



Environmental degradation and its consequences for biological diversity in urban streams of the Southwestern Amazon

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Abstract

Urban expansion and intensified human activities have threatened the integrity of small lotic ecosystems, particularly in high biodiversity regions such as the Amazon. This study investigated the influence of habitat quality on the biological diversity of urban streams (locally known as “*igarapés*”) in the Southwestern Amazon, focusing on the fish communities, aquatic insects of the Odonata order, and EPT (Ephemeroptera, Plecoptera, and Trichoptera) in 10 *igarapés* in Porto Velho, Rondônia, Brazil. The results revealed that preserved *igarapés* exhibited higher diversity, richness, and evenness, indicating environments which are more favorable to native biodiversity. Conversely, degraded habitats showed a high dominance of opportunistic and non-native species, such as *Poecilia reticulata*, reflecting the impacts of environmental degradation. Habitat integrity and canopy cover were identified as key variables influencing community composition. Sensitive species, such as *Pyrrhulina* cf. *brevis* and EPT families, were associated with preserved habitats, whereas generalist species, like *Perithemis mooma*, prevailed in degraded areas. These results highlight the importance of conservation and restoration strategies to mitigate anthropogenic impacts. Given the environmental variability observed in aquatic habitats, we emphasize that future studies should expand the spatial and temporal scales of sampling and reduce the taxonomic resolution for EPT analysis.

Keywords Aquatic ecosystems · Urban ecosystems · Aquatic bioindicators · Conservation

Introduction

Tropical aquatic ecosystems, such as Amazonian *igarapés*, play essential roles in maintaining biodiversity and ecological balance (Santos et al. 2023a, b). These small water-courses significantly contribute to forming larger rivers and

are recognized for harboring rich biodiversity, enhancing these ecosystems’ ecological environmental resilience and supporting vital ecosystem services (Biggs et al. 2017; Ferreira et al. 2023). The vegetation surrounding *igarapés* influences water characteristics and provides essential resources, such as food, energy, and microhabitats, which are crucial for sustaining aquatic life (Leal et al. 2016; Dala-Corte et al. 2020). Moreover, it serves as a vital barrier, filtering or preventing environmental alterations from reaching the main channel. Despite the importance of *igarapés*, urban growth expansion and increased human interventions place these ecosystems at imminent risk, leading to significant alterations in their chemical, physical, and biological characteristics, particularly in urbanized areas (Monteiro-Júnior et al. 2015; Anim et al. 2018; Ferreira et al. 2021; Saviato et al. 2022). As a consequence, these environments undergo simplification in their natural variability, resulting in environmental homogeneity, primarily due to the sparse or absent riparian vegetation, sediment input, burial of microhabitats, polluted waters, elevated temperatures, and low oxygen availability (Ferreira et al. 2021; Catâneo et al. 2024). These

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alterations, whether isolated or acting synergistically, modify environmental conditions and create a filter which affects biodiversity distribution, often resulting in local extirpation of the most sensitive species.

Alterations caused by pollution, improper waste disposal, and the loss of riparian vegetation have significant negative impacts on the structure of aquatic communities, such as fish and aquatic insects (Vieira and Dias-Silva 2015; Monteiro-Júnior et al. 2014; 2015; Prudente et al. 2018; Marques et al. 2020; Ortega et al. 2021; Santos et al. 2021). Environmental stressors trigger physiological, morphological, and behavioral changes in organisms, reducing their abundance and potentially leading to local extinctions and shifts in species' distribution and composition (Miguel et al. 2017; Oliveira-Junior et al. 2019; Paul et al. 2020; Mendoza-Penagos et al. 2020; Faria et al. 2021; Ghisi et al. 2022; Santos et al. 2023a, b).

Fish and insects from the Odonata (Anisoptera and Zygoptera), Ephemeroptera, Plecoptera, and Trichoptera (EPT) orders are widely used as indicators for monitoring aquatic ecosystems' health. They respond to habitat conditions (Mendonça et al. 2005; Nessimian et al. 2008; Monteiro-Júnior et al. 2014; Larentis et al. 2022), water quality (Souza et al. 2022; Sinche et al. 2023), pollution (Beltrão et al. 2018; Do Prado et al. 2020; Gomes-Silva et al. 2020), urbanization (Monteiro-Júnior et al. 2014; Martins et al. 2017; Ortega et al. 2021; Sganzerla et al. 2021), loss of riparian and forest vegetation, and land-use changes (Lorion and Kennedy 2009; Dala-Corte et al. 2020; Marques et al. 2021; Faria et al. 2021).

Environmental disturbances lead to significant changes in abundance patterns, the occurrence frequency of certain taxa, richness, diversity, trophic dynamics, and the functional structure of aquatic groups (Peláez and Pavanelli 2019; Do Prado et al. 2020; Luiza-Andrade et al. 2020; Faria et al. 2021; Monteles et al. 2021; Lima et al. 2022). As a result, resistant and tolerant species often become dominant, while sensitive species tend to disappear or experience drastic population declines (Couceiro et al. 2007; Francis and Chadwick 2015; Gaertner et al. 2017; Beltrão et al. 2018; Marques and Cunico 2021; Rico et al. 2022). Similar responses are observed globally, where the simplification of fish and Odonata communities, along with a decline in EPT, is often linked to increased anthropogenic pressures (Buss et al. 2004; Jourdan et al. 2018; Wong et al. 2020; Jargal et al. 2022). This loss of structural complexity and environmental quality not only reduces local biodiversity, promoting biotic homogenization, but also compromises the ecosystem services provided by these habitats and their biodiversity (Biggs et al. 2017; Ranta et al. 2021; Bylak et al. 2022; Ferreira et al. 2023).

Understanding the interaction between biological diversity and environmental characteristics in urban *igarapés* is

essential for effective management and conservation efforts, and for mitigating negative impacts. The health of these ecosystems is typically assessed through monitoring limnological parameters (Ferreira et al. 2021; Catâneo et al. 2024), evaluating physical integrity, or analyzing the response of bioindicator species (Herman and Nejadhashemi 2015; Brasil et al. 2020a; Pereira-Moura et al. 2021; Ghisi et al. 2022). These components can be assessed individually or in an integrated manner. Still, evaluations that incorporate a broader set of metrics, particularly biological ones, tend to more accurately capture the complexity of interactions within these components. This makes them more effective in assessing ecosystem conditions, identifying causes of degradation, and understanding their impacts (Chen et al. 2017; Prudente et al. 2018; Brasil et al. 2020a, b). Despite growing advances in studies using multimetric approaches (Herman and Nejadhashemi 2015; Chen et al. 2017; Prudente et al. 2018; Ranta et al. 2021; Feio et al. 2023), few studies simultaneously evaluate limnological, environmental, and bioindicator metrics across different taxonomic groups, such as fish, Odonata, and EPT in Amazonian *igarapé* ecosystems. This gap is particularly notable in the Southwestern Amazon, a region still underexplored in biodiversity and conservation knowledge, but which faces significant pressures from anthropogenic activities.

