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Article

Ecological and biological patterns of stream fish studies from the Piracicaba-Capivari-Jundiaí Basin (PCJ Basin, SP) assessed through a systematic review

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Abstract: Tropical streams are among the most threatened ecosystems in the world. As such, studies carried out and compiled over spatial and temporal scales can provide useful information to examine patterns of species diversity and threats to their survival. Here we conducted a systematic review of published research on biological and ecological aspects of stream fish fauna found in the Piracicaba-Capivari-Jundiaí Basin, an industrial watershed of São Paulo State. We aimed to detect main patterns, trends and gaps in studies related to species composition, distribution, spatial and temporal scales, as well as in the covered topics. Results were related to main land uses, biomes and Conservation Units. A constant increase in published articles occurred from 2003 until 2016 with an average of 1.8 articles/year. Twenty-six publications were considered for the present study, reporting on fish samples obtained in 67 sites and resulting in 89 species. A high proportion of studies were concentrated in the Corumbataí sub-basin, and rarefaction curves indicated that stream fish richness in the PCJ Basin may be considerably higher than that shown by the actual numbers. Basin studies were unevenly distributed and did do not include such highly preserved areas as the Camanducaia, Jaguari and Jundiaí sub-basins. We emphasize the importance of further surveys in these regions, as well as in high priority conservation areas, which may lead to new insights for developing appropriate conservation strategies for this basin.
Keywords: *Conservation; Freshwater fish; Neotropical streams; Synthesis of the literature; Spatial scale.*

Padrões ecológicos e biológicos de estudos de peixes de riachos da Bacia Piracicaba-Capivari-Jundiaí (Bacia PCJ, SP) avaliados por meio de uma revisão sistemática

Resumo: Riachos tropicais estão entre os ecossistemas mais ameaçados do mundo e a compilação de estudos temporais e espaciais pode fornecer informações úteis para examinar padrões de diversidade de espécies e ameaças nesses sistemas. Realizamos uma revisão sistemática das pesquisas publicadas sobre aspectos biológicos e ecológicos da ictiofauna de riachos da bacia do Piracicaba-Capivari-Jundiaí, uma bacia industrial do Estado de São Paulo. O objetivo foi detectar os principais padrões, tendências e lacunas em estudos relacionados à composição, distribuição de espécies, escalas espaciais, temporais e temas abordados. Os resultados foram relacionados aos principais usos do solo, biomas e Unidades de Conservação. Foi verificado um aumento constante de artigos entre 2003 e 2016, com média de 1,8 artigos/ano. Vinte e seis publicações foram consideradas para o estudo, que indicaram 67 locais amostrados, e o registro de 89 espécies. Uma alta proporção deles concentrou-se na sub-bacia de Corumbataí e curvas de rarefação indicaram que a riqueza de peixes de riacho na bacia do PCJ deve ser consideravelmente maior do que os números atuais. A distribuição desigual de estudos na bacia, que não inclui áreas altamente preservadas como as sub-bacias de Camanducaia, Jaguari e Jundiaí, enfatiza a necessidade de se obter mais informações nessas regiões, bem como em áreas de conservação de alta prioridade. Novas abordagens relacionadas a conceitos e teorias ecológicas em estudos futuros poderão fornecer informações que ajudem a desenvolver estratégias de conservação adequadas para esta bacia.
Palavras-chave: *Conservação; Peixe de água doce; Riachos neotropicais; Síntese da literatura; Escala espacial.*

Introduction

The growing biodiversity crisis has led to several global initiatives that compile datasets from studies carried out over time and space (Pereira & Cooper 2006). Although these databases have proved extremely useful and allowed major advancements in ecological research (e.g., Kendall et al. 1998; Sibly et al. 2005), few of these studies concern riverine fishes, despite several independent, often local in extent, academic research programmes (Matthews & Marsh-Matthews 2017). In Brazil, studies of stream fishes have increased in the last decades. These studies have emerged from the introduction of new sampling techniques (Alves et al. 2021) as well as the implementation of inventories aimed to characterize the biodiversity of different ecosystems, which have promoted the discussion of conservation strategies, economic potential and sustainable use (FAPESP 2016).

Despite institutional and academic monitoring efforts to produce data on freshwater fish studies, such data are dispersed and fragmented in hundreds of works and publications, often in sources that are difficult to access, and, in most cases, in a format that makes a direct application unfeasible. This poses a problem for researchers and policymakers who use scientific information on biodiversity, with the available data still being underused (Rodrigues & Bononi 2008). More specifically for stream fishes, these data need to be taxonomically verified and updated and regional databases must be compiled and maintained for the analysis of new species, long-term impacts and trends, in order to make management projects viable (Winemiller et al. 2008). Furthermore, regional databases can be combined to facilitate the analysis of patterns on a broader biogeographic scale, including regional variation in species richness and invasions by exotic species (Winemiller et al. 2008). Several of these approaches may be obtained through systematic reviews, considered a useful tool to integrate the information of a group of studies (Sampaio & Mancini 2007). Thus, causative factors of habitat loss, species introduction or chemical pollution and hybridization may be identified in freshwaters, which is not always possible due to inadequate data (Allan & Flecker 1993).

Studies in this direction were made by Dias et al. (2016). They found that research on Brazilian stream fish assemblages have been conducted mainly at small temporal and spatial scales relative to the dimension and importance of Neotropical freshwaters, but with homogeneous objectives that have varied little over the last 20 years. More recently, Junqueira et al. (2020) conducted a scientometric analysis to detected trends in published research of Brazilian stream fish assemblages. They found that the Paraná River Basin was the most studied region. Their review reveled greater financial and scientific resources available in this region as well as access to streams, owing to the high level of urban development and associated infrastructure (Dias et al. 2016).

