specialization (Blüthgen et al., 2006).

Furthermore, we used null models to test modularity, WNODF and H'_2, calculated after 1,000 randomizations of matrices based on the CE algorithm (Guimarães & Guimarães, 2006), to evaluate whether the observed metrics values differ from the expected under random interactions.

To estimate the robustness, we first calculated all trophic interactions in the upstream and downstream stretches and progressively removed food items until all resources were removed. We performed 1,000 random randomizations of the food web structure to simulate the random loss of food resources in both reaches of the SHP. We assessed the proportion of fish that lost all their interactions by counting how many columns changed to all 0 entries. These columns of consumers with zeros due to the loss of a particular resource are called “secondary extinctions”. A graphical representation of the proportion of consumers lost relative to the proportion of resources removed indicates the extinction curve for a given food network (Dunne et al., 2002) and the area below this curve represents the level of robustness to resource loss (Burgos et al., 2007).

All statistical analyzes and food network graphs were carried out in the R software (R Core Team, 2023), using the “bipartite” packages (Dormann et al., 2008). While volume and occurrence graphs were created with the help of the “ggplot2” package (Wickham, 2016).

3.2 RESULTS

A total of 33 food items were consumed by 386 individuals belonging to 19 fish species. The fish sampled upstream consumed 25 food resources, with emphasis on fish and debris and terrestrial insects, with the Orthoptera resource being exclusive in this stretch. In the downstream stretch, fish consumed 31 food resources, with emphasis on detritus, aquatic insects, and algae, with some exclusive items such as: Empididae (L), Simuliidae, Lepidoptera (A), Plecoptera, Isoptera, Cladocera, Bivalva and Araneae (Tables 1 and 2)

Table 1. Volume of food resources used by fish fauna in the downstream stretch of the Nova Jaguariaíva Small Hydroelectric Plant (SHP), on the Jaguariaíva River, Paranapanema River basin, Paraná State, Brazil. AA = Apareiodon affinis, AI = *Apareiodon ibitiensis*, AL = *Astyanax lacustris*, BI = *Bryconamericus iheringii*, CZ = *Characidium zebra*, CE = *Corydoras ehrhardti,* GI = *Geophagus iporangensis,* HA = *Hypostomus albopunctatus,* HN = *Hypostomus ancistroides,* HH = *Hypostomus hermanni*, HP = *Hypostomus* Paulinus, HS = *Hypostomus* strigaticeps, LA= *Leporinus amblyrhynchus*, PF = *Psalidodon* fasciatus, PP = *Psalidodon paranae*, SN = *Serrapinnus notomelas*. (A) = Aquatic; (L): Larvae; (T): Terrestrial.

	Volume																	**Ocorrence**																
	AA	AI	AL	BI	CZ	CE	GI	HA	HN	HH	HP	HS	LA	PM	PF	PP	SN	AA	AI	AL	BI	CZ	CE	GI	HA	HN	HH	HP	HS	LA	PM	PF	PP	SN
Food resource	**1**	**56**	**1**	**48**	**1**	**2**	**30**	**11**	**27**	**7**	**40**	**11**	**8**	**1**	**9**	**39**	**1**	**1**	**56**	**1**	**48**	**1**	**2**	**30**	**11**	**27**	**7**	**40**	**11**	**8**	**1**	**9**	**39**	**1**
Insects																																		
Diptera pupae	-	0.049	0.019	0.025	0.005	0.001	-	-	-	-	-	-	0.024	-	-	0.071	0.008	-	11	1	10	1	1	10	-	-	-	-	-	2	-	-	9	1
Diptera (L)	-	-	-	0.011	-	-	0.008	0.008	-	-	-	-	0.002	-	-	0.024	-	-	-	-	3	-	-	2	1	-	-	-	-	1	-	-	6	-
Diptera (T)	-	-	-	0.006	-	-	-	-	-	-	-	-	-	-	-	0.051	0.001	-	-	-	3	-	-	4	-	-	-	-	-	-	-	-	13	1
Empididae (L)	-	-	-	0.002	-	-	-	-	-	-	-	-	-	-	-	0.003	0.002	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	1
Chironomidae	-	0.961	0.2	0.068	0.041	0.07	0.044	0.044	0.021	-	0.082	0.003	0.169	0.001	0.002	0.12	0.014	-	35	1	21	1	1	26	8	6	-	18	2	6	1	1	22	1
Ceratopogonidae	-	0.016	0.002	0.007	-	0.006	0.005	0.005	-	-	-	-	-	-	-	0.032	-	-	1	1	4	-	1	2	2	-	-	-	-	-	-	-	4	-
Simuliidae pupae	-	-	-	-	-	-	-	-	-	-	-	-	0.004	0.001	-	0.014	-	-	-	-	4	-	-	-	-	-	-	-	-	1	1	-	4	-
Simuliidae	-	-	-	0.005	-	-	-	-	-	-	-	-	0.001	0.003	-	0.035	-	-	-	-	-	-	-	1	-	-	-	-	-	1	1	-	8	-
Sarcophagidae	-	-	-	-	-	-	-	-	-	-	-	-	0.018	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Lepdoptera (A)	-	-	-	0.004	-	-	-	-	-	-	-	-	-	-	-	0.008	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	-
Trichoptera (L)	-	0.183	0.064	0.088	0.003	0.008	-	-	0.002	-	-	-	0.173	-	0.116	0.234	-	-	12	1	12	1	1	16	-	1	-	-	-	7	-	3	17	-
Coleoptera (L)	-	-	0.1	0.035	-	0.001	0.045	0.045	0.006	0.001	-	-	0.261	0.001	0.294	0.066	0.001	-	-	1	4	-	1	7	3	5	1	-	-	8	1	6	5	1
Coleoptera (T)	-	-	-	-	-	-	0.002	0.002	-	-	-	-	0.059	-	0.002	0.019	-	-	-	-	-	-	-	-	1	-	-	-	-	3	-	1	5	-
Hymenoptera	-	-	-	0.001	0.001	0.001	-	-	-	-	-	-	0.03	-	0.121	0.04	-	-	-	-	1	1	1	1	-	-	-	-	-	1	-	3	7	-
Hemiptera	-	-	-	-	-	-	-	-	-	-	-	-	0.009	-	0.027	0.032	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	2	5	-
Ephmeroptera (L)	-	0.02	0.059	0.127	-	0.016	-	-	-	-	-	-	0.042	-	-	0.285	0.001	-	4	1	10	-	1	6	-	-	-	-	-	2	-	-	23	1
Odonata (L)	-	-	-	0.031	-	-	-	-	-	-	-	-	0.005	-	0.048	-	-	-	-	-	2	-	-	-	-	-	-	-	-	1	-	1	-	-
Plecoptera	-	0.003	-	0.02	-	-	-	-	-	-	-	-	-	-	-	0.062	-	-	1	-	2	-	-	1	-	-	-	-	-	-	-	-	5	-

Isoptera	-	-	-	-	-	-	-	-	-	-	-		-	-	-	0.004	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-
Other invertrebates																																		
Amphipoda	-	-	-	0.002	-	-	-	-	-	-	-	-	-	-	0.021	0.008	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	1	2	-
Cladocera	-	0.001	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Bivalve	-	-	-	-	-	-	-	-	-	-	-	-	-	0.394	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Araneae	-	-	-	-	-	-	-	-	-	-	0.001	-	-	-	-	0.004	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	1	-
Acarina	-	-	0.001	-	-	-	-	-	0.001	-	-	-	0.013	-	-	0.001	-	-	-	1	-	-	-	17	-	1	-	-	-	3	-	-	1	-
Oligochaeta	-	0.004	-	0.003	-	-	-	-	-	-	0.002		-	-	-	0.006	-	-	1	-	1	-	-	1	-	-	-	1	-	-	-	-	1	-
Fish																																		
Fish scale	-	0.025	-	0.003	-	-	-	-	-	-	-	-	-	-	-	0.007	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-	2	-
Fish	-	0.105	-	-	-	-	-	-	-	-	-	-	-	-	0.108	-	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-	1	-	-
Algae																		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Algae	-	0.486	-	1.05	-	-	-	0.35	0.27	0.014	0.024	-	0.059	-	0.355	0.579	-	-	9	-	39	-	-	-	6	4	1	4	-	2	-	2	17	-
Plantae																																		
Fruits	-	-	-	0.004	-	-	0.024	-	-	-	-	-	-	-	-	0.271	-	-	-	-	1	-	-	3	-	-	-	-	-	-	-	-	5	-
Higher plants	0.005	0.747	-	0.107	-	-	0.008	-	0.511	0.013	0.02	-	0.072	-	0.562	0.401	-	1	13	-	17	-	-	3	-	11	2	1	-	4	-	6	14	-
Detritus																																		
Detritus	0.095	1.418	0.003	0.342	-	-	0.131	3.187	4.394	0.723	6.782	1.816	0.084	-	0.01	0.065	-	1	43	1	23	-	-	6	11	23	7	40	11	1	-	1	4	-

Table 2. Volume of food resources used by fish fauna in the upstream stretch of the Nova Jaguariaíva Small Hydroelectric Plant (SHP), on the Jaguariaíva River, Paranapanema River basin, Paraná State, Brazil. AI = *Apareiodon ibitiensis*, AL = *Astyanax lacustris*, BI = *Bryconamericus iheringii*, CE = *Corydoras ehrhardti,* GI = *Geophagus iporangensis,* HM = *Hoplias* malabaricus, HA = *Hypostomus albopunctatus,* HN = *Hypostomus ancistroides,* PP = *Psalidodon paranae*, RQ = *Rhamdia quelen,* (A) = Aquatic; (L): Larvae; (T): Terrestrial. Numbers in bold below the species acronyms correspond to the number of stomachs analyzed.