This study aims to address this gap by investigating how habitat quality influences biological diversity in urban *igarapés* of Porto Velho, Rondônia, in the Southwestern Amazon. We hypothesize that the intensity of environmental and limnological degradation drives distinct occurrence and distribution patterns of fish, Odonata, and EPT taxa, which are more sensitive to these conditions. Specifically, we expected degraded habitats to exhibit a higher abundance of tolerant and non-native fish species, whereas preserved habitats would support greater diversity and abundance of native taxa. For Odonata, we anticipated higher diversity and abundance of Zygoptera in preserved environments, and greater representation of Anisoptera in degraded areas. For EPT taxa, we expected a reduced abundance in impacted streams, although some occurrence was still anticipated. Additionally, we hypothesized that the composition of fish and EPT communities would be primarily influenced by limnological variables, while Odonata would be more closely associated with structural habitat features. Consequently, we expect aquatic entomofauna and ichthyofauna to respond differently to these components, with specific taxa showing stronger reactions to anthropogenic pressures in urbanized environments.

Our study seeks to answer the following questions: (I) What changes occur in the composition of fish, adult Odonata and EPT larvae as habitats transition from preserved to degraded conditions? (II) Which environmental variables influence the composition of these communities in degraded

environments experiencing ecological degradation? And (III) Which taxa are most affected in urbanized environments and can serve as target organisms for monitoring ecological conditions?

Material and methods

Study area

The study was conducted in the Brazilian Amazon, in the municipality of Porto Velho, the capital of the state of Rondônia, in northern Brazil (Fig. 1). Established in 1907 (IBGE, 2024), Porto Velho covers an urban area of approximately 118,960 km² and has a population of 460,434 inhabitants, making it the most populous municipality in the state (IBGE, 2022). The city is situated along the banks of the Madeira River, the second-largest tributary of the Amazon River basin, and is drained by its right-bank tributaries. These waterways are vulnerable to urbanization impacts, including environmental degradation and water pollution (Catâneo et al. 2024). Despite efforts to enforce ecological legislation that designates riparian vegetation areas as permanent preservation areas, compliance is rarely observed within the city. As a consequence, most *igarapés* lack riparian vegetation, straightened channels, or suffer from significant sediment input due to bank destabilization. Additionally, these waterways are often polluted with large amounts

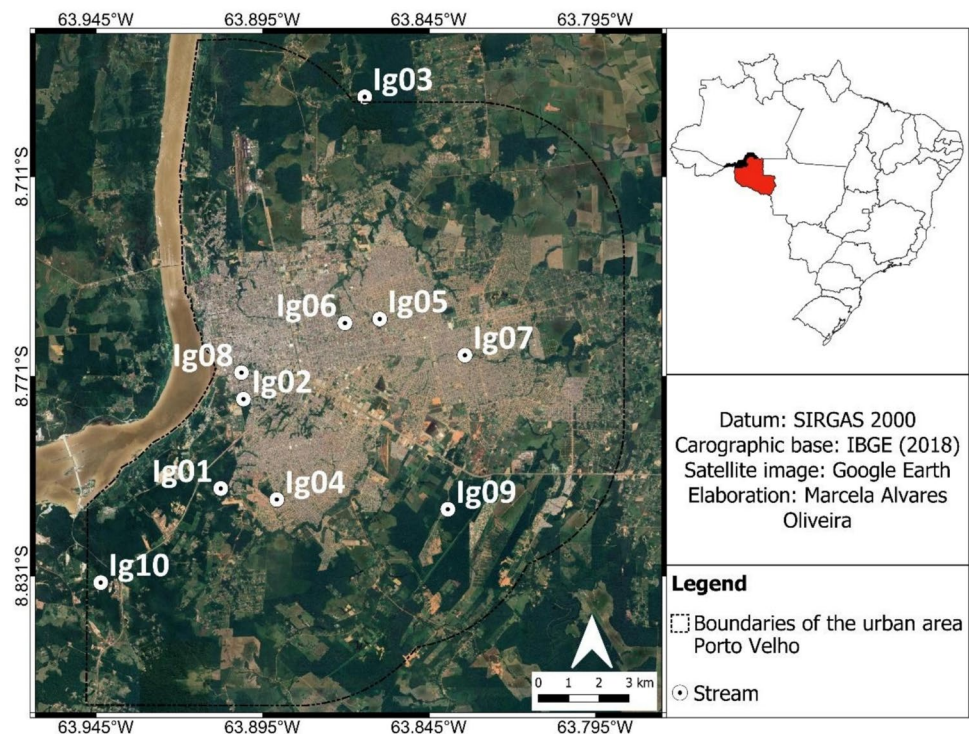
of waste and contaminants directly discharged into their channels.

Sampling sites and habitat characterization

Ten sections of streams, ranging from first to third order according to Strahler (1957), were sampled (Fig. 1). Of these, seven are located within the urban perimeter of the city (Ig01, Ig02, Ig04, Ig05, Ig06, Ig07 and Ig08), while the remaining three are situated farther away (Ig03, Ig09, Ig10). A minimum distance of three kilometers was maintained between the sampling sites to minimize potential spatial autocorrelation and ensure data independence. These sites were initially selected using satellite imagery from Google Earth, followed by on-site visits to verify accessibility and suitability for applying the sampling protocol. The chosen streams were strategically selected to represent all micro basins, capturing the existing environmental variability and accounting for differences in urbanization intensity, a key driver of changes in environmental conditions.

Urban streams were predominantly characterized by high levels of anthropogenic impact, including dense residential occupation, domestic sewage discharge, solid waste presence, and low floristic diversity, often with discontinuous or altered riparian vegetation and a dominance of graminoid and exotic species. Some urban sites were adjacent to sensitive areas such as a military reserve (Ig01) or a municipal park (Ig08), but these did not prevent environmental degradation. In contrast, periurban streams were located within

Fig. 1 Location of sampling sites in Porto Velho, Rondônia, Brazil



protected areas or rural properties, with little to no residential presence, lower pollution levels, and better-preserved vegetation. Ig03 stood out as the most conserved site within a municipal conservation unit, while Ig10 received upstream effluent from a municipal landfill despite being in a preservation zone (see Catâneo et al. 2024).

Stream condition metrics

The habitat conditions of the studied sections were assessed using an adapted version of the Habitat Integrity Index (HII) for urban environments, as proposed by Monteiro-Júnior et al. (2014). The index comprises 12 metrics, including access to the stream, width, and integrity of the riparian forest, vegetation within 10 m of the channel, retention devices, channel structure, water flow in the channel, canopy cover (calculated by: ratio of black pixel area in monochromatic canopy images to the total number of pixels), absence of human occupation, absence of domestic or industrial effluents, absence of construction density, and absence of dumped litter. The assessment provides a final score ranging from 0 to 1. Streams are classified into three integrity categories based on their scores: scores below 0.33 are considered degraded; scores between 0.34 and 0.66 are considered intermediate; and scores above 0.67 are considered preserved.

