Environ Biol Fish (2023) 106:2141–2156
https://doi.org/10.1007/s10641-023-01495-x

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Coastal freshwater stream fish fauna from a threatened estuarine lagoon complex in northeastern Brazil

Robert Germano Alves da Silva · **María Angélica Pérez‑Mayorga** · **Renato Mei Romero**

Received: 18 October 2022 / Accepted: 24 November 2023 / Published online: 23 December 2023

Abstract Freshwater ecosystems play a vital role in sustaining human populations; however, these environments are increasingly subject to human interference, driven by land use modifications, species introductions, pollution, and habitat loss. We sampled the ichthyofauna and collected environmental variables from 24 coastal streams in northeastern Brazil. Fish composition, abundance, and biomass served as the response variables, while physicochemical data, hydrological attributes, riparian characteristics, and substrate composition were considered as predictor variables. Our main objective was to evaluate the impact of a riparian land use gradient, ranging from conserved to degraded scenarios (i.e., forested, grassy, and urban streams), on the structure of fish assemblages. To achieve this, the graphical relationship of ABC plots and their *W* values between the three sets of streams was evaluated, and a Hellinger transformation-based Redundancy Analysis (tb-RDA) was conducted and we compared fish composition among the stream categories using a PERMANOVA test. We identified that the *W* values of forested and urban streams were significantly different, indicating a shift from k to r-strategists; the tb-RDA revealed three stream categories: (i) forested streams and their association with *Anablepsoides bahianus* and *Parotocinclus* cf. *jumbo*, (ii) grassy streams and their association with *Poecilia vivipara* and *Astyanax* cf. *bimaculatus*, and (iii) urban streams and their relationship with *Poecilia reticulata* and *Oreochromis niloticus*. We also found important differences between fish composition along the riparian land use gradient, with urban streams showing a significant divergence from grassy and forested streams. We observed a loss of native species and an introduction of exotic species in the evaluated gradient, consistent with the premises of niche theory.

Keywords Environmental stream quality · Disturbance gradient · Indicator species · Mundaú-Manguaba Estuarine Lagoon Complex – MMELC

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10641-023-01495-x.

R. G. A. da Silva (✉) · R. M. Romero
Programa de Pós-Graduação em Tecnologias Ambientais, Instituto Federal de Alagoas, R. Lourival Alfredo, 176, Poeira, Marechal Deodoro, AL 57160-000, Brazil
e-mail: robertgermano7@gmail.com

R. M. Romero
e-mail: renato.romero@ifal.edu.br

M. A. Pérez-Mayorga
Unidad de Ecología en Sistemas Acuáticos UDESA, Universidad Pedagógica y Tecnológica de Colombia UPTC, Av. Central del Norte, Tunja, Colombia
e-mail: angelicarpathian@gmail.com

Introduction

For millennia, freshwater resources have been crucial for human settlements, leading to the proximity of houses, farms, and industries to water bodies (Strayer and Dudgeon 2010). Human interference in these environments is widespread across most landscapes of the world, and certain areas have undergone modifications for hundreds of years (Ligeiro et al. 2013). Land use modifications (Utz et al. 2010), the introduction of alien species, pollution, and habitat loss are some of the primary causes of human interference, contributing to the ongoing sixth vertebrate mass extinction (Ceballos et al. 2015, 2020).

Streams represent interconnected ecosystems intimately linked to their surrounding environment (Karr 1998), where physical habitat factors (Karr and Yoder 2004), physicochemical attributes (Allan 2004), and landscape alterations (Walsh et al. 2005) collectively influence the ecological structure of biological communities. As streams are intricately connected to historical and current activities within their watersheds (Harding et al. 1998; Gergel et al. 2002), they can undergo significant degradation at various temporal and spatial scales due to land use changes (Allan 2004). Symptoms of the urban stream syndrome include a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology, and reduced biotic richness, with increased dominance of tolerant species (Walsh et al. 2005). The synergistic interplay of these characteristics positions fish stream communities as highly reliable indicators for comprehensive assessments of aquatic ecosystem health (Karr et al. 1986; Otero et al. 2006; Jia and Chen 2013).

Freshwater ecosystems in South America, especially along the Brazilian coast, are characterized by limited legal regulations and face significant threats (Reis et al. 2016). The Atlantic Forest is the primary ecosystem in this region of the country and is also recognized as a biodiversity hotspot (Myers et al. 2000). Northeastern Brazil is a particularly significant biogeographic province, characterized by numerous isolated drainages and a rich endemic ichthyofauna (Ribeiro 2006), which presents a growing challenge for the study of fishes and their habitats amidst rapid anthropogenic changes in the twenty-first century. These anthropogenic changes can also affect the selection of fish species in accordance with their life strategies (Casatti et al. 2006; Moniruzzaman et al. 2021).

The region of Mundaú-Manguaba Estuarine Lagoon Complex (MMELC) in Alagoas state has an estuary region of remarkable environmental and scenic importance. It has a history of human occupation spanning 400 years, driven by its proximity to the state capital (Souza et al. 2004). However, it is currently undergoing urbanization processes and experiencing associated impacts (Walsh et al. 2005). This location encompasses a fragmented landscape comprising preserved forests, agricultural farms, urban housing, industrial zones, and mining areas (Marques 1991; Araújo and Calado 2008; Melo-Magalhães et al. 2009; Cotovicz Junior et al. 2012; Menezes et al. 2012; Guimarães Junior et al. 2017; Santos et al. 2021; Teles 2023). The water resources from MMELC serve as an irrigation source for sugar cane plantations, sugar-alcohol, and petrochemical industries, and it holds enormous potential for the region's tourism sector. It is a vital ecosystem that directly sustains approximately 260 thousand residents in its surrounding areas (Araújo et al. 2011) and indirectly benefits a population of around one million people living in cities connected to it (IBGE 2020).