	Volume										**Ocorrence**									
	AI	AL	BI	CE	GI	HM	HA	HN	PP	RQ	AI	AL	BI	CE	GI	HM	HA	HN	PP	RQ
Food resource	**10**	**1**	**34**	**14**	**14**	**6**	**2**	**6**	**3**	**2**	**10**	**1**	**34**	**14**	**14**	**6**	**2**	**6**	**3**	**2**
Insects																				
Diptera pupae	-	-	0.011	-	0.034	-	-	-	-	-	-	-	6	-	1	-	-	-	-	-
Diptera (L)	-	-	0.011	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-
Diptera (T)	-	-	0.001	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
Chironomidae	0.014	-	0.079	0.03	0.077	0.001	0.002	0.008	-	-	5	-	15	10	6	1	2	3	-	-
Ceratopogonidae	-	-	-	0.006	-	-	0.001	-	-	-	-	-	-	3	-	-	1	-	-	-
Simuliidae pupae	-	-	-	0.002	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
Sarcophagidae	-	-	0.004	-	0.005	-	-	-	-	-	-	-	1	-	1	-	-	-	-	-
Trichoptera (L)	0.002	-	0.002	0.005	0.125	-	0.004	-	-	-	1	-	1	2	6	-	1	-	-	-
Coleoptera (L)	-	-	0.002	-	0.002	-	0.003	-	-	0.05	-	-	1	-	1	-	1	-	-	1
Coleoptera (T)	-	-	0.002	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
Hymenoptera	-	-	0.001	-	-	-	-	-	0.04	0.9	-	-	1	-	-	-	-	-	1	1
Hemiptera	-	-	-	-	-	2	-	-	0.015	-	-	-	-	-	-	1	-	-	1	-
Ephmeroptera (A)	-	-	0.014	0.06	0.073	-	-	-	-	-	-	-	3	10	6	-	-	-	-	-
Odonata (A)	-	-	-	-	0.017	-	-	-	-	0.8	-	-	-	-	2	-	-	-	-	1
Orthoptera (T)	-	-	-	-	-	0.048	-	-	-	-	-	-	-	-	-	1	-	-	-	-
Plecoptera	-	-	-	-	0.004	-	0.001	0.002	-	-	-	-	-	-	1	-	1	1	-	-
Other invertrebates																				

Amphipoda	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	1
Acarina	-	-	-	0.002	0.001	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-
Oligoqueta	-	-	-	0.002	-	-	0.03	-	-	-	-	-	-	1	-	-	1	-	-	-
Fish																				
Fish scale	-	-	0.004	-	-	-	-	-	-	1.24	-	-	1	-	-	-	-	-	-	1
Fish	-	-	-	-	-	26.951	-	-	0.026	0.175	-	-	-	-	-	5	-	-	1	1
Algae																				
Algae	0.23	-	0.442	-	0.006	-	0.11	0.055	0.052	-	3	-	11	-	1	-	2	2	1	-
Plantae																				
Fruits	-	0.375	-	0.002	-	-	-	-	-	-	-	1	-	1	-	-	-	-	-	-
Higher plants	0.257	-	0.036	0.003	0.091	-	0.105	0.21	0.018	-	5	-	6	1	5	-	2	5	1	-
Detritus																				
Detritus	0.261	-	2.081	0.038	0.279	-	0.17	0.958	0.02	-	7	-	32	4	10	-	2	6	1	-

Considering the volume of food resources consumed by fish, we observed that in the upstream section fish (73.38%), debris (9.84%) and terrestrial insects (7.79%) were the most consumed. Downstream, there were debris (60.29%), aquatic insects (16.84%) and algae (10.09%) (Figure 2A). On the other hand, the most used food resources upstream were detritus (33.33%), aquatic insects (28.49%) and plants (14.52%), while downstream were aquatic insects (31.85%), debris (28.03%) and algae (13.38%) (Figure 2A).

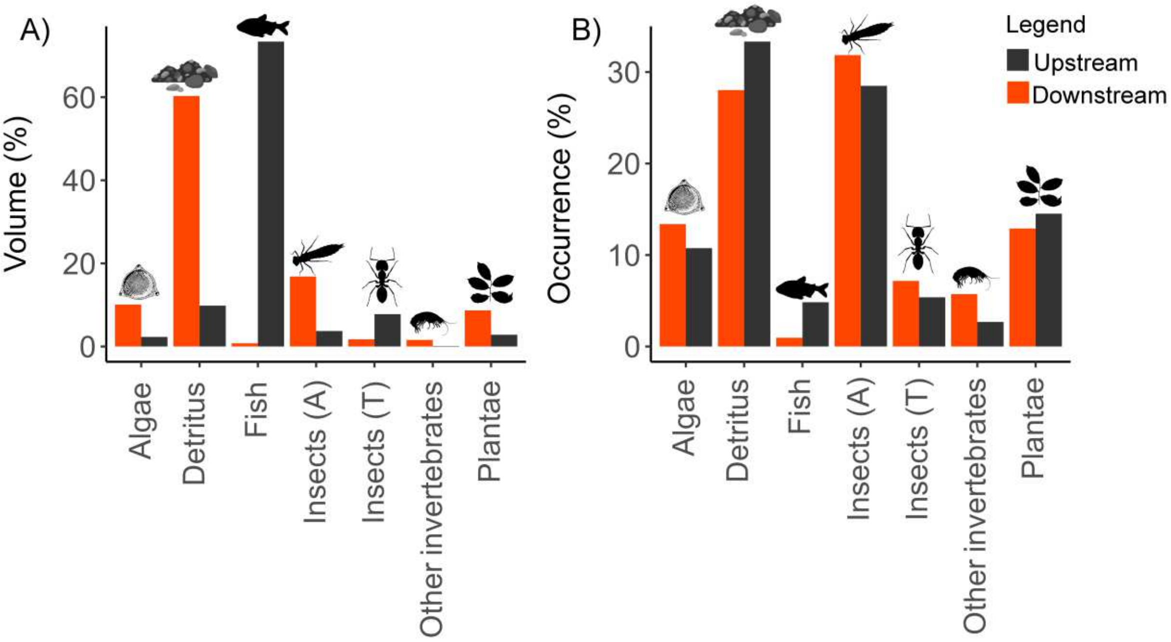

Figure 2. Percentage of A) volume (%) and B) frequency of occurrence (%) of trophic categories in the Downstream and Upstream sections of SHP Nova Jaguariaíva, Paranapanema River basin, Paraná State, Brazil.

When analyzing the food webs of the downstream and upstream stretches, we observed that the connectivity of both networks was low (Downstream: C = 0.30, 163 interactions; C = 0.28; 72 interactions). When comparing them, it is observed that the connectivity of the downstream network was slightly higher, which indicates a more interconnected structure, where species have a greater variety of feeding relationships with other species in the community (Figure 3A and B).

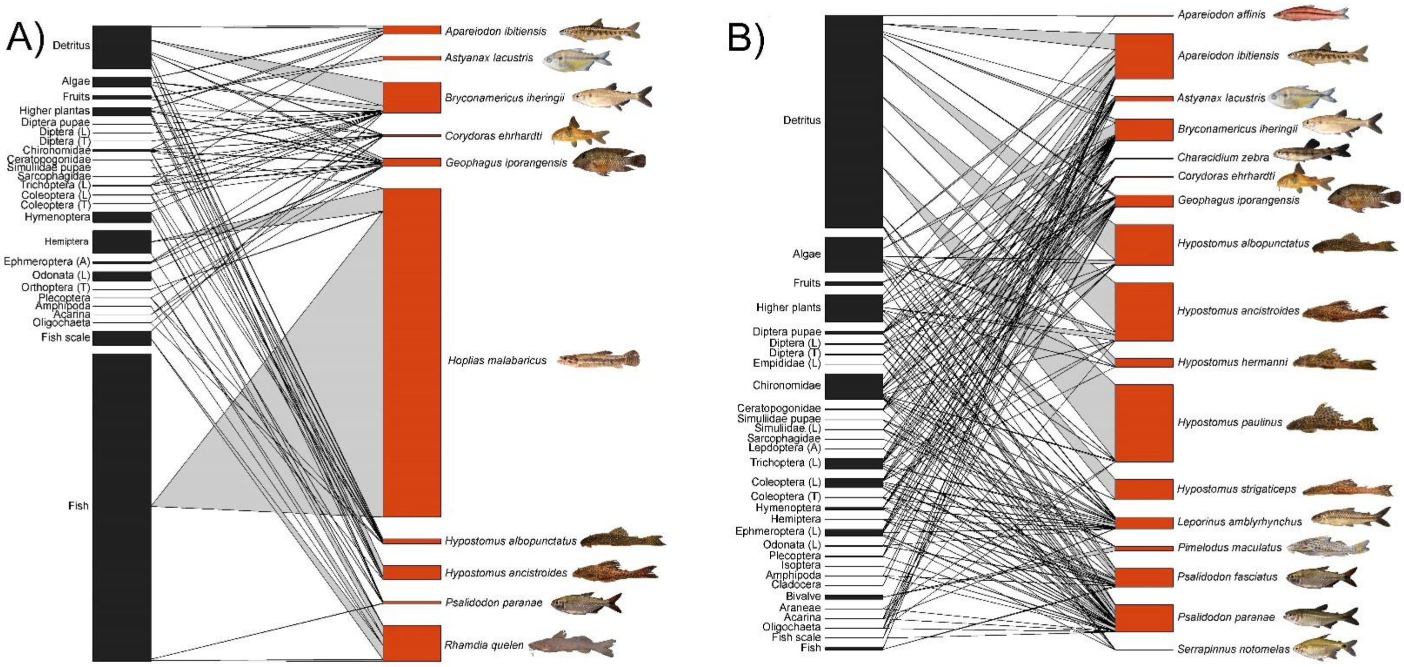

Figure 3. Trophic network showing the occurrence of food resources in the fish diet in sections A) upstream and B) downstream of SHP Nova Jaguariaíva, located on the Jaguariaíva river, Paranapanema River basin, Paraná State, Brazil. The line thickness is scaled to the average density of each food resource. The heights of the colored bars are scaled according to the total food resource density (black bar) in relation to the fish diet (orange bar).