In this study, we followed the same sampling units described by Catâneo et al. (2024). However, based on the integrity scores and a clear discontinuity observed between the intermediate and preserved categories, we grouped the streams into two arbitrary integrity categories to facilitate analysis: degraded, with scores equal to or below 0.66, encompassing seven streams (Ig01, Ig02, Ig04, Ig05, Ig06, Ig07, and Ig08), and preserved, with scores above 0.67, including three streams (Ig03, Ig09, and Ig10).

Stream drains are located in densely populated areas with numerous residences along both banks, domestic sewage discharge, waste accumulation in the streambed and nearby, and low floristic diversity. In contrast, preserved streams are characterized by an absence of settlements along their banks, no visible evidence of sewage discharge, minimal waste accumulation, and surrounding vegetation with a significant presence of pioneer species (Catâneo et al. 2024).

Environmental and limnological variables

The limnological characterization involved measuring 14 physicochemical water parameters: temperature ($^{\circ}\text{C}$), pH, electrical conductivity (mS cm^{-1}), dissolved oxygen (mg L^{-1}), turbidity (NTU), total ammoniacal nitrogen (mg L^{-1}), chloride (mg L^{-1}), dissolved iron (mg L^{-1}), chemical oxygen demand (mg L^{-1}), biochemical oxygen demand (mg L^{-1}),

nitrate (mg L^{-1}), nitrite (mg L^{-1}), sulfate (mg L^{-1}), and sulfide (mg L^{-1}).

Additionally, hydromorphological characterization was conducted using metrics such as width (m), depth (cm), current flow velocity (m s^{-1}), discharge ($\text{m}^3 \text{s}^{-1}$), and substrate type at each point within the sampling unit. These metrics were selected because they are among the most critical factors for explaining aquatic community dynamics, as supported by the literature (Brasil et al. 2020b).

Biological sampling

The sampling was conducted under SISBIO authorization No. 87750–1, following the Continental Aquatic Subprogram protocol for streams, established by the *ICMBio* National Biodiversity Monitoring Program (Monitora) (Dantas et al. 2022). A 100-m sampling unit was defined for each stream, with five marking points established at 0 m, 25 m, 50 m, 75 m, and 100 m along a downstream-to-upstream axis. Each stream was sampled twice during 2022: once in the rainy season (March and April) and once during the dry season (August and September). This approach aimed to maximize the likelihood of capturing the full range of biodiversity present in the streams.

Immature stages of EPT (Ephemeroptera, Plecoptera, Trichoptera)

Non-adult stages of Ephemeroptera, Plecoptera, and Trichoptera (EPT) were collected using a D-frame net with a 0.5 mm mesh size, employing the sweep method with a three-minute effort. Various biotopes within the waterbody were explored, including the surface, margins, under leaves, and substrate. This procedure was performed in triplicate at the 0-m, 50-m, and 100-m points, covering the entire 100-m reach of each stream, following methodologies proven effective for this environment and research objective (Vilardi 2015; Santos et al. 2016). The collected material with the D-frame net were transferred to plastic bags containing 80% alcohol and labeled with the sampling point information. Samples were then transported to the Laboratory of Biology and Diversity of Insects at the Federal University of Rondônia, where they were sorted and identified to the family level using illuminated trays, stereomicroscopes, and identification guides (Hamada et al. 2014, 2018).

Adult Odonata

Adult Odonata were collected using the sweep method within each section of the sampling unit with a handheld entomological net measuring 40 cm in diameter and 90 cm in length. Two collectors conducted the collection for one hour exploring both stream margins (Oliveira-Júnior

and Juen, 2019; Cezário et al. 2021). Collected individuals were placed in entomological envelopes and transported to the Laboratory of Biology and Diversity of Insects at the Federal University of Rondônia. Specimens were euthanized by cooling/freezing and fixed by immersion in absolute ethanol (P.A.) for 12 h (Zygoptera) and 24 h (Anisoptera), followed by air-drying through evaporation. Identification was performed to the lowest possible taxonomic level using stereomicroscopes, identification guides, and manuals (Garrison et al. 2006; 2010; Lencioni 2005; 2006).

Fish

First, a 50-m section within the sampling unit was delineated for fish sampling. The aquatic ends of the section were blocked using two nets with a 5 mm mesh size between opposing knots to confine the fish within this interval (Dantas et al. 2022). Active ichthyofauna sampling was conducted using seine nets, hand nets, and sieves with mesh sizes ranging from 0.1 to 0.5 mm, tools commonly used in ichthyofauna sampling in Amazonian streams studied to effectively explore of microhabitats (Mendonça et al. 2005). The fish collection was actively conducted for one continuous hour by three individuals during daylight hours. Captured specimens were anesthetized using Eugenol, fixed in 10% formalin, and transported to the Laboratory of Ichthyology and Fisheries at the Federal University of Rondônia (LIP-UNIR). There they were sorted, preserved in 70% ethanol and identified using stereomicroscopes and taxonomic keys (Queiroz et al. 2012; Vieira et al. 2016).

Data analysis

Each sampled stream in this study was considered a sampling unit, resulting in a total of 10 sampling units. Spatial autocorrelation among the streams was assessed using Moran's I index. A Principal Coordinate Analysis (PCoA; Borcard et al. 2018) was conducted based on aquatic fauna abundance data, applying Hellinger transformation and Bray–Curtis distance matrices. The first PCoA axis was used as the response variable for Moran's analysis, considering coordinate variables with two distance classes. All statistical analyses considered a significance level of $p < 0.05$. The analysis did not observe significant spatial autocorrelation (Fish: Moran's $I = -0.045$; $p = 0.08$; EPT: Moran's $I = -0.189$; $p = 0.09$; Odonata: Moran's $I = -0.230$; $p = 0.102$), indicating that the biodiversity patterns observed were not spatially structured. Consequently, all 10 streams were included in the analytical procedures, and spatial predictors were not interpreted in the results.

Community structure and composition

Community structure was evaluated using various metrics, with the dataset divided into immature EPT, adult Odonata (suborders Zygoptera and Anisoptera), and fish. Abundance was estimated as the total number of individuals (N), species richness was quantified using Margalef's index (d), and biological diversity was estimated using the Shannon–Wiener index (H'). Species evenness was analyzed by Pielou's evenness index (J').

Community composition differences between preserved and degraded habitats

An ANOSIM was conducted to assess differences in community composition between seasonal periods, ensuring appropriate data treatment for subsequent analyses. The absence of significant differences between the dry and rainy periods for all groups analyzed (EPT: $R = 0.043$, $p = 0.324$; Odonata: $R = 0.000$, $p = 0.441$; Fish: $R = -0.088$, $p = 0.984$) justified treating samples from both periods as a single dataset using absolute counts. The same approach was applied to environmental data, which also showed no significant difference ($p = 0.241$). However, the mean values were used for these metrics.

PERMANOVA analysis was applying using the Bray–Curtis index as the dissimilarity metric to assess differences in community composition between habitat integrity categories (preserved and degraded), addressing question I. Non-Metric Multidimensional Scaling (NMDS), also based on the Bray–Curtis index, was used to represent the distribution of samples in a two-dimensional space, facilitating the interpretation of separation between habitat integrity categories. Differences in richness, diversity, dominance, and evenness metrics were analyzed using a Student's t-test (Zar 2010).