This study represents the first quantitative ichthyological baseline on streams of the MMELC and serves as a model of studies for other similar environments. The main objective proposed was to evaluate the impact of a riparian land use gradient ranging from conserved to degraded scenarios (i.e., forested, grassy, and urban streams) in fish assemblages of Atlantic forest watershed. To achieve this, we conducted analyses focusing on (i) differences in species composition between the three stream categories, (ii) shifts on a classical evolutionary theory of r and k selection strategies adopted by that fish assemblages, and (iii) the relationship between fish numerical abundances and stream environmental variables (physicochemical, hydrological, riparian, and substrate composition).

We are based on the principles of niche theory proposed by Hutchinson (1957), redefined by Leibold (1995), and revised by Pocheville (2015) and on the elements of the urban stream syndrome (Walsh et al. 2005) to propose our hypothesis. We postulate that a gradient in riparian land use will reflect differences in the fish composition, with a dominance of r-strategist species that exhibit a graphical uplift pattern on the abundance curve in degraded ecosystems (urban and grassy streams), while k-strategist species exhibit a graphical uplift pattern on the biomass curve in conserved environments (forested streams). We also expect that different relationships will be observed between environmental variables and fish numerical abundances in each land use scenario. We hope that this approach enables us to identify potential biological indicators and tools for monitoring this watershed.

Material and methods

Study area

The Mundaú-Manguaba Estuarine Complex (MMELC) is a neotropical estuarine complex located in Alagoas, Brazil. It is situated between coordinates 9° 35′ S and 9° 45′ S and 35° 44′ W to 35° 58′ W. The complex can be characterized as a bar estuary (Wilson 1998), where a semi-continuous structure of sandstone and sand restricts the exchange of water between the ocean and the lagoon, resulting in the formation of a diverse biological community (Fig. 1).

The lower portion of MMELC includes, in addition to the state capital Maceió, the municipalities Santa Luzia do Norte, Coqueiro Seco, Pilar, Satuba, and Marechal Deodoro (Guimarães Junior et al. 2017). The region is composed of the Mundaú lagoon (27 km^2) and Manguaba lagoons (42 km^2) and a region of connecting channels (12 km^2) (Menezes et al. 2012). It is one of the main aquatic ecosystems of the state, characterized by its vast spatial extension, ecosystem diversity, and high regional economic relevance (Souza et al. 2004). The downstream portion of MMELC features a coastal plain supported by a tertiary plateau with heights ranging from 50 to 100 m (Ribeiro et al. 2011). The climate is hot and humid, with an average annual temperature of 24 °C (Silva

