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Temporal Variation in Ecological Indices of the Fish Assemblage in a Port- Influenced Amazonian Estuarine System in the Gulf of Maranhão, Brazil

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Abstract

The present study uses the fish community as an indicator of biodiversity in the estuary of Coqueiros Strait on São Luís Island, state of Maranhão, Brazil, which is a region under the influence of port activities. Six collections were performed at four sampling points between February 2022 and June 2023. Fishes were caught by artisanal fishermen using fixed gillnets, with a six-hour standardized fishing effort. After capture, the fishes were transported to the laboratory for taxonomic identification, biometric measurements, and weighing. A total of 8,063 individuals of 47 species belonging to 28 families were caught, with a predominance of the orders Siluriformes (28.79%) and Perciformes (22.68%). The species *Sciades herzbergii* had the highest relative abundance (25.5%). Species diversity varied over time, with the highest values in June 2023 and lowest in February 2022. The Shannon-Wiener diversity index (H') ranged from low (H' = 1.98 in February 2022) to medium (up to H' = 2.61 in other periods), while evenness exhibited spatial and temporal fluctuations. Sampling point P1 had greater uniformity in the distribution of the species, while P2 and P3 had greater similarity to each other. Diversity ranged from low (Feb 2022, H' = 1.98) to medium (other months, up to H' = 2.61), with evenness also fluctuating over time and space. P3 has the lowest diversity and evenness, suggesting a greater dominance of opportunistic species, while P1 and P4 had more balanced communities. The analysis of the ABC curves corroborated these results, indicating relatively more preserved environments at some points and greater anthropogenic pressure at others. The results indicate that the composition and abundance of the ichthyofauna are mainly influenced by seasonal factors, with variations in the structure of the communities over time. Despite the proximity to port activities, no significant changes were found in the ecological indices analyzed. This study highlights the importance of the estuary Coqueiros Strait as a nursery and feeding area for several fish species, underscoring the need for continual monitoring and sustainable management strategies of fishery resources to ensure the conservation of biodiversity and food security for local populations.

INTRODUCTION

Approximately 54.8% of the Brazilian population lives in municipalities located up to 150 km from the coast (IBGE, 2022). This region has faced an increase in activities that exploit its resources, placing pressure that requires monitoring to ensure environmental conservation and the maintenance of the quality of life of the users of these resources (Pardal; Christofoletti; Martinez, 2024).

Estuaries stand out as the most diverse ecosystems on the planet due to their biodiversity as well as social and economic importance (Day et al., 2012). However, anthropogenic actions have transformed these environments into the most threatened natural systems, marked by habitat destruction, sediment contamination, as well as the occurrence of toxic and subtoxic effects on component organisms (Amaral et al., 2025).

Environmental changes are responsible for the loss of biological diversity as environmental conditions are altered (Dudgeon; Strayer, 2025). Frequent anthropogenic impacts affect aquatic ecosystems in a

complex way that cannot be analyzed using physicochemical variables alone (Moulinec et al., 2025).

Ichthyofauna has consistently been used to assess environmental degradation, serving an indicator of direct and indirect stress in the entire ecosystem. Environmental changes can trigger responses in these organisms that emerge in the form of stress as well as changes in metabolic activities, composition, and the structuring of fish communities (Batista; Ferreira; Silva, 2024).

Thus, knowledge on the ecological processes of the fish community is essential for the generation of information on the current environmental condition and trends in time series (Nimasow et al., 2025). Spatial and temporal variability in fish populations and communities can be observed through periodic monitoring, which enables the identification of changes in composition and diversity over time (Li et al., 2024).

The coast of the state of Maranhão extends for approximately 640 km and has the most extensive estuarine areas in Brazil, with a wide continental shelf of shallow waters and considerable river drainage (Gualberto; El-Robrini, 2005). Fishing is an activity of considerable social and economic importance in the state, with 92% of artisanal fishing production coming from the coastal area, where about 267,626 duly licensed professional fishermen work (Almeida et al., 2006; MPA, 2023).

