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Fish assemblages in Rodrigo de Freitas Lagoon, Rio de Janeiro, Brazil: Who remains after years of transformation?

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ABSTRACT

Rodrigo de Freitas Lagoon (RFL) has undergone intense environmental changes in recent decades, driven by accelerated urbanization, domestic sewage discharge, and hydrodynamic alterations. This study investigated the current composition of fish assemblages in RFL, with an emphasis on life history strategies, seasonal variations, and environmental influences. A total of 36 species distributed across 20 families were recorded, with a predominance of opportunistic species such as *Phalloptychus januarius*, *Jenynsia lineata*, and *Geophagus brasiliensis*, which are well adapted to unstable and degraded environments. Comparisons with historical data revealed a marked loss of diversity: of the 64 species recorded between 1991 and 2004, only 13 remain, indicating a process of ecological simplification. Seasonal analysis revealed higher species richness and abundance during summer and winter, associated with pronounced seasonal variations in water transparency, dissolved oxygen, and chlorophyll concentration. The absence of significant differences among sampling sites suggests environmental homogenization, likely resulting from limited water renewal and the intensification of anthropogenic impacts around the lagoon. Environmental variables, particularly salinity and water transparency, played a key role in shaping the fish community structure and the distribution patterns of *Brevoortia aurea*, *Brevoortia pectinata*, *Poecilia vivipara*, and *Phalloptychus januarius*. The resilience of opportunistic species such as *Poecilia vivipara* and *Phalloptychus januarius* contrasts with the presence of species exhibiting Periodic or Equilibrium life-history strategies, including *Micropogonias furnieri*, *Mugil liza*, *Centropomus spp.*, *Diplodus argenteus*, and *Caranx spp*. The persistence suggests that marine influence still occurs, especially in areas closer to the tidal channel. These findings indicate that, although RFL still supports species of ecological and fisheries importance, its biodiversity continues to decline, compromising ecosystem resilience and fisheries sustainability. Our results highlight the urgent need for effective conservation and management strategies tailored to urban lagoon systems.

Keywords: Seasonality, Environmental influences, Life cycle strategies, Coastal lagoons

INTRODUCTION

Urban and industrial expansion has caused severe degradation of lagoon systems and adjacent aquatic environments, especially in tropical coastal regions, where lagoons serve as natural filters that regulate the flow of terrestrial

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materials—both natural and anthropogenic—into the sea (Alves et al., 2021). In such systems, bottom sediments often accumulate high concentrations of toxic elements and compounds derived from domestic and industrial effluents. Rodrigo de Freitas Lagoon (RFL), located in the city of Rio de Janeiro, exemplifies this process. Over recent decades, the lagoon has experienced a reduction in water surface area, continuous sewage inflows, and the buildup of organic matter (Soares et al., 2012). These buildup conditions have led to recurring episodes of eutrophication and fish kills, frequently associated with phytoplankton blooms (Domingos et al., 2012; Vezzone et al., 2018). The severity of these impacts is intensified by the dense urbanization of the watershed, the lack of effective sanitation policies, and limited water renewal,—mainly due to poor maintenance of the sluice gate connecting the lagoon to the sea—making the system particularly vulnerable to anthropogenic pressures (Gandhi et al., 2020).

These transformations have been ongoing since the late 19th century, primarily driven by urbanization and substantial ecosystem alteration in the surrounding areas due to shoreline landfilling and increased surface impermeability (Rodrigues, 2012). Despite these challenges, lagoon and estuarine systems such as RFL play a crucial ecological and socioeconomic role. They provide key ecosystem services, including the regulation of hydro-sedimentary flows, the provision of habitats for a wide array of species, and support for recreational and economic activities such as fishing (Pérez-Ruzafa et al., 2019). As semi-enclosed water bodies subject to seasonal variations in salinity, temperature, and turbidity, these environments are especially sensitive to anthropogenic pressures, highlighting the need for effective conservation and management strategies (Costa et al., 2021).

In support of this concern, a previous study by Moraes et al. (2014) reported significant changes in the ichthyofaunal composition of RFL over two decades, revealing declines in species richness, abundance, and biomass. The study also identified correlations between fish composition and richness across different zones of the lagoon, ranging from more favorable environmental conditions near the marine inlet to more degraded conditions in the inner areas, which are impacted by organic waste and habitat loss. Fish assemblages in transitional ecosystems like coastal lagoons are shaped by complex interactions between biotic and abiotic factors such as salinity, temperature, depth, and the availability of shelter and food, which act as environmental filters (Moraes et al., 2014; Freitas and Araujo, 2025). These systems function as important nursery, feeding, recruitment, and migratory areas for various species and are thus essential for sustaining fish populations (Costa et al., 2021; Franco et al., 2022). Assessing fish diversity and its relationship with environmental variables is therefore a strategic tool for the sustainable management and conservation of these ecosystems.

Given RFL's long history of environmental degradation and its status as a transitional ecosystem subject to pronounced physicochemical fluctuations and anthropogenic pressures, it is important to investigate how such conditions influence the life-history strategies of the resident fish species. Highly disturbed environments tend to favor opportunistic strategists characterized by early reproduction, high fecundity, and short generation times. In contrast, more stable or marine-influenced environments are more likely to support Periodic or Equilibrium strategists, which display moderate reproductive investment, medium to large body sizes, and longer generation times. This study hypothesizes that fish assemblages in RFL reflect this ecological duality. A predominance of Opportunistic species is expected in response to local environmental and anthropogenic stressors, coexisting with Periodic and Equilibrium species associated with residual marine influence. Investigating these strategies will enhance our understanding of the adaptive mechanisms that shape the composition and structure of fish communities in urban lagoon ecosystems.