Influence of environmental variables on community composition

A redundancy analysis (RDA) was subsequently conducted (Borcard et al. 2018; Da Silva et al. 2022) to determine whether environmental variables influence the composition of Odonata, EPT, and fish communities, addressing question II. The analysis was performed separately for fish, adult Odonata, and EPT datasets. Species composition data were standardized using the Hellinger method to reduce the dominance effect of the most abundant species (Borcard et al. 2018). Four abiotic variables related to channel morphology and habitat integrity (channel width, channel depth, canopy cover, and the Habitat integrity index) were selected based on their influence on aquatic communities (Maués-Silva et al. 2024). Additionally, four of the limnological variables

(dissolved oxygen demand, nitrate and sulfide) were selected for exceeding the limits established by CONAMA Resolution 357/05, as documented in Catâneo et al. (2024). Variance Inflation Factor analysis (Faraway 2016) was applied to check for multicollinearity, and variables were adjusted using the *standardization* function from the *vegan* package. The redundancy analysis was performed using the redundancy function from the *vegan* package, with significance tested using an analysis of variance test.

Indicator taxa of ecological conditions in urbanized streams

Finally, a bioindicator species analysis (IndVal; Dufrêne and Legendre 1997) was conducted using the *multipattern* function from the *interspecies* package to identify taxa indicative of the ecological condition of the analyzed environments, addressing question III. This approach evaluates the fidelity and specificity of each species to a specific environmental condition (preserved versus degraded). A perfect indicator species would be exclusively found in locations of a particular category (high specificity) and present in all locations within that category (high fidelity). The significance of the Indicator Value was estimated using a Monte Carlo test with 9,999 randomizations ($P < 0.05$). All statistical procedures used to test our hypotheses were performed in the R computational environment (R Core Team 2023).

Results

Habitat characterization

HII scores ranged from 0.14 in Ig06 to 0.88 in Ig03. The three peri-urban streams (Ig03, Ig09, and Ig10) were classified as preserved with scores of 0.85, 0.68, and 0.69, respectively. Moreover, seven urban streams were classified as degraded, with HII scores ranging from 0.14 to 0.34 (Online Resource 1a).

Environmental and limnological variables

The width ranged from 1 m in Ig03 to 8.75 m in Ig06, being greater in degraded streams and smaller in preserved ones. The depth varied from 0.11 to 0.31 m in streams Ig05 and Ig09, respectively, and was greater in degraded streams, as was the flow, which was higher in Ig02 ($0.69 \text{ m}^3/\text{s}$) and lower in Ig05 ($0.02 \text{ m}^3/\text{s}$). The predominant material in preserved streams regarding substrate type was leaf litter (40.7%), while sand (43%) and mud (29.2%) predominated in degraded streams (mean of the values in Online Resource 1b).

The averages of pH, EC, TP, TB, NH_4^+ , Cl, BOD, and SO_4^{2-} in preserved streams were lower, while the averages

of DO and NO_3^- were higher. On the other hand, the average values of EC, TP, TB, Cl, COD, BOD, and SO_4^{2-} in the degraded streams were higher, as well as the average values of DO, NO_3^- and H_2S , which were low (Online Resource 1c).

Community composition

A total of 10,198 specimens of aquatic biodiversity were collected from the sampled streams. Of these, 8,584 belonged to the fish community, and 1,614 were aquatic insects, including 543 Odonata individuals (354 Zygoptera and 189 Anisoptera) and 1,071 EPT individuals.

The fish community was represented by six orders, 17 families, 43 genera, and 58 species (Online Resource 2a). Among these, the invasive alien species *Poecilia reticulata* and *Oreochromis niloticus* were the most abundant, with 7,453 and 364 individuals, respectively. The native species *Hyphessobrycon agulha* was the most abundant with 126 individuals.

The Anisoptera suborder (Odonata community) was represented by a single family, Libellulidae, encompassing 15 genera and 30 species. The most abundant species were *Erythrodiplex connata* ($N = 44$) and *Perithemis mooma* ($N = 40$) (Online Resource 2b). The Zygoptera suborder included individuals distributed across four families (Coenagrionidae, Calopterygidae, Megapodagrionidae, and Perlidae), comprising 15 genera and 32 species, with *Acanthagrion lancea* being the most abundant $N = 74$.

The EPT community was represented by 520 individuals from the Ephemeroptera order, 28 from Plecoptera, and 523 from Trichoptera (Online Resource 2c). Seven families were identified in Ephemeroptera (Baetidae, Caenidae, Coryphoridae, Euthyplociidae, Leptohyphidae, Leptophlebiidae, and Polymitarcyidae), with Leptophlebiidae being the most abundant ($N = 166$). Plecoptera was solely represented by the Perlidae family ($N = 28$). Trichoptera included 523 individuals distributed across eight families (Calamoceratidae, Glossosomatidae, Helicopsychidae, Hydroptilidae, Leptoceridae, Odontoceridae, Polycentropodidae, and Hydropsychidae), with Hydropsychidae being the most abundant ($N = 124$).

Community structure in preserved and degraded habitats

Fish communities in preserved habitats exhibited high diversity, richness, and low dominance (Table 1). Among the preserved streams, Ig09 showed the highest richness ($d = 4.88$) and diversity ($H' = 2.49$), while Ig10 presented the highest evenness ($J = 0.89$). In contrast, degraded habitats had high abundance and dominance (Table 1). The Ig06 stream had the highest abundance ($N = 4,671$) and

Table 1 Community structure of fish, Odonata, and EPT by habitat integrity category and t-test results. Values under “Habitat” (Preserved and Degraded) represent absolute values of the metrics analyzed.. “Mean Preserved” and “Mean Degraded” indicate means \pm standard error

Taxa/Metric	Habitat		t-test		Difference		IC (95%) parametric	t-statistic	p-value
Fish	Preserved	Degraded	Mean Preserved	Mean degraded					
N	482	8092	2.150	2.813	0.663		(−0.04–1.37)	2.166	0.062
D	0.110	0.850	0.181	0.725	0.544		(0.23–0.86)	3.958	0.004*
H'	2.810	0.420	2.204	0.608	1.597		(0.83–2.37)	4.779	0.001*
d	6.640	3.000	3.671	0.943	2.728		(1.00–4.46)	3.637	0.007*
J	0.750	0.130	0.766	0.342	0.424		(0.14–0.71)	3.434	0.009*
Anisoptera									
N	28	152	0.672	1.285	0.612		(0.05–1.17)	2.522	0.036*
D	0.120	0.180	0.209	0.236	0.027		(−0.12–0.18)	0.417	0.688
H'	2.390	2.070	1.010	1.637	0.626		(−0.13–1.39)	1.915	0.092
d	3.300	2.990	1.065	1.786	0.721		(−0.19–1.64)	1.812	0.092
J	0.960	0.750	0.680	0.904	0.224		(−0.21–0.65)	1.202	0.264
Zygoptera									
N	121	150	44.333	30.000	14.333		(−18.17–46.84)	1.017	0.339
D	0.110	0.240	0.212	0.385	0.173		(−0.16–0.51)	1.179	0.272
H'	2.390	1.850	1.680	1.329	0.351		(−0.54–1.24)	0.906	0.391
d	2.710	2.400	1.456	1.340	0.116		(−0.86–1.09)	0.273	0.792
J	0.910	0.720	0.934	0.801	0.133		(−0.10–0.36)	1.317	0.224
EPT									
N	965	106	321.670	15.143	306.520		(−51.57–664.62)	1.974	0.084
D	0.110	0.490	0.324	1.008	0.684		(0.30–1.07)	4.082	0.004*
H'	2.380	0.880	1.642	28.665	27.024		(−9.05–63.10)	1.728	0.122
d	2.180	0.430	3.011	1.931	1.080		(−2.35–4.51)	0.727	0.488
J	0.860	0.800	0.599	10.340	9.741		(−3.27–22.75)	1.726	0.123