Neotropical streams are known for their high fish biodiversity, with 70% of the 3148 species described from Brazilian freshwaters (ICMBio 2018) consisting of small fish (< 15cm) which live in small rivers and different stream types (Castro & Polaz 2020). In the State of São Paulo, intensive samplings of stream fishes have been conducted in several regions such as the northwest, including sub-basins of the Upper Paraná River (Molina et al. 2017; Zeni et al. 2019); the Paranapanema River Basin (Castro et al. 2003); the Rio Grande (Castro et al. 2004); coastal streams (Sabino & Castro 1990; Esteves & Lobón-Cerviá 2001; Gonçalves et al. 2018; Gonçalves et al. 2020) and the Piracicaba-Capivari-Jundiaí Basin (PCJ Basin). This basin coincides with important axes of economic growth, presenting increasing demands for water supply, irrigation and industry, as well as critical water quality values of the Capivari, Piracicaba and Jundiaí sub-basins (Comitês PCJ/Agência das Bacias PCJ 2020). It occupies 0.18% of the national territory, concentrating around 2.7% of the population and covering the territories of 76 municipalities, 71 of which belong to the State of São Paulo (Comitês PCJ/Agência das Bacias PCJ 2020).

Given the several knowledge gaps in relation to freshwater fishes in the State of São Paulo, especially in regions of increasing pressure to convert natural areas into urban or pasture areas (Casatti et al. 2008), literature searches may help to guide project development by indicating new directions for further investigations. With this in mind, we herein conducted a systematic review of published research on the stream fish fauna of the PCJ Basin in order to identify the main patterns, trends and gaps in studies related to species composition, distribution, spatial and temporal scales and covered topics. We then analysed the obtained results in relation to the main land uses, conservation areas and biomes with the aim of identifying regions or approaches that need greater attention, subsidizing future research and decision-making.

Material and Methods

1. Study Area

The PCJ Basin is part of the Tietê River Basin, belonging to the Upper Paraná River Basin, which covers 900 thousand km^2 and is part of the south face of the Brazilian Shield (Langeani et al. 2007) (Figure 1). It is one of the six units of Water Management of the State of São Paulo (UGHRIs), and is classified as industrial (São Paulo 2011). It has a drainage area of 14,178 km², that accommodates the Atibaia, Atibainha, Cachoeira, Camanducaia, Capivari, Corumbataí, Jaguari, Jundiaí and Piracicaba Rivers. This basin also houses 44 Conservation Units (CUs), comprising 33 categorised as Sustainable Use and 11 categorised as Integral Protection, which, together, correspond to approximately 53% of the total area of the PCJ Basins (Comitês PCJ/Agência das Bacias PCJ 2020).

Approximately 22% of the total area is covered by remnants of native vegetation, with 2% representing grassland formations and 20% forest formations. The sub-basins with the highest percentages of forest remnants are the Atibaia and Jundiaí, where Dense Ombrophilous Forest ("Atlantic Forest") occurs (Comitês PCJ/Agência das Bacias PCJ 2020). Water quality indicators show that the sub-basins of the Capivari and Piracicaba rivers have the worst quality for public supply and the highest trophic state. They also present the lowest quality of protection for aquatic fauna and flora. In contrast, the Jaguari River sub-basin stands out in terms of water quality for public supply and protection of aquatic fauna and flora, presenting a predominantly oligotrophic trophic state (Comitês PCJ/Agência das Bacias PCJ 2020).

2. Systematic review

Our systematic review followed the main steps described by Sampaio & Mancini (2007), who consider three stages: definition of the object of the review, identification of the literature and selection of the studies to be included. Potential papers were searched in the ISI Web of Science (Main Collection), as well as the Scielo and Scopus databases. The "advanced" search mode was used, which allowed to