METHODS

Study area

The Rodrigo de Freitas Lagoon is a hypereutrophic coastal system, highly impacted by the discharge of metals, domestic waste,

and other organic substances (Loureiro et al., 2009; Loureiro et al., 2012). Recent studies corroborate the persistence of this eutrophic condition, indicating that the lagoon remains strongly influenced by allochthonous organic matter and nutrient inputs. Signori et al. (2020) demonstrated elevated concentrations of nitrogen, phosphorus and chlorophyll-a, with ecosystem metabolism dominated by heterotrophic bacterial production rather than autotrophic processes, reinforcing the system's classification as eutrophic and organically enriched. It is an urban lagoon located in the southern zone of Rio de Janeiro city, covering an area of 2.2 km², with an estimated volume of 6,200,000 m³, a mean depth of 2.8 m, and a maximum depth of 4.0 m (RIOÁGUAS, 2013; Gandhi et al., 2020).

The lagoon is artificially connected to the sea through the Jardim de Alah channel, which is approximately 800 m long, with a width varying between 10 and 18 m, and a section where the depth reaches only 0.7 m. Due to the inefficient and irregular water exchange through this artificial channel—which is only intermittently opened to prevent canal overflow and consequent urban flooding—the lagoon exhibits a high water residence time, varying from hours to weeks depending on the channel's operation and the inflow from the two main rivers. This structural dependence on sluice gate operation, combined with sedimentation and partial channel silting, continues to limit effective water renewal, thereby sustaining unfavorable biogeochemical conditions (Gandhi et al., 2020; Rodrigues et al., 2021; Neves and Santos, 2022). This prolonged residence time limits water renewal and promotes the accumulation of organic matter throughout the system, ultimately affecting its ecological dynamics (Moraes et al., 2014).

According to Vezzone et al. (2018), sediments from the northern section of the lagoon are predominantly silty, highly eutrophic, and contain elevated levels of potentially toxic metals and organic matter. More recent evidence confirms the persistence of multiple contaminant classes in lagoon sediments and waters, including trace metals, organic pollutants, microplastics and antimicrobial resistance genes, indicating chronic and ongoing contamination rather than a legacy effect (Vezzone et al., 2023; Martins et al., 2025). In contrast, sediments in the southern section are less contaminated, characterized by a coarser texture and lower concentrations of metals and organic matter. Additionally, most of the lagoon's original perimeter has been altered by landfilling activities (Enrich-Prast, 2012; Souza and Azevedo, 2020).

The hydrographic basin of the lagoon comprises three main rivers: Cabeça, with a drainage area of 1.9 km²; Macacos, with 7.2 km²; and Rainha, with 4.3 km². Continuous inputs from domestic sewage, contaminated stormwater drainage, and diffuse urban runoff from these tributaries remain key drivers of nutrient enrichment and microbiological contamination (Gandhi et al., 2020; Vezzone et al., 2020; Neves and Santos, 2022). Extreme rainfall events have further intensified system vulnerability: intense precipitation episodes recorded between 2018 and 2019 caused abrupt declines in dissolved oxygen, sharp increases in *E. coli* concentrations, and rapid shifts in biotic and abiotic parameters, exacerbating water quality deterioration in an already stressed lagoon (Neves and Santos, 2022).

Rodrigo de Freitas Lagoon was subdivided into five sampling areas (A1 to A5) based on environmental characteristics, surrounding land use, and the distribution of marginal and submerged vegetation (Figure 1). Area A1, located near the outlet to the sea, between the Jardim de Alah Canal and Caiçaras Island, features sandbanks, rocky outcrops, and vegetation composed of grasses, trees, and mangrove remnants. Area A2, situated near Piraquê Island, receives water from rivers and canals, and its shores are occupied by aquatic macrophytes and a narrow strip of mangrove. Area A3, characterized as a stormwater drainage zone, contains marginal vegetation consisting of grasses and tree species. Area A4, located in the central region of the lagoon near the Catacumba Municipal Natural Park, includes a retaining wall with a rocky base, marginal vegetation, and a deck used for rowing activities (Botafogo Rowing Club). Area A5 lies within a cove, with shores vegetated by grasses and a marginal mangrove strip, as well as a recreational deck with paddle boats (Moraes et al., 2014; Rodrigues et al., 2021). Between areas A1 and A3, there are fixed and demarcated lanes designated for rowing sports, where fishing is prohibited.

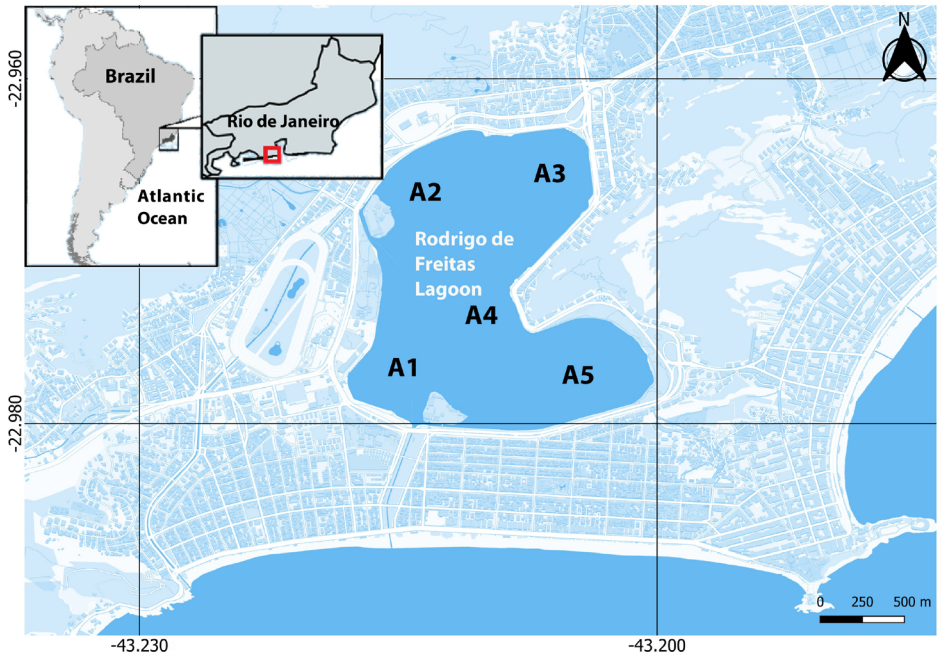

Figure 1. Location of Rodrigo de Freitas Lagoon in Rio de Janeiro, Brazil, and delimitation of the five sampling areas (A1 to A5) used for fish surveys conducted in 2023.