Legend: N—Number of individuals; D—Dominance; H'—Shannon diversity index; d—Margalef richness index; J—Pielou evenness. Bold values indicate statistically significant differences ($p < 0.05$), with the asterisk (*) placed next to the corresponding p -value

dominance ($D = 0.94$), along with low richness ($d = 0.24$), diversity ($H' = 0.13$), and evenness ($J = 0.12$). The t-test revealed significant differences between habitats for most metrics, except for the number of individuals. Dominance was higher in degraded habitats compared to in preserved habitats (Table 1). Similarly, Shannon diversity was significantly higher in preserved habitats than in degraded habitats. Margalef richness was also higher in preserved habitats than in degraded habitats. Finally, evenness was greater in preserved habitats than in degraded habitats.

The number of Anisoptera individuals for Odonata was higher in degraded habitats ($N = 152$) than in preserved habitats ($N = 28$), as indicated by the t-test ($t = 2.522$; $p = 0.036$). Dominance was significantly lower in preserved habitats compared to degraded habitats. Zygoptera abundance was similar between the two environments (preserved: $N = 121$; degraded: $N = 150$), but with no significant difference in the t-test. Dominance was higher in degraded habitats for both Anisoptera and Zygoptera, while richness, diversity, and evenness were higher in preserved habitats (Table 1). However, the t-test did not indicate significant differences for these parameters between the two habitat types. Among individual streams, Ig06 had the highest Anisoptera abundance ($N = 40$), and Ig07 recorded the highest dominance ($D = 0.24$). Ig05 stood out with the highest richness ($d = 3.40$) and diversity ($H' = 2.38$), while Ig09 showed the greatest evenness ($J = 1.10$). Ig09 had the highest richness ($d = 2.5$) and abundance ($N = 81$) for the Zygoptera community, while

Ig05 exhibited the greatest diversity ($H' = 2.21$). The highest evenness ($J = 0.94$) was observed in Ig03 and Ig10.

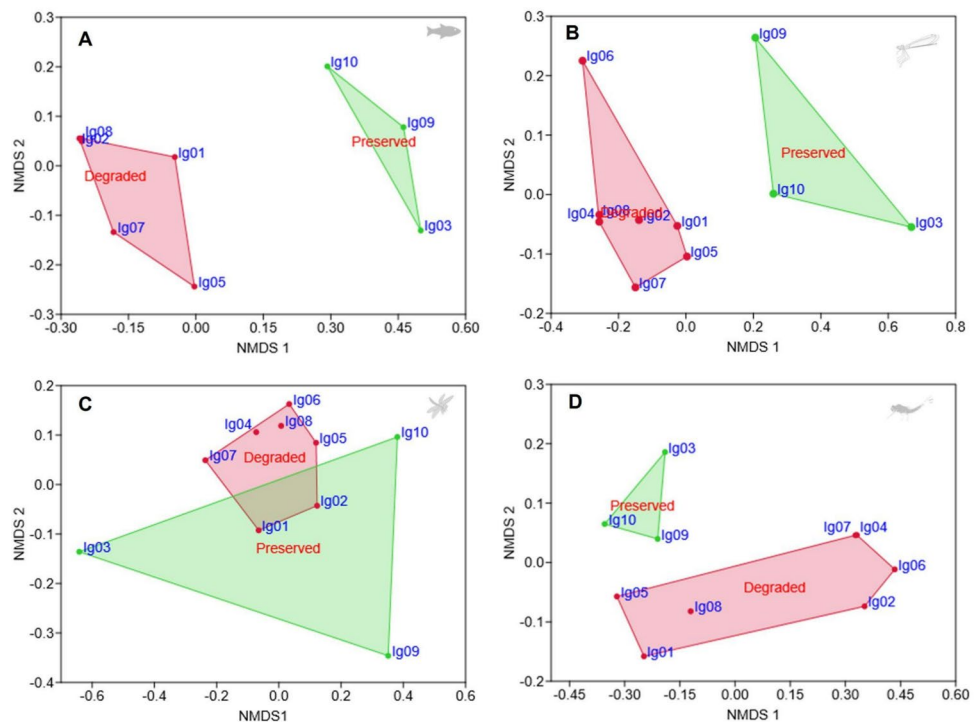
The EPT community showed a highly sensitive response to habitat degradation in preserved habitats presenting high abundance, diversity, richness, and evenness, while they had the highest dominance in degraded habitats and the lowest values for abundance richness, and diversity. The t-test indicated significant differences only for dominance ($t = 4.082$; $p = 0.004$). The Ig03 stream had the highest richness ($d = 3.47$), abundance ($N = 75$), and diversity ($H' = 2.75$), while Ig09 showed the greatest evenness ($J = 0.97$). No EPT organisms were recorded in the Ig02, Ig04, Ig06, and Ig07 streams (degraded).

Community composition across habitat types

The NMDS and PERMANOVA analyses revealed significant differences in community composition between habitat integrity categories (Fig. 2), with the exception of Anisoptera. The NMDS stress value for fish was 0.187, indicating good data representation in the Cartesian plane. PERMANOVA showed a strong separation between preserved and degraded habitats ($F = 6.994$; $p = 0.006$), with 30 exclusive species in preserved habitats and 17 in degraded habitats.

Next, the NMDS stress values for Odonata were 0.124 (Zygoptera) and 0.117 (Anisoptera), indicating a good fit. The PERMANOVA analysis revealed a strong separation between habitats, with F-values of 3.289 (Zygoptera) and

Fig. 2 NMDS ordination of community composition for fish (A), adult Odonata (B—Zygoptera; C—Anisoptera), and immature EPT (D) in streams of different habitat integrity categories. Each point represents a stream, and the proximity between points indicating the similarity in community composition among locations. Green polygons represent the preserved streams, and red polygons represent the degraded streams



3.485 (Anisoptera), both showing significant differences ($p = 0.007$). Preserved habitats had 10 exclusive Zygoptera species and 6 exclusive Anisoptera species, while degraded habitats had 12 exclusive Zygoptera species and 13 exclusive Anisoptera species.

The NMDS stress value for EPT was 0.3792, suggesting less ideal representation. The PERMANOVA analysis showed marginally significant separation ($F = 2.988$ and $p = 0.052$), indicating a tendency for differentiation in community composition between habitats, though not statistically significant at the conventional confidence level ($p < 0.05$).