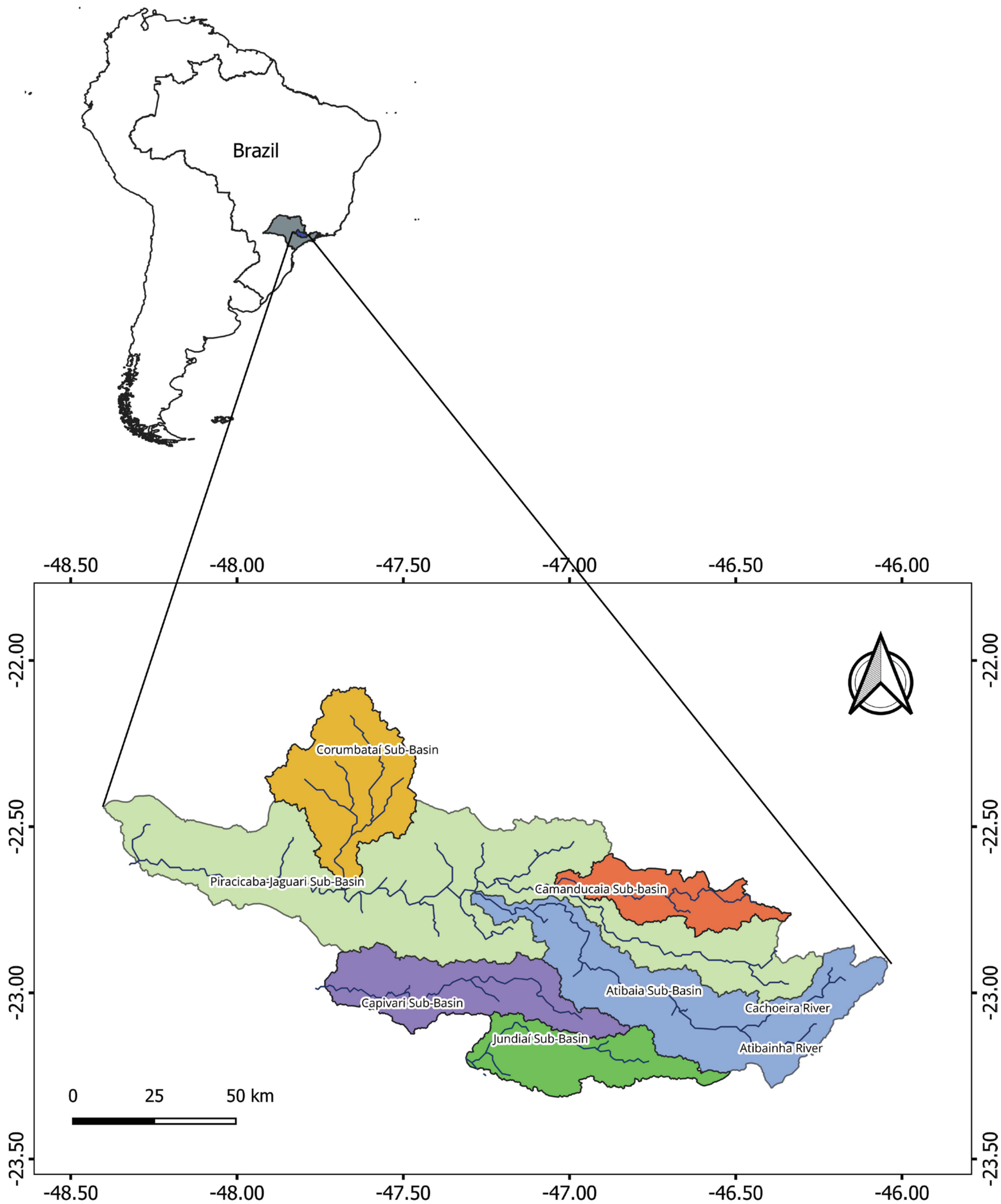

Figure 1. Location of the PCJ Basin in the State of São Paulo showing its main sub-basins.

obtain results using different keywords and their combinations. The used strings were: "*Name of the Sub-Basin*" or one of the main rivers AND (*river** OR *stream** OR *basin**) AND (*fish** OR *ichthyofauna*) for the period between 1987 and 2021. This period was chosen because a preliminary search indicated few indexed publications before 1990. The names of the main rivers and sub-basins were selected according to maps found in articles and on the official websites of the PCJ Basin Agency (https://www.comitespcj.org.br/).

After the searches were completed, all the articles were exported to the *State of the Art Throught Systematic Review (Start)* software developed at the LaPES (Software Engineering Research Laboratory of the Federal University of São Carlos, SP, Brazil). This software program divides research into three phases: planning, selection and extraction. In the first stage, a protocol with the keywords, search engines and the criteria for accepting or rejecting articles is defined. In the selection phase, articles are classified as accepted, rejected or duplicated based on the acceptance and rejection criteria defined in the protocol. Finally, in the extraction phase accepted articles are summarized and may be classified as rejected or duplicated again.

To include the studies of interest, we considered only those carried out in 1st to 4th order streams, placing emphasis on biological and ecological approaches. The subjects of interest were related to population biology, growth, diet, reproduction, morphology, ontogenetic variation, water quality and other anthropic effects on stream fishes. Studies carried out in in dams and reservoirs, large rivers as well as experimental, physiological, genetic, parasitological or systematic studies, were excluded. After reading the abstract of each article, an analysis was carried out to verify whether or not the article met the inclusion criteria. In the extraction step, a complete reading of the selected articles was performed aiming to check the inclusion criteria. To confirm the inclusion of the selected articles within the PCJ boundaries, the coordinates were previously plotted in Google Earth version 7.3.

3. *Data Registration and species validation*

This stage was characterized by the compilation of information obtained from the extracted articles, related to (1) species and its degree of threat (according to ICMBio 2018) (2) location (geographical coordinates) and stream order; (3) species status (native or non-native); (4) sub-basin, micro-basin and river/stream where the survey was carried out; (5) main themes (trophic ecology, growth, environmental impacts, community structure, integrated biological aspects, reproduction, riparian zone influences on the fish community/populations) and (6) temporal trends, defined as the difference between the last and the first sampling year. We considered non-native species to be those introduced outside their natural range (Garcia et al. 2021) and classified them according to Langeani et al. (2007).

To register the species, we did not consider subspecies, and all occurrences that were not identified at the species level were discarded (i.e., occurrences with genera abbreviated to sp., or species affinis commonly abbreviated as aff., and conferatum abbreviated as cf.), as suggested by Tedesco et al. (2017). Validation of the scientific names of the species was performed using the Catalog of Fishes (Fricke et al. 2021), which allowed finding valid species names and species recently described that are still not included in FishBase. The Constancy of Occurrence (Dajoz 1972), a qualitative measure that takes into account the presence or absence of the species in the samplings, was calculated for each species as $F = (P \times 100)/N$, where P is the number of samplings containing the species, and N is the total number of performed samplings. Species were then classified as constant (≥ 50.0%), Accessory (25% – 50%) or Accidental (≤ 25.0%). For these calculations, we considered each article as a sample, since species lists in some of the examined papers were pooled for the different sampling sites.

4. *Species distribution, richness and environmental data*

The geographical coordinates obtained for each selected article were standardized, converting them into the Universal Transverse Mercator (UTM) coordinate system. We considered the *Datum* of each article and used the Geodetic Coordinate system for Latin America (SIRGAS 2000) as the output. Spatial trends of ichthyofauna studies were plotted on maps using QGIS 3.4 (QGis Development Team 2018) overlaid on Ottocoded Hydrographic shapefiles of the PCJ Basin provided by the National Water Agency (ANA). Species distributions were also superimposed on several thematic shapefiles as biomes, priority areas for biological conservation (MMA 2018), and Conservation Units (IBGE – https://portaldemapas.ibge.gov.br/portal.php#homepage). Data on land use were acquired from the Mapbiomas Project (Collection 6, http://mapbiomas.org/) which considers 34 classes, including forests, pasture, agriculture, vegetated and non-vegetated areas and water, among others. Land use was calculated for the years of 2010 and 2020 on the QGIS 3.4 software for the whole basin and its evolution analyzed over the period. The same procedure was used for each site, where a 500-m buffer was delimited around each (Tibúrcio et al. 2016). The area occupied by the different land use classes was calculated with geometry tools and the basic statistics interface of QGis 3.4.