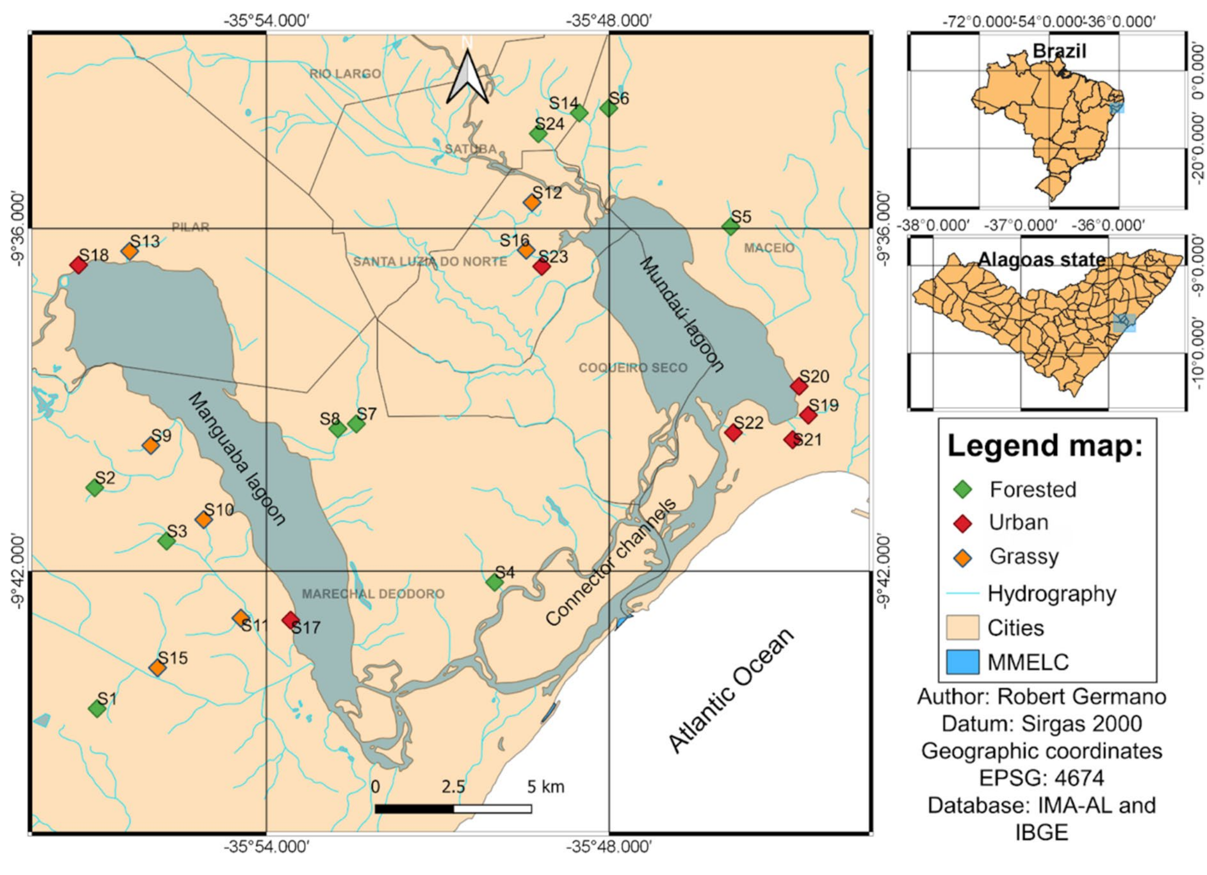

Fig. 1 Location of MMELC in the state of Alagoas (Brazil) (top right) and location of the 24 sampling sites

and Souza 2008). It experiences two well-defined seasons: a rainy season from March to August and a dry season from September to February (Araújo and Calado 2008; Menezes et al. 2012).

The MMELC watershed exhibits diversified riparian land use, including urban areas, industrial zones (chlorochemical, mining, and oil companies), agricultural areas (sugar cane cultivation), and some remnants of Atlantic forest fragments confined to protected areas, such as Catolé-Fernão Velho Environmental Protection Area, Santa Rita Environmental Protection Area, Saco da Pedra Ecological Reserve, Maceió Municipal Park, and several private reserves (Bernard et al. 2011; Guimarães Junior et al. 2017). According to ANA (2006), these watersheds are composed of several small drainages of clear water streams that collectively support multiple cities by providing essential water resources.

Sampling sites

In this study, 24 coastal freshwater streams within the MMELC drainage were selected based on the following criteria: first and second-order streams, permanent flow, similarity between sampled stretches, accessibility, and feasibility of collection (maximum depth up to 1.3 m). The sampled streams were categorized into three riparian land use types: ten streams with a predominance of tree vegetation in the riparian buffer (forested), seven streams with shrub and grassy vegetation (grassy), and seven streams with a predominance of urban occupation and exposed soil (urban) (Fig. 2). The inclusion criteria in this category were based on the highest land use percentage within a radius of 1.6 km (Roth et al. 1996). Data on riparian land use were obtained using Google Earth and QGIS tools in order to generate three stream categories. All samplings took place during the dry period. Streams S1 to S16 were sampled in December 2017, and streams S17 to S24 were sampled in November and December 2018.

Sampling of environmental variables

A stream stretch of 80 m was selected in each location, which was divided into transversal transects every 20 m to characterize the hydrological variables: channel width (cm), depth (cm), and velocity (m/s), using FL K2 hydrometric reel. Variables describe riparian composition (grasses, shrubs, trees, exposed soil, sugar cane, bamboo, fine roots, and coarse roots) and substrate composition (silt, sand, gravel, pebble, rock, slab, coarse litter, fine litter, branches and trunks, and decaying substrate). Riparian and substrate composition were obtained through direct observation and quantified as percentage of occupation in each transect along the stream stretch. The average was taken for all environmental variables.

At each sampling stretch, the following physical and chemical parameters were analyzed on-site: pH, temperature (°C), conductivity (μm/cm), and dissolved oxygen (mg.L-1), using METROHM pH meter (826 pH) and portable HANNA oximeter (HI 9146). For the determination of thermotolerant coliforms, water was collected at a fixed point of the stretch using 250 mL sterile and autoclavable plastic bottles. The collected samples were kept under refrigeration at 4 ± 2 °C (APHA 2017) and later analyzed using the most probable number method for thermotolerant coliforms in 100 mL "SMEWW 23rd 2017 9221 B / E" Standard Methods for the Examination of Water and Wastewater (APHA 2017).

For the other chemical variables, a composite sample was collected by mixing several subsamples from the four transects defined in the stretch. The composite sample was collected in a 20-L plastic bucket and then transferred to 1.0-L PET bottles, along with their respective preservatives, for laboratory analyses. Before samples were added, the bottles were homogenized by mixing them with water from the corresponding stretch of each sample.

Samples were sent to the environmental analysis laboratory of "Qualitex Engenharia e Serviços" company for processing. The following parameters were analyzed: total solids, oils and greases, chlorophyll a, ammonia nitrogen, chemical oxygen demand, biochemical oxygen demand, total hardness, nitrate, salinity, chlorides, true color, total dissolved solids, total sulfate, total alkalinity, total phosphorus, mercury, aluminum, and iron. The analysis was conducted using methodologies described in the Standard Methods for the Examination of Water and Wastewater (APHA 2017).