Environmental drivers of community composition

The RDA revealed a significant influence of environmental variables on the fish community ($F = 2.619$; $p = 0.026$), with habitat integrity and canopy cover being the most influential factors (Fig. 3). These variables were particularly associated with species from the genera *Hyphessobrycon*, *Hemigrammus*, and *Pyrrhulina*. Conversely, channel width showed a strong association with *P. reticulata* (Fig. 3a).

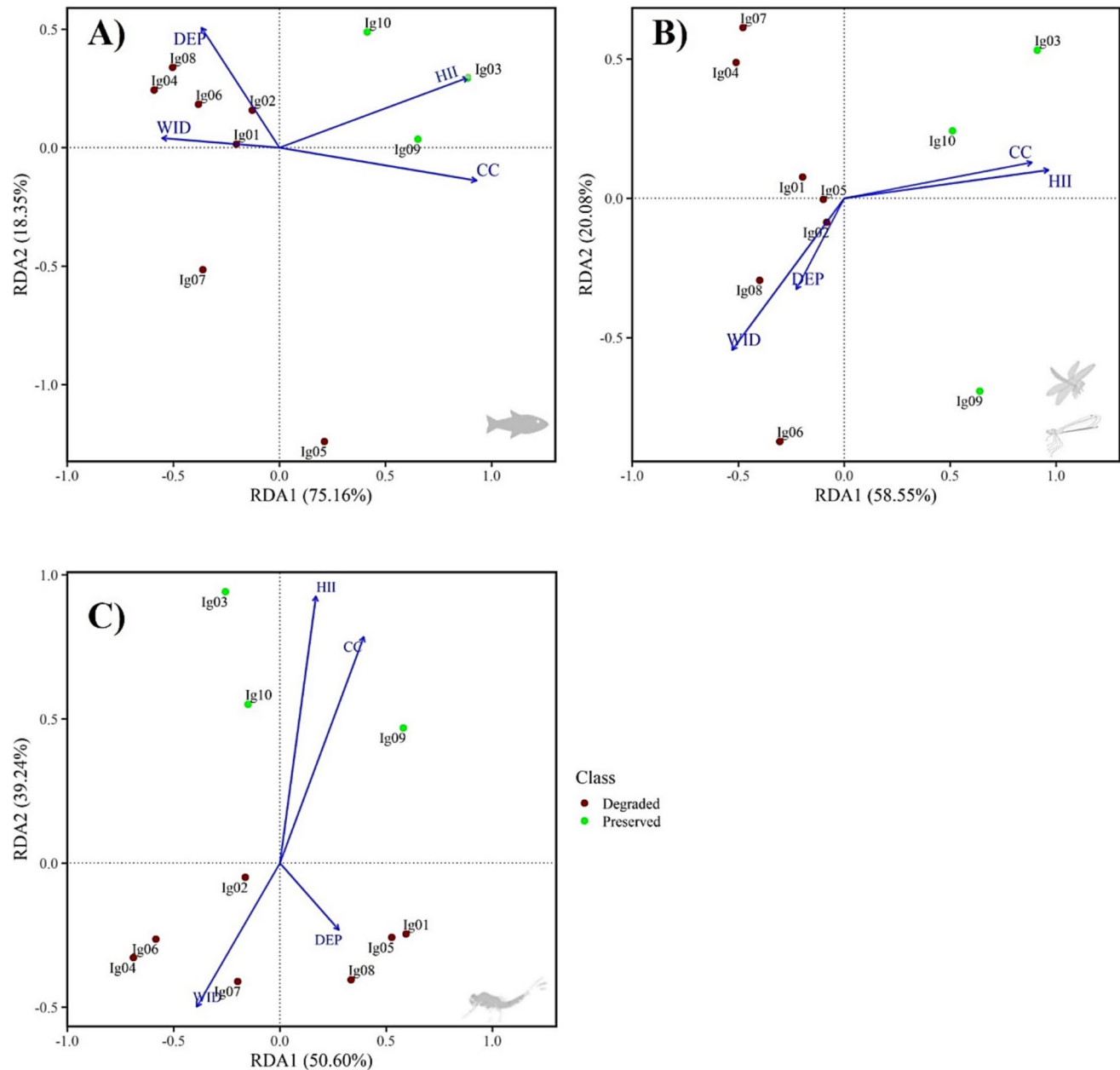


Fig. 3 Ordinations applied on the species composition of fish (a) and Odonata (b), and families of EPT (c), with significantly associated variables. CC = canopy cover (%); DEP = channel depth (cm); HII = Habitat Integrity Index; WID = channel width

The analysis for the Odonata community also indicated a significant association with environmental variables ($F = 1.837$; $p = 0.029$), with canopy cover, habitat integrity, and channel width being the most influential factors (Fig. 3b). Channel width and depth were more important for most species of the *Erythrodiplax* genus, while canopy cover and habitat integrity were more strongly associated with species of the *Epipleoneura* and *Heteragrion* genera, as well as with *Protoneura tenuis* (Fig. 3b).

Similarly, a significant association with environmental variables ($F = 2.399$; $p = 0.006$) was found for the Ephemeroptera, Plecoptera, and Trichoptera families. Canopy cover and habitat integrity were the most influential variables for most families, except for Baetidae and Caenidae, which were more strongly associated with channel depth (Fig. 3c).

The redundancy analysis did not indicate significant influences of limnological variables on the composition of fish communities ($F = 1.28$; $p = 0.31$), Odonata ($F = 1.08$; $p = 0.415$), and EPT ($F = 1.08$; $p = 0.426$).

Indicator taxa

The IndVal analysis applied to fish composition identified *P. reticulata* as the only species associated with degraded sites (Table 2). In contrast, two species, *P. cf. brevis* and *Hemigrammus ocellifer*, were associated with preserved sites (Table 2). The IndVal analysis for Odonata identified three species associated with degraded sites: *P. mooma*, *A. lancea*, and *E. connata* (Table 2). Then, the IndVal analysis for the Ephemeroptera, Plecoptera, and Trichoptera families indicated that only the Hydropsychidae and Polycentropodidae families were associated with preserved sites (Table 2).