Rarefaction/extrapolation curves were built to assess the sampling effectiveness, using sampled-based rarefaction. This is considered a more realistic treatment of the independent sampling units used in most biodiversity studies, and considered adequate for comparing the richness of sample sets (Gotelli & Colwell 2001). The analysis was performed for i) grouped samples of the PCJ Basin, ii) Corumbataí sub-basin and iii) all other sub-basins on PAST 4.09 software (Hammer et al. 2001), with the standard errors converted to 95 percent confidence intervals (± 95% CI).

Results

1. *Search results*

The original search resulted in 281 articles, and after removing duplicates, it yielded 224 studies. Subsequent screening of titles and abstracts excluded 135 studies, of which 59 were deemed potentially relevant. After a second screening, 14 articles were also classified as duplicated, resulting in 45 eligible papers that were included for further analysis. Of these, 19 were excluded because they were outside the limits of the PCJ Basin and/or were not related to the main themes, finally resulting in 26 studies.

Results indicated that the Corumbataí and Piracicaba-Jaguari sub-basins were the most studied regions, with 76.9% and 19.2% of the articles recorded respectively. In the Jundiaí and Atibaia sub-basins, the number of studies was low, while no study was performed in the Camanducaia sub-basin (Table 1). These studies were carried out in 67 different sites, most of which were located in the Corumbataí sub-basin (65.7%), followed by the Piracicaba (16.4%), Jaguari (10.4%), Atibaia (4.5%) and Jundiaí (3.0%) sub-basins.

"Trophic ecology" was addressed as the main topic (26.9 %), followed by "Environmental Impacts" (23.0%), "Community Structure" (19.2%) and "Integrated biological aspects" (15.3%). "Reproduction" and "Riparian zone influences on fish community/populations" were the least common topics (both with 7.7%) (Table 1). The publishing trend for articles is shown in Figure 2. The number of articles published per year was low (mean = 1.85; SD = 1.18). Publications started in 2003 and maintained a constant rate until 2016, after which no articles were found. However, the regression equation for the cumulative number of articles indicates a tendency toward a constant increase after 2016.

2. *Species richness, distribution, land use and conservation units*

We registered 89 species, of which 49.4% were Characiformes, followed by Siluriformes (34.8%), Cichliformes (5.6%), Gymnotiformes (4.5%), Cyprinodontiformes (4.5%) and Synbranchiformes (1.1%). Of these, most were autochthonous species (94.3%), 5.6 % were non-native species and 94.3% were considered least Concern (LC), while only one was classified as vulnerable (*Characidium oiticicai* Travassos, 1967) according to the Brazilian Red List (ICMBio 2018). Three

Table 1. Studies included in the systematic review (n = 26), indicating their location in the sub-basins and main covered topics.

Authors/year	Title	Sub-Basin	Main topic
Alexandre et al. (2010)	Analysis of fish communities along a ...	Piracicaba-Jaguari	Community structure
Cardone et al. (2006)	Diet and capture of *Hypostomus strigaticeps* ...	Corumbataí	Trophic ecology
Cardoso et al. (2016)	Longitudinal distribution of the ichthyofauna in ...	Corumbataí	Community structure
Carmassi et al. (2012)	Composition and structure of fish assemblage ...	Corumbataí	Community structure
Cetra & Petrere (2007)	Associations between fish assemblage and ...	Corumbataí	Riparian influences
Cetra & Petrere (2006)	Fish-assemblage structure of the Corumbatai river basin ...	Corumbataí	Environmental impacts
Esteves & Alexandre (2011)	Development of an Index of Biotic Integrity Based ...	Piracicaba-Jaguari	Environmental impacts
Ferreira & Petrere (2007)	Anthropic effects on the fish community ...	Corumbataí	Environmental impacts
Ferreira et al. (2012)	Diet of *Astyanax paranae* (Characidae) in ...	Corumbataí	Trophic ecology
Ferreira et al. (2012)	Riparian coverage affects diets of characids in ...	Corumbataí	Riparian influences
Gomiero & Braga (2003)	O lambari *Astyanax altiparanae* (Characidae) ...	Corumbataí	Trophic ecology
Gomiero & Braga (2005)	The condition factor of fishes from two river basins ...	Corumbataí	Integrated biological aspects
Gomiero & Braga (2005)	Uso do grau de preferência alimentar para a ...	Corumbataí	Trophic ecology
Gomiero & Braga (2006)	Ichthyofauna diversity in a protected area in the ...	Corumbataí	Community structure
Gomiero & Braga (2007)	Reproduction of a fish assemblage in the state ...	Corumbataí	Reproduction
Lima-Junior & Goitein (2003)	Ontogenetic diet shifts of a Neotropical catfish ...	Piracicaba-Jaguari	Trophic ecology
Lima-Junior et al. (2006)	Fish assemblage structure and aquatic pollution ...	Corumbataí	Community structure
Rondineli & Braga (2009)	Population biology of *Corydoras flaveolus* ...	Corumbataí	Integrated biological aspects
Rondineli & Braga (2010)	Reproduction of the fish community of Passa Cinco stream ...	Corumbataí	Reproduction
Rondineli et al. (2009)	Population biology of *Trichomycterus* sp.	Corumbataí	Integrated biological aspects
Rondineli et al. (2011)	Diet of fishes in Passa Cinco stream, Corumbataí ...	Corumbataí	Trophic ecology
Santos et al. (2015)	Assessing the importance of riparian zone for stream ...	Atibaia and Piracicaba-Jaguari	Environmental impacts
Santos & Esteves (2015)	A Fish-Based Index of Biotic Integrity for ...	Atibaia and Piracicaba-Jaguari	Environmental impacts
Tibúrcio et al. (2016)	Landscape effects on the occurrence of ...	Corumbataí	Environmental impacts
Villares-Junior et al. (2016)	Comparative feeding ecology of four ...	Corumbataí	Trophic ecology
Yoshida & Uieda (2014)	The importance of a Biosphere Reserve of Atlantic ...	Jundiaí	Integrated biological aspects

constant species were recorded, and most were classified as accidental (76.4 %) (Table S1).