On the global scale, an estimated 34.2% of fish stocks are subjected to unsustainable exploitation practices, which substantially increases the risk of population decline and eventual extinction, especially when combined with the limited understanding of fishing potential and the frequent capture of immature individuals (FAO, 2020). Given this scenario, it is essential to adopt integrated approaches that consider the fishing system holistically, incorporating the biological aspects of species and relevant ecological processes on their respective spatial and temporal scales.

Anthropogenic interventions in the estuarine environment promote significant and, at times, immediate changes in fauna diversity, which underscores the need to implement effective management strategies for fisheries. Such strategies should be oriented towards the responsible use of available stocks to prevent the decline and depletion of exploited populations.

The analysis of the distribution patterns in fish communities is an essential tool for highlighting the relevance of the study area as potential foraging, growth, and reproduction grounds for different species, in addition to enabling the identification of interferences and impacts resulting from anthropogenic activities exerted on the estuarine system.

MATERIAL AND METHODS

STUDY AREA

The study area comprises the estuarine system of Coqueiros Strait and the Cachorros River, located at coordinates 2°43'14"S – 2°38' 12"S; 44°17'50"W- 44°23'35"W (Figure S1). Sampling was performed at

four locations: point P1, located in the evolution basin of the Cachorros River near Santa Rita Stream; point P2, located in the drainage area of Tarará Stream; point P3, at the mouth of the Coqueiros strait with Arraia Stream in Arapopai Stream; and point P4, Inhaúma Stream located in a stretch upstream from the industrial plant.

FIGURE S1.

The strait connects with São Marcos Bay through two openings and separates São Luís Island from Tauá-Mirim Island. The area is considered the largest hydrographic network in the south-southwest region of São Luís Island, with an area of 63.7 km². The region also has a large number of small rivers, streams, and simple inlets of the sea that advance inland. The Cachorros River is approximately 7.4 km in length and flows into Coqueiros Strait, close to the ALUMAR private use terminal and 3.5 km from the encounter with São Marcos Bay (IMESC, 2010).

DATA COLLECTION AND PROCESSING

Sampling was performed in 2022 (February, June, September, and December) and 2023 (March and June). Fishes were caught with the aid of fixed gillnets with meshes of 35 millimeters between opposite knots and 200 to 300 meters in length. The catch strategy consisted of blocking the stream during the period between tides with the aim of collecting fish during the low tide period. The entire catch process was performed by local artisanal fishermen working in the region of Coqueiros Strait, with monitoring of the technical team responsible for the identification of the ichthyofauna.

The individuals caught were packed in labeled plastic bags, placed in Styrofoam coolers with ice, and transported to the Laboratory of Ichthyology and Fisheries Resources (LABIRPesq), where identification was made on the species level using the method proposed by Cervigón *et al*. (1992), Figueiredo *et al*. (2000), and Fischer (1978). Biometric characteristics were determined by obtaining total length (cm) and weight (g) and determining the sex and stage of gonadal maturation of each individual, following the scale proposed by Vazzoler (1996).

Voucher specimens were deposited in the ichthyological collection of the of the Federal University of Maranhão (CPUFMA), São Luís, Brazil, under catalog numbers CPUFMA 3920–3966, corresponding to the 47 species identified. Institutional acronyms for ichthyological collections follow the standards proposed by Sabaj (2020) and updated lists provided by Fricke and Eschmeyer (2025).

The dataset was tabulated, organized on Microsoft Excel spreadsheets (version 365), and later introduced into matrices in the PAST 4.03 (Hammer; Harper, 2001), STATISTICA 7.0, and Primer 6.0 software programs, in which statistical analyses were performed to understand data related to the composition and diversity of the community.

DATA ANALYSIS

The Shannon-Wiener diversity index is widely recognized as the most satisfactory measure of diversity, as the index takes into account the relative importance of each species, using abundance and frequency in relation to the total number of individuals in the community (Falcão, 2006). Derived from uncertainty theory, the Shannon index is used to predict the probability that a randomly selected individual within the set of species and individuals belongs to a specific species. As the number of species and their specific distributions increases, uncertainty also increases and, consequently, diversity tends to be greater (Ludwig, Reynolds, 1988).