Sampling

Fish sampling and measurements of environmental variables were conducted quarterly in RFL throughout 2023, with one campaign corresponding to each season: March (summer), May (autumn), August (winter), and November (spring). On each sampling occasion, a standardized protocol was applied, consisting of five cast net throws using three different mesh sizes (0.5 mm, 15.0 mm, and 25.0 mm), along with one gillnet set with 35 mm opposite-knot mesh, composed of 15 panels (each 100.0 m long) and 3.5 m in height. At each sampling site, the following environmental parameters were recorded using a Hydrolab HL7 multiparameter probe: temperature (°C), salinity, dissolved oxygen (DO, mg/L), and chlorophyll-a (µg/L). Water transparency was measured separately using a Secchi disk. All collected specimens (license SISBIO #85777-1) were placed in labeled plastic bags and stored on ice for transport to the laboratory. Individuals were sorted and identified to the lowest possible taxonomic level using standard identification guides (e.g., Figueiredo and Menezes 1978, 1980, 2000; Menezes and Figueiredo, 1985). Each specimen was measured for total length (to the nearest 0.1 mm) and weighed using an electronic scale with 0.001 g precision. All procedures were conducted in accordance with ethical standards and applicable regulations.

Analysis

Environmental variables were standardized by subtracting the mean and dividing by the standard deviation (Z-score standardization) using the *Normalize variables* option in PRIMER. This procedure ensures that all abiotic variables contribute equally to the analyses and prevents variables with larger numerical ranges from disproportionately influencing the results—a requirement for multivariate ordination and modeling techniques such as PCA and DistLM. Fish abundance and species richness data were log-transformed [$\log_{10}(x + 1)$] to generate Euclidean distance and Bray-Curtis similarity matrices, respectively.

A two-way permutational analysis of variance (PERMANOVA) was used to assess differences in environmental variables, fish abundance, and species richness (based on multivariate matrices

with species as variables) across sampling sites and between seasons. When significant effects were detected, post hoc pairwise comparisons were performed to identify which sites or periods differed significantly. To evaluate differences in data dispersion among sites and seasons, a multivariate homogeneity of dispersion test (PERMDISP) (Anderson et al., 2006) was applied. The combined use of PERMANOVA and PERMDISP allowed us to distinguish whether significant patterns were driven by differences in group centroids (location effects), differences in dispersion, both, or neither, thereby improving the robustness of the interpretation.

Community structure and its relationship with environmental variables were evaluated using complementary multivariate approaches. Principal component analysis (PCA) was applied to the normalized environmental variables to identify spatial and seasonal gradients. Prior to PCA, the full set of environmental variables was examined for collinearity using Draftsman plots and a Spearman correlation matrix. Redundant variables with correlation coefficients (r) > 0.7 were excluded from the final model to avoid multicollinearity. The importance of each species across spatial and temporal gradients was assessed using numerical percentage (N%) and frequency of occurrence (FO%). Species were further classified into trophic groups (Elliott et al., 2007) and life-history strategies (Winemiller, 2005) to evaluate functional responses to abiotic conditions.

To complement PERMANOVA results and further assess similarities in species composition among seasons and sites, similarity percentage analysis (SIMPER) was conducted using PRIMER-E v.6 (Clarke and Gorley, 2006). Only species with an overall abundance ≥ 1.0% and a frequency of occurrence (FO) ≥ 15% were included. The relationship between fish assemblage structure and environmental variables was examined using distance-based linear models (DistLM), which identify predictive relationships between multivariate response data and explanatory variables (Anderson et al., 2008). Bray-Curtis similarity matrices were used as the response variable, and environmental predictors were selected using a best-fit procedure based on the Akaike Information Criterion (AIC). Once the optimal model was identified, distance-based redundancy analysis (dbRDA) was performed to visualize the relationships between fish assemblages and environmental variables in a reduced multidimensional space. All statistical analyses were performed using PRIMER v6.0 (Clarke and Gorley, 2006) with the PERMANOVA+ add-on (Anderson et al., 2008).

RESULTS

A total of 2,856 individuals belonging to 36 fish species and 20 families were captured. Families with higher species richness included Gerreidae (4), Clupeidae, Carangidae, Centropomidae (3), Dorosomatidae, Gobiidae, Engraulidae, Poeciliidae, Mugilidae, and Cichlidae (2). The remaining families were represented only by a single species. Eleven species, each accounting for more than 1% of the total abundance and occurring in at least 15% of the samples, together represented over 90% of the total numerical abundance. The five most abundant species (n > 150 ind.)—*Phalloptychus januarius*, *Jenynsia lineata*, *Geophagus brasiliensis*, *Anchoa januaria*, and *Atherinella brasiliensis*—together represented nearly 73% of the total numerical abundance. Conversely, 25 species with individual numerical abundances of less than 1% accounted for just 5.08% of the total catch. The two-way PERMANOVA revealed no significant differences in abundance or species richness between sites and seasons (p > 0.050). Nevertheless, both abundance and richness were notably higher during summer and winter (Summer: 1,303 individuals, 20 species; Winter: 951 individuals, 31 species) compared to autumn and spring (Autumn: 358 individuals, 8 species; Spring: 264 individuals, 10 species) (Table 1).