Sampling of biological variables

To collect fish specimens, an electric fishing equipment (220 V AC current, 50–60 Hz, 3.4–4.1 A, 1000

Fig. 2 Sampled sections showing the riparian land use in the riparian stream. Forested streams: S1, S2, S3, S4, S5, S6, S7, S8, S14, and S24. Grassy streams: S9, S10, S11, S12, S13, S15, and S16. Urban streams: S17, S18, S19, S20, S21, S22, and S23

W) was used for 45 min in the same delimited stream stretch of 80 m, and each stretch was sampled only once. Collected specimens were anesthetized with eugenol (CONCEA 2018), fixed in 10% formalin (after a minimum of 48 h), and subsequently preserved in 70% ethanol. Fish identifications were verified by specialists (Fernando Rogério de Carvalho—UFMS and Francisco Langeani Neto – UNESP/SJRP). The biotic data has been grouped, biomass was measured, and specimens were counted before being deposited in the fish collection of the São Paulo State University, campus of São José do Rio Preto (DZSJRP 21208–21315; 22,719–22,721).

Statistical analysis

To assess sample representativeness, we compared the Coleman Rarefaction curve with non-parametric species richness estimators: incidence coverage estimate (ICE) and abundance coverage estimate (ACE) (Colwell and Coddington 1994), using the *fossil* package (Vavrek 2011) (Supplemental Script 1). The comparative graphical relationship of the abundance biomass curve (ABC) used in the present study was proposed by Warwick (1986) for the diagnosis of pollution in marine environments. In addition to the graphical pattern, the method provides the *W* value which enables the classification of the streams.

The ABC plots and *W* value have a theoretical background in the classical evolutionary theory of r- and k-selection (Yemane et al. 2005) and demonstrate the influence of the physical, chemical, and riparian land use predictors on the ichthyofauna (Clarke and Warwick 1994; Casatti et al. 2006) including in this study region. The concepts of r-strategist species (small generalists with rapid sexual maturation, reproduction, and growth) and k-strategist species (large specialists with slow sexual maturation, reproduction, and growth) (Pianka 1970). The *W* value ranges from -1 to 1, where negative values indicate environmental disturbance, positive values indicate the absence of environmental disturbance, and values close to zero imply moderate disturbance (Warwick 1986; Warwick et al. 1987; Warwick and Clarke 1994; Magurran 2005). To obtain the ABC graphs and *W* values for each stream category, the dataset (abundances and biomass) was transformed with the fourth root method. For this analysis, the *forams* package (Aluizio 2015) was used (Supplemental Script 2). To test differences in *W* values between stream categories, a Kruskal–Wallis *H* test and post hoc analysis with Dunn test (with *p* values adjusted with the Bonferroni method) were conducted. These analyses utilized the *FSA* (Ogle et al. 2023), *lattice* (Sarkar 2008), and *rcompanion* (Mangiafico 2023) packages (Supplemental Script 3). Non-parametric statistical tests were used due to violations of the assumptions of normality and homoscedasticity required for parametric analysis. Levene's test was used to check for homogeneity of variances, while the Shapiro–Wilk test was used to assess normality.

To determine the potential selection strategy for each species, we examined the pattern of ABC curves for each fish species, as proposed by Casatti et al. (2006). Additionally, we conducted a literature review of their life history attributes, including body size, feeding habits, and reproductive strategies (Pianka 1970). Based on these criteria, we classified species according to their tendency to r-strategists or k-strategists. R-strategists were characterized by their contribution in abundance overlapping biomass, small body size, broad trophic plasticity, and low reproductive requirements. Conversely, k-strategists were characterized by their contribution in biomass overlapping abundances, larger body size, specific trophic preferences, and high reproductive requirements.

To reveal gradients in the composition of physical and chemical variables between riparian land use types and species-variable relationships, transformation-based Redundancy Analysis (tb-RDA) was performed (ter Braak and Smilauer 2012) (Supplemental Script 4). Thus, the relative importance of environmental variables in the composition of the fish assemblage by riparian land use was estimated. This method extracts and summarizes the relationship between response and explanatory variables (Legendre and Legendre 1998). All abundance data were transformed using Hellinger series, and all 44 environmental variables collected (Supplemental Table 1) were normalized and arranged in a similarity matrix. Some variables, such as fine and thick roots, sugar cane, bamboo, silt, gravel, pebble, fine litter, thick litter, branches and trunks, decomposing material, slab, chlorophyll a, oils and greases, chemical oxygen demand, total hardness, salinity, solids total dissolved substances, turbidity, alkalinity, and aluminum, were removed due to the positive correlations with the other variables ($r \geq 0.65$, $p < 0.005$). The resulting 21 variables underwent a forward selection procedure (Blanchet et al. 2008), resulting in the removal of variables such as width, speed, conductivity, biochemical demand for oxygen, chlorides, color, sulfate, phosphorus, and total solids. At the end of the selection procedure, 13 variables were retained: depth, dissolved oxygen, mercury, iron, thermotolerant coliforms, pH, nitrogen, rock, exposed soil, sand, nitrate, riparian tree, and shrub cover. An analysis of variance (ANOVA) was used to test the significance of tb-RDA. For these analyses (tb-RDA, correlation matrix, forward selection, and ANOVA), the *vegan* package (Oksanen et al. 2019) was utilized.