The degree of connection between species showed that of the 19 species, 15 had the greatest connection in the downstream stretch, with *Apareiodon affinis* (Steindachner 1879)*, Hypostomus hermanni* (Ihering 1905)*, Hypostomus Paulinus* (Ihering 1905)*, Hypostomus strigaticeps* (Regan 1908)*, Leporinus amblyrhynchus* Garavello & Britski 1987*, Pimelodus maculatus* Lacépède 1803*, Psalidodon fasciatus* (Cuvier 1819) and *Serrapinnus notomelas* (Eigenmann 1915) were exclusive to this stretch. While upstream, only four species presented a higher degree, with *Hoplias malabaricus* (Bloch 1794) and *Rhamdia quelen* (Quoy & Gaimard 1824) being exclusive in this stretch. (Figure 2; Table 3).

Table 3. Degree of connectivity at fish in the interaction network between the upstream and downstream stretch of SHP Nova Jaguariaíva.

Species	Upstream	Downstream
Apareiodon affinis	**0.100**	**-**
Apareiodon ibitiensis	**4.018**	0.764

Astyanax lacustris	**0.448**	0.375
Bryconamericus iheringii	1.941	**2.690**
Characidium zebra	**0.500**	-
Corydoras ehrhardti	0.103	**0.150**
Geophagus iporangensis	**1.051**	0.714
Hoplias malabaricus	-	**29.00**
Hypostomus albopunctatus	**3.641**	0.426
Hypostomus ancistroides	**5.205**	1.233
Hypostomus hermanni	**0.751**	-
Hypostomus paulinus	**6.911**	-
Hypostomus strigaticeps	**1.819**	-
Leporinus amblyrhynchus	**1.025**	-
Pimelodus maculatus	**0.400**	-
Psalidodon fasciatus	**1.666**	-
Psalidodon paranae	**2.442**	0.171
Rhamdia quelen	-	**3.175**
Serrapinnus notomelas	**0.027**	**-**

When comparing the modularity, nesting, and specialization metrics with the null model (observed > expected), we found that modularity showed significance only in the upstream stretch with random interactions ($p < 0.05$). In contrast, both the upstream and downstream networks were found to be significantly more nested and specialized compared to the null model ($p < 0.05$).

The modularity of the downstream network was lower (Z score = 3.877, M = 0.38) compared to the upstream network (Z score = -0.61, M = 0.39). This result suggests a less defined structure of clusters of nodes in the downstream network, that is, nodes tend to be less organized in cohesive communities when compared to the upstream network. In relation to nesting, it was observed that the downstream network presented greater nesting (WNODF = 64.47) compared to the upstream network (WNODF = 58.68), characterizing the downstream network as a more interconnected and integrated structure between its components. Furthermore, in terms of specialization, the results showed that the downstream network was less specialized (H'2 = 0.46), while the upstream network was more specialized (H'2 = 0.81), indicating that the downstream network presents a more uniform distribution of interactions between nodes, with less evidence of distinct groups or highly specialized niches.

Secondary fish extinctions resulting from the removal of food resources using the “random” algorithm varied across both food webs. For the downstream food web, a fish extinction rate of 5.05 was observed, while robustness was calculated at 0.49. On the other hand, in the upstream food web, the fish extinction rate was slightly higher, reaching 6.14, while robustness was measured at 0.54 (Figure 4). These results suggest that, although the upstream food network is more robust compared to the downstream food network, it is also more susceptible to fish extinctions, that is, it has a greater capacity to resist and adapt to these extinctions. maintaining its structure and functionality.

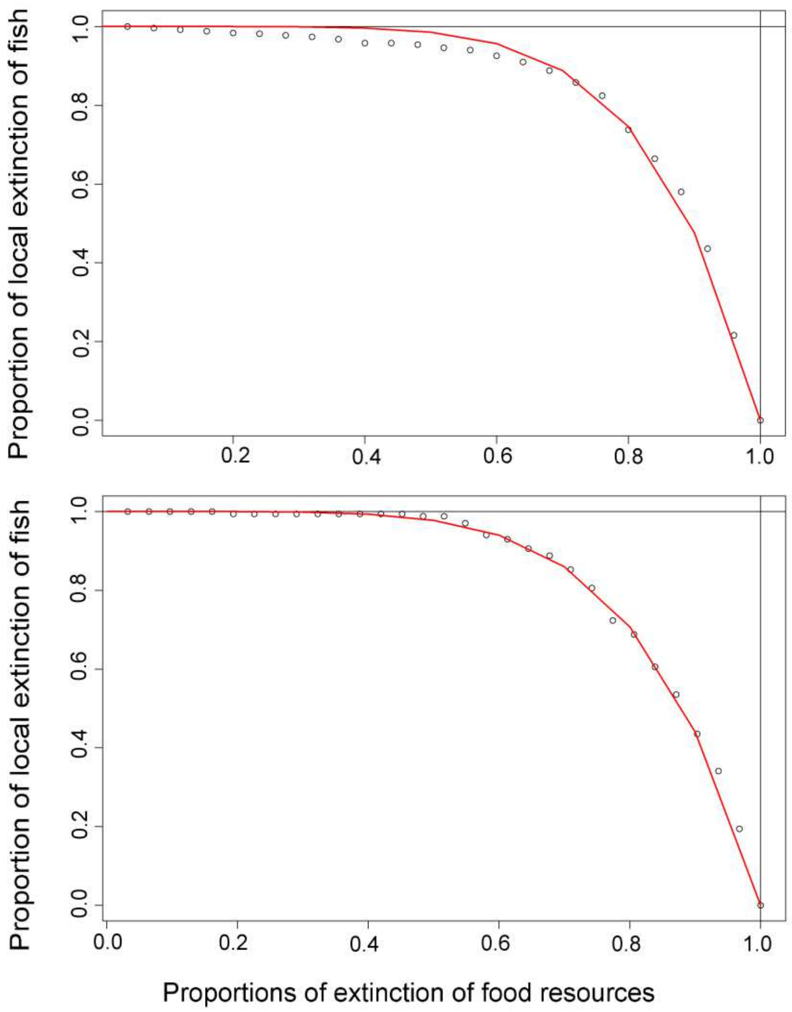

Figure 4. Local extinction patterns for trophic interaction networks, following the random removal of food resources from the least connected or consumed to the most connected. A) Killed: lower (upstream) and B) Killed: lower (downstream). circles = food resources; red line = fish assembly

3.3 DISCUSSION

In general, our results showed that the food network metrics evaluated in both stretches indicated that the downstream network was the most connected, modular, nested, and least specialized, which results in more generalist behaviors, consuming different resources depending on their availability in the environment. The metrics of the food networks evaluated in this study showed that the first hypothesis, indicating that there are significant differences between the networks. The greater connectivity downstream indicates a more generalist diet of fish in this stretch, with a greater number of interactions, or links, between fish and their food resources, as observed in the study by Fráguas & Pompeu (2021) at the Irapé Hydroelectric Plant. This result may indicate a negative consequence of the environmental and biological changes promoted by dam, through changes in the river flow regime, altering the quality and reducing the abundance of food resources mainly macroinvertebrates (Abujanra et al., 2009, Santos et al., 2016; Lobera et al., 2017). While in the upstream network, lower connectivity is associated with greater richness and abundance of food resources, allowing fish to specialize in a certain type of resource, considering that the effects of dams in this stretch are less pronounced than in the downstream (Dias et al, 2020; Fráguas & Pompeu, 2021).

Considering that the availability of resources in the environment is one of the main factors that shape biological communities (Simões et al., 2015), our results show that insects and detritus were the most important resources in trophic networks, corresponding more 67% of its occurrence in the fish diet. The high occurrence of aquatic insects, mainly in the diet of *Astyanax lacustris, Corydoras ehrhardti*, *Geophagus iporangensis*, *Leporinus amblyrhynchus* and *Serrapinnus notomelas*, is associated with the presence of high densities of aquatic macrophytes present in the sampled stretches (personal observation), which provide shelter and protection for invertebrates (Carniato et al., 2014; Cardozo et al., 2021). Regarding detritus, in addition to *A. ibitiensi*, which was classified here in this study as omnivorous, but which consumed a high volume of detritus (> 35%), other strictly detritivorous species *Apareiodon* affinis, *Bryconamericus iheringii*, *Hypostomus albopunctatus*, *Hypostomus ancistroides*, *Hypostomus hermanni*, *Hypostomus Paulinus* and *Hypostomus strigaticeps* were responsible for the large occurrence of this resource in food networks.

At the community level, different factors can structure nested and non-modular patterns in food networks, such as spatiotemporal variation or abiotic variables (Granado-Lorencio et al., 2012). The greater nesting and modularity of the networks downstream are mainly related to the exclusive and rare food resources consumed by species in this stretch, such as Empididae (L), Simuliidae, Lepidoptera (A), Plecoptera, Isoptera, Cladocera, Bivalva and Araneae, while only Orthoptera was exclusive in the diet of fish analyzed upstream. This finding also reflected the specialization of the networks found in this study, as the lower specialization of the network downstream reinforces the idea of an increase in generalist species combined with the influence of the dam on food resources (Turgeon et al., 2019).

Robustness has been widely used to evaluate ecological networks (Dunne et al., 2002; Kaiser-Bunbury et al., 2010; Dallas & Cornelius, 2015), as it helps identify the consequences of species loss caused by activities such as presence of the dam. Thus, the results observed in this study indicated the opposite of our second hypothesis. Despite a higher rate of fish extinction in the upstream network, it is more resilient and capable of recovering or maintaining its structure in the face of these extinctions. This occurs due to the presence of replacement species that can occupy niches and ecological functions left by extinct species, and due to greater functional redundancy within the trophic network, as observed by greater trophic specialization in this stretch (Staniczenko et al., 2010; Monteiro et al., 2018).