Rarefaction curves for the sampled streams showed an increase in the number of species with the number of studies, but did not reach an asymptote, both for the individual and grouped sub-basins (Figure 3). Because of the higher number of samples in the Corumbataí sub-basin, the curve leveled the pattern of the pooled samples, while the curve obtained for the other sub-basins (Atibaia, Jundiaí and Piracicaba-Jaguari) indicated a less intensive sampling effort, which resulted in approximately 58 registered species.

Considering the 67 sampled sites with the buffer of 500m in relation to the total area of the PCJ Basin, we found that only 0.35% of the basin was sampled. The main land use in the whole basin in the period from 2010 to 2020 was "Mosaic of Agriculture and Pasture", followed by "Forests and Pasture" and then "Sugarcane" (Figure 4A). During this period, although less representative in area, soybean plantation, citrus and coffee were the cultures that most increased. Land use of the sampled sites followed the same pattern, with the exception of coffee plantations, which increased 7100% (Figure 4B).

Most of the sampling sites were located within Conservation Units (CUs) (62.6%), especially in State Environmental Protections Areas (EPA's) such as in the Piracicaba-Juqueri Mirim Area I, within the Corumbataí sub-basin (Figure 5A). However, no studies were performed within CUs located in the eastern part of the basin (Sistema Cantareira and Piracicaba-Juqueri Mirim Area II). Although 38.8% of sites were located within high Priority Areas for Conservation in the Cerrado (Corumbataí sub-basin; Itirapina), regions considered of extremely high importance in the western part of the basin (Barra Bonita) and in the Atlantic Forest were not studied at all (Figure 5B). The distribution of sampling sites among biomes was similar, with 55.2% of them located in the Cerrado and 44.7% in the Atlantic Forest (Figure 5B).

Psalidodon fasciatus (Cuvier, 1819), *Hypostomus ancistroides* (Ihering, 1911) and *Rhamdia quelen* (Quoy & Gaimard, 1824) were the constant species registered and occurred in sympatry in most of the sites, even though *P. fasciatus* showed a wider distribution (Figure 5C). On the other hand, all the non-native species, with the exception of *Poecilia reticulata* Peters, 1859*,* were accidental species. They were found mainly in the Piracicaba-Jaguari sub-basin [*Trichomycterus brasiliensis* Lütken,

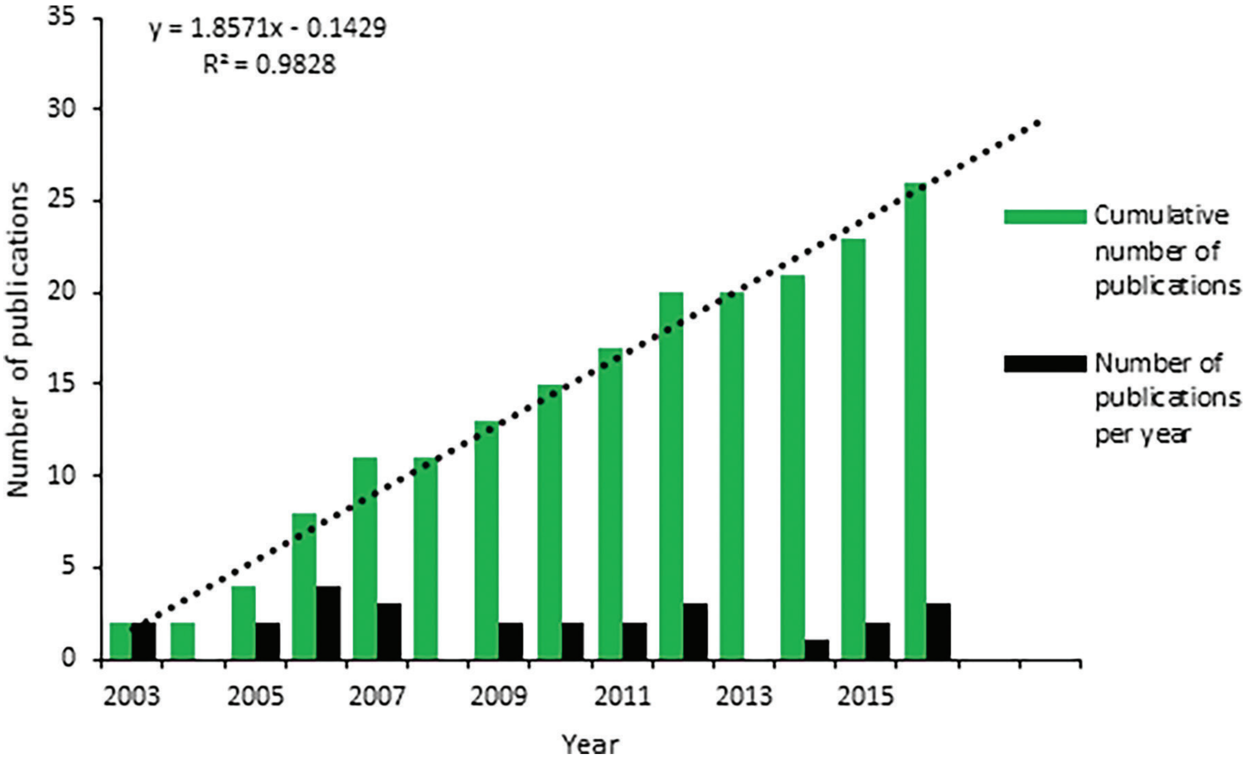

Figure 2. Number of publications per year and cumulative number of publications on stream fishes in the PCJ Basin from 2003 to 2016.