To evaluate the variation in fish species abundance among the stream categories, a non-parametric multivariate analysis method (PERMANOVA with Bray Curtis distances) was employed and was followed by a post hoc pairwise comparison of the Bray

Curtis dissimilarity matrices generated by the PERMANOVA analysis (Supplemental Script 5). The PERMANOVA analysis function from the vegan package (Oksanen 2007) and the post hoc pairwise tests were performed using the Adonis function (Martinez-Arbizu 2020). PERMANOVA, as a statistical technique, accounts for the multivariate structure of ecological data and enables testing for significant differences in species abundance. In this study, all analyses were conducted using R version 4.0.4 (Development Core Team R 2011).

Results

Overall, 33,191 fish specimens were collected, belonging to nine orders, 17 families, 22 genera, and 24 species (Supplemental Table 2). Overall, 17,324 g of fish humid biomass (Supplemental Table 3). The estimated richness with ICE and ACE was 24 species for both, indicating a representative sampling. In forested streams, 1,997 individuals were collected and distributed among 14 families and 19 species, two of which were exclusive (*Parotocinclus* cf. *jumbo* and *Anablepsoides bahianus*). In grassy streams, 1694 fishes were captured and distributed among 15 families, with 21 species, five of which were exclusive (*Serrapinnus piaba*, *Awaous tajasica*, *Hyphessobrycon eques*, *Microphis lineatus*, and *Eleotris pisonis*). In urban streams, 29,500 specimens were collected and distributed among seven families and eight species, without exclusive species. Cyprinodontiformes dominated in abundance in urban streams, especially *Poecilia reticulata*, which had a high abundance in six of them. Among all species collected, six were present in the three riparian land uses (*Astyanax* cf. *bimaculatus*, *Hoplias* cf. *brasiliensis*, *Callichthys callichthys*, *Rhamdia* aff. *quelen*, *Poecilia reticulata*, *Poecilia vivipara*, and *Synbranchus* aff. *madeirae*).

Forested and grassy streams were considered as environments with low disturbances according to ABC plots (Fig. 3), with a *W* statistic value close to zero but positive and different from urban sites. Urban streams were classified as environmentally disturbed, according to the negative values of the *W* and the ABC graphical pattern. According to the Kruskal–Wallis *H* test, there was a significant difference between the three categories of streams ($H(2)=6.98$, $p=0.0305$) (Fig. 4), and the only significative difference was found between forested and urban streams ($p=0.0259$).

The eigenvalues of two first constrained axes ($r^2=0.40$) in the tb-RDA were significant ($p=0.001$ and $p=0.049$) (Table 1) and the variance of significance test of tb-RDA (ANOVA) was also significant ($r^2=0.51$, $p=0.001$) (Table 2 and Fig. 5).

Forested streams were associated with high scores of instream descriptors as rocky substrate

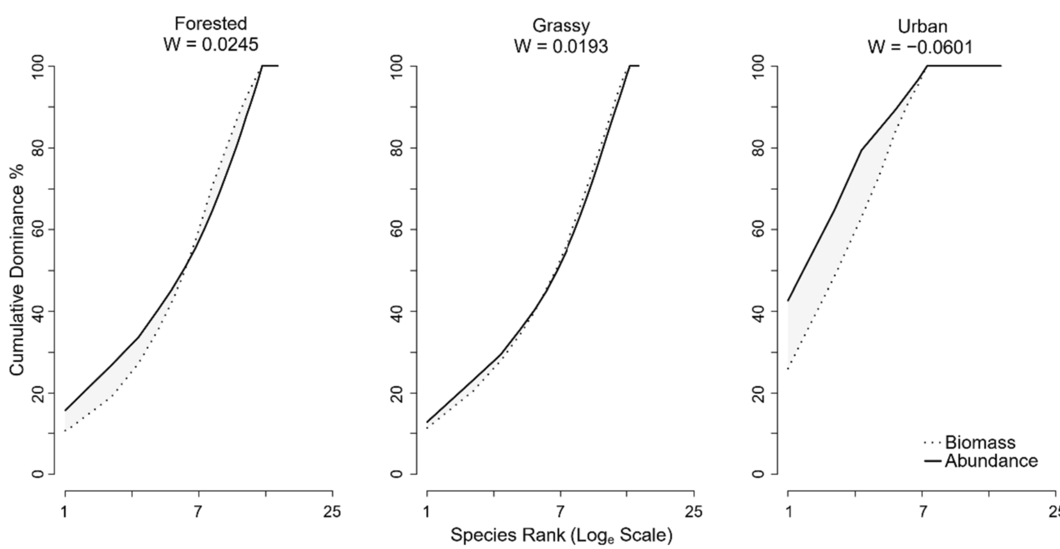

Fig. 3 Abundance and biomass curves (ABC) with *W* values of forested, grassy, and urban streams

Environ Biol Fish (2023) 106:2141–2156

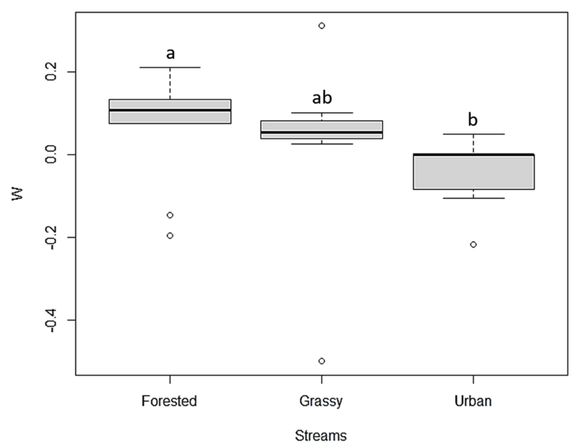

Fig. 4 Boxplot for the values obtained in the *W* statistic for each riparian land use category. Averages followed by the same letter do not differ significantly by the Kruskal–Wallis H test and the post hoc analysis Dunn test