3.4 CONCLUSION

Studies with ecological networks of fish communities are an effective tool for understanding how communities respond to changes that occur in the environment (Fortuna et al., 2010; Rosa et al., 2022). In a scenario of increasing construction of small and medium-sized dams in Brazil, our results, based on null models and trophic networks, showed the great importance of studies with networks to investigate trophic ecology, highlighting the need to deepen the effects caused by dams in the structure of aquatic communities. In this study, the network in the downstream stretch was more sensitive in virtually all metrics evaluated, indicating the greatest effect on the fish's food resources, inducing changes in their diets. The findings, obtained by investigating the behaviors of fish species in response to environmental changes, will inform the development and implementation of conservation programs for freshwater biological communities.

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4 CHAPTER 3

The manuscript was prepared according to *Ecology of Freshwater Fish* journal standards, in compliance with the Postgraduate Program in Biological Sciences.

DOES SIZE MATTER? INFLUENCE OF BODY SIZE ON THE PREDATOR-PREY RELATIONSHIP IN NEOTROPICAL FISH

ABSTRACT

The development of diverse capture mechanisms during foraging allows predators to select their preys and succeed in their capture, with the least energy expenditure possible. In this context, we seek to understand how prey selection mechanisms exhibited by freshwater fish piscivores relate to their foraging mode. The study was carried out in the floodplain of the Upper Paraná River, where fish were captured from March 2006 to June 2013. The fish were identified, measured, and their stomachs were removed, and the stomach contents analyzed. Quantile regressions were used to evaluate possible effects and relationships between the sizes of piscivores and their prey. A significant positive effect on the predator-prey size relationship was observed, indicating an increased size of consumed prey with increased size of piscivore, mainly for *Acestrorhynchus lacustris, Hoplerythrinus unitaeniatus, Hoplias intermedius, Hoplias mbigua, Hoplias* sp.2*, Pseudoplatystoma corruscans, Rhaphiodon vulpinus* and *Salminus brasiliensis.* Ambush predators were more likely to consume slow-moderate and fast prey, while pursue predators only consume fast prey. Several mechanisms can influence a piscivore's foraging behavior and body size is an important factor for both the piscivore and its prey. From the prey's point of view, the way they swim, and the complexity of the habitat are important characteristics to ensure their survival. For piscivores, the foraging mode will influence the type of prey consumed, depending on the prey's swimming mode.

Keywords: Floodplain, Hunting strategy, Piscivory, Predator-prey size, Upper Paraná River

4.1 INTRODUCTION

The relationships between piscivorous fish and their prey are essential for the maintenance of ecosystem structure (Hawlena & Schmitz, 2010) as they are a crucial component of the trophic chain and can drive changes in energy levels (Carpenter et al., 2001; Schmitz, 2006; Stief & Holker, 2006; Frank, 2008; Schmitz et al., 2010). Modern conceptions infer that predator-prey relationships act on the adaptive capacity during foraging. The success of the predator is determined by its efficiency in detecting and capturing prey, while the success of the prey is determined by its anti-predatory responses, leading to higher survival rates (Kotler, 2016; Hempel et al., 2016; Brose et al., 2019).

In this context, the development of various mechanisms for capturing prey by predators is of great importance. This allows predators to capture their prey selectively, using strategies such as the development of "search images" (Ware, 1971; Kono et al., 1998). These images allow the predator to recognize specific types of prey, often the most abundant, while ignoring those that are less common or require greater effort to capture (Ishii & Shimada, 2009; Gerking, 2014). Thus, such mechanisms not only affect direct interactions between predators and prey, but also influence the dynamics and stability of ecosystems.

Prey selectivity by piscivorous fish is strongly related to foraging mode and piscivore morphotype (Walker et al., 2005). In neotropical freshwater environments, it was observed that some prey adjusts their behavior according to the identity of the predator, while others maintain a more stable and predictable behavior, suggesting that the relationships between predators and prey are deeply shaped by the species characteristics and environmental context (Lopes et al., 2021). Is also must be noticed that predator-prey interaction may be linked to the ability of predators to adapt to the peculiarities of their prey, while part of this dynamic may be attributed to chance encounters between predator and prey (Moore & Biewener, 2015; Schmitz, 2017; Lopes et al., 2021).

Ambush predators typically inhabit densely structured environments, allowing them to go unnoticed by their potential prey (Moore & Biewener, 2015). These predators are characterized by limited movements and a high acceleration capacity, thus relying on the active movement of their prey (Greene, 1986; Hobson, 1979; Schmitz, 2017). Pursue predators employ an active search strategy and are characterized by fast movements presenting a high swimming capacity, as they rely on speed to locate and capture their prey (Greene, 1986; Hobson, 1979; Moore & Biewener, 2015; Schmitz, 2017).

For prey, the ability to detect and evade predators is essential to survival, which enables the development of anti-predatory responses over time (Abrahams et al., 2009; Lazzaro et al., 2009; Sih et al., 2010). For example, *Moenkhausia sanctaefilomenae* Eigenmann 1908, is a small characid, exhibits social organization and scaping behavior when detecting physical and chemical stimuli from predators, moving away, and promoting an increase in school cohesion (Felipe et al., 2009). *Apareiodon affinis* (Steindachner 1879) and *Piabarchus stramineus* (Eigenmann 1908) exhibit vigilant behavior and aimless movements (zigzag and turning) upon visual detection of a predator (Kovalenko et al., 2010). This ability of prey to recognize physico-chemical signals from predators ensures greater chances of survival even under predatory threats (Werner & Peacor, 2003; Preisser et al., 2005; Carlson & Langkilde, 2014).

For piscivorous fish, variations in morphology can result in changes in its locomotion and prey capture performance (Webb, 1982), affecting factors such as speed, acceleration, stability, and maneuverability. Meanwhile, the prey morphological diversity allows greater efficiency in the behavior of evasion and escape when detecting the presence of predators (Walker et al., 2005; Higham et al., 2007). These morphological and behavioral adaptations of both prey and predator reflect a complex and dynamic interaction that shapes foraging and survival strategies in aquatic environments.

Body size, for both prey and predator, directly influence foraging success. High swimming ability, greater mouth gape size, and enhanced visual and olfactory acuity increase the chances of a piscivore successfully capture its prey (Christensen, 1996; Graeb et al., 2006). On the other hand, larger prey benefit from greater escape performances, such as increased swimming speed (Rodgers et al., 2014; Cuthbert et al., 2019). Therefore, body size proportions contribute to the predator-prey dynamics, while also determining the population structure and stability of the community (Otto et al., 2007; Sentis et al., 2017).

The theory of optimal foraging, proposed by MacArthur & Pianka (1966), provides a conceptual framework for understanding how these ecological interactions are influenced by maximizing energy gain and how organisms adapt their foraging strategies in response to environmental conditions. On the other hand, the Eltonian shortfall theory (Hortal et al., 2015) highlights the gaps in understanding the interactions between species in natural ecosystems, attributed to the complexity of the systems, environmental variability, and the difficulty in observing and quantifying these interactions in real time. In this context, we seek to understand how prey selection mechanisms exhibited by freshwater piscivorous fish relate to their foraging mode. Two hypotheses are proposed: (i) there is a positive correlation between the body size of the piscivore and the body size of the consumed prey, that is, larger predators capture larger prey, additionally, (ii) predator strategies are directly correlated with its prey's swimming mode, thus the swimming speed of prey (fast or slow) does not interfere with an ambush piscivore selectivity, while pursuer predators, as they are active swimmers, capture prey with greater swimming speed.

4.2 MATERIAL AND METHODS

The study was conducted in the Upper Paraná River floodplain (22–22°50’S and 53°15’–53°40’W) as part of the Long-term Ecological Research Program (Brazil LTER-PIAP site 6) (Fig. 1). Sampling was carried out quarterly, from March 2006 to June 2013, in nine locations, including connected and isolated lagoons, channels, and the main river channel in three distinct rivers in the region (Baia, Ivinhema, and Paraná rivers). The fish were sampled using gillnets of different mesh sizes, which were exposed for 24 h, and checked every 8 h.

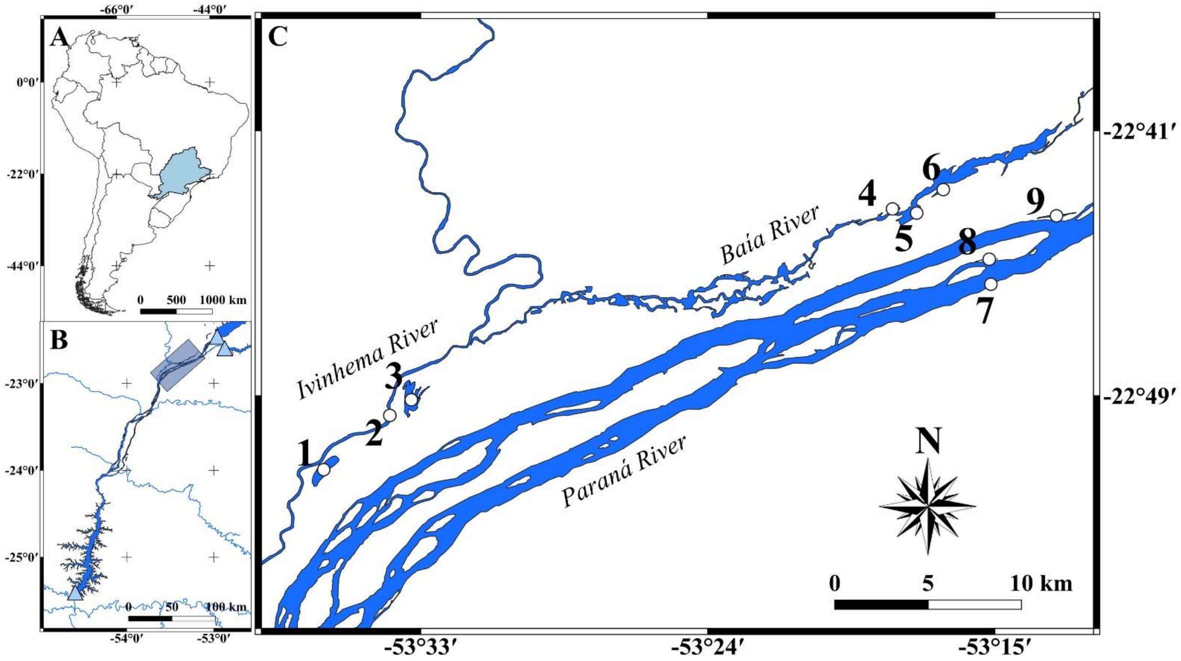

Figure 1 - Flood plain, Upper Paraná basin, indicating the location of the sampling points. **Source:** Cardozo et al., 2023.