The classification criterion used was the one proposed by Valentin *et al*. (1991), in which the biodiversity result was expressed in bits.ind-1: $H' \geq 3.0$ denotes high diversity; $2.0 \leq H' < 3.0$ denotes medium diversity; $1.0 \leq H' < 2.0$ denotes low diversity; and $H' < 1.0$ denotes very low diversity.

Proposed by Pielou (1966), Pielou's evenness index is a measure used in ecological studies to estimate uniformity in the distribution of the relative abundance of species in a community. The index has a range from 0 to 1; values closer to 0 indicate the dominance of one species and values closer to 1 refer to a community with even distribution.

Within a wide variety of diversity measures, the index chosen was the one proposed by Mark Hill (1973), which is widely used in ecology studies to quantify the diversity of species in a given community, taking into account both the abundance and evenness of the species present.

The coefficient developed by Jaccard (1901) was applied to the sampling points based on the presence and absence of fish species. This measure was used to determine the degree of similarity among the communities in the different places investigated.

Permutational Multivariate Analysis of Variance (PERMANOVA) was used to assess potential statistical differences among sampling sites, seasonal periods, and their interaction, considering the multivariate structure of abundance and biomass data. The analysis was conducted using a significance level of $\alpha \leq 0.05$ with 9,999 permutations. According to Montgomery (2010), PERMANOVA is a widely used technique for comparing multiple groups or strata of interest, representing a suitable analytical approach, particularly because it does not require data normality as an underlying assumption.

The rarefaction curve was used to assess the representativeness of the recorded species richness. This method allows for standardizing the number of individuals or samples, enabling more consistent comparisons of richness among the groups analyzed while minimizing the influence of differences in sample size (Colwell, Mao, and Chang, 2004).

The abundance biomass comparison (ABC) method proposed by Warwick *et al.* (1986) is often employed to classify ecosystems that are under pressure due to changes that occur in the environment. As abundance and biomass vary according to the trophic level of aquatic ecosystems, this method is based on the evolutionary theory of *r* and *k* strategists (Clarke; Warwick, 2001).

When aquatic ecosystems are classified as having good ecological quality, the biomass curve extends above the abundance curve, as the community is dominated by *k* strategist species (slow growth, late maturation, and low fecundity). However, as environmental disturbances advance, slow-growing species begin to be replaced by opportunistic species, the so-called *r* strategists (fast growth, high fecundity, and short life cycle) and the abundance curve tend to meet or overlap the biomass curve.

RESULTS

A total of 8,063 individuals were caught during the six sampling campaigns. The individuals belonged to 47 species, 28 families, and 15 orders.

Among the orders caught during the study, Perciformes had the highest richness, with 20 species captured (42.6% of total catch), followed by Siluriformes, with nine species (19.1%), and Clupeiformes with three species (6.4%). Two species each were recorded for the orders Mugiliformes, Pleuronectiformes, and Scombriformes.

Sciaenidae stood out among the families, with the highest number of species caught, accounting for 19.15% of the total catch, followed by the families Ariidae (14.89%), Carangidae (8.51%), Engraulididae (4.26%), and Mugilidae (4.26%).

Regarding species abundance, *Sciades herzbergii* was the most representative, with 2,056 individuals caught, corresponding to 25.54% of the total. This was followed by *Anableps anableps*, with 1,254 individuals (15.55%), *Colomesus psittacus*, with 1,166 individuals (14.46%), *Cynoscion acoupa*, with 679 specimens (8.42%), and *Mugil gaimardianus*, with 605 individuals caught (7.5%).

Sciades herzbergii was also the species with the highest biomass index, totaling 275,596.1 g, followed by *Colomesus psittacus* (118,466.7 g), *Anableps anableps* (57,939.3 g), *Cynoscion acoupa* (30,559.7 g), and *Mugil gaimardianus* (21,406.8 g), as detailed in Table S2.

TABLE S2

The temporal analysis of abundance revealed that December 2022 had the highest catch percentage, corresponding to 29.34% of the total catch. In contrast, March 2023 had the lowest abundance (7.5%). Considering sampling points, P3 had the highest abundance (30.16% of individuals) and P4 had the lowest (14.52%).