Table 1 Permutation test for transformed-based Redundancy Analysis (tb-RDA) under reduced model. Significance codes (*) when $p < 0.05$

	Df	Variance	F	Pr(> F)
RDA1	1	0.3090	27.8494	0.001*
RDA2	1	0.0930	8.3801	0.042 *
RDA3	1	0.0549	4.9472	0.405
RDA4	1	0.0228	2.0555	0.962
RDA5	1	0.0122	1.1010	1.000
RDA6	1	0.0092	0.8270	1.000
RDA7	1	0.0058	0.5265	1.000
RDA8	1	0.0033	0.2981	1.000
RDA9	1	0.0020	0.1772	1.000
RDA10	1	0.0012	0.1040	1.000
RDA11	1	0.0010	0.0924	1.000
RDA12	1	0.0006	0.0561	1.000
RDA13	1	0.0005	0.0409	1.000
Residual	10	0.1110		

Table 2 Analysis of variance (ANOVA) applied to transformed-based Redundancy Analysis (tb-RDA). Significance codes (*) when $p < 0.05$

	Df	Variance	F	Pr(> F)
Model	13	0.515	3.754	0.001 *
Residual	10	0.111		

and dissolved oxygen. In this set of streams, the presence of *A. bahianus* was exclusive. The grassy streams were associated with the physical attributes such as sand substrate and channel depth, and the abundance of *A.* cf. *bimaculatus* was considerable. *Poecilia vivipara* was associated with the transition from grassy to urban environments, showing a strong relationship with iron concentrations, especially in S23 stream. Urban streams were associated with thermotolerant coliforms and chemical predictors such as nitrate, iron, mercury, and nitrogen, as well as pH values and the presence of *P. reticulata* (Fig. 5).

The PERMANOVA demonstrated that the fish species abundance was significantly different between the three stream categories ($r^2 = 0.34$, $p = 0.001$) (Table 3). In the pairwise comparisons (Table 4), significant differences were observed between urban and the other categories of streams.

Discussion

Our study revealed a specious-rich, diverse, and poorly studied ichthyofauna that responded to the environmental gradient in riparian land use, showing consistent differences in fish composition and abundance among forested, grassy, and urban streams. The numerical abundance of fish in urban streams was nearly 15 times higher than in other stream categories, primarily influenced by exotic Cyprinodontiformes. Additionally, forested and grassy streams shared the majority of recorded fish species, highlighting the similarity between these two environmental types. Studies that have evaluated the diversity of ichthyofauna in streams with presence of trees have reported that greater habitat complexity is associated with higher species richness compared to other types of ecosystems (Curtean-Banaduc and Banaduc 2017; Brejão et al. 2018; Virgilio et al. 2018), and this situation could be seen in this study, particularly when we group forest and grassy streams in comparison to urban ones.

In degraded ecosystems, r-strategist species, dominant in abundance, are more present, influencing the overlap of the abundance curve on the graph; while in conserved environments, there is a predominance of k-strategist species that exhibit a graphical uplift pattern on the biomass curve. Despite having different characteristics, forested and grassy environments

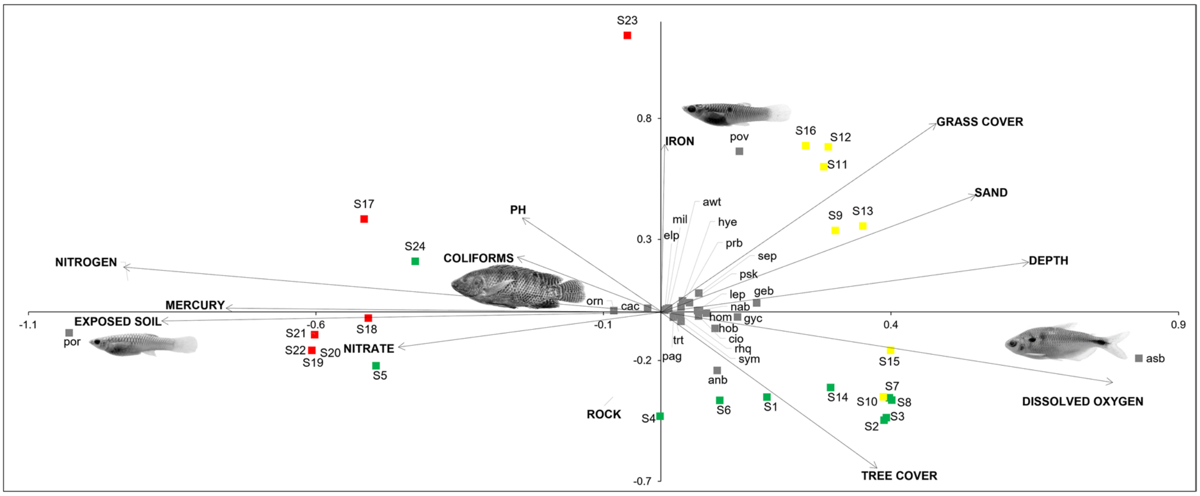

Fig. 5 Ordination biplot for the transformed-based Redundancy Analysis (tb-RDA). Arrows represent the predictor scores. Green, yellow, and red squares are site scores of forested, grassy, and urban streams, respectively. Gray squares are species scores; the species codes are explained in Supplemental Table 2