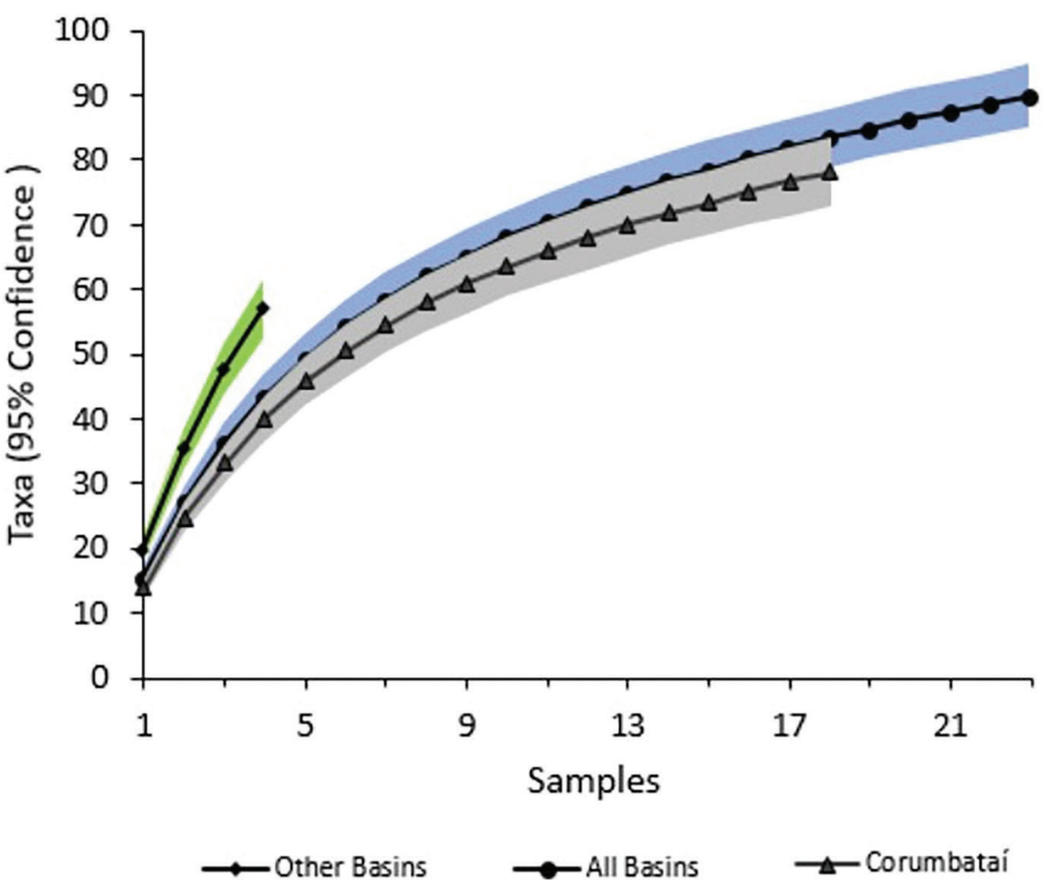

Figure 3. Sample-based rarefaction curves (Mao-Tao) for pooled sites of all studied sub-basins of the PCJ Basin, and separate curves for the Corumbataí and other sub-basins (Atibaia, Jaguari, Piracicaba and Jundiaí).

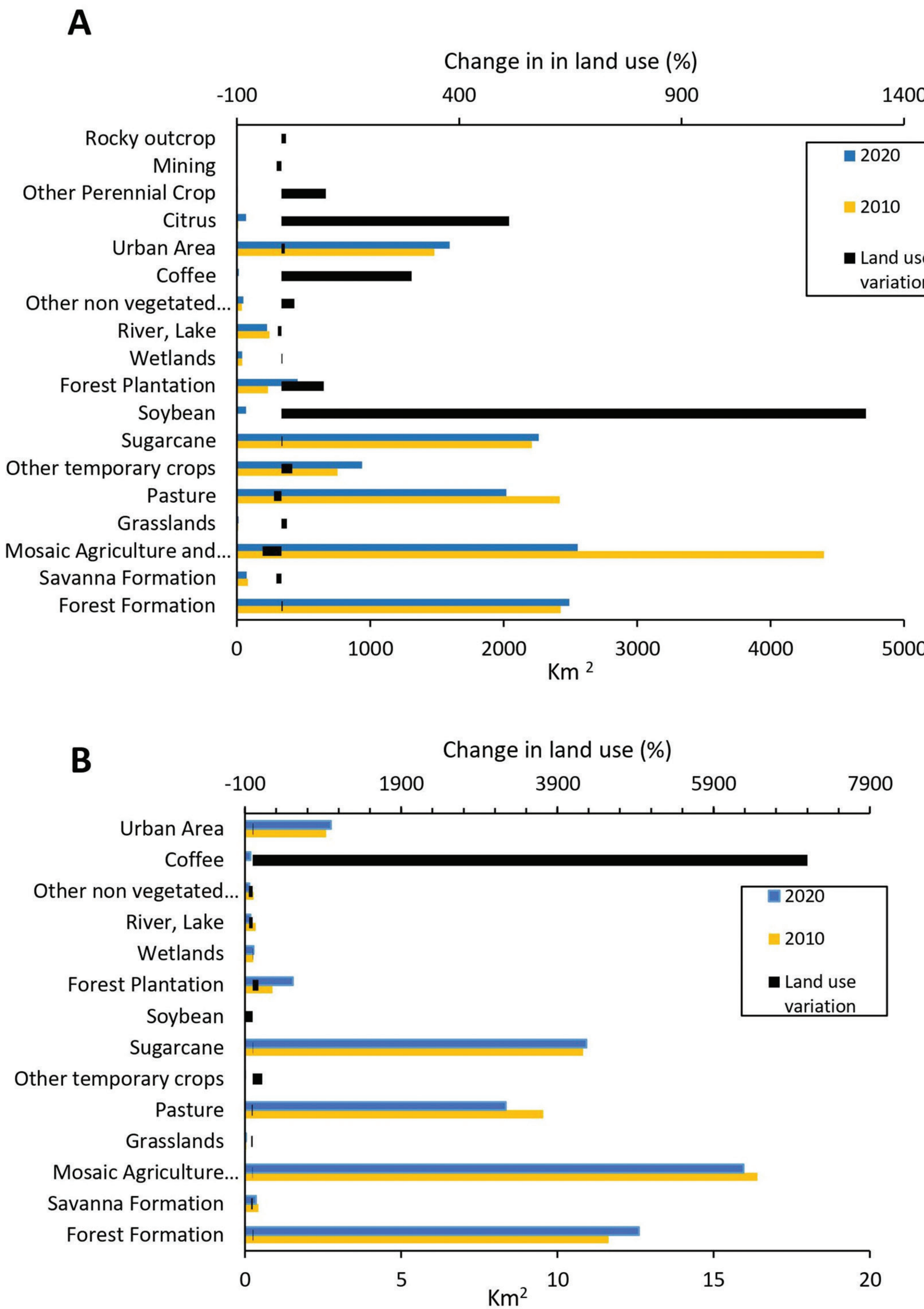

Figure 4. Land cover (km²) in the years 2010 and 2020 and changes in percentage during this period for the whole PCJ Basin (A) and considering 500 m buffers around 67 sampling sites (B).