The temporal analysis of the Shannon-Wiener index (H') indicated that the months of June 2022 (H' = 2.19), September 2022 (H' = 2.24), December 2022 (H' = 2.12), March 2023 H' = 2.32), and June 2023 (H' = 2.61) exhibited average diversity. However, February 2022 (H' = 1.98) had the lowest value and was classified as having low diversity (Figure S3). Regarding the spatial variation of the index, points P1 (H' = 2.63), P2 (H' = 2.38), and P4 (H' = 2.31) had average diversity values. In contrast, point P3 (H' = 1.63) had the lowest diversity value of the entire collection and was classified as having low diversity (Figure S3).

FIGURE S3

In the analysis of the temporal variation in Pielou's evenness index, the months of June 2023 (E = 0.74) and March 2023 (E = 0.72) had the highest values in the entire collection, whereas February 2022 (E = 0.61), June 2022 (E = 0.65), September 2022 (E = 0.67), and December 2022 (E = 0.60) had intermediate values (Figure S4). When performing the spatial analysis of the index, P1 had the highest evenness of the entire collection (E = 0.75), whereas P2 (E = 0.68) and P4 (E = 0.66) had intermediate values and P3 (E = 0.47) had the lowest evenness of the entire collection (Figure S4).

FIGURE S4

The Jaccard coefficient, which was used to associate catch sites, revealed that the Tarará (P2) and Arapopaí (P3) streams had the highest similarity of the entire collection (J = 0.722), whereas the other sampling points had intermediate values of the coefficient. The Santa Rita (P1) and Arapopaí (P3) streams were the most different of the entire collection (J = 0.625).

The temporal analysis of the Hill series identified higher values of species richness in the dry season (June 2023, Dec 2022, and Sep 2022) and lower values in the rainy season (Feb 22 and Mar 22), when $\alpha = 0$ (Figure S5). Analyzing Hill's diversity by sampling site, P1 had the highest values, as the line that represents the catch site remained above that of the other collection points. P2 and P4 overlap, with $\alpha > 0$. In contrast, the line representing P3 remained below that of the other points (Figure S5).

FIGURE S5

The PERMANOVA results based on the abundance data revealed significant differences among the sampling sites ($p = 0.0001$) and the seasonal periods analyzed ($p = 0.0151$). Regarding the interaction among factors, the analysis did not detect significant differences in the sampled community ($p = 0.8321$). The PERMANOVA results are presented in (TABLE S6).

TABLE S6

Rarefaction curves revealed spatial differences in estimated species richness among sampling sites. Site P1 exhibited the highest richness values, approaching an asymptote at approximately 36 species, indicating a tendency toward sampling sufficiency. This was followed by sites P2 and P4, which reached final richness estimates of approximately 32–33 species. In contrast, site P3 showed the lowest estimated richness, stabilizing at around 30 species. Collectively, these patterns indicate moderate spatial variation in species richness among sampling sites (Figure S7).

FIGURE S7

The ABC curve was used to estimate environmental degradation at the collection points. The positive W values at points 1 (Santa Rita Stream) and 4 (Inhaúma Stream) reflect a relatively balanced community

(Figure S8). The negative values found at P2 and P3 (Tarará and Arapopaí Streams) indicate the dominance of opportunistic species in these environments.

FIGURE S8

DISCUSSION

The composition of the ichthyofauna in the study area reflects the high environmental heterogeneity of the area of influence of the ALUMAR private use terminal, which is typical of tropical estuarine ecosystems (Maciel et al., 2024). The predominance of Perciformes is in agreement with studies conducted by Santana et al. (2025) in the same region and Silva et al. (2023) along river-estuary continuum of the São Francisco River, where the group is often dominant due to its ecological plasticity and tolerance to environmental variations.

The prominence of the families Sciaenidae, Ariidae, and Carangidae is in agreement with previous records for the Gulf of Maranhão, where these families are abundant due to their ecological role as predators and intermediate consumers in the food chain (Carvalho *et al.*, 2025).