showed a similar pattern on ABC plots and W values closely clustered and close to zero, with a tendency towards moderately impaired scenarios. Aside from that, grassy and urban streams were also closely related. It is concerning because it shows that forested streams are losing their original characteristics and turning into more disturbed environments, similar to grassy environments, that receive a great physical disturbance. The *W* values for urban streams showed a pattern where k-strategist species are practically absent, and the r-strategists like the exotic *P. reticulata* become dominant in terms of abundance. Exotic species are those species present in a habitat but not native to it (Blanco and Basanta 2015) and tend to be more tolerant of habitat modification and chemical pollution, and this is especially true for the globally distributed species *P. reticulata* (Kennard et al. 2005).

Table 3 Result of PERMANOVA (permutation test for Adonis under reduced model) with 999 permutations; the distances were calculated with the Bray Curtis method. Correlation is considered significant (*) when $p<0.05$

	Df	Sum of squares	R^2	F	Pr(> F)
Stream categories	2	2.5914	0.33971	5.402	0.001 *
Residual	21	5.0369	0.66029		
Total	23	7.6283	1.00000		

The analysis of tb-RDA supports the predetermined three sets of streams and reinforces the relationship between species with specific environmental variables:

(a) Forested streams were characterized by a heterogeneous habitat with two exclusive species, *A. bahianus* and *P.* cf. *jumbo*, where their presence could be considered an indicator of a more con-

Table 4 Pairwise correlation between species abundance composition for three riparian land use groups. Correlation is considered significant (*) when $p<0.05$

Pairs	Df	Sum of squares	*F*. model	R^2	*p*.value	*p*.adjusted
Forested × Grassy	1	0.422310	2.029615	0.1191815	0.094	0.282
Forested × Urban	1	1.798920	9.721251	0.3932346	0.003	0.009*
Grassy × Urban	1	1.847336	13.638196	0.5319484	0.001	0.003*

served environment. Both species have special adaptations to live in forested streams, marked by the presence of rocky substrate and high dissolved oxygen concentrations, as found by Costa (2008) in other Atlantic Forest streams. The *Parotocinclus* genus was also recorded in streams with gravel bottom, clear, shallow, moderate flowing, and high oxygenated waters (Garavello 1977; Sarmento-Soares et al. 2009). These data corroborate other studies that evaluate the biodiversity in freshwater environments with tree cover, confirming that riparian tree vegetation provides greater habitat complexity (i.e., roots, submerged, woody debris, and deciduous leaves) providing micro and meso-habitats that favor rare species in terms of abundance and consequently increase the total richness of fish species (Curtean-Banaduc and Banaduc 2017; Brejão et al. 2018; Virgilio et al. 2018)

(b) Grassy streams were characterized by the dominance of *A*. cf. *bimaculatus* and *P. vivipara* and influenced by the descriptors channel depth, sand substrate, and grass cover. Both species are considered generalists, presenting wide niche breadth (Silva-Camacho et al. 2014) and have omnivorous diets, feeding on aquatic and terrestrial invertebrates, detritus, plants, and insect larvae (Neves and Monteiro 2003). Luke et al. (2019) report that, although the structure of fish communities in grassy/shrubby riparian streams is more similar to those in reference forests, effects on species richness, abundance, and biomass can still be observed, which is also evident in this study. Water depth is an important abiotic factor influencing fish dominance in terms of biomass (Souza et al. 2008), and in our study, this pattern is likely related to channel erosion and siltation process. We also observed other generalist species associated with grassy streams, such as *S. piaba*, *G.* cf. *brasiliensis*, and *P. kennedyi*, which further reinforces the advantage of this feeding habit in environmentally disturbed scenarios. A similar pattern of dominance by generalist species was reported by Casatti et al. (2009)

(c) Urban streams showed low fish richness compared to grassy and forested streams, with dominance in terms of abundance of generalists, tolerant, and exotic species, such as *P. reticulata* and *O. niloticus*. This environmental pattern is strongly associated with environmental disturbance and ongoing impact (Walrath et al. 2016; Ruaro et al. 2018). Impaired streams have poor food availability, favoring species with flexible diets and specialized reproductive strategies that are less vulnerable to environmental degradation (Cruz et al. 2013). *Poecilia reticulata* and *O. niloticus* are considered exotic species capable of surviving in highly contaminated environments (Yesilbudak and Erdem 2014; Gomes-Silva et al. 2020). These species were associated with the descriptors nitrate, nitrogen, iron, mercury, pH, and thermotolerant coliforms. In this context, urban activities contribute to the deposition of nitrogen compounds, heavy metals, fecal contamination, and altered pH values, mainly due to the suppression of riparian vegetation and sewage discharge (Buda and Dewalle 2009; Kaushal et al. 2011; Connor et al. 2014; Wang et al. 2014; Crisigiovanni et al. 2020). The urban streams studied align with the pattern suggested by Hale et al. (2014) where human activities increase disturbances that can alter chemical and physical characteristics of the water body, which in turn influence biological characteristics. Miller et al. (2021) observed significant changes in the functional composition of fish assemblages in response to urbanization, favoring detritivory species with hypoxia tolerance, while ruralization favored only the herbivory feeding habit