The fish were identified, measured (Standard Length, cm), and their stomachs were removed and preserved in formaldehyde 10%. Only adult predatory fish were used for the analyses, except for the species *Pseudoplatystoma corruscans* (Spix & Agassiz 1829) and *Salminus brasiliensis*, whose analyzes included a few juvenile individuals that exclusively consumed fish. The fish were characterized as adults considering the length of the first gonadal maturation ($L_{50\%}$ - which corresponds to the standard length at which 50% of the individuals reproduced for the first time) according to Suzuki et al. (2004). The stomach contents of all predators were analyzed, prey were identified, according to Ota et al. (2018), and measured (Standard Length - cm). Data on the size variation of predators and prey fish are in Supplementary Information - Tables S1 and S2.

Literature data were used to classify predators according to their strategy as ambush and pursuer predators, while prey was classified according to their mobility or swimming capacity, into fast, fast-moderate, slow-moderate or slow species (Supplementary Information – Table S1 and S2). When no published information on the swimming mode was available, personal communication with experts in the field, developing studies and research in the area of systematics and morphology of fish in this region, and have in-depth traditional knowledge about these species.

Data analysis

To test hypothesis (i) that there is a positive correlation between the size of the predator and the size of the prey consumed, a quantile regression analysis was conducted. This method estimates different quantiles, based on the median, of a population represented by quantiles (τ) 0.05, 0.25, 0.50, 0.75, and 0.95 (Koenker, 2015). One of the advantages of such approach is in its improved robustness as it demonstrates the variation in the distribution of variables between quantiles. Furthermore, this analysis allows estimating any desired quantile, which thus enriches the statistical analysis, enabling a more in-depth understanding of the data distribution (Cade & Noon, 2003; Chamaillé-Jammes & Blumstein, 2012). Prey size (response variable) of each species was correlated with predator size (explanatory variable) for five quantile intervals: $\tau = 0.05, 0.25, 0.50, 0.75, 0.95$(median value), in order to provide complementary information to the trend in mean fish length. In addition, an analysis of variance (ANOVA) was performed to test the difference between the τ coefficients of the quantile regression.

To assess whether prey size selection is a specific behavior for a given piscivore species, a generalized linear model (GLM) was performed with a quasi-poisson error distribution due to residual overdispersion (Crawley, 2007), with information on size of the piscivore as a response variable and the size of the prey as an explanatory variable. In this analysis, the adjusted incidence rate ratio (IRR) between prey size and predator size was then estimated. The IRR is a statistical measure used in count data analyzes to compare the incidence rate of an event between different groups or levels of an independent variable. The IRR is commonly used in generalized regression models (GLM), especially when the data has a Poisson distribution and there is a need to deal with overdispersion. Furthermore, it expresses the proportion of the event incidence rate between two groups or levels of the independent variable, calculated as the exponential of the coefficient associated with the independent variable in the regression model.

Data on the presence and absence of prey in the diet of piscivores were used to assess the correlation between the predator strategies (ambushers and pursuers) and the swimming ability of prey (fast, fast-moderate, slow-moderate and slow) (Hypothesis ii), a GLM logit link analysis was performed with a quasi-binomial error distribution, selected due to residual overdispersion, with the presence and absence of prey (0 and 1, respectively) in the predators' diet as the response variable.

All statistical analyses were performed using R software (R Development Core Team, 2022), using the *"quantreg"* (Koenker, 2015), *"lme4"* (Bates et al., 2015), *"sjPlot"* (Lüdecke, 2022), *"MASS"* (Venables & Ripley, 2002).

4.3 RESULTS

A total of 52 prey fish species was consumed by 14 piscivorous fish species, with 11 prey species being exclusive in the diet of some predators, of which, the majority reach large sizes. For example, *Megaleporinus obtusidens* (Valenciennes 1837) was consumed exclusively by *Pseudoplatystoma corruscans*, and *Pterodoras granulosus* (Valenciennes 1821) by *Hoplias* sp. 2 (Table 1; MS1). On the other hand, the most consumed preys were those with a small body size, such as *Astyanax lacustris* (Lütken 1875), *Roeboides descalvadensis* Fowler 1932 and species of the genera of *Moenkhausia* and *Serrapinnus*, in addition to Gymnotiformes *Eigenmannia trilineata* and *Gymnotus* sp. (Table 1; MS1).

Hoplias mbigua (Günther, 1864), *Hoplias* sp. 2 and *Acestrorhynchus lacustris* (Lütken 1875) had the highest richness of consumed prey (all with 27 species), followed by *Hemisorubim platyrhynchos* (Valenciennes 1840) and *Plagioscion squamosissimus* (Heckel 1840) (both with 19 species) (Table 1).

Table 1 – Presence and absence of prey fish in the stomach of piscivorous fish from the upper Paraná River floodplain. AL = *Acestrorhynchus lacustris*, CK = *Cichla kelberi*, CP = *Cichla piquiti*, HP = *Hemisorubim platyrhynchos*, HU = *Hoplerythrinus unitaeniatus*, HA = *Hoplias intermedius*, HM = *Hoplias mbigua*, H2 = *Hoplias* sp.2, H3 = *Hoplias* sp.3, PS = *Plagioscion squamosissimus,* PC = *Pseudoplatystoma corruscans*, RV = *Rhaphiodon vulpinus,* SB = *Salminus brasiliensis* and SL = *Sorubim lima*. Numbers in parentheses represent the number of stomachs analyzed from each predator.

Prey	**Predators**													
	AL (143)	**CK (11)**	**CP (4)**	**HP (60)**	**HU (1)**	**HA (8)**	**HM (33)**	**H2 (25)**	**H3 (3)**	**PS (18)**	**PC (17)**	**RV (8)**	**SB (9)**	**SL (9)**
CHARACIFORMES														
Erythrinidae														
Hoplerythrinus unitaeniatus	X													
Hoplias intermedius				X		X		X			X			
Hoplias mbigua							X	X			X	X		
Hoplias sp.2							X	X	X					
Serrasalmidae														
Serrasalmus marginatus	X	X		X		X	X	X		X				
Anostomidae														
Leporinus sp.	X	X		X			X	X			X			X
Leporinus friderici	X													
Leporinus lacustris			X							X				
Megaleporinus obtusidens											X			
Schizodon borellii				X		X	X	X			X	X		X
Curimatidae														
Steindachnerina sp.	X	X		X			X			X				
Steindachnerina brevipinna	X	X		X										
Steindachnerina insculpta	X			X			X						X	
Hemiodontidae														
Hemiodus orthonops							X							
Prochilodontidae														
Prochilodus lineatus							X	X	X		X			
Acestrorhynchidae														
Acestrorhynchus lacustris	X					X	X	X	X					
Characidae														
Psellogrammus kennedyi	X	X		X		X		X			X			X
Roeboides descalvadensis	X			X		X	X	X		X	X		X	
Stethaprioninae														
Astyanax lacustris	X			X			X	X		X	X	X	X	X
Hyphessobrycon eques	X						X	X						X

Moenkhausia sp.	X		X	X	X		X	X		X		X	X	
Moenkhausia aff. *intermedia*	X	X				X	X	X			X	X	X	
Moenkhausia bonita	X													
Moenkhausia cf. *gracilima*	X							X			X			
Moenkhausia sanctaefilomenae														X
Aphyocharax sp.	X		X					X				X		
Aphyocharax anisitsi												X		
Odontostilbe avanhandava							X							
Serrapinnus sp.	X	X		X	X			X		X	X	X		X
Serrapinnus notomelas	X			X		X	X	X				X		X
Bryconamericus sp.	X		X	X			X	X		X				
Piabarchus stramineus	X												X	
GYMNOTIFORMES														
Gymnotidae														
Gymnotus sp.	X	X		X	X				X	X	X		X	X
Gymnotus inaequilabiatus								X				X		
Gymnotus sylvius							X		X					
Rhamphichthyidae														
Rhamphichthys hahni								X		X	X			
Sternopygidae														
Eigenmannia trilineata	X	X		X			X	X	X	X	X	X	X	X
SILURIFORMES														
Callichthyidae														
Lepthoplosternum pectorale		X						X						
Loricariidae														
Loricariichthys platymetopon		X				X				X			X	
Loricariichthys rostratus						X	X			X				
Hypostomus sp.								X	X	X				
Auchenipteridae														
Parauchenipterus galeatus							X			X				
Doradidae														
Ossancora eigenmanni									X					
Pterodoras granulosus								X						
Heptapteridae														
Pimelodella sp.				X										X
CICHLIFORMES														
Cichlidae														
Cichla kelberi	X		X				X			X	X	X	X	
Cichla sp.	X		X	X			X	X	X					
Cichlasoma paranaense													X	
Geophagus sveni							X			X			X	
Laetacara sp.		X									X			
Satanoperca pappaterra	X						X			X				
PERCIFORMES														
Sciaenidae														
Plagioscion squamosissimus	X			X			X	X		X			X	

The quantile regression analysis of the relationships between the size of piscivores and their prey presented a positive effect at all quantile levels (Estimate, Table 2), and across all quantile levels (ANOVA: $F_{(2:919)} = 9.20$, $p < 0.001$). These effects highlight an increasing pattern with a slight variation at the 75th quantile ($\tau = 0.75$), indicating that as piscivorous fish increase in body size larger preys are consumed (Fig. 2).