Regarding abundance, the dominance of *Sciades herzbergii* confirms the pattern reported in previous studies conducted on São Luís Island by Lima (2013) in three tidal channels of São Marcos Bay and by Pinheiro-Jr, Castro, and Gomes (2005) in the estuary of the Anil River. This dominance may be associated with the opportunistic behavior of the species, its tolerance to a wide variation in salinity, and the occupation of bottom niches, suggesting the relevance of the predation factor in the dynamics of interspecific relationships (Queiroga et al., 2012).

At the same time, the occurrence of *Anableps anableps, Colomesus XXXdentulou, Colomesus Psittacus*, and *Mugil gaimardianus* demonstrates the importance of species adapted to the intertidal zone and transitional environments, with species tolerant to variations in salinity having generalist and opportunistic feeding habits, in addition to different reproductive strategies that enable the prolonged permanence of both juveniles and adults in estuarine environments (Araújo, Fernández, 2018).

The temporal diversity analysis revealed that the greater abundance in the transition period may be associated with migration as well as the aggregation of species for reproduction or feeding, as described for other tropical estuaries (Day et al., 2012). The low abundance in months of greater river discharge can be explained by the increase in turbidity and reduction in salinity, factors that affect the spatial distribution of species, as reported by Duque et al. (2020) and Molina, Duque, Cogua (2020) in tropical estuaries similar to the environment investigated here. This pattern confirms that biological diversity in the ecosystems studied is strongly modulated by the seasonal regime, with a reduction in the rainy season due to physicochemical changes, which limit the occurrence of more sensitive species and favor organisms more tolerant to variations in salinity.

The spatial variation in biological diversity in estuarine ecosystems may reflect the influence of multiple environmental and anthropogenic factors, such as the salinity gradient, intensity of river discharge, food availability, habitat heterogeneity, and water quality (Day et al., 2012; Gomes-Gonçalves; Araújo, 2022). Environments with greater stability and structural complexity tend to favor the accumulation of biomass and the extension of food chains, resulting in overlapping niches and maintaining more balanced diversity (Rodrigues et al., 2022; Maciel et al., 2024).

Studies carried out in the Gulf of Maranhão by Santana et al (2025) and Castro (1997) document this pattern, demonstrating that areas with greater tidal influence and better environmental quality maintain higher diversity, whereas areas more exposed to degradation or intense fluvial influence have lower diversity. Thus, the heterogeneity found among the different sampling points is in line with the typical behavior of tropical coastal ecosystems, in which biological diversity responds directly to the interaction between physical, chemical, and biological factors (Nauta *et al*., 2024).

The temporal analysis of ichthyofaunal evenness revealed a pattern similar to that found for the diversity index, with variations throughout the seasonal cycle. Higher evenness values indicate greater uniformity in the relative abundance of species, suggesting that communities are in a more stable state, with less dominance of specific taxa (Magurran; McGill, 2011). Spatially, the distribution of evenness values confirms the influence of local habitat characteristics on the structuring of communities. Areas with greater evenness tend to have resources and microhabitats capable of sustaining different trophic guilds without a marked predominance of a single taxon, which is associated with more stable, heterogeneous environments (Melo, 2008; Henderson et al., 2021).

When analyzing sampling sites, sites with low evenness, marked by the dominance of a specific species, such as *S. herzbergii*, may reflect environments subject to greater environmental stress or structural simplification of the habitat. Under these conditions, the lower diversity of resources and the reduction in environmental complexity favor opportunistic species with a high capacity for adaptation, resulting in patterns of dominance (Bartholomew, Baird, 2009; Moustaka et al., 2024).

The application of Hill's series (1973) complements the analyses of diversity and evenness, showing that the pattern in the community is influenced by the seasonal regime, which sustains greater richness and diversity in the dry season, whereas the rainy season reduces the complexity of community (Rodrigues et al., 2022). In addition, the spatial analysis of the Hill index confirms that point P1 constitutes a more diversity-friendly environment, whereas P3 has environmental limitations that restrict both diversity and evenness, and points P2 and P4 have intermediate patterns.