The results of the PERMANOVA pairwise post hoc analysis confirm significant differences between forested and grassy streams when compared to the urban streams group. This distinction is reinforced by the graphical positioning of the majority of forested and grassy streams, situated on an axis opposite to that of urban streams. Studies that associate species with land use gradients mainly consider the trophic habit of species (generalists or specialists), demonstrating the importance of understanding how the fish fauna structure responds to gradients (Allan 2004; Casatti et al. 2010, 2012; Teresa and Romero 2010; Pease et al. 2015; Ortega et al. 2021). The combination of methodologies performed in this study reveals structural differences in the fish community related to riparian land uses in the MMELC, and the high abundance of *P. reticulata* and *O.*

niloticus is considered an indicator of poor water quality in this condition.

In describing and comparing the relationship between fish fauna community structure and environmental variables (physicochemical, hydrological, riparian, and substrate composition), we found different responses of the ichthyofauna (composition, abundance, and biomass) to environmental disturbances. This can be explained in the light of niche theory (Hutchinson 1957; Leibold 1995), which considers the niche as a visualization of the ecological mechanisms, the conjunction of the responses to, and of the impacts on, the environmental factors. In this study, we found that the land use types act as an environmental filter that determines habitat and mesohabitat characteristics, selecting the fish species pool. Our findings underscore the significance of riparian vegetation cover, affirming the correlation between the ecotone and ichthyofauna, as discussed by Casatti et al. (2009). The existence of riparian vegetation in lotic environments is linked to heightened diversity and habitat complexity, offering optimal conditions for sustaining aquatic biodiversity, even in moderately impaired scenarios.

In a present scenario of urban expansion and the lack of conservation initiatives, we proposed that the entire MMELC region could be negatively affected by the urban stream syndrome (Walsh et al. 2005; Booth et al. 2016). This worldwide phenomenon considers that human changes in land and riverscapes directly affect fish communities, leading to the loss of sensitive taxa and the substitution and increase of tolerant and exotic species (Walters et al. 2003; Komínková 2012), as was evident in this study.

With the data obtained in this study, it is possible to affirm that especially the Cyprinodontiformes have a better response to the gradients of land use, with the poeciliids being rarely found in the stretches with good physical evaluation, where there is the presence of the Rivulidae member *A. bahianus*. In streams with predominance of grassy vegetation, there were only poeciliids, with few individuals of the species *P. reticulata* and an abundance of *P. vivipara*. In the urban streams with a high level of environmental disturbance, the population structure of these two species was inverted, *P. vivipara* was rarely present, and *P. reticulata* showed a high abundance, being sampled in all stretches of the category.

We consider that these fish species respond to a gradient of degradation (forested, grassy, and urban streams), constituting the observation of their presence and abundance as bioindicators for the environmental quality of streams. Recent studies have confirmed this pattern with the high presence of the alien species *P. reticulata* and a decrease in native fish species in highly degraded urban streams (Miller et al. 2021; Ortega et al. 2021). It was confirmed that fish are good indicators and are considered as "sentinels of the environment" (Karr 1998), and we proposed a set of species that could be used as indicators of water quality in coastal tropical streams from northeastern Brazil.

Moreover, it can be anticipated that a significant decline in fish species richness and the degradation of stream habitat will result in the loss of various ecosystem goods and services that are beneficial to human populations (Colvin et al. 2019). These include, among others, essential resources like clean water and food, as well as the regulation of microclimates and the esthetic value derived from the natural environment (Ferreira et al. 2023). We expect that this approach could support future initiatives of conservation and management of degraded coastal streams to restore the ecosystem goods and services vital to us.

Acknowledgements This study was made possible by funding provided by the Fundação de Amparo à Pesquisa de Alagoas (FAPEAL – Proc. 60030 995/2016). MAPM receives research support from Ministerio de Ciencia, Tecnología e Innovación, MinCiencias, and UPTC (Research call: # 848–2019; Research project code: SGI–3000). The authors thank Fabricio Barreto Teresa for their comments about statistical analysis, Frederico Passos for their help with R software routines, Fernando Rogério de Carvalho and Francisco Langeani Neto for their assistance with fish identification, Jouel Bruno de Souza Lima for their contribution to the construction of electric fishing equipment, and Lilian Casatti and Maurício Cetra for pushing us forward, reviewers, and chief editors for their careful and precise assessment. We also thank our colleagues Michel Santos, Robert França, and Alexandre Lopes for their assistance in the field work and Marina Pascoalino and Angelo Manzotti for their photographic registers. We thank the IFAL for funding the manuscript translation and for logistical support.

Funding Fapeal, 60030 995/2016, Renato De Mei Romero, Ministerio de Ciencia, Tecnología e Innovación, # 848–2019, María Angélica Pérez-Mayorga

Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval All applicable international, national, and/or institutional guidelines for the care and use of animals were followed. The fish collection and transport were authorized by The Chico Mendes Institute for Biodiversity Conservation-ICMBio (Biodiversity Authorization and Information System-SISBIO license 60910–1, 26/Oct/2017).

Conflict of interest The authors declare no competing interests.

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