Table 1. Numerical abundance (N, %N), frequency of occurrence (FO%), trophic groups, and life-history strategies (O – opportunist; E – equilibrium; P – periodic) of fish species captured in Rodrigo de Freitas Lagoon.

Species	N	%N	FO	Trophic groups	Strategy
Phalloptychus januarius	1184.0	41.5	35.0	Omnivore	O
Jenynsia lineata	306.0	10.7	40.0	Omnivore	O
Geophagus brasiliensis	264.0	9.2	55.0	Omnivore/Detritivore	E
Anchoa januaria	172.0	6.0	20.0	Planktivore/Carnivore	O
Atherinella brasiliensis	171.0	6.0	60.0	Omnivore	O
Poecilia vivipara	141.0	4.9	35.0	Omnivore	O
Brevoortia pectinata	137.0	4.8	20.0	Planktivore/Herbivore	O
Brevoortia aurea	103.0	3.6	15.0	Planktivore/Herbivore	O
Mugil liza	88.0	3.1	30.0	Detritivore	P
Eucinostomus argenteus	75.0	2.6	20.0	Omnivore	O
Oreochromis niloticus	70.0	2.5	35.0	Omnivore	E
Diapterus auratus	23.0	0.8	10.0	Omnivore (benthivorous)	O
Opisthonema oglinum	18.0	0.6	30.0	Herbivore/Planktivore	O
Mugil curema	16.0	0.6	10.0	Detritivore	O
Orthopristis rubra	16.0	0.6	5.0	Omnivore	E
Eucinostomus gula	13.0	0.5	10.0	Omnivore	O
Micropogonias furnieri	10.0	0.4	10.0	Carnivore (opportunist)	P
Diplodus argenteus	10.0	0.4	5.0	Omnivore	E
Microgobius meeki	7.0	0.2	10.0	Carnivore (benthivorous)	O
Syngnathus pelagicus	4.0	0.1	15.0	Planktivore	O
Elops smithi	4.0	0.1	10.0	Carnivore/Piscivore	P
Oligoplites saurus	3.0	0.1	10.0	Carnivore/Piscivore	P
Caranx hippos	3.0	0.1	5.0	Carnivore/Piscivore	P
Centropomus pectinatus	3.0	0.1	5.0	Carnivore/Piscivore	P
Cetengraulis edentulus	2.0	0.1	10.0	Planktivore/Herbivore	O
Diapterus rhombeus	2.0	0.1	5.0	Omnivore (benthivorous)	O
Trinectes paulistanus	2.0	0.1	5.0	Carnivore (benthivorous)	O
Awaous tajasica	1.0	0.0	5.0	Omnivore	O
Caranx latus	1.0	0.0	5.0	Carnivore/Piscivore	P
Centropomus parallelus	1.0	0.0	5.0	Carnivore/Piscivore	P
Centropomus undecimalis	1.0	0.0	5.0	Carnivore/Piscivore	P
Harengula clupeola	1.0	0.0	5.0	Planktivore	O
Hemiramphus brasiliensis	1.0	0.0	5.0	Omnivore/Herbivore	O
Mugil sp.	1.0	0.0	5.0	Detritivore	P
Paralichthys orbignyanus	1.0	0.0	5.0	Carnivore (benthivorous)	P
Sardinella brasiliensis	1.0	0.0	5.0	Planktivore	O
Total	2856	100.0			

Environmental conditions in RFL varied significantly across seasons and sampling sites, as indicated by the PERMANOVA analysis (season: Pseudo-F = 13.02, $p < 0.001$; sites: Pseudo-F = 2.07, $p < 0.001$). However, post hoc pairwise comparisons between sites did not reveal statistically

significant differences. To assess whether the observed variation was due to differences in group dispersion, a multivariate dispersion analysis (PERMDISP) was applied. The results showed no significant differences in dispersion among seasons (F = 5.10; p = 0.075) or among sites (F = 2.39; p = 0.200). These findings suggest that the patterns detected by PERMANOVA reflect true environmental differences across temporal and spatial scales, rather than differences in within-group variability. The highest temperatures were recorded during summer ($\bar{x}$ = 30.47 °C), and the lowest during autumn ($\bar{x}$ = 23.36 °C), while winter and spring showed intermediate values ($\bar{x}$ = 28.64 °C and 29.26 °C, respectively) (Pseudo-*F* = 216.11, p < 0.001). Salinity peaked in spring ($\bar{x}$ = 12.98), whereas the other seasons exhibited lower and relatively similar values, ranging from 9.41 to 9.95 (Pseudo-*F* = 49.24, p < 0.001). Water transparency was lower in winter and spring ($\bar{x}$ = 0.87 m and 0.63 m, respectively) compared to summer and autumn ($\bar{x}$ = 2.12 m and 1.64 m) (Pseudo-*F* = 19.66, p < 0.001). Dissolved oxygen and chlorophyll-a displayed similar seasonal patterns, with lower concentrations during summer and autumn (DO: $\bar{x}$ = 3.65 and 5.71 mg/L; Chl-a: $\bar{x}$ = 4.80 and 16.88 µg/L) and higher concentrations during winter and spring (DO: $\bar{x}$ = 19.51 and 12.41 mg/L; Chl-a: $\bar{x}$ = 72.53 and 50.54 µg/L, respectively) (DO: Pseudo-*F* = 14.43, p < 0.001; Chl-a: Pseudo-*F* = 4.80, p = 0.010).