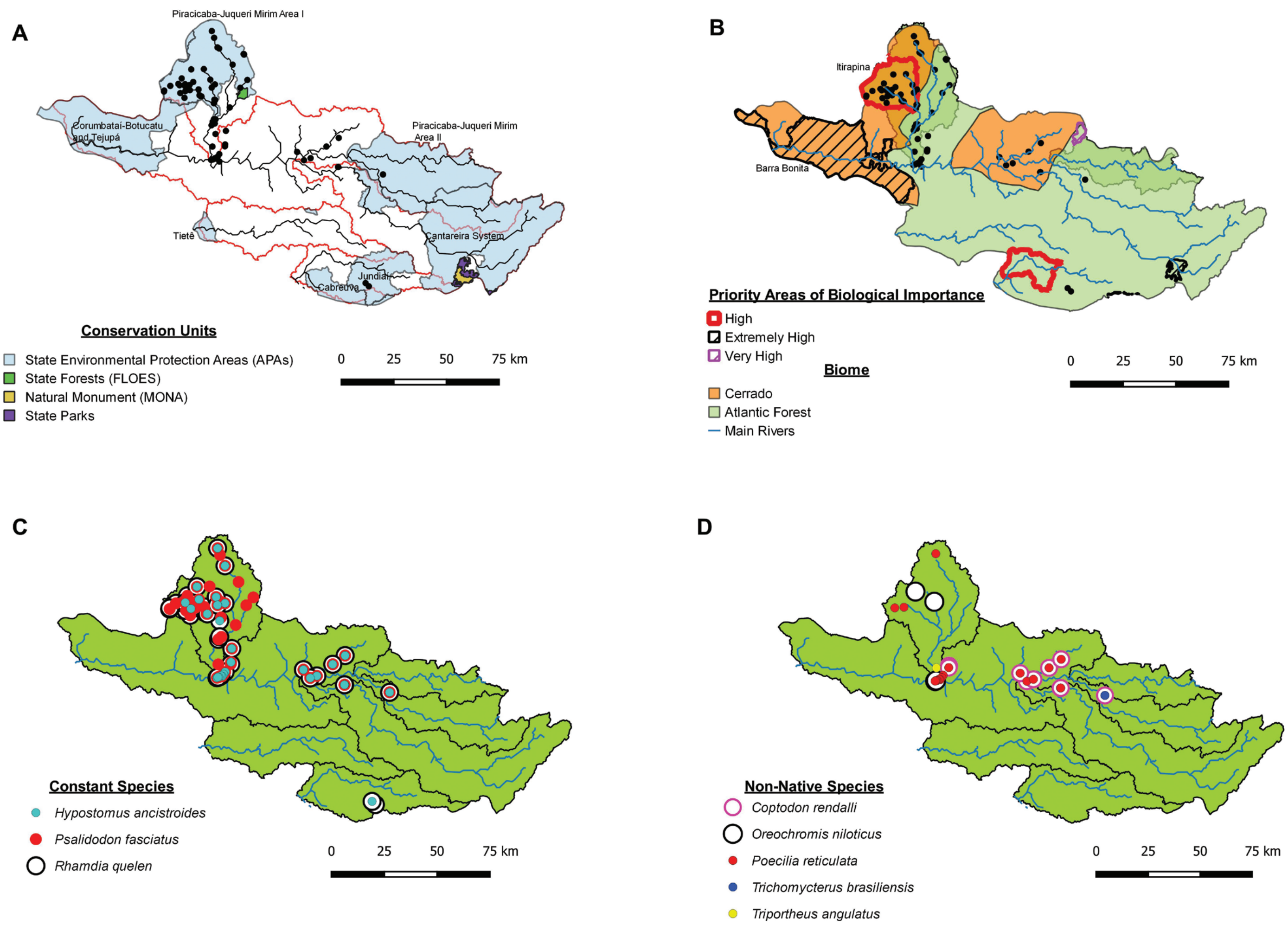

Figure 5. Distribution of 67 sampling sites in the PCJ Basin and in several Conservation Units (A); different biomes and priority Areas of Biological Importance (MMA, 2018) (B); Constant species (C) and non-native species (D). One point can represent more than one locality.

1874*, Coptodon rendalli* (Boulenger 1897) and *Oreochromis niloticus* (Linnaeus 1758)], while *Triportheus angulatus* (Spix & Agassiz 1829) was registered only in the Corumbataí sub-basin (Figure 5D).

Discussion

The present survey showed that studies related to biological and ecological aspects of streams fishes in the PCJ Basin have been carried out during the last 20 years, following the general trends verified for stream fish studies in Brazil (Dias et al. 2016). This increase from the 1990s onwards occurred as a result of the adaptation of specific collection methods for streams, such as electric fishing, as well as the influence of publications that highlighted the importance of stream fishes as a source of diversity in Brazil (Caramaschi et al. 1990). Also, the need for studies on freshwater fish species has been increasing because several assessments suggest that >30% of them are threatened (IUCN 2006).

Nevertheless, the increase in publications in the PCJ Basin has been slow and unevenly distributed among the different sub-basins, focusing mainly on the Corumbataí and Piracicaba-Jaguari sub-basins. This pattern may be related to the proximity of freshwater ecology teams operating from local research centers, as, for example the Instituto de Biociências, Universidade Estadual Paulista, located in Rio Claro, and the University of São Paulo, in the city of Piracicaba. In fact, the close relationship between the presence of universities and number of articles has been verified in other surveys on Brazilian freshwater fishes (Azevedo et al. 2010; Dias et al. 2016; Junqueira et al. 2020), all stressing that more financial and human resources as well as research facilities, have been determinant for the increase in ichthyological studies.