Table 2 Indicator Values (IndVal) for fish and Odonata species, and Ephemeroptera, Plecoptera, and Trichoptera families sampled in the municipality of Porto Velho, state of Rondônia, Brazil

Species	IndVal	Ranking	$P < 0.05$	Class
FISH				
<i>Poecilia reticulata</i>	1.000	1	0.007	Degraded
<i>Pyrrhulina cf. brevis</i>	0.989	3	0.014	Preserved
<i>Hemigrammus ocellifer</i>	0.953	8	0.023	Preserved
ODONATA				
<i>Perithemis mooma</i>	1.000	1	0.008	Degraded
<i>Acanthagrion lancea</i>	0.969	4	0.008	Degraded
<i>Erythrodiplax connata</i>	0.962	5	0.025	Degraded
EPT				
Hydropsychidae	1.000	2	0.008	Preserved
Polycentropodidae	0.963	7	0.008	Preserved

Discussion

The results of this study partially support our initial hypotheses regarding the responses of fish, Odonata, and EPT taxa to environmental degradation in urban streams. As expected, degraded habitats showed higher relative abundance of invasive and tolerant fish species, while preserved streams supported greater diversity and abundance of native taxa. Anisoptera also responded as predicted, with higher diversity and abundance in degraded environments. However, the patterns observed for Zygoptera and EPT were more complex. Zygoptera occurred in both habitat types, but its dominance in degraded sites was primarily driven by tolerant species, suggesting the loss of more sensitive taxa. For EPT, our expectation of reduced abundance in degraded streams was exceeded, as these organisms were entirely absent from several impacted sites. Additionally, contrary to our hypothesis, environmental variables—rather than limnological factors—emerged as the main drivers of community composition across all groups. These findings highlight the differential responses of aquatic taxa to urbanization and underscore the importance of structural habitat features in maintaining biological integrity. Sensitive taxa, including the fish species *P. cf. brevis* and *H. ocellifer*, as well as EPT Hydropsychidae and Polycentropodidae families, demonstrated greater sensitivity to ecological conditions, serving as positive indicators of quality in urbanized areas. Conversely, the presence of generalist and resistant species, such as *P. mooma* and *A. lancea* (Odonata) and fish species *P. reticulata*, highlighted the negative effects of environmental degradation in impacted habitats.

Composition and diversity patterns

The composition of fish communities reflected strong contrasts between preserved and degraded streams. More diverse and balanced fish communities in preserved habitats indicate that structural integrity and lower levels of anthropogenic disturbance promote suitable conditions for the maintenance of native ichthyofauna. In contrast, degraded streams were characterized by the predominance of invasive and generalist taxa, notably *P. reticulata* and *O. niloticus*. The presence and high dominance of invasive exotic species (IES) in the fish community, in degraded streams serve as clear indicators of environmental disturbance (Ruaro et al. 2018). These species are known for their high feeding plasticity and significant tolerance to adverse conditions, compete with native species for resources and cause substantial changes in community structure (Figueiredo et al. 2013; Cassemiro et al. 2018;

Corrales et al. 2020). Similar patterns have been observed in other urban streams across the Amazon, as well as in other regions of Brazil and globally (Beltrão et al. 2018; Marques et al. 2020; Larentis et al. 2022; Costa et al. 2025).

The contrasting response patterns between Anisoptera and Zygoptera reveal how different ecological strategies modulate resilience to degradation and reinforce the group's sensitivity to environmental quality (Oliveira-Junior et al. 2019; Pereira-Moura et al. 2021; Sganzerla et al. 2021). The higher abundance of Anisoptera in degraded habitats suggest that this group exhibits greater tolerance to adverse environmental conditions. In contrast, the higher dominance of Zygoptera in degraded sites, despite their relatively uniform distribution between preserved and degraded habitats, indicates that although present, the Zygoptera community tends to be less diverse and composed of just a few species. This pattern reflects the intensity of anthropogenic alterations in drainage basins, where even the most preserved sites show signs of environmental change. As a highly sensitive group, Zygoptera show clear signs of sensitive taxa loss in these areas, leading to a stable but depauperate community. This finding contrasts with patterns reported in other studies (e.g., Oliveira-Junior and Juen 2019; Oliveira-Junior et al. 2019; Ribeiro et al. 2021). The distinct responses of Anisoptera and Zygoptera likely reflect the ecological and adaptive specificities of each suborder (Oliveira-Junior and Juen 2019; Pereira-Moura et al. 2021).

The tolerance of Anisoptera may be linked to their larger body size and thermoregulation capacity which enable them to withstand high temperatures and thrive in open environments with greater sunlight exposure (Castillo-Pérez et al. 2022). On the other hand, the lower flight capacity and limited thermoregulation of Zygoptera restrict these individuals to areas with denser vegetation cover (Oliveira-Junior et al. 2019). Consequently, Zygoptera are highly susceptible to the loss of critical microhabitats, such as well-preserved riparian areas (Carvalho et al. 2013; Monteiro-Júnior et al. 2014). In addition to these physiological traits, habitat-related parameters such as canopy cover, aquatic vegetation, and riparian complexity directly affect the availability of perching sites, shelter, and suitable substrates for oviposition (Barbosa dos Santos et al. 2024; Brito et al. 2021; Calvão et al. 2020; Oliveira-Junior and Juen 2019). Likewise, water quality parameters such as oxygen levels, turbidity, and nutrient concentrations may influence larval development and survival, especially for sensitive taxa (Brito et al. 2025; Pereira et al. 2025). These environmental drivers likely interact to shape the threshold patterns observed in community structure across preserved and degraded streams.

Although higher values of abundance, diversity, richness, and evenness were observed for the EPT community in preserved habitats, only the difference in dominance was

statistically significant. These patterns may indicate a tendency for EPT assemblages to respond to habitat quality; however, such interpretation must be made with caution, given the lack of statistical significance for most metrics and the unbalanced design of the study (with fewer preserved streams), which may have limited the power to detect differences. Additionally, the taxonomic resolution at the family level may not fully capture the variation in environmental sensitivity among EPT taxa. Despite these constraints, the trends observed are consistent with previous studies that recognize EPT groups as potential indicators of environmental degradation (Brito et al. 2018), reinforcing the importance of further research using more refined taxonomic and spatial resolution. High abundance, diversity, richness, and evenness observed in preserved habitats for the EPT community suggest a strong association of these organisms with favorable environmental conditions. In contrast, the reduced abundance and richness values in degraded streams reinforce their role as bioindicators sensitive to environmental degradation (Brito et al. 2018). EPT taxa are known to have distinct ecological requirements that influence their occurrence and abundance in specific habitats (Luiza-Andrade et al. 2022), as confirmed by our results. The absence of EPT individuals in the Ig02, Ig04, Ig06, and Ig07 streams (all classified as degraded), reflects their reliance on more complex and less impacted habitat conditions. Environmental alterations and intensified anthropogenic pressure in these sites, such as high residential density, absence of riparian vegetation, lack of sanitation, improper waste disposal, and water pollution (Catâneo et al. 2024), reduce habitat structural complexity, potentially limiting EPT occurrence (Martins et al. 2017; Brito et al. 2018; Luiza-Andrade et al. 2022). Although intraspecific variability in response to environmental conditions may influence communities, studies like Godoy et al. (2019) demonstrate that clear environmental patterns can be identified at higher taxonomic levels, such as family. These findings highlight the sufficiency of taxonomic resolution in ecological analyses, particularly for aquatic insects, where environmental and spatial factors play a critical role in community structuring.