The first two principal components (PC1 and PC2) explained 64.9% of the total variance in the environmental data, with PC1 accounting for 44.9% and PC2 for 19.9%. The PCA biplot revealed a clear seasonal separation of samples (Figure 2). Summer samples (red circles) clustered predominantly in the right-hand quadrant, while winter samples (blue squares) were concentrated on the left-hand side of the ordination. Autumn (orange triangles) and spring (green diamonds) samples occupied intermediate positions, indicating a transitional pattern in environmental conditions throughout the annual cycle. Based on the eigenvectors, PC1 was strongly and positively correlated with water transparency (0.618), and negatively correlated with salinity (-0.464), chlorophyll-a (−0.449), and dissolved oxygen (−0.389). This axis appears to represent a gradient from clearer, less productive waters (positive side) to more saline and productive waters (negative side). PC2 showed negative correlations with water temperature (−0.570) and salinity (−0.519), and a positive correlation with dissolved oxygen (0.603), indicating that this component reflects a thermal-salinity gradient inversely related to oxygen availability.

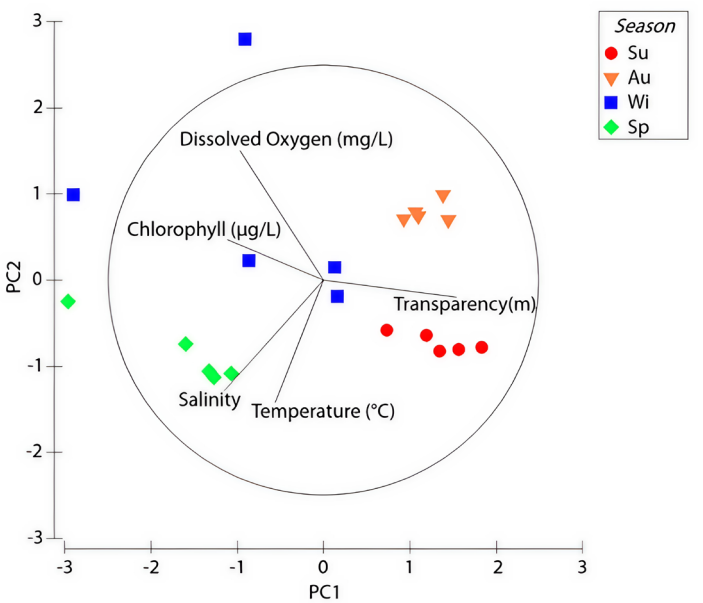

Figure 2. Principal Component Analysis (PCA) biplot of environmental variables across seasons in Rodrigo de Freitas Lagoon. Symbols represent individual samples collected during different seasons: Summer (Su), Autumn (Au), Winter (Wi), and Spring (Sp).

The DistLM analysis indicated that, among the environmental variables assessed, salinity had the highest explanatory power on fish assemblage structure (Pseudo-F = 4.68, $p < 0.001$), accounting for approximately 20.6% of the total variation. Water transparency also showed a significant effect (Pseudo-F = 2.67, p = 0.010), explaining 12.9% of the variation, whereas temperature, dissolved oxygen, and chlorophyll did not present significant relationships with community composition ($p > 0.05$). These patterns are reflected in the dbRDA ordination (Figure 3). The first axis (dbRDA1) explains 23% of the total variation (55.9% of the fitted variation) and is strongly negatively correlated with salinity (r = −0.843), indicating that this variable is the main driver of assemblage separation along this dimension. The second axis (dbRDA2) accounts for 8.7% of the total variation (21.2% of the fitted variation) and is positively associated with dissolved oxygen (r = 0.876) and water transparency (r = 0.374).

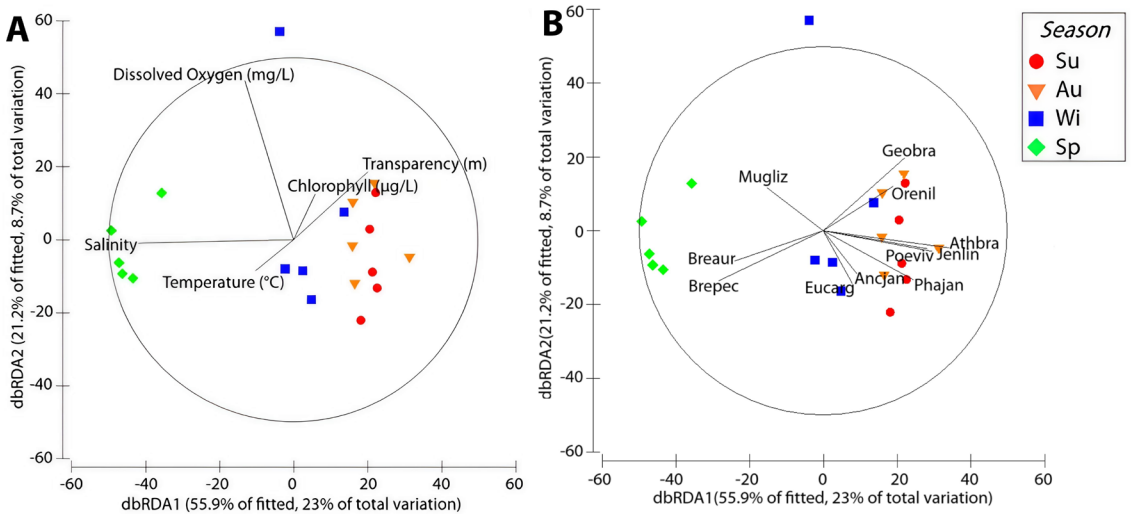

Figure 3. Diagrams of the first two axes of the dbRDA demonstrating the relationship between environmental variables (A) versus fish assemblages (B) (more abundant and frequent) in Rodrigo de Freitas Lagoon. Seasons: Summer (Su), Autumn (Au), Winter (Wi), and Spring (Sp).