One of the main topic of study involved environmental impacts in particular relation to major problems of the Corumbataí sub-basin. Specifically, this basin suffers significant negative environmental impacts owing to the intensive exploitation of monocultures, especially those associated with the cultivation of sugarcane (Monteiro et al. 2008). Additionally, discharge of industrial and domestic effluents has been frequently reported, especially for the period between 1999 and 2002 (Fischer 2003). A similar situation occurs in the Piracicaba sub-basin, one of the most urbanized watersheds of the state (Comitês PCJ/Agência das Bacias PCJ 2020). Other topics such as diet, reproduction and integrated biological aspects, reflect the need to explore unknown aspects of the life-history of many species, which are fundamental at local scales, helping conservation planning.

Despite the concentration of studies in one sub-basin and the low total sampled area of the PCJ Basin (0.35%), the species database indicated that the number of species registered (89) represents 28.7% of the fish species recorded by Langeani et al. (2007) for the Upper Paraná River Basin, and 34.2% of the species for this basin in the State of São Paulo (Oyakawa & Menezes 2011). The rarefaction curves showed that sampling effort was low, even when considering all sub-basins, suggesting that stream fish richness in the PCJ Basin is considerably higher than the actual numbers. These results are similar to those for fish fauna from the Upper Paraná, which, despite having one of the most studied ichthyofaunas, show species curves that lack any stabilizing trend (Langeani et al. 2007). Thus, we recommend that the less studied areas of the PCJ Basin such as the Atibaia, Camanducaia and Jundiaí sub-basins should be more intensively sampled, especially because of their high proportion of Conservation Units, reaching 96.3% in the Camanducaia sub-basin, followed by the Jaguari (66.5%), Jundiaí (61.7%) and Atibaia (60.5%) sub-basins (Comitês PCJ/Agência das Bacias PCJ 2020).

Land use in the PCJ Basin is strongly influenced by agriculture and pasture, followed by sugarcane and forest formations, a situation also observed for the sampled sites where some crops increased along the period from 2010 to 2020. Thus, impacts on streams are expected since these activities may affect water quality, biodiversity, sedimentation and nutrient levels (Corbi et al. 2006; Riseng et al. 2011). Usually, opportunist fishes become dominant under degraded conditions by the reduction or disappearance of sensitive and specialist species (Clarke & Warwick 1994). This may be the case of the species with wide-range distributions in the basin as *Psalidodon fasciatus*, *R. quelen* and *H. ancistroides*, all of them considered tolerant species (*sensu* Karr 1981) (Alexandre et al. 2010). Nevertheless, the first two species have a wide distribution in Central and South America, while *H. ancistroides* is limited to the Upper Paraná and Tietê River Basins (Buckup et al. 2007).

The number of non-native species was low, a situation which may be related to the fact that a great proportion of the sampling sites were located within State Environmental Protection Areas (EPAs). However, a certain degree of human occupation is allowed within the EPAs, which aim to the conservation of natural processes and biodiversity, adapting the various human activities to the environmental characteristics of the area (Fundação Florestal 2022). Nevertheless, the frequency of non-native species was much lower than that documented for the Upper Paraná Basin (21.6% allochthonous and 2.6% exotic species) by Langeani et al. (2007). This difference could be explained by the habitat type considered in their study, which comprised a variety of ecosystems, including species used for food consumption, fish farming, sport fishing or as baits.

Another important aspect is that 3,700 km^2 of Priority Areas for Conservation (PAC) occur in the PCJ Basin (Comitês PCJ/Agência das Bacias PCJ 2020), but only the Corumbataí sub-basin was sampled. PACs cover areas that should be protecting biological richness, endemisms, various phytophysiognomies and ecosystem services where the existing management instruments are not enough to ensure their conservation (MMA 2018). Nevertheless, the planning of these areas is usually based on terrestrial ecosystems using phytogeographic data based on geomorphology, vegetation, soils and altitude (MMA 2007), which have limited advantages for freshwater species, as pointed out by Leal et al. (2020). According to these authors, when freshwater species are prioritized, more terrestrial species benefit than in the reverse, suggesting that a terrestrial-freshwater conservation approach is recommended.

Incorporating data on freshwater stream fishes into the planning of conservation areas may bring promising approaches for stream fish conservation, as conservation planning relies fundamentally on spatial information about the distribution of biodiversity which is still very limited (Margules & Pressey 2000). Besides recommending further studies in the several sub-basins of the PCJ Basin, new approaches can be used to support the establishment of public policies aimed at the conservation and restoration of the remaining biodiversity. These may include studies aimed to test hypotheses related to ecological concepts and theories, such as landscape ecology, macroecology, macroevolution and climatic changes. Finally, substantial freshwater gains in the PCJ Basin could also benefit from the planning of conservation areas based on integrated terrestrial-freshwater approaches, because of maximum achievable benefits related to this approach.

Supplementary Material

The following online material is available for this article:

Table S1 – List of fish species registered in streams of the Piracicaba, Capivari and Jundiaí River Basins (PCJ), SP, indicating their origin (N – Native; NN – Non Native), Conservation Status (LC – Least Concern; DD – Data Deficient; VU – Vulnerable), and Constancy of Occurrence according to Dajoz (1972). Taxonomic classification based on Fricke et al. (2021).

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Author Contributions

Alexia Almeida Ferraz da Silva: contributed to data collection, data analysis and interpretation and manuscript preparation.

Katharina Eichbaum Esteves: contributed to the concept and design of the study, project supervision, data analysis and manuscript preparation, adding intellectual content.

Conflicts of Interest

The authors declare that they have no conflict of interest related to the publication of this manuscript.

Data Availability

Supporting data are available at <https://doi.org/10.48331/scielodata.ROG2NF>.

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