Influence of environmental and limnological variables

The predominance of structural habitat variables as the main determinants of aquatic community composition aligns with previous studies linking diversity patterns to habitat conditions (Monteiro-Júnior et al. 2014; Peressin and Cetra 2014; Leal et al. 2016; Martins et al. 2017; Sganzerla et al. 2021; Luiza-Andrade et al. 2022; Williams-Subiza et al. 2022), and provide important insights for the management and restoration of these systems. These studies suggest that environmental alterations, particularly in riparian vegetation

conditions, which provide substrate, shelter, and foraging opportunities, negatively influence aquatic biota. The RDA results highlighted a close relationship between certain species and specific environmental variables, under which habitat integrity and canopy cover were determining factors for the occurrence of native fish species, such as those from the *Hyphessobrycon*, *Hemigrammus*, and *Pyrhulina* genera, as well as sensitive Odonata species from the *Epipleoneura*, *Heteragrion*, and *Protoneura* genera. Most EPT families also showed this association, except in the more tolerant Baetidae and Caenidae. In contrast, channel width, which is more pronounced in degraded streams and altered by anthropogenic activities in urban areas (Catâneo et al. 2024), was associated with higher abundance of the invasive species *P. reticulata*. These patterns indicate a trend towards structural simplification due to habitat quality loss, favoring the predominance of tolerant species over native diversity. This results in more homogeneous and ecologically less complex environments.

In the case of fish, attributes such as canopy cover, channel integrity, and substrate complexity directly influence the availability of shelter, food resources, and physical stability—factors that are critical for the persistence of native species and those more sensitive to degradation (Leal et al. 2016; Mendonça et al. 2005). For Odonata, particularly adults, the strong association with environmental variables—especially riparian vegetation and canopy cover—highlights their sensitivity to physical habitat degradation and supports their use as effective indicators of structural quality in aquatic ecosystems (Oliveira-Junior and Juen 2019; Brito et al. 2021). In the case of EPT taxa, although traditionally recognized as sensitive bioindicators of water quality, our results indicate that habitat collapse—characterized by riparian vegetation loss, increased sunlight exposure, and fine sediment deposition—was the primary factor driving their disappearance in degraded environments (Martins et al. 2017; Luiza-Andrade et al. 2022). The lack of significant influence of limnological variables on aquatic community composition may reflect a greater physiological resilience of certain groups to physicochemical fluctuations, provided that habitat structure is maintained. However, methodological limitations, such as the use of snapshot water quality data and the temporal mismatch between biological and limnological sampling, may have constrained the detection of more subtle patterns in these relationships.

Indicator taxa

The identification of bioindicator taxa enhances the capacity for environmental assessment in urban ecosystems of the Amazon. Among fish, *P. cf. brevis* and *H. ocellifer* emerge as indicators of ecological integrity and may be incorporated into locally adapted environmental quality indices. In

contrast, the consistent presence of *P. reticulata* in degraded streams reinforces its usefulness as an indicator of severe disturbance, with its dominance potentially serving as a warning sign of advanced degradation processes. In Odonata, the exclusive occurrence of *Heteragrion*, *Protoneura*, and *Epipleoneura* in well-structured environments positions these genera as valuable indicators of habitat quality, particularly at the local scale. The frequent occurrence of *P. mooma* and *A. lancea* in exposed areas suggests that these taxa may serve as markers of riparian vegetation loss. Among EPT, the extreme sensitivity of Hydropsychidae and Polycentropodidae, along with the absence of even relatively tolerant families such as Baetidae, indicates that these organisms are critical for detecting both early and severe ecological changes. Their presence or absence may function as a clear binary metric of ecological integrity. The adoption of an integrated set of bioindicators encompassing representatives from these three groups would support more accurate and multiscale assessments of urbanization impacts in Amazonian lotic systems, strengthening biomonitoring and ecological restoration strategies tailored to regional conditions.

Implications for management and monitoring

The observed association between preserved environments and more diverse aquatic communities highlight the importance of preserving non-degraded areas to protect stable aquatic communities, and to serve as ecological corridor systems. Such corridors would alleviate pressures on more altered areas, facilitating migration and gene flow. However, anthropogenic pressure in the urban areas surrounding the streams exacerbate environmental alterations, leading to increased pollutants, hydromorphological modifications, and changes in limnological parameters (Ferreira et al. 2021; Catâneo et al. 2024). These factors contribute to the reduction of suitable habitats for various native species sensitive to environmental quality loss, thereby jeopardizing local biodiversity. Consequently, it is crucial that public policies prioritize implementing actions to minimize anthropogenic impacts, promote the recovery of degraded areas, and ensure the protection of preservation areas. We particularly emphasize the importance of involving local residents in these initiatives. For instance, the Ig05 stream in the present study, which exhibited distinct diversity patterns compared to other degraded streams, exemplifies the positive impact of community stewardship: residents prevent the discharge of domestic effluents and improper waste disposal, conduct periodic cleanups, and engage in planting activities in surrounding areas. These community-driven practices appear to yield positive effects on local biodiversity, highlighting that local engagement is an essential component for the conservation and environmental recovery of these ecosystems.

Finally, we emphasize that although the results presented herein are consistent, certain methodological limitations should be carefully considered, as they may have influenced the detection of specific patterns. For instance, the difference in the number of streams sampled between preserved and degraded categories may have affected the robustness of the analyses, particularly in terms of variability and statistical representativeness. Future studies including more extended time series and a more significant number of streams could provide a more comprehensive understanding of how the aquatic communities respond to degradation. Further research should be conducted to explore the long-term effects of habitat recovery on aquatic communities or to investigate how varying degradation levels influence ecosystem functioning.

Conclusion

This study demonstrates that habitat quality is a determinant factor for the structure and composition of aquatic fish, Odonata, and EPT communities in the streams of Southwestern Amazonia. Higher diversity, richness, and evenness were observed in preserved streams, particularly for the fish community, indicating environments that are favorable for maintaining native biodiversity. In contrast, degraded streams were dominated by opportunistic and exotic species, such as *P. reticulata* and *O. niloticus*.

Sensitive species showed a strong association with canopy cover and habitat integrity, reinforcing the importance of these factors for the conservation of healthy aquatic communities. Additionally, *P. reticulata*, *P. mooma*, *A. lancea*, and *E. connata* were identified as indicators of degraded habitats, while *P. cf. brevis*, *H. ocellifer*, and the EPT Hydropsychidae and Polycentropodidae families were associated with preserved habitats. These results highlight the importance of conservation and restoration efforts in riparian areas, which are crucial for maintaining biodiversity and the functionality of these aquatic ecosystems.

Additional research efforts aimed at expanding the number of samples, incorporating other biological groups, and improving taxonomic identification may yield a more detailed understanding of aquatic composition and dynamics, thereby contributing to more robust conservation and sustainable management strategies for Amazonian streams.

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Authors' contributions All authors contributed to the conception and design of the study. C. R. C.D., M. A. P. A. S. and D. T. B. S. C. were responsible for conceptualization and methodology. Formal analysis and investigation were conducted by D. T. B. S. C., P. V. C. and L. J. The original draft was prepared by D. T. B. S. C., while all authors contributed to the review and editing process. Funding acquisition was led by C. R. C.D. and M. A. P. A. S., with supervision provided by both.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Compliance with ethical standards This study complied with ethical standards and was authorized by the Brazilian System of Authorization and Information on Biodiversity (SISBIO), under permit No. 87750-1.

Competing interests The authors declare no competing interests.

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