Seasonal patterns are clearly evident in the dbRDA ordination (Figure 3A). Winter samples are clustered in the lower left quadrant and are associated with higher salinity, while spring samples occupy the upper left quadrant, showing stronger relationships with dissolved oxygen. Summer and autumn samples are positioned on the right side of the plot, primarily associated with higher transparency and lower chlorophyll concentrations, indicating seasonal shifts in environmental conditions influencing assemblage structure. The distribution of species vectors (Figure 3B) further supports these patterns. *Mugil liza*, *Brevoortia aurea*, and *Brevoortia pectinata* are positioned between winter and spring samples, suggesting an affinity with more saline and, in some cases, more oxygenated waters. In contrast, *Geophagus brasiliensis* and *Oreochromis niloticus* are associated with summer and autumn samples, reflecting preferences for lower salinity and distinct productive conditions. Species such as *Atherinella brasiliensis*, *Jenynsia lineata*, and *Poecilia vivipara* are closely related to autumn conditions, while *Phalloptychus januarius* and *Anchoa januaria* show affinities with summer and autumn, respectively. *Eucinostomus argenteus* occupies an intermediate position between autumn and winter, indicating an association with transitional environments characterized by intermediate salinity and productivity.

The SIMPER analysis revealed that the greatest dissimilarities in fish assemblage composition occurred between the following seasonal pairs: summer vs. spring, autumn vs. spring, and winter vs. spring (Table 2). These results indicate that spring represents an ecological transition period, marked

by the presence of more euryhaline species such as *Mugil liza*, *Brevoortia aurea*, and *Brevoortia pectinata*. Furthermore, the replacement of winter-associated species by those adapted to less saline and warmer conditions*, such as Geophagus brasiliensis,* contributes significantly to these dissimilarities. Summer, on the other hand, is characterized by a greater abundance of species adapted to warmer, eutrophic environments. Among the species analyzed, *Phalloptychus januarius*, *Geophagus brasiliensis*, *Jenynsia lineata*, and *Poecilia vivipara* contributed most to the dissimilarity between seasons, standing out for their sensitivity to seasonal variation.

Table 2. Results of SIMPER analysis showing the fish species that contributed most to the dissimilarity between seasons Summer (Su), Autumn (Au), Winter (Wi), and Spring (Sp) in Rodrigo de Freitas Lagoon.

Groups	**Su vs Au**		**Su vs Wi**		**Su vs Sp**		**Au vs Wi**		**Au vs Sp**		**Wi vs Sp**	
Average dissimilarity	64.2		75.09		95.03		77.61		96.1		92.33	
Species	**Av.Diss.**	**Contrib %**	**Av.Diss.**	**Contrib%**	**Av.Diss.**	**Contrib %**	**Av.Diss.**	**Contrib%**	**Av.Diss.**	**Contrib%**	**Av.Diss.**	**Contrib %**
Phalloptychus januarius	11.69	18.2	9.96	13.27	12.49	13.15	8.56	11.02	6.91	7.2	8.68	9.4
Jenynsia lineata	9.86	15.35	7.96	6.97	6.25	6.58	7.67	9.89	12.91	13.43	5.23	5.66
Geophagus brasiliensis	8.61	13.41	6.74	8.97	7.03	8.4	6.87	8.86	12.72	13.24	8.99	9.74
Poecilia vivipara	7.77	12.1	5.1	6.79	9.62	10.12	5.71	7.36			5.6	6.07
Atherinella brasiliensis	7.03	10.55	6.83	9.1	12.68	13.34	7	9.02	13.48	14.03		
Anchoa januaria			5.18	7.9			5.71	7.36			5.23	5.67
Mugil liza			4.54	6.05			5.11	6.58			6.36	6.89
Oreochromis niloticus			4.37	5.82			4.1	5.28			3.63	3.93
Eucinostomus argenteus			3.84	5.11			3.38	4.35			3.76	4.07
Brevoortia pectinata					10.52	11.07			12.01	12.5	8.51	9.22
Brevoortia aurea					6.95	7.32			7.92	9.24	6.02	6.52
Microgobius meeki											3.69	4

DISCUSSION

This study demonstrates that, despite more than a century of intense urbanization and environmental modification, Rodrigo de Freitas Lagoon (RFL) still supports a moderately diverse fish assemblage comprising 36 species distributed across 20 families. However, this apparent diversity masks a pronounced structural simplification of the community. The numerical dominance of a small subset of opportunistic and disturbance-tolerant species, such as *Phalloptychus januarius*, *Jenynsia lineata*, and *Geophagus brasiliensis*, indicates strong environmental filtering under chronically degraded conditions. Comparable patterns, in which a few tolerant generalists increasingly dominate assemblages under urban pressure, have been widely documented (Mouillot et al., 2007; Pérez-Ruzafa et al., 2019; Franco et al., 2022; Hernández-Mendoza et al., 2024). These shifts are typically associated with declines in both taxonomic and functional diversity, reflecting the selective persistence of species

capable of tolerating unstable, nutrient-enriched, and hypoxic environments (Zhang et al., 2022; Zhang et al., 2024).

Comparisons between the 2023 survey and historical records reveal a marked and non-random reduction in species richness. While 64 species were recorded between 1991 and 2004—with peak richness reaching 59 species in the early 1990s (Andreata et al., 2004; Andreata, 2012)—only 36 species were detected in the present study. This corresponds to a reduction of approximately 44% relative to the historical species pool, and nearly 80% relative to peak richness. Such losses far exceed the magnitude of seasonal or interannual variability typically expected for estuarine and coastal lagoon fish assemblages. Similar patterns have been reported globally, indicating that when urbanization reaches the high intensity levels typically associated with dense human populations and extensive infrastructure biodiversity loss accelerates, leading to abrupt and persistent shifts in community structure (Chen and Olden, 2020).