Table 1 - Quantile regression estimates and 95% confidence intervals for the quantiles (0.05, 0.25, 0.50, 0.75 and 0.95), of the sizes of fish length (cm) predators and prey in the upper Paraná River floodplain.

tau	Regression parameter	Estimate	Std.Error	t.value	p-value
$\tau = 0.05$	Intercept	10.17	0.41	24.69	< 0.001
	Size prey	0.75	0.06	11.49	< 0.001
$\tau = 0.25$	Intercept	10.94	0.59	18.26	< 0.001
	Size prey	1.46	0.09	15.43	< 0.001
$\tau = 0.50$	Intercept	13.61	0.94	14.43	< 0.001
	Size prey	1.74	0.14	11.66	< 0.001
$\tau = 0.75$	Intercept	24.43	1.64	14.88	< 0.001
	Size prey	1.31	0.26	5.04	< 0.001
$\tau = 0.95$	Intercept	33.57	1.84	18.24	< 0.001
	Size prey	2.12	0.29	7.3	< 0.001

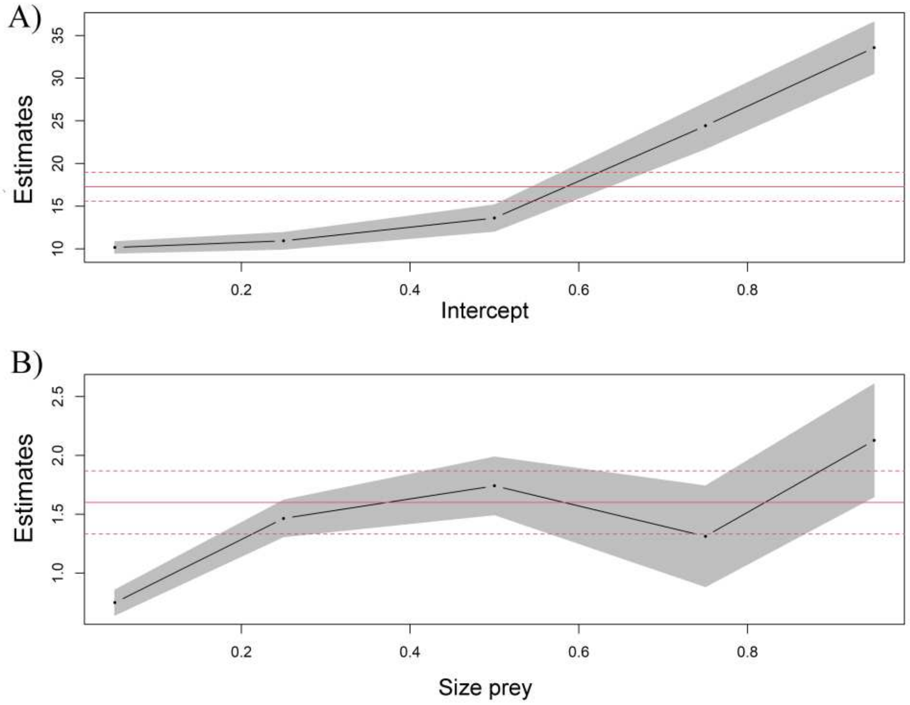

Figure 2 - Quantile regression estimates and 95% confidence intervals (gray bands) for the quantiles (τ = 0.05, 0.25, 0.50, 0.75 and 0.95), of the sizes of fish length (cm) predators (A) and prey (B) in the e Upper Paraná River basin. Each black dot is the slope coefficient for the indicated quantile on the x-axis. The red lines are the least squares estimate and its confidence interval.

When evaluating the predator-prey size relationship separately by piscivorous species, it is observed that the variation in prey size consumption is not the same for all piscivores, In this case, the correlation between body size between piscivores and their prey was observed in *A. lacustris*, *H. unitaeniatus* (Spix & Agassiz 1829), *Hoplias intermedius* Rosso, González-Castro, Bogan, Cardoso, Mabragaña, Delpiani & Díaz de Astarloa 2018, *H. mbigua*, *Hoplias* sp.2, *P. corruscans*, *Rhaphiodon vulpinus* Spix & Agassiz 1829 and *Salminus brasiliensis* (Cuvier 1816) (IRR: 2.08 cm, p-value <0.001). In contrast, the piscivores *Cichla kelberi* Kullander and Ferreira 2006, *Cichla piquiti* Kullander & Ferreira 2006, *H. platyrhynchos*, *Hoplias* sp.3, *P. squamosissimus* and *Sorubim lima* (Bloch & Schneider 1801), did not show size variation when consuming their prey, with the size of the prey being of little or no importance (Table 3, Fig. 3).

Table 2 - GLM-quasipoisson results testing the variation in prey size among predators in an Upper Paraná River floodplain.

Predictors	**Incidence Rate Ratios**	**std. Error**	**CI**	**p**
Acestrorhynchus lacustris	3.85	0.21	3.45 – 4.28	**<0.001**
Cichla kelberi	0.91	0.19	0.58 – 1.35	0.647
Cichla piquiti	1.44	0.40	0.79 – 2.38	0.188
Hemisorubim platyrhynchos	1.07	0.17	0.78 – 1.45	0.655
Hoplerythrinus unitaeniatus	3.51	1.24	1.61 – 6.55	**<0.001**
Hoplias argentinensis	2.19	0.36	1.56 – 2.99	**<0.001**
Hoplias mbigua	1.86	0.19	1.52 – 2.25	**<0.001**
Hoplias sp. 2	1.46	0.18	1.14 – 1.84	**0.002**
Hoplias sp. 3	1.70	0.61	0.77 – 3.20	0.139
Plagioscion squamosissimus	1.16	0.18	0.84 – 1.56	0.347
Pseudoplatystoma corruscans	1.93	0.25	1.49 – 2.48	**<0.001**
Rhaphiodon vulpinus	1.57	0.30	1.06 – 2.25	**0.018**
Salminus brasiliensis	2.08	0.33	1.50 – 2.81	**<0.001**
Sorubim lima	0.67	0.18	0.38 – 1.10	0.144
Observations	304			
R^2 Nagelkerke	0.452			

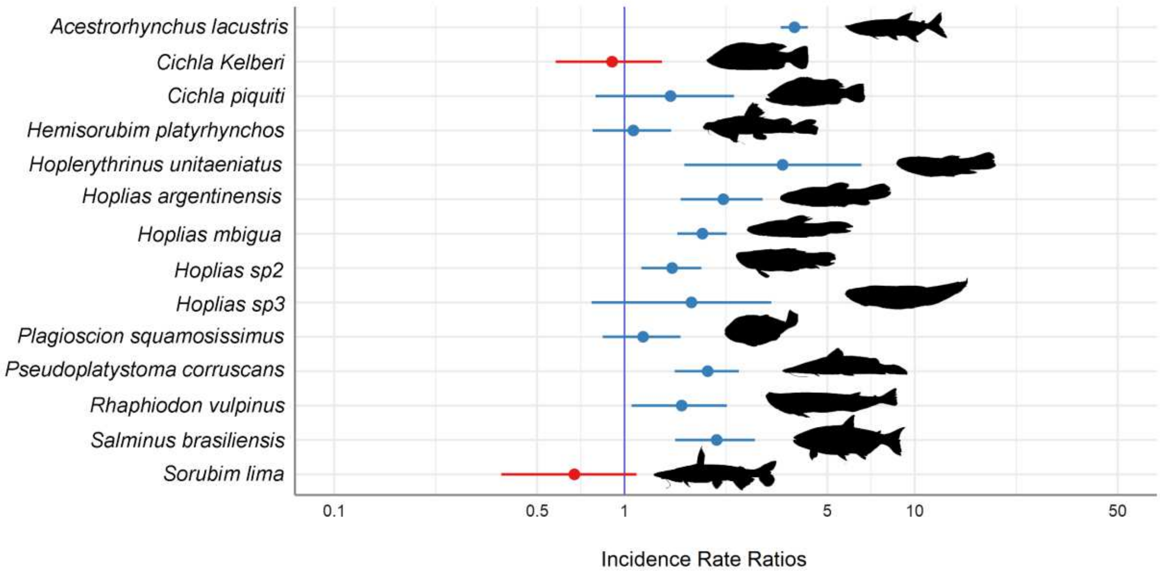

Figure 3 – Estimation of the variation in prey size in the piscivores" diet, analyzed using the incidence rate ratio (IRR) of the GLM effect coefficients, with quasi-poisson distribution error. The circles represent the mean prey size, and the horizontal lines indicate the 95% confidence interval (CI95). Blue colors denote a positive effect, i.e. an increase in prey size relative to predator size, while red colors indicate a reduction in prey size. Significant effects are observed when the coefficient intervals do not cross the horizontal line (IRR = 1).

The GLM-quasibinomial analysis showed a positive correlation between the predator's hunting strategy (pursuer and ambusher) and the prey's swimming activity mode (Fast, Fast-Moderate, Slow and Slow-Moderate; Table 3). Ambush predators were more likely to consume slow-moderate (OR = 2.29 p = 0.005) and fast prey (OR = 2.19; p = <0.001), while pursuer predators consume mainly fast prey (OR = 2.36, p = <0.001) (Table 4, Fig. 4).