The rarefaction curve corroborated the diversity indices, indicating the superior position of site P1, which exhibited the highest species richness, diversity, and evenness. In contrast, the narrower extent of the curve at site P3 suggests lower local richness, supporting a condition of comparatively reduced diversity at this site. In this context, studies conducted in Amazonian estuaries by Barros, Torres, and Frédou (2011) and Carvalho et al. (2025) reported higher diversity indices in more structurally complex channels,

reinforcing that species richness assessments should account for sampling standardization to enable more robust comparisons.

The use of the ABC curve as an environmental analysis tool enabled the investigation of the structure of the communities at the different sampling points, relating levels of environmental stress to the decrease in diversity, richness, and evenness due to the increase of few species in the affected region (Xu et al., 2021). The results reveal that the positive *W* value at P1 reflects a relatively balanced community, with little variation between the abundance and biomass curves, indicating that species of different sizes contribute proportionally, creating stable ecological conditions.

The *W* values at points P2 and P3 located in the Tarará and Arapopaí Streams were negative, indicating the dominance of opportunistic species in these environments. Otero et al. (2006) also found negative *W* values. However, the authors related the results to the high frequency of juvenile individuals in the community and the selectivity of the fishing gear employed, which was more efficient at catching smaller individuals.

The large capture of juveniles of *S. herzbergii*, which was the dominant species in the P3 area, is in agreement with findings described by Karthikeyan *et al*. (2020), who characterize estuaries as ecosystems of high biological productivity and habitats for numerous organisms that use these ecosystems as nurseries, migration routes, and refuge areas.

In contrast, point P4, located in Inhaúma Stream, had the highest value, indicating a more preserved environment with more structured communities. Soares et al. (2011) state that the use of the ABC curve to assess environmental degradation has some methodological flaws. According to the authors, the capture of a large species may suggest that it is a permanent resident of the area and that the community has characteristics of k-strategist species; this is not a frequent finding in this environment.

CONCLUSION

The present study highlights the ecological relevance of the estuary of Coqueiros Strait as an area for reproduction, feeding, and shelter for different species of fish, confirming its strategic role in the maintenance of biodiversity in the Gulf of Maranhão.

Despite the proximity to port activities, no significant changes were found in the ecological indices over the study period, suggesting relative resilience of the local ichthyofauna. However, the dominance of a few species with significant abundance, such as *Sciades herzbergii*, indicates the need for attention to the possibility of future changes associated with anthropogenic pressure.

The temporal patterns identified demonstrate that seasonal factors, such as variations in rainfall and salinity, exert a direct influence on the composition and structure of fish assemblages. Spatial analysis revealed heterogeneity among the sampling points, with more balanced environments contrasting with

areas in which opportunistic species prevailed, which suggests greater vulnerability to environmental impacts.

This study underscores the importance of the continual monitoring of ichthyofauna in Amazonian estuarine ecosystems, especially in regions under the influence of port and industrial enterprises. The maintenance of time series of data is essential to understanding ecological trends and supporting sustainable management policies that reconcile the conservation of biodiversity with the food security of local populations. Thus, there is a need for integrated environmental management actions that ensure the sustainability of fisheries resources and the protection of these critical habitats.

Declarations

ETHICAL STATEMENT

All procedures were conducted in accordance with the legal and ethical standards for scientific research in Brazil. Authorization for fieldwork and biological sampling was granted by the Maranhão State Environmental Agency (SEMA/MA), under permit number 003–22.

COMPETING INTERESTS

The authors declare no competing interests

Author Contribution

Filipe França dos Santos Silva: Conceptualization, Data curation, Investigation, Methodology, Project administration. Scarlleth Patrícia Salomão da Silva: Data curation, Visualization. Danielle Viana Mendes: Data curation, Visualization Larissa Gabrielle Pinheiro Ferreira: Data curation, Investigation. Ingryd Lorena Batista de Oliveira: Data curation, Investigation. Marcelo Henrique Lopes Silva: Supervision, Validation, Writing – original draft. James Werllen de Jesus Azevedo: Supervision, Validation, Writing – original draft. Antonio Carlos Leal de Castro: Conceptualization, Data curation, Funding dentulous Investigation, Methodology, Project administration, Supervision, Writing – Original Draft, Writing – review & editing.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article.

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