The Venn diagram analysis further supports the interpretation that biodiversity loss in RFL reflects a selective environmental filter rather than simple temporal species replacement (Figure 4). Of the 63 species recorded across all periods, only 18 persisted throughout 1991–2004, and just 13 remained present in 2023. These include economically valuable and locally important artisanal fishery species such as *Micropogonias furnieri*, *Sardinella brasiliensis*, *Centropomus parallelus*, *Centropomus undecimalis*, *Mugil liza*, and *Mugil curema*. Although species turnover is an inherent feature of lagoonal systems, the long-term reduction in species persistence, coupled with ordered and non-random species loss, indicates that assemblage changes are driven by directional environmental filters. This pattern reflects the progressive exclusion of environmentally sensitive taxa, resulting in communities increasingly composed of species-poorer subsets derived from historically more diverse assemblages—a hallmark of biotic homogenization under chronic stress (Gámez-Virués et al., 2015; Menegotto et al., 2019; Zhang et al., 2022). Comparable patterns have been documented in heavily polluted and urbanized aquatic systems across South America and other developing regions (Paredes del Puerto et al., 2021; Pinto et al., 2025).

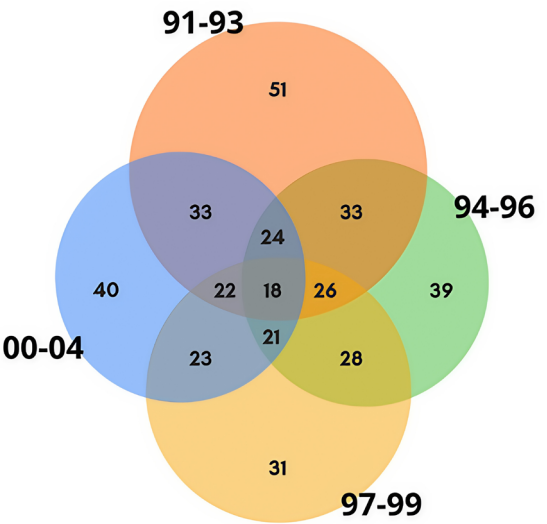

Figure 4. Venn diagram showing the variation in the fish fauna composition of Rodrigo de Freitas Lagoon between the periods 1991 and 2004, highlighting the number of exclusive and shared species among the different time intervals.

Importantly, the sampling period coincided with 2023–2024, years classified as atypical due to the occurrence of a strong El Niño event, according to the Oceanic Niño Index (Null, 2026). Strong El Niño phases are known to alter regional rainfall patterns, freshwater inflow, thermal structure, and salinity

regimes in coastal and estuarine environments, potentially intensifying environmental stress. Accordingly, part of the reduced richness observed in 2023 may reflect a climate-driven amplification of unfavorable conditions rather than exclusively long-term degradation trends. Nevertheless, the environmental variables recorded during the study largely fell within the historically degraded range described for RFL, indicating that El Niño likely acted as an additional stressor superimposed on an already simplified and vulnerable system, rather than as the primary driver of biodiversity loss.

Seasonal variation in assemblage structure remained evident, with higher richness and abundance recorded during summer and winter, reflecting the influence of temperature, rainfall, and salinity fluctuations. Among the measured variables, salinity emerged as the main driver of community structure, consistent with previous studies conducted in RFL and other coastal lagoons (Domingos et al., 2012; Moraes et al., 2014; Franco et al., 2022). Across lagoonal systems, salinity gradients function as strong environmental filters by constraining physiological tolerance and life-history strategies. These gradients tend to favor marine and estuarine species near inlets, while inner lagoon zones increasingly support simplified assemblages dominated by a few tolerant species that share similar ecological traits, resulting in high functional redundancy (Mouillot et al., 2007; Hernández-Mendoza et al., 2024).

The strong negative association between salinity and the abundance of *Brevoortia aurea*, as reported by Moraes et al. (2014), was also observed in our data, although with an opposite pattern, suggesting possible spatial or temporal variations in the species' responses to environmental conditions. Periods and locations with higher salinity levels (A1) tended to be dissociated from favorable conditions for this species, whose greatest abundance was observed in years and sites with lower salinity (A2 and A3 for *Brevoortia aurea*; A3 and A5 for *Brevoortia pectinata*) (Andreata et al., 2004). This pattern may be related to the greater tolerance of *Brevoortia* to less saline and more eutrophic estuarine environments. In addition to restricting distribution, elevated salinity can promote water column stratification and the consequent reduction of dissolved oxygen, especially when combined with factors such as an absence of wind, high temperatures, the presence of organic matter, and freshwater inputs. Such conditions are frequently associated with fish mortality events, as also reported by Andreata et al. (1997) and Domingos et al. (2012).

Another notable factor was water transparency, which showed a significant correlation with community composition, especially during the summer and autumn months when higher transparency coincided with lower chlorophyll-a and dissolved oxygen concentrations. These results suggest that, in periods of greater thermal stability and lower primary productivity, the biological community reorganizes differently compared to winter and spring, which are characterized by higher productivity (elevated chlorophyll-a) and better water column oxygenation. This pattern may be associated with a greater dominance of cyanobacteria during these periods, as observed by Domingos et al. (2012) in years of high phytoplankton biomass and low oxygen levels—conditions that negatively affected sensitive species such as *Brevoortia aurea* and *Brevoortia pectinata*.

The resilience of species such as *Poecilia vivipara* and *Phalloptychus januarius*, frequently abundant even under adverse conditions, corroborates the findings of Moraes and Andreata (1994). They identified a diet based on cyanobacteria and epibenthic algae, alongside high reproductive plasticity, as key factors for the survival of these species during periods of environmental degradation (Pereira and Andreata, 2003; Andreata, 2012). These results reinforce the importance of understanding the seasonal dynamics of environmental variables—particularly salinity, transparency, and dissolved oxygen—in maintaining biodiversity and in the early diagnosis of conditions conducive to fish mortality events in the lagoon.