Table 3 - GLM-quasibinomial results testing the selectivity of predatory fish on prey swimming activity in an Upper Paraná River floodplain.

Predictors	**Probability**	**Odds Ratios**	**CI**	**p**
(Intercept)	0.009	0.01	0.01 – 0.01	**<0.001**
Ambusher × Fast swimming	0.687	2.19	1.22 – 3.72	**0.005**
Pursuer × Fast swimming	0.600	2.36	1.54 – 3.57	**<0.001**
Ambusher x Fast-Moderate swimming	0.595	1.50	1.05 – 2.15	**0.024**
Pursuer × Fast-Moderate swimming	0.695	1.11	0.81 – 1.53	0.533

Ambusher × Slow swimming	0.702	1.47	1.05 – 2.07	**0.025**
Pursuer × Slow swimming	0.526	1.01	0.74 – 1.40	0.945
Ambusher × Slow-Moderate swimming	0.502	2.28	1.62 – 3.21	**<0.001**
Observations	**53954**			
R^2 Tjur	**0.001**			

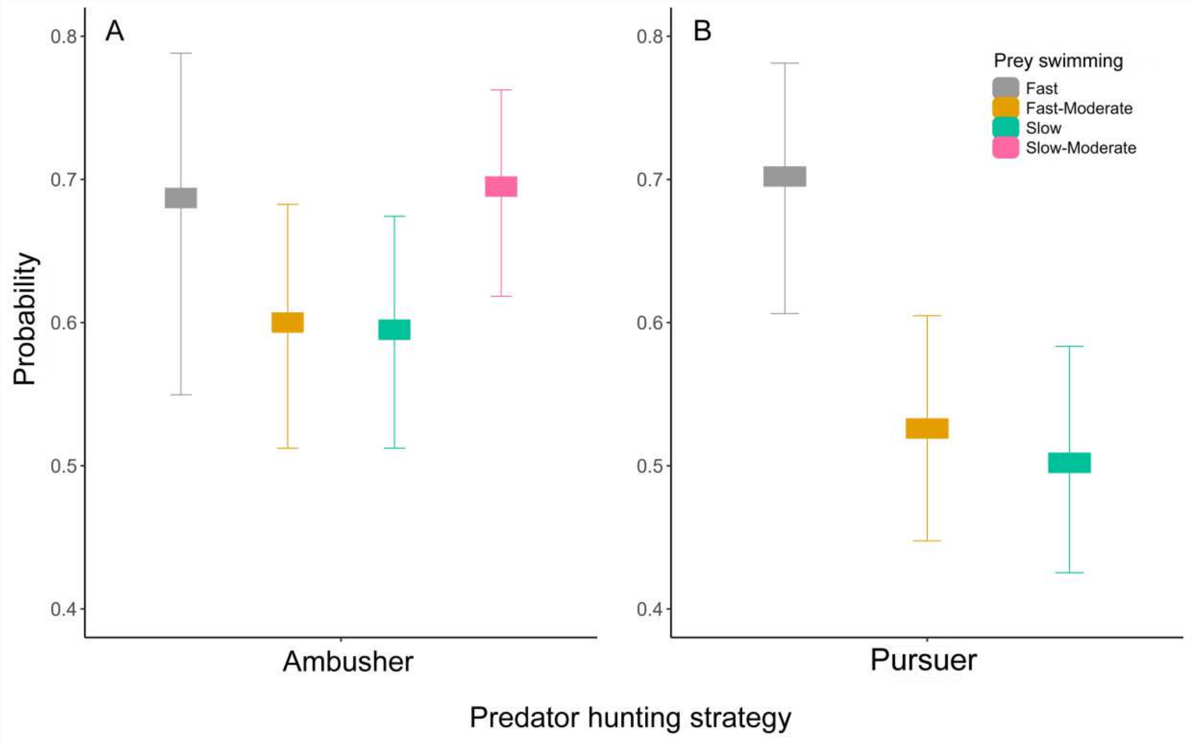

Figure 4 - Probability of ambush and pursuer predators consuming prey with different swimming classes (Fast, Fast-Moderate, Slow and Slow-Moderate).

4.4 DISCUSSION

A positive correlation between predator and prey body size was observed, consistent with the hypothesis that as the body size of the predator increases, larger preys are consumed. However, this positive relationship was not observed for all species, such as *C. kelberi*, *C. piquiti*, *H. platyrhynchos*, *Hoplias* sp.3, *P. squamosissimus* and *S. lima* indicating that prey selection may not be determined by prey size. For the piscivores it was also observed that pursuer predators consume primarily fast swimming prey, while ambush predators tend to consume slow-moderate and fast swimming prey.

The combination of morphological and behavioral characteristics is fundamental to explain the variations in size of consumed prey by piscivorous fish, and often the success in capturing prey is determined by the encounter rate between predator and prey (Juanes et al., 2002; Mihalitsiset al., 2020). The piscivores evaluated in this study consume their prey whole, which restricts the potential preys to requires a relatively small range of sizes, from small prey unable to be detected visually by predators to large prey unable to be consumed due to the maximum limit of the mouth opening of the piscivore (Gill, 2003; Mihalitsis & Bellwood 2017).

The tendency of predators to consume relatively larger prey in relation to their size was observed in almost all quantiles, except in the 75th quantile, which indicated prey consumption in relation to the size of the piscivore. This is, probably, highly influenced by environmental prey availability and the formation of schools. Prey capture success is relatively higher when the prey capture success is relatively greater when prey is one-third the size of predators., while the consumption rate of large prey is low when they reach half the size of their predator (Goulding et al., 1988; Machado-Allison, 1990; Almeida et al., 1997). Scharf et al. (2000) noticed that the diet of predators varied, with prey ranging from 10 to 20% of the predator's size to prey larger than 50% of the predator's size. Although predators have large and distensible stomachs, there is a limit to their extension, which favors the consumption of small prey, as the predator can consume large quantities of small prey, leading to greater satiety compared to consuming small quantities of larger prey (Turesson et al., 2002).

Schooling is a common behavior in several floodplain prey species, such as *Moenkhausia* and *Astyanax* species (Hart & Connellan, 1984; Hambright, 1991; Vandenbyllaardt et al., 1991). This shoal formation mainly favors predators of large body size since it allows the ingestion of several preys at the same time in just a few moments, reinforced by the fact that many individuals of the same species are in the same state of digestion (apparently a single shoal, i.e. *Serrapinus notomelas*, *Bryconamericus stramineus* and *Moenkhausia* cf. *gracilima*) present in the stomachs of larger predators (e.g. *P. corruscans* and *C. kelberi*), indicating that the large number of individuals was the result of only one act of predation (Kovalenko et al., 2010). However, it is still not clear how the piscivore perceives a school. The possibility of a school being observed as a single individual for a large pursuing piscivore, like *P. corruscans*, should be considered as small prey are usually found in their stomachs in large amounts. However, this is not observed in ambush predators, which usually present a larger variety of single species as prey. This hypothesis still needs much research to be confirmed, however the fact that a school is perceived as a single large individual, instead of several small individuals, should not be easily discarded. The optimum foraging theory would explain much better the foraging behavior on schools if they were considered as a single large individual.

Acestrorhynchus lacustris, *H. unitaeniatus* and *H. intermedius* are medium-sized piscivores, which inhabit more structured environments, as macrophytes, to forage (Piana et al., 2006). These environments present great habitat complexity, serving as shelter for many species of small and medium-sized fish, leading to an increase in population density. The selection of larger prey by these predators probably occurs due to the large mouth opening and the presence of canine teeth, resulting in a higher energy rate acquired by these predators. For piscivores that do not have gap limitations, such as *C. kelberi*, *C. piquiti*, *H. platyrhynchos*, and *S. lima*, consumption is more associated with prey availability than with prey size.

A piscivore aim is to successfully capture a prey, which aims at not becoming captured, therefore the piscivore must minimize the duration of prey capturing before the prey can detects it, so no evasive strategies, like seeking for shelter, are prompted (Webb, 1984). For ambush predators the odds of finding both slow-moderate prey and fast prey is high, as these tend to disperse more than low mobility preys in the environment. High explosion of these predators (Webb, 1984) favors the consumption of fast prey which does not have the time to react and evade.

4.5 CONCLUSION

Several mechanisms can influence prey predation, such as body size, in which as the predator increases its size, the larger the size of the prey consumed, and that the hunting strategy of the predators can be influenced by predator and prey encounter rate, prey swimming mode and by habitat complexity. There are still many gaps in predator-prey interaction in the natural environments. Most studies that seek to fill these gaps are carried out through experiments, which might in turn influence fish behavior and skewed results, not being comparable with fish behavior in natural environment. There is still an absence of a clear and comprehensive method to study the detection, locomotion, and behavior of predators and their preys in natural environment. We truly believe that studies performed in natural environment might provide some answers that experiments are not able to provide.

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5 GENERAL CONCLUSION

The aim of this thesis was to evaluate different mechanisms that influence the diet of neotropical fish through a combination of analytical approaches, such as meta-analysis and construction of trophic networks, in order to investigate the influence of dams on the diet of neotropical fish. Furthermore, we sought to understand how the prey selection mechanisms exhibited by predators relate to their foraging mode in a floodplain.

In general, the results showed that spatial variation, represented by the upstream and downstream stretches of the dams, has a great influence on the fish diet, promoting changes in the abundance and composition of food resources. Furthermore, the difference in this variation in the fish diet means that populations in different stretches of the dams begin to form distinct trophic guilds, as observed in our meta-analysis, in which there was an increase in the composition of piscivorous, omnivorous, detritivorous and herbivorous fish in the downstream stretch. While upstream, no increase in the composition of any trophic guild was observed.