The persistence of species exhibiting Periodic and Equilibrium life-history strategies such as *Micropogonias furnieri*, *Mugil liza*, *Centropomus* spp., and *Diplodus argenteus*, in areas closer to the sea connection indicates that marine influence still occurs, albeit intermittently and at reduced

intensity. However, their low relative abundance compared to opportunistic strategists underscores the constraints imposed by eutrophication, hypoxia, and limited water renewal. Similar patterns have been reported in tropical bays and lagoons, where prolonged physical and chemical stress compresses the range of viable functional traits, leading to the exclusion of sensitive species and the persistence of only a narrow subset of tolerant taxa (Freitas and Araújo, 2025).

Although no statistically significant spatial differences in richness and abundance were detected, sites characterized by greater shoreline structural heterogeneity (A1, A2, and A5) tended to support higher species richness. This pattern highlights the role of habitat complexity as a secondary buffer against biodiversity loss, by providing refuges, feeding opportunities, and a diversity of microhabitats. In contrast, A3, which is influenced by stormwater runoff, exhibited reduced vegetation cover, whereas A4, the most strongly artificialized area, was characterized by a rocky substrate and retaining walls, resulting in the lowest structural complexity (Andreata et al., 2004; Andreata, 2012; Moraes et al., 2014; Rodrigues et al., 2021). Nevertheless, several studies indicate that habitat heterogeneity alone is insufficient to counterbalance the effects of chronic nutrient loading, pollution, and hydromorphological alteration, which ultimately drive taxonomic simplification and functional convergence in urban aquatic ecosystems (Rodrigues-Filho et al., 2023; Sala-Mirete et al., 2025).

At broader spatial scales, the patterns observed in RFL are consistent with those reported from urban and peri-urban aquatic systems worldwide, particularly in developing regions (Costa et al., 2021; Zhang et al., 2022; Trovillion et al., 2023; Maeda-Obregon et al., 2025). In these systems, fish assemblages increasingly converge toward simplified configurations dominated by opportunistic generalists and, in some cases, non-native species. This convergence reflects shared responses to urban stressors, such as altered hydrology, pollution, and habitat loss, rather than local biogeographic constraints (Barletta and Lima, 2019; Ribeiro et al., 2025). At megacity scales, urbanization imposes strong filtering on functional traits, resulting in assemblages that are taxonomically impoverished, functionally redundant, and less resilient to additional disturbances (Zhang et al., 2022; Zhang et al., 2024).

Within coastal lagoon systems specifically, multiple anthropogenic pressures—including eutrophication, pollution, hydrological alteration, and biological invasions—have been shown to compromise biodiversity and ecosystem functioning, with direct consequences for fisheries productivity and ecosystem resilience (Costa et al., 2021; Rodrigues-Filho et al., 2023). Long-term studies from lagoonal systems, such as the Mar Menor Lagoon in Spain, demonstrate that once spatial heterogeneity and species turnover decline, ecosystems become increasingly susceptible to abrupt regime shifts, the loss of ecosystem services, and ecological collapse (Pérez-Ruzafa et al., 2019; Sala-Mirete et al., 2025).

Taken together, these results support the hypothesis that fish assemblage composition in RFL reflects the combined effects of intense local anthropogenic pressure and residual marine connectivity. The dominance of opportunistic strategists, coupled with the restricted persistence of Periodic and Equilibrium species, indicates that only a limited subset of the regional species pool is currently able to persist under the strong environmental filtering imposed by chronic eutrophication, reduced water renewal, and pollution. Climatic anomalies, such as strong El Niño events, likely act to further intensify these constraints. This configuration is consistent with a broader global pattern in which urban coastal lagoons, particularly in developing countries, exhibit coupled processes of biodiversity loss, spatial homogenization, and progressive simplification of functional trait diversity (Zhang et al., 2024; Pinto et al., 2025).

CONCLUSION

This study documents a persistent process of ecological simplification in Rodrigo de Freitas Lagoon, evidenced by a marked decline in fish diversity over recent decades and the dominance of opportunistic, degradation-tolerant species such as *Phalloptychus januarius*, *Jenynsia lineata*, and *Geophagus brasiliensis*. The continued, albeit limited, occurrence of marine and estuarine species

exhibiting Periodic or Equilibrium life-history strategies indicates that tidal influence persists but is strongly constrained by restricted water exchange. Seasonal variation in species richness and abundance was primarily driven by salinity and water transparency, while the lack of significant spatial differences among sampling sites reflects pronounced environmental homogenization. Although the 2023–2024 period coincided with atypical climatic conditions associated with a strong El Niño event, the magnitude and selectivity of species loss observed support the interpretation of long-term, chronic degradation rather than short-term climatic effects. The residual presence of marine species of ecological and fishery relevance highlights reduced, but persistent ecological connectivity, reinforcing the need for targeted management and restoration actions to improve water quality, habitat heterogeneity, and ecosystem resilience in urban lagoon systems.

AI use disclosure

Artificial intelligence tools (DeepSeek) were used exclusively to refine the English language of this manuscript. The content was carefully reviewed by the authors to ensure consistency and correctness, and the authors are fully responsible for the final version of the manuscript.

Data availability statement

All data are available from the corresponding author upon reasonable request.

Supplementary material

No supplementary material was provided for this study.

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Author contributions

E.J.G.P.: Conceptualization; Data Curation; Investigation; Methodology; Formal Analysis; Writing – original draft; Writing – review & editing.

F.D.M.C.: Formal Analysis; Software; Writing – review & editing.

L.M.F.: Formal Analysis.

V.M.M.O.: Data Curation; Formal Analysis.

C.E.L.F.: Supervision; Writing – review & editing.

M.R.C.: Investigation; Methodology; Supervision; Resources; Project Administration; Funding Acquisition; Writing – review & editing.

Conflicts of interest

The authors declare no conflicts of interest.

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