It is worth mentioning that trophic guilds may vary due to other variables, such as the size and age of dams, as observed in our meta-analysis, in which as dams age, environmental conditions and available resources change, contributing to the divergence in the composition of trophic guilds. On the other hand, the latitude of the dams did not influence the fish diet, given the proximity of the reservoirs evaluated in this study.

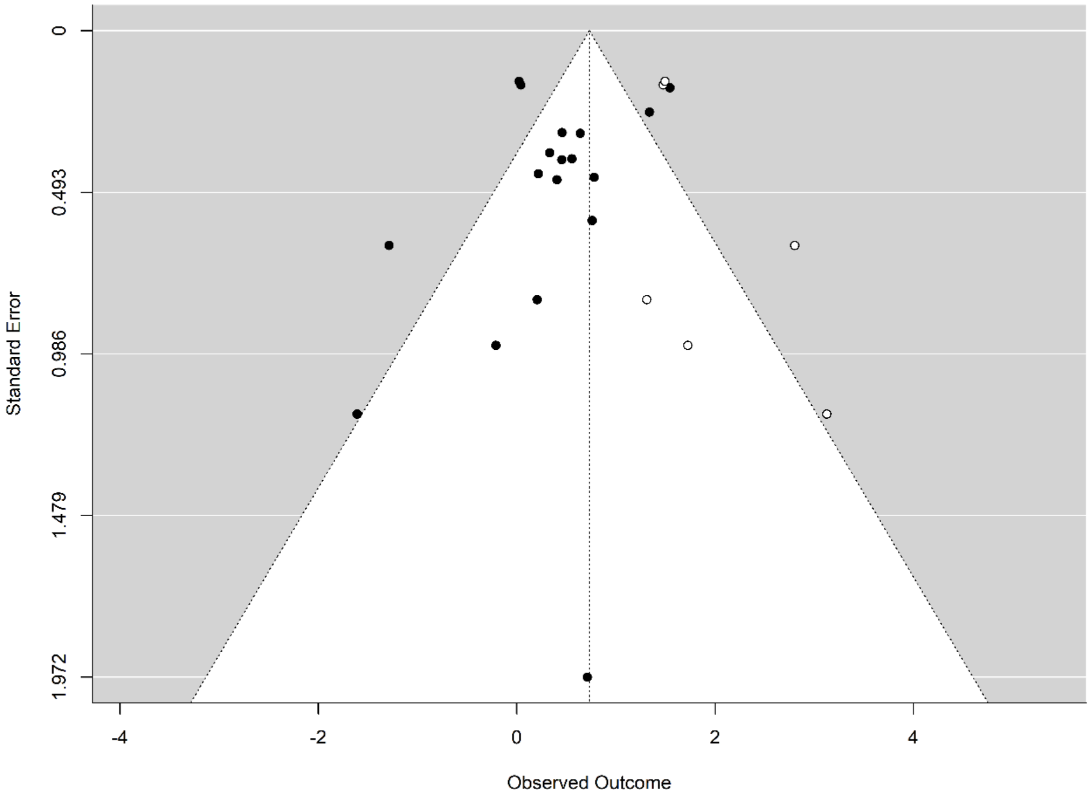
Based on the analysis of fish stomachs and the construction of food networks in two stretches, upstream and downstream, of a Small Hydroelectric Plant, the results showed differences in the structure of both food networks, with the downstream network being more sensitive in practically all metrics evaluated, with greater connectance, greater modularity, more nested, but less specialized. Simulations of loss of food resources indicated that the networks did not differ from each other, but that due to the greater degree of specialization of fish species upstream, the rate of fish extinction is faster.

When evaluating the diet of piscivorous fish in the floodplain, the results revealed a positive correlation in the body size of the predator and its prey, that is, as the predator increases its body size, it will prefer proportionally larger prey. Furthermore, ambush predators are more likely to consume slow-moderate, and fast prey. While chasing predators they prefer to consume only fast prey.

Based on the results of this thesis, we conclude that investigating different approaches in trophic ecology, such as food selectivity, foraging patterns, and anthropogenic impacts, is crucial for implementing effective strategies for the management of aquatic ecosystems. Understanding how human activities affect aquatic ecosystems is crucial for developing effective mitigation measures and conserving biological diversity.

6 SUPLEMENTARY MATERIAL

Chapther 1 - Variation in the composition of fish trophic guilds of neotropical dams: a systematic meta-analytic review



Supplementary Information 2. The evaluation funnel chart studies the trophic guilds between the reservoir stretches (upstream, reservoir and downstream). Each study is represented by a filled circle.

Chapther 2 - Effect of spatial variation on the structure of neotropical fish trophic networks in a small hydropower plant

Table S1. Variation in the size of fish prey (cm) identified in the stomach contents of predators, and swimming mode obtained from the literature.

Prey species	Size	Swimming	Reference
Acestrorhynchus lacustris	3.0 -13.0	Fast-Moderado	24
Aphyocharax anisitsi	1.2	Fast-Moderado	21
Aphyocharax spp.	2.3 - 3.6	Fast-Moderado	21
Astyanax lacustris	1.0 - 13.5	Slow-Moderado	24
Bryconamericus sp.	1.5 - 4.8	Fast-Moderado	9
Cichla kelberi	2.9 - 3.7	Slow	23
Cichla sp.	2.9 - 3.7	Slow	23
Cichlasoma paranaense	10.0	Slow	23
Eigenmannia trilineata	2.3 - 14.0	Fast	4
Geophagus sveni	13.5	Slow	23
Gymnotus inaequilabiatus	NA	Slow-Moderado	6, 7
Gymnotus sp.	2.2 - 13.5	Slow-Moderado	6, 7
Gymnotus sylvius	22.0	Slow-Moderado	6, 7, 25
Hemiodus orthonops	NA	Fast-Moderado	1, 22
Hoplerythrinus unitaeniatus	NA	Slow	4
Hoplias intermedius	14.0 - 15.5	Slow-moderado	2
Hoplias mbigua	5.9 - 14.9	Slow-moderado	2
Hoplias sp. 2	2.9 - 13.0	Slow-moderado	2
Hoplias sp. 3	NA	Slow-moderado	2
Hyphessobrycon eques	1.2 - 3.1	Slow	19
Hypostomus sp.	7.0	Slow-Moderado	5
Laetacara sp.	NA	Slow	23
Leporinus friderici	NA	Fast-Moderado	15

Leporinus lacustris	4.1 - 10.8	Slow	*
Leporinus sp.	2.0 - 12.5	Fast-Moderado	*
Lepthoplosternum pectorale	12.0	Slow	25
Loricariichthys platymetopon	1.5 - 13.7	Slow	22, 23
Loricariichthys rostratus	2.3 - 13.7	Slow	22, 23
Megaleporinus obtusidens	6.3	Fast	3
Moenkhausia aff. intermedia	1.0- 5.1	Slow	20
Moenkhausia bonita	3.1 - 4.3	Slow	20
Moenkhausia cf. gracilima	2.3 - 4.1	Slow-Moderado	20
Moenkhausia sanctaefilomena	NA	Slow	20
Moenkhausia sp.	1.0 - 5.2	Slow	20
Odontostilbe avanhandava	NA	Slow-Moderado	*
Ossancora eigenmanni	6.4	Slow	13
Parauchenipterus galeatus	3.1	Slow-Moderado	8
Piabarchus stramineus	3.8 - 5.5	Fast-Moderado	5
Pimelodella sp.	7.2	Slow-Moderado	22, 23
Plagioscion squamosissimus	1.9 - 10.0	Fast-Moderado	16, 18
Prochilodus lineatus	6.7 - 16.3	Fast	3
Psellogrammus kennedyi	2.9 - 7.5	Slow	10
Pterodoras granulosus	9.1	Fast-Moderado	13
Rhamphichthys hahni	1.2 – 12.5	Slow-Moderado	11
Roeboides descalvadensis	1.2 - 12.5	Slow	*
Satanoperca pappaterra	5.1	Slow	23
Schizodon borelli	5.8 - 10.2	Fast-Moderado	22, 17
Serrapinnus notomelas	0.9 - 7.3	Slow-Moderado	14
Serrapinnus sp.	0.6 - 7.3	Fast-Moderado	14

Serrasalmus marginatus	3.3 - 12.5	Fast-Moderado	22
Steindachnerina brevipinna	0.8 - 9.0	Fast-Moderado	12
Steindachnerina insculpta	4.5 - 7.5	Fast-Moderado	12
Steindachnerina sp.	2.5 - 6.5	Fast-Moderado	12

NA - it was not possible to measure the size of the prey, and it was not used in the analyzes of the predator-prey size relationship, * = Personal information, Augusto Frota.

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Table S2. Variation in the size of predatory fish (standard length - cm) sampled in the upper Paraná River Floodplain, and strategy predator obtained from the literature.

Predator species	Size	Strategy predator	Reference
Acestrorhynchus lacustris	11.7 - 26.6	Pursuer	4
Cichla kelberi	19.8 - 33.4	Pursuer	1
Cichla piquiti	18.0 - 45.6	Pursuer	1
Hemisorubim platyrhynchos	22.3 - 40.5	Pursuer	8
Hoplerythrinus unitaeniatus	22.4	Ambusher	5
Hoplias intermedius	21.5 - 38.5	Ambusher	6
Hoplias mbigua	16.1- 43.5	Ambusher	6
Hoplias sp. 2	22.0 - 33.0	Ambusher	6
Hoplias sp. 3	26.5 - 38.5	Ambusher	5
Plagioscion squamosissimus	17.5 - 47.5	Pursuer	1
Pseudoplatystoma corruscans	31.1 - 93.0	Pursuer	7
Rhaphiodon vulpinus	33.5 - 51.0	Pursuer	2
Salminus brasiliensis	13.0 - 57.5	Pursuer	6
Sorubim lima	22.2 - 43.4	Pursuer	3

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